Modelling and prediction of tyre–snow interaction using finite element analysis–smoothed particle hydrodynamics techniques

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Abstract
This paper focuses on the modelling and prediction of truck tyre–snow interaction to compute tyre motion resistance coefficient. The off-road truck tyre size 315/80R22.5 is modelled using finite element analysis and validated in static and dynamic response against published measured data. The snow is modelled using smoothed particle hydrodynamics technique and hydrodynamic-elastic-plastic material and then calibrated against physical measurements provided by published terramechanics data. The contact algorithm implemented is the node-symmetric node-to-segment contact with edge treatment. The rolling resistance coefficient is also known as the motion resistance coefficient of the truck tyre–snow interaction and is computed for several operating conditions including the vertical load, inflation pressure, tyre longitudinal speed, and snow depth. The influence of the above-mentioned operating conditions on the truck tyre motion resistance coefficient is examined and discussed.

Keywords
Truck tyre, finite element analysis, snow model, smoothed particle hydrodynamics, interaction, rolling resistance

Introduction
The purpose of this paper is to predict the motion resistance coefficient of a finite element analysis (FEA) truck tyre running over a flat-hard surface covered with smoothed particle hydrodynamics (SPH) snow at different operating conditions including inflation pressure, loading, tyre longitudinal speed, and snow depth. To the author’s knowledge, no previous attempt to model snow using SPH technique was done. This research is considered novel in terms of the snow modelling and the combination of FEA-SPH coupling for tyre interaction purpose.

Snow is defined as an accumulation of compacted ice crystals. Snow is highly affected by the atmospheric conditions including the temperature, humidity, and water equivalent.1

When the tyres are running over snow, the performance of the vehicle changes severely. Thus, studying tyre–snow interaction becomes a critical demand as it grows more and more important for safety and performance analysis. In 2003, Seta et al.2 predicted the tyre–snow interaction using explicit finite element model (FEM) to model the snow. The snow deformation was implemented using Eulerian formulation to solve the complex interaction pattern. However, the tyre model was of size 195/65R15 and no snow depth effect was investigated.

Later in 2006, Shoop et al.1 used the finite element modelling technique to produce a three-dimensional (3D) model of tyre–terrain interaction to explore the effect of tyre and terrain parameters on vehicle mobility. The vehicle mobility characteristics included traction and motion resistance. However, 2 years later, Bui et al.3 proved the limitation of FEA technique in modelling deformable terrains such as sand in comparison with that of SPH; however, no attempt has been made to model snow using SPH. In 2009, Li et al.4 developed
a mathematical technique to enhance the prediction of the interaction of a tyre running over snow by examining the influence of the snow depth and density, which resulted in an improved tyre–snow interaction model.

In 2012, Choi et al.5 numerically investigated the tyre traction over snow, and the tyre was modelled using a 3D patterned. The model employs both the Lagrangian element technique and the Eulerian finite volume technique. The metric characteristics of the snow traction were investigated. However, Choi did not attempt to compute the rolling resistance but rather the traction. One year later, Lee6 numerically modelled and calibrated a tyre–snow interaction model. The Gaussian maximum likelihood method was used to determine the snow mechanical properties, in addition to the snow depth and the coefficient of friction. However, Lee did not attempt to compute the rolling resistance coefficient and the snow model used was based on the Drucker–Prager criterion.

Recently in 2017, El-Sayegh et al.7 used FEA-SPH techniques to determine the interaction between a truck tyre running over a flooded surface to predict the critical hydroplaning speed. The SPH water model was developed using Murnaghan equation of state (EOS) for pressure–volume relation. Later, the previously modelled SPH water was used to determine the rolling resistance coefficient of an FEA truck tyre running over a wet surface, the rolling resistance coefficient was determined at different operating conditions and the effect of these operating conditions over the truck tyre performance was examined.

FEA-SPH tyre–snow model

In this section, the FEA tyre model will be presented, and then the SPH snow model will be investigated. Finally, the rolling resistance test procedure will be discussed.

FEA tyre model

Figure 1 shows the off-road truck tyre size 315/80R22.5 with four grooves that is used in this study. In 2009, Slade8 built and validated the truck tyre using FEA technique. The cross-section of the truck tyre was first built node by node and then rotated in 6° increments about the tyre axle axis to develop the full truck tyre.

The FEA truck tyre model includes 27 different materials and consists of 120 beam elements and 1680 layered membrane elements. Most of these materials are considered nonlinear in terms of the stress–strain relationship when undergoing a wide range of loads. The carcass and belt are modelled using three-layered membrane elements and has 14 different material properties. Each of the bead fillers and tread shoulders are modelled using two Mooney–Rivlin materials, while the tread base and tread cap are modelled each using one Mooney–Rivlin material. The beads are modelled using beam elements and materials, with solid circular section and a density of 4.26E–08 ton/mm³. The rim is modelled using a null material shell with a density of 8E–9 ton/mm³ and a Young modulus of 200 GPa.

To simplify the truck tyre model, the rim was implemented as a rigid body. This condition implies that the deformation of the rim is neglected. The FEA truck tyre model was validated in static using the vertical stiffness and static footprint tests and dynamic responses using the drum-cleat test.7

The vertical stiffness test is performed over a hard-flat surface; this test is used to calculate the tyre’s vertical stiffness (spring rate). The centre of the truck tyre is constrained in longitudinal and lateral translational and all rotational directions. A low rate ramp loading (quasi-static) is applied to the tyre’s centre. The loading causes the tyre to deform gradually, and the deformation of the tyre is computed at different vertical loads. The slope of the tyre deflection versus load is calculated and considered to be the vertical stiffness of the tyre.8

The static footprint test is performed to determine the tyre–terrain contact area, this test is usually performed on a hard surface. The test procedure is the same as that of the vertical stiffness test mentioned above and the tyre contact area with the surface is computed. The contact area is calculated and validated against measured published data at 758 kPa (110 psi), the simulated contact area is 498 cm², while the area provided by measurements is about 450 cm².

The drum-cleat test is shown in Figure 2 and it is used to validate the dynamic response of the tyre. The drum-cleat is modelled using FEA technique and the tyre-cleat model is used to compute the first model of vibration. The FEA truck tyre-cleat model is excited, and the vertical force acting on the centre of the tyre is measured in the time domain and then converted to the frequency domain using an algorithm implement by
previous researchers.\textsuperscript{9,10} Table 1 shows the predicted tyre vertical stiffness and the first mode of vibrations at a rated vertical load of 27 kN (6000 lbs) and different inflation pressures.

### SPH snow model

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

The SPH particle governing equations are known to be the Navier–Stokes equations and can be described in the Lagrangian state as the mass and momentum equation which are indicated in equations 1 and 2, respectively.\textsuperscript{3}$p$ is the particle density in kg/m$^3$, $\alpha$ and $\beta$ are the coordinate directions, $v$ is the particle velocity in m/s, $f^\alpha$ is the acceleration produced by the external force and $\sigma^{\alpha\beta}$ donates the total stress tensor of each SPH particle

\[
\begin{align*}
\frac{DP}{Dt} & = -\frac{1}{\rho} \frac{\partial v^\alpha}{\partial x^\alpha} \\
\frac{DV^\alpha}{Dt} & = \frac{1}{\rho} \frac{\partial \sigma^{\alpha\beta}}{\partial x^\beta} + f^\alpha \\
\frac{D}{Dt} & = \frac{\partial}{\partial t} + v^\alpha \frac{\partial}{\partial x^\alpha}
\end{align*}
\]

Equation (3) defines the derivative $D/Dt$ mentioned in the equations of motion. The total stress tensor consists of two main parts: the deviatoric shear stress, $s$, and the isotropic hydrostatic pressure, $p$. Equation (4) presents the total stress tensor with its two parts. The Kronecker’s delta is equal to 1 when $\alpha$ is equal to $\beta$ and zero otherwise

\[\sigma^{\alpha\beta} = -\rho \delta^{\alpha\beta} + s^{\alpha\beta}\]  \hspace{1cm} (4)

An EOS is used to calculate the SPH pressure–volume behaviour in relation to density change. The deviatoric shear stress, $s$, depends on the SPH material and is regarded to as purely viscous. The hydrostatic pressure, $p$, is computed from the relationship indicated in equation (5). $\sigma^{zz}$ denotes the stress tensor in the $x$-direction, $\sigma^{yy}$ denotes the stress tensor in the $y$-direction, and $\sigma^{xx}$ denotes the stress tensor in the $z$-direction

\[p = -\frac{\sigma^{xx} + \sigma^{yy} + \sigma^{zz}}{3} = -\frac{1}{3}(\sigma^{xx} + \sigma^{yy} + \sigma^{zz})\]  \hspace{1cm} (5)

The artificial viscosity of the SPH particles is combined with the momentum equation in the form of a passive term to enhance the numerical simulation stability.\textsuperscript{12} The term $\pi_j$ which represents the artificial viscosity is introduced into equation (1) as indicated in equation (6). In addition, Monaghan indicated that the artificial viscosity can conserve the total linear and angular momenta\textsuperscript{3}

\[
\frac{Dv^\alpha}{Dt} = \sum_{j=1}^{N} m_j \left( \frac{\sigma^{\alpha\beta}}{\rho_j} + \frac{\sigma^{\beta\alpha}}{\rho_j} - \pi_j \delta^{\alpha\beta} \right) \frac{\partial W_{ij}}{\partial x^\beta} + g^\alpha
\]

Equation (7) defines the EOS which governs the pressure–volume relationship for snow. The term $C_0$ to $C_6$ are known material constants and are set to zero except $C_1$, $\mu$ is the ratio of current density to the initial density and can be written as shown in equation (8), and $E_i$ is the internal energy of each particle\textsuperscript{11}

\[
P = \frac{\sigma_{ii}}{3} = \frac{1}{3}(\sigma_{xx} + \sigma_{yy} + \sigma_{zz})
\]

\[
\frac{\sigma_{ii}}{3} = \frac{1}{3}\left(\frac{\partial^2 W}{\partial x^2} + g^\alpha\right)
\]

Snow behaves in a hydrodynamic elastic-plastic manner. Equation (7) defines the EOS which governs the pressure–volume relationship for snow. The term $C_0$ to $C_6$ are known material constants and are set to zero except $C_1$. $\mu$ is the ratio of current density to the initial density and can be written as shown in equation (8), and $E_i$ is the internal energy of each particle.\textsuperscript{11}
\[ p = C_0 + C_1 \mu + C_2 \mu^2 + C_3 \mu^3 + (C_4 + C_5 \mu + C_6 \mu^2)E_i \]

\[ \mu = \frac{p}{p_0} - 1 \]

The terrain properties used for calibration are obtained from terramechanics published data and shown in Table 2. The terrain values \( n \), \( k_c \), and \( k_u \) are used in equation (9) to plot the pressure–sinkage relationship, while terrain values \( c \) and \( \phi \) are used in equation (11) to plot the shear–strength relationship.

To calibrate SPH snow model, the pressure–sinkage and the shear–strength tests are performed. These two tests are modelled in a virtual environment in an attempt to duplicate the physical ones. In 2013, Ranvir implemented the same tests to model different terrains including the dry sand.\(^{14}\)

**Pressure–sinkage test.** This test is performed by applying a desired pressure to a 150 mm radius circular plate. The plate is placed on top of an FEA box (600×800×600 mm) filled with SPH snow particles as shown in Figure 4. The circular plate is subjected to a range of pressure from 0 to 50 kPa with an increment of 10 kPa, and the sinkage of the plate is recorded. The relationship between the plate sinkage and the applied pressure is plotted.

The pressure–sinkage simulation relationships are compared with the relationships obtained from equation (9). Equation (9) consists of measured terrain values shown in Table 2, where \( p \) is the applied pressure in kPa, \( z \) is the sinkage of the plate in mm, \( b \) is the radius of the circular plate in mm, and \( n \), \( k_c \), and \( k_u \) are terrain values provided by terramechanics published data\(^{13}\)

\[ p = \left( \frac{k_c}{b} + k_u \right) z^n \]

**Shear–strength test.** This test is performed by filling an FEA rectangular box (400×200×240 mm) with SPH snow particles, as shown in Figure 5. The box consists of three parts: the top plate which pressure is applied on, the upper plate (sliding plate) which is allowed to move in \( x \)-direction only, and the lower plate which is fixed in all translational and rotational directions. A desired pressure ranging between 0 and 50 kPa with an increment of 10 kPa is applied to the top plate of the FEA box, then a ramp displacement is gradually implemented to the upper and top plates at a rate of 10 mm/s for 10 s. The shear force is computed until the upper and top plate 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\(^{15}\) in

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**Table 2.** Terrain properties of modelled snows.\(^{13}\)

<table>
<thead>
<tr>
<th>Snow</th>
<th>( n )</th>
<th>( k_c )</th>
<th>( k_u )</th>
<th>( c )</th>
<th>( \phi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweden</td>
<td>1.44</td>
<td>10.55</td>
<td>66.08</td>
<td>6</td>
<td>20.7</td>
</tr>
</tbody>
</table>

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**Figure 4.** Pressure–sinkage test with SPH snow particles: (a) initial stage and (b) final stage.

SPH: smoothed particle hydrodynamics.

**Figure 5.** Shear–strength test with SPH snow.

SPH: smoothed particle hydrodynamics.
equation (10). The results are compared with Mohr–
Coulomb failure criterion shown in equation (11)\textsuperscript{13}
\[ \tau = (c + p \tan \phi) \left( 1 - e^{-\gamma/h} \right) \]  
\[ \tau_{\text{max}} = c + p \tan \phi \]  

It should be noted that both the pressure–sinkage and shear–strength tests should be simulated using identical SPH snow material properties. During the calibration process, the SPH snow material properties are adjusted, and both pressure–sinkage and shear–strength tests are repeated using the adjusted material properties until the best agreement between the simulation and experimental for both tests is obtained.

Snow calibration. The SPH snow model presented in this paper is considered to be a first attempt to model snow using SPH technique. The snow is calibrated using the above two mentioned tests. SPH snow is calibrated against snow from Sweden collected from the literature by Wong.\textsuperscript{13} Sweden snow has considerably a high cohesion in comparison with that of sand. In a comparison of the Sweden snow to snow from the United States, Sweden snow has the lowest index \( n \) and the highest cohesion which is 6 kPa.

Figure 6 shows the shear-stress in kPa as a function of the shear displacement in mm for various pressures between 0 and 29.2 kPa. The figure shows a rapid increase and some oscillations at the beginning of displacement curve, the curve then continues in an approximately steady-state motion. The curves can be compared with those obtained from physical measurements.\textsuperscript{13} The results show similarity in shape and slope.

Figure 7(a) and (b) shows the pressure–sinkage and shear–strength relations, respectively. It can be concluded from Figure 7(a) that the SPH snow modelled is in good agreement with that from Sweden, at 50 kPa pressure the SPH snow has a sinkage of 473 mm, while the Sweden snow has a sinkage of 498 mm. It is noted that this test is only done for a pressure up to 50 kPa due to the limitation of snow during pressure.

Furthermore, the SPH snow and Sweden snow are in good agreement in shear–strength behaviour as well. The internal friction angle \( kN \) own as the tangent of the shear–strength line is calculated from simulations to be 20.7\textdegree and that from Sweden snow to be 16.2\textdegree. The cohesion \( kN \) own as the \( y \)-intercept is calculated from simulation to be 1 kPa and that of Sweden snow is 6 kPa.

It should be noted that the snow model may vary significantly depending on the desired terrain properties and the environment conditions. The snow model presented is obtained from various calibrations and simulations.

Rolling resistance test procedure

Three different contacts are defined in the FEA-SPH model setup in Pam-Crash: contact between the FEA tyre and SPH snow known as the tyre–snow interface, contact between the SPH snow and FEA road known as the snow–road interface, and contact between the FEA tyre and the FEA road known as the tyre–road
interface. Node-symmetric node-to-segment contact with edge treatment algorithm is implemented in this study to model the different contacts.

The thickness between the contact parts is used to determine the field at which these parts are in contact without penetrating each other. In addition, the contact algorithm requires the coefficient of friction which is equal to 0.4 between any surface and snow, and 0.8 between tyre and road, based on published research.16

Figure 8 shows the rolling resistance test set up and forces at 200 mm snow depth. The tyre is also constrained in rotational about the longitudinal and vertical directions and only free in the rotational about the lateral direction. On the other side, the road is constrained in all rotational and translational directions. The rolling resistance test starts by inflating the tyre to the chosen inflation pressure, and then the FEA truck tyre is loaded on the snow by applying the desired vertical load (force) at the centre of the tyre. The tyre is then allowed to settle on the snow. Later, a desired constant linear longitudinal velocity is activated to the centre of the tyre. The tyre is retained running until the contact forces between the tyre–snow and tyre–road reach a steady state.

The rolling resistance procedure is repeated for various truck tyre operating parameters by such as: inflation pressures of 379 kPa (55 psi), 586 kPa (rated inflation) (85 psi) and 758 kPa (110 psi); applied vertical loads of 13 kN (3000 lbs), 27 kN (6000 lbs) and 40 kN (9000 lbs); constant linear longitudinal speed of 10, 25, 50 and 75 km/h; and snow depth of 50, 100 and 200 mm. The tyre loading is changed by changing the magnitude of the vertical load, and the tire speed is varied by changing the longitudinal speed applied at the centre of the tyre. The contact forces in both the longitudinal and vertical directions are computed from the results file, and the rolling resistance coefficient (motion resistance coefficient) is determined by dividing the longitudinal force by the vertical one.

Figure 9 shows a fragment of the simulation setup of the tyre–snow model to predict the motion resistance coefficient of the free rolling truck tyre at 586 kPa (85 psi) inflation pressure, 27 kN (6000 lbs) applied vertical load, 200 mm snow depth and constant longitudinal speed of 10 km/h. The contour used in this case is the displacement in the normal direction.

Results and discussion

In this section, the model validation will be discussed. Later, the effect of different operating conditions such
as vertical load, inflation pressure, and snow depth will be investigated.

Model validation

In 1981, Harrison\textsuperscript{17} conducted experimental testing on a shallow snow model for predicting the vehicle performance. The study concluded that the inflation pressure increases the resistance force increases as well, the test was done at Houghton on 30 January 1975. In addition, Harrison found a relationship between the drawbar pull and the traffic snow depth, the relationship indicates that as the snow depth increases, the drawbar pulls force reduces. Furthermore, Harrison investigated the rut depth as a function of the snow depth as shown in Figure 10. The results indicate that the rut depth increases as the snow depth increases which leads to a higher motion resistance coefficient at deeper snow.

In 2006, Shoop et al.\textsuperscript{1} simulated the relationship between the motion resistance coefficient and the snow depth using finite element simulations for different tyres including the heavy extended mobility tactical truck (HEMTT) with 16R20 tyre size. Figure 11 shows the finite element simulations for the Instrumented Vehicle tyre size 235/75 R15 rolling with zero slip, and for unrestricted slip, along with NATO Reference Mobility Model (NRMM) predictions and measured data for motion resistance in fresh snow (density approximately 200 kg/m\(^3\)). This trend is similar to that obtained in this study in section.

Figure 12 shows the truck tyre snow interaction during rolling resistance test for 586 kPa (85 psi) inflation pressure, 27 kN (6000 lbs) vertical load and 200 mm. The path of the tyre on snow can be clearly seen and the density change indicates that the snow characteristics change along the simulation time as well. These observations can also be seen in Figure 9.

In 1995, Richmond\textsuperscript{18} performed motion resistance experimental research of driven vehicles in snow, the study was done by cold regions research and engineering lab Hanove. The study concluded that for a wheeled tyre at constant load and inflation pressure, the motion resistance increases as the snow depth increases. This conclusion was observed in this research as well. Richmond also examined the influence of the tyre speed on the vehicle performance.

Due to the limitations in experimental testing of the motion resistance coefficient of truck tyres over snow, it is difficult to quantify the results obtained; however, the trends and relations are in agreement with previously mentioned published data.

Effect of inflation pressure

Figure 13 present the relationship between the motion resistance coefficient and the truck tyre inflation pressure at different loadings and a constant snow depth of 50 mm. It can be concluded that the motion resistance coefficient slightly increases as the inflation pressure increases. The motion resistance coefficient varies between 0.17 and 0.18 at a rated vertical load of 27 kN (6000 lbs) and 50 mm snow depth for an inflation pressure between 379 kPa (55 psi) and 758 kPa (110 psi).
The increase in inflation pressure reduces the contact area; however, the ratio of load to the contact area, \( L/A \), increases which results in an increase in motion resistance coefficient.

**Effect of loading**

Figure 14 presents the relationship between the motion resistance coefficient and the tyre loading at different inflation pressures and constant snow depth of 200 mm. The motion resistance coefficient reduces as the load increases, for example, an increase of loading from 13 kN (3000 lbs) to 27 kN (6000 lbs) which is doubling the loading the motion resistance coefficient reduces by 57% for an inflation pressure of 758 kPa (110 psi). The same pattern was obtained by El-Sayegh et al.\(^9\) for a truck tyre over flooded surface.

Generally, the motion resistance coefficient ranges between 0.32 and 0.13 at a rated inflation pressure of 586 kPa (85 psi) and 200 mm snow depth for a vertical loading between 13 kN (3000 lbs) and 40 kN (9000 lbs).

**Effect of longitudinal speed**

Figure 15 presents the relationship between the motion resistance coefficient and the tyre longitudinal speed at the rated inflation pressure 586 kPa (85 psi) and loading of 27 kN (6000 lbs), for different snow depths. The longitudinal speed of the tyre was set constant through the simulation, and the simulation was repeated at different longitudinal speeds (10, 25, 50, 75 km/h) and snow depth (50, 100, 200 mm). It can be concluded that as the tyre speed increases for a constant inflation pressure, loading and snow depth, the motion resistance coefficient increases. In addition, as the snow becomes deeper on the road, the motion resistance coefficient increases for constant speed, inflation pressure, and loading; this is the same observation mentioned in effect of snow depth section. For a speed change from 10 and 75 km/h which is about 7.5 times more, the motion resistance coefficient increases around six times from 0.0179 to 0.114.

As mentioned in the rolling resistance test procedure, the tyre is considered free rolling as no driving or braking torque is applied to the centre of the tyre; however, during the free rolling, the angular velocity may vary depending on the snow depth and operating conditions. The change in angular velocity of the tyre is due to the sinkage in the snow. The variation of the angular velocity at constant linear longitudinal velocity will result in a longitudinal slip as shown in Figure 16. To the author’s knowledge, the method used to predict the rolling resistance of a tyre running over any soft terrain is commonly used in physical testing.

**Effect of snow depth**

Figure 17 presents the relationship between the motion resistance coefficient and snow depth at 586 kPa (85 psi) for different loadings. It is concluded that as the snow depth increases, the motion resistance coefficient increases for all loadings. However, the motion...
resistance coefficient does not linearly increase with respect to the snow depth but rather parabolically. It is noticed that at a snow depth of 50 mm, the motion resistance coefficient of 13 kN (3000 lbs) and 27 kN (6000 lbs) is almost the same, and as the snow depth increases, the difference in motion resistance coefficient becomes more clear. For instance, if snow depth is doubled from 100 to 200 mm, the motion resistance coefficient increases by 350% at 13 kN (3000 lbs) vertical load.

As snow depth increases, the tyre–snow contact area increases as well resulting in higher motion resistance coefficient. In addition, the increase in snow depth increases the tyre motion resistance due to bulldozing effect. This trend is similar to that observed by Shoop et al.\(^1\) and mentioned in Figure 11. Also, Figure 10 indicates the increase in the rut as the snow depth increases which leads to the increase in contact area and thus increases in motion resistance coefficient.

**Conclusion**

The motion resistance coefficient of an FEA truck tyre running over SPH snow was investigated. The truck tyre was modelled using FEA technique and validated against published measured data. Snow from Sweden was modelled using SPH technique and calibrated against terramechanics published data. The FEA-SPH coupled interaction was implemented using node-symmetric node-to-segment contact with edge treatment. The operating conditions affecting the tyre performance were investigated, the conditions included the inflation pressure, vertical load and snow depth. Although the results were not quantitatively validated due to testing limitations, however, the trends and patterns were validated against published research results.

It was concluded that as the vertical load increases the motion resistance coefficient of a tyre reduces for constant inflation pressure and snow depth. For example, if the load doubles from 13 kN (3000 lbs) to 27 kN (6000 lbs), the motion resistance coefficient reduces by 57% for an inflation pressure of 758 kPa (110 psi) and 200 mm snow depth.

On the other side, the motion resistance coefficient increases as the inflation pressure increases for a constant vertical load and snow depth. It is noted that the effect of inflation pressure at high vertical loads becomes negligible. In addition, the motion resistance coefficient increases as the snow becomes deeper on the ground for constant inflation pressure and loading. Generally, the highest motion resistant coefficient recorded was 3.276 at 13 kN (3000 lbs) loading, 586 kPa (85 psi) inflation pressure and 200 mm snow depth. Finally, as the tyre speed increases for a constant inflation pressure, loading and snow depth, the motion resistance coefficient increases.

This research will further continue to investigate the effect of other operating conditions on the tyre–snow interaction performance. The results obtained from this study will be used to further examine the effect of snow–ice layering and snow–water mixing on tyre performance.

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