

Scalable Vehicle Models for Tire Testing

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ABSTRACT

Tire manufacturers need to perform various types of testing to determine tire performance under representative vehicle load conditions. However, test results are influenced by a number of external variables other than tire construction. Vehicle load distribution and suspension properties are some of those external variables which can have a significant effect on tire wear rate and durability. Therefore, in order to measure real world tire performance in a controlled and repeatable manner, a representative vehicle and associated tire load conditions are needed.

Laboratory or indoor tire testing offers many advantages over vehicle fleet testing. It provides a well-defined test environment and repeatable results without influence from external factors. Indoor testing has been largely developed around the process of simulating tire wear performance on a specific reference vehicle, including its specific weight distribution, suspension characteristics, and alignment. However this approach is not desirable in some cases, such as Department of Transportation's Uniform Tire Quality Grading (UTQG) wear testing, aftermarket tire development for a vehicle category, and laboratory durability testing. These tests should mimic representative tire loading conditions for a particular tire size and category based on an 'average' or generic vehicle. This vehicle must, however, reflect the general loading and suspension characteristics of the vehicle segments of interest. This approach applies not only to laboratory testing but also to defining generalized but representative loading conditions for tire modeling.

This study reviews a methodology for developing a gradually and continuously scalable generic vehicle model, which yields a consistent tire load history change across tire sizes. This new concept yields laboratory test results free of specific vehicle bias, thus providing a more representative indication of tire performance across tire sizes within a product and vehicle category.

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INTRODUCTION

New generation tire testing equipment has improved controllers and performance capabilities allowing for following real-time load histories that consist of radial, lateral and longitudinal force and camber. Much effort over the last twenty years has been devoted to developing accurate vehicle tire loading histories for use with those testing machines. These load histories are essential for providing the input into laboratory tire testing machines or tire models [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11] for applications such as accelerated indoor wear testing that are used to predict the wear performance of the tire in the field. Load histories are, of course, specific to the tire's stiffness, the vehicle's mass distribution and load transfer characteristics, the suspension alignment, the tire position on the vehicle and road course. Given the specificity of the vehicle model, these tire force histories are also useful for predicting the vehicle's effects on tire performance, especially tire wear.

Vehicle characterization is critical to the generation of accurate and realistic tire load histories for indoor tire testing. CarSim [12] is an empirical vehicle modeling software package that enables accurate vehicle modeling and simulation. CarSim has found wide use in automotive industry for various applications [13, 14, 15].

Until recently, the laboratory tire testing has involved evaluating tire performance on a specific reference vehicle. However, this approach is not desirable in cases of UTQG wear testing, replacement or aftermarket tire development for a particular vehicle segment, and laboratory durability testing. These applications require representative tire loading conditions for a particular tire size and segment based on an 'average' vehicle. This 'average' vehicle must reflect the general characteristics of the vehicle segments of interest.

The purpose of this paper is to introduce a technique used to create CarSim vehicle models for 'average' vehicles for a particular market segment. These models range from the lightest to the heaviest vehicles in that segment, but still capture all of the general

characteristics. These models are referred to as Scalable Vehicle Models (SVM) in which the total vehicle weight is the scaling parameter and vehicle properties are functions of the total vehicle weight [16]. For the creation of a SVM, fifty seven different vehicle property parameters are examined and expressed as functions of the total vehicle weight. Table 1 in Appendix is a generalized list of major vehicle properties involved in a CarSim SVM. In this paper, the application of this technique to the vehicle segment of front wheel drive (FWD) vehicles at curb plus driver ballasting and nominal alignment will be used to illustrate these concepts. This technique can also be applied to construct completely different SVM for other vehicle segments such as FWD mini-vans, rear wheel drive (RWD) pick-up trucks, large RWD SUV's, etc. Specific ballasting conditions, such as those used by the UTQG wear test [17] also constitute a unique segment.

The SVM approach is especially useful for laboratory evaluation of replacement tires with multiple sizes covering a wide range in load carrying capability. To evaluate tire performance over a range of tire sizes it is necessary to remove vehicle-to-vehicle biases from the different load histories but at the same time to maintain a consistent and realistic representation of the vehicle characteristics, application loads, and the road course. The SVM technology allows creation of a family of vehicle models which capture gradually and continuously the general characteristics of a vehicle segment and yield consistent load history from one tire size to the next. This technology permits the laboratory tire test results to be free of vehicle bias, thus creating a much truer evaluation of tire performance. Removing the influence of specific vehicles allows the optimization of tire performance for the broadest range of vehicles in the segment.

MODEL DEVELOPMENT

Modeling of Vehicle Properties

The modeling or characterization of vehicle properties for a SVM involves two major steps. The first step creates an approximation of each measured vehicle property using a polynomial. The second step is a linear regression on the sets of polynomial coefficients to derive properties as a function of total vehicle weight.

The vehicle models created using the SVM approach in this section are for indoor wear and durability applications as opposed to handling, ride, heavy braking, crash, or noise applications. Vehicle maneuvers associated with the wear and durability applications are quasi-static in nature with limited acceleration and deceleration levels, generally not exceeding 0.5g. Therefore, vehicle inertia and shock absorbers have relatively little influence on the vehicle load transfer behavior and suspension spring rate and other compliances can be linearized. It is also assumed that the CarSim internal tire model combined slip predictions from pure cornering and pure braking F&M is sufficiently accurate. All vehicles are assumed to have fully independent suspensions.

A cubic polynomial regression model has been developed to characterize the properties of a SVM vehicle,

$$P(W) = C_0(W) + C_1(W)A + C_2(W)A^2 + C_3(W)A^3 \quad (1)$$

where

$P(W)$ = vehicle dynamic property, e.g. suspension kinematics

W = total vehicle weight

A = independent variable, e.g. jounce or steering angle

$C_n(W) = a_{n0} + a_{n1}W$, regression coefficients, function of W .

Equation (1) was applied to characterize the vehicle properties for a SVM for FWD vehicles at curb plus driver ballasting from 52 sample vehicles covering 15 model years. These vehicles ranged in total weight from approximately 11,100 to slightly over 22,250 N including a 665 N driver. The vehicle properties of those 52 vehicles were first measured. These measurements included but are not limited to wheelbase and track dimensions, load distribution, steering kinematics, and suspension compliances and kinematics. In addition, each vehicle was driven over floor mounted force platforms following predetermined paths at various levels of deceleration and acceleration. Front-to-rear brake distributions and load transfer coefficients were determined using these force platform measurements. The load transfer coefficients were used to estimate the height of vehicle center of gravity, since center of gravity height was not measured directly. Since vehicle inertia and shock absorbers have relatively little influence on the vehicle load transfer behavior for the type of maneuvers simulated, vehicle moments and products of inertia and shock absorbers are not measured and scaled for the SVM.

Each vehicle property then was individually examined for the trend with total vehicle weight, W . Using Equation (1), the vehicle property, $P(W)$, measured from all 52 vehicles, is determined as a function of the total vehicle weight, using linear regression. For example, one of the simplest properties, the front axle load, was found to be approximately 60% of total vehicle weight across the entire range of 52 vehicles. In this case $C_1(W)$, $C_2(W)$, and $C_3(W)$ of Equation (1) are zero and $C_0(W)$ reduces to $a_{00} = 0.60$. Other simple examples are the wheel base and the track as shown in Figures 1 and 2. They are treated as linear functions of total vehicle weight only. Thus, Equation (1) becomes $P(W) = C_0(W) = a_{00} + a_{01}W$. For the wheel base model $a_{00} = 1255$ and $a_{01} = 0.218$ and the track model $a_{00} = 1240$ and $a_{01} = 0.088$.

The scalable properties of the models have been divided into 3 major categories: suspension compliances and kinematics, steering kinematics, and tire F&M. In the following sections, examples will be given of how regression model Equation (1) is applied. To review, creating the SVM involves 2 major steps, of which the first step is approximating vehicle properties with polynomials. The following sections will also discuss the second major step of applying Equation (1) to create functions of total vehicle weight that reproduce those approximated vehicle properties.

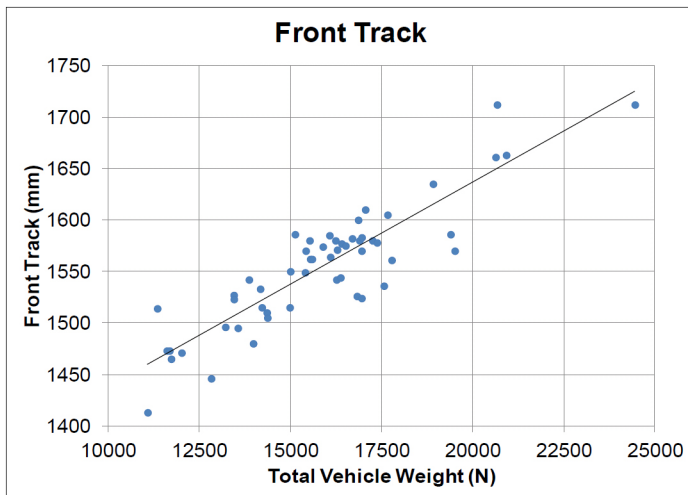


Figure 1. Vehicle track widths generally increase linearly with vehicle weight.

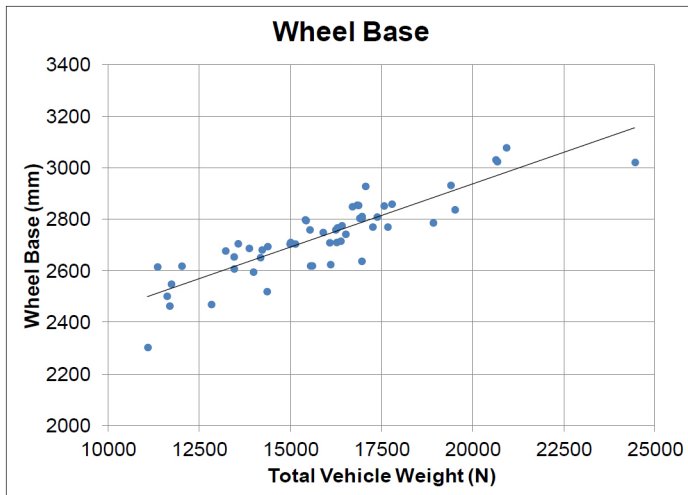


Figure 2. Vehicle wheelbases generally increase linearly with vehicle weight.

Suspension Compliances and Kinematics

Suspension characteristics have a significant effect on the tire F&M that are produced in simulations over road courses. Refer to [Table 1](#) for a list of suspension characteristics that are made a function of total vehicle load, but there are a total of thirty six scalable parameters. Linearized suspension spring stiffness, shown in [Figure 3](#), was also modeled as a linear relationship of total vehicle weight, W . Suspension kinematics includes both static alignment settings and also changes in toe and camber with jounce and rebound. The jounce-toe and jounce-camber relationships are more involved to characterize than the properties discussed previously. [Figure 4](#) shows an example of front suspension jounce-toe measurements for a selected subgroup of twelve vehicles among the 52 vehicles. The total weight of those vehicles ranges from 11,615 N for vehicle A to 20,835 N for vehicle L.

To characterize suspension kinematics, the independent variable A in [Equation \(1\)](#) in this instance is jounce or suspension deflection. The vehicles plotted in [Figure 4](#) were selected to demonstrate the total vehicle weight dependency or independency of the suspension kinematics. In this case it is jounce-toe relationship. [Figure 5](#) shows the jounce-toe measurements for vehicle E from the previous plot. The measurements were performed on a K&C machine. This plot shows that a cubic polynomial can be used to represent these measurements accurately. The resulting cubic polynomial approximation of front suspension toe change for vehicle E is:

$$\text{Toe} = -0.0099 - 0.0085A - 5 \times 10^{-5}A^2 - 3 \times 10^{-8}A^3 \quad (2)$$

where A is jounce.

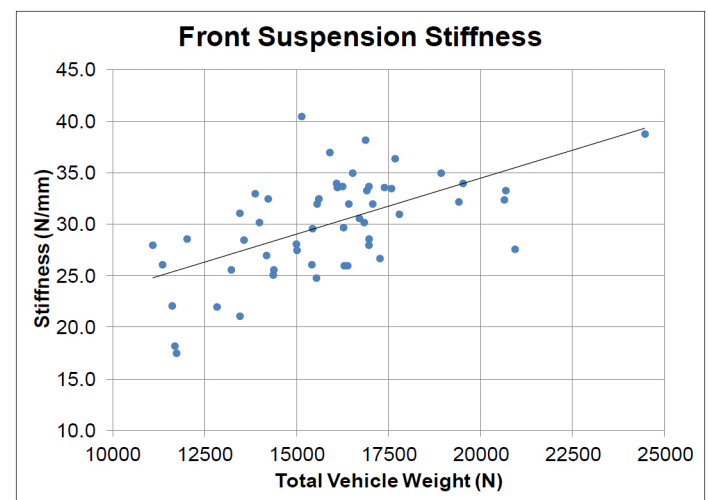


Figure 3. Front suspension spring stiffness of surveyed vehicles and their linear regression

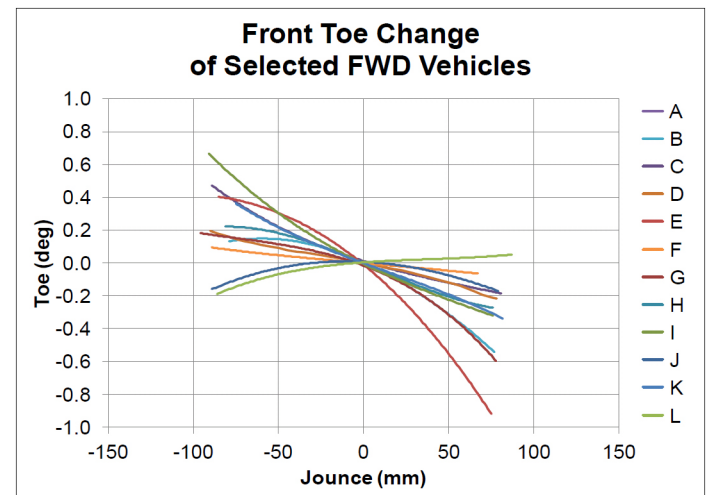


Figure 4. Front suspension jounce-toe characteristics of selected FWD vehicles which demonstrate a wide range in total vehicle weight, from 11,615 N for vehicle A to 20,835 N for vehicle L.