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Study of mobility performance parameters of Planetary Rovers - A Review

*Pala Gireesh Kumar and S. Jayalekshmi

Department of Civil Engineering, National Institute of Technology Tiruchirappalli, Tamil Nadu, India

Email: **gireeshnitt04@gmail.com, jaya@nitt.edu*

Abstract: *Researchers carried out works on evaluation of mobility performance of planetary rovers, which helps to solve and overcome the current existing problems on a loose soil/sloppy terrain. Problems which arise on planetary surfaces are - surface unevenness, obstacles (stones, rivers, boulders etc.), environmental risk (wind, humidity, dust, air, snow etc.), sloping and climbing conditions etc. To optimize and give better performance, it is necessary to study the trafficability, maneuverability and terrainability characteristics related to good performance conditions of the wheeled rover/tracked rover on planetary surfaces before going for its design. The aim of this paper is to bring out the significance of mobility performance parameters of planetary rover on travelling performance. Trafficability has the most significant effect on its traveling performance of planetary rover. Hence, it is needed to conduct major studies on trafficability – how it affects, how it varies, and how it improves, the travelling performance from its parameters behavior. This paper mainly focuses on, and brings out an overview on study of mobility performance parameters of planetary rovers that travels on flat terrain/sloppy terrain. The observations and inferences from the various works carried by researchers on performance indices are also outlined in this paper. Experimental results for compaction resistance and rolling resistance are also presented and influence on its mobility is briefly explained.*

Keywords: *flat/sloppy terrain, mobility, performance indices, rover, trafficability.*

1. Introduction

A wheeled mobile robot has wider applications in planetary space exploration. Planetary surfaces (like Moon/Mars) are covered with dust, loose soil, rocks, stones, ditches, obstacles and steeper slopes. Because of this, mobile robots are moving on a challenging terrain have higher risk, leading to mission failure or deviating path from its original path. For example, Luna 21 landed on the moon in 1973, travelled 37.7 km (estimated 42.1 to 42.2 km) and the mission got failure due to getting stuck on travelled loose soil.

Rover/rover wheel that travels over rough terrain can cause severe slip-sinkage on loose soil, and sometimes it may get stuck on loose soil or in worst case, the mission may get failure; diverting its path from its original path because of presence of obstacles. Slip and sinkage is a critical failure of rover or rover wheel that moves on planetary surface. Hence, it is important for a rover/rover wheel to traverse on sandy terrain without sinking into the soil where obstacles also exists or without getting stuck into the soil [4]. The

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*Corresponding Author

rover/rover wheel mobility improved with wheel slip control [6]. The rover/rover wheel navigation to various destinations safely and correctly while detecting and avoiding hazards are of primary concern to be considered while designing a planetary rover. Hence, mobility performance study on wheeled type robots is carried on basis of terramechanics and is necessary to avoid such problems [16]. The performance of planetary rover depends on three performance indices, namely; Trafficability – ability to travel on loose soils/rigid surface without traction-loss by rover/rover's wheel, Maneuverability – ability to navigate through the environment (moist, heavy wind and dust) that exist and Terrainability – rover ability to negotiate terrain irregularities (slopes/obstacles) [1].

In this paper, we briefly describe the mobility performance parameters (trafficability) which improves the mobility performance of a planetary rover while travelling on a rough/sloppy terrain. Hence, mobility performance on unstructured terrain of a planetary rover has to guarantee the mission to be succeeded.

2. Mobility performance parameter characteristics

To achieve a rover travelling a desired distance (predicted distance from its design) over challenging terrains and to perform more intricate tasks, it is needed to carry out research on improving mobility performance of rover/rover wheel. Some of the problems needed to be concentrated to improve its performance are:

1. Minimizing its slippage during climbing a sloppy terrain covered with loose soil [16].
2. Trafficability of terrain and mobility of rover/rover wheel.

The performance of a rover depends on both trafficability of the terrain and on the mobility of the rover. Terrain is all about occurrence of the obstacles, slope gradient and terrain profile etc. The following section details about trafficability/mobility performance characteristics:

A. Sinkage

A rover/rover wheel that travels on loose soil causes sinkage. It depends on physical and mechanical properties of soil, wheel geometry (dimensions, shape), stiffness and wheel load [1]. Wheel sinkage has been classified into static sinkage and dynamic sinkage [7].

Static sinkage depends on the wheel load and is defined as the amount of sinkage caused by the wheel before its travel, and is given as [18],

$$\text{Static sinkage,} \quad h_s = r\,(1-\cos\theta_s) \tag{1}$$

Static sinkage is a function of radius of wheel and entrance angle. Where, 'r' is wheel radius and'θ_s' is entry angle and is defined as, the angle at which wheel is contacting soil surface (refer Figure.1).

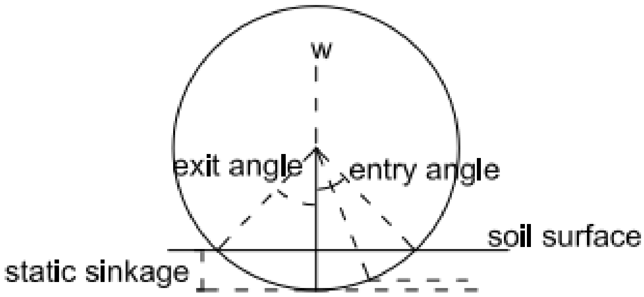

Figure 1: Static sinkage

Dynamic sinkage depends on wheel rotation and is defined as the amount of sinkage caused by wheel after its travel for some distance [7], [18]. Total sinkage is given as [7],

Total sinkage, $h = h_s + h_d$ (2)

The classified types of sinkage have shown in Figure. 2.

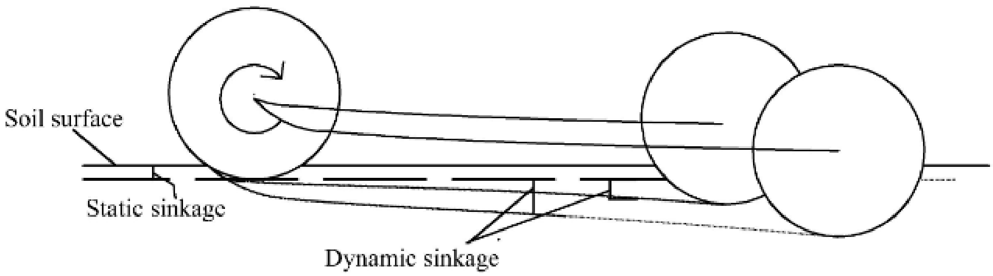

Figure 2: Wheel sinkage

Sinkage can also be calculated as follows [1],

Sinkage of a rigid wheel,

$$z_{rw} = \left[\frac{3w_w \cos\theta}{(3-n)(k_c+b_w k_\phi)\sqrt{d_w}}\right]^{\frac{2}{2n+1}} \quad (3)$$

where, w_w' is wheel weight, 'n' is soil exponent, 'k_c' is coefficient of cohesion, '$k\phi$' is coefficient of internal friction angle, 'b_w' is width of wheel and 'd_w' is wheel diameter. The above equation 3, indicates mobility performance in terms of sinkage as a function of wheel dimensions (d_w, b_w) and soil parameters (k_c , $k\phi$ and n) and is applicable only for rigid wheel.

Using bekker pressure sinkage model and incorporating Reece pressure sinkage relationship [19], [20], sinkage can be determined as [19],

$$z = \left[\frac{3w}{b(3-n)(K_c+g_e K_\phi)\sqrt{D}}\right]^{\frac{2}{2n+1}} \quad (4)$$

Where, $K_c = \frac{k_c}{b}$; $K\phi = \frac{k_\phi}{g}$; w = wheel weight; g_e = acceleration due to gravity on earth; b = wheel width and D = wheel diameter.

Equation 4determines thesinkage caused by the rigid wheel on terrestrial (earth) surface [20].

$$z = \left[\frac{3w}{b(3-n)(K_c+g_{ex}\,K_\phi)\sqrt{D}}\right]^{\frac{2}{2n+1}} \quad (5)$$

g_{ex} = acceleration due to gravity on moon/mars surface.

The above equation 5 can be used to find sinkage caused by rover wheel on extraterrestrial (Moon/Mars) surfaces [20].

B. Slip Ratio

It is defined as the difference in translational velocity and rotational velocity [4], [19].

Slip ratio is given as,

$$s = \frac{v_d - v}{v_d} \quad (6)$$

Where, 'v_d' is wheel rotational velocity, 'v' is linear travelling velocity, 'r' is radius and 'ω' is angular velocity.

Rotational velocity is defined as the product of angular velocity and radius of the wheel, linear travelling velocity is defined as the ratio of distance travelled per unit time. i.e.,

Slip ratio can also written as,

$$s = \frac{r\omega - v}{r\omega} \quad (7)$$

Slip ratio lies between 0 and 1. Slip ratio 'zero' indicates, wheel moving forward without any slippage and slip ratio of 'unity' indicates, the wheel experiencing slippage and facing difficulty while traversing on a particular terrain. Minimum slip ratio gives better mobility [7].

C. Soil Thrust

The soil thrust is the maximum force experienced by the soil before the occurrence of excessive slippage [1], [12]. At wheel soil interface, traction is developed because of soil thrust. In simple, thrust is friction between wheel and soil. Soil thrust is given as,

$$H = H_0\,(1 - e^{sl/K}) \quad (8)$$

$$L = \frac{D}{2}\cos^{-1}\left(1 - \frac{2z}{D}\right);\ H_0 = (blc_0 + W_w \tan\phi)$$

Where, K is coefficient of soil slip, 'l' is length of vehicle contact, 's' is slip ratio, 'W_w' is wheel weight, 'c_0' is soil cohesion, 'ϕ' is friction angle, 'b' is width, 'D' is wheel dia. and 'z' is wheel sinkage.

The above equation 8 is for wheel without lugs and the same equation can be used for lugged wheels with a small change (introducing 'n' no. of lugs) and is given as [1], [3], [11],

$$H_0 = n\,(blc_0 + W_w \tan\phi) \quad (9)$$

The above equation8 can be simplified and given as in [9],

$$H = A\,c_0 + W_w \tan\phi \quad (10)$$

D. Motion Resistance (R)

When a rover/rover wheel moves on soil surface, its energy is consumed in overcoming the rolling resistance between wheel and soil [1], [12]. Motion Resistance is of two types.

a. External Motion Resistance, overcoming obstacles on slopped terrain.

b. Internal motion resistance – the movement against resistance caused by frictional forces.

Motion Resistance (MR) is given [9],

$$MR = (R_c + R_b + R_g + R_r) \tag{11}$$

1. Compaction Resistance (R_c)

Compaction resistance of the soil results in loss of soil thrust in sandy terrain. Wheel compaction resistance relates to the vertical load applied per unit length in soil compression from its actual surface to the maximum sinkage depth (rut depth) [1], [12], [20].

The compaction resistance can be calculated as [12], [20],

$$R_c = \frac{\left(\frac{3w}{\sqrt{D}}\right)^{\frac{2n+2}{2n+1}}}{\left(\frac{k_c}{b}+k_\phi\right)^{\frac{1}{2n+1}}(n+1)b^{\frac{1}{2n+1}}\,(3-n)^{\frac{2n+2}{2n+1}}} \tag{12}$$

Where, ‘b’ is width, ‘k_c’, ‘k_ϕ’, ‘n’ are pressure sinkage parameters of specific terrain, ‘w’ is wheel weight and ‘D’ is wheel diameter.

Wheel diameter and width influence the compaction resistance. An increase in diameter rather than wheel width reduces the compaction resistance [1], [17], (Diameter is inversely proportional to R_c).

2. Bulldozing Resistance (R_b)

Bulldozing is the process of pushing soil up ahead of the wheel, i.e., bulldozing exists only for the front wheels. When wheel sinkage exceeds 0.06 times the wheel diameter, ‘R_b’ becomes a major problem, [1], [11]. It offers less resistance comparatively with the compaction resistance. Wheel width/diameter influences the bulldozing resistance. Increase in width results increase in bulldozing resistance whereas, narrow wheels reduces bulldozing resistance [1], [11].

3. Gravitational Resistance (R_g)

The gravitational resistance comes forth when a rover is subjected to move on sloppy terrain. Maximum slope that can negotiable on Mars is 30^0 to 40^0 but wheeled rover is limited to less than 25^0 [11]. Gravitational resistance is given as,

$$R_g = W \sin\theta \tag{13}$$

4. Rolling Resistance (R_r)

Rolling resistance plays a major role in mobility performance. Rolling resistance is the horizontal force needed to compact the soil [13]. Rolling resistance depends on wheel sinkage and wheel load [13] and is related to soil properties. It is defined as, product of the rolling resistance coefficient and the wheel weight [1], [13] and is given as,

$$\text{Rolling resistance, } R_r = \mu_r W \qquad (14)$$

$$\mu_r = [\frac{z}{d}] \qquad \text{(for rigid wheel)}$$

Where, 'μ_r' is coefficient of rolling resistance, 'W' is wheel weight, 'd' is wheel diameter and 'z' is wheel sinkage.

High rolling resistance indicates poor mobility [13]; lower rolling resistance gives better mobility.

E. Drawbar Pull (DP)

Defined as, the pulling force or pulling ability of a vehicle till it reaches maximum traction. It is also found by deducting thrust from motion resistance [1]. In simple, drawbar pull is lateral forward force that develops when a wheel is moving [13]. The rover/rover wheel must have positive drawbar pull to travel on any specified terrain [11].

Drawbar pull is given as,

$$DP = H - MR \qquad (15)$$

More the drawbar pull indicates better mobility performance [15].

3. State of the Art

A. Literature Review

Apostolopoulos D. S. et al. [1], carried out studies on configuring the wheeled robot locomotion and developed a frame work for synthesizing and evaluating configurations through analytical equations which predicts its performance. Performance indices are introduced and explained, namely –I) Trafficability, deals with the wheel geometry selection; wheel shape and its mechanism. II) Maneuverability, deals with chassis geometry, steering and estimating the overall locomotion dimensions. III) Terrainability deals with selection of optimum number of wheels and suspension types.

Bauer R. et al. [2], conducted experiments using single wheel test bed. Experimental results were compared with the AESCO soft soil tire model (AS^2TM) developed from the single wheel dynamic simulator in Matlab and Simulink's tool box using the wheel-soil interaction models. Drawbar pull is improved by 30% for the wheel (for the18 lugged wheel comparing wheel with 9 lugs).

Ding L. et al. [4], presented various slip ratio definitions of wheel equipped with grouser and without grouser (lug). The equation for estimating the longitudinal velocity of a rover/rover wheel travelling over irregular terrain was given. Experiments were conducted with two wheel types of different radius and different lug heights. Sensors were used to estimate wheel sinkage, drawbar pull and torque. Two estimation methods, calculating the slip ratio were introduced.

Huang H. et al. [5], carried out research work on performance of wire mesh wheel (WMW) on deformable terrains which includes the pressure-sinkage test (quasi-static) and its driving performance. Experiments were conducted using single wheel test bed for the wire mesh wheel with various loads and with different wheel velocities to investigate its sinkage characteristics of WMW type. Also traction test was conducted and analysis has been done for performance indices like, sinkage, drawbar pull (DP) and driving torque (DT). Optimum wire mesh wheel (WMW) type can be designed based on experimental results. The wire mesh wheel has larger sinkage but smaller DP and DT as observed from the test results.

Hutangkabodee S. et al. [**6**], found different soil parameters which are essential to predict the drawbar pull (DP) and torque in order to predict its traversability. A novel technique has been proposed to identify soil parameter which is based on Newton Raphson Method. The predicted drawbar pull, torque from soil parameter identification are used for optimization of vehicle performance.

Ishigami G. et al. [7], works developed an analytical model for investigating the travelling behavior of the rover/rover wheel on loose soil. The rover path was controlled and path planning, performance evaluation method was used to give the safest path to overcome the existing problems (slippage, obstacle climbing, skidding and slope traversability). Experiments were conducted using single wheel test bed, and also slope climbing tests.

Liu J. et al. [**8**], experimental work was carried out using single wheel test bed, to analyze the effect of straight grousers on its travelling performance to optimize wheel configuration of planetary rover with no wheel sinkage and 0 to0.06 slip. The lug height and slip have more influence on travelling performance than lug spacing and its thickness. Lug spacing of 15^0, lug height of 10 mm and lug thickness of 1.5 mm were suitable and optimal value of slip, to be given is 13%, for wheel driving.

Michaud S. et al. [**9**], developed a rover chassis evaluation tool (RCET). The developed tool supports the design, selection and optimization of different wheeled vehicles for space exploration. This gives an efficient motion operation on rover. Wheel ground interaction theories which can help to develop an efficient tool for all its operations are also presented. But, RCET is not only a tool for rover chassis evaluation and design; it is a basic tool for further development related to rover for planetary exploration.

Naiki T. et al. [**10**], proposed a mobility system with active suspension which has more efficiency and higher traversability than rocker bogie suspension. The proposed system has ability to climb slopes and to traverse on various rough terrains. Some indicators for traversability were introduced, namely – adhesion coefficient of the wheels and stability of the rover. Using the indicators, traversability on various terrains has been estimated. In conclusion, simulation results prove that, proposed mobility system has higher traversability.

Patel N. et al. [**11**], developed a software tool for the rover mobility performance evaluation and also for evaluating various rover chassis types. At first, developed a rover chassis evaluation tool (RCET) based on bekker theory. Rover mobility performance evaluation tool (RMPET) has been developed, which can give accurate performance of wheel/tracked or lugged rover either on terrestrial (earth)/extra-terrestrial (Mars/Moon) surfaces. Mobility performance parameters are also been discussed. The developed tool, RMPET reduces the time consumption for computing the fundamental parameters related to its mobility.

Petritsenko A. et al. [12], has presented four interaction cases. The analysis of four interaction cases and mathematical relationships were given and presented in this paper. Namely – rigid wheel moving over rough terrain, deformable wheel moving on rough terrain, rigid wheel moving on deformable terrain and deformable wheel moving on deformable terrain. Also, the major resistance and traction forces of different vehicle-terrain interaction cases were introduced and presented, which can be helpful to select specific wheel parameters at early design stage to get better performance.

Saarilahti M. et al. [13], mainly concentrated on wheel soil modeling which covers elaborately about, trafficability of soil and mobility of the wheel. Each one of these two deals with various parameters. Detailed about, Terrain modeling which includes terrain/machine and environment/transport modeling for different geographical information, on micro profiles and macro profiles are considered. Classification of trafficability and mobility (for example, rolling resistance, pull coefficient, traction, slip ground pressure, etc.,) has been briefly reported.

Sutoh M. et al. [15], conducted experiments using two wheeled rover with 12 types of wheel, different number of lugs of varying lug heights to investigate the effect of lugs on its mobility performance of planetary rovers. The wheel angular velocity is fixed at 2.5 rpm. Experimental results shows, lugs have some effect on its mobility performance over mild slopes; on the other hand, lugs have more effect on the mobility performance on steep slopes. With small number of lugs and increase in lug height, there is decrease in travelling performance of planetary rover on gentle slope; on the other hand, increase in number of lugs and lug height, results in higher traveling performance.

Sutoh M. et al. [16], proposed a methodology for estimating the travelling performance of a wheeled robot over slopes. Verification of the proposed method has been carried by using two wheeled rover with various types of wheel, different no. of lugs with various lug heights through experiments that are carried out- slope climbing tests and traction tests. Slip ratio for different slopes has been estimated based on traction test conducted on flat terrain. Comparisons have been made for estimated slip ratio from slope climbing test with that of estimated slip ratio from traction test. Wheel with large number of lugs estimates lesser slip ratio over steep slopes, and accurately estimates the travelling performance over slopes.

Wong J. Y. et al. [20], Carried out research work and gave a methodology for predicting the wheel performance on Moon/Mars surface, based on the experimental results on terrestrial (earth) surface. Also examination of the effect of gravity on sinkage and compaction resistance of rigid wheels was carried out. The predicted rigid wheel compaction resistance on the Moon/Mars surface is a function of the ratio of gravity on planetary surface to gravity on earth's surface.

4. Experimentation Work

Single wheel test bed is fabricated with dimensions of 1000 mm × 500 mm × 500 mm to carry out experimental work. Test bed is filled up with TRI-1 simulant which is an anorthosite lunar based simulant, developed and characterized [14], that resembles Apollo – 16 site (properties) on the moon. The properties of TRI – 1 Simulant is given in Table 1. With the help of pulley and applied load, wheel is allowed to move and readings are noted as amount of depth caused by its movement as sinkage. Experiments are conducted for three trials and average is taken into account as final sinkage. The experimental results are used to determine rolling resistance and compaction resistance (Refer Figure 3 and 4).

5. Results and Discussions

Rolling resistance and compaction resistance were found to show the significance of mobility performance of planetary rovers. Wheel with dimensions of 210 mm diameter and 50 mm width is considered for the present study. Conducted experiments using single wheel test bed for the wheel with different number of lugs and various lug heights considered (Refer Table 2).

TRI-1 soil simulant is considered for the study and carried out experiments. Table 1 represents properties of TRI-1 simulant.

Sl.No.	properties	Value
1.	Coefficient of cohesion, k_c (N/m^{n+1})	6600
2.	Coefficient of internal friction angle, k_ϕ (N/m^{n+2})	139000
3.	Soil exponent, n	0.404
4.	Density, ρ (g/cc)	1.18

Table 1: TRI-1 Soil Simulant Properties (Sugali Sreenivasulu, 2014)

Table 2 represents wheel geometry considered for the study.

Sl.No.	Wheel type	Dimension	Lug height
1.	plain	210 mm ×50 mm	h = 0
2.	Lugged	N = 8	
3.	Lugged	N = 12	h = 5, 10, 15 mm
4.	Lugged	N = 16	

Table 2: Wheel Geometry for Experimental Work

Rolling resistance and compaction resistance is determined for plain wheel and lugged wheel (Refer Table 2) on TRI – 1 soil simulant. Rolling - resistance versus wheel slip is illustrated in Figure. 3, whereas, compaction resistance versus wheel diameter is shown in Figure 4.

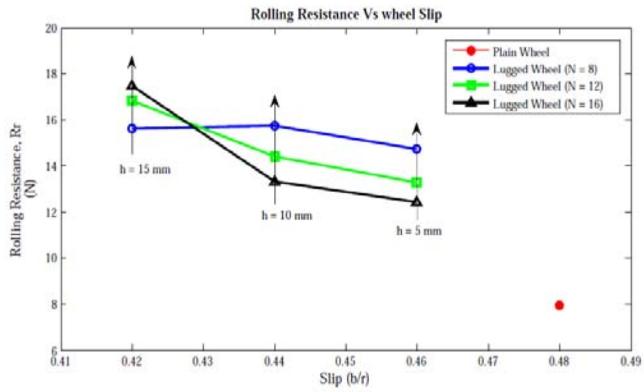

Figure 3: Relationship between rolling resistance and slip

Increase in wheel slip results in reduction of rolling resistance(R_r).Comparing all lugged wheels, for N = 16 and h = 5 mm minimum rolling resistance occurs, i.e., 12.43 N, indicating better mobility performance. Similarly, for plain wheel, minimum rolling resistance of 7.97 N also indicates high mobility performance. Increase in number of lugs influences the rolling resistance. Lower the rolling resistance, higher the mobility [13].

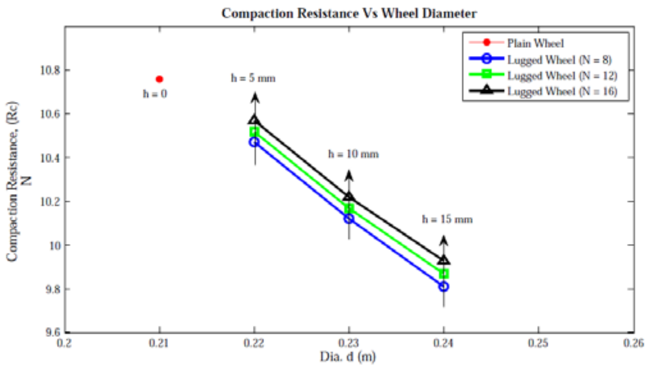

Figure 4: Relationship between compaction resistance and diameter

Equation 12 is used to determine compaction resistance. It is function of wheel geometry (wheel diameter, weight) and simulant properties (k_c , k_ϕ and n). Increase in wheel diameter results in reduction of compaction resistance (R_c). Comparing plain and lugged wheels, minimum compaction resistance occurs at N=8 and h=15 mm, i.e., 9.81 N, indicating better mobility performance. Lower the compaction resistance, higher the mobility [13]. Maximum compaction resistance is 10.56 N for plain wheel. Increase in diameter influences the compaction resistance. Increase in lug height rather than increase in number of lugs, influences the mobility.

6. Conclusion

The aim of this paper is, to bring out the significance of mobility parameters of planetary rovers and to describe how the travelling performances are affected. From the test results, it is inferred that compaction resistance and rolling resistance are influenced by the wheel geometry. As the wheel diameter increases, the compaction resistance reduces. As the wheel slip increases, the rolling resistance decreases. The mobility is inversely proportional to the rolling resistance. Greater rolling resistance results in poor mobility. Increase in diameter influence the compaction resistance. For N = 8, h = 15 mm, mobility holds good as it has lesser compaction resistance than other conditions (N = 12, 16 and h = 5 mm and 10 mm). Increase in lug height rather than the increase in number of lugs influences the mobility. The lower resistance, results in better mobility.

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Authors' Profile:

Pala Gireesh Kumar was born in Kavali, India, in 1991. He received the B.TECH. degree in Civil Engineering from the Sri Venkateswara University College of Engineering, Tirupati, India, in 2012, and the M.Tech. degree in Transportation Engineering and Management from the National Institute of Technology Tiruchirappalli (NITT), Tiruchirappalli, India, in 2014. Currently he submitted his Ph.D. Thesis from National Institute of Technology Tiruchirappalli, Tiruchirappalli, India, in 2018. He is life member of Indian Geotechnical Society (IGC) Trichy Chapter. He received an award from the Commissioner of Trichy in recognition of the project done in M.Tech, 2014. Government of Tamil Nadu is accepted to implement the proposal he made for design of cycle tracks. His main area of research interests are on Planning, Traffic safety and Terramechanics.

S.Jayalekshmi was born in Nagercoil, India, in 1969. She received her B.E. degree with first class in Civil engineering from Government College of Engineering, Tirunelveli affiliated to the Madurai Kamaraj University, India, in 1990, and the M.E. degree with first class(Distinction) in Geotechnical engineering and was the recipient of Thiru Meenakshi Sundaram Merit Prize from Annamalai University, Annamalainagar. She received her Ph.D. degrees in Civil Engineering from the Indian Institute of Technology Madras (I.I.T. Madras) Chennai, India in 2004. She was awarded the International Geosynthetic Society Student award at GEOASIA 2004, Seoul, Korea. In Februaury 2000, she joined the Department of Civil Engineering, in the Regional Engineering College Tiruchirappalli (Now National Institute of Technology Tiruchirappalli, as Lecturer, and is currently serving the same as Associate Professor.. Her current research interests include Geosynthetics, Environmental Geotechnique, Terramechanics and CFST. Dr. S.Jayalekshmi is a Life Member of the Indian Society for Technical Education, Indian Geotechnical Society (Chennai and Delhi Chapters). She is also a member of the Institution of Engineers (India).