Using Systems Analysis to Improve Traffic Safety

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by

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Abstract

Despite the efforts of driver's training and other safety programs to make U.S. highways and roads safe, thousands of U.S. citizens are killed each year in traffic accidents that could have been prevented. A similar problem exists in the U.S. Army where several hundred soldiers have been killed in the last decade in preventable combat vehicle accidents while on operational deployments around the world. This study shows how System Dynamics analysis can be used to better understand the complex root causes of vehicle accidents. It shows how this approach has been used to better understand and predict non-combat related vehicle accidents in Iraq and how it can be used to explain how and why individual accidents take place. Finally, suggestions are provided as to how lessons learned from the modeling and study of combat vehicle accidents in the U.S. Army can be used to model, simulate, analyze and understand various aspects of vehicle safety on U.S. civilian roads and highways.

Introduction

While approximately 15,000 people are murdered in the U.S. each year, this number pales in comparison to the roughly three times this number who are killed annually in vehicle accidents (Dumbaugh & Rae, 2009; Kissinger, 2009; Rothe, 2008). In other terms, in 2005, 4.7 of every 100,000 Americans were murdered, while 15.7 per 100,000 were killed in a traffic accident (Rothe, 2008). Indeed, the leading cause of deaths in America for people between ages 2 and 34 is traffic accidents. These accidents have resulted in over a million deaths in America in the last 25 years (Kissinger, 2009). Traffic accidents are also costly, with approximately $230 billion in damages caused by accidents in 2003 alone. Consequently, there have been many studies and initiatives undertaken at various levels of government and by many institutions in an attempt to make America's roadways safer.

Some of the methods and focus of studies have been on improving traffic safety through enhanced community design (Dumbaugh & Rae, 2009), improvements in safety culture (Kissinger, 2009), the role of sport utility vehicles and pickup trucks in traffic safety (White, 2004), and the careful alignment of streets in designing transportation networks to achieve a "traffic calming" effect (Evans, 1998). Other studies have focused on improving traffic safety by focusing on the effect of state regulations (Neeley & Richardson, 2009), as well as technological solutions such as collision warning and avoidance systems (Chisalita & Shahmehri, 2002) and vehicle to vehicle wireless communication systems (Biswas, Tatchikou & Dion, 2006). There have also been studies that focus on the effects of driver's age, education and experience in traffic safety (Levy, 1990), the role of alcohol in traffic accidents (Caputo, Trevisani, & Bernardi, 2007), and the utility of sobriety checkpoints in enhancing traffic safety (Levy, Shea & Asch, 1989).

This chapter provides a different approach to traffic safety. It demonstrates how systems analysis can be used in a number of different ways to better understand and improve traffic safety. Specifically, it shows how System Dynamics modeling techniques can be employed in various capacities to analyze traffic systems and accidents on different levels. The chapter begins with a brief introduction to the field of System Dynamics, then follows with an example of how System Dynamics modeling techniques can be used to model and simulate large scale traffic systems to determine what policies or levers in the system are most effective in mitigating traffic deaths. The final section describes how the same modeling method can be used to model and better understand how individual traffic accidents occur, providing an explanation for the complex root causes that are often involved in traffic accidents.

System Dynamics

System Dynamics was developed during the 1950s by MIT Professor Jay Forrester as a method for modeling large real world systems. While System Dynamics is grounded in the rigorous mathematical disciplines of control theory and nonlinear dynamics, it was developed with the intention of becoming “a practical tool that policy makers can use to help them solve the pressing problems they confront in their organizations” (Sterman, 2000).

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.” System Dynamics has been used to model a wide variety of different systems including state-stability and insurgencies, supply chain management, software development, command and control systems, and dynamics of economic growth (Abdel-Hamid & Madnick, 1991; Angerhofer & Angelides, 2000; Choucri et al., 2007; Lofdahl, 2005; Minami, 2007) .

In System Dynamics models a “+” sign indicates a positive polarity between variables (i.e. as in Figure 1, 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 1, 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. Therefore, the effect of a reinforcing loop is to reinforce the effect of an initial external stimulus placed on the system. Reinforcing loops typically produce exponential growth. 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. Thus, the effect of a balancing loop is to balance the effect of an initial external stimulus on the system. Balancing loops typically produce goal seeking behavior.

Figure 2 shows the effect of combining balancing and reinforcing feedback loops. In this, case, an increase in Accidents initially leads to an increase in Organizational Stress which causes an increase in the number of Accidents. But over time, the effects of this reinforcing feedback loop are mitigated by the effect of Safety Precautions, which leads to the number of accidents leveling off. This is called S-Shaped behavior, and is typical of systems that combine balancing and reinforcing feedback loops. Finally, a causal arrow with two perpendicular straight lines,  represents a delay in the system (see Figure 4).

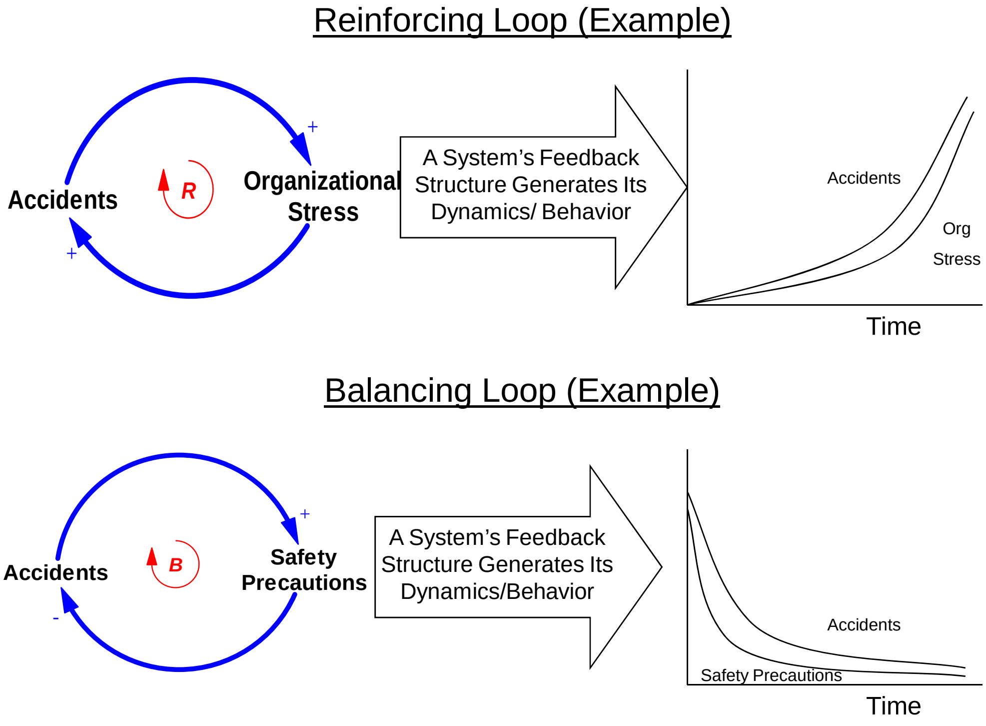


Figure 1 Reinforcing and Balancing Loops

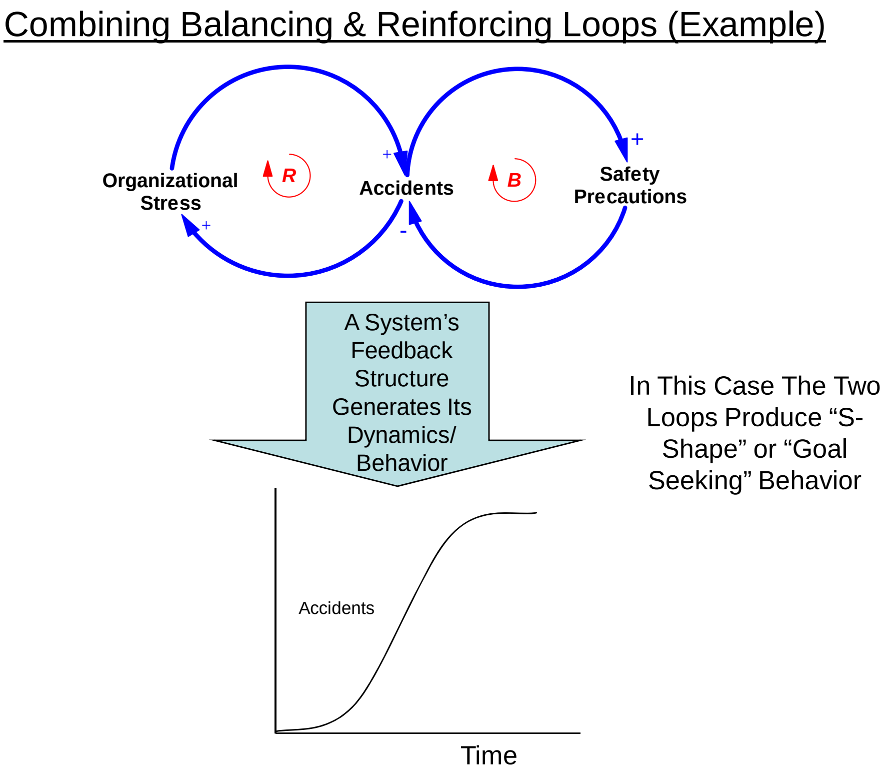


Figure 2 Combining Feedback Loops

Macroscopic System Dynamics Analysis of Vehicle Accidents

System Dynamics can be used to examine traffic safety problems on both a macroscopic level that includes a complex system of systems analysis, as well as on a lower microscopic level that explains how and why individual vehicle accidents occur. This section focuses on the former. It shows how System Dynamics can be used to model and simulate complex traffic systems so that practical lessons can be learned and effective policies implemented that help to reduce accidents and save lives (Minami & Madnick, 2009).

In the study of combat vehicle accidents, the problem examined was that despite extraordinary efforts by Army leaders at all levels, hundreds of soldiers die or are severely injured each year from accidents that should have been prevented. The objective of this System Dynamics model was to help policy makers better understand the effects of various dynamic feedback processes and delays involved with decision making, specifically in regards to accident prevention. This macroscopic model focused on high-level organizational factors that impact safety, which can help policy makers to better understand which levers in the system play the biggest role in risk mitigation.

Background & Context

In attempting to create a System Dynamics model that addresses a complex problem such as organizational processes that affect safety, it is important to first conduct a comprehensive review that addresses the background and context of the problem. Later in the modeling process, this is important because it helps to define the boundaries of the model. In the study of U.S. Army combat vehicle accidents in Iraq, between the initial invasion in March 2003 and May 2007, approximately 20% of the Army's combat casualties were a result of accidents (over 600 total). In comparison, 28% of deaths were non-combat related during WWII and 49.5% were non-combat related during the Gulf War (LSU, 2007). So while the percentage of non-combat related deaths has decreased since WWII, 600 deaths due to accidents in a four year period is hardly acceptable to the Army or the American public. It is particularly interesting to note that roughly 40% of the non-combat deaths in Iraq (about 250 total) during this time period were caused by combat vehicle or motor vehicle accidents.

A review of hundreds of Army combat vehicle accident reports between 2003 and 2007 showed that the results of most investigations cited "human error" as the primary cause of the accident. These reports cited complacency, poor supervision, fatigue, lack of mission awareness, pressure to perform, and perceived conflicts with operational necessities as the primary causes of accidents. Most studies focused on the events or symptoms of an accident and not on the organizational problems and root causes of accidents (Leveson, 1995). Addressing the organizational problems is critical, especially for problems with a complex and dynamic root cause. This typical framework for safety analysis can be seen in Figure 3 (Leveson, 1995).

A typical accident investigation begins by addressing how the accident occurred and what lead to the death of the driver or passengers. As an example this might include a vehicle running off the road, the gunner who was standing in the turret being ejected from the vehicle, and then the vehicle landing on the soldier which led to his death. The typical accident report would then address the events that led up to the vehicle running off of the road, and might find that the driver or vehicle commander fell asleep which led to the vehicle running off the road. Unfortunately, the majority of accident reports stop at this level of analysis, and the conclusion of the accident investigation is that human error caused the accident. While this may be partially true, there is usually more to the story that is never investigated, such as why did that person fall asleep.

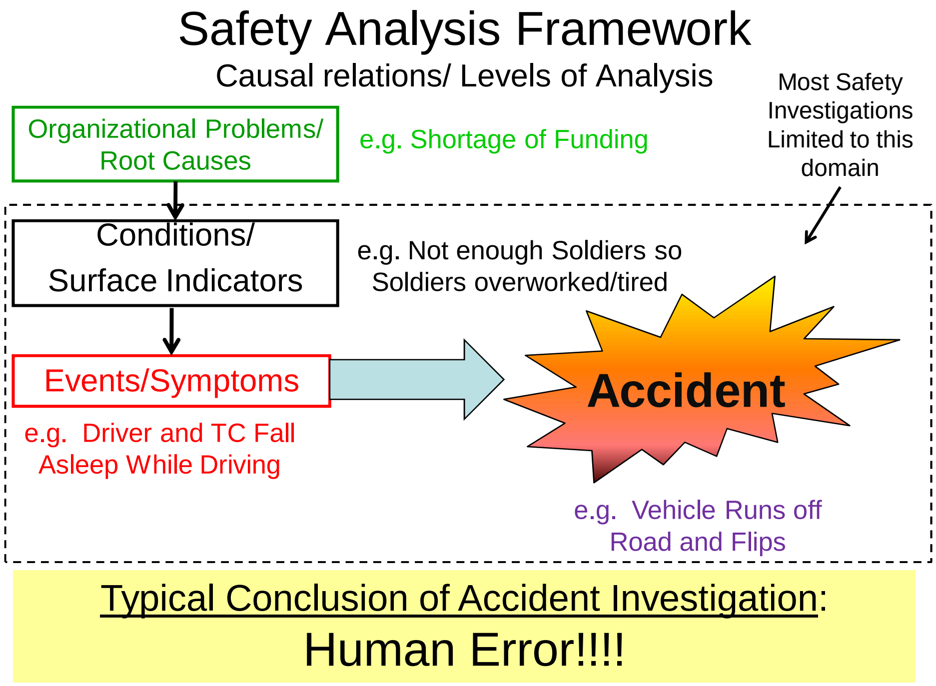


Figure 3: Safety Analysis Framework

Modeling Vehicle Safety

The next step in creating a System Dynamics model of vehicle safety is to create a high level conceptual model that addresses how various variables interact and establishes causality between them. This is possible only after a lengthy review of the literature and proper framing of the problem and research objectives. In the study of combat vehicle safety, 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. Data was collected to determine causality by examining over 500 Class A accident reports provided by the U.S. Army Safety Center and by confirming these findings with evidence from civilian traffic safety literature and other applicable studies. Figure 4 is a depiction of the high-level diagram developed for this study. The key feedback loops are explained below.

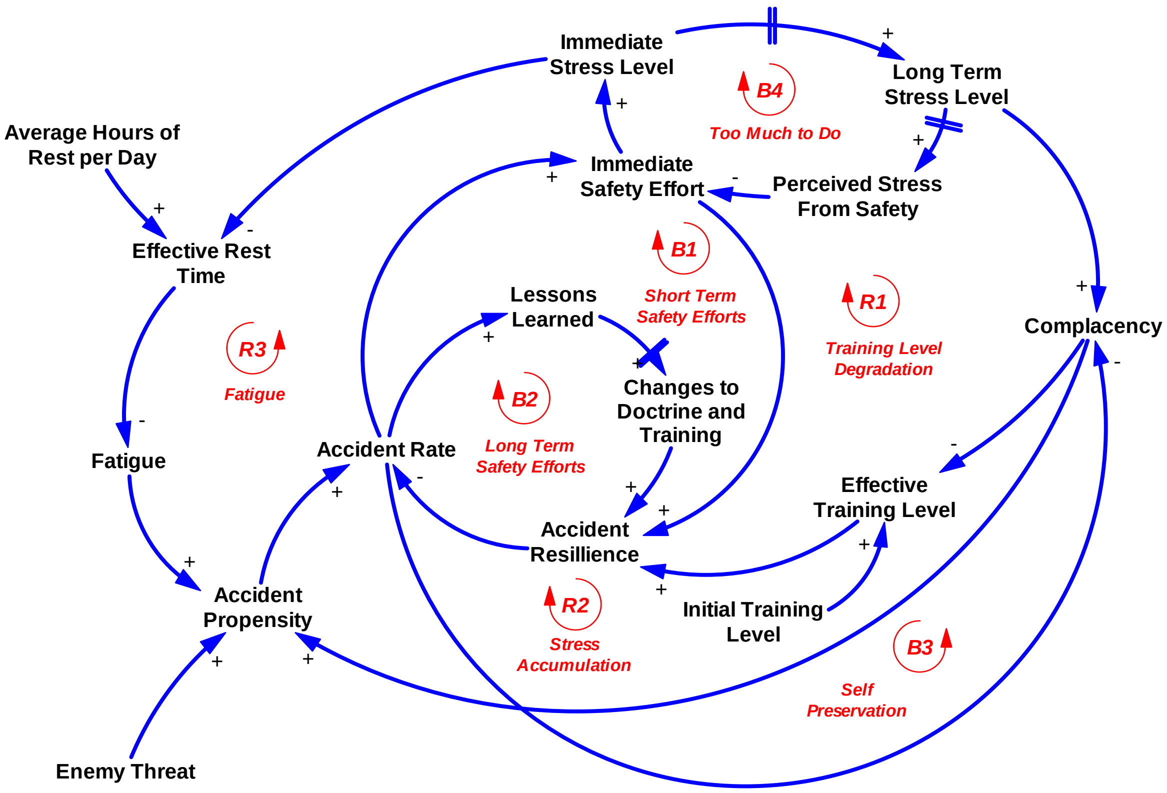


Figure 4: High-Level Model of Vehicle Safety

Reinforcing Loop R1 represents the affect of training degradation. This implies that training level erodes over time if the training is not conducted or reinforced at regular intervals. In this loop, there is a positive relationship between Accident Rate and Immediate Safety Effort, as well as a positive relationship between Immediate Safety Effort and Immediate Stress Level (Carroll, 1998; Cook, 1999; Dekker et al., 2007; Murphy, DuBois & Hurrell, 1986; Rudoloph & Repenning, 2002). There are also positive relationships between Immediate Stress Level and Long Term Stress Level (Carroll, 1998; Carroll et al., 2007; Homer, 1985; Murphy et al., 1986; Selzer & Vinokur, 1974), as well as Long Term Stress Level and Complacency (Carroll, 1998; Homer, 1985; Murphy et al., 1986; Rudloph & Repenning, 2002; Selzer & Vinokur, 1974). There are also two negative relationships in this loop. The first occurs between Complacency and the Effective Training Level (Gunther, 2002; McKelvey, 1988; Rudolph & Repenning, 2008), and the second between Effective Training Level and Accident Rate (Chau et al., 2002; Dorn & Barker, 2005; Gunther, 2002; Mayhew, Simpson & Ferguson, 1998). An important delay exists in this loop between the Immediate Stress Level and Long Term Stress Level. This delay represents the fact that it takes time for stress to build up in the system. This loop is also important because it describes how Long Term Stress and Complacency erode an organization's initial training level. Taken in isolation from the rest of the model, reinforcing loop R1 would lead to an exponential increase in accidents.

Reinforcing loop R2 (Stress Accumulation) is similar to loop R1 but represents the effect of stress accumulation by acknowledging the direct link between Complacency and Accident Propensity (Carroll, 1998; Leveson & Cutcher-Gershenfeld, 2007; Slovic, Lichtenstein & Roe, 1981). The stress accumulation feedback loop represents the important role that Complacency plays in causing vehicle accidents. Complacency achieves this by causing both a direct decrease in Accident Resilience through degradation of the training level and a direct increase in Accident Propensity by decreasing a driver's awareness to hazards and decreasing leader supervision.

Another important loop in the model that by itself would lead to an exponential increase in vehicle accidents is reinforcing loop R3 (Fatigue). Loop R3 represents an interesting example of an unintended consequence of immediate knee-jerk safety efforts (Short Term Safety Efforts). It describes how as the Accident Rate increases, the Immediate Safety Effort and Immediate Stress Level also increase requiring more time and effort, which produces a decrease in the Effective Rest Time (Hefez, Metz & Lavie, 1987; Kalimo, Tenkanen, Hama, Poppius & Heinsalmi, 2000; Kirmil-Gray, Eagleston, Gibson & Thoresen, 1984) and an increase in Fatigue (Fadda & Fratta, 1997; Hefez et al., 1987; Kalimo et al., 2000). This increase in fatigue produces an increase in Accident Propensity (Brown, 1994; Chau et al., 2002; Dinges, 1995; Summala & Mikkola, 1994) and therefore an increase in the Accident Rate. This loop is significant because it addresses the phenomenon where as soldiers are required to do more work, the amount of stress in the organization increases. This is complicated by the fact that stressed out soldiers will not use all of their off duty time resting, as their chain of command might assume. Rather, they will use at least some of their off duty time relaxing and blowing off steam. In many cases, these burnt out and tired soldiers will spend hours playing video games, talking on the phone and chatting on the internet instead of resting for the next mission.

It is also important to address the balancing loops in this model, because without them, accidents would grow exponentially. Balancing Loop B1 describes how short term safety efforts act to decrease the accident rate. Important relationships between variables include the positive relationship between the Accident Rate and Immediate Safety Effort undertaken by lower-level Army units (Carroll, 1998; Carroll, Rudolph & Hatakenaka, 2007; Degger, Siegenthaleer & Laursen, 2007; Cook, 1999). Another positive relationship exists between Immediate Safety Effort and Accident Resilience (Carroll, Rudolph & Hatakenaka, 2007; Dekker et al., 2007; Cook, 1999; Cox & Jones, 2006). As can be seen by the previous citations, the causation between variables in this loop, as well as the other loops in this model, are supported by a number of different independent studies. Loop B1 is specifically interesting because it describes the positive effects of knee-jerk reactions to a safety crisis.

Balancing Loop B2 describes the effect that long term safety efforts has on the system, or what can also be described as institutional learning. In this loop, there is a positive relationship between Accident Rate and Lessons Learned (Carrol et al., 2007; Garvin, 19993; Huber, 1991 & Kock, McQueen & Baker, 1996) and also a positive relationship between Lessons Learned and Changes to Doctrine and Training (Carroll et al., 2007; Garvin, 1993; Huber, 1991 & Cock, 1996). There is also a positive relationship between Changes to Doctrine and Training and Accident Resilience (Carroll et al., 2007; Leveson, 1995; Leveson & Cutcher-Gershenfeld, 2007; Pate-Cornell, 2004). Finally, there is a negative relationship between Accident Resilience and the Accident Rate, which makes this a balancing loop. There is also an important time delay between Lessons Learned and Changes to Doctrine and Training. This is because it takes time for the Army as an institution to conduct detailed studies and implement new policies and procedures which reduce accidents. Ultimately, this delay facilitates the tendency to make immediate knee jerk changes at unit level because of the desire to stop accidents immediately. In most cases, this causes a number of unintended side effects, one of which is increased stress levels in a unit.

Balancing Loop B3 addresses self preservation. In this loop, as the Accident Rate increases, Complacency decreases (Leveson & Cutcher-Gershenfeld, 2007; Slovic et al., 1981; Stave, 2005; Weinstein, 1999). This produces a decrease in accident propensity and a decrease in the Accident Rate. This loop shows that as accidents occur more frequently, a larger proportion of Soldiers will be immediately impacted by the injuries or deaths that they witness. The proximity between these soldiers and the accidents helps to encourage soldiers to take more precautions towards safety.

Balancing Loop B4 describes how having too much work to do encourages soldiers to take actions to reduce stress. Among the relationships between variables in this loop, there is a positive relationship between Long Term Stress Level and Perceived Stress from Safety (Carroll, 1998; Carroll et al., 2007; Homer, 1985; Murphy et al., 1986; Selzer et al., 1974). However, there is a negative relationship between Long Term Stress Level and the Immediate Safety Effort (Carroll, 1998; Carroll et al., 2007; Homer, 1985; Murphy et al., 1986).

Finally, it is important to note one of the critical exogenous variables in the model. Enemy Threat represents the idea that as the Enemy Threat increases, a soldier’s perception of safety hazards decreases. This makes soldiers more likely to violate safety regulations and procedures. A typical example of this is soldiers refusing to wear their seat belts because of the belief that the seat belts will prevent them from exiting the vehicle quickly if they come under enemy fire. Another example that arises frequently in accident reports is drivers driving fast in order to minimize the possibility of a roadside bomb successfully striking the vehicle. Unfortunately, this often result in unsafe speeds, and therefore, more accidents.

Data Collection and Calibration

The next step in creating a System Dynamics model of military vehicle safety is to collect data that can be used to calibrate the mathematical model. Data was collected from the accident reports provided by the U.S. Army Safety Center. For each report, the chain of events that lead to each accident were carefully reviewed to find the underlying conditions that were present in the system that allowed the accident sequence chain to be set in motion. A hypothetical example of an accident sequence chain depicting various levels of analysis is shown in Figure 5.

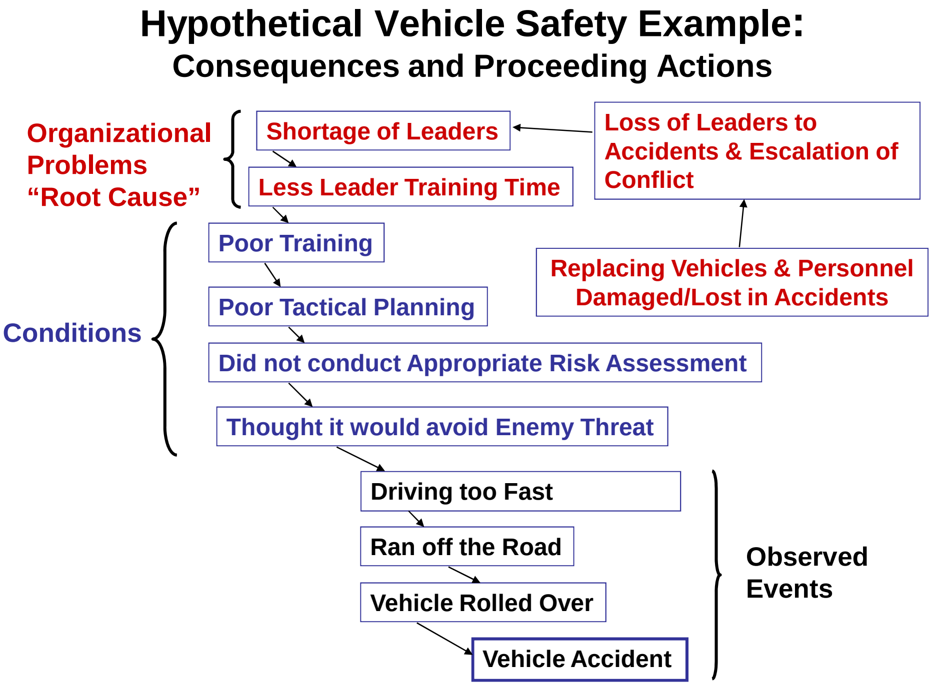


Figure 5: Hypothetical Accident Sequence Chain

In this hypothetical example, a vehicle accident occurred when a vehicle rolled over. The vehicle rolled over because it ran off the side of a road and hit a ditch which caused the vehicle to flip. The vehicle ran off the road because it was moving too fast and the driver lost control. These events did not happen on their own, however, there was also a sequence of conditions that triggered these events. The driver was driving too fast because he or she thought, perhaps correctly, that if they drove faster they would have a greater chance of avoiding an enemy road side bomb. They were driving too fast, however, because they did not conduct an appropriate risk assessment prior to the mission that balanced the threat of roadside bombs which is amplified by driving too slow, with the threat of road and traffic conditions that can be complicated by driving too fast. The reason for the failure to conduct this risk assessment was poor planning on the part of the unit leader, which was a direct result of the leader not having been trained on how to properly conduct risk assessments. This is where a typical accident investigation stops. The driver, vehicle commander, and possibly the patrol leader would be found culpable and blame for the accident assigned. But in reality, there can be much more to this scenario.

It is unlikely the fault of the patrol leader that he or she received poor training, but rather one reason for this poor training is that there is less time for leader training available in the Army. The reason for this dearth in time for leader training is that there are not enough leaders in the Army, which is at least partially a result of leaders who are lost in accidents and the demand for more leaders due to an escalation in conflict. Finally, this loss of leaders and increase in violence is due in part to the Army's need to replace vehicles and personnel who are damaged, killed, or wounded in accidents – which take up a considerable amount of the time and attention of the leaders. Therefore, the accident occurring in itself only contributes to the root cause of the accident, which produces a reinforcing feedback loop of continuing accidents. While this particular example is hypothetical, it is also very plausible. It is important to reiterate that as described in Figure 3, most accident reports focus myopically on the events and conditions of an accident, and fail to address the organizational root causes of accidents, and therefore fail to see the feedback that is involved in a systematic analysis of the problem.

Next, an extensive analysis of Army Accidents during the years 1998 through 2006 was conducted to determine a variety of statistics, including pre-war and war accidents rates. Some of this data can be seen in Figure 6. As Figure 6 shows, there was not a significant increase in the total number of accidents of all categories when comparing the pre-war and war periods. There was, however, a significant increase in the Class A and B accidents (those involving death or serious injuries.) We believe this is because in times of war, not all Class C & D accidents (those involving only minor injuries and damage) are reported due to other demanding requirements. Thus, our analysis used Class A & B reports only.

Accident Type	**Time Frame**	**Ave Monthly Accident Rate**
ALL	1998-2001	64.6
	2002	61.83
	2003-2006	73.04
Class A	1998-2001	1.67
	2002	2.58
	2003-2006	5.19
Class A & B	1998-2001	2.81
	2002	3.5
	2003-2006	7.54

Figure 6: Sample Accident Data

The Mathematical Model

The next step is to create a mathematical model where the concept model of Figure 4 is transformed 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. The low level model for this study with its supporting parameters and equations can be seen in Figure 7. After the model was created, it was then calibrated to ensure that the model behaved plausibly using historical data. This is critical to verify that model parameters are correct and to improve the validity and reliability of simulation results and findings that can be drawn from the model.

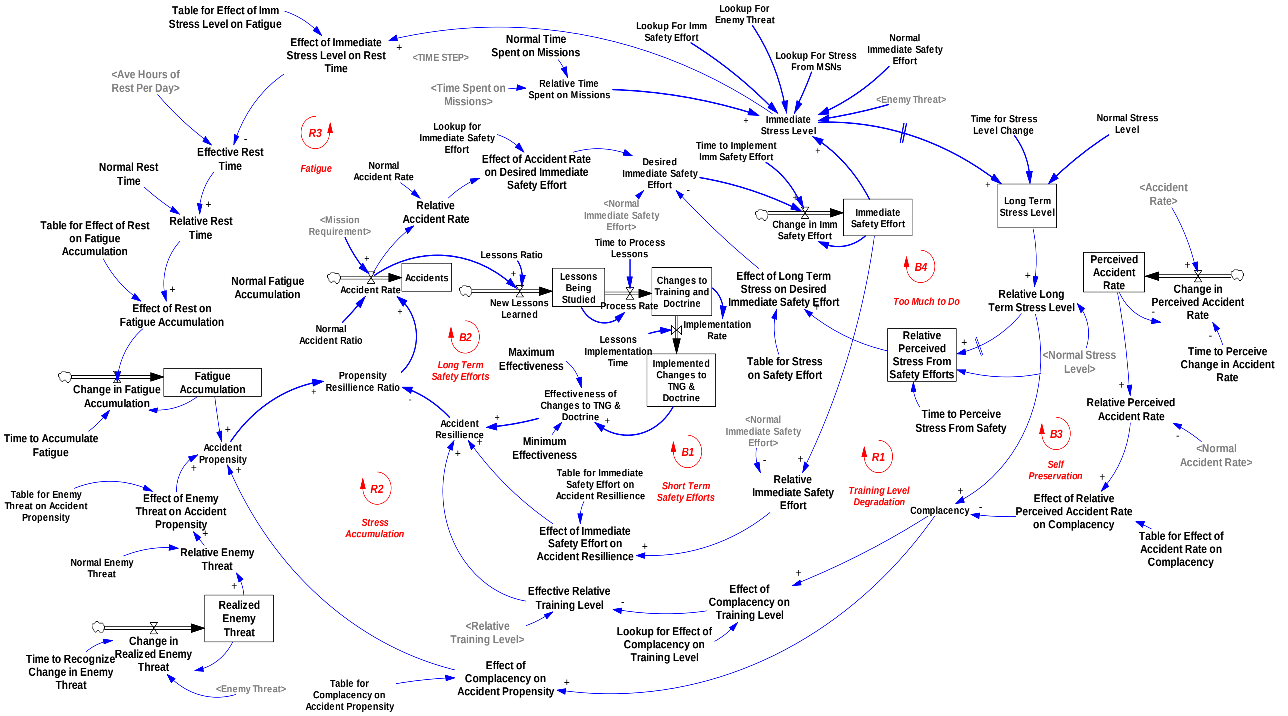


Figure 7: Low-Level Model

Accident Propensity

Parameter	Name	Value
NAR	Normal Accident Ratio	2.92e-005
MR	Mission Requirement	100,000
NAR	Normal Accident Rate	2.92
TIISE	Time to Implement Immediate Safety Effort	1
LR	Lessons Ratio	.1
TPL	Time to Process Lessons	6
LIT	Lessons Implementation Time	6
ME	Maximum Effectiveness	4
MEF	Minimum Effectiveness	1
TSLC	Time for Stress Level Change	6
NSL	Normal Stress Level	1
TPSFS	Time to Perceive Stress From Safety	3
TRCET	Time to Recognize Change in Enemy Threat	1
TPCAR	Time to Perceive Change in Accident Rate	3
NET	Normal Enemy Threat	.05
NRT	Normal Rest Time	12
TAF	Time to Accumulate Fatigue	1
NFA	Normal Fatigue Accumulation	1

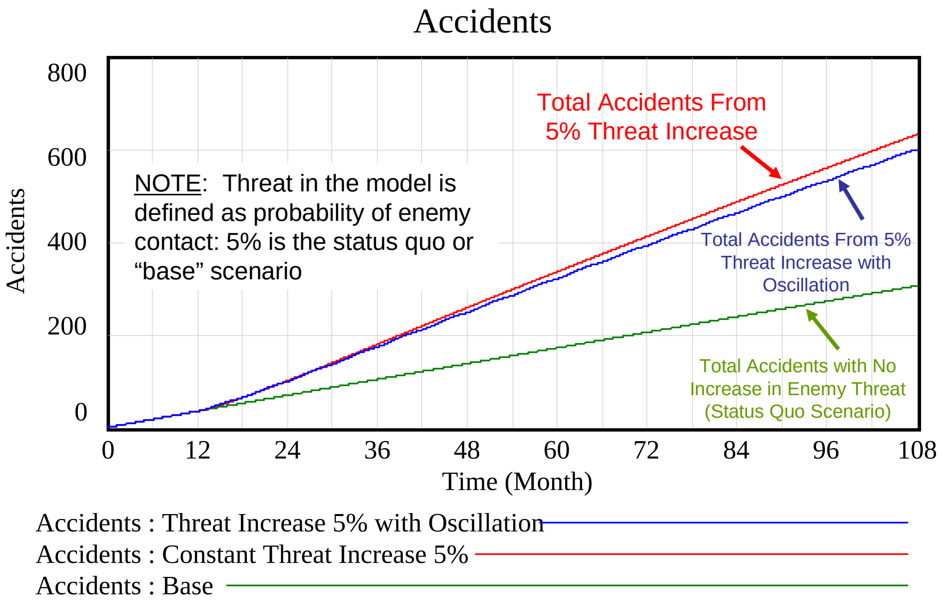
Accident Propensity: AP=ECAP*EETAP*FA
Accident Rate: AR=NAR*MR*PRR
Accident Resilience: AIR=ECTD*EISEAR*ERTL
Accidents: A= $\int_0^t AR\,dt$
Change in Enemy Threat: CET= (ET-RET)/TRCET
Change in Fatigue Accumulation: CFA= (ERFA-FA)/TAF
Change in Imm Safety Effort: CISE=(DISE-ISE)/TIISE
Change in Perceived Accident Rate: CPAR= (AR-PAR)/TPCAR
Changes to Training and Doctrine: CTD = $\int_0^t (PR - IR)\,dt$
Complacency: C= ERPARC*RLTSL
Desired Immediate Safety Effort: DISE= EARDISE*ELTSDIS*NISE

Effect of Accident Rate on Desired Immediate Safety Effort: EARDISE = f(RAR)
Effect of Complacency on Accident Propensity: ECAP= f(C)
Effect of Complacency on Training Level: ECTL= f(C)
Effect of Enemy Threat on Accident Propensity: EETAP= f(RENT)
Effect of Immediate Safety Effort on Accident Resilience: EISEAR= f(RISE)
Effect of Immediate Stress Level on Rest Time: EISLRT = f(ISL)
Effect of Relative Perceived Accident Rate on Complacency: ERPARC= f(RPAR)
Effect of Rest on Fatigue Accumulation: ERFA=f(RRT)
Effect of Long Term Stress on Desired Immediate Safety Effort: ELTSDISE= f(RPSFSE)
Effective Relative Training Level: ERTL= RTL*ECTL
Effective Rest Time: ERT= AHRPD*EISLRT
Effectiveness of Changes to Training and Doctrine:
$ECTD = MIN(MAXE, MINE + (.05 * \sqrt{ICTD})$
Fatigue Accumulation: FA= $\int_0^t CFAdt + NFA$
Immediate Safety Effort: ISE=$\int_0^t CISE\,dt$
Immediate Stress Level: ISL = ET*(ISE/NISE)*RTSM
Implementation Rate: IR= CTD/LIT
Implemented Changes to TNG & Doctrine: ICTD = $\int_0^t IRdt$
Lessons Being Studied: LBS= $\int_0^t (NLL - PR)dt$
Long Term Stress Level : LTSL= $\int_0^t \left(\frac{ISL}{TSLC}\right) + NSL$
New Lessons Learned: NLL=AR*LR
Perceived Accident Rate: PAR = $\int_0^t CPARdt + NAR$
Process Rate: PR=LBS/TPL
Realized Enemy Threat: RET= $\int_0^t CRETdt + NET$
Relative Accident Rate: RAA=AR/NAR
Relative Enemy Threat: RENT=RET/NET
Relative Long Term Stress Level: RLTSL = LTSL/NSL
Relative Perceived Accident Rate: RPAR = PAR/NAR
Relative Perceived Stress From Safety Efforts: RPSFSE=$\int_0^t (RLTSL/TPSFS)dt + NSL$
Relative Rest Time: RRT=ERT/NR

Learning from the Model

After calibrating the model, various simulations can be conducted to learn from the model. One example from many dozens that were conducted for this study is described here. 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.

One of the most important findings in this study involved oscillations in the Enemy Threat. As seen in Figure 8, simulation of the model showed that an oscillation in the enemy threat can result in a decrease in accidents even though the total summation of the threat over time is constant. While this finding is not intuitive, analysis of the simulations shows that complex non-linearities between variables causes this effect on the system. Specifically, analysis shows 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 erode built up stress at times when the enemy threat is low or zero. This same phenomenon occurs with fatigue in the system.

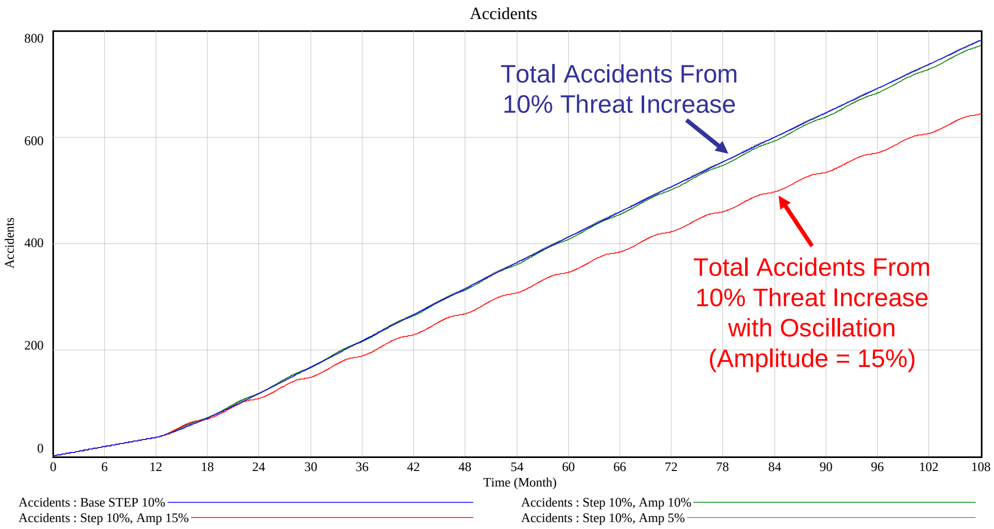


NOTE: Threat in the model is defined as probability of enemy contact: 5% is the status quo or "base" scenario

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 8 Impact of Oscillations in Enemy Threat

Figure 9 shows that that the greater the amplitude of the oscillation, the greater the reduction in the total number of accidents.



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 9 Impact of Larger Oscillations

The study showed that the greatest improvements in the system occur when the greatest amplitudes are applied. This finding suggests that rotating soldiers through more frequent breaks, even if it means exposing them to periods of greater enemy induced hazards, will produce a decrease in accident rate. Figure 10 provides an example of why System Dynamics analysis is so useful and can help to identify realities contained within complex systems that are not intuitive. It shows that with greater amplitudes in the enemy threat, more time is spent in smaller slope areas on the graph of Relative Enemy Threat versus Effect of Relative Enemy Threat on Accident Propensity. Because the relationship between these two variables is non-linear, there is a distinct tradeoff advantage for obtaining frequent periods of rest in return for similar periods of greater exposure to Enemy Threat (Minami & Madnick, 2009).

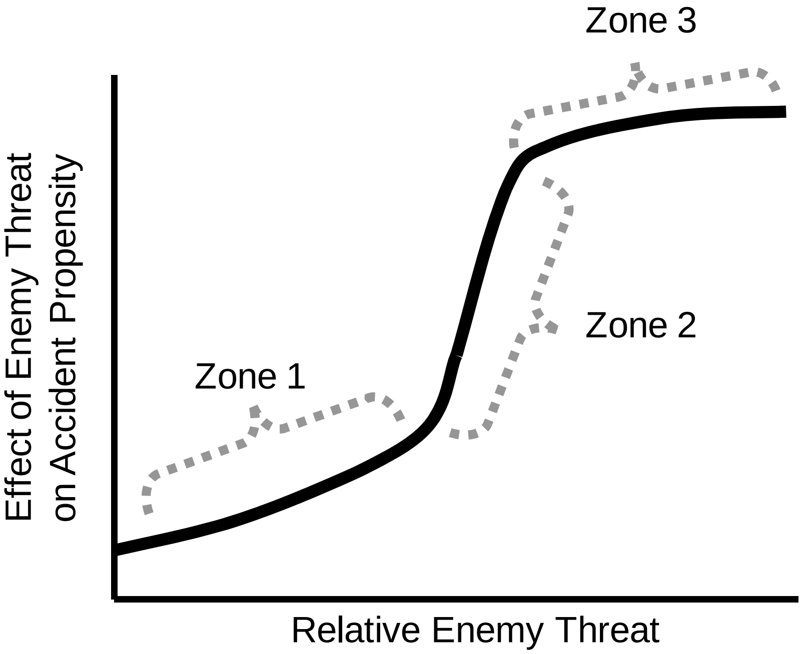


Figure 10: Relationship between Relative Enemy Threat and its effect on Accident Propensity

Findings

There were a number of important findings that emerged from this study. Some of the greatest potential for improving safety can be found by understanding the dynamic effect of various delays in the system. Understanding delays, and either findings ways to minimize the delays or communicating why it is important to wait for effective long term measures to be implemented in lieu of short term actions can be helpful in decreasing the total number of accidents over time. This does not mean that there is not a time and place for short term safety measures, but when they are made efforts must also be made to mitigate the impact of unintended side effects. This might include decreasing the number of other tasks a soldier is normally required to complete in order to make room for newly implemented safety measures, instead of adding the safety measures to a soldier's already busy schedule.

In addition, if everything else is equal, fewer accidents will occur in operating environments with a fluctuating/oscillating enemy threat than those with a constant (and proportional) enemy threat. This also suggests the benefit of rotating soldiers through routine rest periods. In addition, shorter deployment times with more time off could have a critical impact on reducing complacency and fatigue which will lead to fewer accidents. Therefore, while we may not be able to control the enemy threat, we can often control the exposure of our Soldiers to the enemy threat, specifically by adjusting the work-rest cycle.

The study also showed that complacency is the number one immediate cause of accidents and is the most important variable in the model. This does not mean it is the root cause of accidents. Actions must be taken at all levels to reduce complacency, this includes the highest levels of command, by ensuring lower units have the right amount of troops, with the rights skill sets and equipment to accomplish the mission requirements. The training level of Soldiers is another key variable, soldiers must be properly trained to perform tasks and leaders properly trained to supervise soldier actions and assess/mitigate risks. It is impossible to eliminate complacency altogether, and one of the biggest safeguards to the effects of complacency is to ensure that units are highly trained at all times. Finally, the risk assessment process is critical at all levels, but most important are actual patrol leaders (usually platoon leaders) going through the risk assessment process themselves; identifying risks, and developing mitigation measures.

System Dynamics Analysis of Microscopic Safety Problems

System Dynamics modeling can also be used to examine vehicle safety problems on an individual level. Specifically, it can be used to help describe and better understand how complex variables such as stress, complacency, and fatigue contribute to driver errors which can lead to an accident. Systems modeling on the individual driver level can be helpful just as it is on the macroscopic level, because it is difficult for the human mind to understand how feedback, non-linear relationships between variables, and delays impact safety.

The Driver as a System

A simple process model for an individual driver as a system can be seen in Figure 11. In this model, a driver is predominantly occupied with processing various incoming hazards that need to be addressed in order to prevent an accident. Examples of various hazards are narrowing road ways, sharp turns, pedestrians and oncoming traffic. Other examples that apply to the U.S. Army combat vehicle realm specifically are hazards such as possible and actual roadside bombs that need to be avoided, dangerous overpasses that could be used to drop grenades or other explosives onto approaching vehicles, car bombs, and possible ambush locations. A driver must be able to perceive these incoming hazards, process them, and then take corrective actions necessary for avoiding these hazards. This can include slowing the vehicle, increasing speed, turning, and switching lanes. In the military example, other decisions that the driver (or crew) must make to avoid an accident are whether or not to fire warning shots and wave off oncoming traffic. This process occurs within the overall context of each individual driver, her personality, training, and experience. Various controls that the driver has are the gas pedal, breaks, steering wheel and horn.

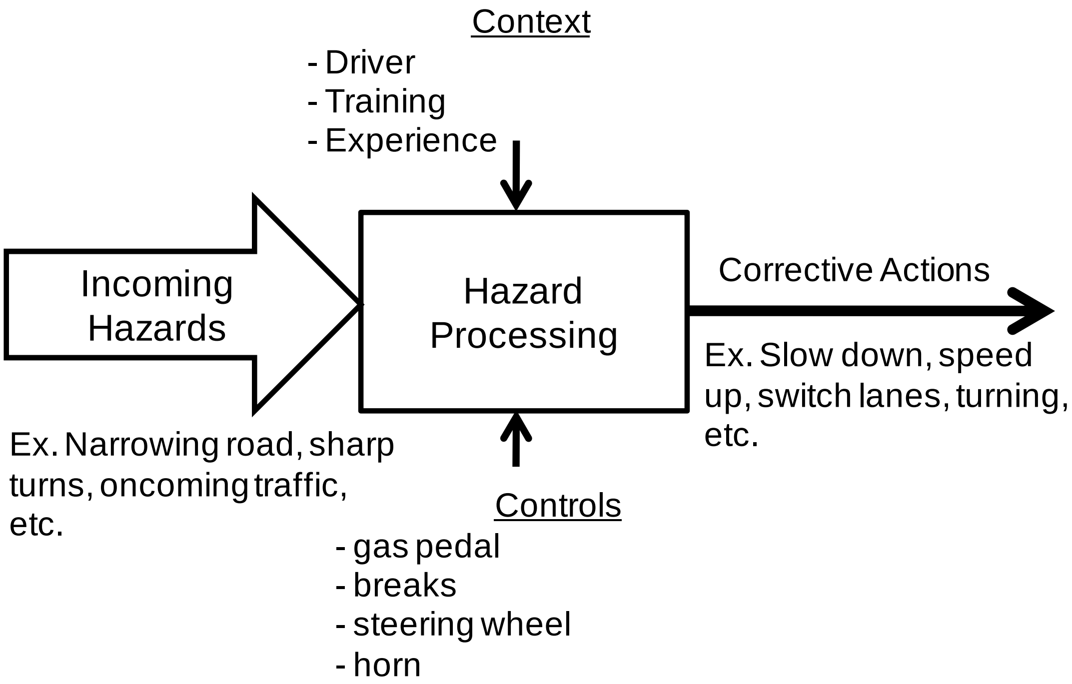


Figure 11: Systems Process Model for an Individual Driver

Understanding the Variables

The following example is based on the same basic U.S. Army example that was described in the preceding section. It differs, however, in that the unit of analysis is the individual Soldier, and not the Army as an organization. This study included a review of over 500 vehicle accident reports between 2003 and 2007, which suggested that stress, complacency, and fatigue are major variables involved in vehicle accidents. The accident reports and findings also suggested that driver's education and attitude can play a critical role in accident prevention. Among these five variables, stress is arguably the most dynamic and profoundly difficult to understand. Rudolph and Repenning (2002) showed in their study of air traffic controller caused aviation accidents that there are two affects of stress on human capacity to process hazards. Specifically, there are both positive and negative effects of stress. This idea is that some stress is good. Stress allows humans to operate at a great level of effectiveness and efficiency. As an example, students who know a test is approaching feel the stress, and therefore study harder for their exams and perform better if they know something (their grade) is at stake. Likewise, salesmen operate at great efficiency and worker harder when they know they must meet a certain quota, or obtain a particular goal in order to receive some expected compensation or to maintain their job. But at some point, too much stress is no longer helpful and actually inhibits a person's ability to perform routine tasks (Rudolph & Repenning, 2002). We see this in life when an athlete "freezes up," or when a firefighter, policeman, or senior executive has a mental breakdown from too much stress and is unable to continue their work.

Figure 12 demonstrates the double edged nature of stress. Theoretical maximums and minimums exist for the amount of stress that a human is capable of, but within this range are zones of both dangers and ideal stress. Review of the safety reports from Army accidents also revealed, that complacency and fatigue were present in a large number of combat vehicle accidents. Therefore, the model presented in this study suggests that fatigue and complacency directly impact stress by adjusting the stress thresholds that define the ideal stress range for an individual. In addition, the model suggests that education and experience have the opposite effect on stress and counteracts the effect of fatigue and complacency. Therefore, a person who is well rested, non-complacent, well educated and possessing a safety conscious attitude will have a larger ideal stress range compared to someone who is heavily fatigued and complacent. The range outside of the ideal stress range, therefore, is the zone where a person is either overwhelmed or underwhelmed. Accordingly, a driver who is either greatly overwhelmed or underwhelmed will have a greater propensity for accidents than a person whose ideal stress range is comparatively larger.

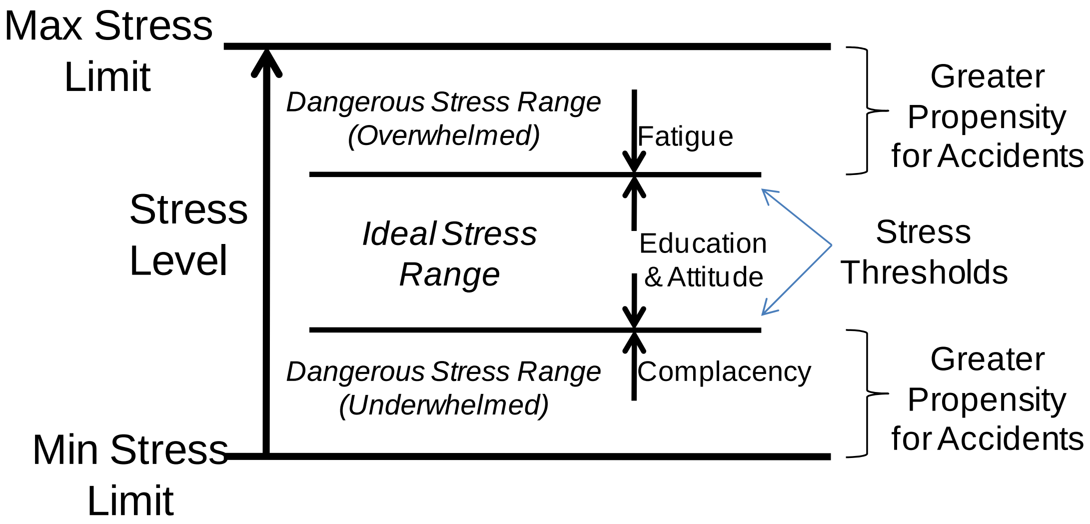


Figure 12: The Dual Nature of Complacency

As noted in Figure 12, complacency plays an important role in stress management and ultimately on accident occurrence. While some researchers have noted that there is little evidence for complacent behavior (Moray & Inagati, 2002), the preponderance of the evidence appears to show otherwise. Indeed, in the review of U.S. Army combat vehicle accident reports, complacency was noted as a major factor in the occurrence of accidents 58 percent of the time (Minami & Madnick, 2008). In other domains, Parasuraman, Molloy & Singh (1993) conducted a study of flight simulation and found that increased use of automation produces increased pilot complacency. Another study showed that complacency is a major factor in bank robberies, “If you’ve never experienced a robbery, you tend to think you never will” (Bielski, 2008, p. 35). In a final study, public complacency was cited as a major tendency for the public to ignore repeated hurricane warnings (Wang & Kapusa, 2008). Further, the evidence seems to demonstrate that complacency deals less with detection mechanisms and more predominantly with monitoring and sampling functions (Moray & Inagati, 2002). This suggests that in the case of driver safety, complacency deals less with the driver’s ability to perceive incoming hazards, but rather, that the driver places less importance on these hazards. This effect is represented in Figure 12 as decreasing the lower stress threshold. Finally, among the most important causes of complacency is the negative impact of an acquired sense of superiority, which can be gained through repeated incidents of success (Bielic, 2009). In the case of driver behavior, this suggests that repeated success in avoiding traffic hazards can lead to increased complacency.

Fatigue also plays an important role in stress management, in that increased levels of fatigue decreases the upper stress threshold. Fatigue was shown to play a major role in combat vehicle accidents in at least 10 percent of accident investigations (Minami & Madnick, 2008). Further, several other studies have shown that fatigue increases the risk of an accident (Akerstedt, 2000; Dalziel & Job, 1997; Summala & Mikkola, 1994; Swann, 2002). One report found that fatigue or drowsiness played an important role in as much as 50 percent of all traffic accidents (Teran-Santos, Jimenez-Gomez & Cordero-Guevara, 1999). Fatigue has also been shown to play an important part in accidents that involve long periods of inactivity and monitoring of equipment or human errors that can be associated with inattentiveness or poor judgment (Lauber & Kayten, 1988).

In their study of taxi cab drivers, Dalziel and Job (1997) showed that the more time a driver spends on the road, the more fatigued they become, which has a corresponding increase in the probability of an accident occurring. Further, the study demonstrated that increased break times directly decreases the accident rate among cab drivers. The use of stimulants has also been correlated with an increase in accident rates (Swann, 2002). Indeed, 23 percent of drivers involved in vehicle accidents in Australia tested positive for the use of stimulants, which is equivalent to having a BAC of .1 to .15 (Swann, 2002). The same study showed that increased accident rates are also associated with night driving and suggested that power naps are more helpful in avoiding fatigue and accidents than using stimulants. Finally, Akerstedt (2002) showed that major causes of fatigue in transportation system accidents are the time of day (night/early morning), long durations of wakefulness, inadequate sleep, pathological sleepers and extended hours of work. The study suggested that fatigue is the largest preventable cause of transportation operations accidents (15-20%).

While stress, fatigue and complacency increase the probability of an accident occurring, previous research in driver safety indicates that education and driver attitude tend to counteract these negative variables (Assum, 1997; Constant, Salmi Lafont & Lagarde, 2007; Evans, 1998; Gregersen, Brehmer & Moren, 2007). For example, in the study of combat vehicle accidents in Iraq, a driver's training level as measured by awareness of potential hazards played an important role in 55 percent of accident reports involving fatal or near fatal accidents (Minami & Madnick, 2008). This suggests that driver education or training plays an important role in mitigating accident occurrence. Indeed, Constant et al. (2007) demonstrated that improved drivers education resulted in fewer accidents and driver training programs in large companies have also been proven to be effective in decreasing accidents among company employees (Gregersen et al., 1996). Individual education programs, such as DUI awareness programs, have also been shown to reduce vehicle accidents by as much as 10 percent (Levy, Shea & Asch, 1989). Complimenting this study, Hingson et al. (1996) determined that driver education programs that aim to adjust driver behavior with focus on speeding and drunk driving can reduce fatal accidents by as much as 25%. Finally, Dorn and Barker (2005) demonstrated that professionally trained drivers, such as police officers, exhibit safer driving habits than non-professionally trained drivers.

It is important to mention, however, that while the preponderance of the literature supports the assertion that driver training and education helps to reduce accidents, there have been a couple of studies that question its effectiveness. First, Potvin, Champagne and Laberge-Nadeau (1988) found that mandatory driver training programs do not produce noticeable improvements in reducing accidents and that they may even increase accidents for young female drivers. The study suggested that this is the case because driver *training* and *education* does not necessarily improve a driver's *attitude* towards following safety laws and regulations. Thus, the evidence shows that understanding and knowing safety procedures and having a safety conscious attitude that encourages an individual to follow these safe driving practices are both important elements in vehicle safety. A second study found that it is not clear whether a positive relationship exists between driver education and training, and that this is particularly the case with the younger population (Mayhew et al., 1998). Therefore, while the preponderance of the evidence seems to support the assertion that driver training and education play an important role in mitigating accidents, it also suggests that another important variable is present.

Positive driver attitude toward safe driving practices appears to be an important role in vehicle accident avoidance, and compliments driver training and education which makes a driver aware of what safe practices should be followed (Assum, 1997). Improved driver attitudes were shown to result in a significant decline in the casualties from traffic accidents in France (Constant et al., 2009). The study showed that this effect was accomplished primarily by encouraging drivers to drive slower. In addition, age appears to play a critical role in driver safety (Levy, 1990). Levy showed that new drivers in the ages of 15-17 were involved in more accidents than older beginner drivers. While these younger beginner drivers received the same driver education that older beginning drivers did, they had more accidents. This suggests that attitude plays an important role in driver safety as younger people tend to be more prone towards risk taking and downplay the importance of safety procedures. Research also suggests that traffic calming efforts, or physical changes in the composition of streets and neighborhoods, can adjust driver attitudes by encouraging drivers to take a more safety conscious approach towards driving, especially with regards to speed reduction (Evans, 1998). Finally, research has shown that attitudes help to decrease traffic accidents by directly effecting the relation between personality traits and risky driving behavior (Ulleberg & Rundmo, 2003). This suggests that a person who is naturally predisposed towards taking risks can be encouraged to not display this predisposition while driving a vehicle through effective efforts to improve the driver's attitude towards safety.

The Model

The theory used in this model is that accident propensity in cases dealing with combat vehicles increases as the number of hazards that a driver must address increases. This means that accidents occur when drivers become overwhelmed by the number of hazards they must address and can no longer resolve the various hazards. A unique threshold exists for each individual that varies depending on the amount of stress, fatigue, education, training and attitude that each driver exhibits towards his job. The idea that quantity can play a role in accidents is not new, and was described in depth by Rudolph and Repenning (2002). Figure 13 shows a simple stock and flow structure of how this works. A driver, and in this case a driver of a combat vehicle in Iraq or another austere environment, has some number of hazards pending at any given time. It might be a hole in the road, oncoming traffic or traffic approaching laterally, civilians walking alongside or across the street, low hanging power lines, narrowing roads, road construction, parked cars along the roadside, a dog running across the street, food venders or other peddlers, as examples. It is important to note that this list does not include the many combat hazards that a driver must address which also affect the total number of hazards pending. These include actions taken to avoid roadside bombs, craters, armor piercing hand grenades, snipers, ambushes, and many other threats. The number of hazards pending at any given time is adjusted by the incoming hazard arrival rate, or the number of new hazards that a driver must deal with in any given period of time. Finally, the number of hazards pending is also affected by the hazard resolution rate, which is the number of hazards that a driver can address with appropriate actions (speeding up, slowing down, turning left, turning right, honking the horn, etc) over a period of time. Consequently, if the hazard arrival rate increases at a greater rate than the hazard resolution rate, the number of hazards pending will increase and at some point the driver will become overwhelmed and the system, or the driver, will collapse. At this point an accident is all but certain to occur.

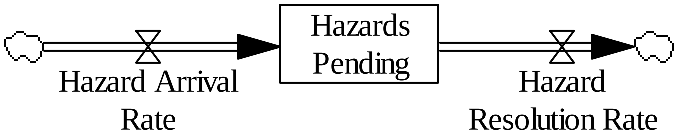


Figure 13: Stock and Flow Structure for Hazards

Figure 14 provides a conceptual model that describes the interaction between these variables. At the heart of the model is the variable, hazards pending, which follows the concept previously discussed and demonstrated in Figure 13. Reinforcing loop R1 in Figure 14 describes how negative stress can have a catastrophic effect on an individual. It demonstrates that as the number of hazards pending increases, the desired hazard resolution rate also increases, which leads to an increase in stress and a decrease in the hazard resolution rate. This decrease in the hazard resolution rate results in an increase in the number of hazards pending. Taken in isolation, reinforcing loop R1 describes a catastrophic interaction between variables that would almost certainly lead to an accident. There are also a number of salient points in this causal loop that demand further examination.

Specifically, there are two important delays in this causal loop, the first occurs between the hazards pending and the desired hazard resolution rate. This describes how as the number of hazards pending increases, the desired hazard resolution rate does not increase instantaneously, but rather it takes time for a driver to recognize the need to address the hazards at a greater rate. For an alert and non-complacent driver, this delay might be insignificant, but as the model shows, fatigue and complacency can greatly increase the time it takes to perceive a hazard which decreases the desired hazard resolution rate. This creates an increase in the amount of stress that a person experiences. The second delay in this loop demonstrates the delay between the amount of stress that an individual experiences and the negative affect that this has on the hazard resolution rate. This means that a person does not necessarily experience the effect of negative stress immediately, but rather it takes time for stress to build up to a point where a person becomes overwhelmed and the stress then begins to negatively affect a driver's ability to operate (Rudolph & Repenning, 2002).

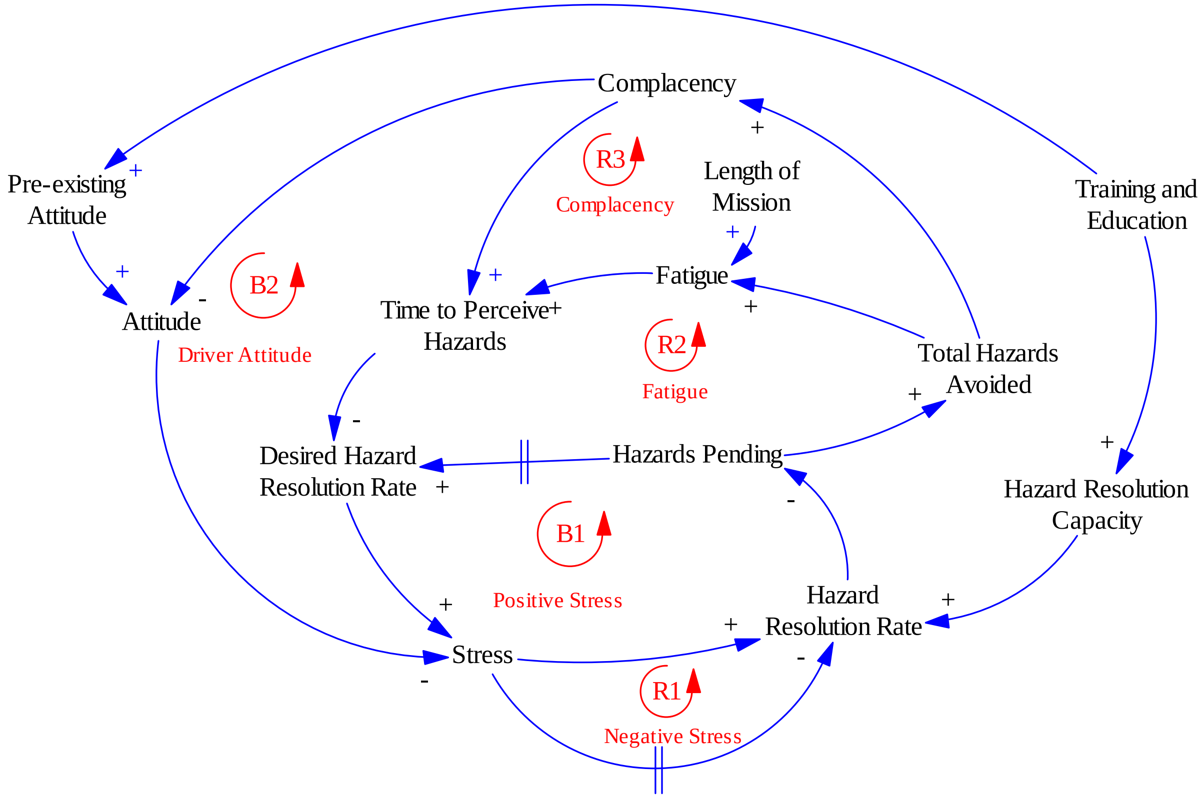


Figure 14: Conceptual Model for the driver as a system

Reinforcing loop R2 describes how as the number of hazards pending increases, the number of hazards avoided also increases as the driver takes action to avoid hazards. As the number of hazards avoided builds up, a driver becomes more fatigued, which results in an increase in the time to perceive hazards and a decrease in the desired hazard resolution rate. In turn, this decrease in the desired hazard resolution rate results in an increase in stress and a decrease in the hazard resolution rate, which produces an increase in the number of hazards pending. An important point in this loop is that the endogenous variable fatigue, is also affected by the exogenous variable length of mission. This means that the longer a soldier spends on the road driving, the more fatigued he will become.

Reinforcing loop R3 describes the affect that fatigue has on the system. As the number of hazards pending increases, the number of total hazards avoided also increases. As the number of total hazards avoided increases the driver becomes more accustomed to the various hazards and eventually his complacency increases as well. As complacency increases, the time it takes to perceive a hazard increases, which decreases the desired hazard resolution rate. This produces a decrease in stress and a decrease in the hazard resolution rate, which then increases the number of hazards pending. These three reinforcing loops are important because they describe how negative stress, fatigue, and complacency can lead to the conditions whereby a driver is no longer able to cope with the number of hazards that must be addressed. If this were all that there was to the model, combat vehicle accidents would be inevitable.

There are also two very important balancing loops in this model, which given the right conditions, counteract the dangerous affect that the reinforcing loops can have on the system. Balancing loop B1 describes the affect of positive stress on the system. As the number of hazards pending increases, the desired hazard resolution rate increases. This produces an increase in stress, which increases the hazard resolution rate and therefore, decreases the number of hazards pending. This loop is critical because in isolation from the rest of the model, it describes how under normal conditions, a driver is able to address increases in the number of hazards pending without accidents occurring.

Balancing loop B2 addresses the role that driver attitude plays in the model. As the number of hazards pending increases, the total hazards avoided also increases. This produces an increase in complacency and a decrease in driver attitude. As a driver's attitude becomes more negative towards safety, stress levels increase, which produces a decrease in the hazard resolution rate and an increase in the number of hazards pending.

Finally, there are important exogenous variables in this model. The role that length of mission has on the system was already discussed, but training and education is also critical and arguably has a much greater effect on the system. First, as training and education increases, an individual's pre-existing attitude towards safety increases as they are more aware of the hazards and risks that exist, have better skills for addressing them, and have seen statistics and other evidence of what actions work, and don't work, in mitigating accidents. Consequently, as pre-existing attitude improves, attitude also improves, which produces a decrease in stress and an increase in the hazard resolution rate, which produces a decrease in the number of hazard pending.

The second way that training and education affects the system is more direct. As a driver receives more training and education, the driver's hazard resolution capacity increases. This is because the driver becomes better informed of improved techniques for addressing hazards. As the hazard resolution capacity increases, the hazard resolution rate also increases, which produces a decrease in the number of accidents pending.

Conclusions

Implementing systems analysis, and specifically System Dynamics analysis in addressing civilian traffic safety problems could be very helpful just as it has been in the analysis of combat vehicle accidents. Macroscopic models that address traffic safety as an epidemic can be helpful in many ways. First, these models can help to inform policy makers as to which levers in the system are most likely to produce a decrease in future accidents. Second, these models have tremendous explanatory power and can help analysts to better understand how concepts such as feedback and delays impact a system. Microscopic models can also be helpful, especially in their ability to explain how accidents occur. For example, dynamic microscopic models can help an accident analyst to piece the variables together in a manner that is often difficult to do using traditional techniques. The simple microscopic model in this paper showed the importance of monitoring individual soldier stress levels, that training and education are critical to safe driving practices, and that other factors such as the amount of time a driver spends on the road and driver’s attitude are also critical in preventing accidents. Ultimately, systems analysis of accidents can help to provide new and innovative insights that enhance safety culture and that make roads safer for all.

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