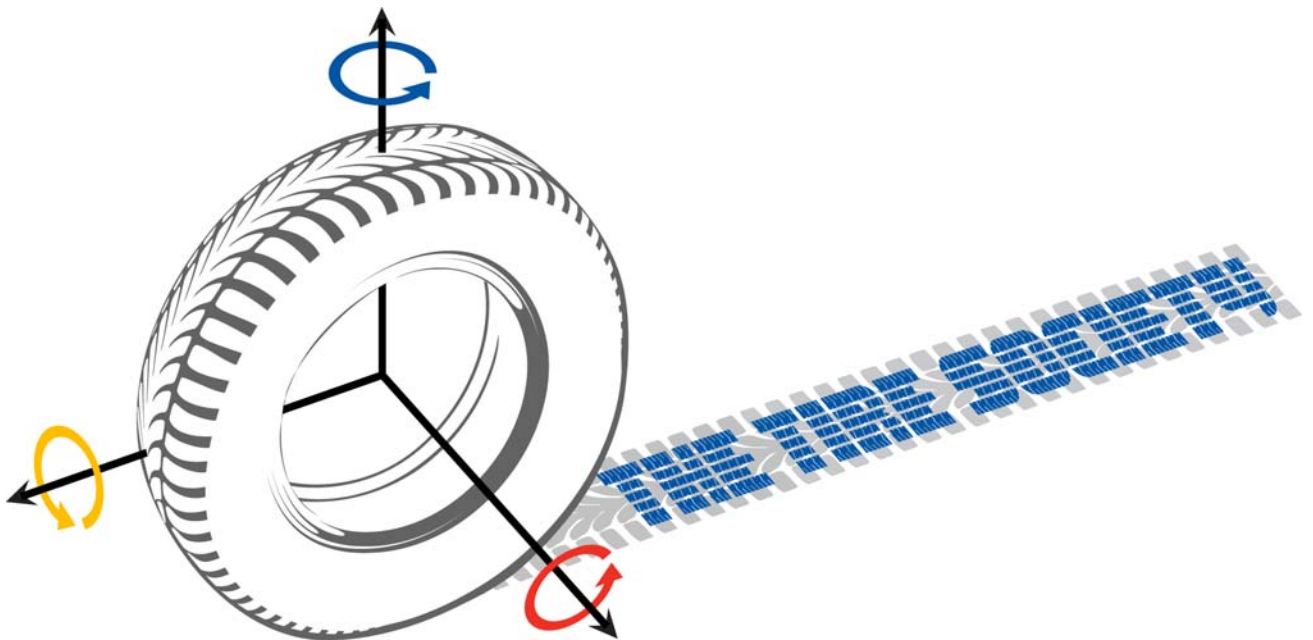


# 29<sup>th</sup> Annual Meeting and Conference on Tire Science and Technology

## Program and Abstracts



**September 20-21, 2010**  
**DoubleTree Akron/Fairlawn Hotel**  
**Akron, Ohio**



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# 29<sup>th</sup> Annual Meeting and Conference on Tire Science and Technology

DoubleTree Akron/Fairlawn Hotel, Akron, Ohio, USA

Day 1 – Monday, September 20, 2010

All Technical Sessions located in the Aspen Ballroom

7:00 AM	<b>Registration – until 5:00PM</b> ( <i>Foyer</i> )		
8:15 AM	<b>Conference Opening</b> ( <i>Aspen Ballroom</i> )		Barry Yavari, Conference Chair
8:20 AM	<b>Welcome</b> ( <i>Aspen Ballroom</i> )		Bob Wheeler, President
8:30 AM	<b>Keynote Address</b> ( <i>Aspen Ballroom</i> )		Seung Hwa Suh, Vice Chairman & CEO Hankook Tire
9:05 AM	<b>Session 1: Friction &amp; Rolling Resistance</b>		Ben Wen, Session Chair
9:10 AM	1.1	Investigation of Friction Mechanisms of Siped Tire Tread Blocks on Snowy and Icy Surfaces	Stefan Ripka
9:35 AM	1.2	Rolling Resistance of a Non-Pneumatic Tire Having a Porous Elastomer Composite Shear Band	Jaehyung Ju
10:00 AM	<b>Break</b> ( <i>Refreshments - Foyer</i> )		Sponsored by Hankook Tire
10:15 AM	<b>Session 2: New Light on Tire Technology 1 (Student Competition)</b>		Marion Pottinger, Session Chair
10:20 AM	2.1	Experimental and Numerical Study of Friction and Handling Characteristics of Rolling Tires	René van der Steen
10:45 AM	2.2	An Investigation Into Wheel Sinkage on Soft Sand	Noel Hathorn
11:10 AM	2.3	Derivation of LuGre Tire Parameters Using Laboratory Tests	Madhura Rajapakshe
11:35 AM	2.4	Vehicle Handling Studies Using An off-Road Tire Model	Brad Hopkins
12:00 PM	<b>Luncheon</b> ( <i>Conrad Ballroom at Hilton</i> )		Provided by The Tire Society
1:15 PM	<b>Session 3: New Light on Tire Technology 2 (Student Competition)</b>		Kory Smith, Session Chair
1:20 PM	3.1	Tapered Aluminum Structure Shear Band for a Non-Pneumatic Tire	Luke Berglind
1:45 PM	3.2	Tire Surface Vibration and Sound Radiation Resulting from the Tire Cavity Mode	Andrew Jessop
2:10 PM	3.3	Piezoelectric Vibration-Based Energy Harvesters for Next Generation Intelligent Tires	Kanwar Bharat Singh
2:35 PM	3.4	Sensor Module Development for Study of Tire Deformation	Vijaykumar Krithivasan
3:00 PM	3.5	Numerical Study of Vibration of An Alternating Spoke Pair Design Concept	Shashank Bezgam
3:25 AM	<b>Break</b> ( <i>Refreshments - Foyer</i> )		Sponsored by Hankook Tire
3:40 PM	<b>Session 4: Materials</b>		Vijayanand Muralidharan, Session Chair
3:45 PM	4.1	An Implementation of Component Material Damping for Tire Vibration Simulations	Bob Wheeler
4:10 PM	4.2	Application of A Simplified Viscoelastic Model to 3-D Simulation of Rubber Extrusion Flow	Minwu Yao
4:35 PM	4.3	Mechanics of Bend-Over-Sheave (Shoeshine) Fatigue Testing of Cord-Rubber Laminates	Philippe van Bogaert
5:00 PM	<b>End of Tuesday's Technical Sessions – Closing Comments</b>		
5:05 PM	<b>Reception</b> ( <i>Conrad Ballroom at Hilton</i> )		(Cash Bar / Hor d'oeuvres)
6:00 PM	<b>Dinner Banquet</b> ( <i>Conrad Ballroom at Hilton</i> )		
7:00 PM	Presentation: 2009 Superior & 2010 Student Paper Awards		Gary Tubb, Award Chair
7:20 PM	<b>Dinner Speaker:</b> Today's Turbulence: A Foundation for Future Automotive Success		Dr. David Cole, Chairman CAR
8:00 PM	<b>Adjourn</b>		

# 29<sup>th</sup> Annual Meeting and Conference on Tire Science and Technology

DoubleTree Akron/Fairlawn Hotel, Akron, Ohio, USA

Day 2 – Tuesday, September 21, 2010

All Technical Sessions located in the Aspen Ballroom

7:55 AM	<b>Registration – until 12:00PM</b> ( <i>Foyer</i> )		
8:05 AM	<b>Opening/Announcements</b> ( <i>Aspen Ballroom</i> )		Barry Yavari
8:10 AM	<b>State of the Society</b>		Bob Wheeler
8:35 AM	<b>Session 5: Noise, Vibration, and Harshness (NVH) Part 1</b>		Ric Mousseau, Session Chair
8:40 AM	5.1	Application of Coupled Structural Acoustic Analysis and Sensitivity Calculations to a Tire Noise Problem	Hamid Aboutorabi
9:05 AM	5.2	Influence of Tire Design Parameters on Vehicle Gravel/Sand Noise	Kiho Yum
9:30 AM	5.3	Directionality of Tangential Force Variation in High Speed Uniformity	Desheng Li
9:55 AM	<b>Break</b> ( <i>Refreshments - Foyer</i> )		Sponsored by Hankook Tire
10:10 AM	<b>Session 5: Noise, Vibration, and Harshness (NVH) Part 2</b>		Ric Mousseau, Session Chair
10:10 AM	5.4	A Training Method for Improving Tire Noise Subjective Evaluation Ability	Dongsoo Kang
10:35 AM	5.5	A New Approach to Tire Parameter Identification	Dietmar Weber
11:00 AM	<b>Plenary Lecture</b> ( <i>Aspen Ballroom</i> ) Application of Computational Mechanics to Tire Design – Yesterday, Today and Tomorrow		Yukio Nakajima, Professor, Kogakuin University
11:45 PM	<b>Lunch – On your own</b>		
1:15 PM	<b>Session 6: Simulation</b>		Hamid Aboutorabi, Session Chair
1:20 PM	6.1	Parallel Computing for Tire Simulations	Harish Surendranath
1:45 PM	6.2	Applications of Abaqus' Coupled Eulerian-Lagrangian Technology to Modeling Tire Interactions	Vivek Katiyar
2:10 PM	6.3	Study on the Indoor Wear Prediction by Using Explicit FE Simulation	SangHyeub Kim
2:35 PM	6.4	Load Capacity Improvement of the Current Lunar Roving Vehicle(LRV) Nonpneumatic Tire by Finite Element Analysis	Thulasiram Gobinath
3:00 PM	<b>Break</b> ( <i>Refreshments - Foyer</i> )		Sponsored by Hankook Tire
3:15 PM	<b>Session 7: Aging &amp; Testing</b>		Sam Knisley, Session Chair
3:20 PM	7.1	Nitrogen Inflation for Passenger Car and Light Truck Tires	John Daws
3:45 PM	7.2	Gas Transport In the Tire Aging Test and Intra-Carcass Pressure Issues	Vladimir Kerchman
4:10 PM	7.3	The Role of Tire Overturning Moment In Steering	Douglas Blue
4:35 PM	7.4	Developing the Next Generation In Tire Testing	James Cuttino
5:00 PM	<b>Closing remarks</b> ( <i>Aspen Ballroom</i> )		
<b>End of Conference</b>			

## About The Tire Society...

The Tire Society was established to disseminate knowledge and to stimulate development in the science and technology of tires. These ends are pursued through seminars, technical meetings and publication of the journal, Tire Science and Technology. The Society is a not-for-profit Ohio corporation managed by a duly elected Executive Board of tire industry professionals who serve on a volunteer basis.

### 2010 EXECUTIVE BOARD:

<b>President:</b>	Robert Wheeler	<i>Hankook Tire Company</i>	Uniontown, OH
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In addition to the Journal Editor, the associate editors volunteer time to contribute to the peer review process associated with publishing manuscripts in the Tire Science & Technology Journal:

### JOURNAL ASSOCIATE EDITORS:

Ronald H. Kennedy	<i>Hankook Tire Company</i>	Uniontown, OH
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Reinhard Mundl	<i>Technische Universität Wien</i>	Austria
Yukio Nakajima	<i>Kogakuin University</i>	Japan
Joseph Padovan	<i>University of Akron</i>	Akron, OH
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In addition to the Executive Board, many members volunteered their time to put together the 2010 conference.

## The 2010 Conference...

### CONFERENCE COMMITTEE:

**Program Chair:** Barry Yavari  
**Assistant Chair:** Saied Taheri

*The Goodyear Tire & Rubber Co.*  
*Virginia Polytechnic Institute and State University*

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*Sam Knisley*  
*Ric Mousseau*  
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*Marion Pottinger*  
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**Gary Tubb (Chair)**  
Rusty Adams  
Mike Pastwick  
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## The 2011 Conference...

Program Chair: Saied Taheri

*Virginia Polytechnic Institute and State University*

The 2011 conference committee would appreciate your assistance and suggestions. A call for papers will be issued to attendees of the 2010 conference and will be available online. Visit [www.tiresociety.org](http://www.tiresociety.org) for updates.



## **Keynote Address**

Monday, September 20, 2010

8:30 AM-9:00 AM

Aspen Ballroom

## **Tire Industry Opportunities and Challenges**



**Seung Hwa Suh, Hankook Tire, South Korea**

*Mr Seung Hwa Suh is the Vice Chairman & CEO of Hankook Tire. More than half of his 38 year career has been in positions related to international business affairs. His management philosophy is based on two main pillars: First, provide customers with the highest level of product & service quality; second, communicate and enhance unity among employees.*

*Under his leadership and priority on quality, Hankook Tire became one of the fastest tire companies to recover from the global financial crisis. In 2003, as Executive Vice President of the Marketing Division, he successfully led the renewal of corporate business intelligence (BI) and has been a key figure behind the company's innovative distribution channel strategy, which has seen it shift from wholesale to focus more on profitable retail partnerships.*

*He received a BA Politics and International Relations at Hankuk University of Foreign Studies (1971). He joined Hankook Tire in 1973, and has held the following positions - Director, Overseas Marketing (1996) - COO, Hankook Tire America Co, Ltd (1997) - Executive Vice President, Overseas Sales (2001) - Executive Vice President, Marketing Division (2003) - President and COO, Hankook Tire Europe Regional Headquarters (2006) - President and CEO, Hankook Tire Co, Ltd (2007 ~ 2009) - Vice Chairman and CEO, Hankook Tire Co, Ltd (2009 ~ Current).*

## **Dinner Speaker**

Monday, September 20, 2010

7:20 PM-8:00 PM

Conrad Ballroom (at Hilton)

## **Today's Turbulence: A Foundation for Future Automotive Success**



**David Cole, Center for Automotive Research (CAR)**

*David E Cole is the Chairman of the Center for Automotive Research (CAR) in Ann Arbor, Michigan. He was formerly Director of the Office for the Study of Automotive Transportation (OSAT) at the University of Michigan Transportation Research Institute. He has worked extensively on internal combustion engines, vehicle design, and overall automotive industry trends. Dr. Cole's recent research has focused on strategic issues related to the restructuring of the North American industry and trends in globalization, technology, market factors, and human resource requirements. Dr. Cole received his BSME & Mathematics, MSME, and Ph.D. degrees from the University of Michigan and recently received an honorary doctorate from Cleary University.*

The turbulence of the past several years has been unprecedented in the modern era of the auto industry. Massive restructuring has dramatically lowered the break-even volume. However many challenges remain including an uncertain economy, exit of the boomers, tough new fuel economy requirements, accelerating global integration and a host of new technologies. The industry business model has been permanently altered as we accelerate into the future but the foundation for success is in place.

## Plenary Lecture

Tuesday, September 21, 2010

11:00 AM-11:45 AM

Aspen Ballroom

# Application of Computational Mechanics to Tire Design – Yesterday, Today, and Tomorrow



**Yukio Nakajima**, Faculty of Global Engineering, Kogakuin University

*Dr Yukio Nakajima is a professor, Faculty of Global Engineering, Kogakuin University, Japan. He was with Bridgestone Corporation from 1977 through his retirement in 2010. He was Director, Tire Research Division prior to retirement. At Bridgestone, he developed technology related to tire mechanics such as noise, wear, maneuverability, RR, snow traction, and then studied the application of computational mechanics to tire design by combining FEA with optimization technique. His hobby is mountaineering. He received his Ph.D. in Mechanical Engineering from the University of Akron.*

The tire technology from the standpoint of yesterday, today and tomorrow will be reviewed.

Yesterday; a finite element method was developed in 1950s as a tool of computational mechanics. In Bridgestone Corporation, FEA was started applying to a tire analysis in the beginning of 1970s and this was much earlier than the vehicle industry, electric industry, and others. The main reason was that construction and configurations of a tire were so complicated that analytical approach could not solve many problems related with a tire mechanics. Since the commercial software was not so popular in 1970s, the in-house codes were developed for three kinds of application such as stress/strain, heat conduction and modal analysis. In 1980s computer speed became reasonable and the commercial software was improved. But in-house axisymmetric code was still mainly used for tire analysis because the computer speed was not still sufficient for a tire analysis. Since FEA could make the stress/strain visible in a tire, the application area was mainly tire durability.

Today; combining FEA with optimization technique, the tire design procedure is drastically changed in tire side wall shape, tire crown shape, pitch variation, tire pattern, and etc. So the computational mechanics becomes an indispensable tool for tire industry. Furthermore, the insight to improve tire performance is obtained from the optimized solution and the new technologies are created from the insight. Then, FEA is applied to a various area such as hydroplaning and snow traction based on the formulation of fluid-tire interaction. Since the computational mechanics enables us to see what we could not see, the new tire patterns are developed by seeing fluid flow in tire contact area and shear stress in snow in traction.

Tomorrow; the computational mechanics will be applied in multi-disciplinary area and nano-scale area to create a new technology.

## **Investigation of Friction Mechanisms of Siped Tire Tread Blocks on Snowy and Icy Surfaces**

**Stefan Ripka**

Hagen Lind

Matthias Wangenheim

Institute of Dynamics and Vibration Research

Leibniz Universität Hannover

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Klaus Wiese

Tire Line Development Winter

Continental Reifen Deutschland GmbH

Hannover, Germany

Burkhard Wies

Tire Line Development

Continental Reifen Deutschland GmbH

Hannover, Germany

Due to general safety reasons and an increasing individual demand on more traffic safety, winter tires become more and more important. This evolution results in a rising requirement of the customers concerning the tire performance on the one hand and the effort of the tire industry for improving the tire characteristics on the other hand. For engineering winter tires in an effective way, the friction influencing factors as well as the contact mechanics should be well known. Normally the design and development of tires is strongly based on vehicle tests, but in modern tire development processes the simulation as well as the experimental investigation of tires and tire components in the lab become more popular. This strategy especially plays an important role for reducing the time of development cycles but also the development costs.

With simulation and experiments in lab, new challenges come up which have to be solved. Lab experiments compete with totally different problems: First of all the environmental influence like temperature and humidity have to be controlled. Furthermore the test tracks used inside must be comparable to the proving ground outside, hence the properties of snow and ice have to be investigated in detail. Therefore it is very important to understand the formation of snow and ice but also finding characteristics of both materials which can be identified and measured with mobile measurement devices outside on the test track and inside in the lab.

Within this publication a general overview of the tire tread block test method as well as the test rig will be given which are used for identifying relevant tread block friction mechanisms on snow and ice. The results of the measurement will be shown and the acting friction phenomena will be explained. Furthermore different approaches for characterizing snow and ice are presented.

## **Rolling Resistance of a Non-Pneumatic Tire Having a Porous Elastomer Composite Shear Band**

**Jaehyung Ju**

Joshua Summers,  
Mechanical Engineering,  
Clemson University,  
Clemson, SC  
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The shear band is the critical component of a non-pneumatic tire to determine the rolling resistance caused by an elastomer's shear friction. In an effort to reduce the rolling resistance of a non-pneumatic tire, a shear band made up of a porous – fiber reinforced elastomer is suggested. The porous shear band is designed to have the same effective shear modulus as the shear modulus of a continuous shear band. The decrease in the volume of the elastomer will reduce the hysteretic energy dissipation. Finite element (FE) based numerical experiment with ABAQUS is conducted to quantify the reduced energy loss of a non-pneumatic tire using hyperelastic and viscoelastic material models. Load carrying capacity and contact pressure response of the non-pneumatic tire with the designed porous shear band are also discussed.

## Experimental and Numerical Study of Friction and Handling Characteristics of Rolling Tires

**René van der Steen**

Ines Lopez

Henk Nijmeijer

Department of Mechanical Engineering

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Bart de Bruijn

Apollo Vredestein BV

Enschede, Netherlands

Antoine Schmeitz

TNO Science and Industry

Business Unit Automotive

Helmond, Netherlands

The aim of this study is to develop a friction model, which captures observed effects of dry friction on the handling characteristics of rolling tires. A phenomenological friction model is chosen, where the parameters are identified using a two-step experimental / numerical approach. Firstly friction experiments are performed on a Laboratory Abrasion and skid Tester to develop a pressure part of the friction model<sup>[1]</sup>. Secondly braking experiments at different velocities with a specially designed non-production tire are conducted to obtain a velocity dependent parameter set. This is described in the present contribution.

The derived friction model is coupled to a FE model of the tire, which is constructed in the commercial FE package ABAQUS. The steady-state transport approach is used to efficiently compute steady-state solutions. The basic handling characteristics, such as pure braking, pure cornering, and combined slip under different loads, inflation pressures and velocities are evaluated and compared with experiments performed with the TNO Tyre Test Trailer.

**Acknowledgements:** This research is funded by the CCAR project 'FEM Tyre Modelling', in cooperation with Apollo Vredestein B.V. and TNO Science and Industry.

[1] R. van der Steen, I. Lopez, H. Nijmeijer, "*Experimental and numerical study of friction and stiffness characteristics of small rolling tires*", Tire Science and Technology, Accepted for publication.

## **An Investigation into Wheel Sinkage on Soft Sand**

**Noel Hathorn**

James Brighton

Kim Blackburn

Centre for Automotive Technology

Cranfield University

Bedford, United Kingdom

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Sinkage is an empirically significant factor in vehicle performance as it can result in an immobile vehicle or environmental damage. Bernstein first proposed a pressure sinkage relationship in 1913, subsequent work by Janosi and Hanamoto and Hedegus concluded that longitudinal wheel slip also plays a role in sinkage. Shinone, Nakashima, Takatsu, Kasetani and Matsukawa identified a linear relationship between slip and sinkage on a lightly loaded tire. In this study the effects of vertical wheel load, wheel slip and tire inflation pressure on wheel sinkage on soft sand were investigated, in order to relate sinkage to a vehicular operating condition.

The tests in this study were conducted using the Cranfield University Single Wheel Tester (SWT) on soft, desert-like sand in the Cranfield Off-Road Dynamics facility soil bin. The SWT uses a closed loop servo-controlled hydraulic ram to actively control vertical wheel load and similar active wheel speed control via a hydraulic motor. The SWT apparatus is mounted on an independent prime mover tractor unit which controls forward speed. True forward speed is continuously measured against a fixed reference point and used to calculate the required wheel speed in real time to give the desired slip profile.

A series of controlled load tests were conducted using a Goodyear G90 tire (7.50 R16C) on a dry desert sand material. Four discrete inflation pressures (10, 20, 30 and 40 psi) and four vertical loads (1, 2, 3, 4 and 5 kN) were chosen to represent the operating range of the tire. Each test run consisted of a slow (30s) ramp of slip ratio from 85% (driven) to -15% (braked).

Although a near linear response was identified for slips greater than 10% as Shinone et al. also found, the overall relationship between slip and sinkage was found to be non-linear.

## Derivation of LuGre Tire Parameters Using Laboratory Tests

**Madhura Rajapakshe**  
Civil and Environmental Engineering  
University of South Florida  
Tampa, FL  
[mrajapak@mail.usf.edu](mailto:mrajapak@mail.usf.edu)

In most of its past applications the LuGre tire friction model has been empirically calibrated by tuning its parameters to fit measured tire-pavement friction data or an already calibrated friction model. However, physical significance of the model parameters is one important advantage of this widely used analytical tire friction model. It enables this model to provide physically intuitive guidelines for harmonizing different tire-pavement friction measuring devices by introducing modifications to their measurement mechanisms.

In modeling dynamic tire forces using the LuGre model, the mechanical properties of the tire are represented by stiffness and damping parameters of the brushes/bristles that resemble the contact surface of the tire. In this study, specially designed laboratory tire tests were carried out to measure stiffness and damping properties of the ASTM E524 standard smooth tire used for testing pavement friction. The properties were measured in vertical, lateral, and longitudinal directions and used to derive lumped LuGre tire parameters. Derived tire parameters were found to be closely comparable to those obtained using data fitting methods, hence validating both derivation and optimization approaches for LuGre model parameterization.



## Vehicle Handling Studies Using An off-Road Tire Model

**Brad Hopkins**

Mechanical Engineering  
Virginia Polytechnic Institute and State University  
Blacksburg, VA  
[bradhopkins@vt.edu](mailto:bradhopkins@vt.edu)

Saied Taheri

Mechanical Engineering  
Virginia Polytechnic Institute and State University  
Danville, VA

An off-road tire model has been developed for use in vehicle handling studies. A baseline force and moment model was first developed for the studied tire by performing force and moment testing on a rolling road. Forces and moments were recorded in response to slip angle, camber angle, and vertical load inputs and a Pacejka Magic Formula model was determined. This baseline force and moment tire model is applicable for a dry asphalt driving surface.

Next, off-road tire testing was performed on a passenger tire by using a portable tire test rig. The tire was subjected to slip angle sweeps at various vertical loads while being driven on dry asphalt, dirt, and gravel. Lateral force scaling factors for use in the Magic Formula were obtained for the dirt and gravel driving surfaces. The scaling factors were then applied to the studied tire to extend its lateral force behavior on dry asphalt to dirt and gravel. The off-road tire model was then used in commercially available vehicle simulation software to simulate vehicle handling behavior on dirt and gravel driving surfaces.

## **Tapered Aluminum Structure Shear Band for a Non-Pneumatic Tire**

**Luke Berglind**

Jaehyung Ju

Joshua Summers

Mechanical Engineering

Clemson University

Clemson, SC

[lbergli@clemson.edu](mailto:lbergli@clemson.edu)

Shear compliant cellular structures are being considered for shear band applications due to low hysteretic energy loss and the ability to design the effective properties of the material through geometric modifications. In this paper, a rectangular shaped cellular shear band for a non-pneumatic tire is introduced which utilizes a tapered bristle geometry.

One challenge in the design of cellular structures is that shear compliance is limited by the maximum stress incurred in the structure during deflection. As such, the structures should be designed to reduce stress concentrations so that material deformation throughout the structure can be utilized efficiently to achieve high compliance.

The bristle concept developed in this paper utilizes a tapered geometry which results in an even distribution of maximum bending stress along the bristle profile, resulting in increased compliance with high stiffness. An analytical model is developed for the tapered profile to determine bending stiffness based on a desired amount of deflection and maximum bending stress. Numerical tests are conducted using Abaqus to validate the analytical model, find the effective properties, the resulting contact pressure and the rolling resistance of the tapered bristle design.

## **Tire Surface Vibration and Sound Radiation Resulting From the Tire Cavity Mode**

**Andrew Jessop**  
J. Stuart Bolton  
Herrick Laboratories  
Purdue University  
West Lafayette, IN  
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It is well-known that acoustic modes exist in tire cavities. Previous research on tire cavity modes has focused on the splitting of this mode owing to tire loading and rotation, and on the transmission of structure-borne noise to the vehicle interior due to force that the tire cavity mode exerts on the wheel hub. In contrast, here the major concern is the identification of the tire surface vibration and the sound radiation from the tire surface that can be attributed to the tire cavity mode.

The tire cavity mode results from the interference of airborne, acoustical waves propagating in opposite directions within the tire cavity. Those waves drive corresponding waves in the tire carcass. Here, the surface normal vibration of a point-driven tire has been measured over a complete circumference by using a scanning laser Doppler vibrometer. When the space-frequency data is transformed to the wavenumber-frequency domain, a clear feature that can be attributed to the tire cavity mode becomes visible. Wavenumber filtering (to remove the effect of structure-borne waves in the tire carcass), followed by an inverse transform, reveals the spatial pattern of vibration on the tire surface resulting from the tire cavity mode. Although the magnitude of the surface vibration resulting from the tire cavity mode is small, its radiation efficiency is high owing to the high phase speed of the acoustic waves that create the tire cavity mode. It has also been found, that, as expected, tire vibration features associated with the tire cavity mode disappear when the tire is filled with fibrous, sound absorbing material. The splitting of the tire cavity mode into two modes having slightly different frequencies will also be demonstrated, and the degree of the split will be compared with theoretical predictions. Finally, measurements of sound radiation from a tire driven by a steady-state, point input, and from a tire driven by a uniform impact over the contact patch area will be presented, and the features associated with the tire cavity mode will be highlighted.

## **Piezoelectric Vibration-Based Energy Harvesters for Next Generation Intelligent Tires**

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The environment inside an automobile tire is typically harsh, with temperature extremes ranging from -25°C to 140°C. Often, these temperature extremes preclude the use of batteries for sensor nodes embedded inside an intelligent tire. The high vibration levels inside a tire have the potential to generate electrical power using vibration based energy harvesting techniques.

In this paper, the feasibility of using an inertial vibrating energy harvester unit to power a sensor module being used to monitor the tire road interaction parameters is assessed. To predict the electrical power output of the generator, a generic analytical model based on the transfer of energy within the system has been derived. The vibration measurements taken from the test conducted using accelerometers embedded in the tire have been applied as an excitation to the model to predict the power output for a device of suitable dimensions and to study the feasibility of this concept. The power generator unit is adapted to the tire vibration spectra and the superimposed acceleration signal.

The harvester utilizes the radial accelerations, which are impacts resulting from the tire–road contact and are present even at constant vehicle speeds. For the intelligent tire applications, a special compact harvester design has been proposed that is able to withstand large shocks and vibrations. Suitable mathematical models for different harvester configurations have been developed to identify the best configuration suited for use inside a tire. The harvester unit demonstrates power generation over a wide speed range and enables sensor systems to transmit tire information at desired rates.

The proposed concept addresses one of the key challenges in the realization of the intelligent tire system concepts, by presenting a battery-less power supply unit which can generate power that is sufficient for a multitude of wireless platforms such as ZigBee and Wi-Fi protocols which are expected to find their way in the next generation intelligent tires. These harvesters designed for the harsh tire environments provide a distinct advantage in cost and flexibility of installation while extending the lifetime of the power supply for sensor data acquisition and communication. Results indicate the viability of the procedure outlined in the paper.

## Sensor Module Development for Study of Tire Deformation

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This paper investigates the use of computational and experimental methods to characterize the behavior of an automobile tire. First a 3D finite element model of standard reference test tire (SRTT) was developed to better understand the tire deformation under loading conditions. A parametric study of inflation pressure, normal loading, camber angle and slip angle was carried out to capture the influence of these parameters. A parametric study of the combined case scenario of the effects of the previously mentioned parameters was also performed.

A wireless sensor suite comprising of analog devices (strain, pressure and temperature sensors) was developed to capture the tire deformation under loading conditions similar to the ones used in running the finite element model. This sensor suite formed the basis for experimentally verifying the trends captured by the finite element model on a custom built tire test stand with capabilities of mimicking real-time conditions of a tire in contact with road. Using the results from the experiments and the finite element model an empirical model was developed which demonstrates how the hoop strains measured on the inner surface of the tire could be used to quantify desired parameters such as camber, slip and normal load. This model outlines empirical equations that relate strains to the contact area, slip (including slip angle and slip ratio), camber and normal load.

## **Numerical Study of Vibration of an Alternating Spoke Pair Design Concept**

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Recently, Michelin has invented an innovative non-pneumatic tire which has potential for improved handling, grip, comfort, and less rolling resistance when compared to a traditional pneumatic tire. During high speed rolling in initial testing, the original prototype showed high noise levels at frequencies above 100 Hz. Previous work studied the effect of geometric parameters on spoke vibration and ground force interaction during high-speed rolling. In the present work, a 2D planar finite element model is used to simulate rolling of the non-pneumatic tire.

The current work considers the design and analysis of new alternate spoke pair concepts wherein from pair to pair the spoke properties are different, with every other spoke pair having the same properties. Alternating spoke pair properties of thickness, curvature, or combinations of both are considered. The results indicate that for equivalent mass, the alternating spoke pair design with small changes, i.e. plus/minus 5% in spoke thickness between pairs, broadens the range and increases the number of frequencies of peak amplitudes for the ground reaction force while reducing the magnitude of these peak amplitudes. However, the model with alternating spoke pair thickness showed the same spoke vibration frequencies and amplitudes compared to a reference model with uniform spoke pairs with the same thickness distribution. In contrast, when small changes in curvature instead of thickness were introduced in the alternating spoke pairs design concept, the spoke vibration amplitudes reduced without much effect on the ground vibration. Combining thin spokes with large curvature within a pair and thick spokes with small curvature within the other spoke pair produces an effective design which reduces the amount of vibration in both the spoke and ground interaction.

## **An Implementation of Component Material Damping for Tire Vibration Simulations**

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This research addresses modeling of material damping at the component level of tires for vibration simulations in the low to mid frequency range (0 to ~200 Hz) using finite element analysis (FEA). Historically in these simulations, damping has been assumed or measured at the global level of the tire and therefore has provided limited usefulness for virtual design processes.

The proposed method introduces an implementation of the material loss moduli at the component level to complement existing material storage moduli and density implementations. It therefore introduces the capability to predict tire damping and making it useful for design and tuning. Testing and analysis techniques developed previously to measure and characterize material storage moduli at vibratory strains are revisited to include the material loss moduli. The vibratory loss moduli are included into FE models used for vibration simulations in a manner parallel to existing vibratory storage moduli.

The technique is first validated on single elastomeric compounds with good correlation achieved between measured and predicted frequency response functions (FRF's) of dual-lap shear specimen modal tests. The technique is then applied to a full tire FE model with multiple compounds and validated with good correlation between measured and predicted FRF's from the unloaded portion of the SAE-J2710 modal test.

## **Application of A Simplified Viscoelastic Model to 3-D Simulation of Rubber Extrusion Flow**

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Rubber is a very unique material. During processing and shaping, the uncured rubber behaves like a viscoelastic fluid. Proper analysis of rubber processing requires special material modeling and nonlinear finite element analysis tools that are quite different from those used for cured rubber. Key features of rubber flow behavior include: shear-rate dependence of the shear-thinning viscosity; presence of normal stresses in viscometric flows; and memory effects associated with the elasticity of the fluid. It has been known that modeling 3-D rubber flow with the traditional viscoelastic models remains to be a great challenge which requires excessive CPU time and memory.

An alternative to the traditional viscoelastic models is the simplified viscoelastic models which have emerged in recent years. To meet the challenge in modeling the die design for contoured rubber extrudates, a special material characterization procedure for a simplified ViscoElastic (VE) fluid model was developed based on the Capillary rheometer measurement data. The fitted simplified VE fluid model was then applied to 3-D rubber extrudate swell simulations. Without the elastic contribution, simulation results show significant unrealistic extrudate shrinkage. When rubber elasticity is incorporated, promising results of predicted extrudate swell were obtained with the simplified VE model. The parameter study results demonstrated that the amount of elastic swell can be easily and effectively controlled in the simplified VE model. Details of the material characterization process, benchmark tests of the simplified VE model and simulation results will be presented in this paper.



## Mechanics of Bend-Over-Sheave (Shoeshine) Fatigue Testing of Cord-Rubber Laminates

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The 'Bend-over-Sheave' test has proven its relevance in the tire industry since the 1930's, especially on fatigue interply delamination and rubber-fabric & rubber-cord adhesion degradation. The typical cyclic load of tension of the sidewalls or tension-compression of the belt can be achieved by the proper definition of 2-ply laminates bended on a wheel with defined radius and traction force.

The new ecological challenges on rolling resistance, wet grip, noise & mileage life are driving the emergence of alternative rubber, filling and hybrid reinforcement materials, for which the overall fatigue behavior should be tested in the early stage of new tire design.

Modern FEA methods like Abaqus are permitting to define the stress & strain within the tire sidewall & belt reinforcing layers and to simulate crack initiation & propagation.

By using the same material properties and calculation methods, relevant fatigue test conditions can be defined to early predict the performance of the new materials.

The results obtained show the relevance for this test of the following points:

- non-linear properties of the reinforcement cord
- the compression of the interply rubber
- interply shear deformation
- free length of the specimen
- clamping method
- specimen manufacturing quality

Also a simplified mathematical model is proposed for rapid estimation of the specimen test conditions.

## **Application of Coupled Structural Acoustic Analysis and Sensitivity Calculations to a Tire Noise Problem**

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Tire qualification for an OE program consists of several rounds of submissions by the tire manufacturer for evaluation by the vehicle manufacturer. Tires are evaluated both subjectively where the tire performance is rated by an expert driver, and objectively where sensors and testing instruments are used to measure the tire performance. At the end of each round of testing the evaluation results are shared and requirements for performance improvement for the next round are communicated with the tire manufacturer. As building and testing is both expensive and time consuming predictive modeling and simulation analysis that can be applied to the performance of the tire is of great interest and value.

This paper presents an application of FEA modeling along with experimental verification to solve tire noise objections at certain frequencies raised by an OEM account. Coupled structural-acoustic analysis method was used to find modal characteristics of the tire at the objectionable frequencies. Sensitivity calculations were then carried out to evaluate the strength of contribution from each tire component to the identified modes. Based on these findings changes to the construction were proposed and implemented that addressed the noise issue.

## **Influence of Tire Design Parameters on Vehicle Gravel/Sand Noise**

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In this research, vehicle gravel & sand noise was studied from a view of tire design. First, the mechanism of gravel & sand noise was identified by driving on the road where sand and small particles of gravel were spread. Second, the influence of tire design parameter on vehicle gravel noise was studied by controlling tire tread pattern and viscoelastic characteristics of tire tread rubber and then the influence on braking and rolling resistance performance was also studied. It was found that high frequency gravel noise was mainly recognized in the rear seat of SUV and decreases as road surface temperature increases. In addition, the directional tread pattern with symmetry was found to amplify gravel noise. Finally, it was found that gravel noise has a relationship with  $\tan\delta$  characteristics in low temperature and braking distance. In particular, gravel noise decreases as braking distance decreases.

## **Directionality of Tangential Force Variation in High Speed Uniformity**

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Tire non-uniformity may affect vehicle ride comfort quality especially while vehicles are running at highway speeds. Spindle force variations in the radial, tangential and lateral directions are normally used as parameters evaluating tire high speed uniformity performance. An interesting physical phenomenon – directionality of tangential force variation has been observed for most tires. The directionality of tangential force variation means that tangential force variation is different when a tire is measured in the clockwise and counter-clockwise directions. In this paper, a theory is developed to explain the interesting physical phenomenon. Simulation and analysis are conducted using a dynamic tire model. It is found that the directionality of tangential force variation is caused by the interaction of different types of non-uniformities in tires such as mass and geometry variations.

## **A Training Method for Improving Tire Noise Subjective Evaluation Ability**

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Physically, noise could be analyzed with respect to energy distribution in frequency range and its level. But it is not the best way to fix the tire noise sometimes if the objective analysis result is not well correlated with human perception. Therefore many studies have been done to make the good objective parameters in noise analysis and we call them sound quality matrix. On the contrary noise subjective evaluator should be studied not only by own experience but also by the intended training program. However we don't have any formal education course for subjective noise evaluation skill upgrade until now.

Triadic comparison tests are done by the best skilled subjective evaluators who have over 15 years' experience. From these noise preferences verbal technical words are unified and they are used for training. Also we made timbral training simulator to improve tire noise evaluation skill. This simulator is tested for several beginners and it shows a good result. We combine two processes and make total training method for improving tire noise evaluation ability.

## A New Approach to Tire Parameter Identification

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Tire parameter identification (PI) for multi-body-system (MBS) tire models is a time-consuming task. Since MBS tire simulations implement highly abstract, effective models, the tire model parameters cannot be interpreted as physical (material) properties directly, they must be seen as macroscopic entities in an integral sense. In a set of typically 30 and more parameters with varying orders of magnitude, optimal values are to be found that make various tire simulation results fit best to experimental data in some sense.

Interpreted as an optimization program, some numerical schemes can be applied to reduced (sub)-sets of programs - but this approach always includes making an initial guess based on physical tire properties or experience. Also, repeated manual interactions take place during a typical program - monitoring the current progress by visual inspection and iterating over this process until a certain optimum is reached. Due to the variety of parameter combinations and the relatively long simulation time, the global optimum for all available measurements usually cannot be found with acceptable effort (if at all); instead a subspace strategy is typically applied.

Hence the definition of "optimum" often lies in the eye of the beholder, i.e. identical PI tasks done by different experts generally lead to different optima. Real test data are acquired by static experiments (e.g. vertical/longitudinal stiffness), stationary experiments (longitudinal/lateral slip) and dynamic experiments (e.g. cleat runs). The way of comparing experimental and simulation results also influences the detected optimum and leads to the problem of defining suitable error criteria (i.e. what is "good" PI).

This paper focuses on a new programmatic approach developed at Fraunhofer LBF relying on a rule based expert system. The new PI-Tool makes PI faster, more standardized, as automatable as possible and the results at least as good as achieved by current processes. Special focus was put on developing error criteria which try to mimic the human skill while comparing measurement and simulation results - a multi-layered and complex process. Various local signal properties and signal processing algorithms are derived to simulate the experiment-conform, visual human inspection.

Together with the presentation of this new PI method, results achieved with our new tool will be shown using the tire model CDTire for an already parameterized tire.

## Parallel Computing for Tire Simulations

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Over the last few decades, finite element analysis has become an integral part of the overall tire design process. Engineers need to perform a number of different simulations to evaluate new designs and study the effect of proposed design changes. However, tires pose formidable simulation challenges due to the presence of highly non-linear rubber compounds, embedded reinforcements, complex tread geometries, rolling contact and large deformations. Accurate simulation requires careful consideration of these factors, resulting in extensive turnaround time, often times prolonging the design cycle. Therefore, it is extremely critical to explore means to reduce the turnaround time while producing reliable results.

Compute clusters have recently become a cost effective means to perform high performance computing (HPC). Distributed memory parallel (DMP) solvers designed to take advantage of compute clusters have become increasingly popular. In this paper, we examine the use of HPC for various tire simulations and demonstrate how it can significantly reduce simulation turnaround time. Abaqus/Standard is used for routine tire simulations like footprint and steady state rolling. Abaqus/Explicit is used for transient rolling and hydroplaning simulations. The run times and scaling data corresponding to models of various sizes and complexity are presented.

## **Applications of Abaqus' Coupled Eulerian-Lagrangian Technology to Modeling Tire Interactions**

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Hydroplaning, Snow-Tire Interaction, and Mud-Tire Interaction are becoming of increasing interest to Tire industry. With the availability of High Performance Computing, these analysis can now be routine and included as part of tire workflows.

These interactions are either Fluid-Structure Interaction type (i.e., Hydroplaning), or involve complex material behavior undergoing large permanent deformation in both volumetric and shear (i.e., snow or mud). The Eulerian framework where the mesh is stationary and the material moves within mesh is more effective than the traditional lagrangian framework for these cases. Abaqus' Coupled Eulerian-Lagrangian (CEL) technology can model the contact of the lagrangian tire with the eulerian material (water, snow or mud) in the General Contact framework of Abaqus/Explicit. A general overview of this capability along with general material models will be presented to demonstrate the application of CEL within Abaqus.



## **Study on the Indoor Wear Prediction by Using Explicit FE Simulation**

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A majority of tire makers make an effort to improve irregular wear that has a strong influence on tire performance. The standardized indoor wear tests or FE simulations are representative methods used to predict the tread wear performance. Especially, tread wear prediction method is developed using FE simulation that was more effective to reduce tire development time and cost.

In the previous paper, tire tread wear was predicted by explicit FEM and compared with the indoor wear test results under a set of actual driving conditions. For the FE simulation, pressure dependent friction model, the selected wear rate equation and the simplified driving conditions were applied and the simulated wear results for the patterned tires were compared with the indoor wear test results.

For the enhancement of tread wear prediction, pressure and slip dependent friction model is adopted in this study. And, 205/55R16 tire is used to determine the most appropriate friction model and wear rate equation. The selected friction model and wear equation is verified through alterations of size, loading severity, pattern, as well as velocity. In order to enhance the wear simulation efficiency, simplified 9 conditions that consider the driving condition frequency and weighting factors are selected to predict the indoor wear tests. As a result, the simulated wear shows good agreement with the indoor wear test.

## **Load Capacity Improvement of the Current Lunar Roving Vehicle(LRV) Nonpneumatic Tire by Finite Element Analysis**

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The 1971 moon mission Lunar Roving Vehicle (LRV) used tires that were designed to have a load capacity of about 57 lbs of moon weight. NASA's next moon mission is intended to be an ambitious one, which is expected to raise the load capacity requirement of the tire by nearly ten-fold.

Concept designs that would achieve this aggressive target were evaluated by finite element method and the results were presented to NASA. Comparisons with the prototype test data were done wherever appropriate to ascertain accuracy of the predicted structural responses.

Two different and novel numerical approaches to evaluate the lunar tire are described. The first approach involves modeling the wire-meshed tire as rebars embedded in membrane elements and sandwiched between two continuum elements. The membrane approach utilizes the explicit time integration finite element scheme, and the method's effectiveness is shown by the excellent agreement between the numerical and laboratory results.

The second approach involves modeling the wires explicitly by depicting the two layers of wire mesh as two layers of beam elements interconnected by interlocking joints representing the crimp joints used in manufacturing these tires. It is demonstrated here that the joint motions can be simulated by utilizing the connector elements capability in ABAQUS and enforcing a limit on the rotation on the joint angles. It was found that the limiting angle configurations can be determined by a simple shear mode experiment of a square grid sample. The validation of the computational approach is shown by demonstrating extremely good correlation to the measured force-deflection curves in vertical, lateral, longitudinal and torsion directions. An extension to the approach is demonstrated by attaching tread plates to the wire carcass. The effects of the tread plate geometry on the tire stiffnesses and footprint are quantified.

## **Nitrogen Inflation for Passenger Car and Light Truck Tires**

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Nitrogen as an inflation gas for passenger car and light truck tires use is widely available commercially. Consumers are confronted with a bewildering selection of offerings, and suppliers tout the purity of their nitrogen generation systems and effectiveness of using the gas in place of air. This paper develops models for the initial tire nitrogen purity, the inflation pressure loss rate, and the evolution of the nitrogen gas purity in the tire as a function of the gas used to top off the tire over its life. A series of simulations using the basic model is developed for air and various purities of nitrogen initial inflation with monthly top-off using air or various purities of nitrogen. The initial inflation pressure loss rate is shown as a function of the tire's initial nitrogen purity. This paper proposes the use of the total oxygen passing through the tire over its lifetime as a metric for evaluation of various inflation schemes. This metric is developed for several of the popular available nitrogen inflation purities using both air and nitrogen as a top-off gas.

## **Gas Transport in the Tire Aging Test and Intra-Carcass Pressure Issues**

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Development of the laboratory-based accelerated service life testing - "tire aging test"- encountered difficulties due to complexity of multi-disciplinary processes in the tire materials while trying to induce thermo-oxidative degradation, similar to that taking place in the 'worst case' in-service. Preliminary experience with the oven aging at elevated temperatures showed that in some light truck tires damaging conditions occur in the form of sidewall blisters/detachments and casing separations due to inflation gas built up in interior tire layers during aging, even prior the roadwheel endurance testing<sup>[1]</sup>.

Analysis and comprehensive modeling techniques are developed for gas diffusion and oxidation in the tire structure, with focus on the Intra-Carcass Pressure (ICP) build-up predictions. In Finite Element models temperature dependent diffusion properties are used with account for their high heterogeneity in different tire components. Results of transient simulations predict higher oxidation/ degradation rate in the sidewall and detrimental effect of ICP build-up for Load Range E tires. Influence of the butyl liner barrier permeability and gauge is evaluated, as well as impact of other construction variations. Predicted trends agree with the available observations and measurements. ICP levels in simulations of the long-term gas diffusion under regular service conditions are significantly lower than in the aging test modeling. Modified aging test conditions are proposed that will greatly reduce deleterious side-effect of the ICP buildup, as assessed in simulations.

1. DOT HS 810799 "Research Report to Congress on Aging" (2007)

## The Role of Tire Overturning Moment in Steering

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Tire overturning moment measurements have traditionally been used primarily for rollover threshold analysis, and have often been ignored for linear range maneuvers. This paper explains how overturning moment is related to aligning torque for a tire under tractive force. This relationship can be used to develop a better understanding of tire properties necessary to achieve better steering refinement. A free rolling overturning moment measurement is shown to provide useful information for aligning torque performance. Example force and moment test results are shown to illustrate the concepts.

## Developing the Next Generation in Tire Testing

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New advances in automotive technology have made significant inroads to making vehicles safer and reducing injuries and fatalities. Protocols developed by the US Department of Transportation and the automotive industry, such as NCAP rollover tests, FMVSS 126 electronic stability control, and the TREAD Act, promise to be second only to seat belts in reducing fatalities and accidents. These new performance specifications, though, are also quite expensive to develop, often leading to more prototype vehicles for proving ground testing.

Automotive companies can greatly reduce the design cycle through simulation, with one major limitation - accurate tire data, particularly in the varying environments that a vehicle sees. Tire companies are seeking ways to validate performance more accurately under extreme conditions to meet the criteria laid out by their automotive customers. Current capabilities are limited to laboratory conditions to provide repeatability, but at the expense of accuracy.

Camber Ridge has been working with automotive companies, tire companies, controls companies and testing equipment companies to develop a new generation of tire testing capabilities to address many of the limitations of current equipment. This presentation will address the shortcomings identified by the industry, the desire for new dynamic testing capabilities, and the approach to developing a custom built capability to address these needs.

**The Tire Society, Inc.**  
**29<sup>th</sup> Annual Meeting and Conference on**  
**Tire Science and Technology**

September 20-21, 2010  
DoubleTree Akron/Fairlawn Hotel  
Akron, Ohio

**Schedule Overview (detailed schedule inside)**

**Day 1 - Monday, Sept 20**

**7:00am Registration:** Foyer (all day)

**Day 1 Presentations: Aspen East/West**

**8:15am Opening:** *Barry Yavari*,  
Program Chair

**8:20am Welcome:** *Bob Wheeler*, President

**8:30am Keynote Address:** *Seung Hwa Suh*, CEO & Vice Chairman,  
Hankook Tire

**9:05am Friction & Rolling Resistance:**  
2 Presenters

**10:00am Break - Refreshments:** Foyer

**10:15am Student Competition #1:**  
4 Presenters

**12:00pm Lunch:** *Provided by Tire Society*

**1:15pm Student Competition #2:**  
5 Presenters

**3:25pm Break - Refreshments:** Foyer

**3:40pm Materials:**  
3 Presenters

**5:00pm Day 1 Technical Sessions**  
Closing

**Awards Banquet:** Conrad Ballroom (Hilton)

**5:05pm Reception**

**6:00pm Dinner Banquet**

**7:00pm Best Paper Awards:** *Gary Tubb*

**7:20pm Dinner Speaker:** *David Cole*,  
*Center for Automotive Research*

**8:00pm End of Day 1**

**Day 2 - Tuesday, Sept 21**

**7:55am Registration:** Foyer (half day)

**Day 2 Presentations: Aspen East/West**

**8:05am Opening:** *Barry Yavari*

**8:10am State of Society:** *Bob Wheeler*

**8:35am NVH (part 1):**  
3 Presenters

**9:55am Break - Refreshments:** Foyer

**10:10am NVH (part 2):**  
2 Presenters

**11:00am Plenary Lecture:**  
*Yukio Nakajima*,  
*Kogakuin University*

**11:45am Advisory Board Meeting:**  
Birch Room

**11:45am Lunch Break**

**1:15pm Simulation:**  
4 Presenters

**3:00pm Break - Refreshments:** Foyer

**3:15pm Aging & Testing:**  
4 Presenters

**5:00pm Closing Remarks**