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INDIVIDUAL SOLDIER LOADS AND THE EFFECTS ON COMBAT PERFORMANCE

by

Jeremiah M. Sasala

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Thesis Advisor:	Imre L. Balogh
Co-Advisor:	Curtis L. Blais
Second Reader:	Anthony D. Smith

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The goal of this research is to determine how load affects the performance of individual Soldiers. In this context, performance means speed; speed is estimated (not predicted) through the use of a mathematical model. This model calculates speed given a number of factors, including body weight, load, terrain surface, and terrain steepness. The mathematical model produces realistic movement rates and further reveals several important relationships. First, when load increases, speed decreases. Second, as the terrain becomes more difficult to traverse, speed also decreases. Finally, loads can become so heavy that movement stops altogether. In other words, this model recognizes that there is a point at which any additional load is simply too much. As part of this research, the model's usefulness is demonstrated using an A* search algorithm that determines the path of least resistance when considering human capabilities; this means that the quickest path can be identified, and not just the shortest. The model also provides a means to examine the trade-offs between added weight and added capabilities within combat simulations. Ultimately, this model demonstrates how load and terrain affect individual-level performance.

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INDIVIDUAL SOLDIER LOADS AND THE EFFECTS ON COMBAT PERFORMANCE

Jeremiah M. Sasala
Captain, United States Army
BS, United States Military Academy, 2008

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June 2018

Approved by: Imre L. Balogh
Advisor

Curtis L. Blais
Co-Advisor

Anthony D. Smith
Second Reader

Peter J. Denning
Chair, Department of Computer Science

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ABSTRACT

The goal of this research is to determine how load affects the performance of individual Soldiers. In this context, performance means speed; speed is estimated (not predicted) through the use of a mathematical model. This model calculates speed given a number of factors, including body weight, load, terrain surface, and terrain steepness. The mathematical model produces realistic movement rates and further reveals several important relationships. First, when load increases, speed decreases. Second, as the terrain becomes more difficult to traverse, speed also decreases. Finally, loads can become so heavy that movement stops altogether. In other words, this model recognizes that there is a point at which any additional load is simply too much. As part of this research, the model's usefulness is demonstrated using an A* search algorithm that determines the path of least resistance when considering human capabilities; this means that the quickest path can be identified, and not just the shortest. The model also provides a means to examine the trade-offs between added weight and added capabilities within combat simulations. Ultimately, this model demonstrates how load and terrain affect individual-level performance.

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I. INTRODUCTION

Within the military modeling and simulation community, it is common knowledge that combat simulations do not model meaningful differences among human entities. These simulations have little ability to represent the physical, mental, or emotional readiness within a simulated human being. These variables are either ignored or they are assumed to be insignificant when considering the larger picture of full-spectrum operations, and this prevents simulations from accurately representing reality. Modeling and simulation (M&S) professionals have confidently asserted that there is very little difference between unmanned systems and human systems within a variety of simulations, which leads to "very limited (if any) representation of the variations in human performance from one individual to another and, perhaps more importantly, across different force sides" (Blais, 2016, p. 9). The fact that these problems have not yet been fully addressed does not make them insignificant. On the contrary, examinations of these types of issues may be far overdue.

Surprisingly, the idea to improve simulated representation of humans is nothing new. Members of the M&S community have argued that "there is an enormous gap between the current state of the art in human and organizational modeling technology on the one hand and the military needs on the other" (Mavor & Pew, 1998, p. 17). It has been twenty years since this statement was made. Given that the human elements of simulations can be greatly improved, then the next step is to choose a starting point for this effort. A logical place to begin is to integrate the effects of the surrounding environment on the individual Soldier. Often these effects are simply overlooked. The lack of focus on the human element seems paradoxical. Human beings are responsible for accomplishing military objectives. It is not weapons, equipment, technology, or even autonomous systems that close with and destroy the enemy. This is why the individual Soldier is ultimately regarded as the key factor in determining who wins and who loses on the modern battlefield (Fefferman et al., 2015). Thus, the human element cannot be ignored and it becomes necessary to model individuals and their interactions with the world around them.

A. PROBLEM STATEMENT

Simulations must provide a means to better understand the tradeoffs that directly affect individual Soldiers. More specifically, the tradeoff between enhanced capabilities gained by certain equipment and its corresponding weight is a very important question worth further consideration. The reason to examine this tradeoff is clear: loads that Soldiers must carry continue to increase over time and have nearly doubled since Vietnam (Knapik, Reynolds, & Harman, 2004). Loads in Afghanistan often exceed 45 kg. (≈100 lbs.) and "a load of 45 kg constitutes well over 50% of the body's weight" (Weyand, 2014, p. 4). The loads we ask the modern infantryman to carry onto the battlefield are staggering. This is no easy task for even the fittest individuals.

As more and better technology becomes available, Soldiers are asked to carry heavier loads into combat. Existing research must become the foundation for a model that explains the relationship between loading and combat performance. Ultimately, carrying heavy weight negatively affects a Soldier's ability to fight and has historically resulted in death or military losses (Knapik et al., 2004). Since the consequences of additional loading can be extremely severe, it is imperative that modelers incorporate the effects of loading. This better represents reality by including human limitations. Furthermore, loading up a platoon with every weapon and resource imaginable does not make them more lethal. In fact, it has quite the opposite effect. The next step is to identify key ideas and studies in order to create an effective model that determines the effects of load and terrain.

B. THESIS SCOPE

A primary objective of this research is to simulate realistic movement rates with respect to added loading. In regard to this application, realistic means the ability to account for the most important factors that determine an individual's movement rate. These most important factors contribute to two distinct sub-models: a sustained movement rate and a rapid movement rate. Sustained movement rate is the rate at which the Soldier travels as they cover large distances and are not in enemy contact. This rate represents the normal speed when walking from one place to another, which decreases as the Soldier's load gets heavier. Rapid movement rate is the maximum speed that a Soldier can move while running, which is also affected by the amount of loading relative to his body weight. This speed is important to consider when the unit comes under fire or needs to move a short distance quickly.

In order to accurately reflect reality, both walking and running speeds need to be represented. Furthermore, variability in human performance should be represented which can be achieved by assigning each entity distinct characteristics from every other. Entities must have a uniquely assigned body mass and an individual load amount. These characteristics enable variation from one entity to another, which more accurately represent reality. As one team of researchers noted, “many models will execute a task the same way every time and for every equivalent agent. In the real world, this is not the case” (Ritter et al., 2003, p. 17). Variation increases how closely the model mimics reality. As the fidelity of the model increases, so does its value. Admittedly, increased levels of detail can decrease the usefulness of any model. In this instance, however, accounting for these specific variations in human performance is absolutely necessary.

Ultimately, the goal of this research is to better represent human limitations within entity level modeling. More specifically, the desired end state is a model that estimates speed while accounting for load and terrain. Within this thesis, the literature review discusses the most applicable concepts within this area of focus. Immediately following the literature review is a discussion of the mathematical model. This discussion shows that the model provides an appropriate estimation of human performance. Since the model provides a means to estimate speed in realistic circumstances, the next step is to demonstrate the model’s usefulness within an application. The application is an algorithm that finds optimal paths over three-dimensional terrain. The algorithm considers not only distance, but time as well. Finally, this research closes with recommendations for future work and overall conclusions.

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II. LITERATURE REVIEW

It is not difficult to find research that addresses how loading affects performance. The real challenge lies in selecting the most useful research that can be used to build an effective and realistic model. Many studies, at first glance, seem useful and easy to understand. They can also be groundbreaking and noteworthy across multiple disciplines. Often, however, they do not provide recommendations for incorporating their results into some sort of model useful for simulations. Likewise, Silverman, Johns, Cornwell, and O'Brien (2006) state, "Too often, factors described in the human performance literature are only roughly quantified. Informed judgment and/or additional testing is required to parameterize factors" (p. 141). Prior research discussed within this literature review provides excellent analysis, useful insights and detailed evidence to support all of the findings, but it is still up to the modeler to determine a method for implementing this knowledge.

A. MODELING AND SIMULATION

The purpose of this section is to introduce several concepts that are common to much of the M&S community. These ideas transcend their specific focus and can be applied to a much broader range of topics. To begin, the goal of artificial intelligence is to produce behavior that mimics human behavior with high fidelity (Russell et al., 2010). Likewise, the goal of this thesis is to develop a model capable of producing reasonable movement rates (i.e., speeds that actual humans can be expected to travel). While the model needs to accomplish this specific goal of replicating human behavior, the model also must serve a purpose. Leaving the realm of artificial intelligence, one specific model's purpose is to examine force characteristics by comparing losses during battle (Hughes, 1995). More specifically, Hughes develops a salvo model that examines ship lethality and survivability during naval battles.

Essentially, Hughes' model is a system of equations that can compare friendly and enemy forces; this comparison is made possible by measuring the rate at which each side imposes and resists casualties (Hughes, 1995). Hughes' salvo model investigates the tradeoffs between several ship attributes which include: staying power, offense, defense and the number of ships. Through the use of this model, Hughes is able to conclude that the number of ships is the best predictor of who wins and who loses. Ultimately, this study demonstrates that building one massive battleship is inferior to a fleet of smaller less powerful ships. Hughes' model makes a compelling case for real world decisions based on his mathematical model. The Hughes' salvo model is relevant to the purpose of this thesis as it allows complex situations to be better understood and provides a way to effectively assess force readiness.

The Department of Defense Modeling and Simulation Coordination Office defines emergent behavior as "a behavior or property that appears when a number of simple entities (agents) operate in an environment, forming more complex behaviors as a collective" ("M&S Glossary," n.d.). "Simple" in the context of a Soldier means that not every single detail is included in order to represent them as a unique individual. If a Soldier's ability to carry additional loading can be represented, then this may lead to changed unit behaviors (i.e., the platoon would have to wait for those falling behind). Demonstrating that simple individual actions lead to emergent organizational behavior, Brown (2000) uses a combat simulation with a limited set of behaviors for two opposing forces. Within Brown's simulation, individual entities have few, yet very specific goals. These entities are very basic representations of combat forces that only have a limited set of attributes. Nonetheless, Brown observes that simulated combatants behave similarly to what is expected in the real world. He states that "avoiding the enemy while maintaining an aggressive drive towards the goal kept losses minimal. This leads to the notion of maneuver warfare and maintaining tempo on the battlefield" (Brown, 2000, p. 108).

The types of individual Soldier entities generated for Brown's (2000) thesis could not be more different from humans. They have not received training in fire and maneuver. They have no sense of patriotism, duty or loyalty. They have simply been given a set of goals or parameters that drive behavior. These variable parameters determine whether entities seek to kill the enemy, group with allies or simply travel to a specific location. By adjusting these basic parameters, collective behaviors begin to emerge that mimic reality. The parameters developed within Brown's thesis represent a very effective compromise between scenario complexity and producing realistic behaviors. These simulated combatants produce recognizable behavior, but the differences from an actual human being are vast. The challenge is to find the most effective parameters that can produce realistic behavior. Load and terrain are likely two of the most significant determinants of collective, realistic behavior.

B. LOAD CARRYING CAPACITY OVERVIEW

One specific research group, which includes military officers, concludes that excessive loads can lead to fatigue, injury or even death (Knapik et al., 2004). Furthermore, they observe that loads have only increased as time has passed. According to their research, loads have more than tripled since the US Civil War. The importance of their study is made clear: loads tend to increase over time and their effects can be severe. The authors provide an excellent overview of load distribution, injuries associated with load carriage and other impacts of carrying added weight. Knapik et al. (2004) provide an excellent review of how loading can affect movement and this study serves as a solid foundation to understand this particular topic. However, the authors do not recommend techniques for incorporating this information into a model or simulation.

The Australian Government developed a handbook for leaders that specifically addresses the load carrying ability of the individual (Drain, Orr, Attwells, & Billing, 2012). The authors of this guide discuss the many factors that affect load carrying ability: these factors include energy expenditure, speed, load distribution, terrain, climate, altitude, and even nutrition. Overall, this work by Drain et al. (2012) presents the information that is most important to members of dismounted organizations This study serves as an excellent foundation to understand the many factors affecting load carriage. However, this is a planning guide for military service members and does not easily translate into something useful for a model.

C. FACTORS INFLUENCING MOVEMENT RATE

A particular advantage of studying load carriage is that the overall effect on movements is easy to determine. Increased loading results in decreased speed: more specifically, “load and speed have a generally inverse relationship whereby increases in load reduce the speed at which load carriage tasks are completed" (Drain et al., 2012, p. 37). Any formula or function developed to represent this relationship must show decreasing speeds as loads are increased. To model a Soldier's ability to carry added weight, it is necessary to develop a system of inputs and outputs. The outputs are the individual movement rates across a military organization or formation. The primary input is the load to be carried, but other factors also determine the speed at which an individual Soldier can move. These factors include body mass, excessive loads, load distribution, physical fitness, terrain, and weather.

1. Body Mass

According to Harman and Frykman (1992), body size and composition are two key determinants of load carriage capacity. Their work demonstrates that larger individuals frequently have an increased ability to move faster with heavier equipment. There are exceptions to this general rule. Harman and Frykman make it clear that excess fat causes individuals to move more slowly. The authors plainly state, "It can be seen that fatness is associated with slower load carriage. Higher lean body mass is associated with faster load carriage" (Harman & Frykman, 1992, p. 111). Thus, the relationship between increased movement rates and increased size only exists when individuals maintain healthy body weights. Harman and Frykman also explain that smaller, leaner individuals often have the advantage when it comes to running, sit-ups, and push-ups. The authors state that load carriage tasks, however, favor an individual with more muscle mass.

Undeniably, Soldiers who are larger perform better on ruck-marches than Soldiers who are lighter or smaller (Harman & Frykman, 1992). As a result, a key determinant of movement rate is body mass (Drain et al., 2012). More specifically, there exists a strong relationship between increasing amounts of fat free mass and an increased capacity to carry loads (Knapik, Staab et al., 1990). A review of eight separate studies shows that healthy body mass (e.g., fat-free mass or muscle mass) is a universally excellent predictor of load carrying capacity (Dijk, 2009). In regard to this research, the effect of a specific load is determined by comparing the mass of the load to the mass of the Soldier. Essentially, the pack that a Soldier needs to carry is not felt the same by each and every individual. A certain weight to some is very heavy, while to others it may feel reasonable or perhaps even comfortable for them to carry. For both models within this thesis, this relationship is largely explained by the size of the Soldier conducting the movement.

2. Excessive Loads

After interviewing US Soldiers who fought in Grenada, Dubik and Fullerton (1987) conclude that, "In the tropic heat of Grenada, excessive loads not only led to poor fighting, but in some cases, to no fighting at all" (p. 39). Now, the challenge is to develop a method to define where any additional weight may simply be too much. Extremely heavy loads, defined as 70% or more than maximum load carrying capacity, can very much limit the amount of time that Soldiers can conduct a movement (Koerhuis, Veenstra, van Dijk, & Delleman, 2009). Koerhuis et al. use max load carrying capacity to predict loads that are essentially unbearable. Not only do the authors determine the loads that are too heavy, but they also determine the limited duration that excessive loads can be endured. Table 1 presents the results of this study.

Table 1. Maximum Load Carrying Capacity (MLCC). Adapted from Koerhuis et al. (2009).

	70% MLCC	**80%MLCC**	**90%MLCC**
Mean Absolute Loads ± standard deviation (lbs)	159.8 ± 16.5	178.6 ± 19.4	205.7 ± 22.3
Mean Endurance Time ± standard deviation (min)	40.9 ± 17.2	24.5 ± 7.4	17.7 ± 5.8

Table 1 illustrates that loads around 150 lbs. are extremely difficult to carry and clearly limit the ability of a Soldier to move with that load (Koerhuis et al., 2009). Koerhuis et al. further demonstrate that there is an associated time limitation that decreases as the load increases. The efforts of Koerhuis et al. are corroborated by personal testimony from Grenada as one Soldier claimed, "We attacked to secure the airhead. We were like slow-moving turtles. My rucksack weighed 120 pounds. I would get up and rush for 10 yards, throw myself down and couldn't get up. I'd rest for 10 or 15 minutes, struggle to get up, go 10 more yards and collapse" (Dubik & Fullerton, 1987, p. 39).

3. Load Distribution

Load distribution is evaluated by determining the following two attributes: where a particular load is centered and that load's corresponding moment of inertia (Hasselquist, Bensel, Norton, Piscitelle, & Schiffman, 2004). According to Hasselquist et al. (2004), "moment of inertia (MOI) of a body describes the distribution of mass about a specified axis of rotation and, therefore, is the inertial property that represents a body's resistance to angular acceleration" (p. 1). As a result, this same study states that higher MOI values represent loads that are more difficult to move. Hasselquist et al. further prove that the loads with the highest mass do not always have the highest MOI, therefore it is important to consider how the load is packed. This study provides detailed equations to calculate MOI and in-depth explanations for all of their findings. This level of detail, however, is unnecessary for the model developed in this thesis.

Indeed, there are techniques to move heavy objects that are better than others: carrying items using the hands, feet or thighs results in significantly more energy expenditure than using the torso (i.e., using a backpack or rucksack) (Knapik et al., 2004). The optimal positioning for load distribution within a pack is the top part of the pack as near to the body as possible (Drain et al., 2012; Hasselquist et al., 2004). Position within the pack, however, is not the only means of maximizing efficiency while carrying a load. Making adjustments to hip, shoulder and chest straps can serve to maximize mobility and to minimize discomfort (Knapik et al., 2004). The position of a load may significantly impact the ability to move, but developing a model that can define load distribution in detail is well outside the scope of this thesis. This issue is dealt with in Chapter III, Section A, "Assumptions."

4. Physical Fitness and Training

Without question, increased levels of physical fitness can greatly enhance an individual's ability to move farther and faster while carrying heavy loads. Training for road marches includes a variety of techniques (e.g., cardio with and without loading, or weight training) and all of them serve to increase the capacity to move more quickly with additional loading (Dijk, 2009). Deliberately training for road marches is crucial, but the frequency of this training is also a very important element to consider: at least two road march training sessions per month are needed to increase road marching capability (Knapik, Bahrke, Staab, Reynolds, & Vogel, 1990). Moreover, load carriage specific training is most beneficial when it occurs at least once a week (Knapik, Harman, Steelman, & Graham, 2012). Accounting for physical readiness is a key component of Chapter III Section E, “A More Adaptive Model.”

5. Terrain and Weather

With regard to terrain, gradient and surface characteristics can greatly inhibit movement (Drain et al., 2012). Gradient is a measure of the steepness of the terrain, whereas surface characteristics describe conditions that can impede movement such as snow or sand (Pandolf, Givoni, & Goldman, 1976). Another important factor to consider is altitude. When working at higher altitudes, Soldiers ought to have a 10-14 day acclimatization period because sudden changes in altitude can reduce performance and can even cause injury or illness (Department of the Army, 2017). The effects of weather can also play a significant role. Both high and low temperatures can negatively impact the Soldier’s ability to conduct movements, while precipitation (e.g., snow and rain) can make the ground more difficult to walk on and can even cause loads to become heavier when they become wet (Drain et al., 2012). The challenge is to develop a model that accounts for the most meaningful effects of terrain and weather.

D. ESTIMATING MAX SPEED

The US Army wrote an entire publication dedicated to dismounted movements and determining maximum movement rates for a military formation (Department of the Army, 2017). This specific publication, Army Techniques Publication (ATP) 3-21.18, offers a number of useful tools and guidelines to any leader planning a movement on foot. This same publication provides recommendations for max speed given a variety of conditions which include load, distance, surface characteristics and even visibility. Maximum speed recommendations can be a useful starting point for anyone planning a dismounted operation. However, ATP 3-21.18 is not extremely useful from a modeling perspective. This publication mostly applies to groups of Soldiers and is not intended to determine the effects on any one individual. The facts and figures presented in this publication are essentially averages. While averages are useful, they cannot be used to create a model that shows variability in human performance.

Alternatively, Theodore. R Hayes (1996) conducted a study to determine the max speed that an individual Soldier can move given various circumstances. This study determines max sustainable speeds given temperature, humidity, terrain grade and terrain type. Hayes' work relies heavily on the equation developed by Pandolf et al. (1976), but he misses a powerful capability within this equation. Hayes claims that as, "the Pandolf equation is not directly solvable for speed, an incremental approach was used to determine the speed which produced the maximum metabolic rate" (1996, p. 3). Chapter III within this thesis, however, demonstrates that the Pandolf equation is solvable for speed. Hayes oversight reduces the usefulness of his study; all of his data is in lengthy tables and complex charts that would be extremely difficult to incorporate into a computer program. Furthermore, Hayes does not account for load or body weight. His work is missing several key components and cannot be used to effectively model human performance.

E. SUSTAINED MOVEMENT RATE

Ideally, one equation would relate all the factors that influence movement rate and would be validated through experimental testing. Pandolf et al. (1976) introduce such an equation along with validation results, which links many of the factors that impact movement rate:

$$M = 1.5W + 2.0(W+L)(L/W)^2 + \eta(W+L)[1.5V^2 + 0.35VG] ,$$

which calculates energy expended (M), given body weight in kilograms (W), load in kilograms (L), a terrain factor (η), speed in meters per second (V) and steepness of the terrain or gradient (G). The terrain factor (η) within this equation deals with certain characteristics of the ground surface. According to Pandolf et al., the terrain factor can be used to represent a variety of surfaces such as blacktop (η = 1.0), dirt road (η = 1.1), heavy brush ($\eta = 1.5$), swampy bog ($\eta = 1.8$), loose sand ($\eta = 2.1$), and snow of different depths ($\eta = 2.5 - 4.1$).

A key purpose of any literature review is to identify areas where experts within a certain field tend to agree (Knopf, 2006). With this in mind, the equation of Pandolf et al. has greatly contributed to the works of many other researchers and is always referenced as a trusted place to begin any load carriage study (Dijk, 2009; Drain et al., 2012; Harman & Frykman, 1992; Hayes, 1996; Knapik et al., 2004; Koerhuis et al., 2009; Weyand, 2014). The prominence of the work of Pandolf et al. is likely due to a 0.96 correlation between predicted and measured energy expenditure (Pandolf et al., 1976). The Pandolf equation calculates energy, however, and not speed. If energy consumption is known or considered constant, then it is possible to solve for speed. The process of solving for speed is illustrated in a later section using this equation.

Despite its trusted reputation, the Pandolf equation has certain limitations within a military setting (Drain, Aisbett, Lewis, & Billing, 2017). According to Drain et al. (2017), "the Pandolf load carriage equation does not accurately predict the metabolic rate of contemporary military load carriage" (p. S108). Drain et al. (2017) argue that this inaccuracy is partly due to differences regarding load distribution: while the Pandolf equation deals strictly with backpack loads, in their study "load was distributed between hands (weapon, 4.7 kg), feet (combat boots, ~2.0 kg) and the torso (body armour, webbing, backpack)" (p. S107). Load distribution is one issue, but the authors of this study further claim that the Pandolf equation is accurate only between certain movement rates. Additionally, Drain et al. (2017) claim that the equation seems to misrepresent the true nature of increases in energy expenditure: metabolic rate does not increase in a straight line, but seems to grow faster as it grows larger. Overall, the authors of this study bring up valid points and their contributions must be a component of future work. However, the goal of this research is to provide a means to estimate speed, and not predict it. As a result, the limitations described by Drain et al. (2017) do not prohibit the use of Pandolf's equation.

F. RAPID MOVEMENT RATE

While a great deal of research addresses load carrying and the effects on Soldier performance, much of this data is not designed to translate directly into a model of any type. Many studies examine specific hypotheses in an effort to answer pointed research questions, and the authors often provide large amounts of data to convince readers of their findings and conclusions. Still, studies are rarely designed to build exact frameworks for modeling and simulation. Peter Weyand provides an exception to this general rule, with the development of the following equation:

$$V_L = C_1 \times (L / W_b) \times V_{UL} \ ,$$

which calculates max speed (V_L) given body weight (W_b), load (L), and max speed without loading (V_{UL}), where C_1 is "a coefficient describing the load-induced decrements in speed resulting from fractional additions to the body's weight" (Weyand, 2014, p. 9).

Weyand's equation (2014) is useful for determining the speed for an individual entity. This equation is appropriate only in certain instances: when the unit faces incoming direct or indirect fire, moves to treat or evacuate a casualty, or moves to catch up with the rest of the formation. Of course a period of rest is necessary before the Soldier can move at this rate again. Moving for short periods of time with no rest in between would quickly come to represent a very long sprint. For the purposes of incorporating this equation into a simulation, a brief duration is a time that does not exceed ninety seconds. Further limitations may also be necessary. For example, the period of rest must be equal to or greater than the period of exertion (i.e., a Soldier must slow to a walk for a period of time at least equivalent to the time they were moving at max speed).

III. THE MATHEMATICAL MODEL

As previously discussed, Pandolf et al. (1976) provide an equation that accurately predicts energy expended, given load, body mass, terrain characteristics and speed. The challenge now becomes converting this equation into a form that solves for speed. Figures 1 and 2 illustrate how the Pandolf et al. equation is capable of calculating speed.

1. $M = 1.5W + 2.0(W + L)(L / W)^2 + \eta(W + L)[1.5V^2 + 0.35VG]$

2. $M - 1.5W - 2.0(W + L)(L / W)^2 = \eta(W + L)[1.5V^2 + 0.35VG]$

3. $\dfrac{M - 1.5W - 2.0(W + L)(L / W)^2}{\eta(W + L)} = [1.5V^2 + 0.35VG]$

4. $1.5V^2 + 0.35GV - \dfrac{M - 1.5W - 2.0(W + L)(L / W)^2}{\eta(W + L)} = 0$

Figure 1. Initial Steps to Solve for Speed

The equation in step four is now in the general quadratic form of:

$$ax^2 + bx + c = 0 \ .$$

Now, it is possible to apply the quadratic formula in order to solve for speed. Figure 2 shows the final operations that transform this equation into a means of calculating speed.

$$4.\quad 1.5V^2 + 0.35GV - \frac{M - 1.5W - 2.0(W+L)(L/W)^2}{\eta(W+L)} = 0$$

$$5.\quad ax^2 + bx + c = 0$$

$$6.\quad x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$7.\quad V = \frac{-0.35G \pm \sqrt{0.35G^2 - 4(1.5)\left(-\frac{M - 1.5W - 2.0(W+L)(L/W)^2}{\eta(W+L)}\right)}}{2(1.5)}$$

Figure 2. Solving for Speed Using Quadratic Formula

Again, the fourth step shows the equation in the quadratic form, while the fifth step simply shows a generic quadratic equation for a direct comparison. At this point, the corresponding components can be substituted into the quadratic formula: the quadratic formula is shown in step six. As seen in the seventh and final step, speed is now a function of environmental and human characteristics. This equation uses varying elements of terrain, load, and human factors as inputs. After combining all of these variables, speed is the output for a simulated human entity. The adapted form of the Pandolf et al. (1976) equation accounts for a great deal of variability in the environment. This equation also demonstrates performance variation between individual Soldiers: Soldiers with different body weights do not move at the same speed given similar circumstances. Through the use of this new equation, a wide range of factors help determine individual movement rates.

A. ASSUMPTIONS

Load (L), body weight (W_b), and terrain characteristics (η, G) are inputs directly from a given scenario: these enable the original equation to calculate energy very accurately (Pandolf et al., 1976). In order to use the speed equation, the original Pandolf equation must first calculate energy expenditure. Because energy expenditure is a function of five separate variables, the next step is to decide on characteristics for a baseline energy expenditure (M). To begin, the first component to establish a baseline performance standard is a reasonable speed (V): 2.5 kilometers per hour is considered a maintainable rate for durations of over twelve hours, even when moving with a load (Department of the Army, 2017). Consequently, the speed to determine a baseline energy expenditure is 2.5 kilometers per hour (km/h) or an equivalent 0.7 meters per second (m/s). The components of the baseline performance standard address terrain, which reflects an environment consisting of zero incline (G = 0) and a walking surface that is free of obstruction (η = 1.0). The final step to determine a baseline performance standard requires each load (L) for any simulated entity to be exactly half that of his body weight (W).

Given these baseline performance parameters, calculating energy expenditure becomes a function that is driven by realistic expectations of human performance. The load is equal to half the body mass, the movement rate is 0.7 m/s and the terrain is easy to navigate. This ensures that calculated energy expenditures will not exceed human capacity. Ultimately, this allows all entities to have a personalized energy expenditure. The next step is to determine if this set of assumptions replicates real world scenarios. To begin, larger individuals have greater load carriage capacity than equally fit individuals who are smaller (Harman & Frykman, 1992). Therefore, the mathematical model needs to return increasing speeds as body mass increases. This comparison requires similar terrain and similar loads with the only variation being the mass of the individual. Results for three differently sized entities are shown in the Table 2. The original Pandolf et al. (1976) equation uses kilograms and meters per second. In this section and throughout the rest of thesis, pounds replace kilograms and kilometers per hour (km/h) replace meters per second (m/s). Calculations still use correct units. These are simply helpful conversions.

Table 2. Movement Rates Given Various Body Weights

Body Weight (W)	Load (L)	Grade (G)	Surface (η)	Watts of Energy (M)	km/h (V)
140lb	35lb	0.0	1.0	212.0	3.41
180lb	35lb	0.0	1.0	273.0	3.56
220lb	35lb	0.0	1.0	334.0	3.65

Table 2 represents three separate humans. All entities have the same 35 lb. load, but they do have unique body weights, 40 lbs. apart from each other. In this instance, the terrain is flat and the surface is free of obstruction. The original equation provided by Pandolf et al. (1976) calculates different energy expenditures for the differently sized individuals. These energy expenditures use the baseline performance parameters previously discussed. As a result, increasing body weights produce increased energy expenditures. This does not mean that larger individuals struggle more to move the same load. Simply put, the model assumes that baseline energy expenditures increase as body weight increases. This assumption is reasonable because there is a known correlation between increased lean body mass and increased energy expenditure (Müller, Illner, Bosy-westphal, Brinkmann, & Heller, 2001). The last column in Table 2 shows that larger individuals move more quickly when given the same load. These results serve to verify initial results from this model.

Within the model, the next assumption is that loads are evenly distributed around the torso. According to this assumption, equipment configuration is optimal. A single load that a person carries may have multiple components, but the model represents the entire load as one amount. Those various components can be body armor, a vest carrier, a helmet and a pack of some sort. Weapons too can be part of the load, but they are not strictly carried in the hands. For the purposes of this model, they have slings or some attachment to the body that serves to distribute the load comfortably. Different load configurations may increase energy expenditure and decrease the accuracy of this model. Assuming ideal load distribution prevents the model from needing to address complex load configurations. Finally, this model does not seek to represent the effects of fatigue from previous physical events or injury rates: individual human entities are healthy and free from the effects of fatigue due to prior physical tasks.

B. CONSTRAINTS

This model does not account for varying levels of fitness. Instead of physical fitness, body mass is the key determinant of load carriage capacity. This is not necessarily a weakness of the model; lean body mass is an effective predictor for load carriage ability

(Harman & Frykman, 1992). Additionally, this model does not suggest that the larger an individual becomes the faster they are capable of moving. Soldiers that are obese have a reduced ability to move quickly with or without an added load (Harman & Frykman, 1992). To prevent unrealistic results, entities within this model represent individuals who are fit. As a result, this model shows that entities with more body mass have a greater capacity to carry loads. This is because the increase in mass is healthy and not due to excess weight.

The mathematical model also does not take into account potential differences due to gender or other intrinsic characteristics. The inherent dissimilarities between men and women cause noticeable differences in load carriage capacity (Knapik et al., 2004). Some of these differences diminish when comparing equally sized men and women (Weyand, 2014). However, men are generally larger than women and this only serves to widen the gap between the genders (Garn, 1992). Finally, this model does not consider injury rates. There are a variety of injuries commonly associated with load carriage and these can negatively impact the ability to complete a movement (Knapik et al., 2004). The relationship of injury to movement rates is complex and for that reason is excluded from this model.

C. LIMITATIONS

The purpose of this model is to improve the representation of Soldier load carrying capacity within simulations. More specifically, the mathematical model calculates speed. However, this cannot be used to predict individual movement rates in the real world. This model cannot account for all the factors that go into determining individual speeds for specific humans. Because the model cannot be used as a tool for prediction, that does not make it any less useful. This model relies heavily on existing research that is based on real world conditions. Nonetheless, models are abstractions of reality and can only do so much. Calculated speeds are estimates given a variety of factors. These estimates are reasonable and based on credible research that has taken several decades to compile. This model reflects reality, but cannot be used to predict it.

D. INITIAL VERIFICATION EFFORTS

Given that calculated speeds are estimates of real world expectations, the next step is to determine how close these estimates are to reality. The model must determine baseline energy expenditures given certain parameters. As previously stated, these parameters for individual entities are a 0.7 m/s movement rate, over easy terrain, while carrying a load equivalent to half of his own body weight. This is uniquely tailored to each individual and is independent of time. In other words, Soldiers can maintain this energy expenditure for long periods of time. According to the Army's guideline on foot marches, speed and load determine maximum energy expenditure given a certain duration (Department of the Army, 2017). Taking duration into account, it is possible to increase energy expenditures beyond the baseline developed for this model.

Figure 3 is an adaptation from the information presented in the Army's manual on foot marches (Department of the Army, 2017). The y-axis represents maximum energy that can be expended given a certain duration. Duration is seen on the x-axis. The Army foot march manual includes amounts in kilocalories per hour, but Figure 3 puts this in general terms for each entity that is based on the baseline energy expenditure. Anything above the value of one on the y-axis is an energy multiplier. A value of one for energy expenditure is the baseline already described for this model. This shows that additional energy is available when moving for shorter durations (i.e., if moving less than two hours, nearly twice the amount of energy can be expended). More available energy results in faster speeds.

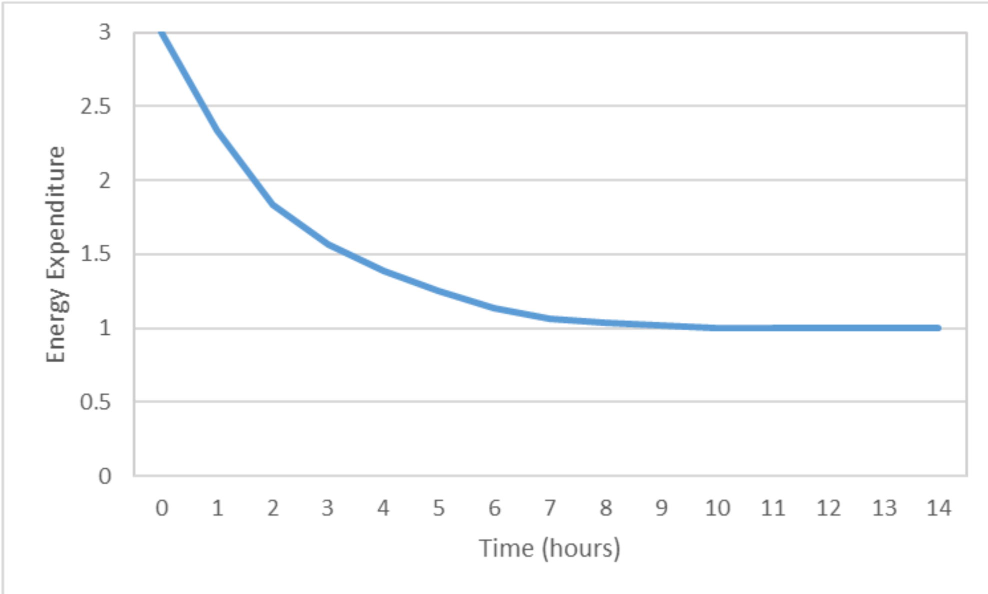

Figure 3. Max Energy Expenditure. Adapted from Department of the Army (2017).

As seen in Figure 3, increasing time durations result in decreased max energy expenditures. Within combat simulations, changing energy expenditures may be very useful. Entities could potentially expend more energy during the first few hours. Performance, or speed, would then diminish over time. Figure 3 directly supports the idea of decreasing performance over time. This idea is not fully discussed within this thesis and may be a key component of future work. To quickly demonstrate the effects of decreasing energy expenditures, the next step is to apply additional energy allowances to several simulated entities. Results are shown in Table 3.

Table 3. Speeds Given Increased Energy Expenditures

Body Weight	Duration	Energy Multiplier	Energy (watts)	Speed (km/h)	Speed (mins/mile)
140lbs	1 Hour	Baseline x 2.3	494.67	6.51	14.74
	2 Hours	Baseline x 1.8	388.67	5.55	17.28
	3 Hours	Baseline x 1.6	332.13	4.97	19.32
	10+ Hours	Baseline x 1.0	212.00	3.41	28.15
180lbs	1 Hour	Baseline x 2.3	637.00	6.70	14.32
	2 Hours	Baseline x 1.8	500.50	5.73	16.75
	3 Hours	Baseline x 1.6	427.70	5.14	18.69
	10+ Hours	Baseline x 1.0	273.00	3.56	26.96
220lbs	1 Hour	Baseline x 2.3	781.56	6.84	14.04
	2 Hours	Baseline x 1.8	614.56	5.86	16.39
	3 Hours	Baseline x 1.6	524.38	5.25	18.29
	10+ Hours	Baseline x 1.0	334.00	3.65	26.29

In Table 3, each simulated human is carrying a 35 lb. pack and is moving across similar terrain. The bottom row for each body weight reflects the previously described baseline. The rows representing the first three hours of a movement show increased energy expenditures. This increase in available energy is based on the exhaustion line found in ATP 3-21.18 (Department of the Army, 2017). The resulting speeds are shown in the final two columns. Speeds decrease as less energy is made available. The last two columns represent the same speed just in different units. The inverse relationship found in the last two columns is due to the units used. The kilometers per hour (km/h) column is distance per time and the minutes per mile (mins/mile) column is time per distance.

The next step is to compare the results in Table 3 to real world expectations. In order to qualify for the U.S. Army Expert Infantry Badge (EIB), a Soldier must complete a 12-mile movement with a 35 lb. pack in three hours or less (i.e., the standard is to travel at least a mile every 15 minutes) (United States Army Infantry School, 2016). Interestingly, the mathematical model shows speeds that at first are better than 15 minute miles. Then movement rates lag behind the 15 minutes per mile mark in the second and third hours. The EIB standard is difficult. The model shows that, in order to achieve that standard, individuals will need to push slightly beyond the exhaustion line. In other words, the model shows that a difficult to achieve standard is in fact difficult. Ultimately, the speeds produced by the model appear very similar to real world expectations.

The effects of load and terrain can further verify the outputs of this model. Estimated speeds for a single entity must decrease as loads increase. Likewise, estimated speeds must decrease as the terrain becomes more difficult to navigate. Figures 4, 5 and 6 illustrate the relationship between speed and more difficult movement circumstances. Figures 4, 5, and 6 depict someone with an ordinary body weight (W) of 170 lbs. Each figure changes one of three parameters: these three parameters are load (L), terrain surface (η), and terrain grade (G). Each variable being manipulated has a range of values, while the others remain constant.

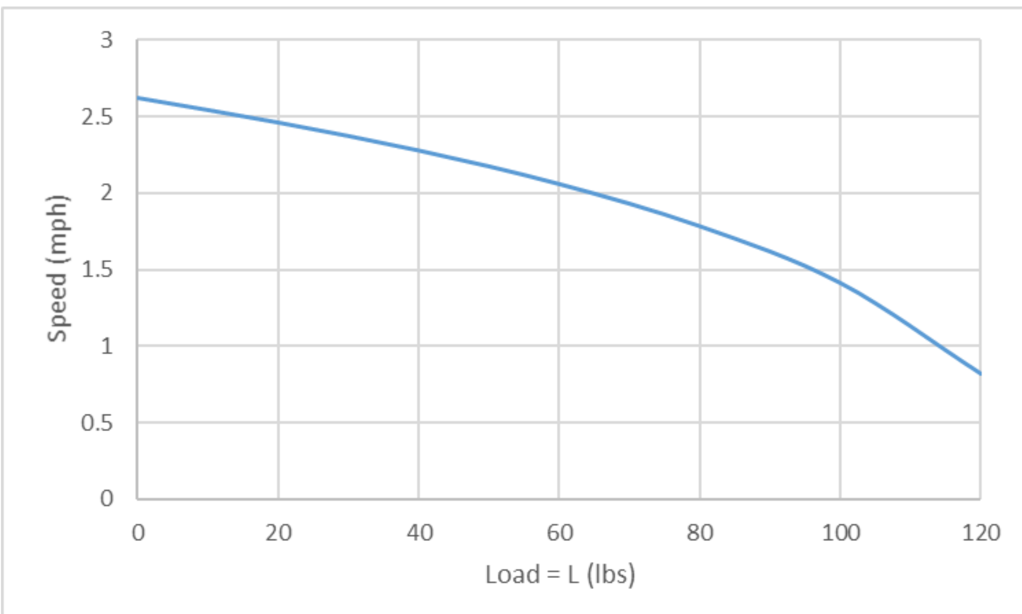

Figure 4. Speed as a Function of Load (L)

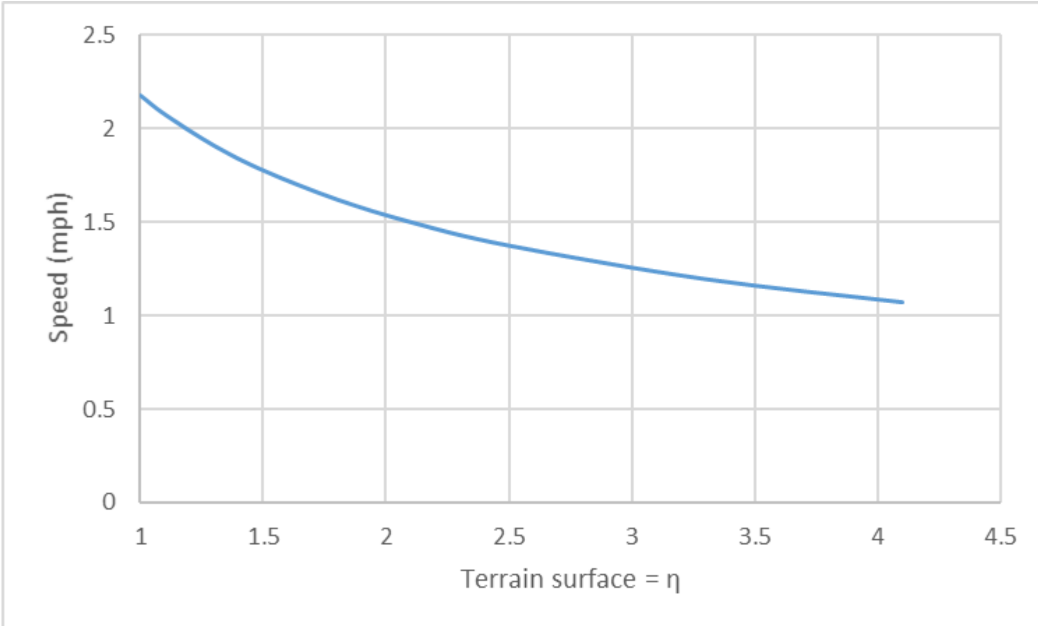

Figure 5. Speed as a Function of Terrain Surface (η)

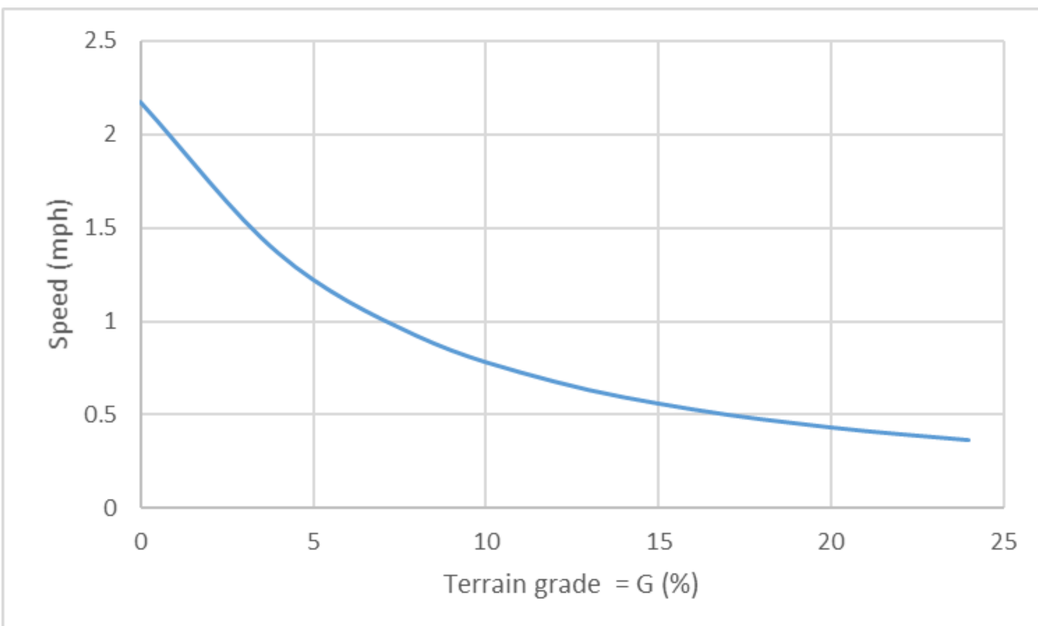

Figure 6. Speed as a Function of Terrain Grade (G)

Figures 4, 5, and 6 show that the mathematical model behaves precisely as expected. Speed decreases as load increases or the terrain becomes more difficult to traverse. All curves are decreasing, but only the curve in Figure 4 is concave down. This is interesting because this graph deals with load. When accounting for increased loading, speed does not approach a limit but goes beyond zero. Values beyond zero are irrelevant (i.e., there cannot be a negative speed). Given a body weight of 170 lbs., loads of 130 lbs. or greater prevent speed from being calculated and the equation ceases to work. This may seem like a problem, but this is consistent with real world behavior. Loads approaching 150 lbs. limit the time period that someone can move (Koerhuis et al., 2009). According to this model, the limitation for load increases as body weight increases (i.e., the model further suggests that larger Soldiers have greater load carrying capacity).

E. A MORE ADAPTIVE MODEL

This section discusses recommendations for developing a mathematical model that is more responsive to real world conditions. The model does not take into account a number of factors. The most important of these are fitness, altitude, fatigue and injury. Additional variables allow the mathematical model to more closely approximate reality. The new equation now becomes:

$$V' = V\tau\alpha\beta\sigma$$

where:

V = speed derived from the original equation

τ = physical fitness scaling factor ($\tau \geq 0$)

α = altitude scaling factor ($0 \leq \alpha \leq 1$)

β = fatigue scaling factor ($0 \leq \beta \leq 1$)

σ = injury scaling factor ($0 \leq \sigma \leq 1$)

V' = speed incorporating fitness, altitude, fatigue and injury.

Now it is possible to better account for a variety of factors that definitively impact movement rate. Fatigue, injury and altitude have ranges from zero to one. This means that these factors can only reduce speed. A value of one represents conditions free of injury or fatigue. In the case of altitude, a value of one corresponds to sea level. Values approaching zero represent increasing levels of fatigue, debilitating injuries or very high altitudes. These three factors all include zero in their range. This is necessary due to the fact that fatigue, injury and altitude can become severe enough to stop movement altogether.

The fitness factor requires a slightly different approach. This does not have an upper limit of one. This means that fitness can become a speed multiplier. This too must have some upper limit. A value with even two digits is highly unlikely if not altogether impossible. An exact limit is not suggested here, but one is definitely needed. As with the factors for fatigue and injury, values of less than one represent an individual whose physical fitness is degrading and movement rates slow as a result. Real world observations must support these various parameters. In other words, this is another area for future work that must incorporate empirical results to determine values for each parameter. However, suggesting specific values for each of these parameters is outside the scope of this thesis.

F. MODEL OUTPUTS AND RESULTS

The purpose of this section is to examine the effects on speed when adjusting the various inputs (e.g., load, body weight, terrain steepness and terrain surface). To illustrate this point, the inputs that can be changed are load, body weight, terrain steepness and terrain surface. If the model is meaningful, then speed must decrease when loads increase or the terrain becomes more difficult to navigate. Terrain is more difficult to navigate when either terrain surface (η) values increase or terrain grade (G) values increase. This section includes a number of three dimensional graphs that reveal these various interactions. Again, speed is a function of four distinct parameters. In the following graphs, two of these will remain constant while two will vary. Overall, this demonstrates that the model produces decreasing speeds as conditions become increasingly difficult.

1. Speed as a Function of Load and Body Weight

In Figure 7, both load and body weight have a range of values. However, terrain values are constant and represent an environment that is relatively easy to navigate: the terrain is flat ($G = 0$) and the surface is free of any type of obstruction ($\eta = 1.0$). Loads range from 10 lbs. to 88 lbs., while body weights range from 120 lbs. to 200 lbs. Clearly, speed decreases as loads increase. Speed also decreases as body weight declines. Figure 7 further demonstrates that larger Soldiers are the least affected by increasing loads, while smaller Soldiers are the most affected. Finally, Figure 7 reveals a non-linear relationship between load and speed. This means that added weight does not always have the same effect. For example, a pack that increases in weight from 20 to 30 lbs. has a slight effect. However, a pack that changes in weight from 70 to 80 lbs. can slow movement rates considerably. The regions where load has an increased effect deserve to be further investigated. Accelerated decreases in speed may lead to second and third order effects. This highlights the necessity to incorporate this model into a combat simulation.

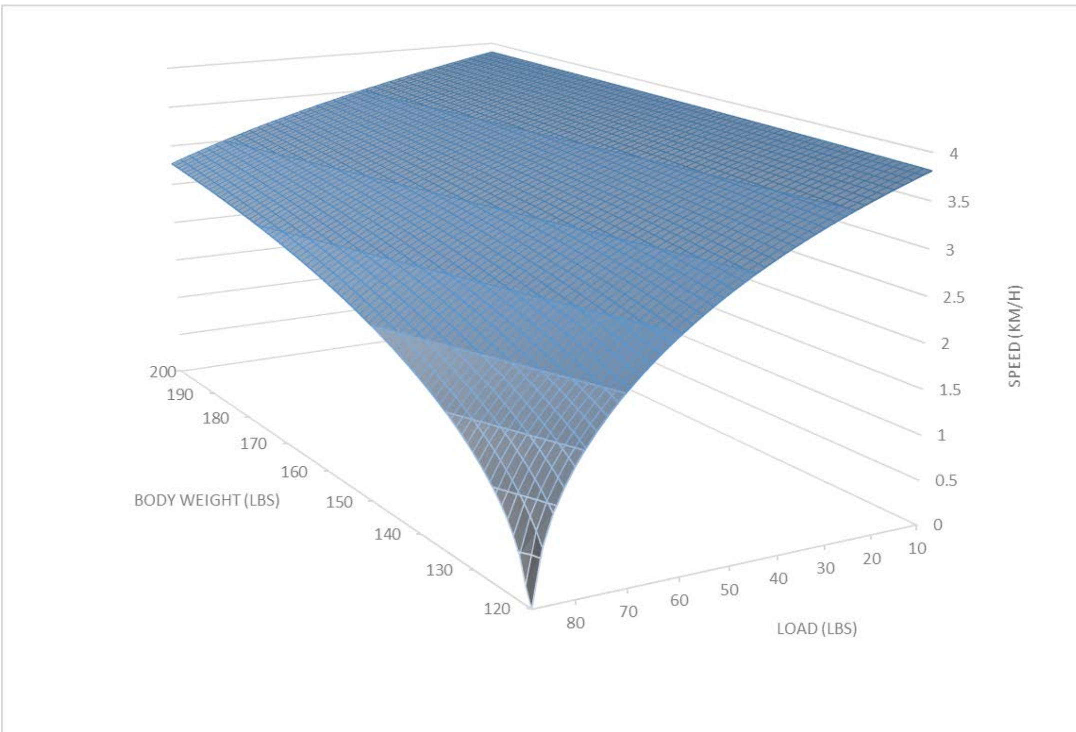

Figure 7. Speed as a Function of Load and Body Weight (Flat Terrain)

As illustrated in Figure 7, a 120 lb. Soldier's movement rate is at zero with an 88 lb. load. In this instance, the load carried is roughly 75% of his body weight. To deal with this type of situation, the model cannot simply return a movement rate of zero. For use within simulations, a recommended alternative is to never calculate speeds based on a load that is greater than 70% body weight. If the load is greater than 70% of the Soldier's body weight, then simply calculate the speed using a load equal to 70% of his body weight. The next step is to initiate a countdown until the Soldier becomes too exhausted to continue. The time allotted for this countdown will decrease as loads approach 100% of the Soldier's body weight (i.e., times must decrease from roughly an hour to several minutes). Additionally, loads should be limited to amounts that are less than or equal to 100% of the individual's body weight.

In Figure 8, load and body weight are varied while terrain values are held constant. Again, loads range from 10 lbs. to 88 lbs., while body weights range from 120 lbs. to 200 lbs. This time, however, the value characterizing terrain grade (G) is equal to 24%. This represents an environment that is difficult to navigate despite the surface being free of obstructions ($\eta = 1.0$). This scenario reveals that walking up a very steep hill is extremely difficult. As a result, movement rates never exceed one kilometer per hour. Figure 8 is comparable to Figure 7. The only difference is the steepness of the terrain. This represents a more difficult environment to traverse and movement speeds slow significantly.

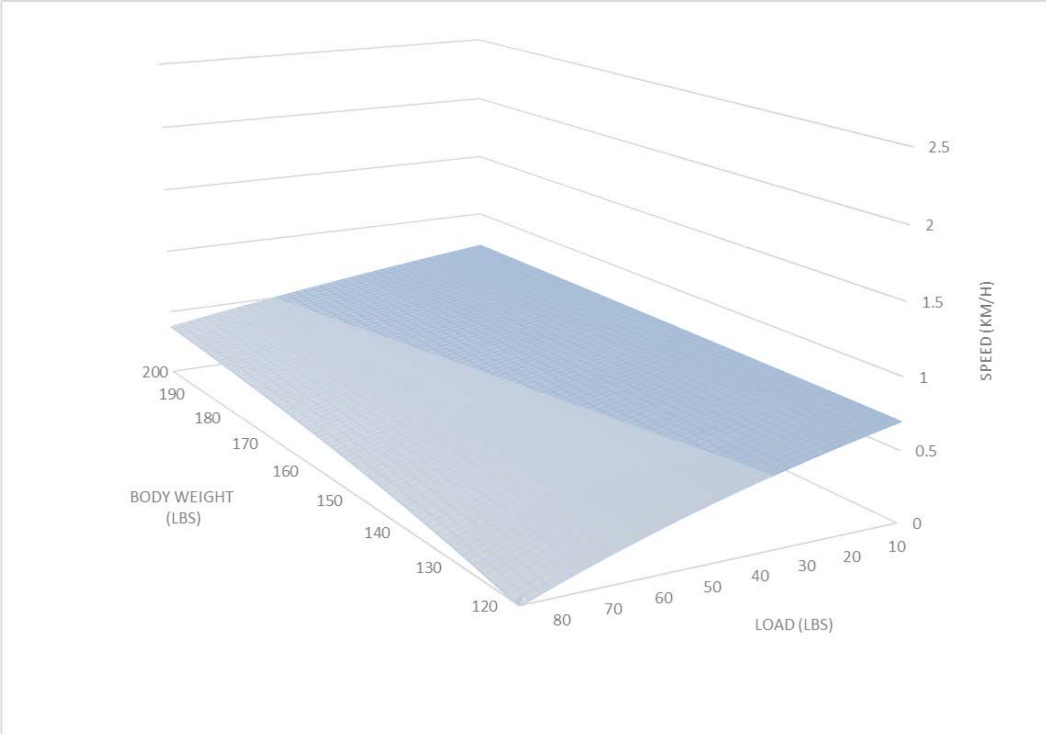

Figure 8. Speed as a Function of Load and Body Weight (Steep Terrain)

2. Speed as a Function of Load and Terrain

Figure 9 demonstrates how terrain surface and load can affect movement rate. The scenario depicted here is different than the previous three dimensional plots. Now, body weight and grade are constant. This situation represents a single Soldier who weighs 160 lbs. and is moving over flat terrain. Loads range from 10 lbs. to 116 lbs., while the surface factor ranges from one to just over four. Speeds again decrease in the expected manner. Terrain that is increasingly difficult to traverse causes speed to diminish. Likewise, increasing loads result in decreasing speeds. As before, loads that near 75% of the individual's body weight result in speeds that approach zero kilometers per hour.

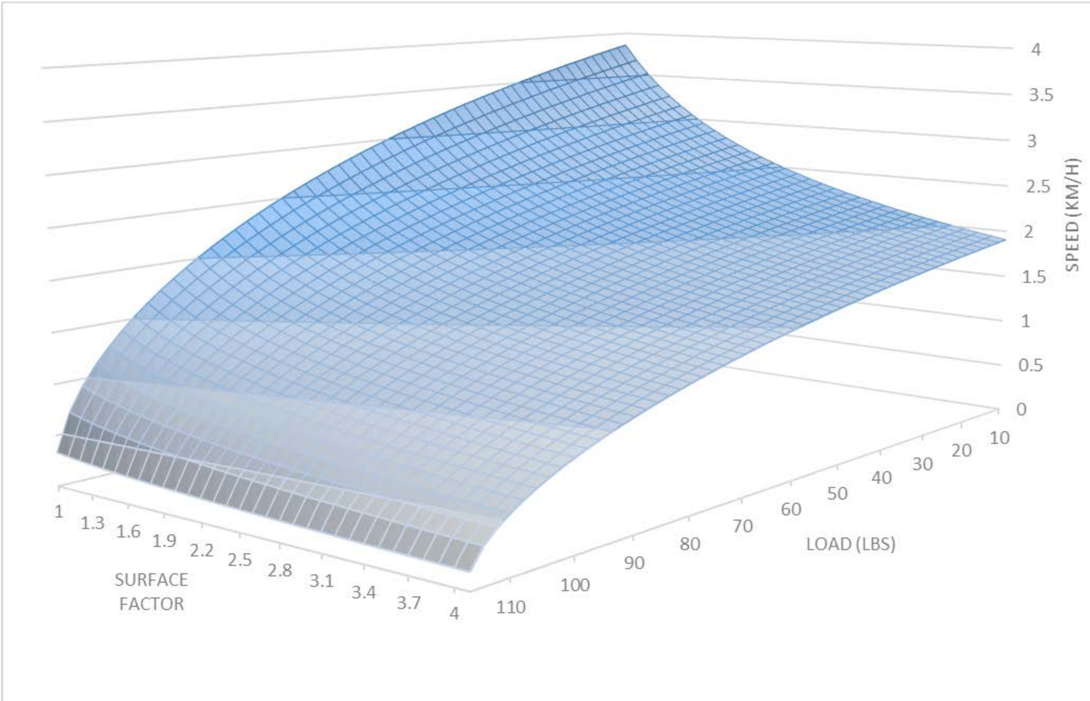

Figure 9. Speed as a Function of Load and Terrain Surface

3. Speed as a Function of Terrain Characteristics

The scenario depicted in Figure 10 represents a Soldier with a body weight of 160 lbs. In this situation load is equal to one-fourth of his body weight or exactly 40 lbs. While load and body weight remain constant, both terrain parameters have a range of values. As a result, speed quickly diminishes due to the combined effects of both terrain factors. Steeper terrain, with added obstructions, results in speeds that are consistently less than one kilometer per hour. In fact, the resulting speed is often less than even half of a kilometer per hour. Yet again, the model produces realistic results: walking uphill through deep snow slows movement considerably. At the extremes, speed ranges from nearly 3.5 kilometers per hour to less than 0.15 kilometers per hour. Clearly, the model demonstrates that terrain greatly affects speed: the minimum values for speed are approximately four percent of the maximum in this situation.

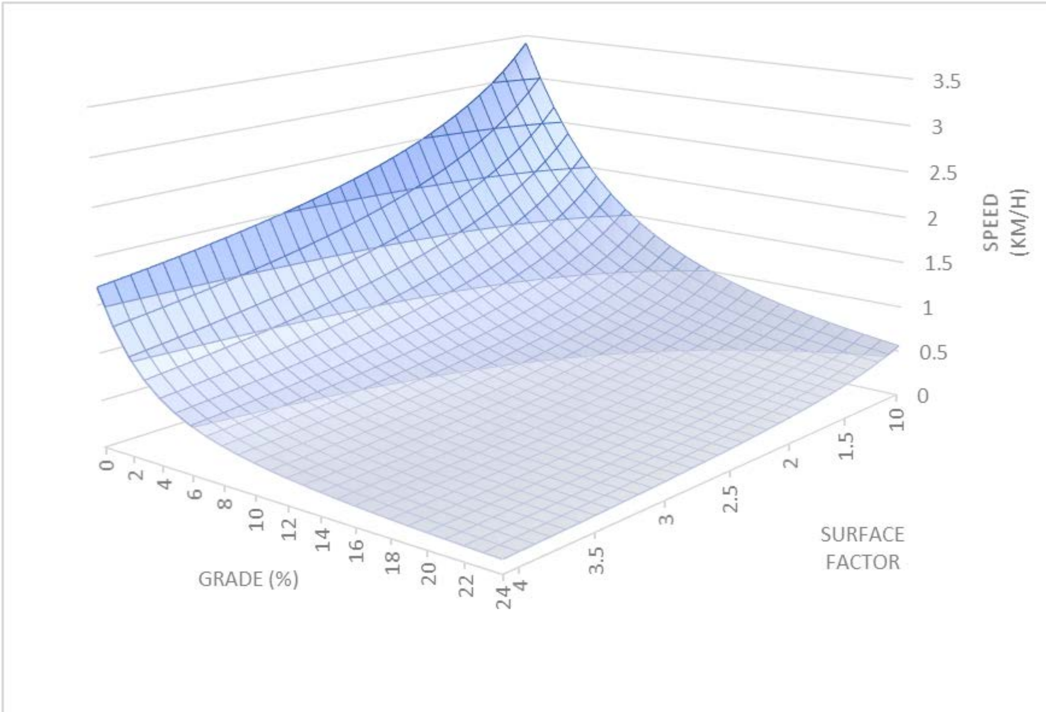

Figure 10. Speed as a Function of Terrain Characteristics

4. Speed as a Function of Steepness and Body Weight

As a final demonstration, steepness and body weight are manipulated in order to determine speed. In Figure 11, load is a constant 70 lbs. and the terrain is free of any obstructions. Body weight ranges from 120 lbs. to 200 lbs. Terrain steepness ranges from perfectly flat to a grade of 24%. Not a single value for body weight is resistant to the effects of steep terrain. Furthermore, the effects of increased steepness are vastly different than the effects of increased load. With increased loading, the movement rates for larger individuals slow to a certain degree, but speeds for smaller individuals suffer a great deal more.

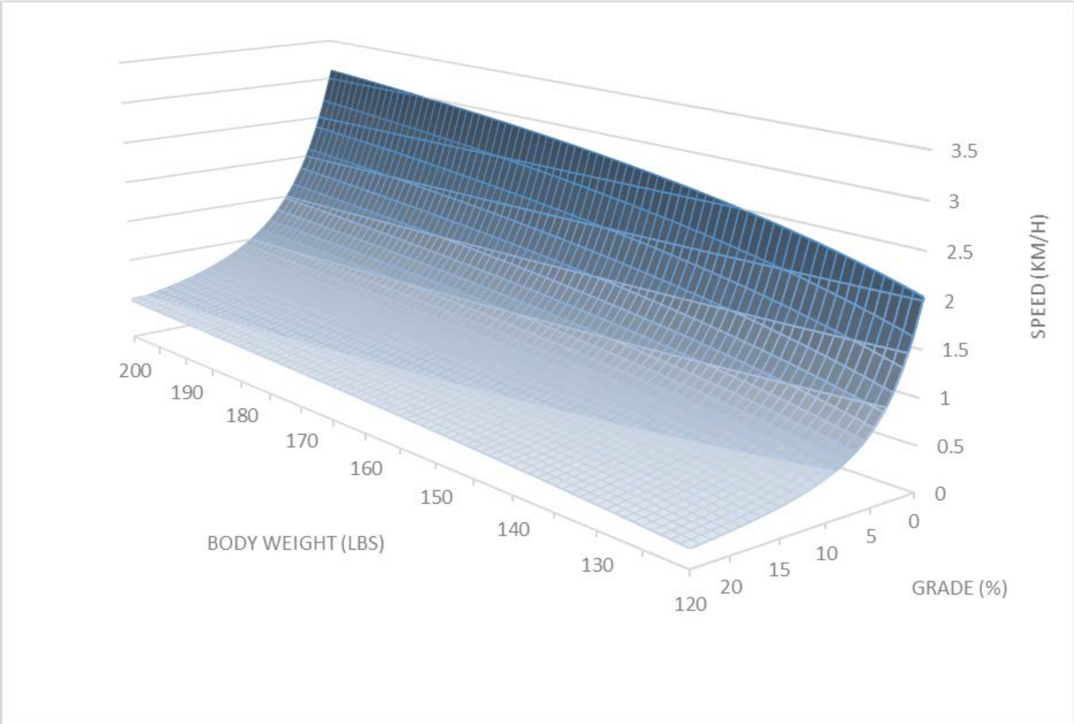

Figure 11. Speed as a Function of Steepness and Body Weight

5. Summary of Results

Each three dimensional plot illustrates that speed decreases when circumstances become increasingly difficult. Speed diminishes as load increases or the terrain becomes more restrictive. Furthermore, lower body weight results in slower speed. As a reminder, this is not a tool for prediction, but simply a method to estimate movement rates for dismounted Soldiers. It may be the case that smaller Soldiers in certain units have a greater load carrying capacity than larger Soldiers in other units. This issue is easily solved using the more adaptive model presented earlier. This is a matter of fitness for each individual and cannot influence the base model. For each parameter, the general relationship to speed must always hold true. Therefore, the model's usefulness is unmistakable. Speed increases or decreases in the expected manner as each parameter adjusts. Furthermore, each parameter causes non-linear changes to speed. This curvilinear relationship may cause second and third order effects, which means this model deserves further examination within a combat simulation. Ultimately, the three dimensional plots demonstrate that the model is sensitive to all the different parameters, and each of these have a unique effect on speed.

G. THE CASE FOR THIS PARTICULAR MODEL

Admittedly, speed is not the only variable affected by load and terrain. The model could instead estimate energy expended, mental readiness, or fatigue. However, these types of factors present additional challenges. First of all, they do not directly translate into recognizable behaviors. In other words, these factors may relate to behaviors, but they are not behaviors in and of themselves. As a result, speed provides a very specific advantage that the other factors do not. In order to connect factors other than speed to an actual behavior (e.g., marksmanship or cognitive abilities), a simulation must incorporate a series of models. For example, a simulation attempting to do this must develop a model that determines fatigue and also a model linking fatigue to the desired behavior. This type of approach certainly is feasible, but it seems that a focused effort on energy or fatigue only creates more questions than it answers.

This research effort began as an examination of the effects of load on fatigue. It became clear, however, that linking fatigue to actual behaviors requires making a series of assumptions. Making too many assumptions creates a purely speculative model that ultimately produces unrealistic behaviors. For this reason, speed is the preferred behavior and is a logical starting point for this effort. Furthermore, consider the promising results of this model: speeds produced by this model are well within human performance limitations, and the model obeys known rules when accounting for load and terrain. Speed decreases when load increases or the terrain becomes more difficult to traverse. This model avoids making unnecessary assumptions, produces realistic behaviors, and effectively considers load and terrain.

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IV. APPLYING THE MODEL TO A SIMULATION

The mathematical model developed as part of this thesis is a very useful component of pathfinding over three-dimensional terrain. This provides a supplement to techniques that only account for distance. Distance is an important part of the equation, but it is not the only part. The fundamental question we must seek to answer is how long does it take to get somewhere, and not simply how far away is the destination. Now that we can determine speed, we can calculate the time it takes to travel between two points. This means we can determine the quickest route, and not just the shortest. In regard to pathfinding, the best answers are in terms of hours and minutes, not simply miles or meters. As part of this research, an A* search algorithm determines the cheapest path in terms of time, where the path is computed using the following equation (Russell et al., 2010):

$$f(n) = g(n) + h(n)$$

where:

$g(n)$ = the total cost from start to current location and

$h(n)$ = the estimated cheapest cost to the destination.[1]

A* continues to explore the cheapest possible path in an iterative fashion until the destination is reached and the path is complete. This section is simply an introduction to the A* search algorithm. If more information is needed, Russel et al. (2010) provide an excellent and detailed description of this algorithm and its capabilities. As the algorithm relates to this thesis, A* search computes the quickest path, and not simply the shortest. The algorithm calculates the speed traveled on each segment. Cost for each segment is the distance divided by the speed. For example, dividing miles by miles per hour returns a value in terms of hours. With this method, the algorithm finds the quickest path.

The shortest distance is irrelevant if it requires climbing cliffs with extremely heavy packs. When considering terrain that includes vertical faces, the distance may be minimal,

[1] The idea to incorporate the mathematical model within the A* search algorithm began during a discussion with a colleague in the MOVES curriculum (M. Blankenbeker, personal communication, April 17, 2018). As a result, Mike Blankenbeker deserves credit for helping to shape this thesis.

but the time it takes to move that distance is extraordinary. Time is the real metric when comparing routes. In this sense, time is the most useful measurement because it reflects the actual cost to Soldiers. Time must be a function of the load carried, while also accounting for elements of the terrain. This is the true cost of any particular route and this is a vast improvement when compared to approaches that only consider distance.

A. ABOUT THE A* APPLICATION

This A* search application is an adaptation of material from a course at the Naval Postgraduate School (C. Darken, class notes, July 19, 2017). The purpose of the original application is to implement the A* search algorithm and find the shortest path between two points. The updated version has several important differences. First, the original terrain was an urban environment that was meant to simulate military training areas. The new three dimensional terrain includes a randomized set of hills, ridges, valleys and other terrain features. Second, the technique for determining paths is vastly different within the new application. The updated version includes routes based on minimum distance, but also determines the routes that require the least time to travel.

B. SHORTEST ROUTE VERSUS QUICKEST ROUTE

The next step is to demonstrate the difference between the shortest and the quickest route. Given mountainous terrain, the optimal route changes when the path cost is based on time and not just distance. The difference between these two routes is clear in Figure 12. The shortest route is blue and the quickest route is red. Both routes are traveled by a 160 lb. Soldier carrying a 10 lb. load. The locations where the route begins and ends are on opposite ends of two separate ridgelines. This means that the search algorithm must navigate a number of factors in order to calculate the path with the least cost: the cost is based on either minimum distance or minimum time.

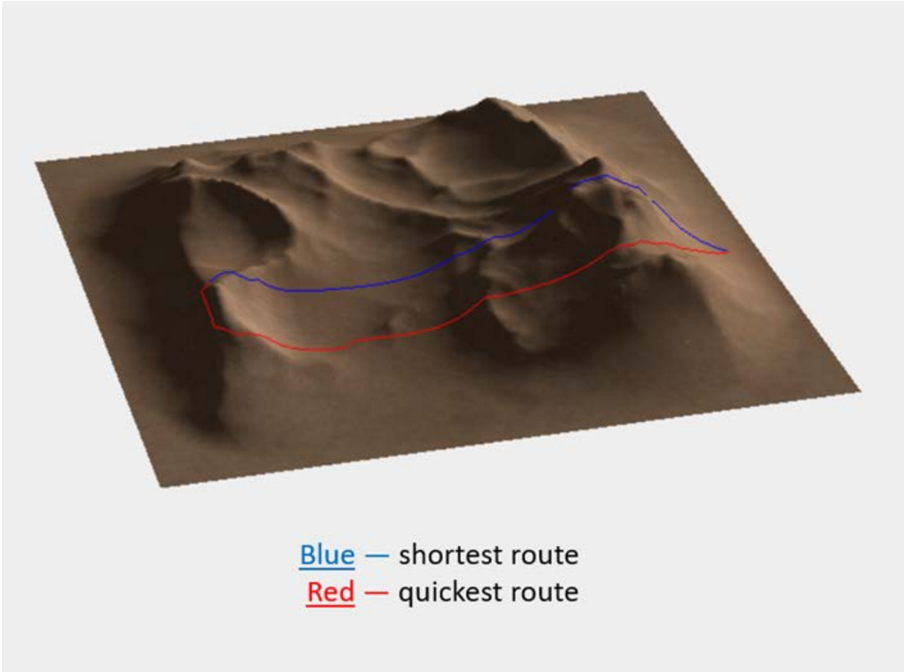

Figure 12. Shortest Route versus Quickest Route

Figure 12 demonstrates clear differences between the shortest route and the quickest route. The blue route, the shortest route, is only 87% as long as the red route, the quickest route. It heads directly over the steepest parts of the mountain. The path for the blue route takes into account changes in elevation in order to determine the total distance, but does not assign a penalty for incredibly steep terrain. In other words, the blue route only accounts for the total distance. Alternatively, the red route considers the speed that can be traveled in order to determine the quickest route. The time it takes to complete this route is only 75% of the time that it would take to travel the blue route. Although the red route is clearly longer, travel time is significantly less. Clearly, there is a difference between the quickest route and the shortest route and this difference is not trivial. This provides an initial face validation for this model; the model is sensitive to load and terrain variations.

C. THE EFFECTS OF LOAD AND TERRAIN

This section illustrates how changing loads can significantly alter the route selected. Figure 13 depicts three different routes that have the exact same endpoints. Each route represents the same Soldier in similar terrain. While surface characteristics are not visible on the three dimensional terrain image, the surface is uniform and covered in light brush ($\eta = 1.2$). For each route, body weight is exactly the same: load is varied for only the yellow route. The blue route is simply the minimum distance between the two points. This is independent of load or the effects of terrain on the individual. This is simply the shortest route. On the other hand, both the yellow and red routes take into account load, body weight and terrain characteristics. The yellow route is the quickest route given a 40 lb. pack. The red route is the quickest route given a 140 lb. pack. A portion of the red route is not visible as it overlaps with the blue route. The start and endpoints are where the red, yellow, and blue routes intersect.

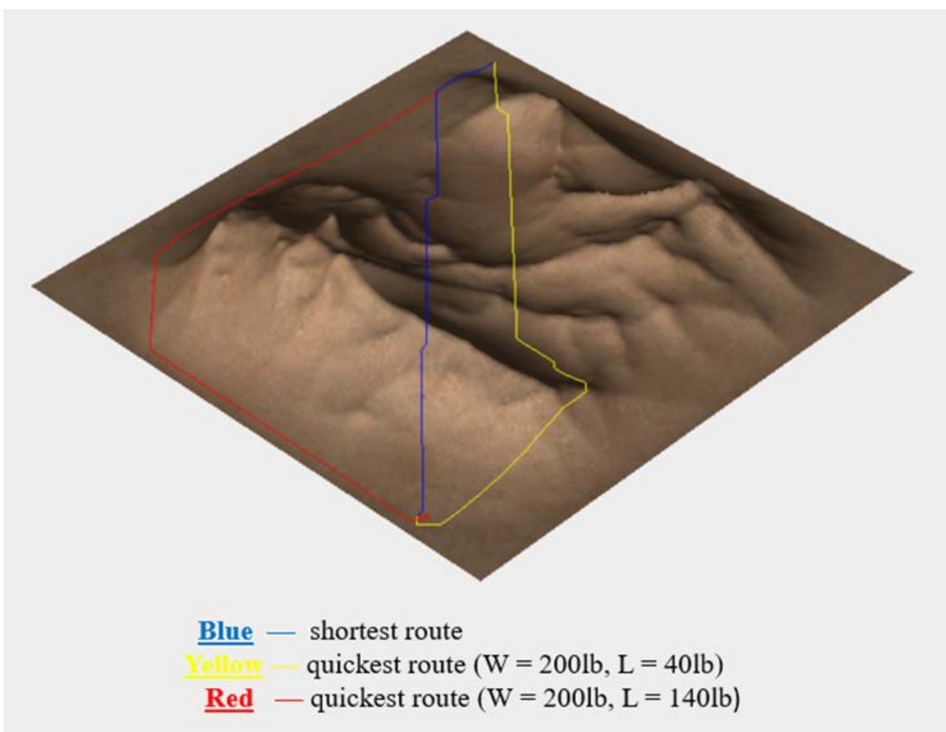

Figure 13. The Effects of Load on Route Selection

Figure 13 demonstrates a number of interesting effects. First, when load is increased to a heavy amount (i.e., 140 lbs.), the quickest route avoids all hills and travels the greatest distance. This is represented by the red route. If the same individual were to travel the shortest (blue) route, then it would take them nearly three times as long to reach the destination. This is despite the fact that the blue route is roughly 20% shorter than the red route. When load is decreased, the quickest route better approximates the shortest route. This is represented by the yellow route, which is 800 meters shorter than the red route and can be traveled in less than half the time. In the instance represented by the yellow route, the load is only 40 lbs. Consequently, the route takes a more direct approach between the start and end points and requires significantly less time to travel. Overall, this shows that the model is sensitive to load and terrain and further demonstrates that the shortest route is not always the fastest.

D. THE EFFECTS OF BODY WEIGHT AND TERRAIN

According to the mathematical model, larger individuals have increased carrying capacities. In the previous A* examples, body weight was the same for each route. Figure 14, however, demonstrates the effects of body weight when carrying equivalent loads. This example represents two separate individuals with the exact same load. The blue route is again the shortest distance between the start and end points. The green route represents the path for a 200 lb. Soldier, while the red route represents the path for a 120 lb. Soldier. In both cases, the load is exactly 84 lbs. The 120 lb. Soldier carries a load equal to 70% of his body weight, while the 200 lb. Soldier carries a load equal to 42% of his body weight.

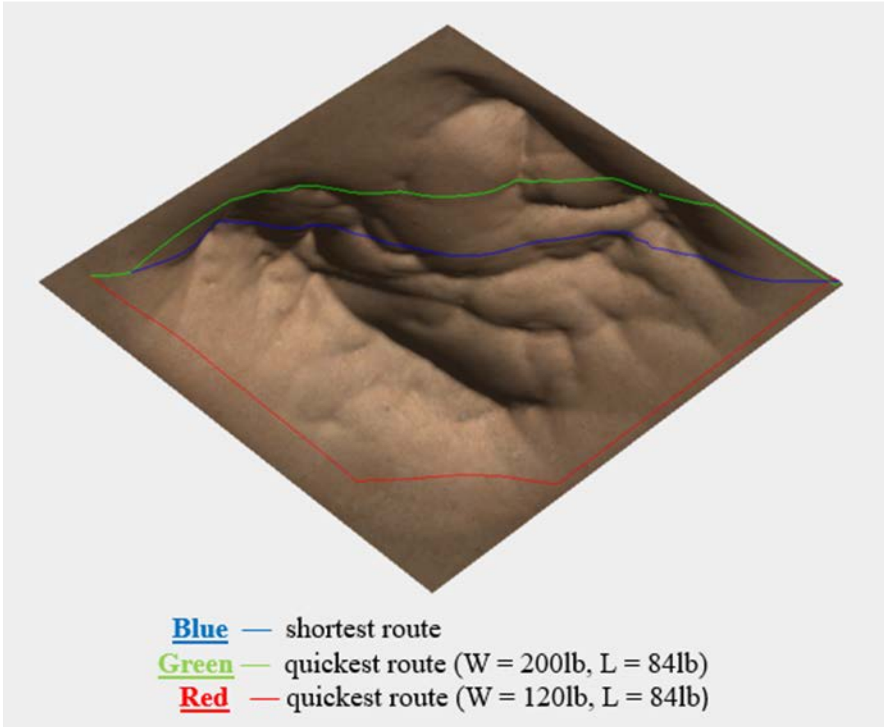

Figure 14. The Effects of Body Weight on Route Selection

Figure 14 demonstrates significant differences between the three routes. The shortest route takes a very direct approach between the two points: the blue route is approximately 20% shorter than the red route. However, the blue route increases travel time by a factor of five when compared to the red route. The red route is definitely longer, but it does not require the same amount of time. The green route is also longer than the blue route, but shorter than the red route. The 200 lb. Soldier travels the green route in less than half the time that the 120 lb. Soldier can complete the red route. The optimal route with the exact same load is different when considering unique individuals. The differences between the green and red route are due to the disparity in body weight. The larger Soldier chooses to navigate changes in elevation and takes a more direct approach. The smaller Soldier stays on flat ground and avoids steep terrain altogether. When considering the blue route for both Soldiers, it takes the 120 lb. Soldier over six times as long to complete the journey. Clearly, the larger Soldier can complete the blue route much more quickly.

E. SUMMARY OF A* SEARCH RESULTS

Overall, the A* search application demonstrates a number of interesting points. First of all, the shortest route is rarely the quickest route: this is especially true when considering three-dimensional terrain with changes in elevation. In many cases, the shortest route requires considerable more time to complete. The A* search application also demonstrates that the ideal route changes as parameters change. Changes to load and body weight result in entirely different paths. Increasing the load not only changes the route, but also increases the time needed to complete the alternate route. Decreasing body weight exhibits a similar relationship: the route changes and time increases. Adjusting the surface factor uniformly does not change the optimal path. Within this application, the surface factor applies equally across each part of the terrain. As a result, it does not affect the optimal path. None of the examples illustrate this point because the path simply does not change. Ultimately, the pathfinding application demonstrates that the model is sensitive to load, body weight and terrain. Changing these parameters alters the optimal route and leads to interesting observations.

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V. CONCLUSIONS AND RECOMMENDATIONS

In summary, the mathematical model reveals several important relationships. First, movement rates decrease when load increases. This may not always be the case in real life, but the model must return slower speeds when loads become heavier. Again, the model provides estimates and not predictions. Secondly, speed decreases as the terrain becomes more difficult to traverse. Terrain becomes more challenging when it is steeper or when the surface offers additional obstructions. According to the model, the effects of load and terrain are consistent in that increased load or more difficult terrain always case slower speeds. Finally, the model recognizes that there is a certain point where any additional load is simply too much. This is particularly useful because it represents human limitations. These limitations are worth considering, especially in regard to combat simulations.

The model, when applied within an A* search algorithm, further illustrates the effects of load and terrain. Finding the shortest path is relatively straightforward. Determining the quickest path is an entirely different matter. The shortest path is concerned only with distance. On the other hand, the quickest path is a function of distance and speed: speed accounts for load, various terrain factors, and body weight. The A* search algorithm reveals significant differences between the shortest path and the quickest path. Often, the quickest path is much longer than the shortest path. However, the quickest path often requires a fraction of the time when compared to the shortest path. Additionally, the A* search algorithm demonstrates that the model is sensitive to load and terrain. This relationship is clear as speed often changes along different portions of most routes.

This research demonstrates the ability to estimate movement rates for individual Soldiers. These estimations are particularly useful because they account for the effects of load and terrain. Speeds are not the same for differently sized entities: this is especially true when considering different loads over varying terrain. These differences in speed serve as a foundation for variability in human performance. Variability occurs not only from entity to entity, but also as speed changes due to changing conditions. Speed is not simply determined at the beginning of a simulation and never revisited. Within a simulation, an agent changes speed when either load or terrain changes. While it is now possible to estimate movement rates, this effort is far from over. This research must be validated, and there are many opportunities for future work and for further simulation applications.

A. FUTURE WORK

As previously discussed, the mathematical model reveals that loads approaching 75% body weight stop movement completely (i.e., speed equals zero at a certain point). Speeds of zero are not useful for the purposes of most combat simulations. Once load exceeds 70% body weight, a good recommendation is to use a slightly different approach to determine behavior. Loads greater than 70% should trigger a countdown. In this case, it is best to assign a time limit to simulated entities carrying these heavy loads. Table 4 illustrates a possible technique for assigning time limits when loads exceed 70% body mass. As a general recommendation, it is best to calculate speed based on 70% body mass, but award less time as loads approach or exceed 100% body mass. Table 4 incorporates time limits from a previously mentioned study (Koerhuis et al., 2009); time limits within a simulation can be based on these average durations.

Table 4. Limited Movement Durations for Heavy Loads

Percentage of body weight	Load amount to determine speed	Time limit averages with standard deviation
$L \leq 70\%$	Actual load	N/A
$70\% < L \leq 80\%$	70% body weight	40.2 ± 17.2 min*
$80\% < L \leq 90\%$	70% body weight	24.5 ± 7.4 min*
$90\% < L \leq 100\%$	70% body weight	17.7 ± 5.8 min*
$L > 100\%$	70% body weight	11.0 ± 4.0 min

*Data from Koerhuis et al. (2009).

To truly determine the usefulness of this research, the mathematical model must be scrutinized by subject matter experts. In regard to this thesis, the model is a combination of several unique concepts. Experts must review this model as part of a verification, validation and accreditation process. A good starting point is an investigation of the assumption concerning baseline energy expenditure. For example, a speed of 0.7 m/s might be too conservative. It may be more appropriate to use speeds that are closer to 1.0 m/s instead. Regardless of the approach, those investigating this model should keep several things in mind. First, the base model has already been verified as accurate: Pandolf et al. (1976) showed a 0.96 correlation between predicted and actual energy expenditures. Secondly, speeds determined by this model are estimates. The goal is not to predict movement rates, but to roughly estimate reasonable speeds.

In its current form, the model does not address several important relationships. First, the model does not differentiate between uphill and downhill movement. Gradient is simply a comparison of vertical and horizontal distance. According to the model, downhill movement takes just as much time as uphill movement. Undeniably, speed decreases when moving either uphill or downhill (Department of the Army, 2017). Uphill and downhill movement speeds, however, likely have significant differences worth considering. Second, this model does not consider side-hill movement: moving along the side of a mountain is the same as moving on flat terrain. Movement along the side of a steep hill likely has negative consequences and needs to be further investigated. The following serves as a general checklist for future work:

1. Incorporate results of the Drain et al. (2017) study.
2. Investigate the assumption concerning baseline energy expenditure.
3. Set limits for maximum loads.
4. Investigate the effects of downhill and side-hill movement.
5. Allow for both running and walking speeds.
6. Allow for further variables (i.e., expand on Chapter III, Section E, “A More Adaptive Model”).
7. Select simulation platform. For example, COMBATXXI (Combat Twenty-One) provides an excellent system to explore the tradeoff between load and performance.

B. FUTURE APPLICATIONS

In order to successfully incorporate this model within a simulation, M&S professionals must consider several key components. First, the simulation must include both sustained (walking) and rapid (running) movement rates. Additionally, M&S professionals must clearly define conditions that determine when to use either mathematical model. Entities must run only in certain circumstances. The default speed must be the sustained or walking speed. Finally, the simulation must assign unique body weights to each individual entity. This enables performance variation from one entity to another and better represents differences among actual Soldiers. Overall, this model is most useful as a means to examine the tradeoffs between added capabilities and added weight. Scenario possibilities are virtually limitless when it comes to examining these tradeoffs: composition and disposition for both friendly and enemy forces can be combined with any number of terrain configurations. Given an endless number of scenarios to explore, the model enables M&S professionals to fully investigate the effects of load on individual Soldiers.

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