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MODELING SIGNAL LATENCY EFFECTS USING ARENA™

Shane Dougherty

Det 1 28 TS/F-22
6257 Beale Ave.
Nellis AFB, NV 89191, U.S.A.

Raymond R. Hill
James T. Moore

Department of Operational Sciences
Air Force Institute of Technology
2950 P Street, Building 640
Wright-Patterson AFB, OH 45433, U.S.A.

ABSTRACT

Recent military operations have showcased the abilities of unmanned aerial vehicles (UAVs), particularly in their ability to effectively perform those tasks too dangerous for manned aircraft. We examine non-autonomous operations of an UAV in those instances where the vehicle is used for laser target designation in support of precision guided munitions with non-line-of-sight command and control of the UAV. Non-line of sight UAV control requires a satellite communications link which involves a level of signal delay, or signal latency. This latency may impact the accuracy of the laser designation and thus the accuracy of the guided weapon. A simulation model is defined, built, and used to address the signal latency impacts of our defined UAV targeting scenario.

1 INTRODUCTION

Recent military operations have showcased the abilities of Unmanned Aerial Vehicles (UAVs). UAVs provide intelligence, surveillance, reconnaissance, and command and control information to commanders in real-time or near real-time format. The success of UAVs raised questions about future roles for UAVs in military operations. These roles include weaponizing UAVs and using UAVs for target designation; these missions are commonly grouped under the title, Unmanned Combat Aerial Vehicles (UCAVs). A concern with UCAVs is the potential impact of time-delays or signal interruptions on UCAV to ground control unit (GCU) communications and interactions. This paper discusses a simulation model defined, built, and used to quantify the effect of signal latency on UCAV targeting effectiveness.

Typical UCAV missions are the attack of heavily defended high value targets, active Suppression of Enemy Air Defenses (SEAD), and target designation for standoff precision guided munitions. This use of UCAVs is not new as the Israeli military used Electro-Optical seeking Maverick missiles attached to AQM-34 Lightning Bug drones to attack Soviet-built Egyptian air defenses in the Bekka Valley in the 1970s.

The true military value of UCAVs lie in their ability to effectively perform those tasks too dangerous for manned aircraft (Canan, 1999). Laser designation of targets is one such dangerous mission. A UCAV provides a means to aim a laser designator at some target, while a precision-guided munition, fired outside the lethal range of enemy systems, tracks in on the UCAV-maintained designation point. An issue with this target designation scenario is whether or not the designator is accurately located on the desired target.

2 BACKGROUND

A critical UCAV operational issue is what degree of autonomy is used in the control of a UCAV system. Current UCAV literature identifies two methods of UCAV control: fully autonomous control or remotely piloted (man-in-the-loop) control.

A totally autonomous command and control structure is fully reliant on its own systems, such as automatic target recognition (ATR), to make engagement decisions (Clark, 2000). As the degree of UCAV autonomy increases, a UCAV system must possess an increased capability to sense changes in its environment and make appropriate decisions (Lawson, 1998). The combination of on-board sensors, control and analysis software, and pattern recognition software that provide UCAVs the ability to think for themselves is often referred to as their "wetware" (Nolan, 1997). The question surrounding the development of "wetware" type of machine intelligence is how to ensure UCAVs make and learn the appropriate lessons in the presence of the fog and friction of warfare. Another question is whether or not wetware can exhibit the reasoning and cognitive capabilities of an experienced combat pilot (Kopp, 2001)? Further, are we willing to let software (in the UCAV) cause potential fratricide and missed targeting given these events still occur with fully manned systems?

A man-in-the-loop (MITL) controlled UCAV requires a two-way communications/data-link. The data link relays signals from the UCAV's sensors to the remote controller who then returns instructions to the UCAV (Lawson, 1998). This can limit UCAV operations as the telemetry signals for each UCAV/controller combination must be unique, and satellite bandwidth availability limits the number of simultaneously operated UCAV aircraft (Nolan, 1997).

A problem with MITL UCAV is the requirement for a data-link transmission. Data-link or radio-control transmissions are vulnerable to jamming. The adversary's jamming effort could occur at the most critical engagement moment – aiming and delivering ordnance (Marsh, 2001). The enemy only needs to jam the data-link for a few seconds, possibly even milli-seconds, to produce profound, and negative effects (Marsh, 2001).

A less severe, but more likely, problem is signal latency. Signal latency is the delay between a signal transmission and its receipt at the designated receiver location. Some level of latency will always exist in a communications signal link. In the envisioned high-tech combat operations of the future, the amount of bandwidth available for UCAV operations may be limited and thus a concern. The transmission of analysis quality target pictures significantly expands the amount of data that occupies available bandwidth (Clark, 2000). If the data-link system gets overloaded, it may result in transmission delay (latency) or even shut down (Clark, 2000). With MITL control, it is reasonable to assume that video transmissions will greatly increase bandwidth requirements, especially if multiple UCAVs are operating simultaneously within close proximity.

A tolerable level of latency for targeting data depends significantly upon the target type, as shown in the notional chart in Figure 1 (Naval Studies Board, 2000). Our concern is with moving ground targets. In particular, what exactly is the impact of a given level of signal latency, be it in the acceptable range or in the unacceptable range, on the expected targeting accuracy of a HITL UCAV platform? For example, Table 1 provides the minimum latency levels for three satellite orbits. Our question is what are the accuracy impacts of these minimum latency levels and further what happens to accuracy as latency levels drift away from these minimum levels?

3 METHODOLOGY

To quantify the effects of signal latency on UCAV targeting effectiveness, an ARENA™ discrete-event simulation model was designed, built and tested. The SIMULATION model captured latency effects in the UCAV to GCS two-way signal and control link (Dougherty, 2002).

Several assumptions were required in order to simplify the UCAV laser designation scenario. We assume that the lazing of the mobile ground target is always successful. Another assumption is that once the designator is turned on, it stays on. We assume that the GCS operator's cueing data once received is 100% accurate in relation to a desired weapon impact point. We assume the effects of any terrain elevation or location are negligible. We also do not model bandwidth effects, picture quality to GCS, weapon delivery altitudes, type of weapon, seeker gimble limits, or a weapon's ability to make last second corrections to strike a target at the laser designation point. Collectively, these assumptions imply that our results are aggregate and conservative.

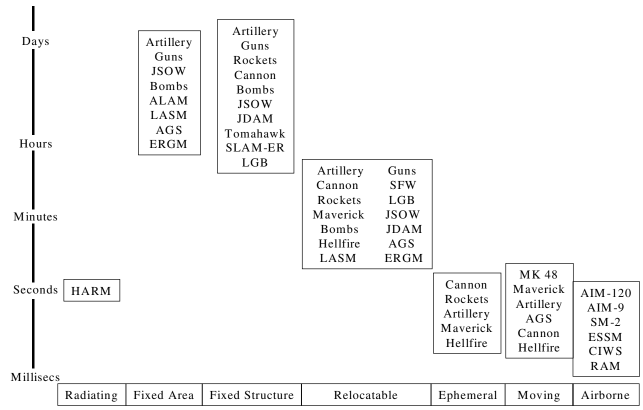

Figure 1. Acceptable Data Time Late vs. Target Types (Naval Studies Board, 2000)

Table 1. Satellite Data and Minimum Latency Levels

Orbit	Altitute (miles)	Min. Latency
Geosynchronous	22,241	0.24 sec.
Medium Earth	6,250-12,500	0.06-0.14 sec.
Low Earth	below 3,150	less than 0.1 sec.

The SIMULATION model simulates the transmission of video from the UCAV to the GCS as snap shot pictures of a mobile ground target. The GCS operator is attempting to designate that mobile target in order to deploy a precision guided munition. The GCS operator designation command is based on the picture presented on the workstation. We model a picture transmission every 0.001 seconds, as this provided a reasonable level of run-time and model fidelity. Two factors determine whether or not the GCS receives UCAV-transmitted pictures. These factors are the latency of the signal and whether the signal is jammed or lost. This paper focuses just on the latency issues.

The effects of signal latency are examined across a range of latency bands with the lower and upper bounds for each band shown in Table 2. Latencies were modeled as uniformly distributed random variables within the latency band.

Since the latencies are modeled as random variables, it is possible for picture deliveries to occur out of sequence.

Table 2. UCAV-GCS Latency Bounds

Sets	Lower Bound (sec)	Upper Bound (sec)
Set 1	0.0001	0.0005
Set 2	0.001	0.005
Set 3	0.01	0.05
Set 4	0.1	0.5
Set 5	1	5
Set 6	10	50

To solve this problem, if a picture is scheduled to arrive prior to a preceding picture, the latter picture is dropped.

The real concern with signal latency during UCAV targeting missions is targeting error due to a disconnect between perception (what the operator sees as a target location) and truth (what is the actual target location). Any signal delay means the operator is effectively viewing the past (not the present). The SIMULATION model tracks ground truth (actual target location) and operator perception. A UCAV designator is pointed based on operator commands and recall that to remain conservative in our approach, we assume the laser is designating exactly where commanded i.e., final miss distances are calculated based on ground truth and GCS-commanded target designation locations. The research hypothesis is that latency increases the difference between ground truth and operator perception and this equates to increased weapons miss distances at impact. Figure 2 depicts our research hypothesis in a graphical form.

The model also simulates the transmission of GCS command data for a laser designator mounted on the UCAV. The GCS operator designator centering commands are based on coordinates corresponding to the view in the GCS system (the operator perception).

Latency effects control data transmission just as it effects video transmissions. However, bandwidth requirements for control data are less than required for video transmission. Thus, the latency bands considered are different than those used for the UCAV-to-GCS link. These bands are provided in Table 3 and are also modeled as uniformly distributed random variables.

The scenario associated with determining the location designated by the GCS is depicted in Figure 3. The black tank depicts an actual target, while the gray tank symbolizes the location of the target as displayed in the GCS. The first segment (Figure 3a) shows the UCAV transmitting the actual target location via satellite to the GCS. The second segment (Figure 3b) shows the delivery of the UCAV transmission to the GCS monitor, and the GCS designation point (depicted by the cross-hair on the monitor). Because the signal from the UCAV to the GCS is delayed (due to latency), the tanks displayed in Figure 3b show the disconnect between the actual target and the target as perceived by the GCS. The final segment, Figure 3c, shows the UCAV designating the location specified by the GCS operator. Again due to latency, there is a disconnect between the actual location designated (depicted by white cross-hair) and GCS displayed designation location. The over-all miss-distance between the actual target and the location designated has two components. The first component is the difference between the actual target location and the target location perceived by the GCS. The second component is the difference between the displayed designation location on the perceived target and the actual designation location.

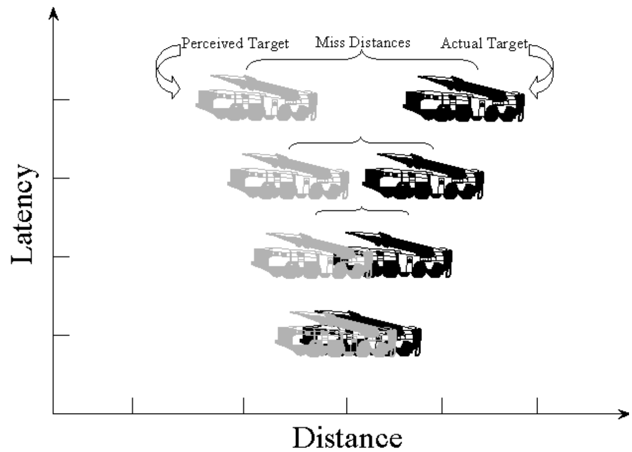

Figure 2. Hypothesized Signal Latency to Miss-Distance Relationship

Table 3. GCS-UCAV Latency Bounds

Sets	Lower Bound (sec)	Upper Bound (sec)
Set 1	0.00001	0.00005
Set 2	0.0001	0.0005
Set 3	0.001	0.005
Set 4	0.01	0.05
Set 5	0.1	0.5
Set 6	1	5

4 RESULTS

Two scenarios are investigated, a non-maneuvering and a maneuvering target scenario. In each scenario, each latency band along with five levels of target velocity are examined.

4.1 Constant Velocity, Non-maneuvering Target

Both signal latency and ground target velocity impact potential targeting miss distance. These relationships are direct and linear in logarithmic form.

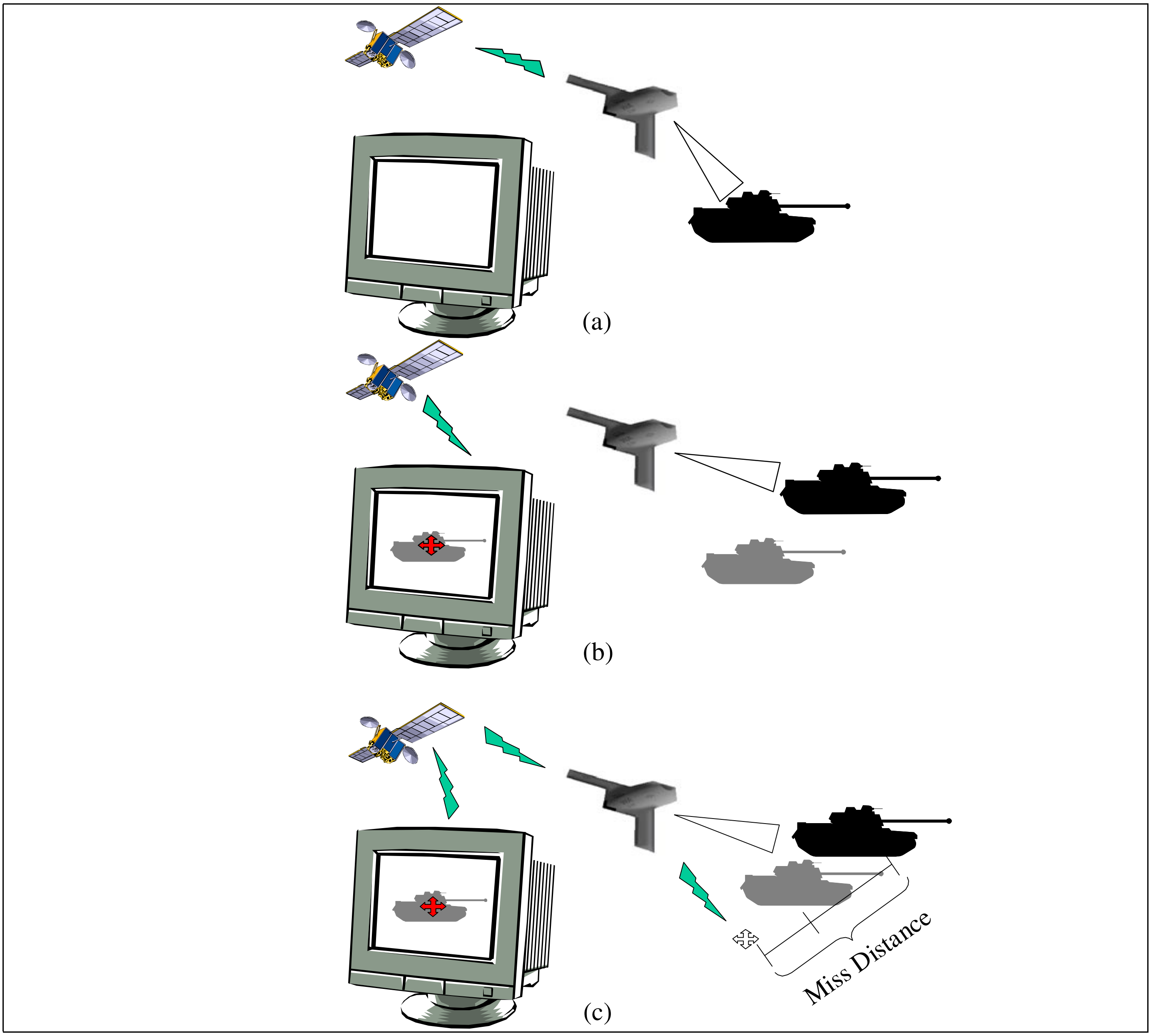

Figure 3. Location Designation and Target Relationship

Figure 4 depicts, on log scale, the average miss distance as a function of signal latency for each target ground speed modeled. As expected, target ground speed directly influences miss distance – higher speeds mean larger differences. As expected, near real time latency translates to very low miss distances (less than a foot), but as latency increases, miss distance increases rapidly. The implication is clear; minor signal problems mean poor targeting accuracy resulting in inaccurate bombs.

Latency and target velocity also influences the miss distance distribution. Since signal latency is modeled as a random variable with a specified mean, the miss distance is also a random variable. As seen in Table 4, the variance of observations increases with latency and ground target speed.

To gain a better understanding on the average miss distance in the 1 to 10 second latency range, and to look for potential nonlinear interactions, we examined average latency levels of 2, 3, 4, 5, 6, and 7 seconds.

Figure 5 depicts the average miss distance as a function of signal latency for each target ground speed modeled. The relationship is linear– higher speeds mean larger miss distances. The tighter range of latency levels removes the need to logarithmically transform the data to produce a meaningful graph.

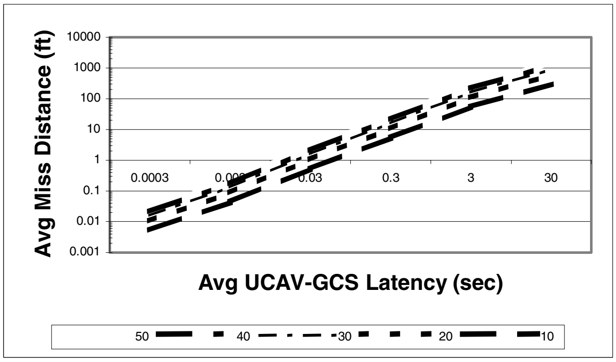

Figure 4. Mobile Target Engagement with Constant Velocity (30-second engagement)

Table 4. Average Miss Distance Variance (Scenario 1, 30-second engagement)

Latenc (sec)	Velocity (ft/s)				
	50	40	30	20	10
0.0003	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
0.003	0.002	0.002	0.001	0.0004	0.0001
0.03	0.046	0.030	0.017	0.007	0.002
0.3	0.622	0.398	0.224	0.099	0.025
3	7.097	4.542	2.555	1.136	0.284

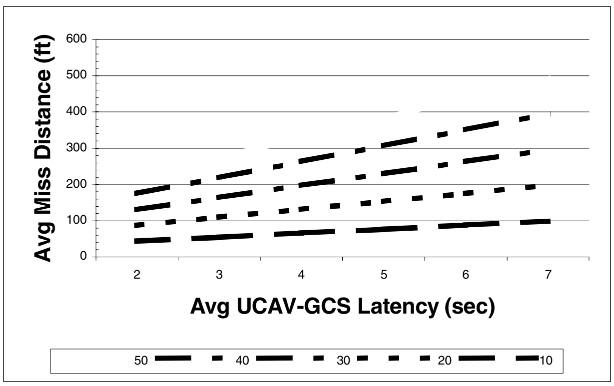

Figure 5. Mobile Target Engagement with Constant Velocity (Latency 2-7 sec)

4.2 Constant Velocity, Maneuvering Target

Both signal latency and ground target velocity impact potential targeting miss distance; however, maneuvering capability did not impact the average potential targeting miss distance. This, however, may be an artifact of our modeling approach.

Figure 6 depicts, on log scale, the average miss distance of a maneuvering ground target as a function of signal latency for each ground speed modeled. The ability of a target to maneuver does not significantly change miss distance above the influences due to target ground speed and latency. This result may be an artifact of the random natures of the maneuvers and thus further investigation should be conducted using maneuvering target scenarios where the target assumes some systematic maneuvering. In short, the random nature of our modeled maneuvers may be canceling out and leaving effectively a non-maneuvering scenario.

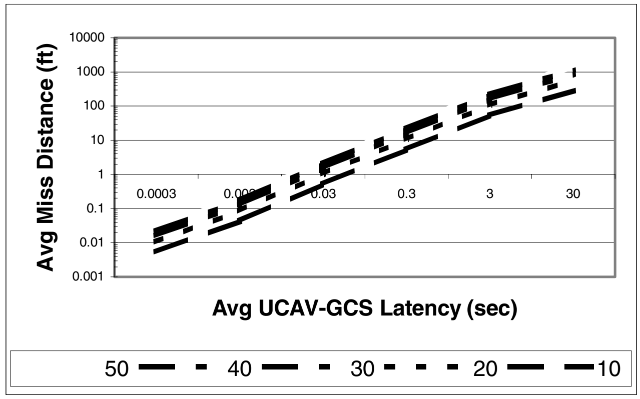

Figure 6. Maneuvering Target with Constant Velocity

Maneuvering, similar to latency and target velocity, does influence the miss distance distribution. The variance of observations expands as latency and ground target speed increase.

5 CONCLUSIONS

Target designation is a dangerous mission for manned aircraft. UCAVs offer an alternative capability. Under autonomous control, the UCAV acts independently. Such independence produces risks the military have yet to accept. Ground control alleviates problems with autonomy; yet it introduces problems associated with signal delays, or latencies. We developed an Simulation model to quantify the effects of signal latencies. Our results suggest that satellite signal latency and ground target velocity influence targeting miss distance with varying degrees of severity. The larger the signal latencies or the higher the target ground speeds, the larger the average miss distances.

There are many areas to extend in this research. The first is to identify true satellite latency levels between a UCAV and GCS in multiple environments. Since there is a lack of actual latency data associated with UCAV operations, we have taken the option of providing conservative estimates of latency effects. Another extension would be to develop a user-friendly interface to the model for input parameters and scenario definition. This would allow the model to be used in a wider variety of scenarios.

Additionally, there are avenues to expand the fidelity of this research model. The first avenue would be to incorporate a laser designation algorithm. This algorithm could take into account the probability of designation, angle of incidence, heading angles, and other factors to determine whether or not target designation was successful.

A second avenue would be to incorporate a GCS operation algorithm to take into account operator error. A final avenue would be to include a weapon effectiveness algorithm. This algorithm could include attributes of type of weapon, weather effects, delivery altitudes, seeker gimble limits, and weapon energy envelopes. This would augment miss distance data with lethality assessments to provide probability of target kill information in addition to simply providing target miss distance information.

Disclaimer: *The views expressed in this article are those of the authors and do not reflect the official policy of the United States Air Force, Department of Defense, or the US Government.*

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AUTHOR BIOGRAPHIES

SHANE DOUGHERTY, is a Captain in the United States Air Force. Capt Dougherty received his M.S. in Operations Research from AFIT in 2002.. His e-mail address is <Shane.Dougherty@nellis.af.mil>.

RAYMOND R. HILL, Ph.D., is a Lieutenant Colonel in the United States Air Force and an Associate Professor of Operations Research in the Department of Operational Sciences at the Air Force Institute of Technology. Lt Col Hill received his M.S. in Operations Research from AFIT in 1988 and his Ph.D. in Industrial Engineering from The Ohio State University in 1996. His research interests include modeling and simulation, applications of optimization and heuristics, and military applications of modeling. His e-mail address is <Ray.Hill@afit.edu>.

JAMES T. MOORE, Ph.D., is an Associate Professor of Operations Research in the Department of Operational Sciences at the Air Force Institute of Technology. Dr Moore received his M.S. in Operations Research from AFIT in 1981 and his Ph.D. in Industrial Engineering from The University of Texas at Austin in 1988. His research interests include applications of optimization and metaheuristics to mobility and transportation problems. His e-mail address is <James.Moore@afit.edu>.