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Design Method Development for the Design of Traction Systems

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DESIGN METHOD DEVELOPMENT
FOR THE DESIGN OF TRACTION SYSTEMS

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ABSTRACT

The objective of this research is to develop a design method for rapid exploration of traction concepts primarily for off-road vehicles. Different approaches available to achieve this objective are discussed and compared, such as computational, analytical, and physical methods. Computational approaches are based on simulations performed using Finite Element Method (FEM), Discrete Element Method (DEM), and combined Finite Element-Discrete Element (FE-DE) methods. Analytical approaches are based on closed form mathematical models developed by previous researchers based on the theory of plasticity. Physical approaches include fabrication and testing of prototypes at different levels of abstraction. This thesis compares these different approaches to design with respect to design process requirements of (1) timeliness, (2) cost, (3) required expertise, (4) accuracy of results, (5) flexibility to adapt to new designs and (6) stage of design process. This comparison is done both at a theoretical level and at an implemented level where each of the strategies are used to try and delineate between different classes of traction concepts. It is proposed that the physical prototyping approach should be the preferred approach with respect to these criteria. A new structured design approach is developed based on these findings to employ the different modeling schemes at stages of the design process that are most appropriate based on the technological maturity of this specific application domain.

To the love of my life, my family:

Raghunatha Babu, Sasi Devi and Bhargav

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CHAPTER ONE:
MOTIVATION FOR TRACTION DESIGN METHOD DEVELOPMENT

This research has two main foci: developing in-vehicle trafficability and a design method for developing traction systems. Design methods are needed to solve every engineering problem in a structured and predictable manner. Traction system design follows a unique design sequence that takes exceptions from general design process. This raises the need for developing a systematic design method to solve design problem similar to designing traction systems. The work presented in this thesis develops a need for design method, how the problem deviates from the normal design method, and finally proposes a new design method that when followed will lead to better traction systems. Before developing a design method for traction systems, traction systems should be understood.

Traction is defined in the literature by many researchers as [1,2,3] the ability of preventing two contacting surfaces from shear failure [3]. Alternatively, tire traction is defined as the ability of the tractive element (e.g. tire, track etc.) to generate enough forces to overcome all types of vehicle resisting forces [1]. It plays a dominant role in trafficability of the vehicle moving over an interacting surface such as sand or soil. If sufficient traction is not created, it may lead to shear failure along the contact planes, such as in the case of soft soils, digging the interaction element into the surface resulting in sinkage. This develops an agglomeration of soil in front of the tractive element leading to the phenomenon referred to as the bulldozing effect [1]. In order to prevent the bulldozing effect, sinkage and other factors such as shear failure that leads to loss of traction, a proper tread system needs to be developed. An efficient tread system needs lower effort in generating trafficability leading to improved fuel efficiency. The objective of this research is to support the design of these traction systems through systematic method development.

1.1 Traction Concept Development Problem Scope

The scope of this research is governed by two different projects at Clemson University that are aimed at developing tractive solutions on sand specific domains: (1) an Automotive Research Center (ARC) project funded by the US Army's TACOM to develop improved trafficability of military vehicles in soft soil (2) NASA Lunar Wheel development project focused on designing new large scale non-pneumatic tires for extra-terrestrial habitation rovers.

1.1.1 US ARMY PROJECT

The primary objective for the US Army project is to develop novel tread solutions for tire on sand [5]. Efficient tread systems help to increase traction thus improving fuel economy, thereby reducing operating costs. These concepts should be tested and evaluated rapidly. In order to meet these requirements, the physical prototyping technique is being used to develop concepts for traction systems [21]. Figure 1.1 shows a prototyped traction system on a tire mounted to an ATV for testing. These prototypes mounted are qualitatively tested to find the concept that proved to be most efficient.

Figure 1.1: Prototype mounted to the test vehicle (left) and the prototyped tire (right)

Apart from developing tread solutions, the project also aims at developing analytical extensions to current tire-soil interaction models. This helps to model traction analytically once the required understanding of tire-sand interaction is achieved. Development of full computational model for tire-sand interaction that helps in validating the analytical models and experimental results are also planned, but are beyond the scope of this thesis.

1.1.2 NASA LUNAR WHEEL PROJECT

The research at Clemson is focused on developing a non-pneumatic tire that can perform over an extreme temperature range specified by NASA [20]. This tire is referred to as a TWEEL™ tire. The TWEEL™ tire also needs tread system for increasing traction [6]. Since the environment on the moon is sand specific, the application domain for the developed traction system is sand. A test rig has been developed by an undergraduate Creative Inquiry team to test the endurance of the TWEEL™ tire on sand that simulates moon's surface. Figure 1.2 shows the lunar wheel endurance testing system developed by the Creative Inquiry undergraduate team at Clemson University [21]. This lunar wheel testing system is used to perform an evaluation of the endurance tests on the lunar wheel as well the tread system developed for it. There are several phases of traction tests and wear tests planned for evaluating the performance of traction systems and tires in sand.

Figure 1.2: Lunar wheel endurance testing system [21].

1.2 Current Practice Overview

Three approaches are currently available for designing traction systems, each having distinct strengths: analytical modeling [7,11,32], computational simulations [8,9,12,30,31,33,35], and physical prototyping and experimentation [7,13,39,38]. Analytical methods are based on closed form mathematical formulations and may not require extensive prototyping. However, all the models make use of experimental data. Thus, these approaches are cost effective. Computational models use virtual simulations used to perform traction tests by modeling techniques through commercially available analysis codes. This approach requires basic understanding of modeling contact between tractive elements and interacting surfaces. On the other hand, the experimental approach uses prototyping to create designs and does not require high amounts of expertise with respect to fundamentals of traction mechanics. Based on the requirements on short development time, low level of expertise, and low cost, one of the approaches may be preferred over the others where the other approaches may be used to validate the results obtained. A simple cantilever beam example is used as an illustration to show the differences between three different modeling approaches. The problem statement for finding deflection in a cantilever beam has been specified as: *"A cantilever beam of length, l with a Young's modulus, E is subjected to a load 'P'at a distance 'a' from the fixed end. The objective of the problem is to find the deflection in the beam at the extreme end as well as the point at which the load is applied".* This problem can be solved in the three different approaches discussed below.

1.2.1 Analytical Methods

Analytical methods are developed based on the mathematical formulations of physical principles. There are many assumptions that are made in order to minimize the complexity of relations. It may not be possible to consider all the parameters that cannot be determined with mathematical procedures this is due to fact that analytical models assume ideal conditions which may not be in accordance with reality. Many unknown design parameters that are beyond the prediction of a selected theory must be defined based on experimental data [7]. In order to develop analytical models for predicting traction, the knowledge of tire-sand interaction is needed [11]. In Chapter Two the analytical approaches available for tire-sand interaction modeling and how these models will be used to find traction are discussed.

An example of a cantilever beam subjected to a point load ‘P’ is shown in Figure 1.3. This problem can be solved with simple analytical model of a cantilever beam with a point load is illustrated below.

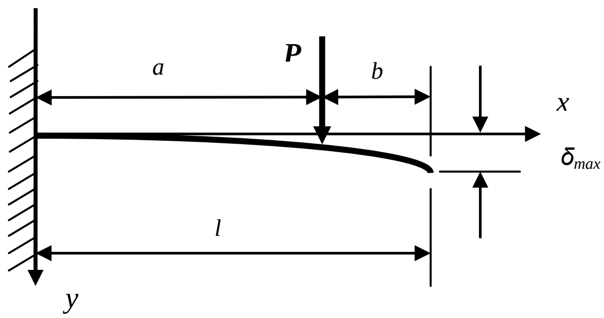

Figure 1.3: Cantilever Beam Subjected to a Point Load [14]

The deflection between load and support can be calculated from the formulae:

$$y = \frac{Px^2}{6EI}(3a - x) \tag{1.1}$$

The deflection after the loading point in the beam can be calculated using the formulae:

$$y = \frac{Pa^2}{6EI}(3x - a) \tag{1.2}$$

The maximum deflection, δ_{max} in beam can be calculated from the formulae:

$$\delta_{max} = \frac{Pa^2}{6EI}(3l - a) \tag{1.3}$$

These analytical equations help calculate the results without any need for computational and experimental set up. These may actually deviate from reality due to the fact that these equations assume ideal conditions which may not be possible. Some of the basic assumptions that were made while predicting these equations are:

1. The beam is uniform in cross-section as well as the material distribution.
2. The load acting on the beam is on a single point.
3. The load acts absolutely normal to the beam axis with no deflections.
4. All these analytical calculations are valid within the elastic region of the material while following Hooke's law. Non-linear deformations in the material may be defined through experimental curve fit data.
5. Another major deviation lies in boundary conditions at the fixed end of the beam.

Even though there are some assumptions that affect the results, analytical methods are quite accurate for most beam problems.

1.2.2 Computational Methods

Computational methods are virtual simulations that are used to predict results without any use of physical prototyping. There are two popular approaches for modeling tire-sand interaction: the Finite Element Method (FEM) [6,12,29,30,31] and Discrete Element Method (DEM) [8,9,34,35]. Additionally, a new approach is being developed: coupled Finite Element and Discrete Element Method for modeling traction [8]. Each of these three approaches is explored in Chapter Three.

These methods make use of computational effort to find the results and are used to identify the critical parameters that govern these results. An example of cantilever beam is performed in a commercial FEM package, ANSYS[1]. There is a systematic procedure followed to implement FEM code within the commercial software that collects the model data and solve the problem. Finally, post processing will yield the results. The model defines the physical shape, the material, and boundary conditions through discrete connected elements (meshes). Post processing of the data generates results that should be comparable to the results obtained from analytical models. This proves that the results obtained are found to be in accordance with the theory.

There are other factors that govern the accuracy of the results that are based on the level of fidelity in the model and can be varied by meshing the model finer. As the number of elements and nodal points is increased, the approximated, computed solution converges to the true solution. Increasing the number of elements increases the computational time. Thus, there is an optimized mesh, after which the accuracy of the result may not significantly change. This is referred to as convergence point [40]. After achieving convergence, there may not be a significant change in the result. This test is performed in order to minimize computational time while retaining the accuracy of the results. Figure 1.4 shows the post-processed results of the cantilever beam subjected to a point load. The figure shows the final position of the bean when subjected to a point load, *P*. Using this results, displacement and stress distribution at any given point can be

[1] http://www.ansys.com/

identified. As explained above, convergence test must be done in order for the solution set to be obtained accurately.

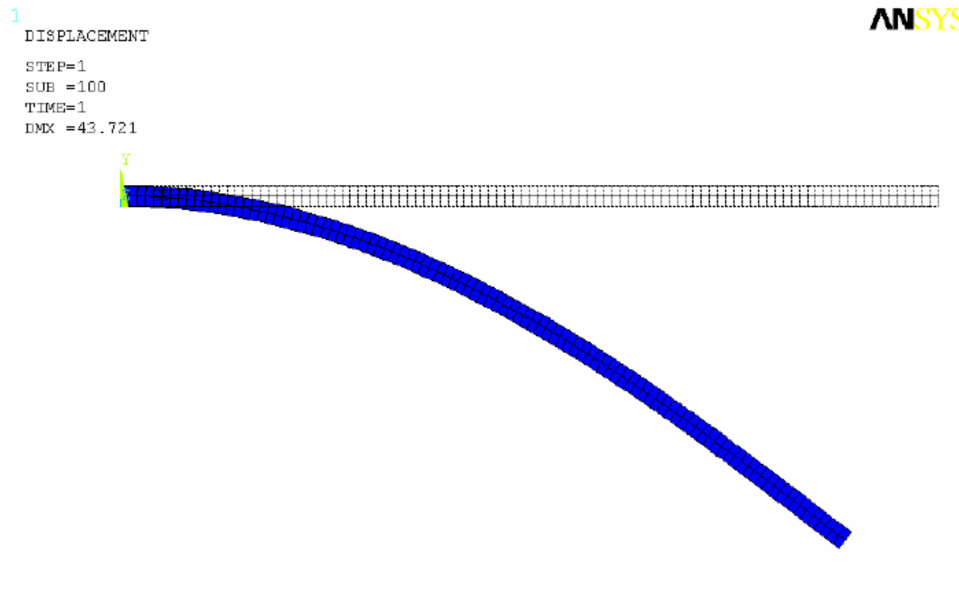

Figure 1.4: Simple cantilever beam experimented simulated in FEM Package, ANSYS

1.2.3 Prototyping Methods

The third approach is the physical prototyping. This method does not make use of any complex analytical models requiring computational effort. "Prototype" is a physical approximation of the product along one or more aspects of interest [16,18]. Prototypes play a major role in identifying the design defects and problems that play a crucial role in product design and development. Unlike computational models, physical prototypes can be felt and understood more clearly [17]. In order to predict traction, physical prototypes help in designing and developing tread concepts more rapidly when compared to analytical and computational approaches. More details on this method are described in Chapter Four.

The simple cantilever beam experiment is shown in Figure 1.5 that was used to calculate the deflection in the beam that can be found through the dial gauge. The beam is fixed along one side and is left free along the other side. A dial gauge is used to find the deflection in the beam when loaded using standard weights.

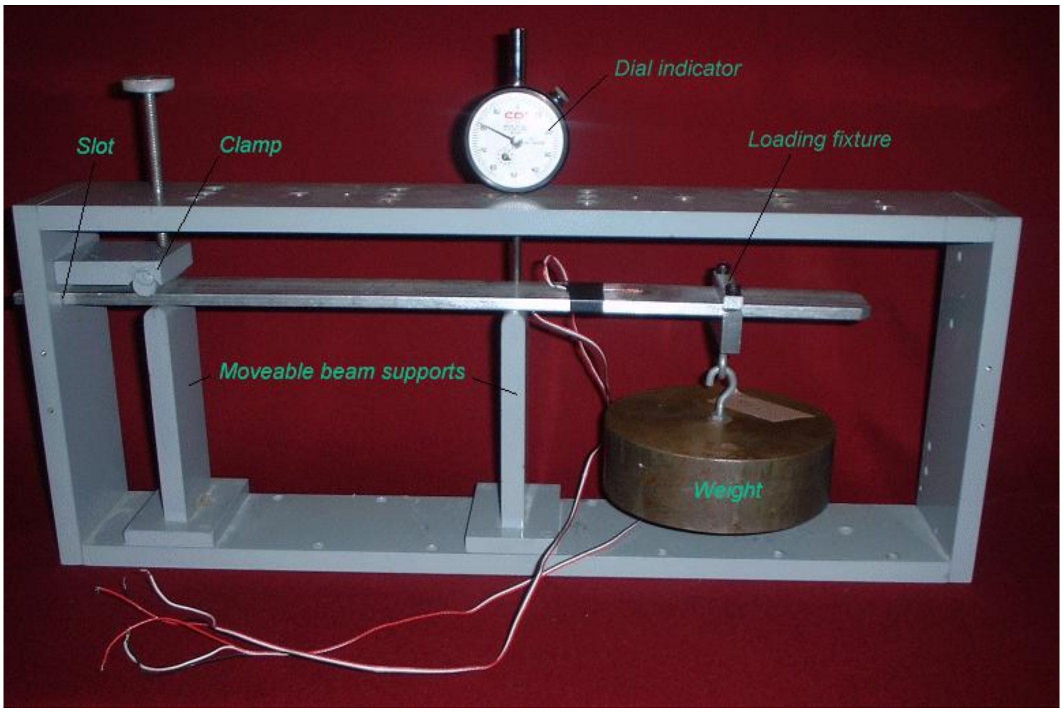

Figure 1.5: Experimental set up to measure deflection in a cantilever beam [15]

This example shows the various approaches within which we can find a solution. In this example problem, a cantilever is beam is subjected to the same loading and boundary conditions in all three different approaches available. The three approaches are the means of arriving at the solution, but the result needs a systematic method to verify validity of the solution. The three approaches help to design a cantilever that can withstand a particular load. Analytical models help to predict the maximum displacement it can withstand, but it may sometimes fails to consider some of the effects that are uncontrollable and uncertain. If the deformation is beyond the yield point, material non-linearity will affect the solution. Simulation based approaches help to improve the design by optimizing the geometry. Experimental method is a final validation step that proves the results obtained from the other two approaches.

1.3 Systematic Engineering Design

Designers are challenged with a wide variety of tasks for which they adopt different solution approaches. To meet these challenges, they use a wide range of skills and tools based on broad design knowledge. This can be made easier if they adopt a general working procedure to arrive at the solution. A systematic design process helps to efficiently rationalize the design in early stages [19]. An ordered and stepwise approach will provide solutions that can be reused through design catalogues [28]. Structuring the problem and task makes the design easy to establish solutions. *Design methods* are courses of action that derive from design science, cognitive psychology, and from practical experience in different application domains [19].

Thus, a design methodology should provide [19]:

1. A problem-directed approach which means the solution should always be addressing some aspect of the problem at any point in the design process.
2. Inventiveness and understanding that is it should accommodate optimum solutions.
3. The application of known solutions to related tasks which again shows the problem directed approach with current knowledge and expertise.

4. Easy learning experience. This means that the designer should not have difficulty in understanding the design method, which may shift focus away from the solution for the design problem itself.
5. Guidance for the product development team.
6. Compatibility with electronic data processing.

Each of the above points explains the importance of having a systematic design method. There are several conventional methods that are followed during the design. The following are some of the generally used methods [19].

1. Analysis
2. Abstraction
3. Synthesis
4. Method of persistent questions
5. Method of negation
6. Method of forward steps
7. Method of backward steps
8. Method of factorization
9. Method of systematic variation
10. Division of labor and collaboration

Some of these methods are followed in the prototyping approach which will be explained in detail in Chapter Four.

Any generalized design process follows five important steps namely, *define goals, clarify tasks, search for variants, evaluate,* and *make decisions.* Each step has its own significance and they help to make the designer arrive at the solution in systematic way. During the initial design stage, overall objectives for the project will be established along with individual sub goals. This strengthens the motivation to solve the task and also supports insight into the problem. Later, the conditions will be clarified by defining the problem domain. Then various solutions will be identified within the design space which is determined by the problem domain. After this step, each solution will be evaluated with respect to the goals and conditions, so that final decisions can be made which concludes the process of design.

There are several tools developed to aid designers in each of the design steps. In the first step, setting up requirements, there are two steps. The first step involves recording and defining requirements. This is followed by further refining requirements and converting them to engineering design specifications. This process is followed by solution finding. There are several tools used to achieve different solutions that meet the requirements. Some of the conventional solution-finding tools are [19]:

1. Information gathering:
2. Analysis of natural systems
3. Analysis of existing technical systems
4. Analogies
5. Measurements and model tests

As a result of developments in design research, several intuitive methods for solution finding are developed. They are [19]:

1. Brain storming

2. Method 6-3-5
3. Gallery method
4. Delphi method
5. Synetics

Although these methods help designers to seek solutions for difficult problems that involve multiple solutions and solution dependent variables, they all have certain drawbacks and require attention from designers.. Due to inadequate information, new solutions may fail to reach the consciousness of the designer.

In the design process, the next step is followed by identifying working principles within the problem domain. In this step the solutions are evaluated against set criteria that are established to meet the requirements. Finally, a solution will be adopted that meets the requirements. The importance of a systematic design method has to be realized for every engineering problem in order to simplify the approach to the solution. This thesis flow will realize each stage in the design process while the search for solutions is in progress. This general design method is compared against the process followed in designing traction systems. Although the design method proposed in this thesis is in the conceptual phase of the design that follows the principles of solution finding and establishing working principles.

1.4 Research Objectives:

The main objective of the research presented in this thesis is to establish a design method for designing traction systems. To achieve this objective various approaches for modeling traction systems have been identified and employed. Each method has been explored in order to systematize the flow of design approach.

The research motivation came from two projects comprising of a common objective to design traction systems. Progress is being made in developing analytical and computational methods while prototyping of these concepts is being explored. In this particular research, the flow of process for developing traction systems starts with prototyping. After physical prototyping, computational methods are used to develop traction models. Computational methods are helpful to conduct parametric study and design of experiments that could identify the critical parameters governing traction.

Finally, analytical models are used to validate the results obtained from both prototyping and computational methods. Analytical methods are helpful to correlate the results obtained based on traction mechanics. A comparative study on each of the approach has been studied with respect to six different criteria that could help explain the benefits of each approach. They are:

1. Required input information; helps to find the level of input information required to obtain results.
2. Reliability of results, to fine the reliability of the results from each approach.
3. Required Expertise, to evaluate the expertise required in each method to arrive at solutions.
4. Flexibility to adapt to new traction concepts, to find the level of flexibility in each approach so that the designer can evaluate multiple design solutions.
5. Cost which includes initial cost, fixed cost and operational cost

6. Stage of design process, helps identify the stage of the approach in the design process.

1.5 Thesis Overview

This thesis is divided into six chapters: (1) an introduction that gives the background, motivation and research objectives for this work, (2) a discussion on analytical approaches for traction which explain the past and current research on modeling traction using closed form mathematical equations for predicting traction, (3) a discourse on computational approaches for modeling traction that are currently available to model traction while briefly reviewing the literature on computational methods, (4) physical prototyping approaches are introduced explaining the current progress on the projects and the methods followed to develop and test different traction concepts, (5) a comparison of these approaches, and (6) concluding remarks with a proposed integrated method for designing traction system.

CHAPTER TWO:
ANALYTICAL BASED TRACTION MODELING APPROACHES

Analytical models are one of the three different approaches available for designing traction systems. These models are governed by closed-form mathematical equations that are formulated based on mechanics. In order to model traction, understanding of tire-sand interaction is needed which includes tire models, sand models, and interaction models. The theory of hyper–elasticity is used to model the tire; the theory of elasto-plasticity models the behavior of sand; and the contact theory determines the interaction behavior between tire and sand. There are several models that are based on these theories [1,2,7,27]. Analytical models for tires are not known to be researched from the literature. Significant amount of research was done on modeling tire through simulation based approaches which are explained in section 3.1.1. For this reason, sand models are described followed by traction modeling in section 2.2.

2.1 Analytical Models of Sand

Sand behaves as an elasto-plastic material that exhibits both elastic and plastic properties [23]. An elasto-plastic material follows five different sequential stages within which the material follows: 1) elastic stress-strain law, 2) yield criteria, 3) work hardening/softening, 4) flow rule, and 5) failure criterion. Table 2.1 shows the function of each stage of sand's behavior.

Table 2.1: Significance of each stage in sand deformation [23]

Region	Stage of the material	Function
Elastic Behavior	Hooke's law or elastic stress-strain law	Elastic strains under condition of stress change
Plastic behavior	Failure criterion	Limits the maximum stress
	Plastic potential function	Plastic strain increments
	Yield criterion	Initiation of plastic strain
	Hardening-softening region	Measures the magnitude of plastic strain increments.

The elastic stress-strain law governs the material behavior within the elastic region of the material. Yield criterion explains the material behavior after the formation of initial yield after which the initiation of plastic strain occurs. The hardening or softening law governs the rate at which the yield surface grows after initial yielding. The yield surface in a material model is shown in Figure 1.2. The flow rule relates the state of stress to the corresponding increments of plastic strain. Finally, the failure criterion shows the point of failure of the material [23]. It also limits the maximum stress the material can withstand, before it fails. This helps determine the shear strength of the material.

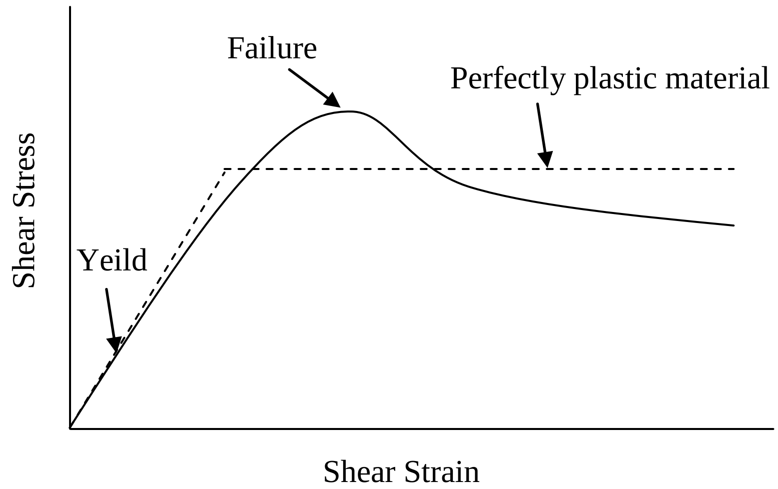

Figure 2.1: Typical stress strain behavior of soil

There are three popular sand models that follow these behaviors: Mohr-Coulomb model, Drucker-Prager model, and Lade's model [22,23,26]. Each of them is explained in detail below.

2.1.1 Mohr-Coulomb model

Mohr-Coulomb theory is generally applied to materials that have compressive strength exceeding the tensile strength. Thus, finding its application in geologic materials to define shear strength, defined as the resistance of the sand to increasing plastic shear strains [22]. Initially the material behaves elastically and develops elastic shear strain. Further increase in shear stress would lead the material to a point where plastic shear strain starts to develop and the point of initiation of plastic strain is said to be *yield* point. Initially, the plastic strains are limited because they result in an increased resistance to further deformation otherwise known as work or strain hardening [22].

Coulomb has given the behavior of shear strength of a material in the form of an equation:

$$\tau_f = c + \sigma_n \tan\phi \qquad (2.1)$$

Where τ_f is the absolute value of the shear stress in the soil at failure.

σ_n is the normal stress on the surface of failure

While compressive stress remains positive. *c, φ* are the parameters which are constant for any particular type of soil defined as cohesion and angle of internal friction. Typical value of *c* ranges from 0 to 300 depending on the type of sand. For dry sand, it is zero. The value of *φ* ranges from 0 to 90^{o}. It is practically not possible to achieve infinite slope. Typical value ranges from 20^{o} to 60^{o}. This equation was later modified, as the shear stress cannot be expressed in terms of total stress as:

$$\tau_f = c' + \sigma'_n \tan\phi' \qquad (2.2)$$

Where σ'_n, the effective normal stress defines as the changes in total stress and in the pore pressures in the soil lead to changes in volume and in shear strength [24].

c' and *φ'* are the soil parameter constants.

For saturated soils, $\sigma'_n = \sigma_n - u$,

Where *u* is the pore water pressure.

The angle φ' not a true angle of internal friction, it is the slope of the line representing shear strength in terms of effective normal stress on the surface of failure and is called as angle of shearing resistance. The parameter *c*' represents the shear strength independent of effective normal stress and is known as apparent cohesion. Figure 2.2 shows the critical plane in the Mohr-Coulomb yield criterion. The intercept gives the value of cohesion for the soil and the angle of the line AB with the horizontal gives the angle of internal friction for the soil.

A limitation of this model is that it neglects two important aspects of any material behavior, strain and yield following failure. Taking failure criterion into consideration, the equation was re-written as:

$$\tau_f = c' + (\sigma'_n - u)\tan\phi' \qquad (2.3)$$

The line AB represents the failure loci. For states described in between the line AB, the strain is said to be finite and so can be determined. The Mohr's circles in Figure 2.2 shows the effective stress at some point within a soil mass. The three principle stress components of effective stress are represented by σ_1', σ_2' and σ'. Coulomb's failure condition states that the failure occurs if the largest Mohr circle, defined by the greatest and least principle stress components, σ_1' and σ_2', is tangent to the Coulomb's failure loci. This is known as Mohr-Coulombs failure condition.

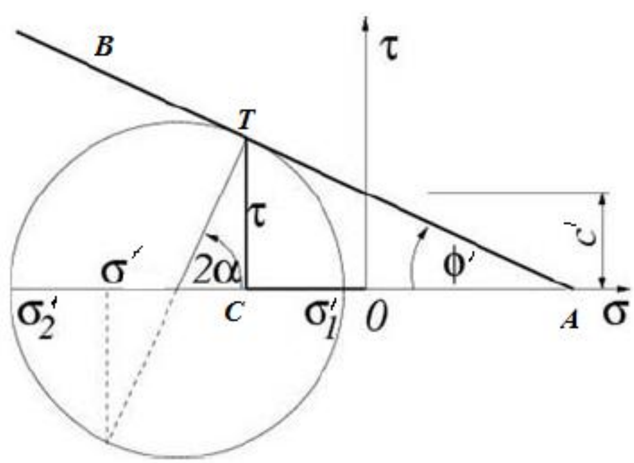

Figure 2.2: Inclination of the critical plane in the Mohr-coulomb yield criterion [22]

Although this model helps to find the shear strength of the material, still the parameters required, cohesion and angle of internal friction have to found through experiments such as direct shear tests and consolidated shear tests. The procedure for finding the properties of any kind of sand remains the same, although the properties itself may change based on the type of sand. The shear strength of the material helps determine the ability of the sand to generate enough traction for the vehicle.

2.1.2 Drucker-Prager model

The Drucker-Prager model is one of the most widely used models for modeling sand in virtual finite element methods [26]. This model is close to soil behavior as it can capture the effect of stress history, stress path, dilatancy, and the effect of the intermediate principal stress when compared to Mohr-Coulomb model. Although Lade's model can effectively represent sand, there are no algorithms developed to include the model in FEM packages. The yield surface of the Drucker-Prager model has three parts: the Drucker-Prager shear failure surface, an elliptical cap that intersects the mean effective stress axis at a right angle, and a smooth transition region between the shear failure surface and the cap. The graph constructed in *p*-*t* plane in Figure 2.3 shows the behavior of the material in all the three parts.

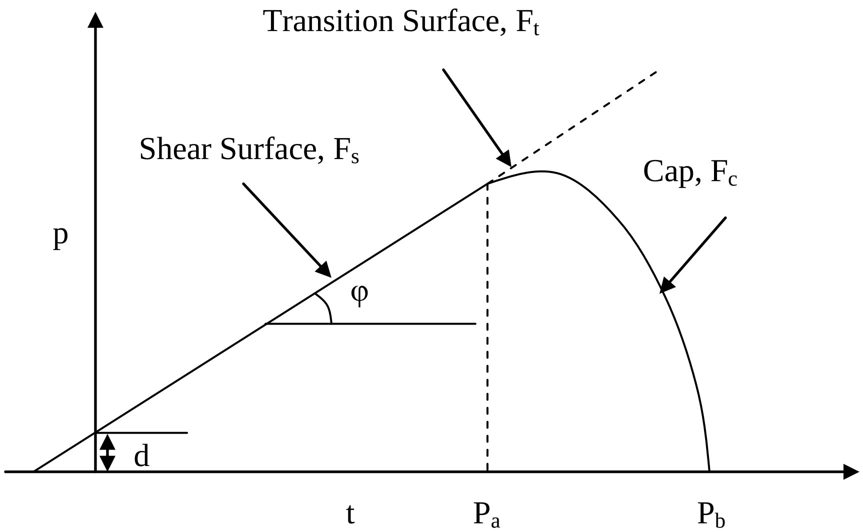

Figure 2.3: Yield surface of Drucker-Prager cap model [6]

The elastic behavior is modeled as linear elastic using the generalized Hooke's law. The plastic behavior is determined by the Drucker-Prager shear failure surface and the cap using the equation:

$$F_s = t - p\tan\phi - d = 0 \qquad (2.4)$$

Where φ is the angle of internal friction of the soil and

d is its cohesion in the *p*-*t* plane.

In this model, the flow potential surface that determines the direction of the plastic strain increment generated by a stress increment consists of two parts. In the cap region, the associated plastic flow is defined which means that the flow potential surface is identical to the yield surface. Figure 2.3 shows the yield surface of the Drucker-Prager cap model. For the Drucker-Prager failure and the transition yield surface, a nonassociated flow is assumed which means that the shape of the flow potential surface G_s in the p-t plane differs from the yield surface (F_s and F_t).

In order to use Drucker-Prager plasticity model, at least three tri-axial compression tests are needed to determine the parameters α and φ. In addition, one isotropic consolidation test needs to be conducted with several unloading-reloading cycles to determine the hardening-softening law that relates the hydrostatic compression yield stress p_b and the corresponding volumetric plastic strain. The procedure for performing these tests can be found in [22].

2.1.3 Lade's model

A series of experiments were conducted by Lade on different types of sand. From these, twelve constraints are determined based on three tri-axial compression tests and one isotropic compression test. These are grouped into the five basic stages of sand behavior as explained in section 2.1. The total strain increment, $d\varepsilon$ is calculated as the sum of elastic and plastic strain components which is:

$$d\varepsilon = d\varepsilon^{e} + d\varepsilon^{p} \tag{2.5}$$

The elastic strain is calculated based on nonlinear form of Hooke's law and the plastic strains by a plastic stress-strain law.

In the elastic region the strain is calculated using the equation:

$$E = Mp_a = \left[\left(\frac{I_1}{p_a} \right)^2 + 6\frac{1+\upsilon}{1-2\upsilon} \left(\frac{J_2\,'}{p_a{}^2} \right) \right]^{\lambda} \tag{2.6}$$

Where υ is the poison's ratio.

I_1 is the first invariant of the stress tesnsor

J_2' is the second invariant of the deviatoric stress tensor.

p_a is the atmospheric pressure.

M is the modulus number and

λ is the exponent.

M, υ, and λ are determined from the loading-unloading cycles of tri-axial compression tests. The failure criterion is determined in terms of first and third stress variants, I_1 and I_3 respectively. The equation is written as:

$$f_n = \left(\frac{I_1^{\ 3}}{I_3} - 27 \right) \left(\frac{I_1}{p_a} \right)^m \tag{2.7}$$

There are two more parameters that are determined using tri-axial compression test results. The flow rule is used to calculate the plastic strain in the sand. Later on the yield criterion is determined is identified from an isotropic compression test by fitting the results with the following equation:

$$W_p = Cp_a \left(\frac{I_1}{p_a} \right)^p \tag{2.8}$$

Lade's model can represent sand more closely than the other two models. The Von-Mises and Tresca criterion can effectively represent the elaso-plastic behavior of metals, but fails for frictional materials like sand. To overcome this drawback, Mohr-coulomb model has made an extension for Von-Mises criteria and Drucker-Prager model has made an extension for Tresca failure criterion. These two extensions still are not able to represent sand closely when compared to Lade's model [24].

2.1.4 Comparison of Approaches

Among these sand models Lade's model and the Drucker-Prager model are more realistic. The two criteria that can effectively represent the elasto-plastic behavior of metals are Von-Mises and Tresca. However, these criteria fail when capturing the behavior of sand. In order to overcome this limitation, the Mohr-Coulomb model has extensions for Tresca and Von-Mises criteria respectively. However, Drucker-Prager and Mohr-Coulomb models cannot exactly model the behavior of sand [22]. Lade's model has overcome these shortcomings and is well applicable for modeling sand. The Drucker-Prager model is close to real behavior of sand because it takes into consideration the history of stress, the path of stress, dilatancy, and the intermediate principal stress [24]. For computational modeling of sand, Drucker-Prager model is best suited [6] because of the non-availability of established algorithms to input Lade's model.

2.2 Analytical Models of Sand-Tire Interaction

Research on understanding sand-tire interaction has been done since early 1960's with Bekker's initial model being developed [2]. Later, extensions and improvements for Bekker's model were developed to model traction with higher resolution [1]. All the analytical models developed since have been based on the data obtained from physical experiments [1,2,3,13]. Three of the models of tire-sand interaction, Bekker's initial approach, Yong and Fattah's approach, and Ravi and Alcock's approach, are described below in detail.

2.2.1 Bekker's modeling approach

The relationship between tire-soil interaction was initially formulated by Bekker based on the relations formulated by Bernstein (1913) and Letoshnev (1936) for rigid wheel on soil. The model is represented by three equations for a basic rigid wheel. They are:

$$R = \frac{0.87}{(bk)^{1/2}} \frac{W^{3/2}}{D^{3/4}} \tag{2.9}$$

$$R = \frac{0.86}{(bk)^{1/3}} \frac{W}{D^{2/3}} \tag{2.10}$$

$$R = \frac{W^2}{kbD} \tag{2.11}$$

Where, *R*, is the towing resistance;

b, is wheel width;

D is the diameter of the wheel;

W, is the wheel load;

k, is the modulus of soil and

z= Sinkage of the soil and can be found from the equation:

$$p = kz^n \tag{2.12}$$

Where *P*, is the unit load and

n, is the exponent of sinakge can be found from experiments and varies for each type of soil. The value of *k* depends on the wheel width, *b* and soil type [2].

From these equations Bekker [2] developed a model for calculating towing resistance for a rigid wheel on any type of soil and is given by:

$$R = \frac{(3W)^{\frac{2n+2}{2n+1}}}{(3-n)^{\frac{2n+2}{2n+1}}(n+1)(k+bk_{\phi})^{\frac{1}{2n+1}} D^{\frac{n+1}{2n+1}}} \tag{2.13}$$

The co-efficients, *n, φ* and *b* can be found from experiments are fitted in the equations. This equation results from curve-fitting data are obtained experimentally. The wheel is assumed to be rigid and the soil uniform, thus, generating uniform pressure distribution along the contact patch. Bekker improved the formulae by making the rigid wheel as an elastic tire that represents the pneumatic tire and is converted to:

$$R = \frac{[b(p_i + p_c')]^{\frac{n+1}{n}}}{(k_c + bk_{\phi})^{\frac{1}{n}}(n+1)} \tag{2.14}$$

Where p_i is the critical inflation pressure of the wheel and

p_i', is the pressure exerted by the stiffness of the carcass.

The critical inflation pressure, p_i can be found from the equation:

$$p_i = \frac{W(n+1)}{b\left[\frac{3W}{(3-n)bk\sqrt{D}}\right]^{\frac{1}{2n+1}}\sqrt{D-\left[\frac{3W}{(3-n)bk\sqrt{D}}\right]^{\frac{2}{2n+1}}}} - p_c' \tag{2.15}$$

The value of p_c' can be determined experimentally by using load-deflection data for the pneumatic tire. Apart from motion resistance due to soil, there is also resistance due to carcass stiffness of the tire which is:

$$R_t = \frac{Wu}{p_i^{a}} \tag{2.16}$$

Where *u* and *a* are empirical resistance co-efficients that needs to be determined experimentally using towed wheel resistance load tests.

Graphs are plotted from these tests to plot the relation between resistance and sinkage pressure. Thus, the net motion resistance is calculated from the equation:

$$R_g = R + R_t \tag{2.17}$$

This is followed by the introduction of *drawbar-pull (DP*), defined as the difference between soil thrust, *H* and motion resistance *R*, is introduced that takes into consideration, the tractive ability of the vehicle moving on a particular terrain. Soil thrust, *H*, is obtained by considering, the contact area *A*, wheel load *W*, and soil properties *c* and φ. This is given by:

$$H = Ac + W \tan\phi \tag{2.18}$$

After considering the plasticity of the soils, the relationship to find the shear force along the contact patch was found by Janoshi and Hanamoto [27] as:

$$\tau = (c + p\tan\phi)(1 - e^{ix/K}) \tag{2.19}$$

Where, *K* is the slip coefficient for the soil.

p is the ground pressure along the contact pact and can be found from the relation:

$$p = (\frac{k_c}{b} + k_\phi)z^n \tag{2.20}$$

x denotes the distance between the front edge of the contact area and the slip area.

Even though attempts [2] were made to minimize errors associated with these relations by a series of experiments with in various soils, results deviate from the actual values obtained through mathematical formulations. This is due to assumptions associated with this model described previously. Bekker's initial attempt to find relations for finding motion resistance is partially successful in understanding tire-soil interaction. Modeling traction using analytical relations is still not clear due to some of the assumptions and due to the lack of developments in analytical models that define the behavior of soil. Yong and Fattah have suggested another approach with two different ways to model traction using analytical relations. The model is described in detail below.

2.2.2 Yong and Fattah's Modeling Approach

Yong and Fattah have described two different approaches for modeling traction: (1) dimensional modeling and (2) mathematical modeling. Both approached are intended to calculate the same parameter, *net draw bar pull* (*P*) which is ratio of *towed force, TF*, over the *vertical load on tire, W*.

2.2.2.1 Dimensional Modeling:

In this approach of modeling, the formulations for calculating traction were based on experimental data. A basic equation has been derived that gives the performance of tire n non-dimensional terms as a function of interaction parameters between tire and soil [1], which is:

$$\frac{\mathrm{TF}}{W}, \frac{P}{W}, \frac{Q}{rW} = \mathrm{f}\left(\frac{\mathrm{CIbd}}{W}, \frac{b}{d}, \frac{r}{d}, \mathrm{S}\right) \qquad (2.21)$$

Where, *TF* = Towed force;

W = Tire Load;

P = draw-bar pull;

Q = Input torque;

r = tire rolling radius;

CI = soil cone index;

b = tire section width;

d =overall tire diameter;

S = tire slip;

s = (1-Va/rw); *Va* = tire translational velocity;

Some of the extreme limitations of the current model are the inaccuracy in the data collected by approximation while conducting experiments and also the assumptions that were made in the theory deviates from the actual conditions.

2.2.2.2 Mathematical modeling:

The approach for this model is based on simple equation that makes use of the principle of force equilibrium which is:

Net draw-bar pull = Tractive force – Motion resistance (2.22)

The tractive force was calculated from Mohr-coulomb failure criterion, and expressed as:

$$\tau = C + \sigma \tan\varphi \qquad (2.23)$$

Where τ = shear stress;

σ = normal stress and

C and φ are the mathematical constants which are cohesion and angle of internal friction of the soil respectively that are calculated from triaxial compression tests.

This can be re-arranged as below assuming a uniform pressure distribution:

$$F = CA + W\tan\varphi \tag{2.24}$$

While calculating the tractive force, F, if the degree of slip, δ is also considered then, it can be obtained from the basic relation:

$$\delta = ix \tag{2.25}$$

Where, i = degree of slip;

x = distance from the first contact end;

δ = tire-soil shear displacement along the contact plane.

The general behavior of soil is used to predict the soil shear stress-shear deformation relationship expressed as:

$$\frac{\tau}{\sigma} = fm \tanh \frac{\delta}{k_\tau} \tag{2.26}$$

Where, f_m is the ratio of residual shear strength to the contact stress at large displacements.

k_τ is the displacement required to reach the peak shear stress.

If the shear stress-shear displacement curve is asymptotic then it can be given by:

$$\tau = C + \sigma\tan\varphi \quad 1 - e^{-\delta/k} \tag{2.27}$$

For large deformations, this equation approaches Mohr-Coulomb's criterion:

$$\tau = C + \sigma \tan\varphi \text{ as } \delta \to \infty \tag{2.28}$$

Differentiating this equation leads to the slope of the tangent at a given point on the curve and is given by:

$$\frac{C + \sigma \tan\varphi}{k} \tag{2.29}$$

Where *k* is the deformation modulus of a soil shear-stress curve as the distance between the intercept of the tangent drawn at the origin.

This equation gives the values of cohesion and angle of internal friction.The assumptions made here are that the shear shear deformation at the tractive element-soil interface changes linearly with slip and the pressure distribution is uniform.

The total tractive force can be predicted by integrating the tangential stresses along the tire-soil contact area written [27] as:

$$H = AC + W \tan\varphi \left[1 - \frac{1}{j\ 1 - e^{-j}}\right] \tag{2.30}$$

Where $j = \frac{il}{k}$;

l = contact area length;

k = deformation modulus.

The parameters *C, φ, k,* k_τ are called sled parameters and can be obtained experimentally in the laboratory using sled plate tests and by drawing the results graphically. Thus, the tractive force obtained by the tire is calculated as per Eq. 2.22 above.

Now that the relation for tractive force has been established, we need to find the forces associated with motion resistance. The motion resistance is the sum of the three different types of resistances. They are:

1. Motion resistance encountered due to compaction of sand in vertical direction otherwise termed as sinkage.
2. Motion resistance due to bulldozing efforts in the horizontal direction, and
3. Motion resistance due to flexing of the tire (can be due to inflation pressure).

The compaction inside the soil in vertical direction due to the load on the tire can be calculated from the plate-penetration test as:

$$P = kz^{n} \tag{2.31}$$

Where *P* = pressure on the plate;

z = depth of plate penetration;

k = coefficient which is a function of n and plate geometry

n = property of the soil.

Bekker (1960) proposed a modification for the calculation of pressure as [41]:

$$P = \left(\frac{k_c}{b} + k_{\varphi}\right) z^{n} \tag{2.32}$$

The sinkage , Z_0 and compaction resistance on a rigid tire can be written as:

$$Z_0 = \left(\frac{3W}{bk\sqrt{D}\ 3-n}\right)^{2/(2n+1)} \tag{2.33}$$

$$R_c = \frac{bk}{n+1}\left(\frac{3W}{bk\sqrt{D}\ 3-n}\right)^{2n+2\ /(2n+1)} \tag{2.34}$$

Where $k = \left(\frac{k_c}{b} + k_{\varphi}\right)$

Bulldozing effect is defined as the force required pushing the terrain mass at a sinkage z ahead of the track or wheels. The bulldozing resistance has been established by the relation:

$$R_b = \frac{b\sin(\alpha+\varphi)}{2\sin\alpha\cos\varphi}\left[2zck_c + \gamma z^2 k_\gamma\right] \qquad (2.35)$$

Where $k_c = (N_c - \tan\varphi)\cos^2\varphi$;

$$k_\gamma = \left(\frac{2N_\gamma}{\tan\varphi}+1\right)\cos^2\varphi;$$

$$\alpha = \cos^{-1}\left(1-\frac{2z}{D}\right);$$

N_c, N_γ = bearing capacity factors obtained from standard relationship graphs between bearing capacity and angle of internal friction, φ.

Motion resistance due to flexing of the tractive element is dependent on many other factors such as:

a. Number of plies,

b. Thickness of the carcass,

c. Tread design,

d. Inflation pressure,

e. Wheel-soil relative stiffness.

The flexing resistance on the rigid surfaces was found experimentally as:

$$\mathbf{R_t} = \frac{\mathbf{W.u}}{\mathbf{P_i^a}} \qquad (2.36)$$

Where u and a, are empirical fitting constants obtained from laboratory experiments as described in section 2.2.1 and

P_i = tire inflation pressure.

The compaction resistance calculated from the plate penetration test assumes the tire to be a rigid circular disc. The compaction resistance for a deformable tire is written as [41]:

$$R_c = \frac{\left[b \; P_i + P_c\right]^{\frac{n+1}{n}}}{\left[k_c + bk_{\varphi} \;\; n+1\right]} \tag{2.37}$$

Where P_c = carcass pressure (Pressure on the carcass due to the load on wheel)

$P_g = P_c + P_i$ = ground pressure.

The total motion resistance forces were given as $\boldsymbol{R = R_t + R_c + R_b}$. This may even be easier in case of the newly developed non-pneumatic tire called as TWEEL™ as there is no carcass pressure. Currently the research studies in predicting the motion resistance of the TWEEL™ are beyond the scope of research presented in this thesis.

The relationship for the derivation of *Net Draw-bar Pull (DP)* has been derived. This model gives the basic understanding of tire-soil interaction. It assumes a uniform stress distribution along the contact patch, which is unrealistic. The mechanics behind the interaction and more refined testing approach is needed to predict the behavior of tire and sand. Ravi and Alcock have suggested a more definitive approach in formulating relations for traction.

2.2.3 Ravi and Alcock's approach:

Ravi and Alcock has defined a more refined relationship that is obtained from experiments and proved to be successful [7]. This model has a well defined procedure that needs to be followed in order to find the tractive effort of the vehicle in particular, $\frac{P}{W}$. Wismer and Luth [42] suggested the base equation for traction which is based on asymptotic curve fit of shear stress versus soil deformation :

$$\tau = \tau_{\max}\left(1 - e^{-\frac{j}{k}}\right) \tag{2.38}$$

$$\frac{P}{W} = 0.75\ \ 1 - e^{-0.3C_N i} \tag{2.39}$$

Where P is the pulling force of the vehicle,

W is the vertical load acting at the center of the axle and

C_N is the cone index derived based on cone penetrometer resistance for sand.

Janoshi and Hanamoto [27] has proposed an equation for calculating pull. This will help find the tractive effort which is the ratio of Pull, P over the vertical load, W. The pull on the tire is expressed as:

$$P = F\left[1 + \frac{K}{il}\left(e^{-i\frac{l}{k}-1}\right)\right] \tag{2.40}$$

Where F is the maximum shear force,

l is the contact length;

K is the soil deformation modulus, and

i is the slip experienced by the tire.

This was further developed by Ravi and Alcock to get the equation for predicting traction as:

$$\frac{P}{W} = \left(\frac{A}{W}c + \tan\phi\right)\left[1 + \frac{K}{il}\left(e^{-\frac{il}{K}} - 1\right)\right] \tag{2.41}$$

This final form of equation takes into consideration, the contact patch area which could be in two different configurations.

If the contact patch on a rigid surface is rectangular, the area of the area of the contact patch, $A = 4f\sqrt{DS}$, and if it is elliptical in shape, $A = \pi f\sqrt{DS}$,

where f = tire deflection,

D = tire diameter and

S = tire section height.

Tire deflection can be found from experimental data using load deflection tests and the procedure implemented for calculating this is explained in detail in [7]. It is calculated from the load-deflection curve. The results show that this approach is proved to be successful in predicting traction. But still the effect of tread design parameters such as width and length, were not studied.

2.3 Comparison of Analytical Approaches

A comparison of three approaches presented above is done against a set of criteria discussed in section 1.4 that help in assessing the strengths of each approach for modeling traction. During this comparison phase, the benefits of each approach are determined with respect to the stage in the design process and its role in the overall design.

2.3.1 Required Input Information

This is one of the important criteria that help in modeling traction, because the input design parameters govern the output solutions. The first model introduced by Bekker explains the interaction between soil and tire, but does not take into account the geometric, stiffness and material parameters such as wheel width, diameter, and inflation pressure of the tire and shear modulus of the soil, required for the design of traction systems.

Yong and Fattah's approach has taken into account, the material properties of the soil and stiffness characteristics of the tire but did not consider material properties of the tire.. This model is an improvement to Bekker's model yet still neglects the effect of tire stiffness and elasto-plasticity of sand.

Ravi and Alcock's model is a further development to Yong and Fattah's model which has clearly considered the effects of soil plasticity. The important parameters such as tire stiffness and inflation pressure of the tire were considered. The design parameters required for modeling traction systems such as tread material and geometric properties were sill not considered. The design of traction systems is mainly based on the design of tread systems. The analytical models available so far has evaluated tire models with no tread on the surface. This shows that there are considerable developments that needs to be happened before analytical can be used for tread systems design.

2.3.2 Reliability of Results

The strength of the model lies mainly on the reliability and accuracy of the results obtained from the model. All the models make use of experimental data and are formulated based on curve fitting. Bekker's model is the first model that had attempted to find the performance of tire on sand. Initially due to lack of expertise, the model has several approximations that led to lower reliability in terms of results. Yong's model that was developed as an improvement of Bekkers model and has introduced a parameter called *Drawbar pull* that calculates the net traction based on input pull in the tire and the motion resistances associated with tire moving on sandy terrain. This method is proved to be valid for pneumatic tires by considering the elastic properties. Soil models are not reliable and this aspect of modeling is rectified in Ravi's model for predicting traction However, the model is restricted to pneumatic tires which is a major limitation. This approach may not be applicable to the newly developed non-pneumatic tire.

2.3.3 Required Expertise

The level of expertise in this comparison includes the ability of the designer to perform process and interpret the results available from the models that are governed by theories in physics. Bekker's model requires the understanding of experiments that are explained in his model. Yong and Fattah's approach requires the knowledge of *Drawbar Pull* and its importance in computing traction. This models details the theory of elasticity in sand and tire through the introduction of shear modulus of soil, inflation pressure and carcass pressure. Ravi and Alcock's approach extends the computation of traction more in detail with the term pull over load, $\frac{P}{W}$. The modeling of sand through elasto-plastic models described in section 2.1. Modeling tire requires the theory of hyper-elasticity which has not been considered. Modeling traction through analytical approach needs high expertise and therefore is not appropriate for novice engineers and organizations without a significant amount of corporate experience in both sand/soil modeling and tire modeling.

2.3.4 Flexibility to Adapt to New Traction Concepts

This criterion determines if the model allows the flexibility of designing new traction concepts. The initial Bekker's model is developed to understand the interaction mechanics between tire and soil. This model does not describe any equations that are needed to predict traction. Another analytical model is the Yong and Fattah's approach which has introduced traction but has neglected the influence of traction design parameters. Ravi and Alcock's model has explained traction in a better way compared to Yong and Fattah's model taking into account several sand and tire parameters that has an influence on the vehicle performance. However the current models need significant development for them to be used in the design of traction systems.

2.3.5 Cost

Three different types of costs are considered namely, fixed costs, recurring costs, and operational costs. To obtain data required for input into the analytical models, experiments needs to be conducted which comes under initial or fixed cost. In Bekker's model, plate penetration tests are done in order to find the sinkage of the tire in sand. Even Yong and Fattah's model needs these tests to find sinkage. Apart from the penetration test, Yong and Fattah's model require shear tests, to find the shear stresses induced inside the soil and also to find the bulldozing effect.

Ravi and Godbole's method requires entirely new set-up that takes a lot of cost associated with building the set-up. It also needs tire-deflection test in order to understand the behavior of tire on sand. Apart from the costs associated with constructing experiments, an operational cost involves the cost associated with searching literature.

2.3.6 Stage of Design Process

The Analytical modeling approach falls within the conceptual design phase of the design process. The tests that are needed to obtain data for modeling will be coming under validation phase. In this stage, several analytical models are studied through the available literature. This type of approaching comes under one of the conventional solution finding method named as analysis of existing technical systems as described in [19]. From the three different approaches for modeling sand, Drucker-Prager model is chosen. The analytical models are used as input for simulations that are performed to validate the traction design concepts.

2.3.7 Summary

Although theoretical models explain the mechanics behind modeling tire-sand interaction, the parameters required for designing traction systems were not explained. This proves that the level of expertise currently available on this modeling approach is not sufficient and there is a need for further research that needs to be done to improve analytical modeling. Table 2.2 explains the summary of comparison among the different methods discussed in this chapter. There are three means by which the data has been compared: high, medium and low indicating the ease with which they meet the criteria.

Table 2.2: Summary of comparison among the three different analytical models

	Bekker's approach	Yong and Fattah's approach	Ravi and Godbole's approach
Required input information	High	High	Medium
Reliability of results	Low	Medium	Medium
Required Expertise	Low	Medium	Medium
Flexibility to adapt to new concepts	Low	Low	Medium
Cost	Low	Low	Medium
Stage of design process	Conceptual	Conceptual	Conceptual

CHAPTER THREE:
SIMULATION BASED TRACTION MODELING APPROACHES

Simulation based approaches are used in most of the problems associated with tire-sand interaction due to their ability to model in a detailed manner and with acceptable accuracy [29]. To model traction using simulation based approach, tire sand interaction modeling must be done in detail. Currently three different approaches are available based on the mechanics of the method followed: Finite Element Method (FEM) [6,12,29,30,31], Discrete Element Method (DEM) [8,9,34,35] and Coupled FE-DE Method [8,9] . Each of the methods is described below in detail.

3.1 Finite Element Approaches

.In computational analysis, deformations of both the tire and the soil can be predicted with an acceptable accuracy once the constitutive behavior of both materials is well represented. The geometry of the contact area between the tire and the soil does not need to be prescribed beforehand and is simply the result of the deformation of tire and soil. Stress distributions in both tire and soil as well as on their interface can be predicted and compared to experimental results for validation. Attempts to simulate the behavior of tire and soil in these conditions are done and were demonstrated successfully [12]. Modeling traction with this approach still needs the design of tread and its behavior on sand. There is no evidence thus far that shows the studies in this direction. Modeling of these interactions and the influence of grousers on traction was shown, but not to a detailed extent [12]. Studies on tread design are still needed to be researched.

3.1.1 Previous Research

The modeling of tire was first attempted in [30]. The stress analysis of a vertically loaded tire was done by using FEM and is validated with the data obtained from experimental results. This is followed by a 2-D modeling of a tire rolling over the surface of soil [31]. Later FEM modeling of tire rolling on sand was done [12]. Figure 3.1 shows the FE modeling of a tire. The effect of inflation pressure is modeled using experimental data obtained from load-deflection curve. This proved the potential for modeling of tire soil interaction using FEM. The influence of inflation pressure on the performance of tire was studied. The previous studies on modeling the tire has considered the inflation pressure, but has neglected the soil compaction due to the loading on tire [31].

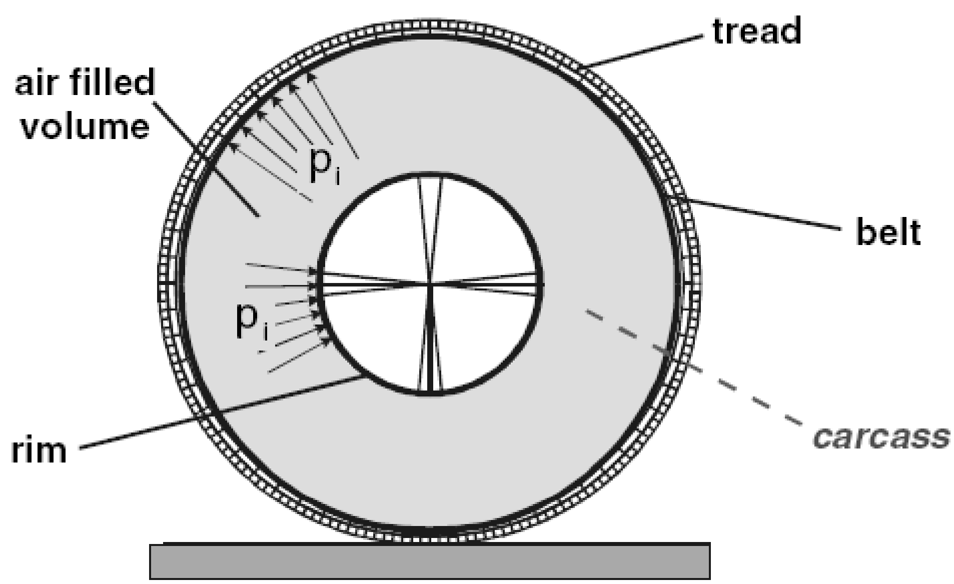

Figure 3.1: FEM Model of 2-D tire with inflation pressure [12]

The effect of soil compact was taken into consideration while soil was modeled with Drucker-Prager cap-plasticity model that can simulate the real behavior of sand using commercial FEM code, ABAQUS[2] [12]. Compaction in the sand is identified by stress contour plots. Several simulations were conducted to find the performance of tire on different terrain conditions. Studies proved that the deflection of the tire has a strong influence on the excitation of the wheel axle on deformable ground. Another important finding from this research is that the energy dissipated is lesser at low inflation pressures. Another conflicting finding is that the tread design takes nearly no influence on traction when the terrain is sand. However, there are no experiments to validate the statement.

The dynamic effects of tire-soil interaction are also studied [32]. FE Simulations are also used to design the ATV Tires [10]. Using other simulation techniques such as Computational Fluid Dynamics (CFD), the flow of tire patterns under vertical tire loading conditions was shown. CFD is also used for modeling tire-sand interaction and is currently out of our research scope.

3.1.2 Current work in CEDAR

FE Modeling of Tire-soil interaction was attempted to study as part of research. Tire is modeled as non-pneumatic in order to meet the requirements for NASA [6] as well as to avoid complexities associated with modeling pneumatic tire. Simulations were performed both in 2D and 3D. 2D modeling of non-pneumatic tire-sand interaction is shown in Figure 3.2. Sand is modeled using modified Drucker-Prager cap plasticity theory. Tire is modeled using 1-D beam elements. Initially contact pressure was measured inside the non-pneumatic tire [6]. Plastic strain is found from the stress contour plots on the sand surface. Modeling tread was not done.

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[2] http://www.simulia.com/products/abaqus_fea.html

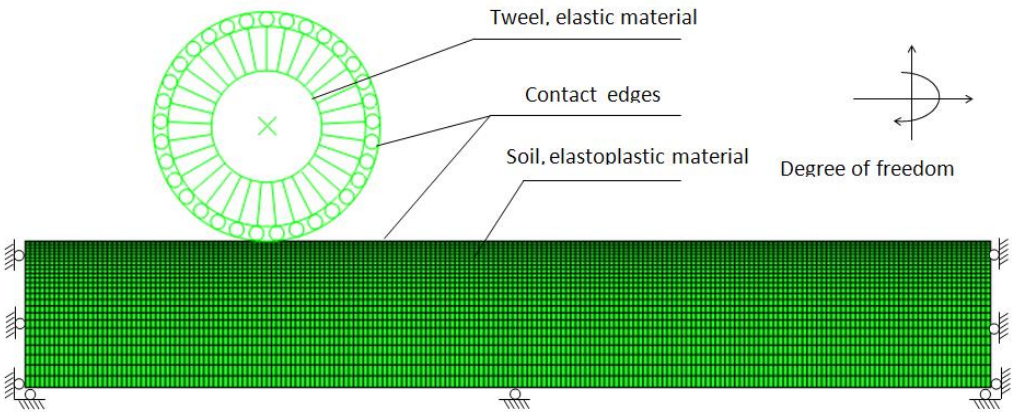

Figure 3.2: FEM model of tire-sand interaction [6]

With improved capabilities in modeling sand and tire, three dimensional modeling of tire-sand interaction was done including tread modeled with novel material and geometric pattern that has created better traction [21]. The simulation set up for three dimensional tire-sand modeling is shown in Figure 3.3. Contact pressure profiles are collected and its relation with tractive ability is under research.

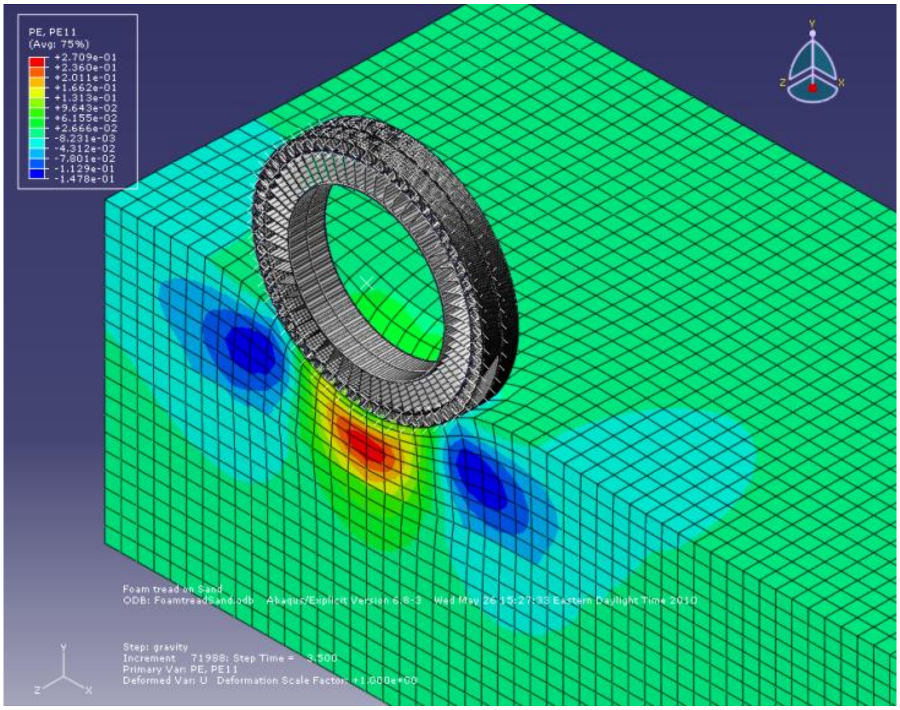

Figure 3.3: Three dimensional tire-sand interaction modeling using FEM

FEM is capable of modeling the interaction with good accuracy, but large deformation, flows and cracks that appear in the soil are very difficult to simulate [8]. The use of Discrete Element Method (DEM) can solve this problem.

3.2 Discrete Element Approaches

DEM is a technique introduced to describe the behavior of granular material and its interaction with rigid bodies [33]. This method is capable of modeling very large plastic deformations and also discontinuities associated with a material like sand [33]. The interaction between particles is governed by a contact law that is obtained by a combination of springs and dampers. The contact between both the particles is governed by coulomb friction law [9,35]. Since sand is a granular material, modeling sand using

DEM technique is closer to simulate its behavior [35]. However, modeling a continuous medium such as tire is difficult [8]. To overcome this drawback, some of the work the used DEM technique, has modeled tire as a rigid wheel while studying tire-sand interaction [34].

Modeling tire-sand interaction using DEM was first attempted in [9]. A series of experiments were conducted for rigid wheel-sand interaction. The results proved to show good correlation with experimental data. However, the particle parameters of the model were not clearly identified. This model was further improved in the research presented in [8]. A set of 12 parameters that define sand and six parameters that define the model of wheel and 2 more parameters that define the interaction between wheel and sand are used to simulate the interaction [9]. Wheel is assumed to be rigid and therefore it does not deform. A series of experiments were carried out to find the traction coefficient of the wheel, soil displacement and force distributions inside the soil and the wheel performance at high slip. Results were found to be in accordance with those from experiments [9]. This finally proved that this method has a potential for modeling sand. In all these simulations, the tire is assumed to be rigid. Since this technique keeps track of each and every particle of the granular material, the computational time required is much higher when compared to FEM simulations [8]. In order to overcome these drawbacks associated with DEM, a novel approach has been introduced, namely combined FE-DE method [9].

3.3 Combined FEM and DEM Approaches

Coupled FE-DE method is introduced in order to explore the advantages of both FEM and DEM, and extend the capabilities of modeling tire-sand interaction. In this method, tire is modeled using FEM and sand using DEM. Several commercial packages are available for modeling tire and sand in FEM and DEM respectively. Both the models are coupled using commercially available codes such as FORTRAN[3] and MATLAB[4]. Modeling tire and sand individually is relatively easier when compared to modeling both of them together in which case; interaction has to be strongly defined using contact laws.

The first attempt to model tire-sand interaction using FE-DE method is described in [9]. Tire is modeled using FEM and soil using both FEM and DEM. DEM is used to model upper layers of the sand where it is interacting with sand. This was done to minimize the computational expense of DEM. Commercial FE code, ABAQUS is used for modeling tire. Commercial DE code, PFC2D is used to model upper layers of sand using DEM. The interaction between both models and the coupling of both models, and the execution final analysis was done in FORTRAN [9]. Initial experiments conducted for finding sinkage of tire with vertical load proved to be in accordance with experimental results [9]. Thus, the model has been validated and proved to be accurate. Figure 3.4 shows the simulation set up done using FE-DE approach for modeling tire-sand interaction.

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[3] http://www.fortran.com/
[4] http://www.mathworks.com/

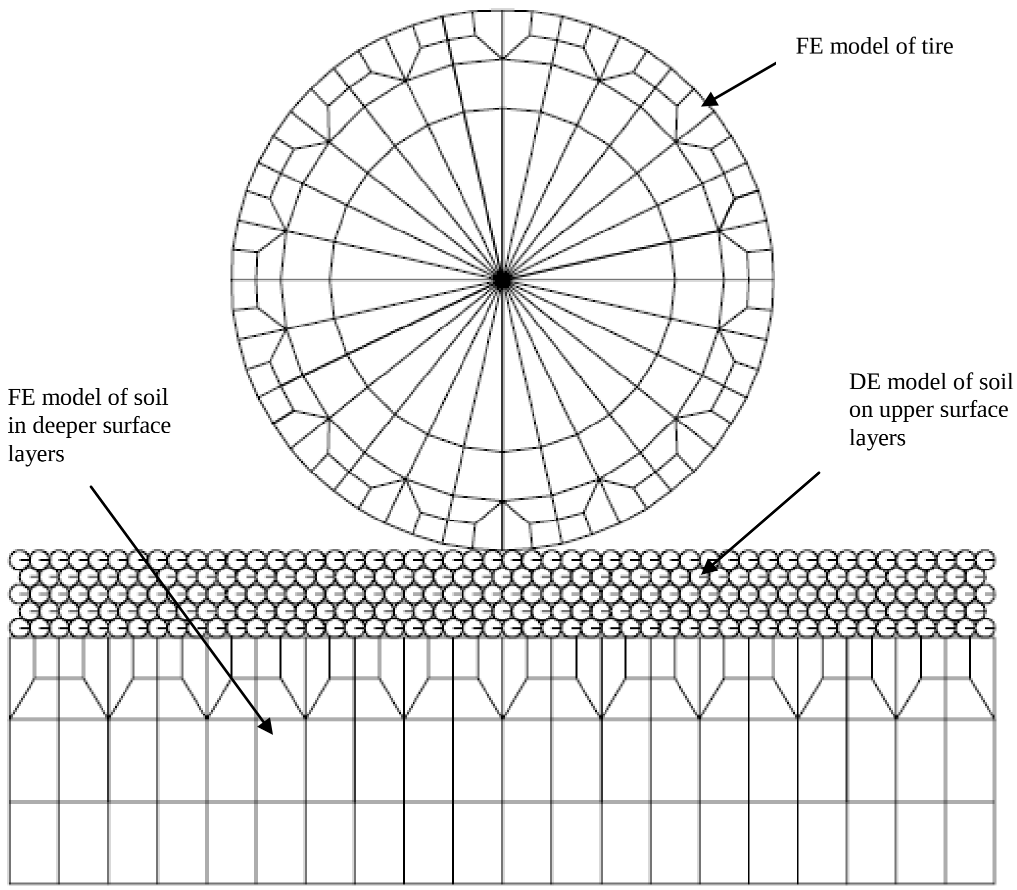


Figure 3.4: Simulation set up for tire-sand interaction using coupled FE-DE method [9]

Another attempt towards FE-DE method was done to find the tractive performance of the model [9]. Vertical load sinkage calculations were done in order to validate the model and then the model was simulated with draw-bar pull and slip tests [9]. The results proved potential benefits of using the FE-DE method in predicting the tire-soil interaction behavior. In this study, the tire surface is assumed to be smooth [9]. Further studies are in progress to introduce tread in to the tire model.

3.4 Comparison of Simulation Approaches

Three types of simulation based approaches are compared against the criteria set forth to describe the strengths of each method.

3.4.1 Required Input Information

For modeling traction, tire-sand interaction has to be modeled along with modeling tire and sand individually. Both of the approaches need inputs like material properties, physical dimensions and contact theory for modeling. Both FEM and DEM follow a step by step approach initially by modeling the physical shape of the tire and sand. Both the methods make use of analytical models for modeling sand. In FEM, material properties and section properties will be described for both sand and tire. In DEM, contact law between adjacent particles is defined. This step follows the definition of boundary conditions which remains basically the same for both of them. The physical properties of the material are needed for FEM, where as in DEM the material properties are adjusted by varying the contact properties between each particle.

3.4.2 Time Scale

The computational time required in FEM is relatively lesser than that of DEM. DEM takes huge amounts of time in terms of modeling and performing simulations. In order to overcome this drawback, coupled FE-DE method is introduced. However, designing a tread pattern is difficult to model and may take longer time when using both methods, since the combined FE-DE method introduces another software code to combine both of them.

3.4.3 Reliability of Results

Results obtained from FEM can be comparable to that of experiments. Based on the literature, it was found that the simulation results obtained using DEM closely matches with experimental results. This proves that DEM is a more reliable tool for modeling traction. When using FE-DE approach, the computational time may be minimized while retaining greater reliability in results.

3.4.4 Required Expertise

For modeling traction, knowledge on the basic mechanics as well experience in using the software package is needed. This takes additional effort in getting trained in the particular software that is being used. Compared to DEM, FEM is most widely used method and requires lower effort when compared to DEM. Finally the combined FE-DE approach needs additional expertise in programming.

3.4.5 Flexibility to Adapt to New Traction Concepts

Modeling traction needs the model changes in tire. Modeling tire in FE is easier when compared to DEM. Modeling tire in DEM may be difficult. In FE-DE approach, modeling interaction may be difficult with different tread patters that interact with sand.

3.4.6 Cost

The fixed cost refers to the cost for obtaining licenses. The current FEM package used during this research is ABAQUS and DEM package is PFC2D. The cost for obtaining ABAQUS software is more. Operating costs for ABAQUS is more but there are many workstations that use this software. Taking net cost for each work station for ABAQUS and PFC2D, PFC2D is more costly.

The cost associated with modeling DEM is more when compared to FEM. For FE-DE method, cost associated is even more where the initial and operating costs for FORTRAN or a comparable software code will be added.

3.4.7 Stage of Design Process

Simulation based modeling can either be in conceptual or embodiment design phase. In conceptual phase, simulation will be carried in order to obtain the final working solution. In the NASA Project, the non-pneumatic tire was modeled in several different configurations in order to find the best possible solution that meets the requirements of the design. Similarly in the Army project, several sand models are investigated to find the appropriate sand model. Also while modeling sand, several models available in the literature is investigated. This search is the conventional solution finding method known as information gathering [19]. For simulating the model, several available technical systems are also investigated which shows that a conventional solution finding method is followed. In the embodiment stage, the finalized concept is further developed by assigning material and shape [19].

3.4.8 Summary

FEM is the most widely used method by most of the researchers [37]. This method is capable of modeling continuum mechanics problems in a very detailed manner with lower computational expense. However, while modeling problems associated with tire-sand interaction, this method is lot more complex and there are more parameters that are needed to define the material and interaction parameters. Mesh distortions are very high due to large strain deformations that make the solution difficult to converge. To overcome this drawback, new methods are introduced into FEM package such as Coupled-Eularian-Legrangian (CEL) formulation. With this method, modeling large strain problems is made easier.

DEM has the capability of modeling granular materials in a very detailed manner. The computational time required is currently prohibitive to conduct tire-sand interaction simulations. Modeling tire is one of the major challenges in DEM, as it is mainly intended to model discontinuous materials. A combined FE-DE technique is used to overcome the challenges associated with both modeling techniques. Even in this model, contact laws that govern the interaction between tire and sand needs to be refined. Modeling tread systems for tire that helps to predict traction is still in research. Table 3.1 shows the summary of comparison against the set of criteria that were taken into consideration.

Table 3.1: Summary of comparison of simulation based approaches

	FEM	DEM	Combined FE-DE method
Required input information	Medium	Medium	High
Reliability of results	Medium	High	High
Required Expertise	Medium	Medium	High
Flexibility to adapt to new concepts	High	Low	Low
Cost	Low	High	High
Stage of design process	Embodiment	Embodiment	Embodiment

CHAPTER FOUR:
PHYSICAL PROTOTYPING BASED TRACTION MODELING APPROACHES

Prototyping based approaches rely on experimental prototypes for results. There are several traction modeling approaches that were adapted by researchers to calculate the tractive performance of tire on sand [3,13]. A special device named single wheel tester (SWT) was developed in order to find the performance of tire on sand. This tester was used to find the shear stress applied on the sand and the displacement in the tire, after which the shear stress-displacement curves were obtained. From this curves, the soil deformation modulus, K also known as bulk modulus of the soil was found. Traction is quantified further based on the analytical model developed in [13]. Although there are some of the experimental methods that help find traction, there are some drawbacks that restrict the validity of the model of which some of them include, the assumption that shear stress is uniformly distributed across the contact patch [7,13].

4.1 Up-Hill Traction Tests

Confirming to the requirements of current research at Clemson, an undergraduate research team was recruited under the name of Creative Inquiry (CI) to develop and test several prototypes to demonstrate traction [21]. The creative inquiry team consists of students from all levels of undergraduate degree. The Creative Inquiry Team at Clemson is aimed at solving critical engineering problems that will requires the students to be challenging and creative.

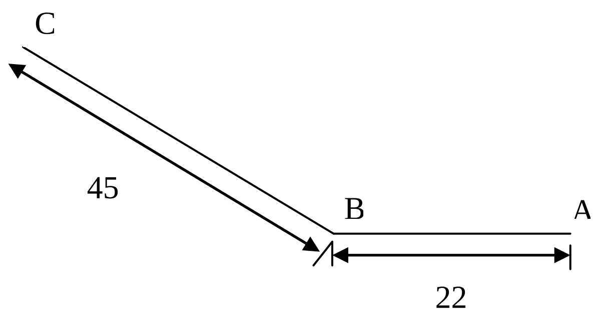
Prototype concepts here refer to different geometric patterns and materials for tire tread. These concepts provide a basic understanding of the interaction between tire and sand and its influence on traction. Several concepts were developed by the team. Generation of all the concepts was done in four different periods starting spring through the summer of 2009.

Testing of prototypes involves a proper test bed and a protocol that governs it. The protocol was developed after a proper location for test was chosen. Traction is quantified using two methods after which all the concepts are compared qualitatively. The first method is based on the distance travelled by the test vehicle on the test bed while the second method is based on the calculations of slip experienced by each test prototype.

4.1.1 Test Location:

Three different locations were chosen out of which, one location was finalized for testing. Criteria selected in choosing location are the slope of the test bed and flatness of the bed. It is important that there should not be any rapid changes in inclination of the test bed. This may hinder the accuracy of results. Testing is performed on a sand bed that is made along the slope of a hill starting from the basement. A standard test bed is developed to test traction. Tests are carried out on a course made of sand that is 45 feet in length, 8 feet in width and 6 inches in depth. The angle of test bed ranges from 20-25 degrees. The test bed starts at the bottom of the hill and continues up the hill as shown in Figure 4.1. A 22 ft. run-up distance before the bed is used for the test vehicle to attain a constant speed while climbing up the hill. The layout explains the overall test track Position A indicates the start point of the test while point B is the point where the ATV starts climbing up the hill and the same time reaching certain speed. Pont C is the maximum limit distance of 45 ft. for the ATV to complete the test track. The final location depends on the amount of traction yielded by the test prototypes. A constant speed of 5 mph is maintained in order to have the same amount of input power for all the tests. As there are fair chances of sand being eroded, a fence was built around the bed with a plastic fiber material supported by wooden stands. This helps to trap the sand inside the bed while protecting it from foreign mud/sand invasion.

Test bed location (left)



layout (right)

Figure 4.1: On-Vehicle Testbed Configuration

4.1.2 Test Vehicle:

The test vehicle is Kawasaki Brute Force all terrain vehicle (ATV) with a 650 cc engine. The front tires of ATV are replaced with slick tires used for races, obtained from the Clemson's Formulae SAE team. The pressure inside the tires is maintained at 25 psi. The ATV is kept in four wheel drive at a low gear (high torque) in order to assess the performance of the prototype tires in driving condition. A throttle hard stop is used to attain the speed of desired 5 mph before reaching the incline.

Figure 4.2: Prototype mounted to the test vehicle

While calculating slip, the theoretical distance the tire can travel is needed. To obtain this data, the number of revolutions the tire makes is needed. This is achieved by using a counter sensor that is mounted to the axle that senses metal particles that are attached to the axle as shown in Figure 4.2. Metal particles mounted are shown on left side of the image while sensing probe is shown to the right hand side. A cluster of aluminum metal wires were wrapped around the front axle in equal intervals. A camera is also mounted on the ATV in order to capture the sand tire interaction. Figure shows the location of camera mounted to the vehicle.

4.1.3 Testing Procedure:

The ATV is allowed to enter the hill course at a speed of 5 mph as specified, while the driver maintains it for the length of the course with the help of a governor that prevents further throttle, after the desired mph speed is attained. The ATV is allowed to climb the hill at 5 mph speed with 22 ft. run-up distance on the level ground. The ATV is allowed to drive at a constant straight steer up the hill. The run completes when the tires starts slipping without any further motion. It can be observed from the slip in the tire without further motion.

Then the distance the ATV has covered from the start of the hill is measured. The amount of slip is calculated from the total distance it travels and is compared against theoretical distance that it should travel. The counter mounted allows the theoretical distance traveled to be calculated by multiplying the circumference of the tire by the number of revolutions. The circumference is measured to the outside of the tread and if the tread diameter changes across the width of the tire, average diameter is used. The actual distance includes the initial 22 ft. run up distance and the distance the ATV travels up the hill. The number of revolutions on the level ground is subtracted from total to get the number of revolutions the tire made while climbing the hill. Slip is assumed to be zero while the tire is on level ground. The sand is raked up following the completion of each run to prevent compaction.

$$\text{Slip} = \frac{\text{Actual distance travelled}}{\text{Theoretical distance}} \times 100 \tag{4.1}$$

$$\text{Theoretical distance} = 2\pi r \text{N in.} \tag{4.2}$$

Where r is the radius of the tire

N is the number of revolutions made by the tire.

Each prototype will be tested in a set of 10 runs in order to minimize any errors out of observations. The data is post processed in Microsoft excel sheet to obtain results and then a bar graph is generated with mean values of slip and actual distance travelled.

Data is populated to qualitatively compare all the prototypes tested. The data has been further analyzed using statistical tool; ANOVA was to find if there is any variance existing between different groups.

These tests help the students as well as the research to find a traction system that yields better traction. A more refined approach has been experimented at the NASA Glenn research center to quantify traction for various concepts.

4.2 NASA Glenn Traction Tests

Research at NASA Glenn is also focused on developing traction systems. There are some physical tests that were done to find a better traction system. Testing was done on three traction systems that differ in tread design. They are:

1. Grousers
2. Metal fabrics
3. Carpet treads

A test environment has been set up to perform draw-bar pull tests that quantify the tractive performance of each system. The description of the test set-up and test vehicle are explained below

4.2.1 Test Vehicle

The test vehicle is a lunar vehicle named SCARAB on which the non-pneumatic tires are attached. Tread systems are attached to the non-pneumatic tires attached to the front axle. Figure 4.3 shows the configuration of the set-up described. Rigid wheels are fixed to the back axle. The normal load on the vehicle is 1000 kg which distributes load uniformly allowing each wheel to bear a load of 250 kg. The tests are performed on a wheel that is 28 in. in diameter.

Figure 4.3: Test Vehicle-SCARAB

4.2.2 Testing Procedure

Drawbar pull tests are used to predict the tractive performance of the traction systems. Drawbar pull is the gross force obtained by the vehicle minus rolling resistance. The gross force is called *tractive effort*, which the torque created by the transmission on the driving axle that propels the vehicle [36]. The draw bar pull test rig is shown in Figure 4.4. The vehicle is allowed to move while there is a horizontal resisting force from the draw-bar. The weight on the drawbar pull is added after obtaining slip data. Slip is calculated as the total distance travelled by the vehicle under drag over the total expected distance that it should travel which is obtained from the motor rotation and the diameter of the wheel. Data collection will be done though a computer which projects the data in graph with percentage of slip experienced against percentage of weight applied on the drawbar pull.

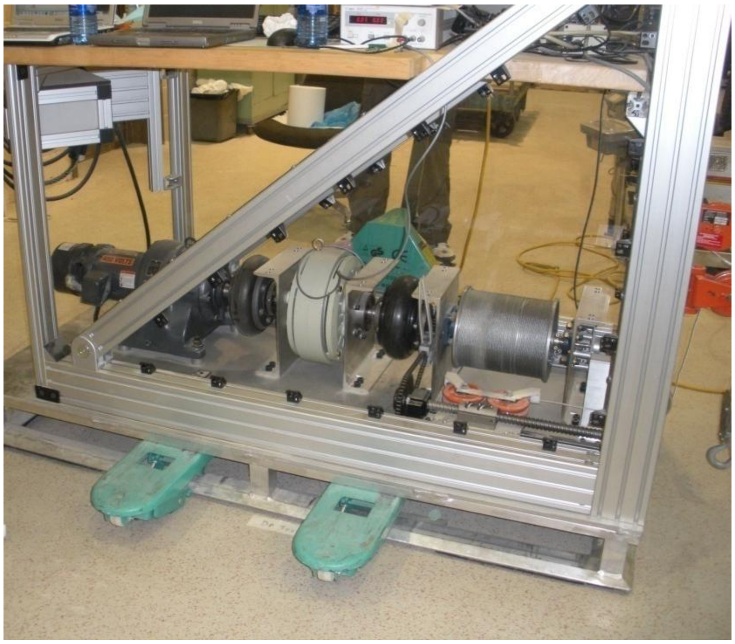


Figure 4.4: Draw-bar pull set up

4.3 Comparison of Prototyping Approaches

Both the prototyping approaches quantify traction based on slip experienced by the systems. But the tests performed at NASA Glenn are more controlled and governed by a single standard procedure. Each of the methods is compared against a set of criteria to find its advantages.

4.3.1 Required Input Information

The required input information for both the tests is about the same, but the source through which the data is obtained is different. During the uphill tests, the input required to obtain results are the distance travelled by the vehicle and the number of revolutions it made. The distance travelled is collected manually while the data for number of revolutions made by the tire is obtained from a metal probe counter. In case of drawbar pull tests at NASA, the results for number of revolutions the motor makes will be obtained from a data collection system.

4.3.2 Time Scale

The time required for testing through both methods differs. During the uphill tests, the experiment for each prototype is repeated 10 times in order to average the value obtained. Since the environment is more controlled, the experiment is performed only once. However, the NASA Glenn testing has several data points that are collected as the weight on the drawbar pull is varied each time.

4.3.3 Reliability of Results

The results obtained from NASA Glenn testing are more reliable as the environment is more precisely controlled in terms of sand preparation. Raking of sand is done uniformly in order to have equal sand distribution while testing is in progress, where as in uphill tests the sand bed is raked but are not precisely raked and as the testing is performed in an open place, the moisture content in the sand may not be the same throughout the bed. There are some uncertainties associated with data collection as there are different groups involved in the testing.

4.3.4 Required Expertise

The expertise required is more in case of NASA Glenn testing, as the environment is more controlled which means more expertise is needed to understand the testing and perform it. In case of uphill tests there is much simpler protocol made to the students to understand the procedure.

4.3.5 Flexibility to Adapt to New Traction Concepts

The uphill tests have the most flexibility to adapt to the new traction concepts that are prototyped and made. The prototypes can be made readily as required within a time frame of 1-3 days. The only probable difficult in switching the concepts is when the prototypes have to be peeled off from the slick baseline tires. In NASA Glenn testing, the prototypes will be prepared very precisely confirming to the results obtained through FEM.

4.3.6 Cost

The initial cost involves the cost required to set up the test bed and build test procedures. Recurring costs are the costs associated with developing prototypes and operating costs involves the cost for performing the tests. The cost associated with uphill tests is lower when compared to NASA Glenn tests considering any type of cost.

The cost involved with building the test rig for NASA Glenn tests is higher when compared with uphill tests. The cost required for making the prototypes us much lesser in case of uphill tests. The prototypes are built on a normal slick tire and the measurements will be taken manually which lowers the cost to a considerable extent. NASA Glenn testing uses automated testing equipment that is custom built and so takes much higher costs.

4.3.7 Stage of Design Process

Both of the testing procedures fall in the same stage of the design process, which is the conceptual design phase. Both of the methods make use of prototyping as their approach to initially model the concepts.

4.3.8 Summary

Finally to conclude, both uphill and NASA Glenn tests helped to design, build and validate several prototypes to find a traction system that performs better. This should be followed by validation of results using virtual simulations and analytical models that support them. Table 4.1 shows the summary of comparison of the two different approaches that were studied in this research.

Table 4.1: Summary of comparison between the two physical prototyping based approaches

	Up-hill traction tests	NASA Glenn traction tests
Required input information	Low	Low
Reliability of results	Medium	High
Required Expertise	Low	Medium
Flexibility to adapt to new concepts	High	Medium
Cost	Low	High
Stage of design process	Conceptual	Conceptual

CHAPTER FIVE:
COMPARISON OF TRACTION DESIGN AND MODELING METHODS

This chapter compares the three different approaches for developing traction systems that are explained in Chapter Two, Chapter Three and Chapter Four. All the three approaches discussed are within the conceptual phase of the design process. While prototyping, several traction concepts were developed that corresponds to the design step of finding solutions. After identifying solutions the final design is further taken to the next level of selecting working principles or refining solutions which also falls within the conceptual phase of the design. The validation step that is done using simulation based approach falls within the embodiment phase of the design process where the design is further optimized to refine results.

5.1 Comparison Criteria

All the three different approaches and the differences between each method within each of the three methods are presented in the previous chapters. This chapter compares and explores the strengths of each of the three modeling approaches available for designing traction systems.

5.1.1 Required Input Information

The required input information varies with each method we follow while designing traction systems. Traction based analytical modeling requires the understanding of tire-sand interaction and the mechanics involved with modeling tire, sand and its interaction. Analytical models require input data that is obtained through curve fitting [2]. The data for generating these curves are obtained from physical experiments [2,3,4]. Each analytical method uses a unique way for obtaining data for formulating the model. Simulation based approaches uses some of the popularly used sand models to model sand.

Modeling sand using simulation based approach needs analytical sand models. This shows that analytical models are used as an input for simulation based approach. Experimental data is being used for modeling sand which implies experiments are needed for sand models to be used as an input for simulations. Experiments are also conducted to validate the results obtained through simulations [8,34]. In developing analytical sand models, tri-axial compression tests were performed to model sand.

From the above scenario it is clear that experiments are needed for input information into both analytical and simulation based approaches. Considering prototyping based approach for modeling traction, the requirements on the design are needed to develop, test and refine the prototypes using experiments.

5.1.2 Time Scale

The time scale required for developing analytical methods is higher when compared to other two approaches. This may involve high level of expertise and in-depth research in studying mechanics between tire and sand. The research group at Clemson took 12 months to find an appropriate model that closely defines sand. These sand models were used as an input for modeling sand in simulation based approach.

The research group at Clemson took nearly 14 months to develop a full tire-sand interaction model. Still some experiments are being conducted to validate the sand models used in DEM. In case of developing sand bed for experiments and finding appropriate location for test rig it took 4 months for the undergraduate team. This proves that physical prototyping approach takes lesser time when compared to other two approaches even when working with less expertise from undergraduate students. Comparison of expertise is done in another section below.

5.1.3 Reliability of Results

Results obtained from the analytical models may not be accurate, as there are some assumptions that were made to avoid complexities associated with modeling sand and tire such as shear stress distribution and tire deflection. Even though research was done on developing analytical models for tire sand interaction, traction modeling is still under development [3].

Simulation based modeling techniques have demonstrated their ability to model tire-sand interaction in a detailed manner. FEM is the most widely used technique for modeling this interaction. Modeling tire-sand interaction through DEM is still under research which has a long way to go for modeling traction using DEM, due to its limited capabilities in modeling tire [8]. While simulation based modeling require a very good modeling expertise with the analyst, it may also require validation from experiments. The uphill tests help to find traction qualitatively which is a comparison of performance among various concepts tested. However, the reliability of tests is higher when tested in controlled environment as in the case of NASA Glenn tests.

5.1.4 Required Expertise

The required expertise for developing an analytical modeling is too high as the researcher needs to have a thorough understanding on the mechanics of tire, sand and its interaction. Simulation based modeling also require expertise on the simulation tool that is being used. Expertise is still required in understanding tire-sand interaction as the simulation based approach uses analytical modeling as an input. The results rely on the post processing and it does require expertise. In case of prototyping based approach, expertise required for building and testing prototypes may be low when compared to the other two approaches.

5.1.5 Flexibility to Adapt to New Traction Concepts

Adapting to new concepts requires a thorough understanding and the mechanics behind the geometric structures and materials developed while designing tread systems. This require a higher expertise and makes it lesser flexible to design new traction concepts when using analytical and simulation based approaches. Physical prototyping has the flexibility to design more new concepts with low level of expertise. In the uphill tests, there are 14 different concepts prototyped and tested within a span of 1 year. This may be difficult when using simulation based approaches, because the materials and geometric properties need to be well defined for the tread systems. When using analytical modeling this makes even difficult as the new material developed has its own theory that needs to be incorporated into the model.

5.1.6 Cost

The cost associated with developing analytical models is the research cost that may involve physical experiments to obtain data. This falls under fixed costs as the cost. Operating costs include the cost involved with obtaining literature from the previous researchers.

In simulation based modeling, fixed costs are more as the cost to obtain license for the software is high. Even the recurring and operating costs are also more because of the costs due to renewal of license and technical support from software provider.

In Prototyping approaches the fixed cost of setting up test rig may be higher or lower depending upon the testing environment. In case of uphill tests, it is lower when compared to NASA Glenn tests because the testing at NASA Glenn is performed in a more controlled environment. Later on recurring and operational costs may be lesser compared to simulation approach. But it will be higher than the costs associated with analytical modeling. The cost associated with funding the researcher is the same as the same person can perform all the three approaches.

5.1.7 Stage of Design Process

Analytical models and simulation based approaches fall within the conceptual and embodiment design phases respectively. However, simulation based approaches also be used in the conceptual phase of the design. Depending upon the type of the design problem, prototyping based approach can be anywhere in the design phase as needed [19]. This is one of the main motivations for this research as to find when prototyping is used, how it has an influence on the design and what factors has an influence to prefer prototyping approach as against simulation and analytical approaches. In the current research, Analytical modeling and prototyping falls within the conceptual phase of the design and the simulation based approach is used in the embodiment phase of the design.

5.1.8 Summary

Finally it has been found that when compared to analytical and simulation based approaches, prototyping approach can yield better results when designing complex problems such as the traction systems design as the research in sand-tire interaction using the other two approaches is under development. This raises the requirement of a procedure or a sequence of steps involved while finding solutions for design problems like traction systems. To conclude, all the different approaches are compared against the criteria described in Chapter One. Table 5.1 shows the high level comparison of all the three different approaches available for designing traction systems. This comparison shows that prototyping based approach is better. However, relying entirely on prototyping method proves to take more time and the costs involved with optimizing the design. This is another reason to develop a systematic design approach that could be used.

Table 5.1: Comparison of three approaches available for modeling traction

	Analytical Approach	FEM	Prototyping
Required input information	Medium	High	Low
Reliability of results	Low	Medium	High
Required Expertise	High	Medium	Low
Flexibility to adapt to new concepts	Low	Medium	High
Cost	Medium	Medium	Low
Stage of Design Process	Conceptual	Embodiment	Conceptual

In order to develop a systematic and optimized design method that could maximize the usage of strengths associated with each method a lower level of comparison is done. This comparison could help identify a systematic design method.

5.2 Method Working Principles

There are several possible combinations that are identified for proposing a design method for developing traction systems, from Table 5.2. The method should be in a way that there should be another method (or tool) to validate the results obtained from the method initially followed. This allows choosing a possible combination to choose a method from each of the three approaches.

Table 5.2: Summary of comparison of all the methods available for modeling traction

	Bekker's approach	Yong and Fattah's approach	Ravi and Godbole's approach	FEM	DEM	FE-DE method	Uphill tests	NASA Glenn traction tests
Required input information	High	High	Medium	Medium	Medium	High	Low	Low
	See 2.3.1			See 3.4.1			See 4.3.1	
Reliability of results	Low	Low	Medium	Medium	High	High	Medium	High
	See 2.3.2			See 3.4.3			See 5.1.3	
Flexibility to adapt to new concepts	Low	Low	Low	Medium	Low	Low	High	Medium
	See 2.3.4			See 3.4.5			See 4.3.5	
Cost	Low	Low	Medium	Medium	Medium	Medium	Low	High
	See 2.3.5			See 3.4.6			See 4.3.6	
Stage of design process	Conceptual			Embodiment			Conceptual	

From the combinations chosen, there are no analytical approach methods that can be used in designing traction systems. These combinations are made to choose in a way that the results can entirely be dependent on the chosen approach. This shows that modeling traction entirely based on analytical approach is not preferable. However, analytical models are used for input information into simulation based approaches and cannot be neglected.

CHAPTER SIX:
CONCLUDING REMARKS AND FUTURE WORK

From the identified possible combinations of steps involved in the design of traction systems, a new design method is recommended for the design of traction systems. The typically prescribed design method [19,18] makes use of analytical methods followed by simulation based approaches to design and finally use physical prototyping to validate the results obtained through simulations. The traction problem does not follow this conventional approach due to the lack of extensive modeling capabilities in simulations and weak developments in analytical approaches as well. This is a special case of problem that has few analytical models available to predict the interaction between tire and sand. From the literature review, it was found that there is a great lack of growth in the maturity of analytical models that help predict traction based on the tractive surface without making use of experiments or simulations. Conversely, in the study presented, designers were able to prototype and test fourteen different concepts and only two concepts were partially modeled using FEM. Modeling sand in DEM is still under development. This suggests need for this design problem to follow a new method that could enhance the design of traction systems.

A critical phase of design is conceptual design where several possible combinations of the design are identified and a final working procedure is suggested. Designing traction systems is a difficult task for the designers as they are challenged with limited developments in analytical modeling of tire-sand interaction modeling and, thus, traction systems. In order to propose a method several design approaches are evaluated and compared. The analytical, simulation and prototyping approaches presented are evaluated, using the models shown in Table 5.2, are evaluated against a set of criteria that could explain the advantages of using a particular approach or model. Modeling traction is difficult when using analytical models and simulation based models alone.

6.1 Possible Combinations

From Table 5.2, only one model can be chosen out of the three clusters: the three analytical models (columns 2-4) of which only one model out of the three models can be chosen, the three simulation models (columns 5-7), and the two prototyping methods (columns 8,9). Thus, only $1 \times 3 \times 2 = 6$ valid combinations for mixing analytical, simulation, and prototyping methods can be obtained. In Table 5.2, the model that was proved to be better compared to the others based on the criterion, as illustrated in Table 5.2 are highlighted. Thus, the best combination, out of the six illustrated above, can be obtained by combining the best candidate from each section, which is further illustrated as the proposed design method. The physical prototyping method as a whole is preferable while designing traction as seen from Table 5.2. Using this approach alone may not help understand the mechanics within tire and sand. It is important to understand the mechanics associated with the interaction modeling as it helps to identify and visualize the critical factors that govern traction. This understanding and visualization can be enhanced with a simulation based approach. Simulations enable the designer to observe each and every step, thereby helping to find the behavior of tire and sand individually. This understanding may be critical and detailed design of the tractive systems. The challenge remains in how to validate the simulation approach without expensive physical experimentation. Current study suggests that the use of prototyping methods over simulation and analytical based approaches is useful in exploring more concepts as seen from Appendix B:. Analytical modeling maybe used to design the design concepts through the theory involved with tire and sand modeling. However there are no models currently available to predict traction. This is evident from Table 5.1. Also, due to the limitations on current modeling capabilities of FEM and DEM, they are not being used for the initial design of the concepts In the section below, the actual design process that was followed in the case study are presented. This is followed by extensions to the method that could complete the design.

6.2 Actual Process Followed

The research group at CEDAR is mainly concentrated on improving capabilities of designing and modeling traction through developing analytical extensions to current tire-sand interaction models and computational models that could predict traction. Appendix B: shows the timeline of the project as it progresses.

The project was started in summer of 2008 comprising of two graduate students and a post-doctoral researcher guided by three faculty members. Preliminary studies were conducted to find the previous research progress in traction modeling. The group has also attempted to model tire-sand interaction using FEM [6]. Due to lack of expertise in modeling tire, an easier TWEEL™ tire model was chosen for modeling traction. Parameters/properties required for modeling sand were obtained from the literature [6]. DEM was introduced due to its potential in modeling sand in a detailed manner [35]. However, there is a lack in developments in modeling sand using DEM. In Appendix B:, the developments in FEM and DEM are shown separately dividing the tasks performed by each researcher. Considerable progress was made using FEM. However the attempts made to computationally models are still in development and no major developments were seen, as a result of which physical prototyping of traction systems to predict traction was chosen.

An undergraduate Creative Inquiry team (explained in Section 4.1) was introduced to the research group to perform a test protocol was developed by the students based on the project requirements. A sand bed was laid out within two months and tests were started. Initially four different traction concepts were prototyped and tested to quantify traction. The test setup, procedure and data collection techniques are described in Section Appendix B:. Uphill tests were performed to develop and test several prototyped traction concepts [21]. The prototyped traction concepts are shown in Figure 6.1. The procedures were refined in order to improve the reliability of the results. Ten new concepts were tested; some of which are integrated to improve the tractive ability of the design. After completing the tests and processing results, some of the highly performed concepts were chosen. This step has shown promising results. One of the concepts was filed as an invention disclosure that has shown outstanding results in uphill traction tests.

Astroturf

Coir-rug

Paddle wheel

Carpet mat

C&M Wire mesh

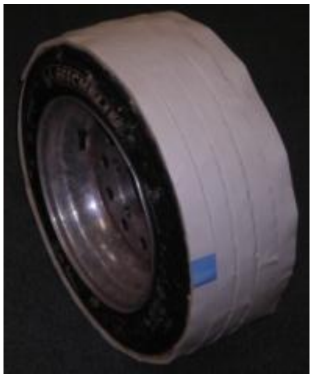
V-Shaped Grouser

Concave rubber

Aluminum Mesh

Traction tape

Snow chain



Foam Tape

Astroturf grouser

Gravel

Stiffer foam

Figure 6.1: Prototype concepts developed to test traction

The results of the tests performed using the prototypes concepts that are shown in Figure 6.1 are presented in Figure 6.2. From the results shown in Figure 6.2, concepts that are performed better in terms of slip are modeled in FEM to understand the behavior of the interaction between both tire and sand. Two of the concepts, foam tape and concave foam tape, were chosen based on their performance rankings for further development using simulations.

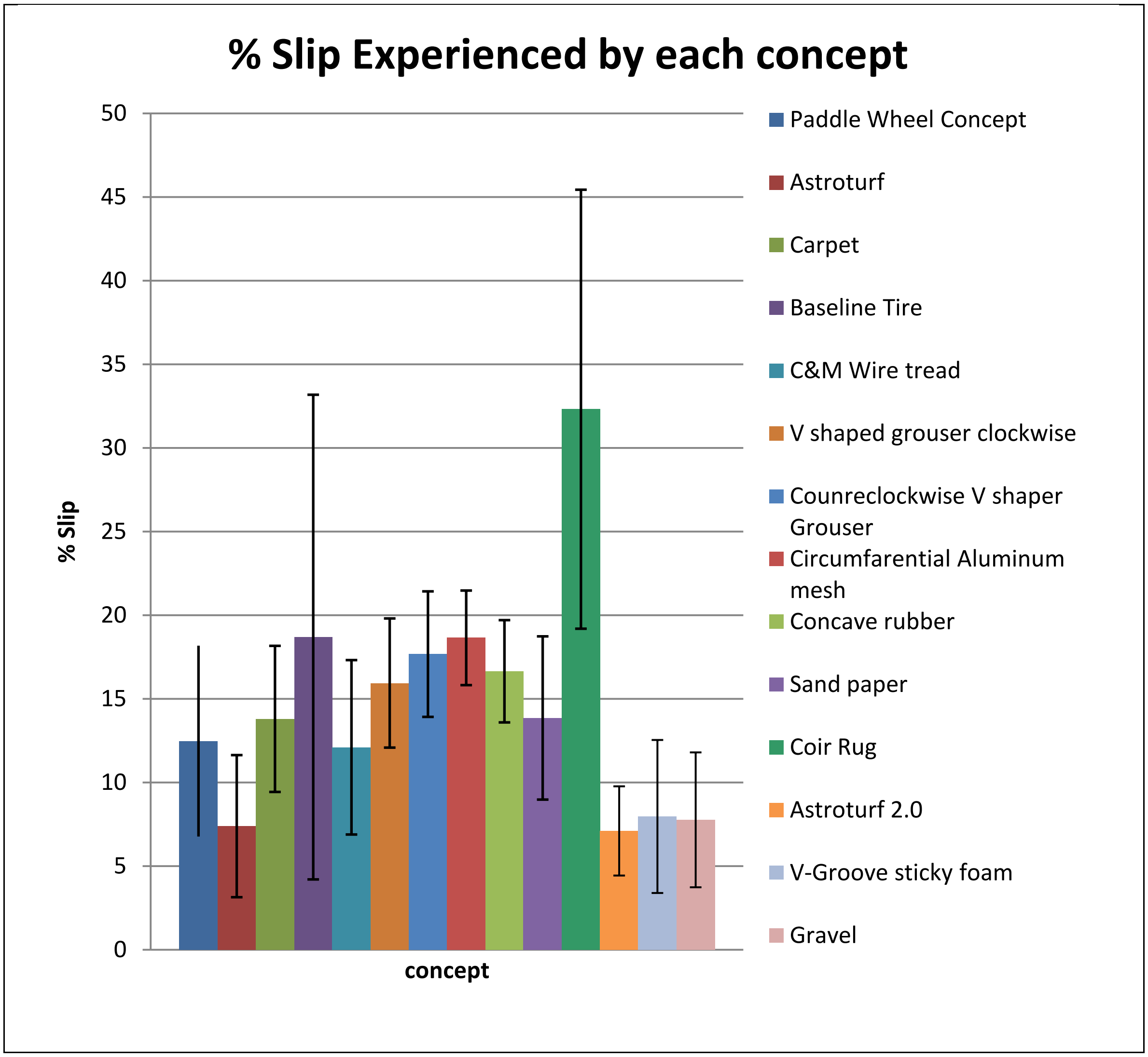


Figure 6.2: Results showing the percentage of slip experienced by each tested concept

Sand models developed based on Drucker-Prager cap plasticity theory were obtained from the available literature [23] and used to model sand. Due to difficulties in modeling pneumatic tires and to support the NASA lunar wheel development project, a TWEEL™ tire that was used for FEM modeling by the other two researchers was chosen for this behavior study in simulation. FEM modeling is used to help understand the behavior of sand and tire while interacting and also the mechanics between them.

Identification of this behavior helps the researcher to find the relation between contact pressures are governed by some of the design parameters and traction. After modeling the foam concept from the results obtained, it led to an inference that lower and uniform contact pressure profiles could generate better traction. This claim is still under investigation and has to be proved completely. Identifying these traction design parameters such as tread profile, material properties can help the designer to predict traction thus enables the creation of novel concepts.

Throughout this process, the prototyping approach has yielded faster results compared to any other approach. This can be inferred from the GANTT chart presented in Appendix B:. In modeling sand, the simulation group comprising of two doctoral students and a post-doctoral researcher took seven months to model sand while the Creative Inquiry (CI) team had setup the sand required for testing within two months. The CI team completed testing fourteen different tread concepts within eight months while the computational group has not yet shown valid results with the effect of tread systems on traction in over two years of work. As a result, the prototyping method is preferred over the other two approaches.

6.3 Suggested Extensions to the Process

A schematic representation of the method is shown in Figure 6.3. In this method shown in Figure 6.3, prototyping followed by refining the results is shown as step one. Step two would be the modeling of design using simulation based approach. FEM is used to model tire and sand.

Extensions for the method are suggested that could complete the design. After modeling traction using FEM, the model can further be optimized and the design is taken to the next step. In step three (Figure 6.3) the concept is further modeled using the more computationally intensive, but more comprehensive FE-DE traction modeling which is used as a validation tool for the optimization results obtained through FEM. In order to have a DEM model that is valid; experiments are needed to prove its validity. However, a valid FE-DE model is not achieved which can be seen from the project timeline chart in Appendix B:. To achieve this objective, experiments are needed to model sand using DEM. FE-DE traction modeling may yield more reliable results when compared to FEM modeling due to the sand modeling capabilities of DEM [33]. This has been discussed in section 3.4.3. However, optimizing the model in FE-DE modeling is not affordable in terms of computational cost. This design can be further validated by using analytical models that are to be developed as part of the objectives of the US Army sand tire-interaction modeling project. The objectives of the project are presented in section 1.1.1.

In this design method, a systematic approach has been presented to design traction systems. As physical prototyping has higher flexibility to design traction concepts, it has been suggested for the initial design. After obtaining qualitative results from the tests performed, the refined concept can be further modeled with FEM to help the designer in understanding the behavior of the concept. This, in turn, can support the optimization of the design allowing better design. At this point, the design enters the embodiment phase where the geometric and material properties are clearly defined. To model tire and sand using FEM, analytical models of sand and experiments that could help obtain material data of sand are needed. These models provide input data for modeling tire and sand. Physical experiments such as tri-axial tests are needed to obtain this data. Finally, the results obtained through FEM can be verified using FE-DE approach that could model sand and tire in a detailed manner. Analytical models developed may further be utilized to generate new concepts.

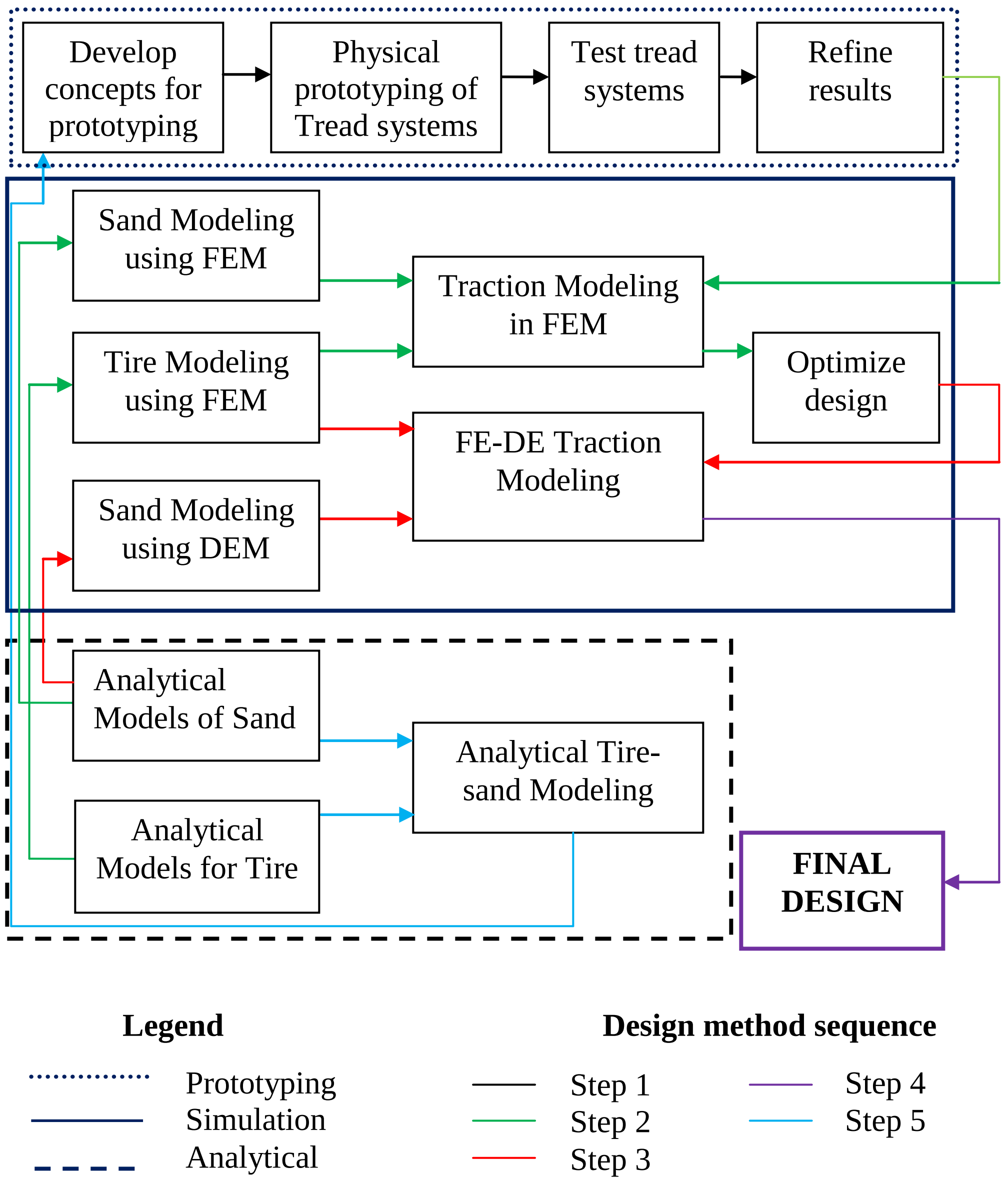


Figure 6.3: Proposed design method for designing traction systems

In this research, several modeling approaches available for designing traction systems are explored. From the available approaching techniques, a method that could essentially improve the design of traction systems has been suggested. The new design method could possibly increase the reliability of results and substantially reduce the cost and time of the design. Several criteria that could critically examine each of the models have been suggested while designing traction systems. These criteria basically are the tools that help validate each model with respect to the design. Chapter Two explained several analytical models that were developed by previous researchers and the comparison between each method is described. In Chapter Three, various simulation based approaches were studied and Chapter Four explains the different prototyping approaches that were used to perform experiments on the prototypes developed. In Chapter Five, all the three different approaches were compared and a possible combination that could enhance the design of traction system was suggested based on the research done. Finally, a design method is proposed based on the results obtained through comparison of the three modeling approaches and the recommendations made for the design of traction systems. As per the current developments, prototyping and FE modeling of traction is possible, but DE modeling of sand and FE-DE modeling of traction are still under development and requires further improvements in order for the proposed design method to be implemented completely.

The major take away from this thesis is the comparison of different modeling approaches against a set of criteria that determines the strengths of each approach. This helps the designers in making decisions required for designing traction systems effectively. An application study has been used to make comparisons among the approaches. Several analytical modeling techniques were discussed that are used in comparison. Current computational modeling capabilities of each technique were clearly outlined. It is shown that the current best practice of prototyping for concept exploration in tractive system design is preferred to the simulation and analytical studies. Further, it does not appear that without significant experimental efforts, these same simulation approaches will present themselves as viable design tools in the near future. Ultimately, this demonstrates that not all design problems should be addressed in analytical and computational approaches, and that structured prototyping is a viable and necessary design approach for these problems.

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APPENDICES

Appendix A: ABSTRACT

The objective of this research is to develop a design method for rapid exploration of traction concepts primarily for off-road vehicles. Different approaches available to achieve this objective are discussed and compared, such as computational, analytical, and physical methods. Computational approaches are based on simulations performed using Finite Element Method (FEM), Discrete Element Method (DEM), and combined Finite Element-Discrete Element (FE-DE) methods. Analytical approaches are based on closed form mathematical models developed by previous researchers based on the theory of plasticity. Physical approaches include fabrication and testing of prototypes at different levels of abstraction. This thesis compares these different approaches to design with respect to design process requirements of (1) timeliness, (2) cost, (3) required expertise, (4) accuracy of results, (5) flexibility to adapt to new designs and (6) stage of design process. This comparison is done both at a theoretical level and at an implemented level where each of the strategies are used to try and delineate between different classes of traction concepts. It is proposed that the physical prototyping approach should be the preferred approach with respect to these criteria. A new structured design approach is developed based on these findings to employ the different modeling schemes at stages of the design process that are most appropriate based on the technological maturity of this specific application domain.

Appendix B:<u>Gantt chart describing the project timeline</u>

This GANTT chart shows the timeline of the application study that has been used in the thesis. This chart also provides with the information regarding the major achievements made while the research is in progress.