Haul truck tire dynamics due to tire condition

R Vaghar Anzabi, D S Nobes and M G Lipsett
Department of Mechanical Engineering,
University of Alberta, Edmonton, Alberta, CANADA, T6G 2G8
E-mail: michael.lipsett@ualberta.ca

Abstract. Pneumatic tires are costly components on large off-road haul trucks used in surface mining operations. Tires are prone to damage during operation, and these events can lead to injuries to personnel, loss of equipment, and reduced productivity. Damage rates have significant variability, due to operating conditions and a range of tire fault modes. Currently, monitoring of tire condition is done by physical inspection; and the mean time between inspections is often longer than the mean time between incipient failure and functional failure of the tire. Options for new condition monitoring methods include off-board thermal imaging and camera-based optical methods for detecting abnormal deformation and surface features, as well as on-board sensors to detect tire faults during vehicle operation. Physics-based modeling of tire dynamics can provide a good understanding of the tire behavior, and give insight into observability requirements for improved monitoring systems. This paper describes a model to simulate the dynamics of haul truck tires when a fault is present to determine the effects of physical parameter changes that relate to faults. To simulate the dynamics, a lumped mass ‘quarter-vehicle’ model has been used to determine the response of the system to a road profile when a failure changes the original properties of the tire. The result is a model of tire vertical displacement that can be used to detect a fault, which will be tested under field conditions in time-varying conditions.

1. Introduction
Off-road tires are critical components of haul trucks used in surface mining of metals, coal, and soils such as oil sands. These tires experience severe operating conditions, on rough roads in sub-arctic weather conditions. Tires are non-redundant elements of the vehicle suspension system, supporting the weight of the truck plus a load of up to 400 tons. As such, they are critical components in any mining operation that uses trucks.

Tires can account for 20-25% of haul truck operating costs [1]. A pneumatic tire has a complex structure, composed of high modulus flexible filaments (such as metal or plastic fibers) bonded to a low modulus rubber or rubber-like polymer. The rubber tread varies with the type of tire. The tread of a heavy truck tire should have high resistance to abrasion, tearing, and crack growth, and low hysteresis to reduce internal heat generation and rolling resistance [2]. In hard rock mines, cut resistance is often more important than heat resistance.

In contrast with tires for highway vehicles (which are designed for controlled road conditions), tires in off-road service experience highly variable operating conditions. The factors that affect tire life can be presented in different categories: tire-truck interaction (such as truck load, truck size, truck speed, wheel position), tire-road interaction (curves, grades, super-elevation, tire friction, road surface profile), tire-maintenance interaction (tire alignment, tire rotation, tire air pressure, preventive
maintenance), and tire-environment interaction (weather, temperature, snow or rain). As summarized in table 1, there are various reasons why tires are removed from service [3].

**Table 1.** Tire removal reasons [3].

| Interest Area | Removal Reasons          |
|---------------|--------------------------|
| Tread         | Cuts                     |
|               | Separations              |
| Shoulder      | Cuts                     |
|               | Separations              |
| Sidewall      | Cuts                     |
|               | Separations              |
|               | Radial splits            |
| Bead          | Separations              |
|               | Flange erosion           |
|               | Cracking                 |
| Liner         | Splits                   |
|               | Lifting liner            |
|               | Wrinkled liner           |

There is a strong motivation to study methods to detect operational damage to haul truck tires before they cause loss of productivity or putting personnel at risk in mining operations. The general approach for detecting faults is to compare a set of features measured from the current situation to a reference set for a no-damage case. Researchers have investigated the behavior of tires by monitoring systems that rely on measured features such as suspension vibrations or strut pressure, which can also be used to characterize mine haul-road quality [4]. Another monitoring strategy is to measure the temperature and pressure inside the tire using a wireless sensor [5]. This work entails using optical methods to detect anomalies in tire geometry to identify the faults that develop during operation [6].

The complex structure of a tire and the nonlinear nature of its behavior make it challenging to determine how its properties change when a fault occurs. Modeling the tire and its interaction with the ground and the vehicle suspension can provide a good understanding of tire behavior, and thus provide information on what must be observed from the system to monitor behavior that relates to tire condition. Researchers have developed numerous parametric models, such as: single-point contact model (parallel spring and damper), roller contact model (spring and damper with a single contact point), fixed footprint model (distributed springs and dampers at contact area), radial spring model (springs distributed in circumference of the tire), and flexible ring model (thin ring connected to springs around the tire) and finite-element models [7].

In order to evaluate dynamics of haul truck tires, a model is required that can present the effect of changes in physical parameters. Existence of fault in a tire affects its characteristics, and therefore the fault will change the dynamic behavior of the system. Tire model suitability depends on what the model will be used for: detailed structural modeling to describe damage mechanism, and reduced order models to describe the effects of damage on overall system behavior.

A lumped-parameter model can be used for reduced-order dynamic modeling of the effect of a fault on vehicle dynamics. A high-order model may be necessary to describe how a fault progresses, and how a fault may be observed. A finite-element approach can yield the three-dimensional deformations of the tire under load, which is useful for gaining insight into the effect of specific geometric changes on overall tire stiffness that can occur when a tire is damaged. Low-order parametric modeling will be considered first. Higher fidelity modeling and experimental studies will be discussed later in the paper.
2. Tire dynamics simulation

To study the behavior of haul truck tires and the role of tire fault on the results, the present work considers a model to simulate the dynamics of haul truck tires during vehicle motion in the presence of a fault on one part of the tire. The objective of this work is a model that can show the vertical displacement of a typical haul truck tire as a response to a road profile, considering the fault effect. The response of the system may assist in detecting a fault in a tire using observable features in the dynamic response of the system.

2.1. Quarter Vehicle Model

A two degree-of-freedom 'quarter-vehicle' model is widely used for the analysis of ride dynamics of vehicles. The tire in this formulation is considered to be a point-contact system, represented by a parallel spring and damper combination that transmits the support force from the terrain to the vehicle and contacts the ground through a point follower. The spring constitutive relationship is chosen to simulate the effects of tire inflation pressure and carcass elasticity. The damping provides the energy dissipation caused by carcass deformations.

As shown in Figure 1, the vehicle body is represented by the sprung mass \( m_s \) and the tire-wheel-axle is represented by the unsprung mass \( m_t \). These elements are connected by springs and dampers and constrained to move in the vertical direction only. The input to the vehicle is the road profile \( u(t) \) at the tire point contact, \( k_s \) is the suspension stiffness, \( C_s \) is the suspension damping coefficients, and \( k_t \) and \( C_t \) are coefficients of tire stiffness and damping. The simplest case considers only constant coefficients and linear system response.

![Figure 1. Quarter-vehicle model.](image)

The rigid-body dynamic equations of motion can be written in second-order matrix form as:

\[
[M]\ddot{X} + [C]\dot{X} + [K]X = F
\]

(1)

Where:

\[
[M] = \begin{bmatrix}
m_s & 0 \\
0 & m_t
\end{bmatrix}
\]

the mass matrix,

\[
[C] = \begin{bmatrix}
C_s & -C_s \\
-C_s & C_s + C_t
\end{bmatrix}
\]

the damping matrix,

\[
[K] = \begin{bmatrix}
k_s & -k_s \\
-k_s & k_s + k_t
\end{bmatrix}
\]

the stiffness matrix,

\[
X = \begin{bmatrix}
x_s \\
x_t
\end{bmatrix}
\]

the vector of displacements,

\[
F = \begin{bmatrix}
0 \\
c_t \ddot{u} + k_t u
\end{bmatrix}
\]

the vector of forces imparted by the displacement input.
2.2. Definition of Parameters

2.2.1. Tire and truck coefficients. The computational model needs information about the properties of truck and tires. Based on experimental data of a sample truck tire under rated loads and inflation pressures, it is found that the value of stiffness $k_t$ and damping coefficients $C_t$ varies in a range for different types of tires or inflation pressure [2]. In this project, the parameters have been chosen from a typical haul truck tire values, which are listed in table 2.

| Parameter            | Value                        |
|----------------------|------------------------------|
| sprung mass          | $m_s = 3600$ kg              |
| suspension stiffness | $k_s = 400$ kN/m             |
| suspension damping   | $C_s = 10$ kNs/m             |
| including mass       | $m_t = 400$ kg               |
| tire stiffness       | $k_t = 1.5$ MN/m             |
|                     | $C_u = 1.5$ kNs/m            |

2.2.2. Road profile. One of the challenges in modeling the mechanics of an off-road tire is modeling the ground (that is, a time-varying displacement input to the vehicle). In the general case, soil dynamics are included in the soil-tire interface [8] but for a simplified model of the tire, a rigid surface is commonly assumed for the driving surface. Rigid ground has been assumed in this project, which is reasonable for most mines.

The road profile (that is, the vertical displacement $u(t)$ as a function of horizontal distance traveled) is generally a random variable; but forced response due to road profile excitation has been considered for a road roughness profile excitation defined by a function that is a deterministic combination of two different oscillations. A set of periodic wave functions is reasonable for an oil-sands mining bench surface in summer, or a gravel roadbed that has an undulating surface. Forced response due to road profile excitation has been considered for two cases. In the first case, the disturbance is a step function defined by its magnitude. For mining conditions a magnitude of about $0.1$ m is not unreasonable. In the second case, the output response of the tire is studied with a road roughness profile defined by a oscillation function which happens every $4$ m by maximum amplitude of $0.3$ m, plus a small roughness of $0.03$ m. The parameters of this profile are based on observations at an operating site.

2.2.3. Tire fault. If tire has a fault, the key challenge includes modeling what the effect of the damage is on parameters such as the local stiffness of tire, that is, variability in the tire as it rotates. In this case, as shown at figure 2, $k_t$ changes as a function of rotation angle.

![Figure 2. Change of tire stiffness with respect to rotation angle $\theta$.](image-url)
In this project, the tire stiffness is assumed to follow a sigmoid function with maximum amount of normal tire stiffness (without any fault) and minimum stiffness that is 40% of the maximum. The modeled fault occurs after $\pi/4$ radians of a full rotation, but its effect on stiffness varies within $\pm \pi/9$ of the fault location. The stiffness function $K$ with respect to rotation angle $\theta$ is thus

$$K(\theta) = \frac{1}{1 + e^{-a_2(\theta-c_2)}} - \frac{1}{1 + e^{-a_1(\theta-c_1)}}$$

(2)

where

- $a_1$, $a_2$: thresholds of function
- $c_1$ : $\theta - d\theta$
- $c_2$ : $\theta + d\theta$

This function is a theoretical estimation, which will be tested against experimental data for different types of damage that can occur during operation. In order to create a well-defined relationship between tire fault and its stiffness, there is a need to design experiments to investigate tire characteristics with known faults. Not only does such an empirical study provide a set of simple constitutive relationships for tire stiffness in different fault cases, the results also provide boundary conditions for validating an equilibrium finite-element model.

2.3. Dynamic Model Results

A MATLAB code has been developed to solve the governing equations of motion using typical haul truck and road parameters. ODE45 has been used to solve equation (1) considering the parameters of a typical haul truck listed in Table 2. The analysis is based on two different road conditions and whether the tire is undamaged or has a fault. Figure 3 depicts the displacement of the simulated tire in the time domain when the road is assumed to have infinite stiffness and a vertical step disturbance. In part (a), the tire is assumed to have no fault. This can be compared to part (b) where the road conditions are the same but tire suffers from a fault at a certain angle.

![Figure 3. Plots of vertical displacement of tire exited by step disturbance.](image)

In figure 4, the profile of road has been changed to account for road roughness. Part (a) shows the response of tire without a fault as a function of time; and and part (b) is the displacement of the tire in the presence of a fault.
From these simple simulations, it is apparent that with sufficient stiffness change, the tire displacement is affected by a fault condition. The results obtained from this model should be subjected to further validation by experiment. Depending on the type of fault, different road conditions and tire stiffness values are prescribed, which in turn incurs different final tire response. Therefore different constitutive relationships should be investigated, with the intent of applying parametric system identification methods for feature extraction related to dynamic parameters and stiffness functions, and assessing the sensitivity of parameters on observable system outputs.

3. Methodology for determining tire constitutive relationship

To establish the constitutive relationship of the tire with different structural anomalies or faults, structural loading (that is, boundary conditions) controlled variables are related to deformations of the surface of the tire using an optical method for measuring local deformations.

The presence of any damage in a tire will change its strain field at the tire surface. This strain field can be measured optically by three-dimensional digital-image correlation (3-D DIC), which uses a set of images of the tire surface as input data to obtain the strain field from speckles or other features on the surface of the object. These data are then used in a finite-element model to study the effect of faults on tire characteristics.

3.1. Tire strain measurement using optical method

Digital image correlation (DIC) is an optical technique to measure the deformation of an object using images of the surface provided by camera which collects data during deformation. The main idea of the method is based on tracking the motion of points in a small region when the object is undergoing mechanical or thermal stress. Studies show that DIC method is ideal for tire surface strain measurement, as a non-contact technique, because it does not require any instrumentation on the tire itself [9].

The experimental setup of DIC method for tire strain measurement is designed and implemented at the University of Alberta to investigate tire fault detection in a laboratory scale. The setup is shown schematically in figure 5, comprising two high-resolution digital cameras, a lighting source, and an image processing computer. The procedure is to acquire images from both cameras simultaneously with a region of the tire in both camera fields of view. Digital images of the surface of the tire are processed in the DaVis software to obtain deformation vectors of the tire surface. The strain field is determined by dividing the deflection vectors with respect to the original displacements between surface features on the object in the region.
Figure 5. Schematic of 3-D experimental setup for tire strain measurement.

To study the effect of faults on tire strain field, a set of cuts with known geometry will be created on coupons to verify the method for reinforced rubber under dynamic load, and to examine the effect of the fiber elements within the rubber. Once this has been done, then DIC will be applied to the strain field on the tire surface to find the deformation of the tire under controlled loading condition. The results will be compared to an intact tire to find the tire stiffness changes.

3.2. Tire FEM modeling

The finite-element method has been widely used in tire modeling, dating back to the early 1970s. There have been many research efforts to develop models and simulations to describe dynamics of tires. There are different sources of non-linearity in structural modeling such as: geometry, material properties, and boundary conditions. All of these factors are important in tire modeling, because different materials are used in tires, and the tire experiences different boundary conditions depending on operating conditions. Rubber as the main material of tire is soft and virtually incompressible, but it can be stretched more than 500%, and so it is considered to be a hyperelastic material. The strength of the tire structure comes from the carcass of fabric that is encased in rubber. Belt ply cords consist of steel or rayon, while body plies cords can be made of nylon or polyester [10]. Bead wires are usually made of steel. The applied loading and boundary conditions are generally time-varying during vehicle operation. A rough road has great influence on the contact area; and therefore road profile is closely related to friction. The real contact area is in most cases different from the apparent contact area.

In the field of failure analysis, most previous works are based on experimental measurements of rubber components; and a finite-element approach is used to find the energy release rate (J-integral) for a failure in the tire. In 1996, T. G. Ebbott [11] first used a two-dimensional, plane-strain tire model to predict the number of cycles in a real tire, with a focus on bead separation. He modeled an initial flaw near the bead area with the assumption of crack existence around the circumference. Zhong [12] used the virtual crack closure technique to calculate energy release rate, in order to evaluate fatigue crack growth and durability in tires. A three-dimensional finite element model was developed to study the effect of a belt-edge crack on the thermal and mechanical characteristics of a tire. Sethy et al. [13] utilized a J-integral approach in the context of large strain and non-linear elastic material behavior to characterize durability and fatigue.

Some FE code packages such as ABAQUS can detect the maximum J value around a crack tip. This approach has been used to obtain both crack sensitivity and the crack direction. Han et al. [14] developed a finite-element model to calculate the energy release rate at the belt edge area. They assumed a steady-state rolling tire, and conducted a three-dimensional fracture analysis in conjunction with a global-local technique, obtaining the J-integral variation in the crack region. Ok et al. [15]
modeled the belt edge separation, using the finite-element method and fracture mechanics concepts to study the initiation and growth of a rectangular crack and calculating J-integral as part of the fatigue crack growth. Feng et al. [16] used Irwin’s virtual-crack-close technique and finite-element analysis together to calculate the energy release rate of the delamination crack growth of a radial tire. The model can reveal the crack growth dependence on the relative size of energy release rates at the left and right crack tips and the interfacial material property.

Figure 6 illustrates how a three-dimensional finite-element model of a radial tire is implemented in ABAQUS to find the strain field of the surface of the tire. In this model, shell elements and hyperelastic characteristics have been used for rubber material; and constant inflation pressure and truck load provide the loading condition.

![Figure 6. Tire FE modeling using ABAQUS.](image)

Tire modeling becomes more challenging if a failure happens due to the nucleation and growth of defects or cracks. Fracture mechanics analysis provides an efficient approach to study tire parameters due to different faults by understanding the mechanics underlying the failure process. There are different models to predict tire failure by focusing on crack nucleation, given the history of quantities such as strain. The other approach is based on growth of a particular crack, given the initial geometry and energy release rate [17].

During alternating loads, the tip of a crack dissipates energy and creates a significant amount of heat. Rubber is a poor thermal conductor, and so there is the potential for a large increase in temperature within the crack. A combined thermal and structural model can yield insights into the relationship between the loading on a developing crack, heat generation, observable temperature increase at the surface, and breakdown of structural properties due to excessive heat, which can accelerate damage accumulation.

3.3. Rubber fracture mechanics tests
A number of studies have been done to characterize the crack growth behavior of rubbers by measuring different parameters such as temperature, using thermocouples, or crack growth rate, using fatigue testing machines. For instance, Kaang et al. [18] used ASTM standards for specimens of reinforced rubber with length and width of 200 and 20 mm, respectively, and an initial edge cut, about 30 mm long. They tested the rubber specimen under cyclic loads to find crack growth rate as a function of the tearing energy.

Figure 7 shows the different types of test specimens that can be used for rubber fracture analysis tests. In single edge cut tension specimen, the energy release rate has an especially simple form; and cut growth results only in translation of the crack tip. The trouser specimen has been used in early studies of fatigue crack growth in rubber [17].
In the current study, standard test methods will be used to design experiments to determine the fracture behavior of rubber coupons and composite coupons. In the first stage, pure rubber will be tested under controlled loading conditions, using DIC to observe the strain field. Different loading conditions can be applied to obtain different characteristics of the material static forces will determine the strain-stress relationship and strain released energy of the specimen in presence of a known crack. On the other hand, cyclic loads can lead to fatigue behavior and crack growth analysis. A thermal camera to observe temperate variations under alternating loads over time. Then, fiber-reinforced specimens resembling geometries typical of tires will be tested under the same set of conditions to examine the effect of fibers on the response of specimen, including thermal conductivity.

4. Discussion and future work
The simple dynamic simulations presented in this paper have shown that the differences between tire motions can be an indicator to determine the presence of fault in the tire, even with changes in different road conditions. However, there is a need to test the validity of the provided dynamic model. To better mimic the tire responses and hence achieve reliable results, real tire stiffness function should be considered, which can be obtained from a finite-element model that has been validated with experimental results.

The type of fault, operating conditions, and other factors (such as tire internal pressure and temperature) affect the tire stiffness. Although to date, these effects have been ignored for the sake of simplicity. In addition, road condition has a major effect on the results. This effect will be evaluated by using an actual observable variable such as strut pressure, or wheel axle and frame vertical accelerations, as an indirect measure of road quality [19].

In this project, to investigate the effect of faults on tire behavior, different steps are necessary to be considered. At the first step, finite-element models are being developed for specimens of rubber with a defined fault. The models will be used to evaluate the stress-strain field associated with the nucleation of cracks, and their subsequent growth, obtained under different loading conditions.

To observe the fracture response of tire material under dynamic loading, experimental design is in progress. Certain standard cuts with known geometry will be implemented on coupons of pure and reinforced rubber which can lead to determine the effect of fibers within the rubber.

At the next part of the project, the DIC method will be applied to find the deformation of the tire under controlled loading condition and known faults. The results will determine the tire stiffness changes in comparison to an intact tire. Quasi-static analysis [20] can be used to validate the overall vertical stiffness of the finite-element tire model.

Acknowledgments
The authors wish to thank Dr. Khaled Obaia, Angus Munro, Bob Tupper, Dr. Ian Parsons, and Tom Demorest of Syncrude Canada Ltd. for field information. Funding support is gratefully acknowledged from the Natural Sciences and Engineering Research Council of Canada (NSERC) and Syncrude.
References

[1] Dhillon BS 2008 Mining Equipment Reliability, Maintainability, Safety, Springer, pp. 57-70.
[2] Clark SK 1981 Mechanics of pneumatic tires (2nd Edition), U.S. Dept. of Transportation, National Highway Traffic Safety Administration, S/N 050-003-00377-8.
[3] Zhou J 2007 Investigation into the improvement of tire management practices, Master’s Thesis, University of British Columbia.
[4] Thompson R, Visser A, Miller R, Lowe T 2003 Development of Real-Time Mine Road Maintenance Management System Using Haul Truck and Road Vibration Signature Analysis. Journal of the Transportation Research Board, Vol 1819A, pp 305-312.
[5] Brothen C, Lee T 2008 An ounce of prevention. Canadian Institute of Mining Magazine, Vol.3 No. 1.
[6] Vaghar Anzabi R, Lipsett MG 2011 Reliability analysis & condition monitoring methods for off-road haul truck tires, COMADEM 2011
[7] Miege AJP 2004 Tyre model for truck ride simulations, CPGS dissertation, Department of Engineering, University of Cambridge, UK
[8] Zhu Y, Chen X, Owen GS 2011 Terramechanics based terrain deformation for real-time off-road vehicle simulation. Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 6938 LNCS (PART 1), pp. 431-440.
[9] Moser R, Lightner, JG 2007 Using three-dimensional digital imaging correlation techniques to validate tire finite-element model, Experimental Techniques, 314, 29-36.
[10] Steen R, Nijmeijer H 2007 Tire/road friction modeling, Eindhoven University of Technology, Department of Mechanical Engineering, Dynamics and Control group
[11] Ebbott TG 1996 An Application of Finite Element-Based Fracture Mechanics Analysis to Cord-Rubber Structures, Tire Science and Technology, Vol. 24, No. 3, pp. 220-235
[12] Zhong XA 2006 Computational Fracture Mechanics Analysis of Truck Tire Durability, Journal of Applied Mechanics, Vol. 3, Issue 5, pp. 799-806
[13] Sethy A, Amarnath S.K.P., Sankarganesh P., Mohamed P.K. 2007 Fracture Sensitivity of Tire Structures Using J integral, Abaqus India Regional Users
[14] Han YH, Becker EB, Fahrenthold EP, Kim DM 2004 Fatigue life prediction for cord-rubber composite tires using a global-local finite element method, Tire Sci Technol, 32, pp. 23-40
[15] Ok A, Ozupek S, Becker EB. 2007 Crack simulation in pneumatic tires using the finite element method, Proc. IMechE Vol.221 Part D:J Automobile Engineering, pp. 157-166
[16] Feng X, Yan X, Wei Y, Du X 2004 Nonlinear Finite Element Modeling of Delamination Crack Growth Process between Belts of a Radial Tire, Journal of Reinforced Plastics and Composites, Vol. 23, No. 4, pp.373-388
[17] Mars WV, Fatemi A. 2002 A literature survey on fatigue analysis approaches for rubber, International Journal of Fatigue, 24 9, pp. 949-961.
[18] Kaang, S., Jin, Y.W., Huh, Y.-i., Lee, W.-J., Im, W.B., 2006 A test method to measure fatigue crack growth rate of rubbery materials Polymer Testing, 25 (3), pp. 347-352.
[19] Lipsett MG, Hajizadeh, M. 2011 Using Telemetry to Identify Haul Truck Engine and Suspension Faults. Proceedings 1st International Conference on Maintenance Performance Measurement and Management (MPMM), Lulea, pp. 61-68.
[20] Lee C, Kim J, Hallquist J, Zhang Y et al. 1997 Validation of a FEA Tire Model for Vehicle Dynamic Analysis and Full Vehicle Real Time Proving Ground Simulations, SAE Technical Paper 971100, doi:10.4271/971100.