Improved Tire-Soil Interaction Model Using FEA-SPH Simulation

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Abstract
The purpose of this paper is to predict the rolling resistance of a free rolling off-road truck tire (size 315/80R22.5) over several soils. The soils are modelled using Smoothed-Particle Hydrodynamics (SPH) in the software package “Pam-Crash”. The soil models are calibrated using data obtained from published pressure-sinkage and shear-strength tests. The truck tire used in this study was modelled using Finite Element Analysis (FEA) and validated in previous studies. The tire-soil interaction algorithm is implemented in Pam-Crash software package to capture node-symmetric node-to-segment contact with edge treatment. The rolling resistance coefficient is computed from simulations and then validated against physical measurements. The rolling resistance coefficient is calculated for different terrains, such as dry sand, dense sand, clayey soil and hard surface. In addition, the rolling resistance is also computed for various tire inflation pressures and applied vertical loads. The research results presented in this paper will be further used for soil mixing-layering investigation.

Keywords: Off-road truck tire; Finite Element Analysis (FEA); Smoothed-Particle Hydrodynamics (SPH); Rolling resistance; Dry sand; Dense sand; Clayey soil, Soil modelling and calibration.

1. Introduction
This paper presents a novel simulation method to predict the rolling resistance of a free rolling off-road truck tire over several terrains including dry sand, dense sand, clayey soil and hard surface. The truck tire is modelled using Finite Element Analysis (FEA) technique and validated against measured data, while the soils are modelled and calibrated using Smoothed-Particle Hydrodynamics (SPH) technique. The work presented in this paper is considered to be an improvement of the existing tire-soil interaction simulation techniques, which models the terrain as an elastic medium; such as a plastic medium; based on the critical state soil mechanics; using Finite Element Methods (FEM) and Discrete (distinct) Element Methods (DEM) as explained by Wong [1]. SPH technique is used to model soil instead of these techniques to better duplicate the soil behaviour, in particular the cohesive properties [2]. Therefore, the SPH method improves the prediction of the rolling resistance and the tire-soil interaction. The prediction of rolling resistance coefficient is highly important to evaluate the vehicle performance on different terrains. The accurate prediction of a tire-terrain interaction leads to better predict a vehicle while operating on-road...
Figure 1. Forces acting on a free rolling tire over soil and off-road, in particular in the case of mining and industrial constructions where the environment could be extremely challenging.

Figure 1 shows schematic of the forces acting on a free rolling tire over a soft soil. The rolling resistance force acts in the opposite direction of the tire motion. The tire is considered freely rolling when a constant longitudinal speed is applied at the tire centre, as if the tire is towed without applying driving torque. On soft soil, the angular velocity of the tire may not remain constant and varies depending on the tire operating conditions and soil type. The rolling resistance coefficient is calculated from the ratio of the rolling resistance force to the vertical load. The tire rolling resistance force is generated at the tire-soil contact due to shearing and bulldozing the soil, in addition to the friction and tire hysteresis.

On hard surface, the rolling resistance force developed during the free rolling (approximately 0% longitudinal slip) of the tire along a straight direction. The rolling resistance force is applied to the tire at the contact area against the tire rolling direction. The carcass deflection due to hysteresis in the tire materials along with the road surface conditions are the primary causes of the rolling resistance. Each road surface condition has a significant rolling resistance coefficient. Generally, the rolling resistance coefficient of a truck tire varies between 0.006 and 0.01 on a concrete or asphalt road surface. The coefficient is lower than that for passenger car tires due to the difference in tire tread rubber compound, larger diameter and higher inflation pressure. The rolling resistance coefficient of a radial-ply truck tire can be estimated using equation (1). Where \( f_r \) is the rolling resistance coefficient, and \( V \) is the tire velocity in km/h.

\[
f_r = 0.006 + 0.23 \times 10^{-6} \times V^2
\]  

(1)

As the vertical contact pressure is distributed over the contact area unevenly, the vertical resultant reaction force tends to shift toward the leading edge. Thus, the moment can be developed against the tire rotational direction. This moment is defined as the rolling resistance moment.

1.1. Previous work

Modern computers and technology allow virtual tire testing in 3D environments. FEA tire models have been established to design progressive, and safer tires. Several truck tires have been modelled and validated using a virtual environment.

In 2006 Chae modelled the Goodyears truck tire size 295/75R22.5 for tractor semi-trailers. The truck tire is a radial ply tire with rim diameter of 22.5 inches. The truck tire-rim assembly model includes 27 different material definitions with 4,200 solid elements, 1,680 membrane elements, and 120 beam elements. The section width of the off-road tire is 315 mm, and the aspect ratio is 75-percent. Later in 2009, Slade modified the truck tire model built by Chae to represent the off-road truck tire size 315/80R22.5 with four grooves. The off-road tire built by Slade is a modification of the rigid ring tire model developed by Pacejka and Zegelaar. Slade model includes additional
parameters to incorporate the flexibility of the soil. The cross-section was then rotated about the tire axle axis in 6-degree increments to create the full tire with 60 equal pieces. This tire model is built using 9,200 nodes, 1,680 layered membrane elements, 120 beam elements, 27 material definitions, and one rigid body definition. The rim is defined as a rigid body for the simplicity of the model because the deformation of the rim is negligible.

In 2016, Mehrsa et al. investigated the interaction between wide base truck tire and dry sand, the dry sand was modelled using SPH and hybrid FEA-SPH technique [7]. However, the main difference between the work presented in this paper and Mehrsa’s work is that three different types of soils were modelled using improved SPH parameters as well as using different truck tire (off-road).

In 2017, Zeinab et al. implemented the SPH technique to model water to predict and validate the hydroplaning phenomena of truck tires, such as wide base and off-road tires. In addition, a novel equation is developed to predict truck tire hydroplaning speed under several operating conditions such as inflation pressures, vertical loads, water depth and tread groove depth [8,9].

Figure 2. 315/80R22.5 truck tire basic dimensions [6]

1.2. SPH technique

Smoothed-Particle Hydrodynamics (SPH) is a purely lagrangian mesh-free technique. SPH was originally designed for astrophysical application and then extended to general geotechnical problems. SPH is also applied to a massive range of implementation such as the dynamic response of material strength free surface fluid flows turbulence flows. The need for SPH analysis triggered when the deformation of materials modelled by FEA, becomes very high; element tangling may occur [2]. In this case, FEA technique is no longer reliable. SPH incorporates significant deformation and post- failure of geometrical in the framework. Thus, it is applied to simulate the significant deformation of the continuum or discrete material.

The SPH particles carry material properties such as velocity, density, stress, etc. and move with the material speed according to the governing equations. The partial differential equations for the continuum are converted into equations of motion of these particles and then solved by an updated Lagrangian numerical scheme. The mass and momentum conservation equations are as follows [2]:

\[
\frac{D\rho}{Dt} = -\frac{1}{\rho} \frac{\partial v^\alpha}{\partial x^\alpha}
\]

\[
\frac{Dv^\alpha}{Dt} = \frac{1}{\rho} \frac{\partial \sigma^{\alpha\beta}}{\partial x^\beta} + f^\alpha
\]

Where \( \alpha \) and \( \beta \) denote the Cartesian components \( x, y, \) and \( z, \) \( \rho \) is the SPH density, \( v \) is the velocity, \( \sigma^{\alpha\beta} \) stands for the total stress tensor of SPH and \( f^\alpha \) is the component of acceleration caused by external force. The \( D/Dt \) is defined as:

\[
\frac{D}{Dt} = \frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla
\]

In traditional SPH a fluid, the total stress tensor is normally divided into two parts, the isotropic hydrostatic pressure \( p \) and
Table 1. Material properties for various soils [10]

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Elastic Modulus E</th>
<th>Bulk Modulus K</th>
<th>Shear Modulus G</th>
<th>Yield Stress σ</th>
<th>Density ρ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense Sand</td>
<td>22</td>
<td>15</td>
<td>9</td>
<td>0.016</td>
<td>1.6E-9</td>
</tr>
<tr>
<td>Dry Sand</td>
<td>17</td>
<td>11</td>
<td>7</td>
<td>0.004</td>
<td>1.44E-9</td>
</tr>
<tr>
<td>Clayey soil</td>
<td>54</td>
<td>133</td>
<td>23</td>
<td>0.025</td>
<td>2.01E-9</td>
</tr>
</tbody>
</table>

a deviatoric shear stress.

\[ \sigma^{\alpha\beta} = -p\delta^{\alpha\beta} + g^{\alpha\beta} \]  \hspace{1cm} (5)

Where \( \delta^{\alpha\beta} \) Kronecker’s delta, \( \delta^{\alpha\beta} = 1 \) if \( \alpha = \beta \) and \( \delta^{\alpha\beta} = 0 \) if \( \alpha \neq \beta \). SPH is normally calculated as a function of density change by an "equation of state", whereas the deviatoric shear stress is typically purely viscous and depends on the fluid models. The hydrostatic pressure of SPH soil is instead calculated directly from the soil constitutive equation by:

\[ p = \frac{\sigma^{yy}}{3} = \frac{-1}{3}(\sigma^{xx} + \sigma^{yy} + \sigma^{zz}) \]  \hspace{1cm} (6)

Where \( \sigma^{xx}, \sigma^{yy}, \sigma^{zz} \) are the components of the stress tensor in the x, y and z directions. Equations [7] and [8] are used to define the SPH materials as shown in Table 1 where, K is the elastic bulk modulus, G is the shear modulus, E is the modulus of elasticity and \( \nu \) is Poisson’s ratio.

\[ K = \frac{E}{3(1 - 2\nu)} \]  \hspace{1cm} (7)

\[ G = \frac{E}{2(1 + \nu)} \]  \hspace{1cm} (8)

Moreover, the SPH artificial viscosity is added to the virtual environment to improve the numerical simulation stability. It is noted that shocks are always present, mostly in the first stages when initial conditions must relax. A passive term should be introduced to the governing equations to reduce the unwanted unphysical oscillations. Thus, to improve the numerical stability and to damp out such undesirable oscillations, a dissipative term \( \pi_{ij} \) (or artificial viscosity) is introduced into the pressure term of the momentum equation.

\[ \frac{Dv^i}{Dt} = \sum_{j=1}^{N} m_j (\frac{\sigma_{ij}^{\alpha\beta}}{\rho_i} + \frac{\sigma_{ij}^{\alpha\beta}}{\rho_j} - \pi_{ij}\delta^{\alpha\beta}) \frac{\partial W_{ij}}{\partial x^j} + g^i \]  \hspace{1cm} (9)

According to Monaghan the artificial viscosity can vanish the rigid-body rotation and conserve the total linear and angular momenta [2]. Monaghan selected an artificial viscosity within the range of 0.01 and 0 for his first implementation of SPH for quasi-incompressible free surface flow.

2. Simulation models setup

The simulation models consist of an FEA off-road truck tire running over soft soils modelled using SPH technique. The contact algorithms between the tire and the soil, between the soil and the box will be explained in section 2.3.

2.1. Tire modelling and validation

Several tire characteristics must be matched closely to achieve the appropriate tire response. The FEA tire model is validated in both static and dynamic responses. The static response is verified by vertical stiffness and footprint tests. The dynamic drum-cleat test validates the dynamic response of the tire.

The vertical stiffness test was implemented by Chae [5], Slade [6], and Mehrsa [7]. The vertical stiffness test allows for the calculation of the tire’s spring rate. During the vertical stiffness test, the tire is constrained in all directions except for the
vertical direction. Then, the tire is subjected to a low rate ramp loading (quasi-static) which causes the tire to slowly deform. The resultant deflection is then recorded for the corresponding vertical loads, and the relationship between vertical load and the deflection is considered.

Static footprint test is the second validation test applied to validate the tire. The contact patch of a tire is affected by the inflation pressure and vertical load. In the static footprint test, the same procedure of the vertical stiffness test is applied. However, in this case, the contact patch area is recorded instead of the deflection. The computed area is then validated against the measured data at 758 kPa. The computed contact area is 498 cm$^2$, while the measured area is about 450 cm$^2$.

The dynamic validation of the tire is done through the drum-cleat test. A significant amount of the tire mass is concentrated near the tread. The rolling tire radius is not constant due to the radial stiffness. However, the stiffness of the tire is affected by the inflation pressure and the material properties. During this test, the drum-cleat test is virtually simulated to determine the first mode of vibration by exciting the tire over a cleat on a rigid circular drum. Vertical forces acting on the spindle of the tire are translated due to the vibrations. These vertical forces are measured and converted from a time domain to a frequency domain using a Fast Fourier Transformation (FFT) algorithm. Table 2 further shows the predicted tire vertical stiffness and the first mode of vibrations at a rated vertical load of 27 kN and various inflation pressures.

<table>
<thead>
<tr>
<th>Parameters/ Inflation Pressure</th>
<th>379</th>
<th>586</th>
<th>758</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Stiffness kN/m</td>
<td>575.45</td>
<td>817.91</td>
<td>9993.65</td>
</tr>
<tr>
<td>First Mode Frequency Hz</td>
<td>46.002</td>
<td>53.002</td>
<td>56.502</td>
</tr>
</tbody>
</table>

2.2. Soil modelling and calibration

The SPH is defined as a sphere centred on the particle centre of mass with radius $r$, as shown in figure 3.

Each SPH particle has a particular mass, velocity and stress state which change according to the discretized conservation equations. Each SPH also has 3 Degrees of Freedom (DOF), the centre of mass, the volume, and the domain of influence. SPH is composed of a finite collection of particles; these particles are created from an FEA mesh. SPH is modelled first by creating an FEA mesh of the desired size, then the centre of every FEA square is taken to be one SPH particle. Thus, the SPH particles replaces the centre of each FEA element.

In 2010, Lescoe modelled soil using FEA and SPH techniques in Pam-Crash for dense sand. Lescoe solved the equation of state to find the pressure-volume relationship for dilatational elastic materials. In 2013, Dhillon validated different FEA and SPH soil models using pressure-sinkage and shear-strength tests of dry sand and clayey soil.
Dhillon investigated material properties of several terrains such as mixed sand and gravel, and clayey soil (Thailand) [13]. In 2016, Marjani developed a new modelling combination which reduces the computational time, using hybrid FEA-SPH soil models for an optimized tire-soil interaction process [7, 14].

SPH requires element part definition which needs several control parameters that influence the behaviour of the soil model apart from the material properties. SPH has some restrictions such as each particle is not allowed to exceed 10% of the internal energy. The neighbouring distance between each two consecutive SPH particles is specified by the smoothing length, while the minimum and maximum smoothing lengths, $H_{\text{min}}$ and $H_{\text{max}}$ respectively (figure 3) are governed by equation (10), where $h_0$ is the initial smoothing length.

$$H_{\text{min}} \times h_0 \leq CS LH \times h(t) \leq H_{\text{max}} \times h_0 \quad (10)$$

SPH element part requires the particle smoothing length to radius ratio, and it is recommended within the range 1.8-2. $H_{\text{min}}$, is the minimum smoothing length and is defined by default to be zero. $H_{\text{max}}$, is the maximum smoothing length and it is a user input with a range of 0 to 100.

The Anti-Crossing force (ETA) is defined using equation (11), where $\epsilon$ is the relative strength which is usually smaller than 0.5.

$$\text{ETA} = u_i + \epsilon \sum_j m_j \frac{u_j - u_i}{2(\rho_j + \rho_i)} W_{ij} \quad (11)$$

The material used to model the soils is called isotropic-elastic-plastic-hydrodynamic. Equation (12) defines the Equation of State (EOS) for this material which governs the pressure-volume relation, and behaves as an elastic-plastic material at low pressure. The elastic-plastic behaviour is inputted by specifying the yield stress and tangent modulus parameters. $C_0$ to $C_6$ are material constants, $\mu = \rho/\rho_0 - 1$ is the ratio of current over initial mass density, and $E_i$ denotes the internal energy [4].

$$p = c_0 + c_1 \mu + c_2 \mu^2 + c_3 \mu^3 + (c_4 + c_5 \mu + c_6 \mu^2)E_i \quad (12)$$

The materials used in this study are obtained from Wong’s book which defined the terrain properties as shown in table 3. These material properties are used to calibrate the modelled SPH soil accordingly, to have a similar behaviour. Equations (13) and (15) are used to plot the pressure-sinkage and shear-strength relation for the materials from the measured data listed in Wong’s book [3].

It is significantly important for tire-soil interaction study to have a well-calibrated soil. To calibrate soil models two test are performed the pressure-sinkage and the shear-strength tests. These tests are performed in virtual environment using Pam-Crash in an attempt to duplicate the physical tests.

### 2.2.1. Pressure-sinkage test

The pressure-sinkage test is performed by applying a known pressure to a plate with 150 mm radius placed on a box (600 × 600 × 600 mm) filled with SPH soil particles shown in figure 4 [3]. This test can be applied to both FEA and SPH soil models. The SPH soil particles are subjected to a range of pressures from 0 kPa to 200 kPa with an increment of 50 kPa, and the sinkage of the plate is measured. The relation between the pressure applied and the plate sinkage is computed.

The pressure-sinkage simulation results are compared with the results obtained from equation (13) that contains measured terrain parameters show in table 3 [3]. Where $p$ is the pressure in kPa, $b$ is the smaller dimension of the contact patch, that is the width of a rectangular contact area or the radius of a circular contact area in mm, $z$ is the sinkage of the plate in mm, and $n$, $k_c$, and $k_q$ are pressure-sinkage parameters. Finally, the process is repeated several times for different SPH material parameters.
Table 3. Terrain properties of modelled soils [3]

<table>
<thead>
<tr>
<th>Soil name</th>
<th>Moisture</th>
<th>$n$</th>
<th>$k_c$</th>
<th>$k_0$</th>
<th>$c$</th>
<th>$\phi$</th>
<th>$\theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry sand</td>
<td>0</td>
<td>1.1</td>
<td>0.99</td>
<td>1528.43</td>
<td>1.04</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>Dense sand</td>
<td>15</td>
<td>0.7</td>
<td>5.27</td>
<td>1515.04</td>
<td>1.72</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>Clayey soil</td>
<td>55</td>
<td>0.7</td>
<td>16.03</td>
<td>1262.53</td>
<td>2.07</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

2.2.2. Shear-strength test

The shear-strength test is performed by constructing a rectangular box of $400 \times 200 \times 240$ mm size filled with SPH soil particles, shown in figure 5 [3]. The box is made of three parts: the top plate which pressure is applied on, the upper which is the sliding plate and the lower plate which is constraint from moving in all direction. A known pressure ranging between 0 kPa and 200 kPa with an increment of 50 kPa is applied to the top plate of the box, then a small ramp displacement is applied to the upper and the top plates at a rate of 10 mm/s. The shear force is computed until the top box displacement reaches 100 mm. The shear stress is calculated and plotted against the shear-stress displacement relation described by the exponential function proposed by Janosi and Hanamoto in equation [14] [15]. The results are compared with Bekker’s shear-strength relation shown in equation [15] [3]. The test is repeated for different SPH material properties until optimal results are obtained.

\[
\tau = c + p \tan \phi 
\]

(15)

It should be noted that both the pressure-sinkage and shear-strength tests must be simulated using identical SPH material properties to get optimal behaviour for both tests. During the calibration process, the SPH material parameters are continuously adjusted, and both tests are continuously repeated until the best agreement is reached between the simulation and experimental results. The pressure-sinkage and shear-strength
simulations are repeated several times, the number of repetition of the test varies from one soil to another and could vary between 10 to 30 repetitions.

2.3. Tire-soil interaction

In 1985, Hallquist et al. established comprehensive two and three-dimensional contact algorithms to solve static and dynamic impact problems computationally [16]. Later in 1990, Benson and Hallquist examined the behaviour of a shell structure after it buckled. They specified that when a structure collapsed completely, a single surface might buckle enough to encounter itself [17]. In 2001, Hirata et al. performed computational contact simulations of elastic solids using an implicit FEM approach [18]. Hirata et al. developed a new penalty FE formulation based on the concept of material depth. This penalty represented the distance between a particle inside an object and the object’s boundary. The new algorithm was implemented in their in-house implicit FEA program for static and quasi-static analysis of nonlinear viscoelastic solids.

In 2004 Fervers investigated the interaction of tires on soft soils using FEA technique. Fervers further developed a tire-soil simulation with an exceptional view [19]. One year later in 2005, Bauer and Barfoot investigated the results of wheel-soil interaction for planetary rovers experimentally and simulation. They concluded that the experimental and simulation results were in good agreement [20]. Then in 2010 Xia modelled the tire-terrain interaction using FEM technique. Xia used the model for predicting soil compaction and tire mobility [21]. One year later in 2011, Senatore and Sandu used semi-empirical off-road tire model for predicting the longitudinal and lateral forces [22].

In this study two contacts are required during the model setup; A contact between the tire and soil (tire-soil contact), and a contact between the soil and box (soil-box contact). The contact implemented is defined as node-symmetric node-to-segment contact with edge treatment. This contact requires a definition of master-slave which in this case for the tire-soil contact the tire is considered the master and the soil is regarded as the slave, while for the soil-box contact the box is regarded as the master, and the soil is considered the slave. The input requires the definition of the thickness between the master and slave entities; this defines the field of which master and slave entities are considered in contact without penetrating each others. Some of the friction and damping parameters set in the contact are the constant friction coefficient between the entities, which in this case is defined to be 0.6 between tire-soil and soil-box. The friction coefficients depend on the terrain used, and it may vary for different terrains.
In this simulation, the tire is first inflated to the desired inflation pressure, and then the tire is loaded on the soil by applying the desired vertical load. After allowing the tire to settle on the soil, a constant linear longitudinal velocity is applied at the centre of the tire. The simulation runs until the contact forces reach steady state. It should be noted that a constant longitudinal velocity is applied at the centre of the tire as shown in figure 1. However, the angular velocity may change depending on the soil type, inflation pressure, and applied vertical load. The change in angular velocity even without applying driving torque is due to the sinkage of the tire in the soil while its towed with constant linear longitudinal velocity. Therefore, the predicted rolling resistance may not be under pure free rolling condition as it is the case on hard surface. The variation of the angular velocity at constant linear longitudinal velocity will result in longitudinal slip which is found to be between 14 to 40%. To the authors knowledge the method used to predict the rolling resistance of a tire running over soft soil is commonly used in physical testing.

The simulation of each terrain (dry sand, dense sand, and clayey soil) is repeated for several tire operating parameters such as; inflation pressures to model under inflation of 379 kPa (55 psi), nominal inflation of 586 kPa (85 psi) and over inflation of 758 kPa (110 psi) conditions; and applied vertical loads of 13 kN (3000 lbs), 27 kN (6000 lbs), and 40 kN (9000 lbs). The contact forces in the x and z directions are extracted from the simulation, and the rolling resistance coefficient is computed as a function of time. The reported rolling resistance coefficient is calculated as a mean value when the tire settles, and forces become steady.

Figure 6 shows a sample of the simulation setup of the tire-soil model (dense sand) to predict the rolling resistance of the free rolling truck tire at 586 kPa inflation pressure, and 40 kN applied vertical load. Figure 6a shows the simulation before running the tire over the soil, while figure 6b shows the compaction of the soil (residual rut) in the vertical direction due to running the tire over the soil at a constant linear longitudinal velocity of 10 km/h.

3. Results and discussion

The SPH soil calibration results will be presented and compared to measured data provided from literature in section 3.1. The tire-soil model validation will be presented in section 3.2. In addition, the results of the rolling resistance coefficient of the tire running over different soils will be investigated in section 3.3. The sensitivity of rolling resistance coefficient to operating parameters such as inflation pressure and applied vertical loads will be explored in sections 3.4 and 3.5, respectively.

3.1. Calibration results

Soil calibration was done for dry sand, dense sand and clayey soil. Figures 7a and 8a show the measured and simulated pressure-sinkage and shear-strength results for dry sand, respectively. The pressure-sinkage shows a perfect consistency compared to that of the measurements. As for the shear-strength results, the simulation and measurement curves are almost parallel which inherit similar characteristics. Figures 7b and 8b shows the same calibration results for dense sand and figures 7c and 8c shows the results for clayey soil.

It is proven that the soil calibrated matches the soil tested in behaviour and terrain characteristics for dense sand and dry sand. It should be noted that neither the tests or the simulation of the modelled soil captures the soil yield point or post-failure behaviour due to the nature of this type of soils. Moreover, the SPH technique doesn’t accurately capture the shear characteristics of the clayey soil behaviour completely due to its hardness in comparison to the dense sand and dry sand. Furthermore, the SPH technique still gives better results than FEA hydro-
dynamic elastic-plastic material type which cannot capture any shear properties of the soil while the tire is running over it.
3.2. Validation of rolling resistance model

Our research team in cooperation with Volvo Group Truck Technology performed series of testing in Volvo facility in North Carolina [14]. The truck tire tested is the XOne Line Energy T on dry sand. The tire was tested under various loads while fine transducers are assigned to the tire to record three-dimensional forces and moments. The tests were performed with a tractor equipped with the desired tire on pusher axle (free rolling tire). The tire was tested under nominal inflation pressure of 758 kPa (110 psi) and constant tractor speed of 8.05 km/h. The truck type reflects the tire loading thus a bobtail truck is an unloaded truck with a vertical load per tire of 8 kN (1774 lbs), a light truck has a load per tire of 12 kN (2680 lbs), Load 2 is 36 kN (8183 lbs) and Load 1 is 39 kN (8706 lbs).

Figure 9 shows the test tire with the equipped transducers. The transducer used is the MSVLW-2T-50K/MSCLW-2T-100K-2 with 6-Axial single or dual wheel load transducer stainless steel. The transducers have a maximum force capacity of 222 kN in the longitudinal and vertical direction and a 111 kN capacity in the lateral direction, the maximum torque capacity in all directions for full-scale output is one mV/V nominal. The transducer is five arm strain gage bridges and a nonlinearity ogles that 1% of full-scale outputs. Hysteresis and repeatability are also less than 1% of full-scale output. The zero balance before installation is less than 2% of rated output while the radial sensitivity variation is less than 1% of the radial load. The temperature range is -40 to 125 °C. The excitation voltage is 10 VDC, and the insulation resistance from the bridge case exceeds 1000 MΩ. Finally, the vehicle power input voltage is 10 to 36 VDC [23].

The purpose for this comparison is to compare the trend of the measured and predicted rolling resistance coefficients not to quantitatively compare the values. It is noted that the tire tested is a wide base truck tire which is different than the off-road truck tire used in this study. However figure [10] compares the measured rolling resistance coefficient of the wide base truck tire freely running over dry sand, and the predicted rolling resistance coefficient of the off-road truck tires at the same operating conditions over the same soil. Figure 11a shows the variation of the coefficient of rolling resistance as a function of the tire diameter for different terrains. While, figure 11b shows the variation of coefficient of rolling resistance
as a function of tire inflation pressure for different terrains. In the case of sand the curves indicate that the rolling resistance coefficient increases as the inflation pressure increases.

Figure 11. Variation of rolling resistance coefficient as a function of different parameters

3.3. Rolling resistance coefficient for different soils

Figure 12a shows the variation of rolling resistance coefficient as a function of applied vertical load for different soils and hard surface at a nominal inflation pressure of 586 kPa. The clayey soil has the highest rolling resistance coefficient which ranges between 0.30 and 0.64 for a vertical load of 13 to 40 kN, respectively. The rolling resistance over dry and dense sand is relatively in agreement regarding variation as a function of the applied vertical load as both adhere parallel behaviour. Figure 12a also shows that the rolling resistance coefficient over a hard surface is remarkably lower and vary between 0.008 and 0.004.

Figure 12. Rolling resistance coefficient for different soils
for the given vertical load range. This indicates that when the truck is driving over clayey soil the rolling resistance is highest and thus fuel consumption is higher than on sand.

Figure 12b shows the variation of rolling resistance coefficient as a function of tire inflation pressure for different soils and hard surface at a vertical load of 27 kN. Similar to the previous results the clayey soil has the highest rolling resistance coefficient varying between 0.43 and 0.46 for an inflation pressure range of 379 to 758 kPa. In addition, dry and dense sand adhere a similar behaviour, and hard surface records the lowest rolling resistance coefficient. Spite of the fact that the clayey soil has less sinkage than that of dry sand the resistance force is higher due to the higher density of the clayey soil.

3.4. Effect of load on rolling resistance coefficient

Figures 13a, 13b, and 13c show the variation of tire rolling resistance coefficient as function of vertical loads at different inflation pressures running over dry sand, dense sand, and clayey soil, respectively. All soils maintain a general pattern, as the applied vertical load increases the rolling resistance coefficient increases at a given constant inflation pressure, and as the inflation pressure increases the rolling resistance coefficient also increases due to the higher sinkage of the tire in the soil. However, each soil adheres different behaviour, for dry sand, the rolling resistance coefficient increases in a logarithmic trend, while dense sand increases almost in a linear trend as a function of load. The effect of applied vertical load on rolling resistance can be shown; an increase of the vertical load of 300% can increase rolling resistance coefficient in soils as high as 213%. Thus, the applied vertical load has a major effect on the truck fuel economy.

3.5. Effect of inflation pressure on rolling resistance coefficient

To demonstrate the relationship between the rolling resistance coefficient and the tire inflation pressure at various ap-
applied vertical loads for different soils in a clear way figures 14(a), 14(b) and 14(c) are implemented. Figures 14(a), 14(b) and 14(c) show the variation of the rolling resistance coefficient as a function of tire inflation pressure for different applied vertical loads for dry sand, dense sand, and clayey soil, respectively. For clayey soil, the inflation pressure has a minimal effect on rolling resistance coefficient as the curves are mostly parallel to the inflation pressure axis, an increase in inflation pressure of 200% increases the rolling resistance coefficient by 7%. On the other side, in the case of dry sand the rolling resistance coefficient is highly influenced by the tire inflation pressure, an increase of 200% in pressure increases the rolling resistance coefficient by 20%. Dry sand adheres similar behaviour to that of dense sand regarding curves patterns.

4. Conclusions

The tire-soil interaction for the off-road truck tire (size 315/80R22.5) running over different terrains was performed. The developed soil models included dry sand, dense sand, and clayey soil. The soils were modelled and calibrated using SPH technique, and the results were presented. The analysis focused on determining the rolling resistance coefficient at different tire inflation pressures and vertical loads for various soils. The predicted tire rolling resistance coefficient over dry sand was verified against physical measurements, the results showed a good trend agreement between simulation and measurements.

It was concluded that the rolling resistance coefficient is strongly dependent on the applied vertical load. The more the truck is loaded, the more fuel consumption is needed. On the other side, the tire inflation pressure has less effect on the rolling resistance coefficient at low vertical loads, but stronger effect at high vertical loads. The highest effect of inflation pressure was observed in dense sand.

In comparison to the truck running on different terrains. It
was concluded that the tire has the highest rolling resistance coefficient over the clayey soil. Thus, if a truck is running over clayey soil, it will require more fuel than if it was running under the same conditions on dry sand. The behaviour of the tire on dry sand was similar to that on the dense sand, as they both adhered similar characteristics.

Furthermore, the soil models developed in this study will be used to better predict real environment soil types by mixing/layering SPH soils. The layered/mixed soil will be utilized for predicting tire-mixed soil interaction properties such as rolling resistance and cornering characteristics.

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