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TIRE MODEL FOR SIMULATIONS OF VEHICLE MOTION ON HIGH AND LOW FRICTION ROAD SURFACES

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Abstract: *An on-road analytical tire model has been developed to predict tire forces and moments at the tire/road interface. The model is computationally efficient and it only requires a limited set of easily obtained input parameters. Force and moment calculation are based on mechanical analogs that describe longitudinal and lateral tire tread and sidewall deflections during braking, traction and cornering. Longitudinal deflections are determined using a simple linear elastic spring model, while lateral deflections are calculating using an elastic beam model. Surface sliding friction is define by experimental curves relating the friction coefficient to the wheel/road differential velocity. Source code has been developed to include the model as a force element subroutine in commercially available dynamic analysis software known as DADS (Dynamic Analysis Design System). The tire model has been successfully demonstrated in DADS using a simple simulation of a tire test device. Preliminary comparisons of model predictions with available test data have been favorable. Efforts are underway to incorporate the tire subroutine into a DADS model of a HMMWV to conduct driving simulations on dry, snow and ice covered road surfaces.*

Keywords: *tire, tire – road interaction, contact patch*

1. INTRODUCTION

On-road vehicle mobility is important to the military, as it is a major factor governing the movement of troops and material in the field. Accurate representations of wheeled vehicle maneuvering capabilities (traction, braking and cornering) are needed via high resolution dynamic simulations to predict maximum over the road vehicle speeds as road conditions worsen due to degraded weather. Personnel at the Cold Regions Research and Engineering Laboratory (CREEL) are using DADS to create dynamic simulations of vehicles operating under winter conditions.

A critical element in any wheeled vehicle dynamic model is the set of algorithms that defines the interaction between tire and road. A model is provided in the current version of DADS that predicts tire response to vertical loading. A tire model is also provided in DADS that predicts longitudinal and lateral reaction forces and moments during combined traction.

2. TIRE MODEL DEVELOPMENT

Numerous approaches to tire modeling are documented in the literature. Two simple ones are adopted here to describe tire deflection and forces in the vertical (i.e. normal to the road surface) and longitudinal (in the tire plane, tangent to the road surface) directions. A novel approach involving elastic elastic beam theory is used to define displacement and forces in the third "lateral" direction.

2.1 FORCE AND MOMENT CONVENTIONS

Figure 1 shows the force and moment vectors calculated by the tire model being discussed. These act at the central intersection point of the tire disk and road surface plane. They constitute an equivalent orthogonal representation of the road forces generated along the displaced tire patch. The x and z axes shown are parallel to the longitudinal axis of the tire and the road surface normal, respectively.

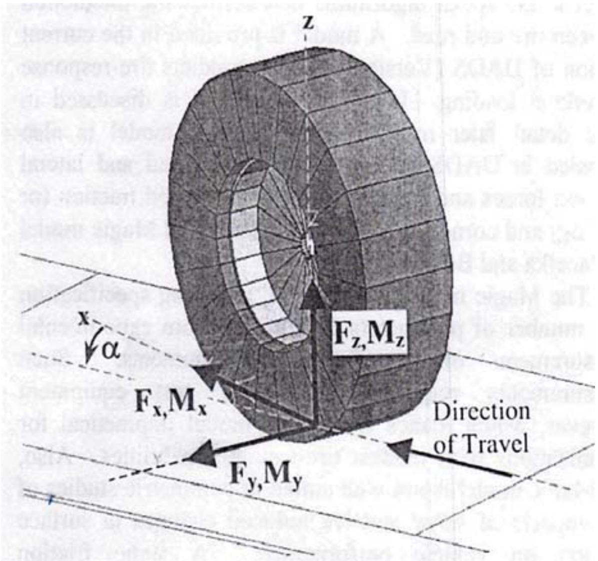

Fig. 1 Calculated Tire Forces and Moments [1].

2.2 VERTICAL TIRE RESPONSE

"Vertical" tire/road interactions (normal to the road surface along the z axis) are treated independently of lateral and longitudinal interactions, and calculated using the distributed contact model currently in DADS. This model describes tire normal deflections and velocities based on the lateral cross-sectional area generated by an equivalent undeformed disk intersecting with the road profile. The normal deflection of the actual of the flattened tire is computed from the intersected arc length of the undeformed disk. Tire normal force is calculated using a simple linear spring model with user-specified spring constant. The latter is easy to measure; Table 1 lists the spring constant K_{vert} for a light-truck tire that was determined for measurements made at CRREL. [3]

Damping can be affected as well in the normal direction in the current DADS code if the user provides a damping constant. The stiffness and damping constants can also be replaced by empirically-based curves.

2.3 LONGITUDINAL TIRE RESPONS

Longitudinal tire/road interactions are represented in the CRREL tire model by a simple I-dimensional quasi-static "Brush" (or "Cantilevered Spoke") mechanical analog described by Dixon (1996) and a nominal expression for rolling resistance. Figure 2 depicts the brush analog.

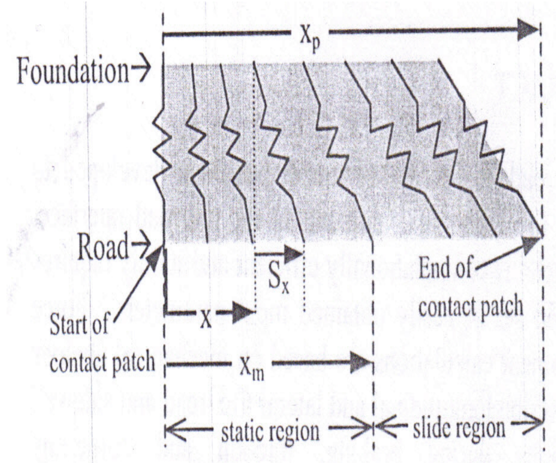

Fig. 2 "Brush" Analog used to Describe Longitudinal Tire Behavior along Tire Contact Patch

2.3.1 TIRE PATCH STATIC REGION

In the Brush model, the contact patch is divided into two sections: a forward "static" region where the tire tread adheres to the road surface, and an aft "slide" region where sliding occurs between tire and road. Contact patch displacement is limited by the tire longitudinal foundation stiffness C_1 and surface frictional forces. In the forward static region, at a distance x from the leading edge of the patch, the tire tread streatches an amount S_x equal to:

$$S_x=(1-V_x/\omega R)x \quad (1)$$

-V_x is the velocity of the wheel center in the longitudinal direction;
-ω is the wheel rotation rate;
-R is the tire rolling radius.

The longitudinal friction force $f_{x,st}$ exerted on the tire in the static region is the product of S_x and the foundation stiffness C_1 integrated from x=0 to x_m, where x_m marks the transition point from the static to sliding regions. This equates to:

$$F_{x,st}=C_1/2\ (1- V_x/\omega R)x^2_m \quad (2)$$

The tire foundation stiffness C_1 can be obtained from a simple static pull test. Figure 3 shows the test setup used a CRREL to determine C_1. A load cell capable of measuring horizontal and vertical forces supports a vertically loaded tire. The load cell itself is supported by a frictionless bearing, which is pulled by a pneumatic cylinder. Longitudinal load and tire displacement are recorded and plotted, and the slope of the resulting curve determined. This value is then divided by the length of the tire contact patch to arrive at the foundation stiffness.

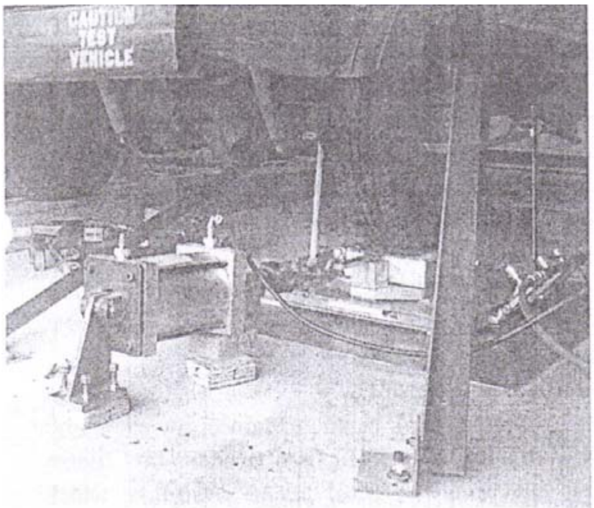

Fig. 3 CRREL Test apparatus for measuring tire foundation stiffness.

2.4 LATERAL TIRE RESPONS

Lateral tire behavior is non linear and complex, and most often described using empirical and semi-empirical approaches (Pacejka and Bakker 1993, Brach and Brach 2000, and Nicholas and Comstok 1972). In addition, several analytical models exists, such as the one describe by Shim, Margolis and Belltawn 2000. This model simulates combined braking and cornering, but is limited to linear tire behavior at small slip angles. Ellis (1969) proposes two analytical for tire lateral response: the taut string with elastic curtain and the beam on an elastic foundation. While the former, like the previously discussed model is only applicable to small slip angles, the latter applies to all longitudinal and lateral slip conditions. The mathematical derivation for Ellis' elastic beam model uses several numerical approximations however, and he treats tread and carcass/sidewall deflections separately. Application of the model, either by its author or others, is not evident in the literature as well. The beam-on-elastic-foundation is a useful analog nonetheless, and an alternate set of equations is offered here to describe it.

2.4.1 ELASTIC BEAM THEORY

The tire is treated as a beam restrained by an elastic foundation attached to a fix base (wheel rim). Beam deflection represents tire tread lateral deflection, which follows a linear path in the static region of the tire patch determined by the slip angle **α**, and a parabolic

curve in the slide region.

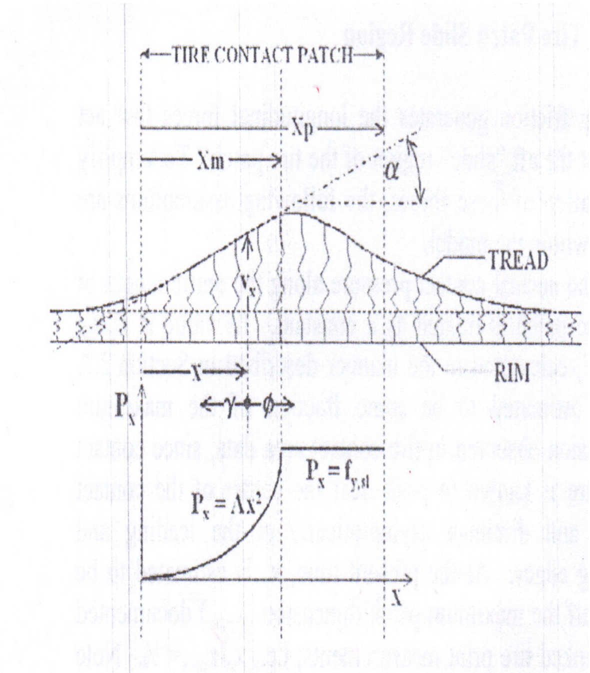

Fig. 4 Plan view of tire patch lateral deflection using a beam on elastic foundation model

3. MODEL IMPLEMENTATION IN DADS

A simple simulation of a tire tester device was created and used to debug and fully implement the new code in DADS. The tire tester is shown in figure 5. In this simulation, a tire supports a dead weight while being guided along a ramp al constant speed and constant slip angle. Longitudinal slip is gradually varied during the simulation such that the tire is free rolling at the beginning and fully braked by the end.

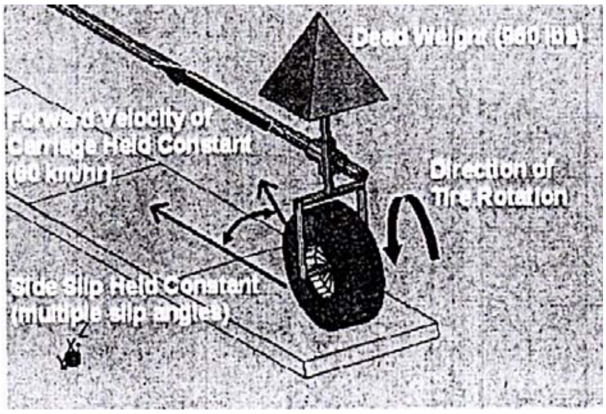

Fig. 5 DADS Tire tester simulation

Figures 6-11 display sample predictions of tire forces and moments for different slip angles from the tire tester simulation. The tire input parameters used are those listed in table 1.

Table 1: Tire model parameters for a light truck tire Goodyear Wrangler AT, P235/75R15, 35 psi

Vertical stiffness	K_{vert}=1327 lb/in
Longitudinal foundation stiffness	C_l=284 lb/in^2
Lateral foundation stiffness	k=36 lb/in^2
Rolling resistance coefficient	k_{rr}=0,01
$\beta=(k/EI)^{1/4}$	β=0,148 in^{-1}
Undeflected tire radius	R_u=14,438 in
Patch length coefficient	M_{est}=2300 lb/in

Figures 6 and 7 show longitudinal and lateral forces generated during combined cornering and braking on dry pavement for all ranges of longitudinal slip (i.e. braking) and slip angles of 2 and 5 degrees. Curves extracted from Bakker, Nyborg and Pacejka for an unspecified radial tire at the same vehicle speed and normal load are shown for relative comparison. The CRREL predictions are slightly different from the Bakker, Nyborg and

Pacejka curves, but this is to be expected, as the tires represented are likely different.

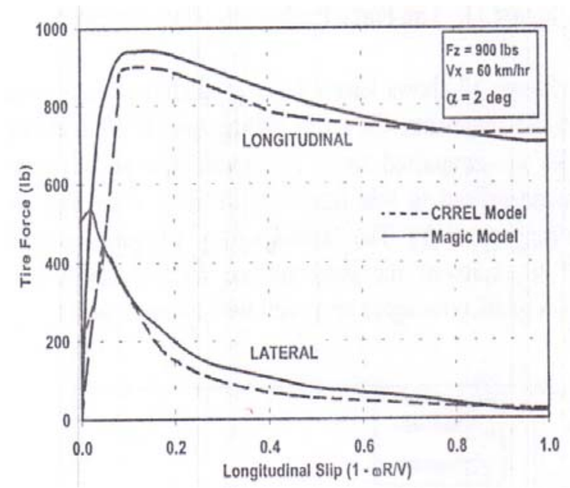

Fig. 6 Tire forces on dry pavement –**α**=2 deg

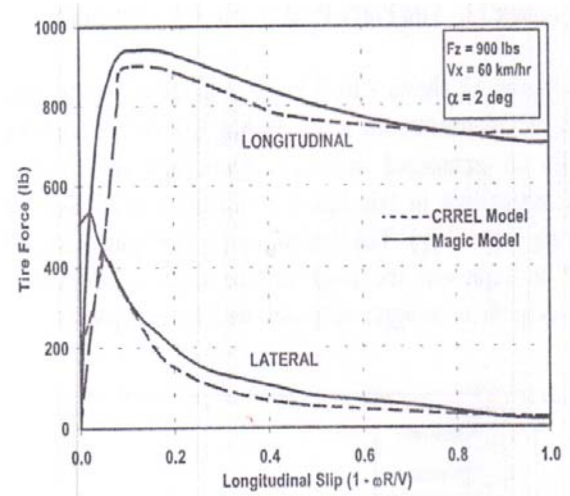

Fig. 7 Tire forces on dry pavement –**α**=5 deg

Figure 8 shows model predictions of lateral force vs. longitudinal force for different slip angles. The appearance here of dual lateral force values at a single longitudinal force is due to the drop-off in sliding friction with increasing DIV. This behavior is commonly seen in tire test data in the literature, and appears to justify the manner in which the friction coefficient is expressed in the model.

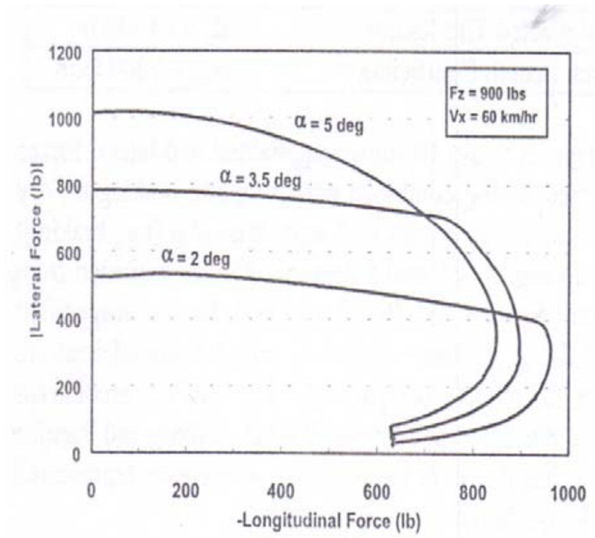

Fig. 8 Tire force prediction-dry pavement

Figure 9 shows lateral force predictions, along with field measurements for a free roling tire at different slip angles on compacted snow. (Lateral force F_y is nondimensionalized in this figure by dividing it by the tire vertical force F_z). The "snow" curve is used here to represent the road surface friction coefficient. Model predictions agree very well with measurements.

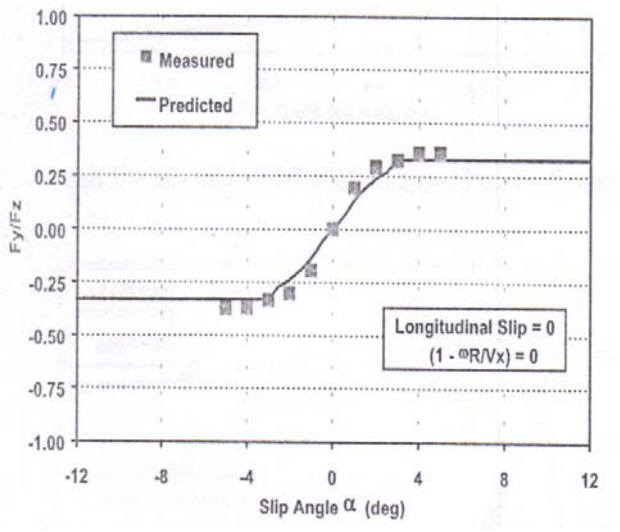

Figure 9 Lateral force predictions-packed snow

Figures 10 and 11 show sample predictions of roll moment and aligning moment on dry pavement. Both are plotted vs. longitudinal force for different slip angles. Test data are not included in these figures for comparison, as it was difficult to obtain accurate representations of these types of measurements.

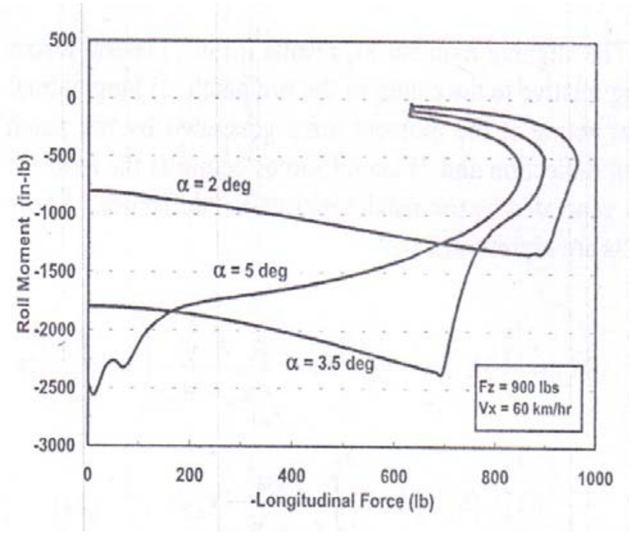

Figure 9 Roll moment predictions-dry pavement

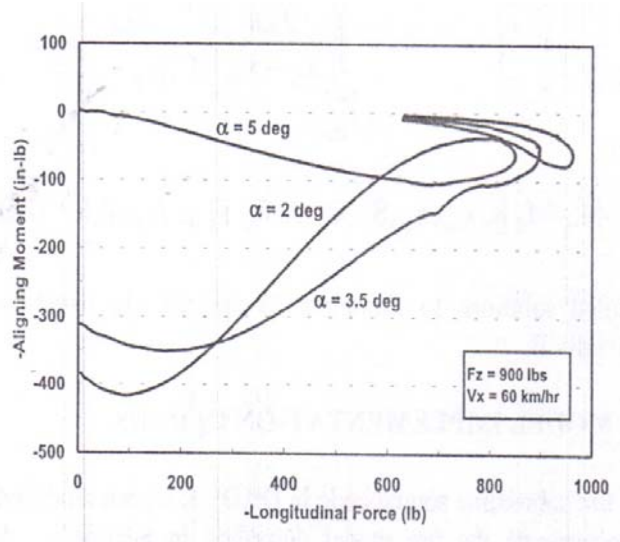

Figure 11 Aligning moment predictions-dry pavement

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