UTILITY TRUCK: MORPHING BOOM EQUIPMENT FOR TERRAIN MOBILITY

Parth Y. Patel[a], Vladimir V. Vantsevich[a], and Jordan A. Whitson[a]

[a] *University of Alabama at Birmingham, 1720 2nd Avenue South, Birmingham, AL 35294*

parth144@uab.edu, vantsevi@uab.edu, jordanaw@uab.edu

Abstract

Utility trucks with boom equipment function on environmentally sensitive areas and severe terrains where off-road conditions may cause significant damage to the trucks' mobility and their safe operation. Indeed, considerable variations of landscape elevation and dynamic changes of terrain properties lead to extensive differences in the wheel normal reactions, drastic fluctuations of the rolling resistance at each tire, and finally, substantial changes in the total resistance to motion, which includes both the tire rolling resistance and the resistance due to the truck gravity component. Additionally, lateral forces caused by truck inclinations can lead to instability in motion, too. As a result, a utility truck can become immobilized in either longitudinal or lateral direction of movement because of one or the combination of the following events – loss of longitudinal mobility due to extensive tire slippage at some/all wheels, loss of lateral mobility due to tire side skid or rollover of the truck.

To eliminate the above-listed causes that can lead to the utility truck immobilization, this study suggests a novel approach to managing the input/output factors that influence both longitudinal and lateral forces of the utility truck. In fact, the 3D morphing of the boom equipment is proposed as the input factor for managing the wheel normal reactions as the outputs. Ultimately, a changeable positioning of the boom equipment relative to the truck frame results in variable wheel normal reactions, which are the main contributors to the normal tire deformation and soil compaction, and thus, to the rolling resistance of each and all tires.

This paper presents and discusses the method and results of computational simulations of the F450-based utility truck with boom equipment on medium mineral soil. The normal reaction at each wheel is evaluated under which the boom equipment morphs safely without causing roll over of the truck and, consequently, the total resistance to the motion force is determined. Modeling and simulation of the truck were conducted with the use of terramechanics-based tire-terrain models. This research study of the rolling resistance contributes to a research project on morphing utility truck, dynamics in severe terrain conditions.

Keywords: Utility Truck, Morphing, Terrain Mobility

1. Introduction

The freight, and utility transportation systems are the dominant methods of moving commerce, providing services, and saving lives, nationally and internationally. Moreover, the truck fleets "rule" the strain on the environment, resource consumption, and amplify citizen's exasperation. There were approximately 2.83 million truck drivers in the country in 2014, 28.2% of drivers drove various service trucks [1]. Utility trucks (also known as boom trucks) as shown in Fig. 1, are the first responders in extreme climate and weather situations for saving people's lives, for restoring electric power, cutting trees, and restoring traffic on roads. However, such trucks can increase the possibility of road accidents in many ways and additionally, it can create dangerous situations on off-road conditions, while moving, and performing tasks due to their geometry change as represented in Fig. 2.

Multi-phase hazardous weather, and roadway conditions are typical climate features nationally. Studies of the tire-terrain interaction have mostly been done on vehicles with conventional wheels [2-4], but not much work has been done regarding large trucks which carry a large manipulator on off-road conditions. Terrain wheeled utility trucks are expected to maintain high mobility over deterministic conditions of the terrain. Researchers analyzed various methods to improve the mobility of wheeled vehicles in a deterministic approach due to their limitations and implementation of the technology [5-7]. Several approaches were developed to improve the mobility of conventional vehicles through these years [8-16].

Continuing in this direction, this paper represents a novel technical approach to manage the input/output factors that influence both longitudinal and lateral mobility of the utility truck. Moreover, the 3D morphing of the boom equipment is proposed as the input factor for managing the wheel normal reactions as the outputs. Ultimately, a morphable positioning of the boom equipment relative to the truck frame results in variable wheel normal reactions, which are the main contributors to the normal tire deformation and soil compaction, and thus, to the rolling resistance of each and all tires.

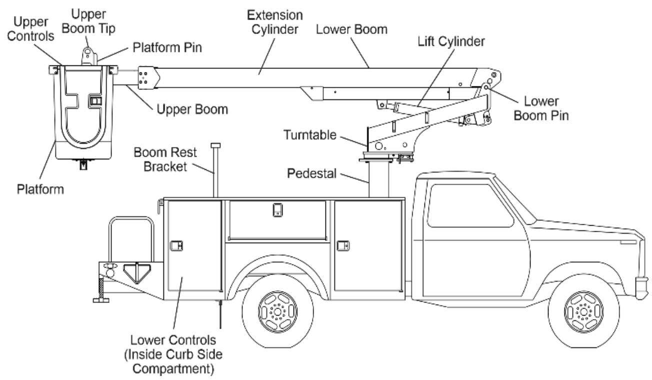

Fig. 1. Configuration and component identification of the utility truck.

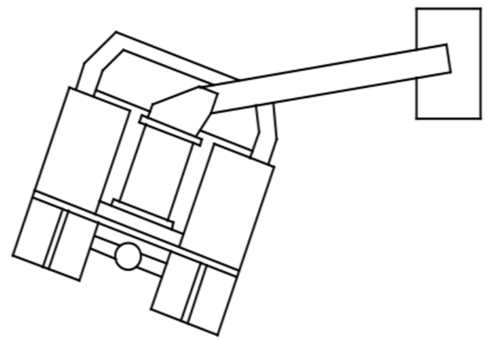

Fig. 2. Rollover of the truck due to geometry change of the boom equipment.

2. Utility truck terramechanics-based tire-terrain wheel normal reaction and rolling resistance computation algorithm

The utility truck terramechanics-based tire-terrain model integrated with the mathematical model of the truck multi-body system goes through the following procedure of steps, i.e., a computational algorithm described as follows:

1) Defining the utility truck's boom equipment as a five-degree of freedom manipulator with revolute and translational joints with the geometrical constraints of the utility truck and calculating the static normal loads acting on the wheels.
2) Approximate whether the pneumatic tire behaves like a rigid wheel or an elastic wheel under a given operating terrain condition and the corresponding condition's parameters.
3) Solve a set of six terramechanics-based tire-terrain equations by using an iterative procedure to get the following parameters: average ground pressure, tire deflection, tire contact width, contact length, pressure-sinkage, and the normal reaction acting on the flat and curved section of the elastic tire.
4) Based on the values of above-listed parameters, calculate the soil compaction resistance and tire flexing resistance.
5) Finally, based on the total resistance force at provided normal load, calculate the rolling resistance coefficient.

In this analysis, the utility truck is considered as a multi-body system moving at a constant small speed, thus the inertia is neglected. The truck frame is considered as rigid when computing the static normal reaction at each wheel.

3. Wheel static normal reaction/load calculation

The normal load acting on the wheel's change markedly in lieu of the various configuration of the boom equipment. Additionally, when the truck is on the tilted and/or inclined surface from side to side the normal reactionary forces of the wheels are noticeably affected. Figure 3 represents a two-dimensional drawing of the utility truck's mass and geometry on a horizontal surface. The constraint imposed by the truck's boom geometry [17] are identified in table 1.

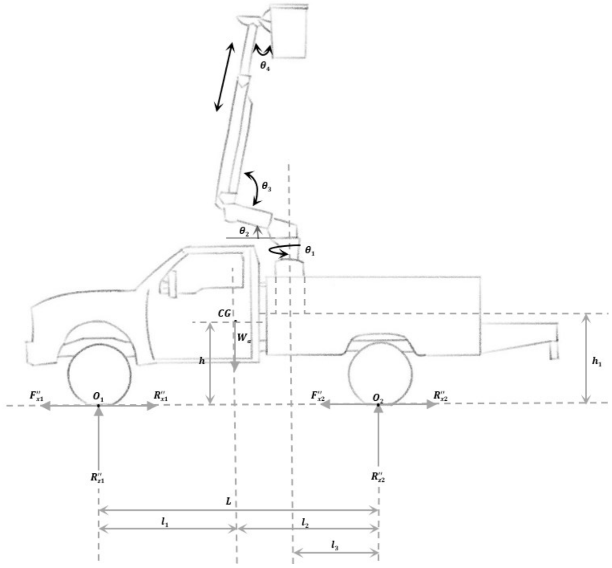

Table 1. Constrained of utility truck's boom geometry

Parameter	Working range
Turntable Angle (θ_1)	-15.0 to 370 degrees
Turntable Boom Angle (θ_2)	15 degrees
Boom Articulation Angle (θ_3)	-13.5 to 80 degrees
Bucket Articulation Angle (θ_4)	0 to 76 degrees
Upper Boom	3.683 m

Fig. 3. 2D Drawing of a utility truck on horizontal flat surface

In this analysis, the boom equipment is considered as a five-degree of freedom manipulator, as represented in Fig. 3. Thus, the boom equipment has around 68 million possible combinations (increments of each theta by one degree) to visualize the static normal reaction/load. Out of which, one case is presented to show how normal reactions/loads are affected at each wheel when the boom equipment morphs its orientation in Fig. 4 in which, θ_1 i.e., turntable angle rotates from -15° (Initial position) to 370°, θ_2 = 15°, θ_3 = 0°, upper boom is fully extended, and θ_4 = 0°. Also, only tire and suspension stiffness of the utility truck are considered to calculate the static normal reaction on hard surface.

The static normal reactions (R_z) at various orientation of the boom equipment are considered as a normal load W_w acting on the wheels for the tire-terrain interaction dynamics model to calculate the reaction forces imposed by the terrain.

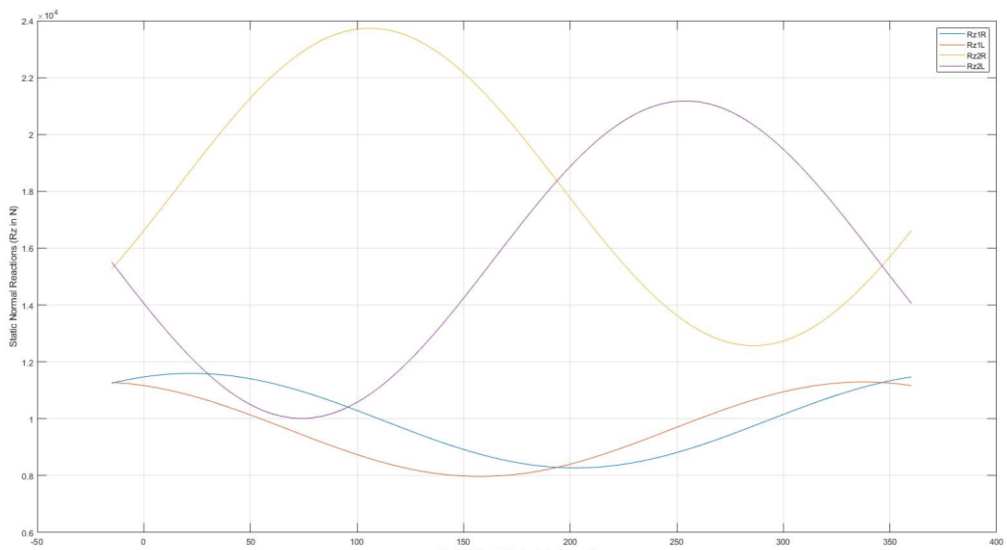

Fig. 4. Static normal reactions/loads at each wheel when the boom configurations are θ_1 = -15° to 370°, θ_2 = 15°, θ_3 = 0°, θ_4 = 0°, upper boom is fully extended, and tilt angle (∅) = 0°.

The dynamics of the boom equipment and dynamic normal reactions are not provided here, since the new technical approach of this analysis is to show that various values of the static normal reactions/loads can be achieved by morphing the boom equipment at various position and how the normal reaction distribution influences the rolling resistance of the morphing truck. The dynamics of the truck is an ongoing study.

4. Prediction of the operating mode of a pneumatic tire

A vast collection of methods has been developed to study the wheel-terrain interaction. Wong [18] proposed the following equation for determining the critical ground pressure p_{gcr} to improve the accuracy in the prediction of the operation mode of a pneumatic tire, and to provide a smooth transition from one operation mode to another:

$$p_{gcr} = \left[\frac{k_c}{b} + k_\emptyset\right]^{1/(2n+1)} \left[\frac{3W_w}{(3-n)b\sqrt{D}}\right]^{2n/(2n+1)} \tag{1}$$

where b is the tire contact width when it is the smaller dimension of the contact patch; n, k_c, and $k_\emptyset$ are pressure-sinkage parameters for the Bekker equation, D is the wheel diameter, and W is the normal load.

The pressure-sinkage relationship proposed by Bekker [19]:

$$z_0 = \left(\frac{p_i + p_c}{k_c/_b + k_\emptyset}\right)^{1/n} \tag{2}$$

where p_i is the inflation pressure and p_c is the pressure due to carcass stiffness. When tire contact length l_t is less than tire contact width *b,* it's value should be used as the denominator of k_c in calculating pressure-sinkage z_0 and critical ground pressure p_{gcr}. The pressure due to carcass stiffness p_c is difficult to ascertain. If the sum of the inflation pressure p_i and the pressure due to carcass stiffness p_c is greater than the pressure defined by Eq. 1, the tire will remain round like a rigid wheel under given normal load and terrain condition. On the other side, if the sum of p_i and p_c is less than p_{gcr}, a portion of the circumference of the tire will be flattened, and the tire is assumed to be in the elastic mode of operation and the contact pressure on the flat portion will equal to the average ground pressure p_{gr} which is equal to the $(p_i + p_c)$.

5. Tire-terrain interaction dynamics model

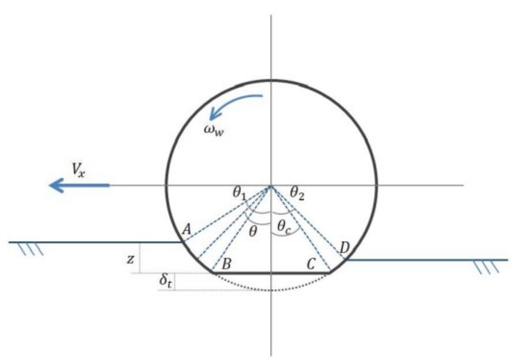

Fig. 5. Three sections in tire-terrain interaction: AB, BC, and CD

The normal pressure is assumed to be uniformly distributed and equal to the average ground pressure of the tire as shown along the flat section BC in Fig. 5. In practice, the pressure exerted on terrain due to carcass stiffness p_c is very difficult to determine as it varies with the inflation pressure and normal load of the tire. So, Bekker [19] recommended to use the average ground pressure of a tire to represent the integrated impact of the tire inflation pressure and normal load on the ground pressure.

The average ground pressure p_{gr} for a specific tire at a given inflation pressure and normal load can be derived from the tire manufacturer's chart known as a "generalized deflection chart". However, such information is usually proprietary, and it is hard to be found in open sources. To resolve this issue in a first approximation of computing, it may be assumed that the tire deflection δ_t is a function of normal load, inflation pressure, and section width of the tire [20]:

$$\delta_t = \frac{W_w}{\pi P_0 \sqrt{D * sw}} \tag{3}$$

and approximated tire contact width *b* is given by

$$b = \frac{2W_w}{\pi P_0 \sqrt{D * \delta_t}} \tag{4}$$

where W_w is the normal load acting on the tire, P_0 is the tire inflation pressure, and *sw* is the tire section width.
In the same way, first approximated contact length, average ground pressure and pressure sinkage is given by [5]

$$l_t = 2\sqrt{D\delta_t - {\delta_t}^2} \tag{5}$$

$$P_{gr} = \frac{W_w}{b\, l_t} \tag{6}$$

$$z_0 = \left(\frac{p_{gr}}{{k_c}/{b} + k_\phi}\right)^{1/n} \quad \text{(When the tire is operating in elastic mode)} \tag{7}$$

$$z_0 = \left[\frac{3W_w}{b(3-n)(k_c/b + k_\phi)\sqrt{D}}\right]^{(2/(2n+1))} \quad \text{(When the tire is operating in rigid mode)} \tag{8}$$

When tire contact length l_t is less than tire contact width *b,* it's value should be used as the denominator of k_c in calculating pressure-sinkage z_0. In a first approximation, AB in Fig. 5 may be assumed to be a circular arc with radius r = D/2. The vertical reaction R_{zAB} along the curve AB may be determined using following equation given by [5]

$$R_{zAB} = \left[b\left(\frac{k_c}{l_t} + k_\phi\right)\sqrt{D}(z_0 + \delta_t)^{n-1}\right] \times \frac{\left[(3-n)(z_0+\delta_t)^{\frac{3}{2}} - (3-n)\delta_t^{\frac{3}{2}} - 3z_0\sqrt{\delta_t}\right]}{3} \tag{9}$$

The equilibrium equation for the vertical forces acting on the tire is given by

$$W_w = bp_{gr}l_t + R_{zAB} \tag{10}$$

The $(bp_{gr}l_t)$ in the Eq. 10, represents the normal reaction action on the flat portion of the tire patch i.e., along BC in Fig. 5. Hence, $(bp_{gr}l_t + R_{zAB})$ in the Eq. 10 represents the wheel total normal reaction imposed by the terrain. When the truck with morphing boom equipment is moving on terrain, the average ground pressure is continuously changing at various normal loads of the wheels and tire inflation pressure. It can be seen from the Eq. 9 and 10 that the normal reaction of a given tire is a function of b, p_{gr}, l_t, z_0, and δ_t. This demonstrates that for a given tire with known different normal load, there is a specific combination of tire deflection δ_t, average ground pressure p_{gr}, tire contact width *b*, tire contact length l_t, and pressure-sinkage z_0 which satisfies Eq. 10.

In practice, it is more appropriate to follow an iterative procedure to determine specific combinations of tire contact width *b*, tire contact length l_t, average ground pressure P_{gr}, pressure sinkage z_0, and tire deflection δ_t values. With the values of *b,* l_t, P_{gr}, z_0, and δ_t known, the normal reaction of the tire is determined using Eq. 10. If the assumed values are correct one, then the calculated normal reactions should be equal to the given normal load W_w. If not, then new values of *b,* l_t, P_{gr}, z_0, and δ_t should be assumed and the whole process of iterative procedure should be repeated until convergence between normal load and normal reactions is achieved.

In short, following six equations must need to solve simultaneously using iterative procedure in order to get the required parameters as mentioned in third statement of section 2.

1. Contact length equation (Eq. 5)

$$l_t = 2\sqrt{D\delta_t - {\delta_t}^2}$$

2. Elastic mode pressure-sinkage equation (Eq. 7)

$$z_0 = \left(\frac{p_{gr}}{{k_c}/{b} + k_\phi}\right)^{1/n}$$

3. Normal reaction on curved section of the elastic tire equation (Eq. 9)

$$R_{zAB} = \left[b\left(\frac{k_c}{l_t} + k_\phi\right)\sqrt{D}(z_0 + \delta_t)^{n-1}\right] \times \frac{\left[(3-n)(z_0+\delta_t)^{\frac{3}{2}} - (3-n)\delta_t^{\frac{3}{2}} - 3z_0\sqrt{\delta_t}\right]}{3}$$

4. Normal load and total normal reaction forces equilibrium equation (Eq. 10)

$$W_w = bp_{gr}l_t + R_{zAB}$$

5. Tire deflection equation (Eq. 3)

$$\delta_t = \frac{W_w}{\pi P_0\sqrt{D*SW}}$$

6. Contact width equation (Eq. 4)

$$b = \frac{2W_w}{\pi P_0\sqrt{D*\delta_t}}$$

The steps involved in this analysis are depicted in the flow chart shown in Fig. 6.

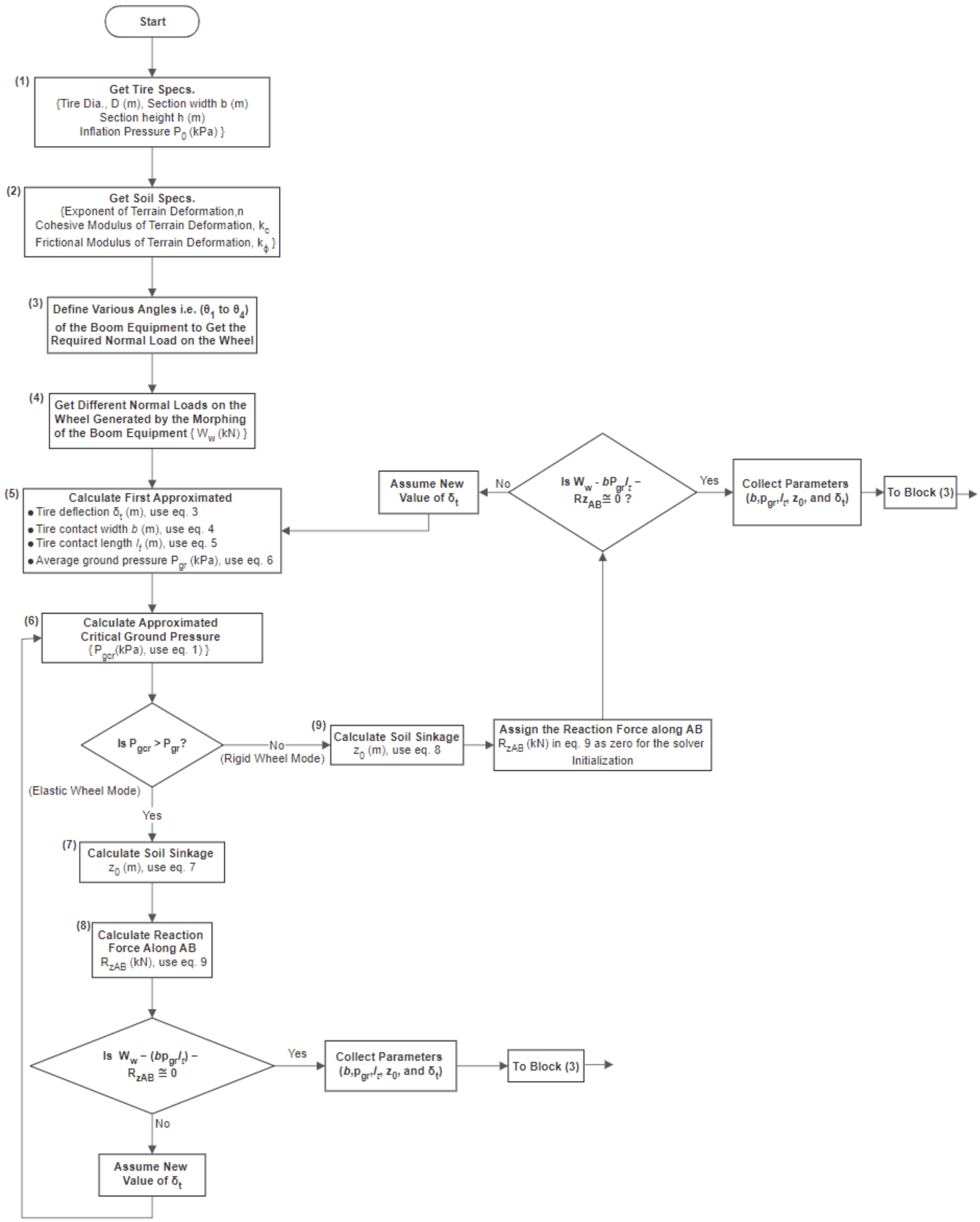

Fig. 6. Flow chart for calculating the parameters (b, p_{gr}, l_t, z_0, and δ_t) at various normal loads

6. Wheel motion resistance force

The motion resistance is the sum of several components that occurred between the terrain and tire in the longitudinal direction that is opposite to the motion. The main components of the resistance to motion are expressed as

$$R_x = R_c + R_b + R_f \tag{11}$$

where R_x is the total motion resistance force , R_c is the component due to soil compaction, R_b is the component due to bulldozing the soil in front of the wheel, and R_f is the component due to the tire flexing [15].

Bekker proposed the following expression to determine the compaction resistance [21]

$$R_c = b\left(\frac{k_c}{b} + k_\phi\right)\left(\frac{z_0^{n+1}}{n+1}\right) \tag{12}$$

where b is the width of the wheel when it is the smaller dimension of the contact patch in the denominator of k_c. After the correct values of b, l_t, P_{gr}, z_0, and δ_t obtained, the compaction resistance can then be determined by using Eq. 11. Due to the hysteresis of the tire material caused by the tire flexing, resistance force R_f against the motion of the tires appears. Bekker proposed following semi-empirical equation for predicting the motion resistance due to tire deformation [21]

$$R_f = \frac{\left[3.581bD^2 p_{gr}\varepsilon(0.0349\theta_c - \sin(2\theta_c))\right]}{\theta_c(D - 2\delta_t)} \tag{13}$$

where $\varepsilon = 1 - \exp\,(-k_e\delta_t/h_t)$, and $\theta_c = cos^{-1}[(D - 2\delta_t)/D]$ is the contact angle in degrees, while h_t is the tire section height, δ_t is the tire deflection, the coefficient k_e is equal to 15 for bias-ply tire and 7 for radial-ply tire [15].

Bulldozing resistance R_b is developed when a substantial soil mass is displaced by a wheel. The wheel compresses the surface layers of the soil and pushes the compacted soil in front and behind of the tire [19]. This phenomenon is apparent in the case of a vast wheel traversing very loose soils where bulldozing resistance causes a significant increase in total motion resistance for sinkage values greater than 6% of the wheel diameter [22]. Medium mineral soil is used in this analysis and thus, bulldozing resistance R_b is ignored. Reaction R_x is also known as the rolling resistance in vehicle dynamics studies.

7. Simulations results and analysis

The F450-based utility truck has a 225/70R19.5 tires mounted on it. It has single tires on the front axle and dually tires on the rear axle to withhold the normal load of the utility truck with the boom equipment. The gap between dually tires is very small and negligible. Thus, a pair of dually tires is assumed as a single tire with two times tire width on the contact patch on the rear axle. 225/70R19.5 tire data used in this analysis is shown in table 2.

Table 2. 225/70R19.5 tire details

Parameter	
Diameter	0.8128 m
Section width of front tires	0.2261 m
Section width of rear tires	0.4522 m
Section height	0.1575 m
Inflation Pressure (P_0)	524 kPa

The performance of the utility truck was simulated on medium mineral soil terrain at various normal loads caused by the morphing of the boom equipment. The pressure-sinkage pertinent parameters for the medium mineral soil are in table 3 [15].

Table 3. Pressure-sinkage parameters for the medium mineral soil

Terrain type	**Terrain parameters**					
	n	$k_c(kN/m^{n+1})$	$k_\emptyset(kN/m^{n+2})$	c (kPa)	Ø (Degrees)	Moisture content (%)
Medium mineral soil [15]	0.8	29.76	2083	8.62	22.5	12

As described in section 3, the normal load acting on the wheels is greatly influenced by the morphing of the boom equipment and thus, the rolling resistance force. There are several combinations of the boom equipment angles which can provide a vast range of the wheel normal loads. Few variations of the wheel normal load and its effect on the motion resistance force is shown in table 4 to show how the motion resistance force can be managed by varying normal load and thus, mobility of the utility truck in off-road condition. In house MATLAB code is made to solve the terramechanics based tire-terrain model iterative procedure described in section 5.

Table 4. Total motion resistance force and coefficient of rolling resistance at various normal loads on flat even terrain of medium mineral soil

Tire	**Parameters**							
	Normal Load (kN)	Contact length (m)	Contact width (m)	Contact Area (m^2)	Tire deflection (m)	Pressure-Sinkage (m)	Total motion resistance force (kN)	Coefficient of rolling resistance (R_x/R_z)
Front Tire	11	0.3212	0.0815	0.0262	0.0331	0.0802	1.4197	0.1291
	10	0.3122	0.0763	0.0238	0.0312	0.0784	1.277	0.1277
	8	0.2913	0.0656	0.0192	0.027	0.0743	0.996	0.1245
	6.5	0.2734	0.0569	0.0156	0.0237	0.0704	0.7904	0.1216
	2.5	0.1991	0.0303	0.0060	0.0124	0.0523	0.2698	0.1079
Rear Tire	23	0.2728	0.2019	0.0551	0.0236	0.0823	3.117	0.1355
	21	0.2526	0.1995	0.0504	0.0201	0.0795	2.830	0.1350
	19	0.1868	0.2454	0.0458	0.0109	0.0697	2.578	0.1357
	13	0.312	0.0993	0.0309	0.0311	0.0815	1.703	0.1310
	9	0.2759	0.0781	0.0216	0.0241	0.0748	1.139	0.1265

It can be inferred from the listed values that the rolling resistance force can be managed by morphing the boom equipment at various angles according to the requirement on different terrain conditions. It should be noted that the rolling resistance coefficient approximately falls under given value of the terrain characteristics with respect to the tire diameter [23] which gives an assurity of the derived results. Morphing of the boom equipment provides vast range of normal loads at each wheel according to the requirements at the tire-terrain interaction.

As seen in Table 4, the contact area regresses as expected as the normal load is reduced on the tire. The effective contact area from the solver, the motion resistance force, and the coefficient of rolling resistance signal well-formed simulated data. For most cases and inspections, all parameters follow a logical sequence expected from physical conditions, as seen in the front tire's data. Small discrepancies in the parameters do not necessarily infer a mathematical issue, but involves finding appropriate zeros in the complex, terramechanics iteration solver. These parameters do not negatively affect the overall computations of necessary values of motion resistance force and the rolling resistance coefficient because of the parameters mathematical link.

8. Conclusion

In this paper, a novel technical concept is proposed based on terramechanics tire-terrain model integrated with the model of morphing truck multi-body system to supervise the input/output factors that influence the normal reactions of the wheels and the resistance to motion at each wheel. First, 3D morphing of the boom equipment is proposed as the input factor for managing the wheel normal reactions as the outputs. Eventually, morphing of the boom equipment relative to the truck frame results in a variable wheel normal reaction, which are the main contributors to the normal tire deformation and soil compaction, and thus, to the resistance to motion of each and all tires. From this research of above-listed forces at the wheels, it can be seen that mobility of the utility truck in off-road conditions can be managed by morphing of the boom equipment. This research study of the rolling resistance contributes to an on-going research project on morphing utility truck dynamics in severe terrain conditions.

Nomenclature

A_t	Tire contact area	[m²]
b	Wheel width	[m]
c	Soil cohesion	[kPa]
D	Wheel diameter	[m]
h_t	Tire section height	[m]
k_c	Bekker's pressure-sinkage equation cohesive component	$[kN/m^{n+1}]$
$k_\varnothing$	Bekker's pressure-sinkage equation frictional component	$[kN/m^{n+2}]$
l	Contact patch length	[m]
l_{BC}	Contact length of flat section BC	[m]
n	Bekker's pressure-sinkage equation exponent	
P_c	Tire carcass stiffness pressure	[kPa]
P_{gcr}	Tire critical ground pressure	[kPa]
P_{gr}	Tire average ground pressure	[kPa]
P_0	Tire inflation pressure	[kPa]
R_b	Bulldozing resistance	[kN]
R_c	Soil compaction resistance	[kN]
R_f	Tire flexing resistance	[kN]
R_x	Total rolling resistance	[kN]
W_w	Normal load	[kN]
z_0	Pressure-sinkage	[m]

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δ_t	Tire deflection	[m]
θ	Wheel angle at contact patch	[Degree]
θ_c	Contact angle	[Degree]
θ_1	Entry angle	[Degree]
θ_2	Exit angle	[Degree]
$\varnothing$	Soil internal friction angle	[Degree]

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