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Research Article

A Fuzzy Simulation Model for Military Vehicle Mobility Assessment

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There has been increasing interest in improving the mobility of ground vehicles. The interest is greater in predicting the mobility for military vehicles. In this paper, authors review various definitions of mobility. Based on this review, a new definition of mobility called fuzzy mobility is given. An algorithm for fuzzy mobility assessment is described with the help of fuzzy rules. The simulation is carried out and its implementation, testing, and validation strategies are discussed.

1. Introduction

Recently there has been an increasing interest in various aspects of combat vehicles. Kempinski and Murphy studied the technical challenges of ground combat vehicles in [1]. Dattathreya and Singh discussed energy management strategies of combat vehicles in [2, 3]. Several authors have shown interest in predicting the mobility of military vehicles [4–6]. Mobility in general can be defined as the ability to move or to be moved freely and easily. Mobility in case of a ground combat vehicle is defined as, "vehicle's capability to move over a specified terrain, which is influenced by other environmental conditions such as weather" [4]. The basic function of a military combat vehicle is the transportation of the soldiers and weapons. According to a recent research on the cost/benefit analysis for the military combat vehicle, a 10% weightage is given for mobility by the ground combat vehicle analysis of alternatives [1]. Other main attributes obtained from the analysis are total life cost, lethality, survivability, and so forth, as given in [1] and shown in Figure 1.

Mobility has a different definition when viewed from a military vehicle's perspective. Such a definition in [7] for the mobility of military vehicle is "the ability to move freely and rapidly over the terrain of interest to accomplish varied combat objectives." From this definition, mobility is the freedom of movement in diverse terrains under different environmental conditions. Freedom of movement can be defined as good speed, less vibration, and so forth. A report by Unger discusses several aspects of mobility in [8]. Mobility assessment for the military vehicle is carried out in diverse terrains with different environmental conditions. It is necessary to test the mobility of a vehicles before using it on the field. The conventional methods for defining mobility revolve around pure mathematical modeling. Different mathematical models are available in the literature. Studies by Engineering Research and Development Center (ERDC) treat mobility as a function of trafficability [9]. A modified mathematical model based on trafficability studies for wheeled vehicles was also proposed in [10, 11]. A stochastic approach for predicting mobility is developed by González et al. [12]. Mobility model for ground vehicles based on soil-moisture can be found in [13]. An extended Kalman filter based mobility estimation for unmanned ground vehicles is presented in [14]. The tire-soil interaction simulation based on absolute nodal coordinate formulation (ANCF) is developed by Recuero et al. in [15]. A physics-based simulation model is discussed in [16]. This deals with light tracked vehicles, weigh less than 100 lb, operating on deformable terrains. These complex mathematical models focus on the effect of individual input attributes on the mobility. With the improvements in technology, newer

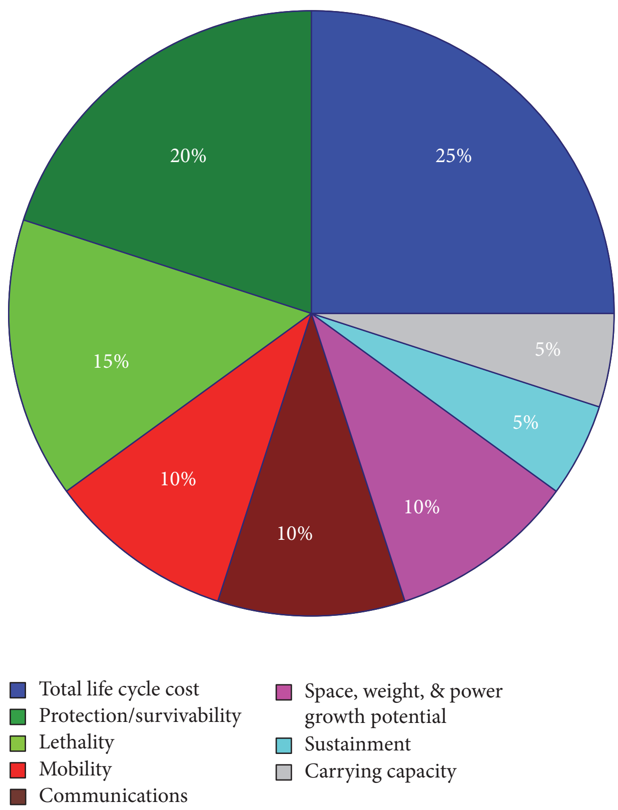

FIGURE 1: Ground combat vehicle (GCV) criteria and weighting from cost/benefit analysis in the Army's analysis of alternatives.

compact vehicles are being developed, and a generic mobility model which can be applicable to all these vehicles is still a challenge.

The military vehicle has to travel in different terrains under different environmental conditions. Thus, mobility is an important attribute for the combat vehicle. The mobility is subjective in nature, and, hence, an accurate measure of mobility is difficult to define. The terrain information which is one of the major attribute in predicting the mobility, is highly associated with uncertainty. It is difficult to define them mathematically and modify them later with the technological advances in the field of military vehicles and sensors. The best way to incorporate such uncertainties is by using linguistic variables. These linguistic variables can be used in the rules. These are developed from the expert knowledge. For example, if the vehicle is traveling in off-road, with slower speed, with higher vibration, then the mobility will be less.

In this paper, the authors are giving a brief review of the existing mathematical models for calculating mobility first. The mobility is then determined from a set of linguistic fuzzy rules. Two of the authors of this article gave an introductory idea of fuzzy logic in mobility [4]. The authors used the parameters such as speed and tire pressure as the input variables. These attributes are depending only on the vehicle. The mobility of a vehicle depends on the vehicle parameters as well as the environmental parameters and terrain of travel. In this paper, we are considering practical and implementable parameters such as type of vehicle, terrain information, speed, and weight of the vehicle as input parameters. Each of these attributes is defined using a set of membership functions and a rule set which relates these attributes to the mobility. Another advantage of using fuzzy based model is that the models can incorporate new findings by simply modifying the fuzzy rules. A procedure for fabricating an integrated chip from the fuzzy model is also discussed in this paper. This can be integrated in the military vehicle.

The organization of the paper is as follows. The attributes to be considered for calculating the mobility of a combat vehicle are discussed in Section 2. Section 3 gives a brief review of the existing mathematical methods for computing mobility. Section 4 gives a detailed explanation of the new fuzzy model proposed for calculating the mobility of a military combat vehicle. The procedure for implementing this fuzzy mobility model in a real-time application is also discussed in this section. The simulation results for hypothetical inputs and an overview of simulation based testing are given in Section 5. Section 6 gives the concluding remarks.

2. Main Attributes of Mobility

The attributes used to determine mobility in a normal vehicle may not be applicable to a military combat vehicle. Normal vehicles are commonly used on roads where they can move fast. Therefore, weight and speed are not prime concerns for them. In case of a military combat vehicle, the terrain of operation is entirely different. The mobility of the military combat vehicle is primarily based on the terrain. For instance, in military operations and peace keeping missions the time frame will not be short. They have to be there for a long time and have to move through narrow bridges, ruined roads, tunnels, and so forth. In such a situation the terrain, weight, and speed will be the key contributors in determining the mobility of the vehicle. It can be noticed that the attributes for mobility in different terrains will be different. We can address this problem by classifying the mobility into on-road and off-road mobility in general [1].

2.1. On-Road Mobility. The on-road mobility primarily depends on the type of the vehicle used. The achievement of required speed will be easy in the case of a wheeled vehicle. While focusing on military combat vehicles, a majority of them are tracked vehicles. The tracked vehicles are particularly designed for off-road operations. It is not always the case; they may have to travel on-road as well. Since the tracked vehicles are primarily designed for off-road operations, the rigorous operation of these kinds of vehicles for on-road operations may cause problems [17].

In on-road operation the wheeled vehicles give better mobility. For wheeled vehicles the dash speed is a function of horsepower and weight. Consequently, mobility of the wheeled vehicle increases with increasing horsepower and decreases with increasing the vehicle weight. Another important factor to be considered for wheeled vehicle is the friction between the tire and the road. This will vary with the environmental conditions such as snowy and rainy. Under these circumstances the mobility of the wheeled vehicles will decrease, and, thus, a good choice will be the tracked vehicles.

2.2. Off-Road Mobility. For military operations, off-road mobility is essential. A military vehicle is said to have good mobility if it is having good off-road as well as on-road mobility. The military vehicles are constrained to travel through off-road in many operations. This may be to avoid the danger of IEDs planted on raod, or sometimes there is no proper road at all. The statistics shows that the casualty is severe by IEDs compared to other kinds of attacks [18]. Thus, a military vehicle has to travel off-road intensively.

Compared to on-road mobility, off-road mobility is very complex and depends upon a number of factors. The measurability of these parameters is also challenging. The weight of the vehicle is taken as an attribute for off-road mobility, but not in a direct form. Here, the resistance of the surface is playing a vital role. This resistance is related to the type of surface and the ground pressure. The ground pressure is calculated as the ratio of gross weight of the vehicle to the surface area of ground contact with the vehicle. Another term used in literature to calculate off-road mobility is vehicle cone index (VCI) [7]. VCI is a function of soil strength and vehicle ground pressure. Priddy and Willoughby [19] define VCI as "the minimum soil strength necessary for a self-propelled vehicle to consistently make a prescribed number of passes in track without becoming immobilized."

The ground pressure and VCI are having an inverse relationship with mobility. Another important factor to be considered for computing the mobility of an off-road combat vehicle is the freedom of movement of the vehicle in that particular terrain. The freedom of movement depends on the minimum acceptable value of ground pressure or threshold ground pressure. This value varies for different combat vehicles. Another terminology given in literature is percentage no-go terrain [7]. It is a measure of immobile terrain and can be directly related to the ground pressure [20].

The tracked vehicles are preferred for off-road movement over wheeled vehicle, as the tracked vehicles provide greater surface area and, consequently, lesser ground pressure [21]. For better off-road mobility, there should be a higher horse power to weight ratio, low VCI, low ground pressure, and advanced suspension system for the vehicle.

3. Review of Mobility Models

There are different models available in the literature for predicting the mobility of a combat vehicle. Some of these are used as simulation models while others are mathematical models with complex equations. Some of the popular models available in the literature are discussed in this section.

3.1. Simulation Models. The simulation model is useful to understand the performance of the vehicle in different terrains and other conditions. It is always a good idea to test the mobility in the simulation model with expected attributes for a particular kind of military vehicle. The simulation models differ from each other on the attributes they are using for computing the mobility.

One of the most popular simulation models for analyzing mobility is NATO Reference Mobility Model (NRMM) [22]. There are three modules associated with NRMM: (1) vehicle dynamic module, (2) obstacle crossing performance module, and (3) primary prediction module. This model can predict the mobility of a combat vehicle for both on-road and off-road operations. The mobility is predicted as the effective maximum speed by analyzing different attributes. The disadvantage of NRMM is its limited range of operation. This model will not fit in complex terrains. Lessem et al. proposed NRMM adaptation to stochastic orientation [5], so that the model can be used for high resolution combat zones. In [15], a mobility simulation model based on tire flexibility and deformation of terrains is presented. This simulation model is limited to wheeled vehicles. A simulation model which focuses on small autonomous vehicles is discussed in [16]. This simulation deals with the obstacles in the path of vehicles and its impact on the mobility of the light autonomous vehicle and can simulate different terrains such as flat rigid terrain and deformable terrain.

The testing of simulation models can be performed by developing a set of virtual operating conditions. Such a framework is called Virtual Evaluation Test (VET) framework [6]. Evaluation suites like VET can be used for many simulation models to study mobility, stability, durability, and so forth. These frameworks evaluate the existing simulation models and provide a report on the progress of the model.

3.2. Mathematical Models. The Engineer Research and Development Center (ERDC) defines vehicle cone index in two different ways. One is one-pass vehicle cone index (VCI_1) and other is fifty-pass vehicle cone index (VCI_{50}) [9]. These values are calculated from the vehicle attributes such as weight and dimensions, by conducting multipass experiment, and are expressed in PSI [19]. As discussed earlier, the soil strength is an important parameter for calculating mobility. The International Society for Terrain Vehicle Systems (ISTVS) defines VCI as the "minimum soil strength in the critical soil layer, in terms of rating cone index for fine grained soils or in cone index for coarse grained soils, required for a specific number of passes of a vehicle, usually one pass (VCI_1) or 50 passes (VCI_{50})" [23]. VCI is a common parameter for both on-road and off-road analysis; hence, it can be used as a common parameter for defining mobility of all ground combat vehicles.

Other important factors used in the calculation of mobility are the mobility index (MI) and deflection correction factor (DCF) [19]. Combat vehicle mobility in soft soil terrain is defined by a parameter called "mean maximum pressure (MMP)." MMP was developed by UK MOD's Defence Science and Technology Laboratory (DSTL) [19]. According to this model, the mobility is calculated from the ground contact pressure. MMP is calculated by taking the average of magnitudes of maximum pressure at each wheel. Therefore, MMP is related to the dimensions of the wheel and also to the weight of the vehicle.

Modifications on original MMP calculations based on terrains and different sensors are discussed in [24–27]. An extensive review of mathematical modeling of mobility is best given by Priddy and Willoughby in [19]. Mobility index (MI) for wheeled vehicle is given in [19] as

$$\mathrm{MI} = \left(\frac{(\mathrm{CPF})(\mathrm{WF})}{(\mathrm{TEF})(\mathrm{GF})} + \mathrm{WLF} - \mathrm{CF}\right)(\mathrm{EF})(\mathrm{TF}), \tag{1}$$

where CPF is the contact pressure factor, WF is the weight factor, TEF is the traction element factor, GF is the grouser factor, WLF is the wheel load factor, CF is the clearance factor, EF is the engine factor, and TF is the transmission factor.

Now CPF can be calculated as follows:

$$\mathrm{CPF} = \frac{w}{0.5ndb}, \tag{2}$$

where n is the average axle loading in lb, n is the average number of tires per axle, d is the average tire outside diameter (inflated; unloaded) in in., and b is the average tire section width (inflated; unloaded) in in. Similarly, other parameters are given by

$$\mathrm{TEF} = \frac{10 + b}{100},$$
$$\mathrm{WLF} = \frac{w}{2000}, \tag{3}$$
$$\mathrm{CF} = \frac{h_c}{10},$$

where h_c is the vehicle minimum clearance height in in.,

$$\mathrm{GF} = 1 + 0.05c_{\mathrm{GF}}, \tag{4}$$

where $c_{\mathrm{GF}} = 1$, if tire chains are used or 0 if not.

$$\mathrm{EF} = 1 + 0.05c_{\mathrm{EF}}, \tag{5}$$

where $c_{\mathrm{EF}} = 1$, if PWR < 10 hp/ton or 0 if not.

$$\mathrm{TF} = 1 + 0.05c_{\mathrm{TF}}, \tag{6}$$

where $c_{\mathrm{TF}} = 1$, if manual transmission or 0 if automatic.

$$\mathrm{WF} = c_{\mathrm{WF1}}\frac{w}{1000} + c_{\mathrm{WF2}}, \tag{7}$$

where $w < 2000$ lb $\Rightarrow c_{\mathrm{WF1}} = 0.553$ and $c_{\mathrm{WF2}} = 0$; $2000 \le w < 13{,}500$ lb $\Rightarrow c_{\mathrm{WF1}} = 0.033$ and $c_{\mathrm{WF2}} = 1.050$; $13{,}500 \le w < 20{,}000$ lb $\Rightarrow c_{\mathrm{WF1}} = 0.142$ and $c_{\mathrm{WF2}} = -0.420$; $20{,}000 \le w < 31{,}500$ lb $\Rightarrow c_{\mathrm{WF1}} = 0.278$ and $c_{\mathrm{WF2}} = -3.115$; $31{,}500 \le w \Rightarrow c_{\mathrm{WF1}} = 0.836$ and $c_{\mathrm{WF2}} = -20.686$.

A deflection correction factor (DCF) is required to account the effect of tire deflection on VCI performance [19].

$$\mathrm{DCF} = \left(\frac{0.15}{\delta/h}\right)^{0.25}, \tag{8}$$

where δ is the average hard-surface tire deflection expressed in in. and h is the average tire section height (inflated; unloaded) in in.

The analysis and test data of different vehicles under different environments were studied. Based on the past 50 years' data, the researchers came up with an expression in which the VCI_1 is a function of MI and DCF [19].

$$\begin{aligned} &\mathrm{MI} \le 115 \Longrightarrow \\ &\mathrm{VCI}_1 = \left(11.48 + 0.2\mathrm{MI} - \frac{39.2}{\mathrm{MI} + 3.74}\right)\mathrm{DCF}, \\ &\mathrm{MI} > 115 \Longrightarrow \\ &\mathrm{VCI}_1 = \left(4.1\mathrm{MI}^{0.446}\right)\mathrm{DCF}. \end{aligned} \tag{9}$$

A stochastic model which relates the geometry of the surface and soil type to the mobility map was proposed by González et al. in [12]. The mobility map produced in this model shows the surface elevation at each location. In [13], the effect of soil-moisture on the off-road mobility is studied based on satellite soil-moisture data. It is found that the type of vehicle, the environmental conditions, and so forth will significantly vary the soil-moisture and, thus, the off-road mobility. Another approach for mobility estimation of unmanned ground vehicle, which uses a Gauss-Markov state space dynamic model and a first-order semi-Markov model along with an extended Kalman Filter, is discussed in [14]. This approach can give a real-time path planning for the unmanned ground vehicle.

4. Proposed Method

Mobility models explained in Section 3 consist of very complex mathematical equations. The modification of these models is very difficult and cumbersome. Mobility is subjective and depends on the user comfortableness. A fuzzy based model gives the freedom for the designer to improve the model without much effort by taking feedback from the user.

4.1. Fuzzy Logic Outline. Fuzzy logic is a technique which uses the degree of truth instead of discrete values such as 0 or 1. Fuzzy logic also uses "linguistic" variables such as *low, medium,* and *high*, along with numerical variables for the calculations. The relationship between inputs and outputs is given by some simple statements rather than complex mathematical equations [28]. Fuzzy based systems are widely used in many real-time applications [29].

Let A be a fuzzy subset. We can represent A as

$$A = \frac{\mu}{y}, \tag{10}$$

where μ is the degree of membership of y in fuzzy subset A. If A is having more number of membership functions associated with it then A can be represented as

$$A = \sum_{i=1}^{N}\frac{\mu_i}{y_i}, \tag{11}$$

where μ_i is the degree of membership of corresponding y_i in A. Here, the + sign indicates the union of different

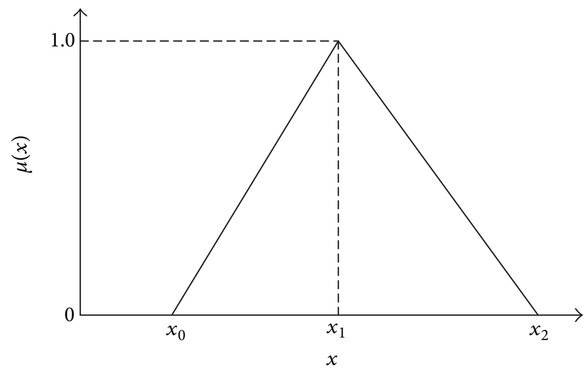

Figure 2: Triangular membership function.

memberships. The membership degree is having a value between 0 and 1. For a fuzzy subset A,

$$\mu(x) = 0 \quad \text{if } x \notin A,$$
$$\mu(x) = 1 \quad \text{if } x \in A, \tag{12}$$
$$\mu(x) \in (0,1) \quad \text{if } x \text{ possibly in } A, \text{ but not sure.}$$

There are different types of membership functions available in Fuzzy. Triangular function and Gaussian distribution function and so forth are some of the commonly used membership functions. A triangular membership function is shown in Figure 2. The degree of the membership function $\mu(x)$ is given by

$$\mu = \begin{cases} 0, & \text{if } x \le x_0, \\ \dfrac{x - x_0}{x_1 - x_0}, & \text{if } x_0 \le x \le x_1, \\ \dfrac{x_2 - x}{x_2 - x_1}, & \text{if } x_1 \le x \le x_2, \\ 0, & \text{if } x_2 \le x. \end{cases} \tag{13}$$

4.2. Fuzzy Mobility Model. The block diagram of the proposed fuzzy mobility assessment model is shown in Figure 3. The proposed scheme consists of three parts. The first is the input section. The inputs can be analog signals directly from the sensors such as speed and weight of the vehicle in the proposed method. The other inputs are vehicle and the terrain types. The data is either preset or entered manually by the operator.

The second part of the proposed method is the fuzzy logic controller. The fuzzy logic controller consists of four different sections. The first section is a fuzzifier. The fuzzifier converts the numerical value obtained from the input signal into fuzzy sets. That is, the input variables are represented in terms of their degree of membership for different membership functions. The second section is a rule base. The rule base contains all the rules for the fuzzy model. The rules use if-then structure to relate the input fuzzy sets with the output fuzzy sets. The third section is an inference engine. The inference engine takes the input fuzzy sets and decides which rules should be applicable from the rule base and creates the output fuzzy set. The last section is a defuzzifier which takes the fuzzy set output created by the inference engine and produce the corresponding output.

Table 1: Linguistic parameters for the weight variable.

Weight in lb.	Linguistic parameter
10,000–30,000	Low
30,000–50,000	Medium
50,000–70,000	High

Table 2: Linguistic parameters for the speed variable.

Speed in mph	Linguistic parameter
0–20	Low
20–40	Medium
40–60	High

Table 3: Input and output variables for fuzzy model.

Input variables				Output variable
Terrain	Vehicle type	Weight	Speed	Mobility
Dry	Wheel	Low	Low	Low
Wet	Track	Medium	Medium	MediumLow
Snow		High	High	Medium
Sand				MediumHigh
				High

The fuzzifier consists of membership functions. The membership functions are expressed using linguistic parameters. Important attributes considered for calculating mobility of the military vehicle are type of vehicle, terrain information, speed of the vehicle, and the weight of the vehicle. The weight and speed of the vehicle are numerical values. They are converted to linguistic parameters such as *low, medium,* and *high*. In the proposed example, the weight of a vehicle varies between 10,000 and 70,000 lb. This range is divided into three sections. The linguistic parameters for the weight are shown in the Table 1.

Linguistic parameters for the speed are defined in Table 2. In this case the normal range is from 0 to 60 mph. Likewise, the membership functions for the mobility of the military vehicle are also expressed by 5 different linguistic parameters. The input and output linguistic variables used for the proposed fuzzy model can be summarized as shown in Table 3. Different types of membership functions are available in fuzzifier. A trigonometric membership function is used for the proposed model. The arrangement of membership functions for the speed of military vehicle and normalized mobility output is shown in Figures 4 and 5, respectively. The fuzzifier converts the numerical value of input to fuzzy set which is a set of membership function and corresponding degree of membership. For example, if the speed is 26 mph, then, the fuzzifier will represent it by *low* with a degree of 0.2

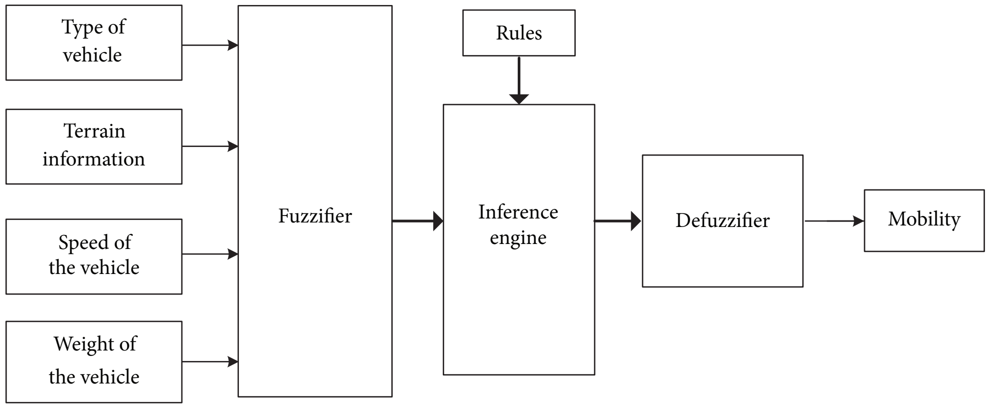

Figure 3: Block diagram of the proposed mobility assessment method.

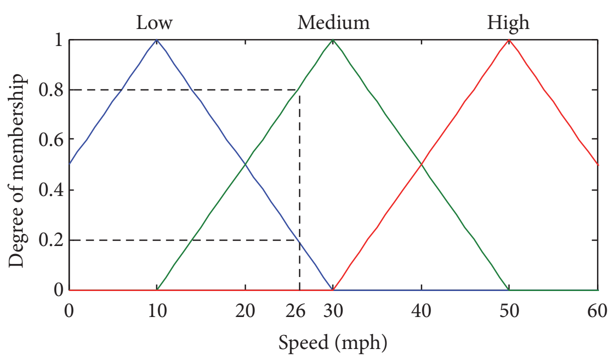

Figure 4: Speed input variable partitions using triangular functions.

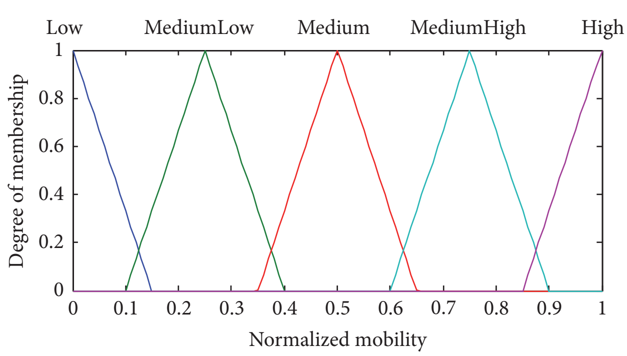

Figure 5: Military vehicle mobility variable partitions using triangular functions.

and *medium* with a degree of 0.8 and *high* with a degree of zero.

After studying the characteristics of the military vehicle mobility defined by different mathematical models, it is possible to define a set of approximate rules for the mobility assessment. The linguistic parameters are used in deriving appropriate rules for the proposed fuzzy logic model. These rules are made up of simple logic employing IF, AND, OR, and NOT operators. The mobility output is categorized as *Low, MediumLow, Medium, MediumHigh,* and *High*. In other words, the input and output parameters of the proposed models are fuzzy sets. The rules used to calculate the mobility are simple sentences with some logical expressions. The list of all the rules used in the fuzzy logic model is listed in Table 4. Here, each input membership function is connected with AND statement. Such as the following:

(i) If terrain is *dry* and vehicle type is *wheel* and weight is *high* and speed is *low* then mobility is *low*.

(ii) If terrain is *dry* and vehicle type is *wheel* and weight is *low* and speed is *high* then mobility is *high*.

For each input combination, the mobility output is defined using these rules. The inference engine selects the rules that are applicable for the input values and produce the corresponding output fuzzy set. The fuzzy set is then converted to a crisp value by a defuzzifier. The surface diagram of the mobility output with respect to different set of inputs is given in Figure 6. The simulation of such a fuzzy model can be tested using Matlab simulation. The military vehicle mobility output obtained in such a simulation will also be in a normalized form.

After the simulation, the fuzzy rules can be converted to a Verilog code. This is simple and straightforward. The Verilog program can be written in a behavioral level with *if* statements. The linguistic parameters used in the fuzzy rules are converted to digital numbers while writing the Verilog code. For instance, the speed input variable linguistic parameters *low, medium,* and *high* can be converted to 00, 01, and 10, respectively.

After completing the Verilog code, it should be tested with some tools. The simulation and hardware testing for the code are possible. The simulation of the Verilog code can be done using Cadence NClaunch or some other software which can do the simulation. For hardware testing, the Verilog code can be implemented on an FPGA. If both the simulation and hardware results are satisfactory, the next step is to design the fuzzy chip using this Verilog code.

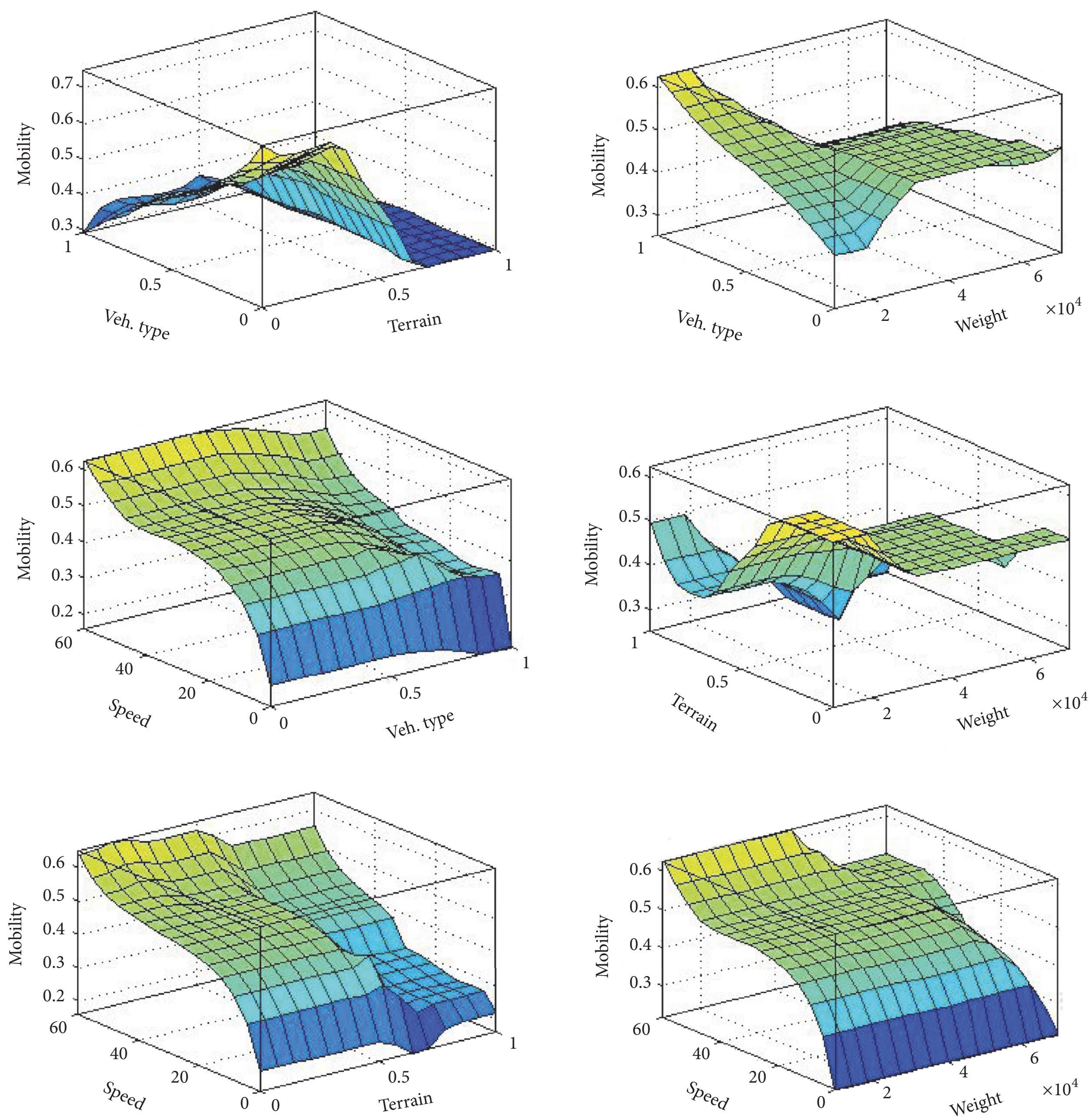

Figure 6: Surface plot obtained for different set of inputs (vehicle type-terrain, vehicle type-weight, vehicle type-speed, terrain-weight, terrain-speed, and weight-speed) versus mobility.

For building the chip from the Verilog code, the first step is to convert the behavioral level code to a netlist or gate level code. This can be done by Cadence synthesizer. After completing the gate level code, a layout for the circuit can be produced using Cadence Encounter. The Encounter uses some standard cell libraries to complete the layout. Once the layout is ready, the next step is to do the padding for the chip. A Cadence Virtuoso software is used for this purpose. After completing the padding the design can be sent to the manufacturer to fabricate the final chip. The process flow chart for the proposed scheme is shown in Figure 7.

Once the chip is ready to use, it can be installed in the military vehicle and the mobility output can be displayed to the driver in a range of 0 to 100%. The inputs for the chip can be from a sensor and the output can be displayed inside the vehicle which is shown in Figure 8 [30]. For a

Table 4: Fuzzy logic rule set.

Terrain	Veh. type	Weight	Speed	Mobility
Dry	Wheel	Low	Low	Low
Dry	Wheel	Low	Medium	MediumHigh
Dry	Wheel	Low	High	High
Dry	Wheel	Medium	Low	MediumLow
Dry	Wheel	Medium	Medium	MediumHigh
Dry	Wheel	Medium	High	High
Dry	Wheel	High	Low	Low
Dry	Wheel	High	Medium	MediumHigh
Dry	Wheel	High	High	High
Dry	Track	Low	Low	MediumLow
Dry	Track	Low	Medium	Medium
Dry	Track	Low	High	MediumHigh
Dry	Track	Medium	Low	Low
Dry	Track	Medium	Medium	MediumLow
Dry	Track	Medium	High	Medium
Dry	Track	High	Low	Low
Dry	Track	High	Medium	MediumLow
Dry	Track	High	High	MediumLow
Wet	Wheel	Low	Low	Low
Wet	Wheel	Low	Medium	Medium
Wet	Wheel	Low	High	MediumHigh
Wet	Wheel	Medium	Low	MediumLow
Wet	Wheel	Medium	Medium	MediumHigh
Wet	Wheel	Medium	High	MediumHigh
Wet	Wheel	High	Low	Low
Wet	Wheel	High	Medium	Medium
Wet	Wheel	High	High	MediumHigh
Wet	Track	Low	Low	MediumLow
Wet	Track	Low	Medium	MediumHigh
Wet	Track	Low	High	MediumHigh
Wet	Track	Medium	Low	Low
Wet	Track	Medium	Medium	MediumLow
Wet	Track	Medium	High	Medium
Wet	Track	High	Low	Low
Wet	Track	High	Medium	MediumLow
Wet	Track	High	High	Medium
Snow	Wheel	Low	Low	Low
Snow	Wheel	Low	Medium	MediumLow
Snow	Wheel	Low	High	Medium
Snow	Wheel	Medium	Low	Low
Snow	Wheel	Medium	Medium	MediumLow
Snow	Wheel	Medium	High	Medium
Snow	Wheel	High	Low	MediumLow
Snow	Wheel	High	Medium	Medium
Snow	Wheel	High	High	MediumHigh
Snow	Track	Low	Low	MediumLow
Snow	Track	Low	Medium	Medium
Snow	Track	Low	High	MediumHigh
Snow	Track	Medium	Low	Low
Snow	Track	Medium	Medium	MediumLow
Snow	Track	Medium	High	Medium

Table 4: Continued.

Terrain	Veh. type	Weight	Speed	Mobility
Snow	Track	High	Low	Low
Snow	Track	High	Medium	MediumLow
Snow	Track	High	High	MediumLow
Sand	Wheel	Low	Low	MediumLow
Sand	Wheel	Low	Medium	Medium
Sand	Wheel	Low	High	MediumHigh
Sand	Wheel	Medium	Low	MediumLow
Sand	Wheel	Medium	Medium	MediumLow
Sand	Wheel	Medium	High	Medium
Sand	Wheel	High	Low	Low
Sand	Wheel	High	Medium	MediumLow
Sand	Wheel	High	High	Medium
Sand	Track	Low	Low	MediumLow
Sand	Track	Low	Medium	Medium
Sand	Track	Low	High	MediumHigh
Sand	Track	Medium	Low	Low
Sand	Track	Medium	Medium	MediumLow
Sand	Track	Medium	High	Medium
Sand	Track	High	Low	Low
Sand	Track	High	Medium	MediumLow
Sand	Track	High	High	MediumLow

Table 5: Simulation results of fuzzy mobility model.

Terrain	Veh. type	Weight	Speed	Mobility
Snow	Track	30000	20	0.3617
Sand	Track	30000	40	0.4782
Dry	Wheel	50000	50	0.8089
Wet	Wheel	70000	20	0.4077
Dry	Wheel	20000	60	0.9139
Sand	Wheel	50000	40	0.3568
Dry	Track	25000	45	0.5469

given operational scenario, the parameters of the vehicle are constant. However, the speed, terrain, and weight may vary depending on a mission. The fuzzy electronic chip can estimate instantaneous mobility of the military vehicle and display it on the vehicle.

5. Testing of the Fuzzy Based Method

The simulation of the proposed fuzzy mobility model in Matlab is carried out with different set of input combinations. The results are given in Table 5. Furthermore, the simulation of the proposed method is done by setting the weight of the vehicle to 30,000 lb and varying the speed from 0 to 50 mph. The mobility of the vehicle is plotted under different terrains with track and wheel vehicle. The graph is shown in Figure 9.

The validation of the results can be done in different ways. One way of testing is by comparing the simulation model with user data obtained from similar real life experience. The proposed method can be verified by taking the feedback from vehicle users. Their feedbacks can be used to optimize the model by comparing the user data with the outputs of the fuzzy model for the same set of inputs.

In the second method, the human factor is introduced in predicting the mobility of a vehicle. The block diagram of the simulation model is given in Figure 10. This diagram shows the flow of mobility prediction from the visual information of a vehicle mobility in a computer simulation. The different attributes that decide the mobility are given as input to the computer model and the computer model gives simulation display, where the given type of vehicle moves through a particular terrain with specific weight and speed.

5.1. Overview of Simulation Based Testing. The cost for making hardware is massive. To improve the accuracy of the hardware, more emphasis should be given to modeling and simulation. For the simulation based testing, Autonomie software can be used [31]. This software has a large database of vehicles, and these data can be used to make the simulation more effective. Autonomy helps to simulate the model with plug-and-play functionalities. The models built in standard format can be added to the autonomy software for simulation. The library and tested models available with the software package make the simulation more accurate.

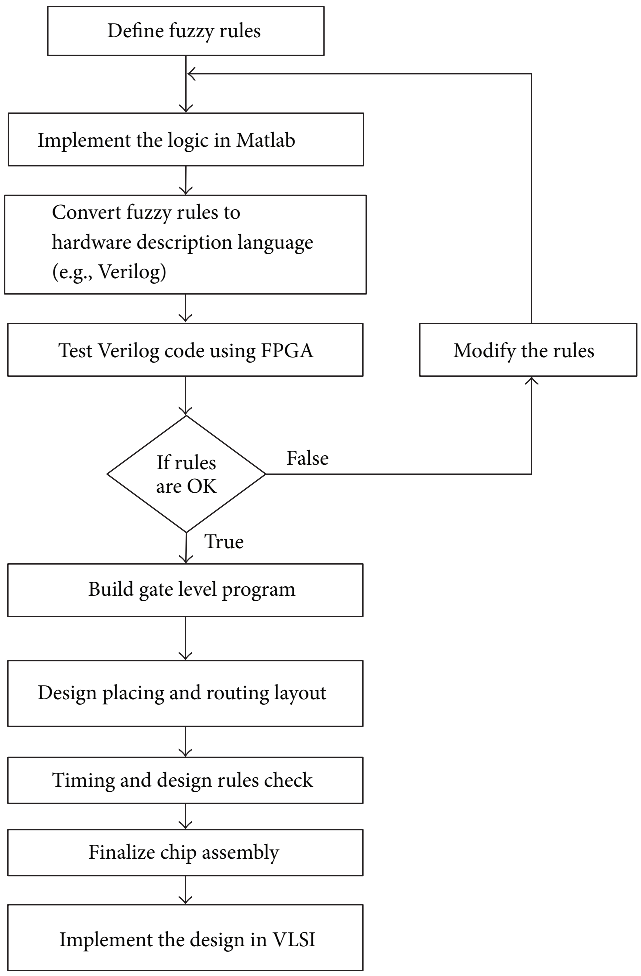

FIGURE 7: Flowchart showing the design of proposed fuzzy model chip.

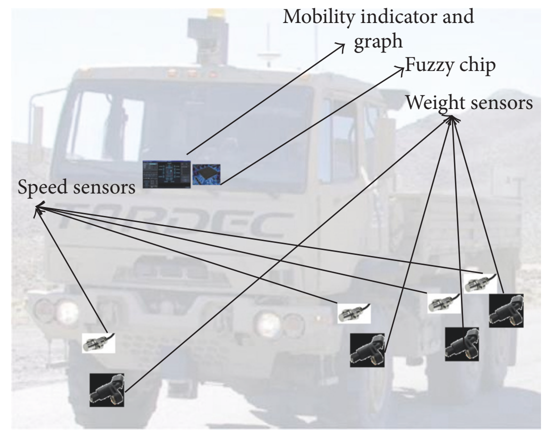

FIGURE 8: Diagram showing the position of sensors and displays in a military vehicle.

The algorithm for testing the the fuzzy model can be summarized as follows:

(i) The Simulink software can be used to create the simulation of the vehicle by using the proposed fuzzy model. This simulation model can be converted to S function which can be used in the Autonomie software.

(ii) Some signal formatting is necessary while integrating the simulation S function with the Autonomie software. Some of the vehicle parameters are already available in the Autonomie software and the *s*-function can use these input variables.

(iii) Interface the modified *s*-function with the Autonomie software. The Autonomie software has the ability to identify the *s*-function parameters. Normally the input and output variables used with the *s*-function may not be documented in the standard format. The Autonomie converts these into a standard format and ensures compatibility of input output variables with the rest of the vehicle. Instead of *s*-function it is also possible to use the vehicle simulation programs such as TruckSim.

(iv) Run the simulation with a set of input data. For example, the performance can be tested with a tracked vehicle in a snow terrain with a medium weight and medium speed. The simulation is repeated with different set of inputs.

(v) For each simulation, let the vehicle users view the simulation and take their comments on vehicle mobility. The mobility can be described in linguistic parameters such as *Low, MediumLow, Medium, MediumHigh,* and *High*.

(vi) From the set of inputs getting from the vehicle users, compute a correlation between the mobility data provided by the vehicle user with the data calculated by the fuzzy chip.

(vii) Change the rules of the fuzzy model if required and repeat the experiment to achieve optimum results.

6. Conclusion

In this paper, the existing mobility models of military vehicles are reviewed. These methods use complex mathematical equations and, hence, are difficult to adapt. A fuzzy based mobility assessment model is developed here. Different attributes which affect the mobility such as terrain, vehicle type, speed, and weigh of the vehicle were taken as inputs. Mobility is defined in a range from 0 to 100%. The fuzzy mobility assessment model is simulated with different input combinations. The implementation of the proposed model in an integrated chip is discussed. The algorithm for testing the proposed fuzzy model is presented. The fuzzy based mobility model gives the designer the freedom to optimize the model without much effort by taking feedback from the user. The paper essentially describes an approach which can possibly be used for developing a chip to access the mobility of military

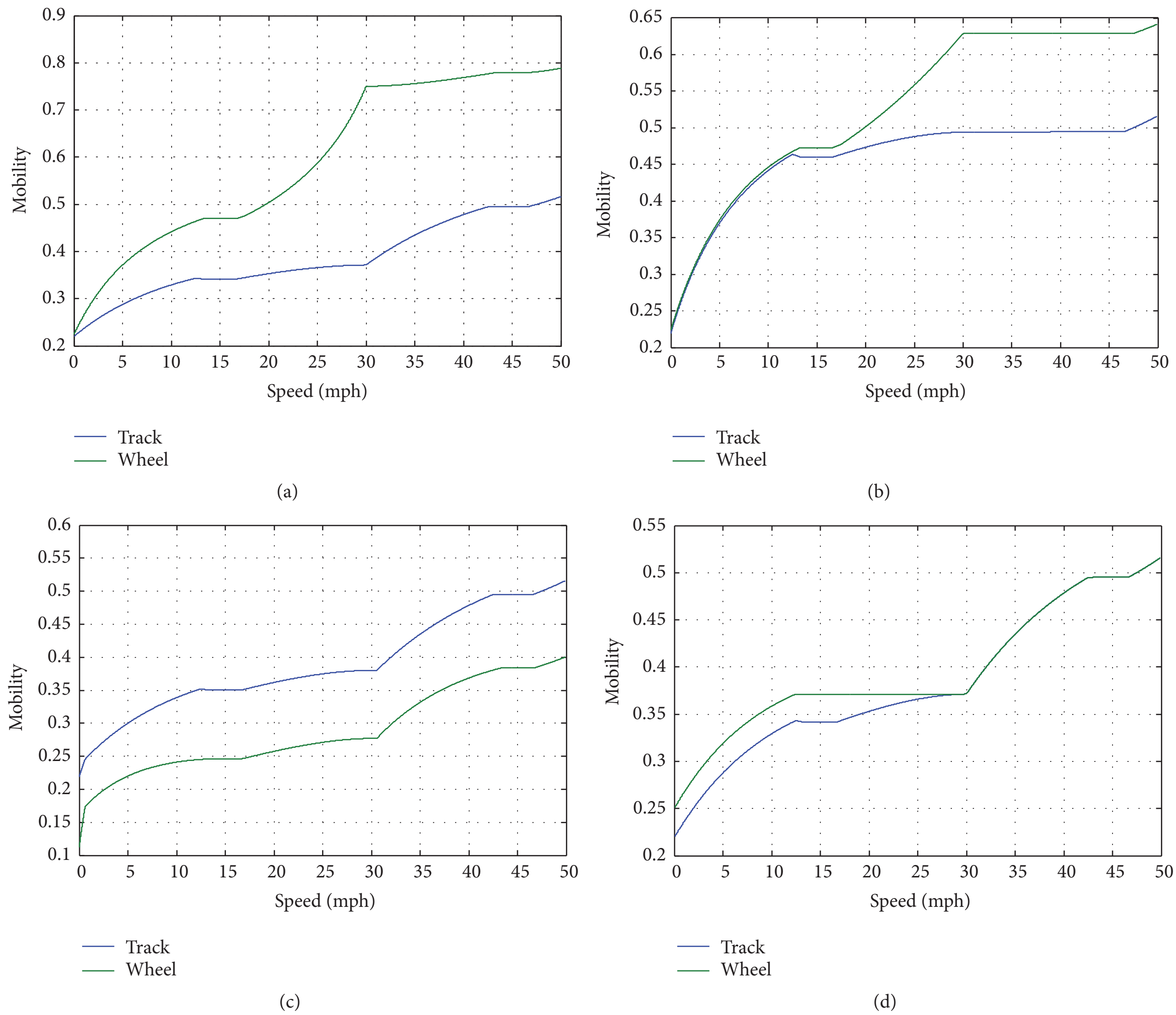

Figure 9: Speed versus mobility graph for track and wheel vehicles with weight = 30,000 lb in different terrains: (a) dry, (b) wet, (c) snow, and (d) sand.

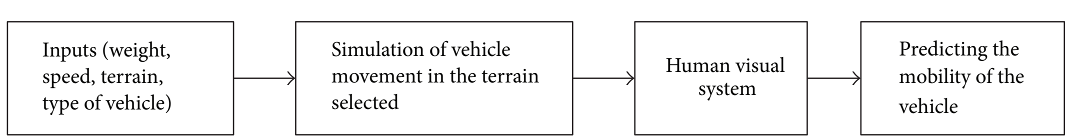

Figure 10: Block diagram showing the testing of the proposed method.

vehicle. More work is needed to modify the model so as to implement a real life chip which would be used ultimately in the military vehicle.

Disclosure

Unclassified: Distribution Statement A. Approved for public release; distribution is unlimited.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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