WP-2005-6

Simulation of Tire Interaction with Curbs and Irregular Terrain

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ABSTRACT

The reconstruction of vehicular loss of control often involves a path that includes irregular terrain, such as pavement edges, curbs and soft soils. Depending on the angle of impact and soil characteristics, these irregularities can significantly influence the vehicle's trajectory. To draw proper conclusions regarding accident causation requires an understanding of how such irregularities may have affected the trajectory or contributed to the loss of control. This paper describes a new tire-terrain model that includes the capability of simulating tire interaction with irregular terrain. In addition to simulating non-homogeneous pressure distributions at the contact patch, the model also simulates the forces and moments produced by tire sidewall interaction with pavement edges, curbs and soft soils. This paper presents the details of the modeling approach. Examples are provided illustrating the use of these models, including tire interaction with a curb, pavement edge and soft soil. The new model is compared with the existing point contact tire model.

VEHICULAR LOSS OF CONTROL does not always occur on a flat, level surface. Even when it does, loss of control on the roadway often leads to an off-road event during which the vehicle travels over rough, and possibly soft, terrain.

Virtually all current tire models assume the tire force is applied at a single point in the tire contact patch beneath the wheel center. Current models also assume the terrain is flat, uniform and non-deformable.

This paper describes a new tire-terrain model that was designed for simulating vehicle trajectories over irregular terrain. Examples include curbs, potholes and plowed fields. Generally, these types of terrains are problematic because they produce tire forces that are not located near the center of the tire contact patch. Instead, the tire forces may exist on the tread surface ahead of the contact patch or at the sidewall (see Figure 1). In addition, the forces may not be well modeled as shear forces, such as those that normally exist at the contact patch. Thus, they may not be limited by coulomb friction as is normally the case, but may be

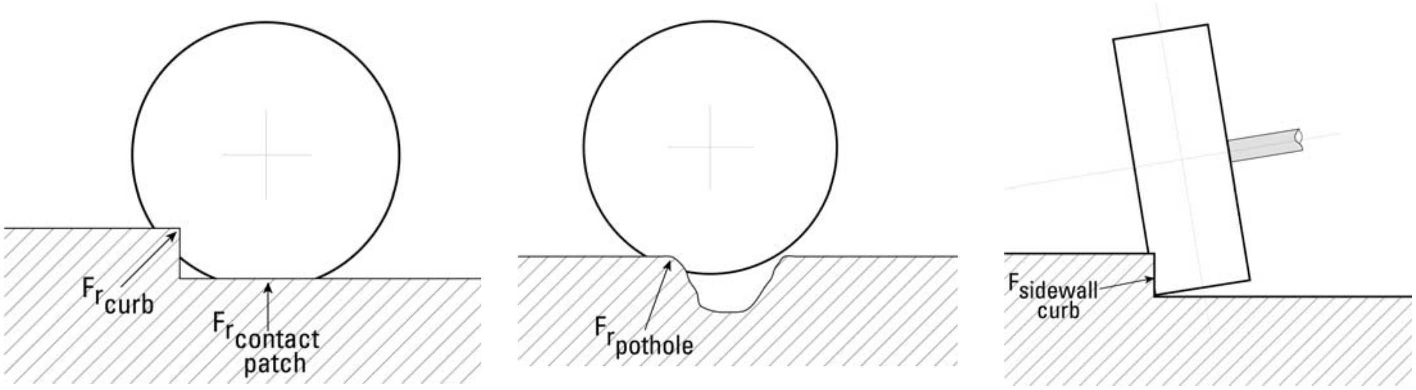

Figure 1 – Tire-terrain conditions involving tire radial forces, F_r, located ahead of the tire contact patch and on the tire sidewall

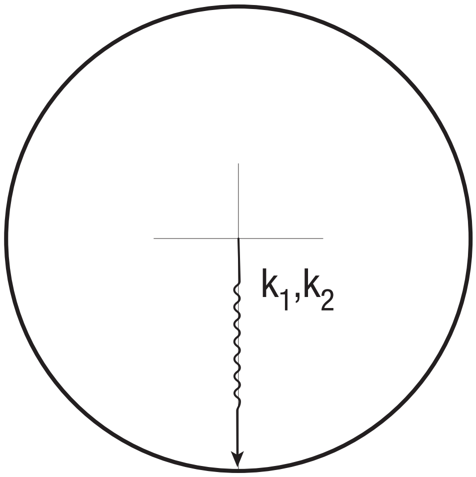

Figure 2 – Point Contact Tire Model

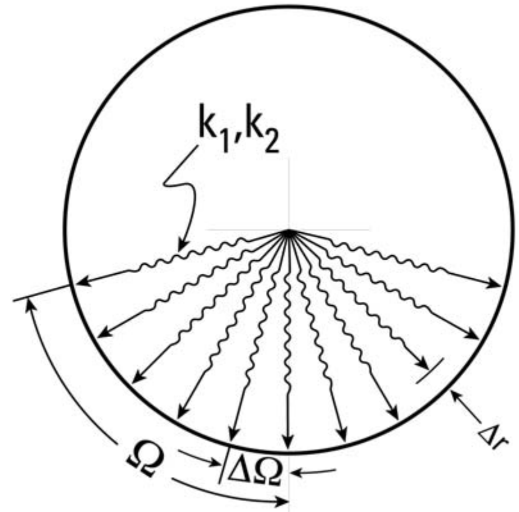

Figure 3 – Radial Spring Tire Model

significantly greater. This, in turn, may lead to significantly larger moments acting on the sprung mass. The curb-tripped rollover is a classic example. For these reasons, the development of a new tire-terrain model was important.

MODEL DESCRIPTION

The typical tire model, often referred to as the Point ContactTtire Model, is shown in figure 2. Tire radial force is modelled as a bi-linear spring acting beneath the wheel center. The model may also include pneumatic trail.

The new tire-terrain model includes three components:

- Radial Spring Tire Model
- Sidewall Impact Tire Model
- Soft Soil Tire Model

These components are described below.

Radial Spring Tire Model

The Radial Spring Tire Model models the tire as a series of springs lying in the tire plane and projecting radially outward from the wheel center (see Figure 3).

The radial springs are defined by:

Radial Spring Rate, k_1, k_2 – This 2-stage, bi-linear spring rate is derived from the tire's physical properties (initial and secondary stiffness). These rates are distributed between individual springs when the model is initialized. This initialization process results in an equivalent tire deflection for the Radial Spring Tire Model when compared to the Point Contact Tire Model.

Angular Span, Ω – It would be computationally unnecessary (and wasteful) to calculate radial spring forces about the entire perimeter of the tire, since only a small portion at the bottom of the tire is normally in contact with the ground. Starting at the ground, the *Angular Span* is an angle that defines how much of the tire's perimeter is modeled by radial springs (see Figure 3). The default value is +/-90 degrees, meaning that the entire lower half of the tire is modeled. For normal contact with relatively flat terrain, this value may be reduced to +/-30 degrees. A logical test produces a message if the *Angular Span* needs to be increased.

Angular Increment, $\Delta\Omega$ – The radial springs are placed at discrete angular intervals about the tire. This angle defines the increment between radial springs (see Figure 3).

Radial Adjustment Increment, Δr - The current force on each radial spring is determined by its displacement according to the terrain elevation beneath the spring (actually calculated as the intersection of the radial spring vector with the terrain). The *Radial Adjustment Incremen*t is used, along with quadratic interpolation of the radial spring look-up table stored for each radial spring, to determine the radial spring force.

Sidewall Impact Tire Model

The Sidewall Impact Tire Model is an extension of the Radial Spring Tire Model. In the Sidewall Impact Tire Model, each radial spring (see above) has springs projecting laterally from the wheel plane to the tire sidewall plane (see Figure 4).

[*] Numbers in brackets designate references found at the end of the paper.

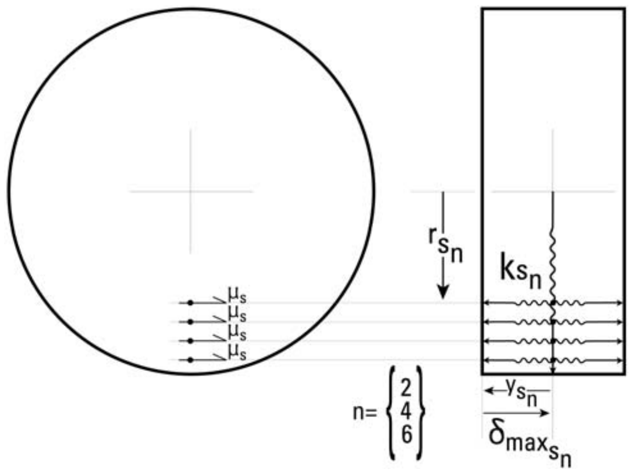

Figure 4 – Sidewall Impact Tire Model

The lateral springs are defined by:

Sidewall Slide Friction Coefficient, μ_s – This parameter defines the coulomb friction between the tire sidewall and the terrain. This value has a null band that requires relative velocity between the tire and terrain in order to produce frictional force (in the direction of the tire sidewall tangential velocity relative to the terrain).

Number of Sidewall Springs, n – This parameter defines the number of lateral springs for each radial spring. The user may specify two, four or six lateral springs.

Radial Distance from Wheel Center, r_{s_n} – The springs are evenly spaced at this radial distance from the wheel center. By default, the springs are located along the section height of the tire (the spacing differs according to the tire section height and the number of sidewall springs, above).

Lateral Distance from Wheel Center, y_{s_n} – This distance specifies the resting length of the springs. By default, this length is one-half of the tire width.

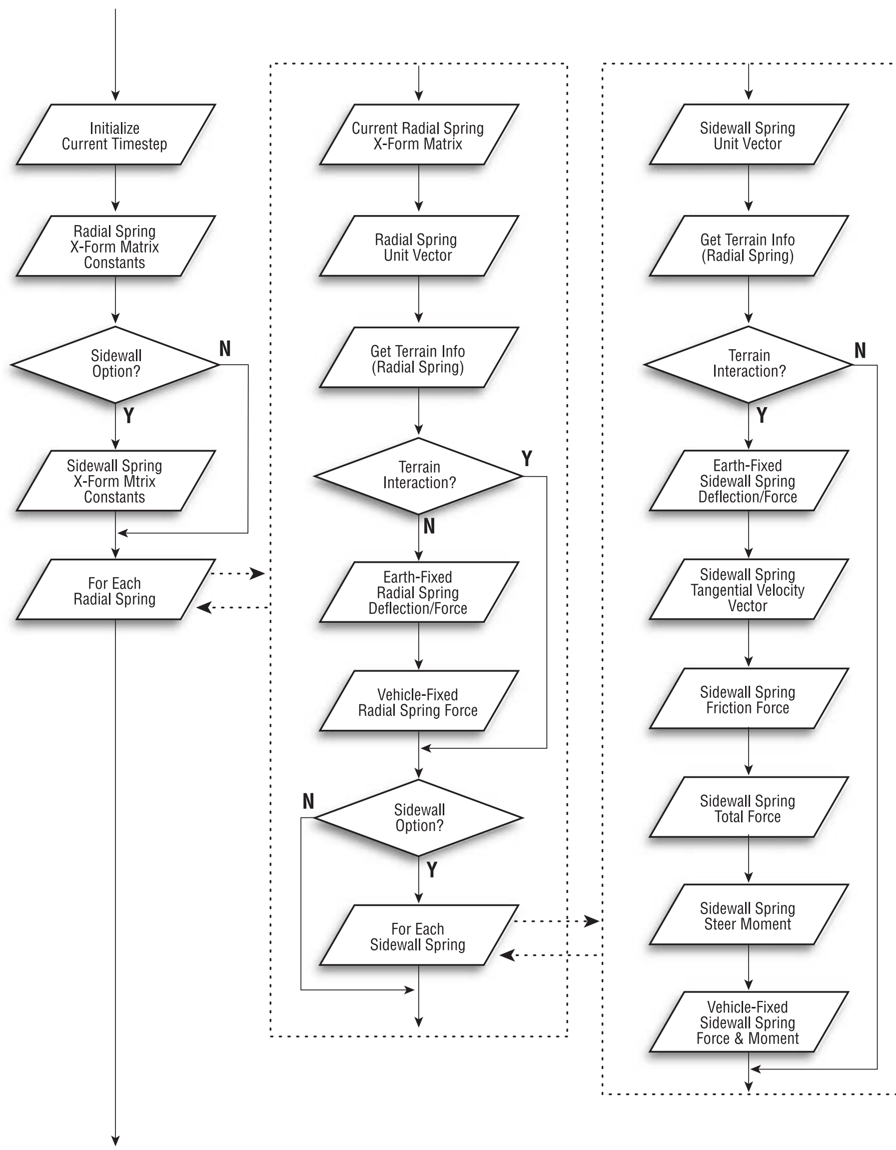

Figure 5 – Flowchart for Radial Spring Tire Model and Sidewall Impact Tire Model option.

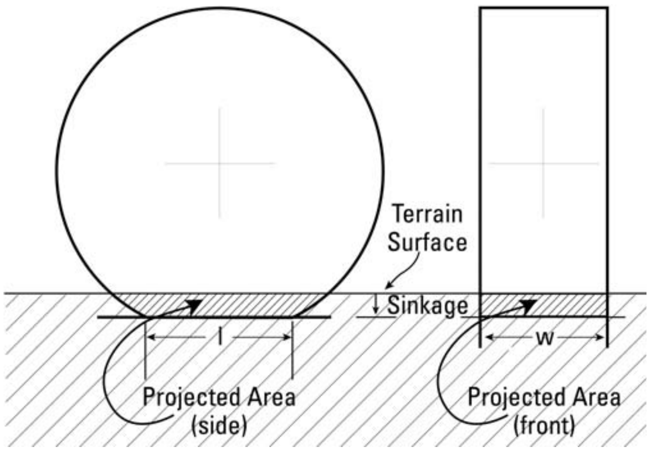

Figure 6 – Soft Soil Tire Model

Sidewall Spring Stiffness Ratio, k_{s_n} – This value provides the linear stiffness of each sidewall spring. The stiffness is assigned as a ratio of the tire radial spring stiffness. By default, the sidewall stiffness is equal to the tire radial spring stiffness divided by the number of sidewall springs.

Saturation Deflection, $\delta_{max_{s_n}}$ – This value represents the maximum sidewall spring deflection. The simulation terminates if thelateral spring deflection exceeds this value.

The forces acting at the tire sidewall produce additional forces and moments. Because these forces are not friction-limited, they can be much greater than forces generated at the tire-road interface. Sidewall forces also produce moments about the steering axis, affecting vehicle behavior when the Steer DOF Model option is used. A flowchart for the Radial Spring Tire Model and the Sidewall Impact Tire Model is shown in Figure 5.

Soft Soil Tire Model

The Soft Soil Tire Model is based on research performed by M.G. Bekker [1] at the University of Michigan. The purpose of part of Bekker's research was to predict the performance and tractive effort requirements of the lunar rover (since no one had previously driven on the surface of the moon!). In the model (see Figure 6), tire sinkage into the soil is calculated using an empirical model developed by Bekker. The empirical model uses three soil descriptors:

Bekker Soil Deformation Exponent, N - An empirically derived value describing soil deformation characteristics.

Soil Frictional Modulus, K_{phi} - An empirically derived value describing soil frictional characteristics.

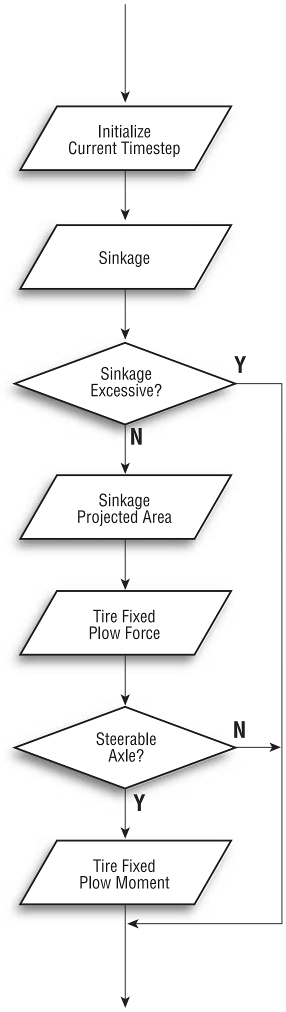

Figure 7 - Flowchart for Soft Soil Tire Model

Soil Cohesive Modulus, K_c - An empirically derived value describing soil cohesive characteristics.

Reference 1 includes a table of these soil descriptors for approximately 40 different soils of varying clay and moisture content. Many of these soils are included in the HVE Terrain Soils Database. Each terrain polygon includes a material attribute having these descriptors. The Soft Soil Tire Model uses these descriptors and current vertical tire load and size (unloaded radius and current rolling radius, and section width) to calculate the current soil sinkage beneath the tire. Sinkage also affects the earth-fixed elevation of the tire contact patch.

Based on the calculated sinkage, the projected frontal and sidewall areas of the tire sinkage are calculated. These areas are then used in conjunction with the three soil descriptors (above) to calculate the $F_{x'}$ and $F_{y'}$ tire forces.

A flowchart for the Soft Soil Tire Model is shown in Figure 7.

```
typedef struct {
    INT    Model;
    FLOAT  SpringForce[MAXRADIALSPRINGINC];
    FLOAT  dRad;
    FLOAT  AngSpan;
    FLOAT  AngInc;

    BOOLEAN SidewallContactIsTrue;
    INT    NumSidewallSprings;
    FLOAT  radSpring[MAXSIDEWALLSPRINGS];
    FLOAT  ySpring[MAXSIDEWALLSPRINGS];
    FLOAT  kSidewallRatio[MAXSIDEWALLSPRINGS];
    FLOAT  yMaxSpring[MAXSIDEWALLSPRINGS];
    FLOAT  muSidewall;
} terrainParams;
```

Figure 8 – Data Structure for Radial Spring and Sidewall Impact Tire Model

```
typedef struct {
    char   Name[MAXNAMELENGTH];
    FLOAT  forceConst;
    FLOAT  forceLinear;
    FLOAT  forceQuad;
    FLOAT  forceCubic;
    FLOAT  rateDamping;
    FLOAT  frictionMult;
    FLOAT  forceUnload;
    FLOAT  BekkerConst;
    FLOAT  Kphi;
    FLOAT  Kc;
    FLOAT  pcntMoisture;
    FLOAT  pcntClay;
} envMaterial;
```

Figure 9 – Data Structure for terrain material attributes used by the Soft Soil Tire Model

IMPLEMENTATION

The new tire-terrain models are included in the HVE Developer's toolkit [2,3]. Thus, any HVE-compatible simulation model may use them. Currently, only the SIMON model has incorporated the forces and moments produced by the new tire-terrain models into its equations of motion.

The data structure for the Radial Spring and Sidewall Impact models is shown in Figure 8. The data structure for the terrain material used by the Soft Soil model is shown in Figure 9.

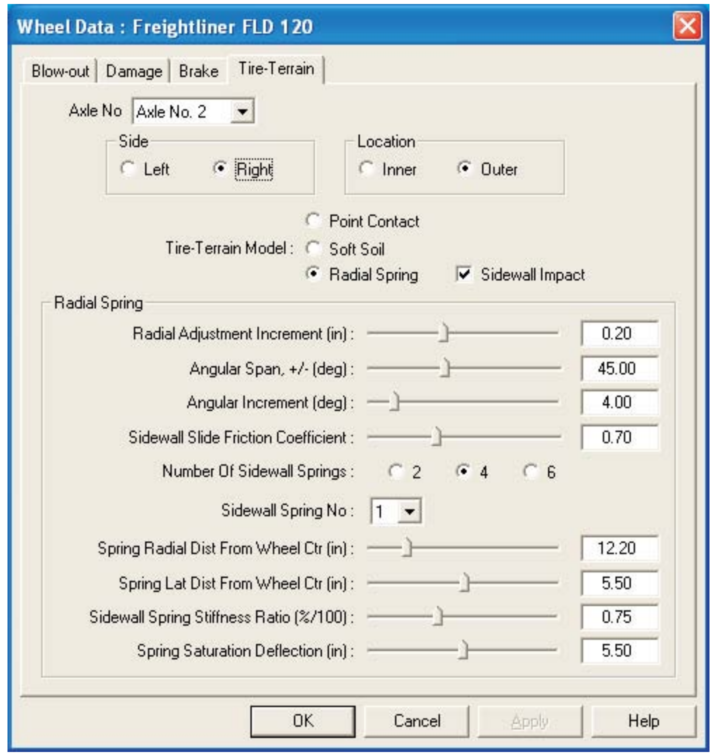

Figure 10 – Tire-Terrain dialog

User Interface

The new tire-terrain models are included as an extension to the existing Wheels options (Tire Blow-out, Wheel Damage/Displacement and Brake). Like these existing options, the Tire-Terrain option may be selected for each individual tire separately. For example, all tires may use the (default) Point Contact model. Alternatively, the left front tire may use the Radial Spring model while the right rear may use the Soft Soil model, while the left rear uses the Radial Spring model with the Sidewall Impact option. This approach provides the flexibility to model many situations. The Tire-Terrain dialog is shown in Figure 10.

Variable Output

Several new time-domain results are produced when the new tire-terrain models are used. These results are included in HVE's Variable Output, in both the Key Results windows (Event Editor) and the Variable Output table (Playback Editor).

Radial Spring Tire Model – No additional results are produced.

Sidewall Impact Tire Model – Individual tire forces and moments cause by contact at the tire sidewall are included and displayed in the Tire Data Group (see $F_{x'sw}$, $F_{y'sw}$ and M_{zsw}).

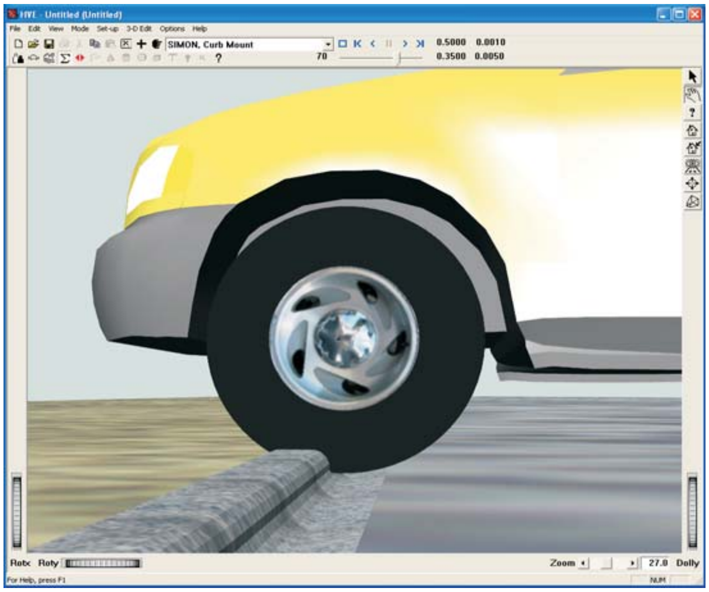

Figure 10 – SIMON simulation using the Radial Spring Tire Model showing a tire mounting a curb.

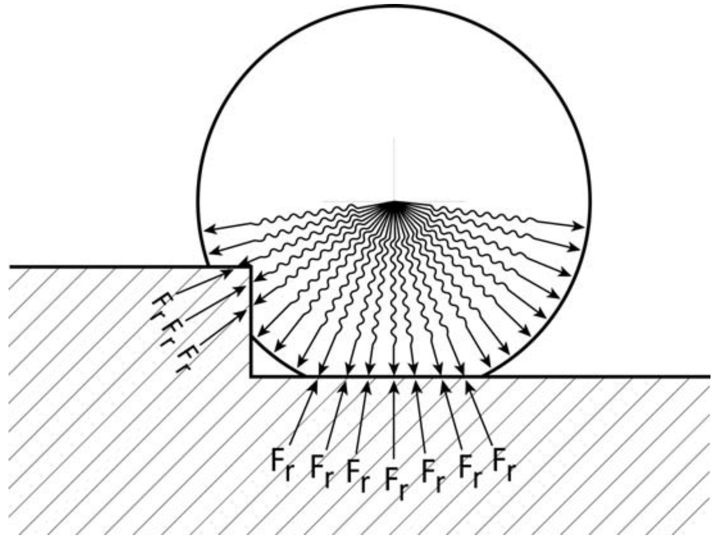

Figure 11 – Conceptualized view of Radial Spring Tire Model as the tire mounts a curb.

Soft Soil Model – The individual tire forces caused by sinkage into the soil are displayed in the Tire Data Group (see Sinkage, $F_{x', plow}$, $F_{y', plow}$). In addition, the current soil descriptors beneath the tire are also displayed in the Tire Data Group (see Moisture, K_N (soil), K_{phi} (soil) and K_c (soil).

EXAMPLES

The following three examples illustrate the use of the new tire-terrain models. Note that these examples are not a rigorous validation study. Rather they are intended to provide typical applications of the tire-terrain models to real-world problems.

Radial Spring

In this example, the Radial Spring Tire Model is used for simulating a curb impact. A simulation using the Point Contact Tire Model will often terminate with a message indicating the wheel "Broke a Rim." This condition occurs because the elevation of the terrain beneath the tire contact patch changes in a single integration timestep by, say, six inches (i.e., the height of the curb). If the change in elevation is greater than the section height of the tire, the Point Contact Tire Model predicts deformation of the rim (a condition not handled properly by any tire model). The Radial Spring Tire Model handles this condition because the individual radial springs contact the curb face and the tire *climbs the curb* (see Figures 10 and 11), just as it does during the actual event. The Radial Spring Tire Model will also properly model a tire bumping into a curb at a low speed and bouncing back.

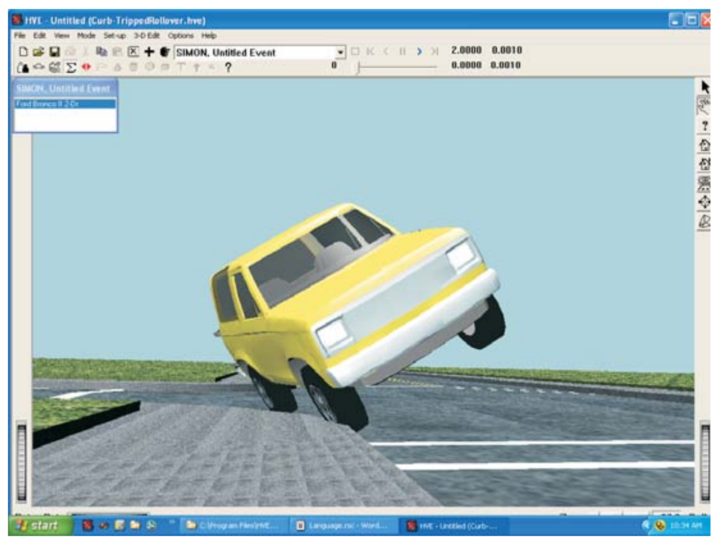

Figure 12 – SIMON simulation of curb-tripped rollover.

Sidewall Impact

This example uses the Sidewall Impact Tire Model to simulate a curb-tripped rollover. In this example, a the right front tire is assigned default Radial Spring/Sidewall Impact parameters. The initial velocity is 35 mph and the sideslip angle is +90 degrees. The result of this simulation is shown in Figure 12.

Soft Soil

In this example, a pickup truck leaves the road and spins out as it travels onto a plowed field. The additional tire

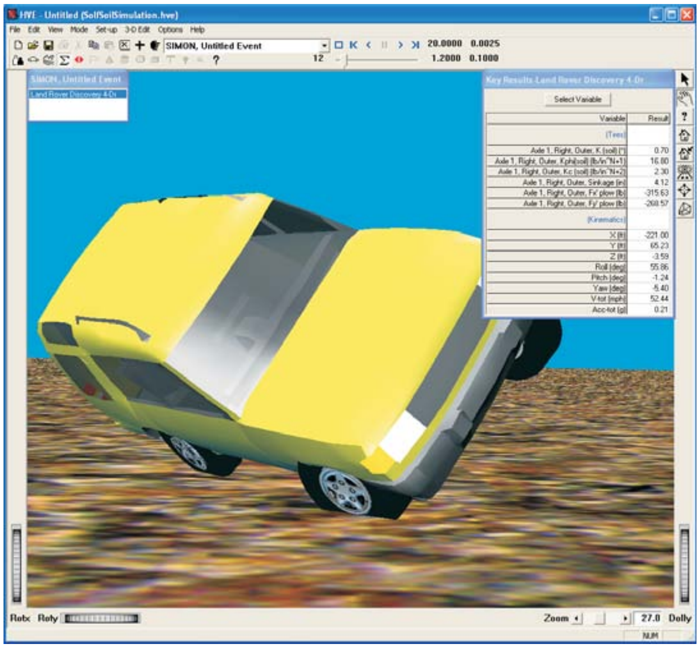

Figure 13 – SIMON simulation of rollover induced by spinning out on soft soil.

forces resulting from sinking into the soft soil significantly increase deceleration and also produce a roll moment large enough to cause the vehicle to roll over (see Figure 13).

DISCUSSION

Prior simulation models required the user to approximate the effects of curb impacts and soft soil, typically by applying a high friction multiplier. These conditions can now be simulated directly using the new tire-terrain models described in this paper.

The Radial Spring and Soft Soil models were derived from similar models in the HVOSM-RD2 model [7]. The Sidewall Impact model is similar to HVOSM, but required additional development, as the HVOSM code was found to be incomplete and non-functional. (Curb impact studies performed using HVOSM published in 1986 [8] did not use the sidewall impact option.)

The Radial Spring and the Sidewall Impact models both use `GetTerrainInfo()` to detect interaction between the tire and the terrain. This method of determining interaction is totally general in that the terrain is defined by a 3-dimensional mesh. It thus allows for the study of a tire traveling over virtually any terrain geometry.

The user interface for the new tire-terrain models does not currently allow the user to simulate both a curb impact and a soft soil event at the same wheel. For example, a curb-tripped rollover followed by lateral furrowing in soft soil at the same wheel location cannot be simulated directly. However, the event may be simulated by breaking the event into two sections.

Bekker's soil model used empirically derived parameters (N, K_{phi}, K_c) that were very non-intuitive. As a result, the user would not be able to view the parameters for a given soil and predict, or even estimate, their effect on a given handling maneuver. Therefore, additional research is required to identify expected results (sinkage, plow forces) for selected soils in the HVE Terrain Soil Database.

Although the examples provided in this paper do not constitute a validation study, the results clearly pass the "reasonableness test." Detailed experiments of instrumented vehicles traveling over potholes, curbs and soft soils have not been found in the literature, making a rigorous validation study difficult. However, some type of validation study should be performed. Further research is required.

SUMMARY

This paper described three new tire-terrain models available in the HVE Simulation Environment: Radial Spring, Sidewall Impact and Soft Soil.

These models allowed for the direct simulation of events involving tires that hit curbs and drove over soft soils

These models were useful for predicting the vehicle response to tire-terrain conditions that may result in rollover.

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