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MORPHING CAPABILITIES AND SAFE OPERATION ZONE OF THE UTILITY TRUCK BOOM EQUIPMENT

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ABSTRACT

Utility trucks are the first responders in extreme climate and severe weather situations, for saving people's lives to restoring traffic on the roads. However, such trucks can create dangerous situations on the roads, and off-road conditions, while moving, and performing tasks. Trucks equipped with large booms for reaching elevated heights can become unstable due to their geometry change, which can cause a drastic variation of the truck-boom system's moment of inertia, and the extreme weight re-distribution among the wheels. Morphing capabilities of the utility trucks need to be investigated together with the vehicle-road forces in order to hold the vehicle safe on the roads.

In this research paper, static analysis and range of the normal reaction at the wheel of the utility truck is performed to characterize a safe working zone of the boom equipment when the truck is in the flat and titled surface. The analysis is performed for 5-degree of freedom boom equipment with revolute and translational joints in a complex constrained space given by the truck design using 3D moment and force-vector analysis. The possible morphing configuration of the boom equipment is examined in order to define static normal reactions at the wheel-road interaction.

Further, the morphing of the boom equipment is investigated to determine limiting configurations that can be reached without rolling over the truck. In this analysis, it is assumed that the wheels provide enough friction between the tires and road so that tire slippage does not extensively occur, and the utility truck is assumed as a rigid body. In this study, utility truck equipped with boom equipment is utilized in this study for numerical illustration.

Keywords: Utility Truck, Morphing Boom Equipment, Static Analysis, Wheel Normal Reaction, Roll Over, Safe Zone.

NOMENCLATURE

F_x	Circumferential force at the wheel
α	Longitudinal angle
ϕ	Lateral angle
i	Subscript for axle, 1 or 2
R_x	Rolling resistance force of the wheel
R_z	Normal reaction of the wheel
W_a	Utility truck gross weight
W_{an}	Utility truck gross weight, longitudinal component
W_{al}	Utility truck gross weight, lateral component
W_{av}	Utility truck gross weight, vertical component
W_B	Utility truck boom equipment gross weight
W_{Bn}	Utility truck boom equipment gross weight, longitudinal component
W_{Bl}	Utility truck boom equipment gross weight, lateral component
W_{av}	Utility truck boom equipment gross weight, vertical component
$'$	Superscript symbol for right wheel(s)
$''$	Superscript symbol for left wheel(s)

1. INTRODUCTION

The freight and utility transportation systems are the dominant methods of moving commerce, and providing services and saving lives, nationally and internationally. Moreover, the truck fleets "rule" strain on the environment, resource consumption, and amplify citizen exasperation. There were approximately 2.83 million truck drivers in the country in 2014, 28.2% of drivers drove various services trucks [1].

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Utility trucks (also known as boom equipped trucks) are the first responders in extreme climate and weather situations, saving people's lives, restoring electric power, cutting trees, and restoring traffics on the road. Multiphase hazardous weather and roadway conditions are the typical climate features nationally.

Industrial leaders such as Mercedes-Benz and BMW have recently shown several concepts in intelligent aerodynamic passenger cars that morph on the move and recent research efforts on bio-inspired robotics systems [2,3,4], which suggest that self-organization, and embodiment are powerful concepts in the development of adaptive, smart, and completely autonomous system. The entire 3D perimeter configuration of an autonomous smart utility truck, also known as ASUT, is autonomously adapted and thus, manages the moment of inertia, tire-road forces and the aerodynamic multi-phase forces, e.g. air wind, meteorology, and several multi-phase hazardous weather and roadway environments. There are only a few technical publications that discuss the statistical and dynamical analysis of utility trucks equipped with booms or manipulators. Most of the dynamic analyses has been done for the geometry similar to the utility truck like the truck-crane [5].

In this work, as an initiative, static analysis of the utility truck with the range of normal reactions at the tire-road contact patch is predicted. The truck is in an inclined longitudinal plane (angle α) with lateral tilted surface (angle ϕ) to establish the safe working zone of the boom equipment, which provides a foundation for more complex dynamical analysis of the utility truck that includes aerodynamics. In this paper, the numerical analysis is performed for zero inclined plane to illustrate to roll over conditions.

2. BACKGROUND

The static normal reaction (R_z) is defined as the force which counterbalances the normal load of the wheel, which includes the weight of the wheel itself when the vehicle is not moving or stationary [6]. Normal reactions are very important in vehicle dynamics because it determines the amount of the traction that the wheel can provide. If the circumferential force F_x exerted by the wheel is greater than the wheel's traction, then the wheel will skid, and it may be possible that the car will spin out.

Static Normal reaction can also be understood as the weight carried by each wheel. If the vehicle is perfectly symmetrical from front to back, then the weight distribution at the front and rear axle are considered as the same; but if not, then the weight distribution must be accounted for each axle. In the case of the utility truck, weight distribution at the front and rear axle are different because of the truck's geometry and the boom equipment as shown in Figure (1).

In most of the literature or in any vehicle dynamic books, it is assumed that the static normal reaction at the left and right wheels are considered as an equal due to symmetry of the vehicle. However, when the boom equipment of the utility truck morphs its orientation during an operation, it cannot be assumed as the same static normal reactions at the left and right tires. Thus, it's essential to find a normal reaction during its operation and prevent it from being rolled over.

In this analysis, the utility truck is considered as a rigid body assuming the truck is not moving i.e., steady and the wheels provide enough friction between the tires and road so that tire slippage does not occur extensively. An assumption is also made that there is no stiffness or deflection in tire, suspension, and soil.

3. UTILITY TRUCK MATH MODEL AND OPTIMIZATION

The utility truck model goes through the following procedure of steps, i.e., a computational algorithm, the equation for which described as follows:

1) Defining five degree of freedom boom equipment with revolute and translational joints with the geometrical constraints of the utility truck;
2) Determining the moments in three dimensions at the boom's pedestal which is created by the platform, upper and lower boom and the boom attached to the turntable;
3) Calculating the static normal reactions where rollover of the truck happens when the truck is in the flat and tilted surface.
4) Finally, the various orientations of the boom equipment are listed where rollover of the truck happens.

4. STATIC NORMAL REACTION FORMULATION

Figure (1) represents the configuration and component identification of the utility truck. Figure (2) represents a two-dimensional drawing of the utility truck's mass and geometry on a horizontal surface, while Figure (3) represents the generalized three-dimensional case of the utility truck with the lateral and longitudinal inclination, and finally Figure (4) represents three dimensional drawing of a utility truck in which forces from the boom equipment are transferred into moments at pedestal base i.e., at point C.

In order to calculate the static normal reactions at the left and right wheels of the truck, an analysis of a boom equipment should be conducted because the boom equipment morphs its orientation non-continuously. Numerous methods are developed in technical literature to determine the static normal reaction but in the case of utility truck with a boom equipment, 3D force-vector and moment analysis [7] is the only option to solve for the forces as boom equipment morphs its orientation.

The constraint imposed by the truck's boom geometry [8] are listed in Table 1. The normal reactions change markedly due to the various configuration of the boom equipment. Additionally, when the truck is in the titled and/or inclined surface from side to side the normal reactionary forces of the wheels are noticeably affected.

Table 1. Constrained of utility truck's boom geometry

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

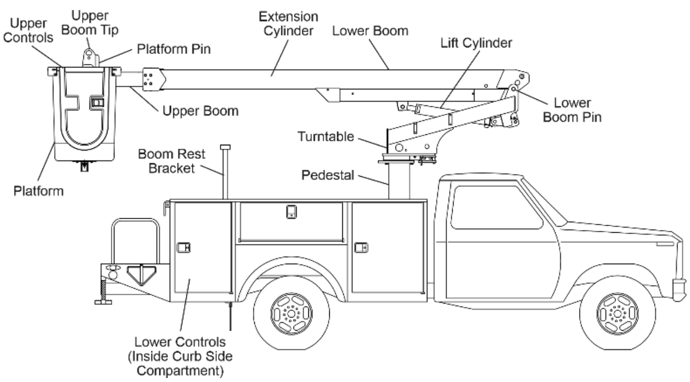

Figure 1. Configuration and component identification of the utility truck.

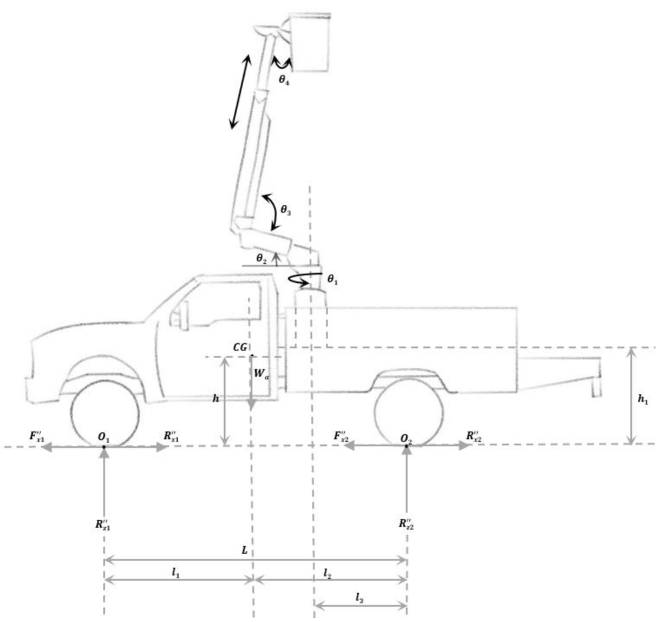

Figure 2. 2D Drawing of a utility truck on horizontal surface.

When the boom equipment is morphing its shape, the normal reaction (R_z) of the wheels are continually affected by the variable forces and moments in three dimensions i.e., W_{Bl}, W_{Bv}, W_{Bn}, M_{cx}, M_{cy}, and M_{cz} created by the 5-DOF boom equipment at the boom's pedestal. This forces and moments in three dimensions at the boom pedestal are calculated as follow using force-vector analysis.

Total moment at the pedestal i.e. at point C:

$$M_c = M_{cx}\hat{\imath} + M_{cy}\hat{\jmath} + M_{cz}\hat{k} \quad (1)$$

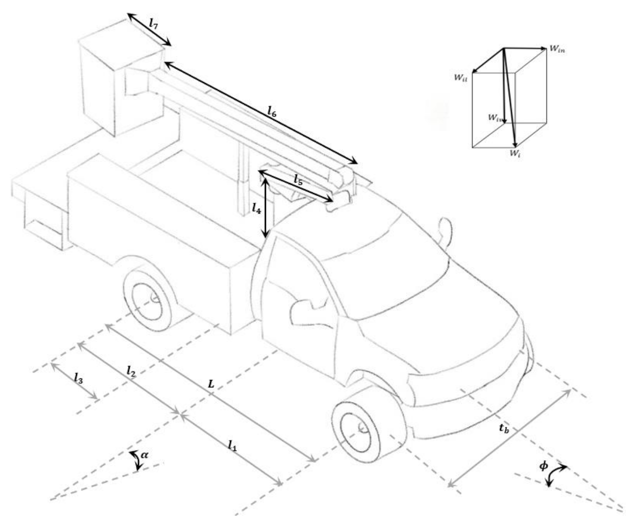

Figure 3. 3D Drawing of a utility truck's general case of motion with lateral and longitudinal inclinations

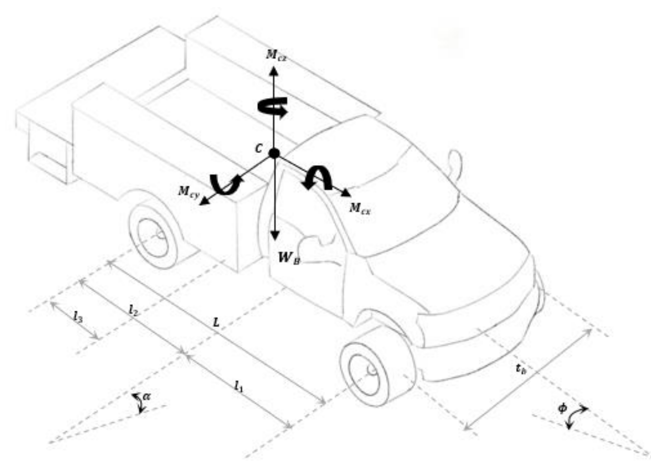

Figure 4. 3D Drawing of a utility truck in which forces from the boom equipment are transferred into moments at pedestal base i.e., at point C.

In the equation (1), three components in x, y, and z directions are defined as follow:

$$M_{cx} = \left\{ \left\{ \left[-\frac{l_5}{2} w_1 \cos\alpha \cos\emptyset \cos\theta_2 \sin\theta_1 \right] - \left[\left(l_4 + \frac{l_5}{2} \sin\theta_2 \right) (w_1 \sin\emptyset \cos\alpha) \right] \right\} + \left\{ \left[[l_5 \cos\theta_2 \sin\theta_1 + l_{6CG} \sin\theta_1 \cos(\theta_2+\theta_3)] * [-w_2 \cos\alpha \cos\emptyset] \right] - \left[[l_4 + l_5 \sin\theta_2 + l_{6CG} \sin(\theta_2+\theta_3)] + [w_2 \sin\emptyset \cos\alpha] \right] \right\} + \left\{ \left[\left[l_5 \cos\theta_2 \sin\theta_1 + \frac{l_7}{2} \sin\theta_1 \cos(\theta_2+\theta_3+\theta_4) \right] * \left[-w_p \cos\alpha \cos\emptyset \right] \right] - \left[\left[l_4 + l_5 \sin\theta_2 + \frac{l_7}{2} \sin(\theta_2+\theta_3+\theta_4) \right] + \left[w_p \sin\emptyset \cos\alpha \right] \right] \right\} \right\} \quad (2)$$

$$M_{cy} = \left\{ \left\{ \left[\frac{l_5}{2} w_1 \cos\alpha \cos\emptyset \cos\theta_2 \cos\theta_1 \right] + \left[\left(l_4 + \frac{l_5}{2} \sin\theta_2 \right) (w_1 \sin\alpha \cos\emptyset) \right] \right\} + \left\{ \left[[l_5 \cos\theta_2 \cos\theta_1 + l_{6CG} \cos\theta_1 \cos(\theta_2+\theta_3)] * [w_2 \cos\alpha \cos\emptyset] \right] + \left[[l_4 + l_5 \sin\theta_2 + l_{6CG} \sin(\theta_2+\theta_3)] + [w_2 \sin\alpha \cos\emptyset] \right] \right\} + \left\{ \left[\left[l_5 \cos\theta_2 \cos\theta_1 + \frac{l_7}{2} \cos\theta_1 \cos(\theta_2+\theta_3+\theta_4) \right] * \left[w_p \cos\alpha \cos\emptyset \right] \right] + \left[\left[l_4 + l_5 \sin\theta_2 + \frac{l_7}{2} \sin(\theta_2+\theta_3+\theta_4) \right] + \left[w_p \sin\alpha \cos\emptyset \right] \right] \right\} \right\} \quad (3)$$

$$M_{cz} = \left\{ \left\{ \left[\frac{l_5}{2} w_1 \cos\alpha \sin\emptyset \cos\theta_2 \cos\theta_1 \right] - \left[\frac{l_5}{2} w_1 \sin\alpha \cos\emptyset \cos\theta_2 \sin\theta_1 \right] \right\} + \left\{ \left[[l_5 \cos\theta_2 \cos\theta_1 + l_{6CG} \cos\theta_1 \cos(\theta_2+\theta_3)] * [w_2 \cos\alpha \sin\emptyset] \right] - \left[[l_5 \cos\theta_2 \sin\theta_1 + l_{6CG} \sin\theta_1 \cos(\theta_2+\theta_3)] * [w_2 \sin\alpha \cos\emptyset] \right] \right\} + \left\{ \left[\left[l_5 \cos\theta_2 \cos\theta_1 + \frac{l_7}{2} \cos\theta_1 \cos(\theta_2+\theta_3+\theta_4) \right] * \left[w_p \cos\alpha \sin\emptyset \right] \right] - \left[\left[l_5 \cos\theta_2 \sin\theta_1 + \frac{l_7}{2} \sin\theta_1 \cos(\theta_2+\theta_3+\theta_4) \right] * \left[w_p \sin\alpha \cos\emptyset \right] \right] \right\} \right\} \quad (4)$$

Total force at the pedestal i.e. at the point C:

$$W_B = W_{Bn}\hat{\imath} + W_{Bl}\hat{\jmath} + W_{Bv}\hat{k} \quad (5)$$

where, three components in x, y, and z directions are defined as follow:

$$W_{Bn} = (W_1 + W_2 + W_p) \sin\alpha \cos\emptyset \quad (6)$$

$$W_{Bl} = (W_1 + W_2 + W_p) \cos\alpha \sin\emptyset \quad (7)$$

$$W_{Bv} = -(W_1 + W_2 + W_p) \cos\alpha \cos\emptyset \quad (8)$$

Total force at the center of gravity i.e. at the point CG:

$$W_a = W_{an} + W_{al} + W_{av} \quad (9)$$

where, three components in x, y, and z directions are defined as follow:

$$W_{an} = W_a \sin\alpha \cos\emptyset \quad (10)$$

$$W_{al} = W_a \cos\alpha \sin\emptyset \quad (11)$$

$$W_{av} = -W_a \cos\alpha \cos\emptyset \quad (12)$$

If the truck is steady, then the sum of all moments acting about a point i.e., all four tires and ground contact points must be zero. In the case of a utility truck, one will end up with 3-moment equations that contain four static normal reactions using 3D force-vector analysis, which is impossible to solve for each static normal reaction at the wheels. Hence, it is recommended that one can solve the equations by adding the left side static normal reactions and the right side static normal reaction to find out the rollover conditions of the utility truck.

This left and right side static normal reactions are defined as follows:

Total static normal reactions on the left side of the utility truck:

$$R''_{z1} + R''_{z2} = \frac{M_{cx}}{t_b} + W_{av}\left(\frac{t_{CG}}{t_b} - 1\right) - \frac{W_{Bv}}{2} - \left(\frac{h_1}{t_b}\right) W_{Bl} - \left(\frac{h}{t_b}\right) W_{al} \quad (13)$$

Total static normal reactions on the right side of the utility truck:

$$R'_{z1} + R'_{z2} = \frac{h_1 W_{Bl} + h W_{al} - M_{cx} - W_{Bv}\left(\frac{t_b}{2}\right) - t_{CG} W_{av}}{t_b} \quad (14)$$

Rollover of the truck happens when the total static normal reaction on either left or right-side wheels is zero, and thus, the orientation of the boom equipment is found out to prevent the truck from the rollover.

5. RESULTS

Rollover of the truck happens when the boom equipment morphs its orientation as shown in Figure (5), and thus, it's very important to know the orentation of the boom equipment at each moment of time.

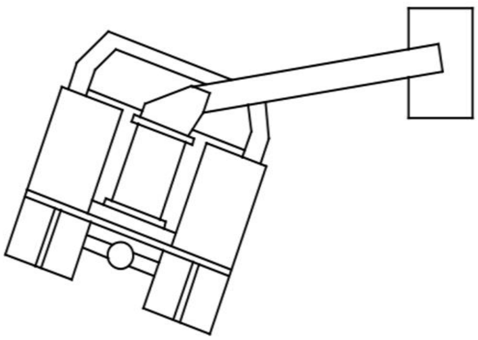

Figure 5. Rollover of the truck at the certain orientation of the boom equipment

Utiltiy truck is used in this analysis with boom equipment attached to it. In house MATLAB code is made to visulaize the static normal reactions at all the possible orientation of the boom equipment. Utility truck is tested for operation at rated capacity on a five degree slope [8]. Hence, the simulations have run for five degrees of tilted slope as one of the limitation of the truck. There are around 69 million possible different combinations (increments of each thetas by one degree) of the boom equipment to visualize the static normal reaction and rollover of the truck, which is very difficult to present in this paper. Hence, some of the critical combintaions of the boom equipment are presented in this paper.

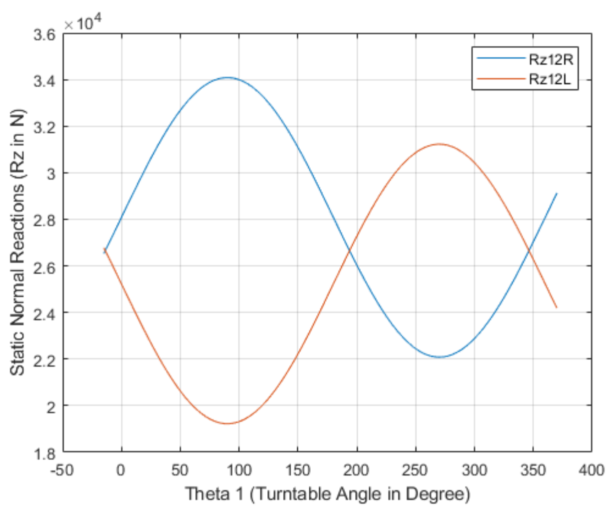

Figure 6. Right and left side static normal reactions when the boom configurations are θ_1 = -15º to 370º, θ_3 = -8.5º, θ_4 = 15º, upper boom is fully extended, and tilt angle ($\emptyset$) = 0º.

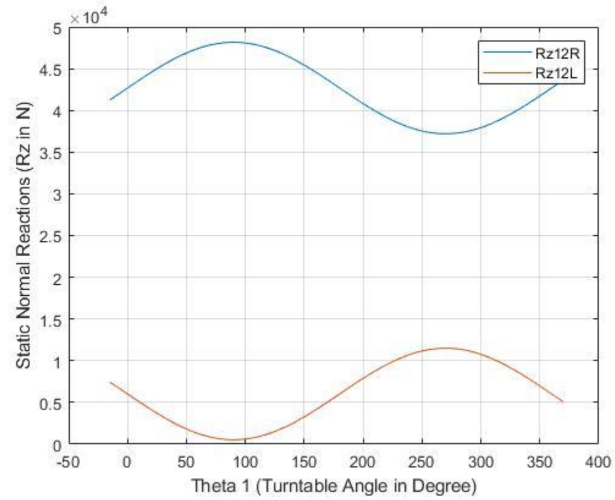

Figure 7. Right and left side static normal reactions when the boom configurations are θ_1 = -15º to 370º, θ_3 = -8.5º, θ_4 = 15º, upper boom is fully extended, and tilt angle ($\emptyset$) = 24º.

Figures (6) and (7) represents the static normal reactions on the left and right side of the truck when the truck is on horizontal and tilted surface respectively. The boom orientation is θ_2 = 15º, θ_3 = -8.5º, upper boom is fully extended, and θ_4 = 15º in both cases. As it can be seen from the Figures (6) and (7), when theta1 i.e., turntable angle rotates from -15º (Initial position) to 370º, static normal reactions on both sides changes continuously. the static normal reactions on both sides are same when the boom equipment is at its initial position and when it's at opposite side of its initial position i.e. at 180º. Similarly, when the truck is on 24º of tilted surface, roll over of the truck is about to start as the left side wheels of the truck starts losing traction from the ground as it can be seen from the Figure(7) when turntable angle is at around 90º.

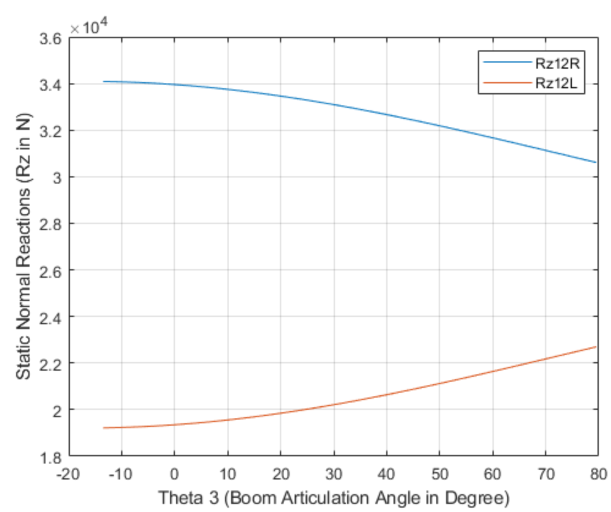

Figure 8. Right and left side static normal reactions when the boom configurations are θ_1 = 95º, θ_3 = -13.5º to 80º, θ_4 = 15º, upper boom is fully extended, and tilt angle ($\emptyset$) = 0º.

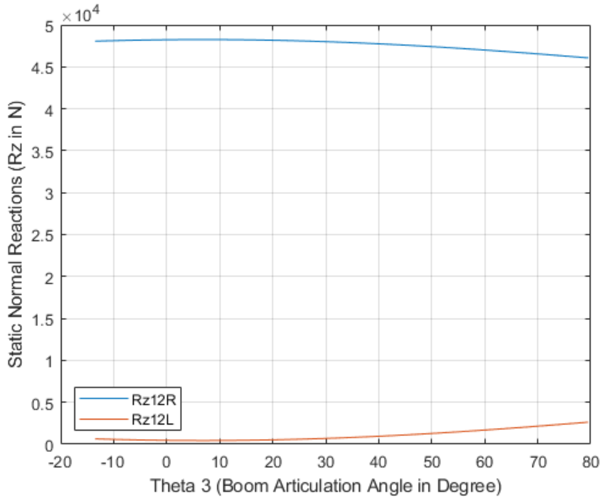

Figure 9. Right and left side static normal reactions when the boom configurations are θ_1 = 95°, θ_3 = -13.5° to 80°, θ_4 = 15°, upper boom is fully extended, and tilt angle ($\emptyset$) = 24°.

Figures (8) and (9) represents the static normal reactions when the boom orientation is θ_1 = 95°, θ_2 = 15°, upper boom is fully extended, and θ_4 = 15°. In both cases, the turntable angle θ_1, is constant while the boom articulation angle θ_3, is changing from -13.5° to 80°. The static normal reactions are different at left and right side of the truck when theta1 has constant value while theta3 is continuously changing from its initial to final position. However, in the same way, when the truck is on a 24° degree of tilt surface, the rollover of the truck is about to start when the boom articulation angle is ranging from -10° to 30° and becomes stable after 40° as it can be seen from the figure 9.

6. DISCUSSION

There are numerous different configurations of the boom equipment in which roll over of the truck can be predicted from the static normal reaction values when the truck is on a flat and tilted surface. By knowing the static normal reactions, the safe working zone of the boom equipment can be established to avoid rollover of the truck. Performing static analysis on horizontal and lateral tilt surfaces, it establishes a foundation to multi-body approach by including dynamics of the vehicle and more complex dynamical problem.

7. CONCLUSION

Utility truck with boom equipment attached to it were first functionally integrated in a mathematical and computer model. Such integration enabled a study of static normal reactions at each orientations of the boom equipment when the truck is in an inclined longitudinal plane with lateral tilted surface. The analysis shows that the influence of the listed characteristics of the boom equipment is not unique and is determined by the morphing conditions of the boom's equipment i.e. the horizontal and lateral inclination of the truck. Utilizing the static normal reactions values at each orientation of the boom equipment, the safe working zone of the boom equipment is established without rollover of the truck.

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