Understanding Complexity:
Dynamic Analysis of Combat Vehicle Accidents

Maj. Nathan A. Minami
Stuart E. Madnick

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Composite Information Systems Laboratory (CISL)
Sloan School of Management, Room E53-320
Massachusetts Institute of Technology
Cambridge, MA 02142

Understanding Complexity: Dynamic Analysis of Combat Vehicle Accidents

Maj. Nathan A. Minami
Instructor/ Analyst
United States Military Academy
Department of Systems Engineering
West Point, NY 10997
Email: nathan.minami@us.army.mil
Phone: (845) 938-5525 (office)

Stuart Madnick
John Norris Maguire Professor of Information Technologies
& Professor of Engineering Systems
Massachusetts Institute of Technology
Sloan School of Management & School of Engineering
77 Massachusetts Ave. (E51-321)
Cambridge, MA 02139-4307
E-mail: smadnick@mit.edu

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Abstract: *Dozens of U.S. soldiers are killed each year as a result of both combat and motor vehicle accidents. The objective of this study is to look beyond the events and symptoms of accidents which normally indicate human error, and instead study the complex and poorly understood upper-level organizational processes and problems that may constitute the actual root causes of accidents – this is particularly challenging because the causes often involve non-linear dynamic phenomena and have behaviors that are counter-intuitive to normal human thinking, these are often called "wicked" problems. After reviewing the available literature, a System Dynamics model was created to provide an analytical model of this multifaceted system that allows for extensive simulation. The results of these simulations suggest that high-level decisions that balance mission rate and operations tempo with troop availability, careful management of the work-rest cycle for deployed troops, and improvement of the processes for evaluating the lessons learned from accidents, will lead to a reduction in Army combat and motor vehicle accidents.*

1. Introduction

Despite extraordinary efforts by Army leaders at all levels, an alarming number of soldiers die or are severely injured each year from accidents that could have been prevented. Currently, the Army uses a qualitative and methodical risk management process called Composite Risk Management (CRM) to help manage operational and training risk.[1] While the CRM process has produced tremendous improvements in accident prevention, both it and the results of most Army accident investigations (the primary source of institutional safety learning) tend to focus predominantly on the immediate events and symptoms of accidents. Consequently, the results of most safety investigations indicate "human error" as the primary cause of accidents - much like the magician who performs his magic by distracting the audience, we are easily distracted away from the real causes of accidents. If we are to solve this problem, we must recognize that there are highly complex, dynamic, and non-linear phenomena involved that defy our normal capabilities to manage and engineer effective responses – that is they are "wicked" problems. To solve them we must explore the rarely examined organizational processes and problems that contribute to accidents.

Thus, the objective of this study is to develop a model that helps Army policy makers to better understand the effects of various dynamic feedback processes and delays involved with decision making, specifically in regards to accident prevention. *This study focuses on high-level dynamic organizational factors that impact safety*, which will help policy makers to better understand which levers in the system play the biggest role in risk mitigation.

2. Background & Context

2.1 Vehicle Accidents & Investigations

Since the beginning of the war in Iraq in 2003, approximately 20% of the Army's combat deaths have been caused by non-combat events (about 600 total as of January 2007). In comparison, 28% of deaths were non-combat related during WWII and 49.5% were non-combat related during the Gulf War.[2] Roughly 40% of the total non-combat deaths in Iraq (about 250 total) were caused by combat vehicle or motor vehicle accidents. These numbers, while better than the historical precedent, are still staggering and represent the number of accidents from Iraq only; they do not include other accidents within the Army.

A review of Army vehicle accident reports reveals that the results of most investigations cite human error as the primary cause of the accident. Furthermore, according to these reports factors such as complacency, poor supervision, fatigue, lack of mission awareness, pressure to perform, and perceived conflicts with operational necessities are often involved in the mechanisms of an accident. While almost all accident investigations take into account the events and symptoms of an accident as well as the conditions and surface indicators, only on rare occasions do accident investigations include organizational problems which are usually the "root cause" of accidents.[3] This typical framework for safety analysis can be seen in Figure 2-1 below. It is critical to note that this phenomenon tends to occur in all types of organizations. For example, in his study of high-hazard industries in the private sector, John Carroll notes that most accident investigations produce problem diagnoses that are worker centric, resulting in extensive written detailed procedures and discipline. This leads to added job complexity and a reduction in trust between workers and management, which leads to slower work speed, alienation of workers, and a reduced flow of information between supervisors and their subordinates. Naturally, this leads to increased problems and therefore, a cycle of accumulating problems, accidents, and worker resentment.[4]

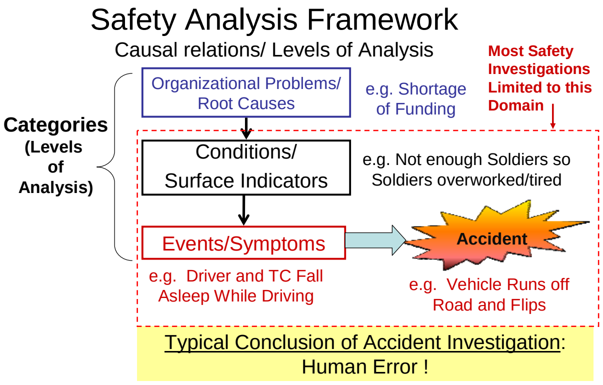


Figure 2-1 Safety Analysis Framework[5]

2.2 System Dynamics

System Dynamics was developed during the 1950s by MIT Professor Jay Forrester as a method for modeling large real world systems. Central to the System Dynamics modeling strategy is the representation of system structure in terms of stocks and flows, which measure the accumulation and dissipation of material or information over a period of time. Feedback loops are connected to these stocks and flows and serve as the building blocks for expressing the relationships between variables and overall dynamic behavior of complex interdependencies on the system. A key aspect of System Dynamics theory is the recognition of complex interdependencies among multiple feedback loops, and a rejection of simple linear cause-and-effect thinking, since in most systems the “effect” might also affect the “cause.”

In System Dynamics models a “+” sign indicates a positive polarity between variables (i.e. as in Figure 2-2, as the number of Accidents increases, the level of Organizational Stress also increases). Similarly, a “-“ link indicates a negative polarity between variables (i.e. as Safety Precautions increases, the number of Accidents decreases). The loop indicators such as “B1” indicate whether the loop is a balancing (B) or reinforcing (R) feedback loop as well as the loop identifier number (1, 2, 3…) which is used to distinguish between loops. Thus, loop “B1” should be read as “Balancing Loop 1.” In reinforcing feedback loops, as seen in Figure 2-2, an increase in one variable (in this case Accidents) produces an increase in another variable (Organizational Stress), which then causes a greater increase in Accidents. In balancing feedback loops, however, an increase in one variable (in this case Accidents) produces an increase in another variable (Safety Precautions), which ultimately causes a decrease in the original variable. Finally, a causal arrow with two perpendicular straight lines,  represents a delay in the system.

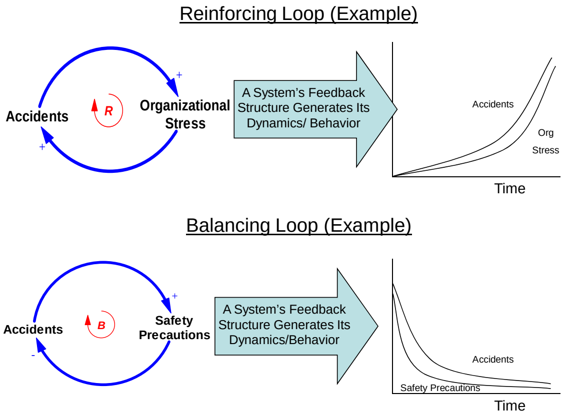


Figure 2-2 Reinforcing and Balancing Loops

3. Modeling Vehicle Safety

3.1 The High-Level Diagram

After a review of the literature and framing of the problem and research objectives, a high-level causal loop diagram was created to help determine the specific domain of the system and to better frame the key variables that might be used in a detailed model of the system. This high-level diagram was necessary for identifying and quantifying key variables which would help to focus efforts for subsequent data collection. Both the variables themselves and the direction of causality between variables were determined by examining over 500 Class A and B accident reports between the years 1998 and 2006 (accident reports were provided by the U.S. Army Combat Readiness Center), and by reviewing similar non-military safety studies from both public and private sectors. Figure 3-1 below is a depiction of the high-level diagram developed for this study.

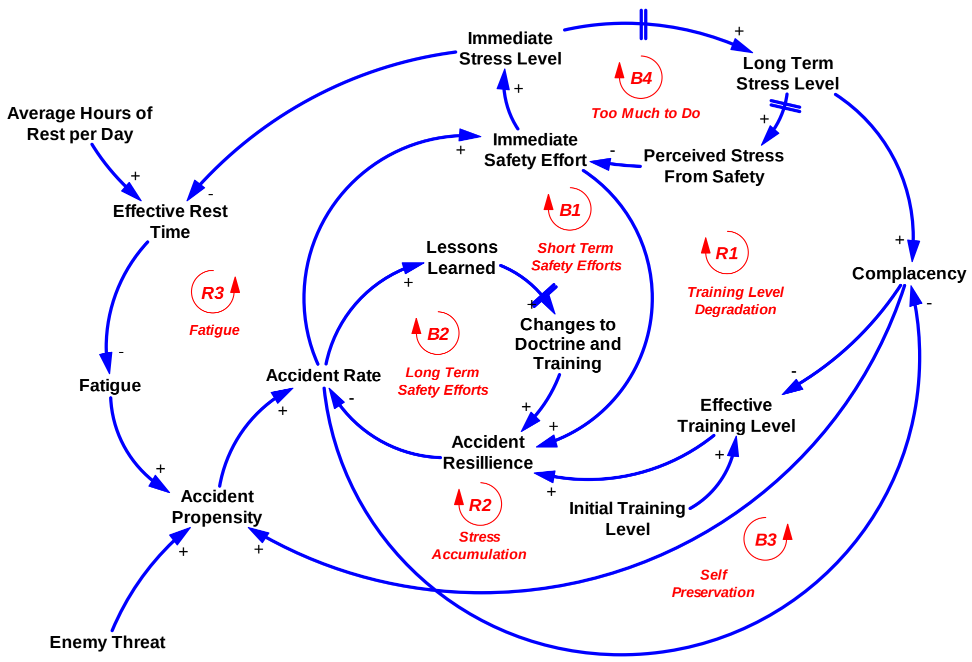


Figure 3-1 High-Level Model of Vehicle Safety

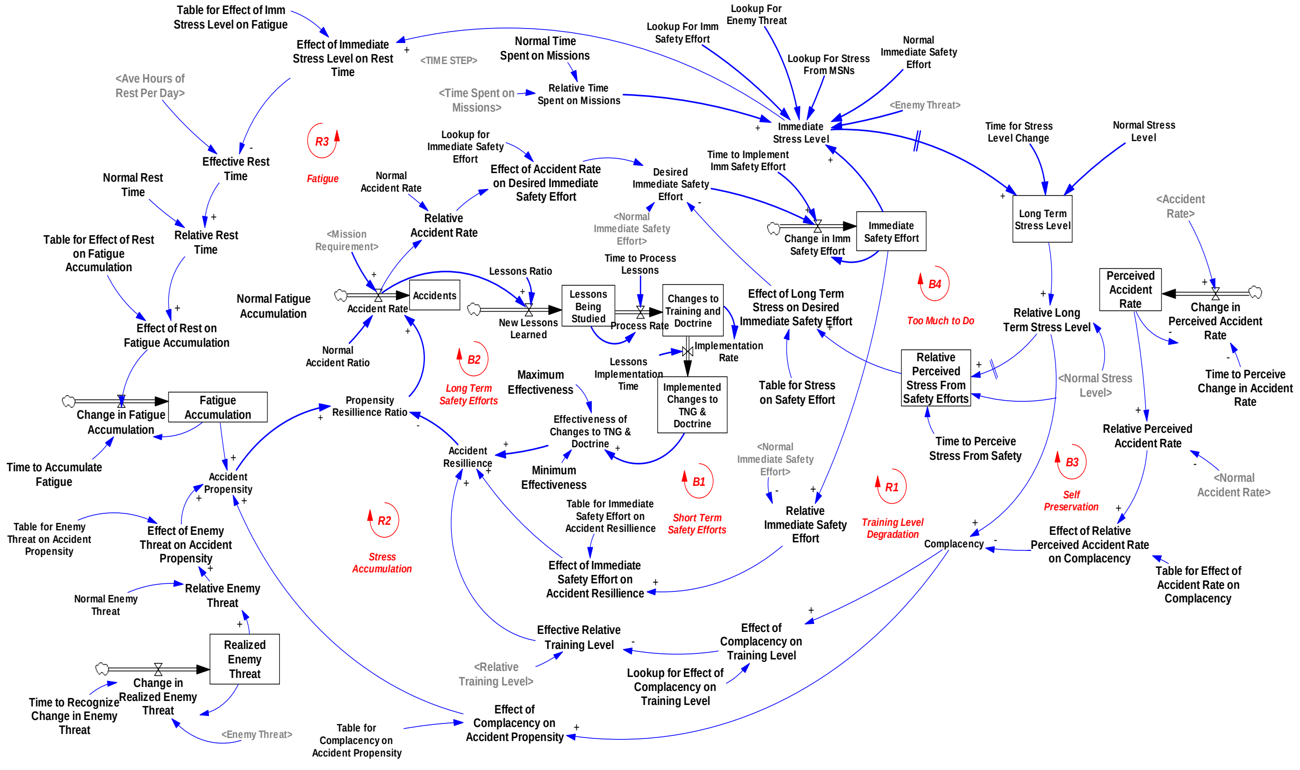


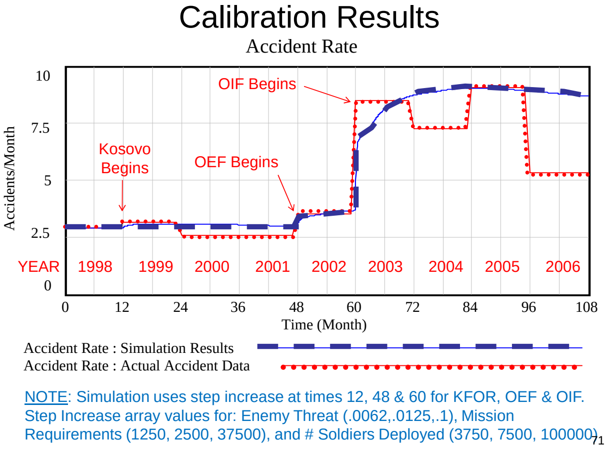
Figure 3-2 Proof of Concept Model

3.2 Proof of Concept Model

After collecting data, a proof of concept model was created. This process transformed the concept model of Figure 3-1 into a low-level and more detailed model that uses model parameters for exogenous variables and equations for endogenous variables to create a mathematical model of the system that can be simulated by changing various exogenous variables over time. Figure 3-2 shows a depiction of the proof of concept model.

3.3 Calibrating the Proof of Concept Model

Once the model was built a number of tests were conducted including sensitivity testing and extreme conditions testing to ensure the model exhibited plausible behavior. Sensitivity testing was conducted by examining how sensitive the model reacted to small changes in various model parameters. In addition, the model was tested under extreme conditions such as a range from zero soldiers deployed to 500 million soldiers deployed to ensure the model behaved sensibly even under unrealistically extreme conditions. Once the model was deemed sound, a final calibration was conducted. In conducting the calibration for this model, the time period from 1998-2006 was used to validate the model. Time Step 12 represents the rise of the Kosovo (KFOR) mission in 1999, time step 48 represents the invasion of Afghanistan (OEF-Operation Enduring Freedom) in 2002, and time step 60 represents the invasion of Iraq (OIF-Operation Iraqi Freedom) in 2003. Arrays of data were used to adjust the exogenous variables Enemy Threat, Mission Requirements, and Number of Soldiers Deployed across each of the three time steps. As seen in Figure 3-3, the simulated accident rate is very close to the actual historical accident rate. It is important to note that the historical data represents the annual average accident rate for each year, and therefore in reality would be more stochastic in nature.



Calibration Results

Accident Rate

NOTE: Simulation uses step increase at times 12, 48 & 60 for KFOR, OEF & OIF. Step Increase array values for: Enemy Threat (.0062,.0125,.1), Mission Requirements (1250, 2500, 37500), and # Soldiers Deployed (3750, 7500, 100000)

Figure 3-3 Model Calibration Results

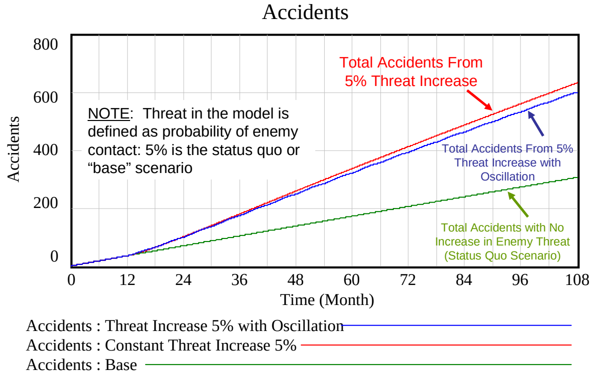
4. Learning from the Model

After calibrating the model, several dozen simulations were conducted with this model. Three of the most insightful simulation scenarios are discussed below.

4.1 Oscillations in Enemy Threat

A series of simulations were conducted to determine what effect an oscillation in the magnitude of the enemy threat would have on the system. These simulations were conducted with the intention of replicating how enemy activity is exhibited in many extended conflicts such as Iraq, Afghanistan, and Vietnam. Especially in low-intensity warfare, it is very difficult for the insurgent to maintain a constant level of offensive operations, as they periodically need to rest, refit, and develop new strategies and tactics.

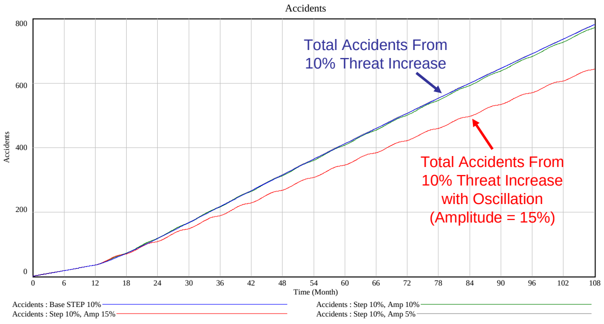
As seen in Figure 4-1, oscillations in the Enemy Threat can produce fewer accidents over time. A careful study of the system showed that Long Term Stress Level does not accumulate to as great an extent when the threat oscillates as it does when the threat is constant, despite the same total threat over time. This is because the system has time to recover and "burn off" stress when the Enemy Threat level is lower. This same phenomenon occurs with fatigue in the system.



IMPORTANT Finding: **An Oscillating Enemy Threat produces less accidents despite the same total enemy threat over time…Why? Because Long Term Stress and Fatigue do not reach the same level as they do when the system remains constant**

Figure 4-1 Impact of Oscillations in Enemy Threat

Figure 4-2 is an extension of this idea and shows that the same basic results apply among a wide range of values for amplitudes.



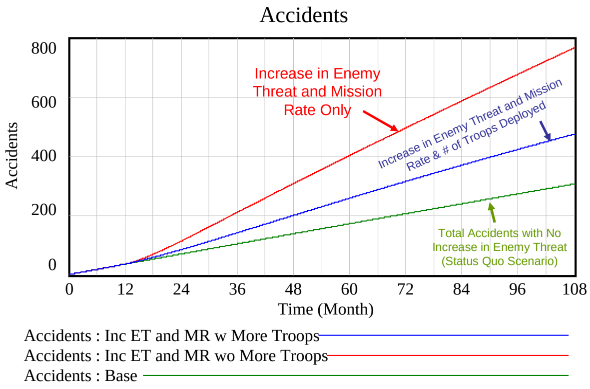
IMPORTANT Finding: **The same behavior is shown with increasing magnitudes in enemy threat AND increased oscillations. Here Enemy Threat increases by .1 vs. .05 previously, and amplitudes are 0, .05, .10, and .15. Thus, despite the same total amount of enemy threat over time in all cases, those with increased oscillations in enemy threat clearly exhibit fewer accidents.**

Figure 4-2 Impact of Larger Oscillations

The greatest improvements in the system occur when the greatest amplitudes are applied. This finding seems to suggest the importance of rotating Soldiers "off the line" and home on leave more frequently. It shows that Soldiers who are exposed to high levels of enemy threat followed by equal periods of rest, where rest in this context is defined as non-exposure to an enemy threat, will be less likely to have accidents.

4.2 Multivariate Simulation

Several multivariate experiments were also conducted to determine the impact that changing multiple variables simultaneously has on the system. As can be seen in Figure 4-3, the Enemy Threat, Mission Requirements and Number of Soldiers Deployed were increased simultaneously to see what effect it would have on the system. One important finding is that even minor increases in the Enemy Threat and Mission Requirements can cause significant increases in the Accident Rate, if the Number of Troops Deployed is not increased proportionately. This suggests that careful management of the troop-to-task ratio at a macro level of control is requisite to reducing combat vehicle accidents. Hence, if commanders on the ground are given too many missions to accomplish under hostile conditions, without enough troops to effectively share the burden, an unnecessary number of vehicle accidents will occur.



IMPORTANT Finding: **Even minor increases of .0125 (1.25%) for enemy threat and 25,000 for mission requirements produces a disastrous impact on accident rate and total accidents, IF the number of troops deployed is not also increased proportionately**

Figure 4-3 Multiple Variables at a Time

4.3 Troop Reduction Example

Finally, a hypothetical but plausible example of how this model might be used to assess the effects of a potential policy alternative is shown below. Several simulations were conducted, to determine the impact of various scaling options for a troop withdrawal. In one scenario troops were withdrawn from a war zone using a scaled approach where the mission rate and enemy threat were decreased proportionately over time with the number of troops in theater over a period of 24 months. In the second scenario, the troops were withdrawn along the same timeline, but the number of required missions and the enemy threat was held constant for the first 12 months, and then decreased at a faster rate during the last 12 months of the withdrawal. Figures 4-4 and 4-5 show the effect of these simulations on the Accident Rate and total Accidents respectively.

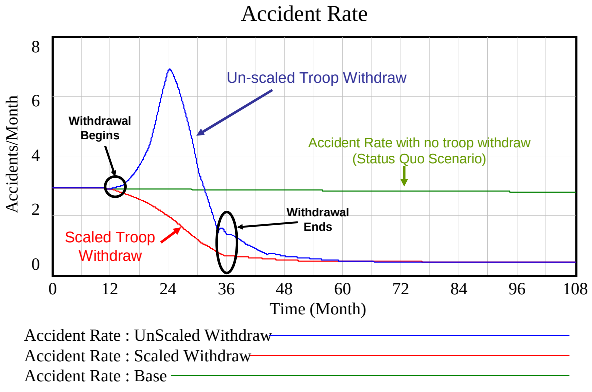
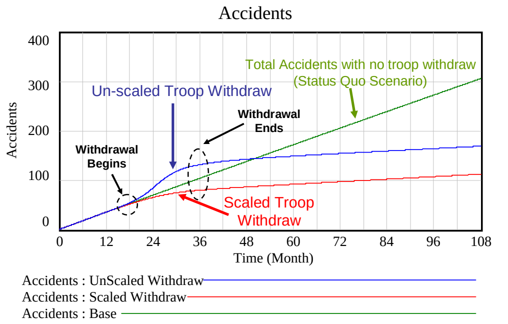


Figure 4-4 Troop Reduction Scenario

As the graphs in Figures 4-4 and 4-5 show, there are serious unintended consequences involved with conducting a troop withdrawal that is not phased proportionately with a decrease in Enemy Threat and Mission Requirements. The graphs of Complacency and Immediate Stress Level, Figures 4-6 and 4-7 respectively, explain this phenomenon.



IMPORTANT Finding:

- **Any troop withdraw must be carefully scaled with a concurrent and proportional decrease in mission rate and enemy threat in order to avoid excessive complacency and fatigue that lead to accidents**
- **Same model behavior with constant enemy threat as with decreasing enemy threat, only exception is constant enemy threat (i.e. no reduction of enemy threat) produces a greater number of accidents proportionately)**

Figure 4-5 Troop Reduction Scenario

The simulations show that Stress and Complacency are much greater in the case where the withdrawal is un-scaled. As can be seen in Figure 4-4, this translates to a much greater Accident Rate for the un-scaled withdrawal, as opposed to the scaled withdrawal, and the total number of accidents caused by the 24 month withdrawal is approximately 75% greater in the un-scaled case.

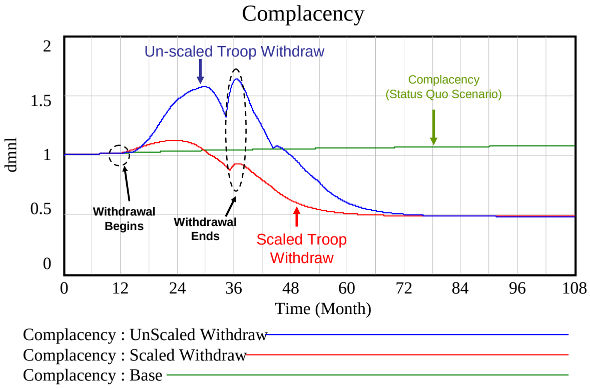


Figure 4-6 Complacency

It is also interesting to note that when the model is simulated for a troop withdrawal with a reduction in Mission Requirements only, and no reduction in Enemy Threat (a factor that often cannot be controlled), the model still exhibits the same behavior. The only exception occurs when the Enemy Threat is not reduced; in this case the total number of Vehicle Accidents will be greater than when the Enemy Threat is reduced over time.

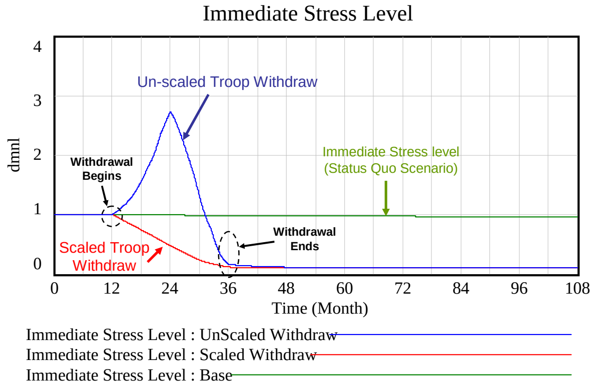


Figure 4-7 Stress

This model could be useful to a policy maker who is contemplating whether or not to conduct a troop withdrawal, and if so, how to conduct it. The results of this simulation would suggest that any troop withdrawal must be carefully scaled with a concurrent and proportional decrease in mission rate and enemy threat in order to avoid excessive complacency and fatigue that leads to accidents.

5. Conclusions

The following conclusions are consistent with the findings in this study. The findings are derived from three sources; the literature review, construction of the model, and simulation using the model.

Understanding Delays. Some of the greatest potential for improving safety can be found by understanding the dynamic effect of various delays in the system. In this model, these delays include the Time to Process Lessons, Lessons Implementation Time and Time to Implement Immediate Safety Effort. These are critical because they speed up the Long Term Safety Efforts Loop which would therefore facilitate a decrease in the Short Term Safety Efforts Loop.

Balancing Short Term and Long Term Safety Efforts is crucial: Too much focus on short term efforts can actually be detrimental to safety over the long term, but some short term efforts are needed to reduce vehicle accidents because of the time delay involved with institutional learning and doctrine/training change.

Balancing the Mission Rate/OPTEMPO with Availability of Troops is paramount to accident reduction. This must occur not only at lower-unit level (e.g. Battalion and Company levels), but also by war planners and decision makers at the highest levels of the military. This has a direct, but potentially unnoticed, impact on fatigue, complacency and stress which are major contributors to accidents.

Troop Exposure to the Enemy Threat. Operating Environments with a fluctuating/oscillating enemy threat will produce fewer vehicle accidents than those with a constant (and proportional) enemy threat. This also suggests the benefit of rotating Soldiers out more frequently “off the line” or on “R&R”. In addition, shorter deployment times with more time off will have a critical impact on reducing complacency and fatigue which will lead to fewer accidents.

Conduct of Accident Investigations. The Army has an outstanding After Action Review process that encourages continuous double loop learning throughout the organization. This process is made possible by open feedback of both positive and negative aspects of mission planning and execution by subordinates and superiors alike. While this process works well for learning from operations and training exercises where retribution is rarely taken for mistakes made, it is not the case with accident investigations. Since most soldiers believe that the purpose of an accident investigation is to assign blame, many Soldiers and leaders involved in accident investigations are likely to remain silent. This is specifically the case with those most directly involved in the accident who have the most important information to share. Therefore, the Army should consider adopting a new approach to accident investigations that focuses on organizational learning in lieu of assigning blame.

Finally, in addition to the insights discussed above, this study shows how the field of System Dynamics can provide both a solution method and tool for understanding highly complex, wicked problems that involve non-linear feedback.

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Major **NATHAN MINAMI** is an instructor of Systems Engineering at the United States Military Academy. His education includes a B.S. from USMA and an M.S. from MIT. Major Minami has been deployed on numerous operational assignments around the world, including as an infantry company commander in Iraq.

Dr. **STUART MADNICK** is the John Norris Maguire Professor of Information Technology and Professor of Engineering Systems at MIT. He has been a faculty member at MIT since 1972 and has served as the head of MIT's Information Technologies Group for more than twenty yeas. Dr. Madnick is the author or co-author of over 250 books, articles, or reports including the classic textbook, *Operating Systems*, and the book, *The Dynamics of Software Development*.