

ABSTRACT

Title of Thesis: TRANSFORMATION PLANS FOR OPTIMIZING
MILITARY VEHICLE TESTING

Timothy Warren Hoy, Master of Science, 2007

Thesis directed by: Associate Professor Jeffrey W. Herrmann
Department of Mechanical Engineering and
Institute for Systems Research

The U.S. Army Aberdeen Test Center is a leading Department of Defense developmental test center and test range. A majority of the testing conducted at the Aberdeen Test Center is automotive in nature. Due to recent conflicts around the world, the U.S. Armed Services need to field new armored systems rapidly. The rapid deployment of automotive systems has caused the Department of Defense test community and the Aberdeen Test Center in particular to reevaluate and redefine traditional test plans and practices in order to maximize the amount of valid and pertinent data obtained from shortened test schedules. As a result, this thesis studies new transformation plans to provide ways to optimize military test plans. These transformation plans take into account existing military vehicle data from multiple sources including the Aberdeen Test Center's automotive road courses. These transformation plans are not only useful for shortened military tests, but can also be easily employed in developing test plans for private industry customers as well as long term test projects. The benefits in all cases are the same: an optimized test plan for automotive endurance operations.

TRANSFORMATION PLANS FOR OPTIMIZING MILITARY VEHICLE TESTING

by

Timothy Warren Hoy

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Advisory Committee:

Associate Professor Jeffrey W. Herrmann, Chair
Associate Professor Linda Schmidt
Adjunct Associate Professor Gregory Schultz

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Dedication

I dedicate the culmination of three years of blood, sweat, and tears to my wife, Elizabeth, without whose faith in God and in me this would never have come to pass. I also dedicate this work to the brave men and women of the United States Armed Forces serving in every capacity to protect, edify, and establish those peoples who are oppressed and downtrodden, and who, with great suffering and hardship, bear the weight of centuries old conflicts and millennia old hope of freedom and happiness on their shoulders in their duties and as they guard our homeland against fear and attack.

Lastly, I dedicate this work to those dearest to me, my family: Susan, Eric, Jack and Joyce, Chris, Sarah, Doug and Lisa, Molly, Cadi, Kiwi, and Bear.

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The LORD is exalted over all the nations, his glory above the heavens.

Psalm 113:4

For God, who said, “Let light shine out of darkness,” made his light shine in our hearts to give us the light of the knowledge of the glory of God in the face of Christ.

2 Corinthians 4:6

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List of Acronyms

ADMAS:	Advanced Distributed Modular Acquisition System
AEC:	U.S. Army Evaluation Command
AMSAA:	U.S. Army Materiel Systems Analysis Activity
AST:	ATEC Systems Team
ATC:	U.S. Army Aberdeen Test Center
ATEC:	U.S. Army Test and Evaluation Command
CDD:	Capability Development Document
CUCV:	Commercial Utility Cargo Vehicle
DOD:	Department of Defense
DTC:	U.S. Army Developmental Test Command
DTP:	Detailed Test Plan
EUDB:	Engineering Unit Database
FMTV:	Family of Medium Tactical Vehicles
GCW:	Gross Combination Weight
GPS:	Global Positioning Satellite
GVW:	Gross Vehicle Weight
GVWR:	Gross Vehicle Weight Rating
HEMMT:	Heavy Expanded Mobility Tactical Truck
HET:	Heavy Equipment Transporter
HMMWV:	High Mobility Multi-purpose Wheeled Vehicle
ICD:	Initial Capabilities Document
ICV:	Stryker Infantry Carrier Vehicle
IPT:	Integrated Product Team
JUONS:	Joint Utility Operational Needs Statement
LRIP:	Low Rate of Initial Production
OEF:	Operation Enduring Freedom
OIF:	Operation Iraqi Freedom
ONS:	Operational Needs Statement
OT:	Operational Testing
OTC:	U.S. Army Operational Test Command
PM:	Program Manager
PM HTV:	Program Manager – Heavy Tactical Vehicles
PM LTV:	Program Manager – Light Tactical Vehicles
PQT:	Production Qualification Test
PVT:	Production Verification Test
RWS:	Roadway Simulator
SOP:	Standing Operating Procedure
T&E:	Test and Evaluation
TACOM:	U.S. Army Tank and Automotive Command
TARDEC:	Tank-Automotive and Armaments Research and Development Command
TDY:	Temporary Duty
TIR:	Test Incident Report
TOP:	Test Operating Procedure
TP:	Transformation Plan

TRADOC: U.S. Army Training and Doctrine Command
TSM: TRADOC Systems Manager
VCW: Vehicle Curb Weight
WIPT: Working Integrated Product Team

CHAPTER 1: INTRODUCTION

In October 2001 the first wave of United States Armed Forces troops entered Afghanistan in order to disperse the Al Qaeda and Taliban militants there under Operation Enduring Freedom (OEF). A year and a half later, on March 20th 2003, Operation Iraqi Freedom (OIF) commenced with the ground invasion of Iraq in order to overthrow the existing Iraqi regime. In both conflicts tactical wheeled vehicles played an integral role in the success of U.S. troops. In Operation Enduring Freedom, the primary vehicles of use were the light High Mobility Multi-purpose Wheeled Vehicle (HMMWV) and the armored Stryker Infantry Carrier Vehicle (ICV). While the HMMWV's were used primarily for mountainous and city operations; the much larger Stryker was used predominantly in more level and open terrain and rural areas. By and large these vehicles were moderately suited to the type of environments and conflicts they were undergoing. It was not until the highly volatile militant tactics were experienced by soldiers in Operation Iraqi Freedom that it became evident that more armor and different operating tactics would be needed to be successful.

At the beginning of Operation Iraqi Freedom, the tactical wheeled vehicles in theatre were ill-equipped for the fighting going on there. The vast majority of HMMWV's present were of the light-duty type and carried little or no armor. The larger vehicles, the Family of Medium Tactical Vehicles (FMTV), the M915 Truck Tractor, the Heavy Expanded Mobility Tactical Truck (HEMMT), and the Heavy Equipment Transporter (HET), came with no armor at all. A request sent in the form of an Operational Needs Statement (ONS) was forwarded to the U.S. Army's Materiel commanders in the United States for immediate relief. Solutions were quickly developed

and implemented in military vehicle systems, tested briefly for safety issues, then manufactured and sent to theatre. Shortly thereafter new complaints arose regarding the rapid rate of vehicle component failures.

In order to help the Commanders in theatre determine the causes and contributing factors of the vehicle failures, the U.S. Army Developmental Test Command in conjunction with the U.S. Army Aberdeen Test Center created a task force to collect various forms of data from vehicles running in theatre. Ultimately, the task force would help transform outdated testing procedures into relevant and flexible test plans aimed at simulating the current extreme driving conditions in theatre. Engineers at ATC designed and fabricated an instrumentation package that collected data such as road speed, vertical, longitudinal, and lateral accelerations, engine load, throttle position, fuel consumption rate, roll, pitch and yaw rate, coolant temperature, transmission oil temperature, engine speed, and transmission output speed. Field engineers then installed the instrumentation packages on different categories of vehicles in theatre, including the HMMWV, the M915 Truck Tractor, and the FMTV. The data described above was recorded for one month and then sent back to ATC for reduction and analysis. The ATC task force decided that multi-objective optimization techniques would be used in order to determine the best combination of ATC courses to match the driving environment in theatre.

This thesis studies problems related to three different goals. At the lowest level the goal is to identify the test that best matches the customer's intent or need. At this level the main deliverable is an ATC road course test matrix. At the intermediate level the goal is to develop a process that identifies or develops ideal test plans for ATC. At this level the main deliverable is a flexible optimization program that can create relevant

test plans based on inputted data. At the highest level the goal of this thesis is to identify and document the steps taken to find the best process to develop optimized test plans in order to advance the science of engineering optimization and decision production systems. The main deliverables at this level are the lessons learned, the end product (a process to identify the most appropriate transformation plan), and the results and evaluations of these different transformation plans when applied to actual test programs.

Chapter 2 provides the relevant background information and literature review of Defense acquisition practices, acquisition and testing decision makers and share holders, and current U.S. Army and industry testing practices. Chapter 3 describes the methodology used in developing military test transformation plans. Chapter 4 details and demonstrates the transformation plans that were developed and includes simplified examples of the optimization algorithm used in one of the transformation plans. Chapter 5 includes the analysis of applying three different transformation plans to an actual M915 Truck Tractor test project. Chapter 6 details the analysis of transformation plans applied to HMMWV developmental testing. Finally, Chapter 7 offers a summarization and conclusion of the thesis and outlines future potential applications of the research obtained from this thesis.

CHAPTER 2: BACKGROUND

The U.S. Army Aberdeen Test Center is a facility owned and operated by the Department of Defense (DOD) and serves as the DOD's leading developmental test facility. ATC specializes in five distinct areas: Automotive testing, Firepower testing, Survivability/Lethality testing, Warfighter equipment testing, and Test Technology and Army Transformation. ATC is located at the Aberdeen Proving Grounds (APG) in Aberdeen, Maryland. APG is classified by the DOD as a major range and test facility base which affords the proving grounds a reputation of distinction and cutting edge technology.

The largest branch of ATC is the Automotive Division. Boasting over 30 miles of test courses ranging from high speed paved courses to level gravel secondary road courses to cobblestone roads to muddy and hilly cross-country courses, ATC offers a great range of testing conditions for any size and any type of wheeled or tracked vehicle. The full range of ATC reliability test courses are listed in Table 1 below, along with the date the test courses were opened and their original intended purpose [1]. It is obvious that some test courses, like Belgium Block, were designed for theatre conditions that were extremely relevant in previous conflicts but that are not necessarily very relevant at the present time.

	Road Courses	Length	Date Built	Description/Intended Purpose
Churchville Test Area	CTA-B	7.4 mi	1942	Hilly cross-country road course, provide engine and powertrain testing
	CTA-C	1.5 mi	1942	Hilly secondary road course, provide engine and powertrain testing for trailers and semi-trailers
Munson Test Area	Gravel	2.0 mi		Compacted bank gravel, improved secondary road course
	Belgian Block	3,940 ft		Granite blocks in concrete, simulate European road conditions
	Imbedded Rock	800 ft		Granite stones in concrete, provide tire and suspension testing
	2-inch Washboard	822 ft		Concrete, provide high frequency testing of vehicle suspension system
	3-inch Spaced Bump	764 ft		Concrete, provide repeatable high amplitude suspension system testing
	Wave Course	443 ft		Concrete, provide high amplitude vehicle frame twisting
Perryman Test Area	PTA-1	5.2 mi		Moderate severity cross-country course
	PTA-2	1.8 mi		Moderately rough cross-country course
	PTA-3	3.3 mi		Rough cross-country course
	PTA-4	2.5 mi		Severe cross-country course, natural marsh
	PTA-A	2.4 mi		unimproved native soil secondary road
	PTA-B	3.2 mi		unimproved gravel and crushed stone secondary road
	Paved	3.8 mi		High speed primary paved road
	Mile Loop	1.0 mi	1933	Level concrete course for continuous high-speed operation tests

Table 1. Common Reliability Road Courses at ATC.

2.1 Common Acquisition Test Programs

The most common type of automotive test project performed at ATC is a DOD system acquisition program. System acquisition programs are major materiel or software purchases made by the DOD to support soldier needs. There are many levels of acquisition programs based on the amount of oversight and funds required to make the purchase and maintain the system. A pictorial model showing a broad view of the DOD acquisition strategy is provided below in Figure 1. The DOD acquisition strategy

describes the process by which a military system is conceived, developed, validated, manufactured, distributed, and ultimately disposed. For the purposes of this thesis, we are interested only in developmental testing which occurs predominately between Milestones A and C.

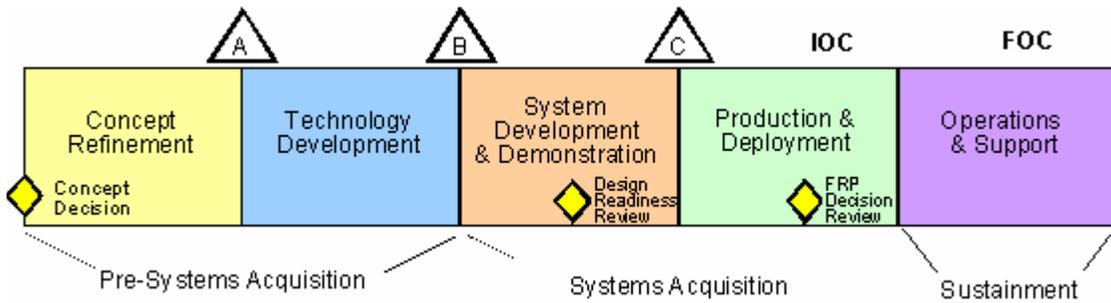


Figure 1. General DOD acquisition strategy [2].

Purchase authority and management responsibility for these programs is given to a Program Manager's (PM) office. Program Managers are responsible for the design, purchase, maintenance, and management of DOD commodities such as the HMMWV. Early in the life cycle of a DOD system acquisition, the system must be proven and validated by an independent test and evaluation community. The PM, Test Center, and Army Evaluation Command (AEC) are all independent organizations, though still under the umbrella of the DOD. The test center's responsibility is to provide accurate and unbiased developmental and operational test results to the evaluation center. AEC then compares the test results to the performance and reliability criteria set for the system and provides a recommendation or approval of the system.

2.1.1 Developmental Testing

Developmental testing (DT) in the acquisition process serves the primary purpose of transforming a fledgling prototype system or product into a mature, production-ready

one. This is accomplished by intensive and strategic engineering performance and reliability testing. For many systems that are still early in the experimental stage the process often follows a test-fix-test pattern. The U.S. Army further divides DT into smaller stages for the acquisition process.

Initial testing of an experimental system is considered as the Concept Demonstration phase. Concept Demonstration testing allows the Army to browse different potential solutions to an advertised need. Promising systems that show design maturity or high potential for meeting or exceeding the Army's requirements move to the next phase of DT. The Concept Refinement test phase allows the system contractors to modify and further develop their designs in the hope of obtaining the government contract. Generally a down select will result at the end of Concept Refinement testing and the system that best meets the Army's requirements will be approved for a low rate of initial production (LRIP).

As the contractor enters LRIP, additional modifications will be made to the system design. The Production Qualification Test (PQT) phase will allow the Army to test production-representative systems in order to ensure the maturity of the designs. Upon the successful completion of the PQT, any deficiencies found during testing will be corrected and the Army will decide whether to purchase the system for fielding and to start full rate production or to cancel the contract and start the DT process over. Assuming the system or product satisfies the Army's needs, the field ready design will undergo full rate production. The final phase in DT is the Production Verification Test (PVT). Within a time period specified by the U.S. Army after the start of full rate production, the contractor will be required to supply a limited number of systems pulled

directly from the assembly line for a PVT. This testing will confirm that the fielded products continue to meet previously achieved performance requirements. The first units produced under full rate production will go directly to Operational Testing.

2.1.2 Operational Testing

Operational Testing (OT) serves the purpose of ensuring a system or product meets user requirements before full fielding or distribution occurs. OT is distinctly different from DT in that the focus is on the soldier or user interface and his requirements rather than strictly system performance as it is in DT. In the OT test environment actual soldiers perform repeated realistic training exercises with the equipment in an effort to validate the findings and corrections made during developmental testing. Unlike DT, OT is conducted very late in the product development stage of the acquisition process when the system is very mature. Major design flaws discovered during OT are rare and bode ill for fielding the new system on time or at all. OT also helps Armed Forces staff to develop and hone training documents and maintenance manuals that will be fielded with the system [3].

2.1.3 Existing Testing Transformation Plan

At this point it is necessary to introduce the existing testing transformation plan that is currently the standard for most U.S. Army acquisition programs. This transformation plan will be the basis of comparison for the transformation plans discussed later in this thesis. The existing transformation plan provides a means for the U.S. Army to determine how best a new acquisition system or product can be tested during DT. OT considerations will not be included in this description of the existing transformation plan.

Army decision makers involved with a new system's acquisition process are concerned with a number of issues when determining how best to developmentally test that system to ensure the best product is provided to the soldiers. Some of the most important of these issues expressed as questions follow: What is the primary intended use environment? What extreme conditions can be reasonably expected for secondary and tertiary environments? What performance standards do the soldiers/users expect? What are the limits they are willing to accept? How do they intend to use the system? What vulnerabilities present themselves for these intended uses?

As these questions are discussed and agreed upon amongst the important shareholders and decision makers associated with the acquisition program, a general test plan is created called the Test and Evaluation Master Plan (TEMP). These shareholders and decision makers are discussed in-depth later in Section 2.2. The TEMP outlines all of the requirements the system must ultimately meet before it is purchased by the U.S. Army and fielded. The TEMP then becomes the basis for discussion on the DT plan of action. Within the U.S. Army Test and Evaluation Command (ATEC) a Detailed Test Plan (DTP) will be developed so as to ensure the system is tested against each of the criteria set forth in the TEMP. The DTP is then the guiding document used by each test center tasked to perform the required tests. The DTP includes all DT of the system, not just automotive reliability testing. However, the majority of this thesis focuses on how reliability testing specifically is impacted by the different transformation plans.

2.1.4 Reliability Testing

Many private industry and DOD acquisition programs come through ATC for automotive developmental testing. The two main categories of automotive

developmental testing are performance and reliability. Reliability testing has to do with estimating the anticipated life and failures of a vehicle in the field. ATC conducts accelerated life cycle testing on over 30 miles of test track. The test tracks are broken into three main categories: primary roads, secondary roads, and cross-country terrain. Commonly a vehicle will undergo 12,000 to 20,000 mile reliability tests on these courses. Of these three categories, the test tracks are broken down further to simulate different driving environments. For primary roads, vehicles run on level and hilly paved roads at speeds up to 65 mph. For secondary roads, vehicles run on an assortment of gravel, cobblestone, level, and hilly country roads. For cross-country terrains, vehicles will run on hilly and level courses that are full of giant pot holes and steep hills and valleys. Often for reliability tests, the vehicles will run 2 ten-hour shifts a day, 6 days a week in order to shorten the overall time of the project.

At the completion of most acquisition program reliability tests, data validation conferences called Test Incident Report Scoring Conferences are conducted. At these conferences the entire Decision Community is present to discuss the failures that occurred during the reliability test. Test Incident Reports, detailed later in Section 2.1.4.2, and their scores determine whether the system contractor is required by contract to correct the problem before production, or if another party is at fault for the failure. While the whole Decision Community participates only three votes are counted, those of the Evaluator, the Customer, and the User. The Decision Community and these participants are discussed later in Section 2.2.

2.1.4.1 Road Course Test Matrix

The most visible and useful representation of the reliability test portion of the DTP is the Road Course Test Matrix. The Road Course Test Matrix provides an outline of the reliability testing plan in tabular format. The Matrix is broken down into three different categories for automotive tests: Primary Roads, Secondary Roads, and Cross-Country Courses. For each road course that the vehicle will accumulate test miles on, a required total number of miles and their subsequent overall percentages will be shown. The Road Course Test Matrix can be regarded as the end result or main deliverable from a test transformation plan. A sample Road Course Test Matrix is shown below in Table 2.

Test Course	Per Course, %	Distance, miles
Paved	75.0	750
Secondary Roads	20.8	208
MTA Gravel	8.3	83
MTA BB/G	3.3	33
CTA-C	9.2	92
Cross-Country	4.2	42
PTA-2	4.2	42
Total	100.0	1000

Table 2. Sample M915 Truck Tractor Road Course Test Matrix

The decisions made regarding the major issues listed above have a direct impact on the result of this matrix. For instance if the primary use environment is paved multi-lane highways like those found across the United States, then as the Road Course Test Matrix shows above, the majority of the test miles will be on the ATC paved course.

The current road course test matrices for the M915 Truck Tractor and HMMWV were both developed under the existing test transformation plan described previously.

The HMMWV Road Course Test Matrix still in use today was developed in the early 1980's when the HMMWV was just entering its acquisition process. The M915 Truck Tractor has been around longer, and its Road Course Test Matrix was developed during the 1970's.

During this era, the U.S. Army planned for these systems to be fielded in similar theatres though for different uses. At that time the U.S. Army still believed the next major conflict would be similar to World War II and the Cold War. As a result vehicles would most likely be deployed in European or North Asian theatres with secondary environments in the United States and areas bordering the primary theatres of interest. This meant the vehicles would have to withstand road conditions such as cobbled streets, poorly maintained paved roads, some highways, and a large portion of gravel or muddy secondary roads.

Though they were meant for similar environments, the uses varied greatly between the M915 and the HMMWV. The M915 was designed to be an over-the-road tractor trailer meant to haul heavy and large cargos long distances over improved terrain. The HMMWV on the other hand was designed to replace the WWII era Jeep and the Vietnam era Commercial Utility Cargo Vehicle (CUCV). Designed to be smaller, lighter, and more versatile than other Army vehicles at the time, the HMMWV was intended primarily to traverse rugged cross-country terrain, such as battlefields, at low to moderate speeds carrying passengers instead of a lot of cargo.

Due to these decisions made by the U.S. Army, the subsequent Road Course Test Matrices for these two vehicles were directly tailored for the intended environments and uses described above by professional judgment and some empirical data from DTC. The

existing or standard Road Course Test Matrix for the M915 Truck Tractor is shown above in Table 2 and the standard HMMWV Road Course Test Matrix is shown below in Tables 3. While the existing transformation plan and subsequent resulting test matrices are logically rendered and sufficient for the specific environments and uses described above, unfortunately the same test matrices have been applied to all M915 and HMMWV test programs to date even though the operational environment, soldier usage, and other aspects that affect the performance and reliability of the vehicles have changed.

Test Course	Per Course, %	Distance, miles
Paved	30.0	3,600
Secondary Roads	30.0	3,600
MTA Gravel	10.0	1,200
MTA BB/G	3.3	400
PTA-A	16.7	2,000
Cross-Country	40.0	4,800
PTA-1	11.7	1,400
PTA-2	8.3	1,000
PTA-3	3.3	400
CTA-B	16.7	2,000
Total	100.0	12,000

Table 3. Standard HMMWV Road Course Test Matrix.

2.1.4.2 Instrumentation and Data

There are typically two different types of data obtained on reliability or endurance tests, Test Incident Reports (TIR's) and Advanced Distributed Modular Acquisition System (ADMAS) data. TIR's are typed detailed reports that are generated by a technician or data collector when a part on a test vehicle fails. The reports include data such as how and when the failure was found, what may have potentially caused it, and how it was fixed. Once the TIR is written it is uploaded into a computer database and then distributed to the test community involved in the project. When the test has been

completed, engineers will condense data from the TIR's, perform statistical analysis on the failures, and report on the subsequent reliability findings. While TIR's are indispensable for recording and tracking failures, they have no bearing on a vehicle project's test plan. ADMAS data has not had an influence in the development of unique test plans until recently.

The ADMAS package is one of several varieties of onboard data acquisition systems currently being employed by ATC. The ADMAS is predominantly used for endurance testing because it is easily and quickly installed in vehicles and because it does not have the high capacity and data resolution needed for performance testing. The ADMAS is roughly 6 inches wide, by 8 inches deep, by 8 inches tall. It can easily fit in small cargo spaces or under the body of a vehicle. There is no instrumentation in the main unit and so it can be placed anywhere convenient on the vehicle. It has built-in acceleration and electrical shock protection and is packed in a sealed, sturdy, and light aluminum casing. The ADMAS was developed at ATC by the Instrumentation Development Division and contracted out for low-scale production. Currently approximately one hundred ADMAS units are in use at ATC.

All ATC onboard data acquisition systems are designed to provide a technologically advanced method to acquire and store large amounts of data commonly requested on reliability tests. Data such as road speed, engine load, engine coolant temperature, acquired via vehicle data buses or data from ATC installed instrumentation, such as GPS, accelerometers, displacement gauges, pressure gauges, or thermocouples, are saved on large Compact Flash cards in the onboard unit or sent to an accompanying data vehicle wirelessly via line-of-sight telemetry. The amount and types of data

collected vary for each test and can depend on what data buses are present on the vehicle, what the customer is interested in, how much time is allotted for instrumentation and subsequently the amount of money available. The data on the Compact Flash cards are then uploaded to databases daily by data collectors. Once the data undergoes quality checks it is provided to test personnel via a web-based database.

In September 2006 Colonel John P. Rooney, Commander, U.S. Army Aberdeen Test Center, initiated a task force and project to create a special onboard data acquisition system using the ADMAS that would collect use data from certain vehicles being used in theatre for Operation Iraqi Freedom. The purpose for the project was to determine how much the operating environment and uses had changed for the HMMWV, FMTV, M915, HEMTT, and HET compared to their original and long standing reliability test plans. The data obtained from 30 days of operation of many of these vehicles in the current theatre has provided new opportunities to develop more sophisticated and viable ways to process design issues into practical and pertinent DTPs and Road Course Test Matrices early in the acquisition process.

2.1.5 Performance Testing

The other major automotive test activity at ATC is performance testing. Performance testing serves the purpose of determining the physical limits to which a vehicle can be taken as well as the overall safety of the vehicle to its occupants. Sample performance tests include longitudinal grades and side slopes, road shock and vibration, fuel efficiency, full-load cooling, maximum effort braking, acceleration and top speed, steering and handling, climatic chamber, and human factors engineering, as well as many others. These tests are performed on many courses shared by reliability testing in

addition to separate performance designated courses. ATC's latest tool to help characterize vehicle performance is the Roadway Simulator (RWS). The RWS facility allows ATC engineers to conduct controlled and highly repeatable vehicle performance testing on a fixed track.

2.2 The Decision Community

The Decision Community is a term that describes the particular private industry customers, governmental agencies, or DOD commands and the individuals that represent them that are involved in a particular test project. The major groups that are involved are brought together generally by DOD regulations, governmental laws, and practical experience. For the current situation, the Army Test and Evaluation Command (ATEC) System Team (AST) is the integrated project team (IPT) that makes up the decision community. The AST has both voting and non-voting members. Voting members have a say in the ultimate procurement of the system. Non-voting members are present to provide support, suggestions, and data for the decisions that will be made. There are three major groups that will always be involved in an acquisition project as voting members: the Customer, the Evaluator, and the User. At ATC, the Customer is most commonly a Program Manager, from this point forward the abbreviation PM will be used to denote the Customer. The final member in the decision community that is always involved but is never a voting member is the Tester.

Though the Tester does not have a vote, he or she greatly influences the Evaluator and his decision. While generally the User is the Soldier, the User and the PM remain independent because of their divergent objectives. The PM endeavors to serve the needs

of the Soldier, while the User acts as the guardian of the Soldier, ensuring that the system the PM is procuring will actually satisfy the need.

2.2.1 The Program Manager

ATC's mission is to serve soldiers defending our country in foreign lands. As declared in their mission statement, ATC's ultimate customer is the Soldier. The Soldier, though, is a somewhat ill-defined entity and is open to interpretation. Most often the Soldier's voice is advocated by the PM. When the soldiers have a problem or observe a shortcoming in mission capabilities and current materiel systems, they approach different PMs according to their area of expertise. If a soldier needs a new tank, truck, or off-road vehicle or changes to existing ones, they approach the Tank-Automotive and Armaments Command (TACOM) with their issues. TACOM manages all wheeled and tracked vehicles developed and procured by the U.S. Army, and ATC primarily works with PMs from this command.

After the Soldier introduces a need for a system, the PM will then request funding from Congress to start the acquisition process to fill this need. It is the PM office that is responsible for finding system vendors, setting performance criteria standards, and funding testing and evaluation efforts that are required by law for purchasing and fielding the system. The PM office is often broken down into two main functions: Administrative and Technical.

The administrative individual or team from the PM office is concerned primarily with programmatic issues, such as budget, logistics, and schedule. This person or group sets milestones and deadlines, coordinates meetings, tracks project funds, and handles system logistics issues. This component of the PM office is not as concerned with testing

and evaluation (T&E) as the Technical component. Their chief concern during T&E activities is to make sure only the right tests are performed and that testing is going as scheduled.

The technical component is most commonly a group of individuals specializing in different areas of expertise. The major technical areas that are commonly staffed are manufacturing, engineering design, reliability and durability, and performance engineering. Different individuals will be emphasized during different portions of the acquisition cycle. For example, the engineering design expert will be most active at the start of the acquisition cycle because that is when the PM office considers technical bids from different vendors. The manufacturing expert will be most utilized during later parts of the acquisition cycle when the system has been developed and is ready for production verification. For T&E activities, it is the reliability and performance engineering individuals who are most involved.

The representative from the PM office responsible for technical issues related to the system handles the majority of the interactions with the test centers and evaluator personnel during the T&E process. He coordinates design changes and modifications during testing, logistics for replacement parts, training of maintenance and test personnel, responds to design failure issues during TIR scoring conferences, and handles issues relating to system performance criteria.

2.2.2 The Evaluator

The U.S. Army Evaluation Center is the Army's independent test evaluator. AEC is very important because they retain the authority to determine whether a PM will be allowed to initiate full production of the system. The AEC representative chairs the IPT

or AST during T&E activities which include developmental and/or operational testing. The Evaluator, sitting as the AST chair, is responsible for determining the test requirements for the acquisition system. He or she also coordinates the necessary planning meetings and staffs the appropriate documents that will be needed to approve the procurement. During T&E activities the AEC representative's largest task is to evaluate the actual performance and reliability data from testing and to compare the results to the system objectives. In doing this, the Evaluator forms his opinion on the system and will then provide his vote in the decision.

2.2.3 The Tester

The Tester is a multi-layered position in the T&E process. The overarching Tester is a DTC Test Manager. He is responsible for managing test activities for multiple acquisition projects at a time. The DTC Test Manager will follow the same project throughout the entirety of its DT in the acquisition process. Below the DTC Test Manager are the test center Test Directors.

At ATC, a Test Director normally handles only one large acquisition project at a time, or if there are less involved projects the Test Director may handle more test projects. Test Directors may or may not follow a single project all the way through its DT. The Test Director is responsible for all day to day activities of the DT. He schedules the necessary personnel, forwards test information to the Decision Community, handles regulatory and safety paperwork for the project, coordinates with DTC for overall test schedule, sits on the AST to provide professional engineering and testing input, and creates the final report at the completion of testing. Most importantly the Test

Director forwards the data and results that are obtained from testing to the Evaluator to help in their assessment of the system performance.

The final layer of the Tester position is the Field Engineer or Test Expert. Like the PM dichotomy, while the Test Director handles more of the administrative aspects of DT, the Field Engineer covers the technical aspects of DT. Field Engineers provide expertise on instrumentation, Test Operating Procedures (TOPs), test courses, data acquisition, data reduction, and engineering principles. Field engineers are commonly not present at most AST meetings except for special instances or TIR scoring conferences.

2.2.4 The User

The User, like the ultimate customer, is the Soldier. The User serves a different purpose than the PM, however. While the PM acts according to the Soldier's request, he is not internally held accountable for the system or product's performance when it is delivered back to the Soldier and fielded. The User, who more directly represents the Soldier, is then given a vote in order to hold the PM accountable to their original goals. For any U.S. Army acquisition program the User is a representative from the Training and Doctrine Command (TRADOC). The representative is commonly referred to as the TRADOC Systems Manager (TSM). There is commonly only one TSM per acquisition project but the TSM serves two very important roles: voicing the needs of the original user, and protecting the intended user.

The original User is the group, unit, or division that made the initial request for a new system through the formation of an ONS. For many requests coming from theatre presently the urgency for solutions is great, so the informal name of Urgent Needs

Statement (UNS) has been given to these documents. The original User describes in non-technical terms the operational gap present and what needs must be met in the solution system. Since the ONS or UNS is most commonly created by a deployed unit, it is difficult to provide a representative to follow the system through the acquisition process, and so a TSM from TRADOC is assigned to advocate for the original User as the intended User.

The TSM representing the intended User handles all of the managerial and administrative duties associated with an acquisition program for the original User. In addition he acts as the advocate for the soldiers during all AST meetings including test planning as well as TIR scoring conferences. The TSM ensures that the system requirements spelled in the TEMP match those specified in the ONS, and that the system is not purchased by the government unless it meets those requirements, as well as ensuring proper training documents and methodologies and maintenance manuals are sufficient for the Soldier. Much of the intended User's influence is based on the scores he provides during the scoring conferences.

CHAPTER 3: METHODOLOGY

This thesis consists of two activities: developing an optimization algorithm that creates a relevant test plan and designing and comparing different transformation plans. This chapter will discuss the methodology used in each.

3.1 Develop Optimization Algorithm to Find a Relevant Test Plan

At the lowest, most technical level, the primary goal of this research was to develop an optimization algorithm that would efficiently and accurately find a road course test matrix that matches a set of PM/User requirements. To do so, existing data provided from the ATC OIF Instrumentation Effort was used in conjunction with Microsoft Excel and MathWorks Matlab software. The road speed data channel was chosen as the primary objective for optimization during single and multi-objective analyses.

Originally a simple polynomial regression analysis was attempted to optimize a set of OIF theatre use data with that of similar data obtained from available ATC test courses. Due to poor correlation between the two sets of data and the flawed application method this direction of research was quickly ended. The next step was to consider applying constrained single objective optimization techniques using the Matlab program for the algorithm set-up and calculations. An objective function was created that calculated the error between the sum of weighted ATC test course data sets compared to a “desired” set of data which represented the soldier’s intended environment and use profile. Using the *fmincon* function from the Matlab Optimization Toolbox, a set of time domain percentage weights for each course were found at the minimized error point for

one data channel at a time (single objective). To match the required mileage domain percentage weights found on the road course test matrix a simple post calculation was conducted using the average speed for each road course multiplied by the time domain weight and then divided by the overall distance traveled for each data set.

With the successful completion of the single objective optimization, multi-objective optimization comparing two or more sets of different data channels was attempted. At first this was attempted using the *fminimax* function from the Matlab Optimization Toolbox. Problems arose in which viable solutions were not being found, the Pareto frontiers were also unreadable. To verify that at least a dual objective optimization was feasible, a simple example was constructed using the Microsoft Excel spreadsheet program. With a successful optimization and Pareto curve using Excel, work was resumed on the multi-objective Matlab problem. Instead of using the *fminimax* function, the second objective function was cast as an inequality constraint that would be satisfied multiple times at different locations, or slices of the Pareto curve, using a *for* loop. Using this method it was possible to perform the optimization search utilizing the *fmincon* function. Finally with a successful set of optimal solutions and a feasible Pareto curve showing definite areas for tradeoff within the optimized set of solutions, additional data channel sets were successfully added to increase the degree of objectives.

Creating an optimization algorithm that finds relevant road course test matrices directly relates to the first goal of this research discussed in Chapter 1. At the most practical level the goal of this research was to identify the test plan that best matched the soldier's intent or need. The optimization algorithm developed and applied to automotive reliability testing satisfied this goal by outputting ATC test course use percentages that

minimized the error between test results using ATC road courses with that of a current environment and use data from OIF.

3.2 Design and Compare Transformation Plans

New potential transformation plans were created and evaluated concurrently with the development of the optimization algorithm. Initially, the existing DOD test transformation plans were researched and documented. Next, a literature review established the current state of test development and research in decision production systems. Informal brainstorming sessions were conducted individually and in groups to obtain ideas of different ways to create automotive test plans. Further development of these ideas among test professionals and engineers provided a set of four distinct and feasible test transformation plans that showed promise for DOD testing applications.

These feasible transformation plans were then applied to two candidate test programs preparing for automotive reliability testing at ATC in order to provide evaluation feedback on the pros and cons of each transformation plan. Three of the four new transformation plans were implemented for a short reliability test for a M915 Truck Tractor. The 3000-mile reliability test was divided into three 1000-mile units with each transformation plan responsible for providing the Road Course Test Matrix for one unit. Though the test was later cancelled, enough preliminary work and data was obtained to make preliminary transformation plan performance assessments.

Similarly, the four transformation plans were implemented on a mock HMMWV test project. Though actual miles were not accumulated for the different transformation plans, the majority of the process data is obtained from preliminary work to the actual

reliability test and enough information was gathered to assess their individual performance. In both cases the transformation plan performance results were compared to one another and to each vehicle's representative standard test transformation plan in order to provide a global analysis of the transformation plans.

Developing, evaluating, and comparing these new test transformation plans addressed the second and third goals of this research. The second or intermediate level goal of this thesis research was to develop a process that identifies or develops ideal test plans for ATC. The end result of this goal was to provide a flexible optimization program that can create relevant test plans based on inputted data. The four new transformation plans developed achieved this goal, as it will be shown later each transformation plan has its place.

The third or highest level goal was to identify and document the steps taken to find the best process to develop optimized test plans in order to advance the science of engineering optimization and decision production systems. The main deliverables at this level were the lessons learned, the process to identify the most appropriate transformation plan, and the results and evaluations of these different transformation plans when applied to actual test programs. By comparing the results from each transformation plan against each other and with the standard transformation plans and by making global assessments of the process this goal was achieved.

CHAPTER 4: DEVELOPING OPTIMIZED TRANSFORMATION PLANS

4.1 Problem Statement

The problem statement for this research can be defined as follows: Find the best Transformation Plan that gives the most accurate representation of an intended use environment for courses available at ATC, given the situation and circumstances surrounding the test project. The creation of multiple test transformation plans is due to the need for flexibility regarding differences in test project initial conditions. While the transformation plan developed to employ highly sophisticated analytical optimization software may give the most accurate representation of an intended use environment, it may not be feasible for situations in which only a few days are given to complete testing or if no road course data will be available for the intended environment. The goal of this research is to determine the best ways to provide endurance tests that meet current operational environment, however, in some cases it is better to use standard test plans. These cases arise when no information is available on the operation environment, when the actual environment is not known, or when the vehicle will be fielded in too many dissimilar environments to create a viable test plan. In these situations, it is better to follow previously approved test plans because they are based on well-established Test Operating Procedures (TOPs) accepted by the professional automotive community. As a result, each Transformation Plan was developed to be optimal for a given set of initial conditions or circumstances for any given test project.

Circumstances play a very important role in the selection of the best Transformation Plan for a test project. Issues such as how much time is available, how

much funding is available, how many vehicles will be tested, is intended environment data available, and has the vehicle been tested on ATC courses before must be considered. It is imperative to discuss these issues and prospective Transformation Plans early in the T&E process to ensure a successful test completion in terms of customer satisfaction and viable test results. While only four test transformation plans were developed for this thesis, ideally any AST or T&E WIPT should be able to develop a test transformation plan specifically tailored to their needs.

The following test transformation plans are alternatives to the existing transformation plan described previously in Chapters 1 and 2. Each of the new transformation plans, in addition to verbal descriptions, is depicted in two graphical forms: the Graphic Model and the swimlane diagram [4]. The Graphic Model is intended to provide an easy method for quick recognition of a transformation plan. The swimlane diagram, used in many manufacturing and decision production systems, serves the purpose of providing a more detailed representation of the individuals or groups involved, the actions taken, and the flow of decisions and information involved in the transformation plan [5].

4.2 Transformation Plan A

This transformation plan is based on the premise that little time is available to gather or analyze data. A decision has to be made quickly and the results are needed without delay. This plan disregards the data that has already been gathered and is present in the database. In place of decomposing and analyzing this data, a conference would be convened in order to discuss what is known and to decide on a path forward. The

decision community would review gross aspects of the desired operational environment based on the User's input. The test center, ATC, would have an opportunity then to provide comments about their particular test courses and what might match the operational environment for the vehicle. Other members of the community, such as technical experts or test modelers, may also provide input to the discussion. If there is a need for additional information that is readily available, the community would have the opportunity to use the telephone, internet during the discussion, or have additional experts on hand to attend the meeting. Ultimately the decision community, having relatively little time, will have to come to a consensus on the Road Course Test Matrix. Due to the lack of additional supporting data or analytical optimization techniques, the correlation of the results with the intended environment is expected to be low when using Transformation Plan A.

Two different plan models were developed to visually describe this alternative transformation plan. The first is a free-form diagram of the plan; it is shown below in Figure 2.

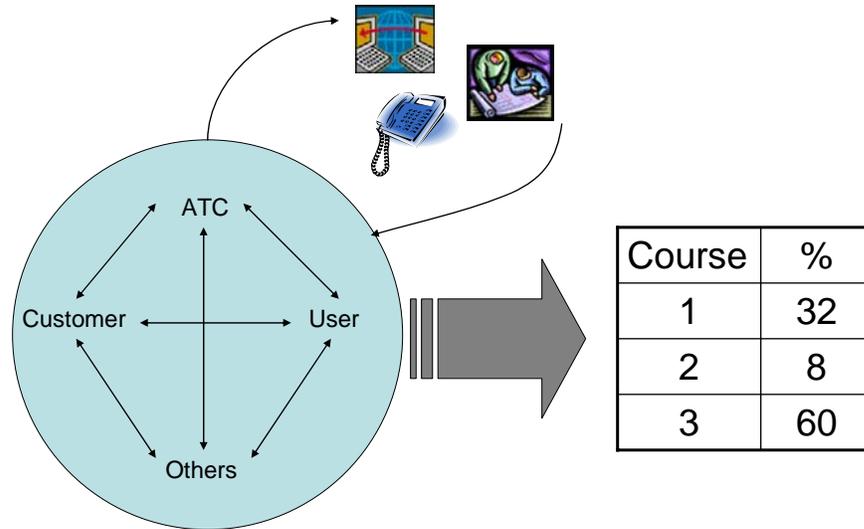


Figure 2. Graphic Model of Transformation Plan A.

This free form diagram is a helpful model for quick visual recognition of Transformation Plan A. The diagram is much different than the other transformation diagrams that follow and it clearly shows that the plan centers on group discussion and quick decisions. The Graphic Model, however, is not helpful for describing the execution of the transformation plan. There is no visual cue for how the resulting test matrix is created. The second model was developed as a swimlane diagram. It is shown below in Figure 3.

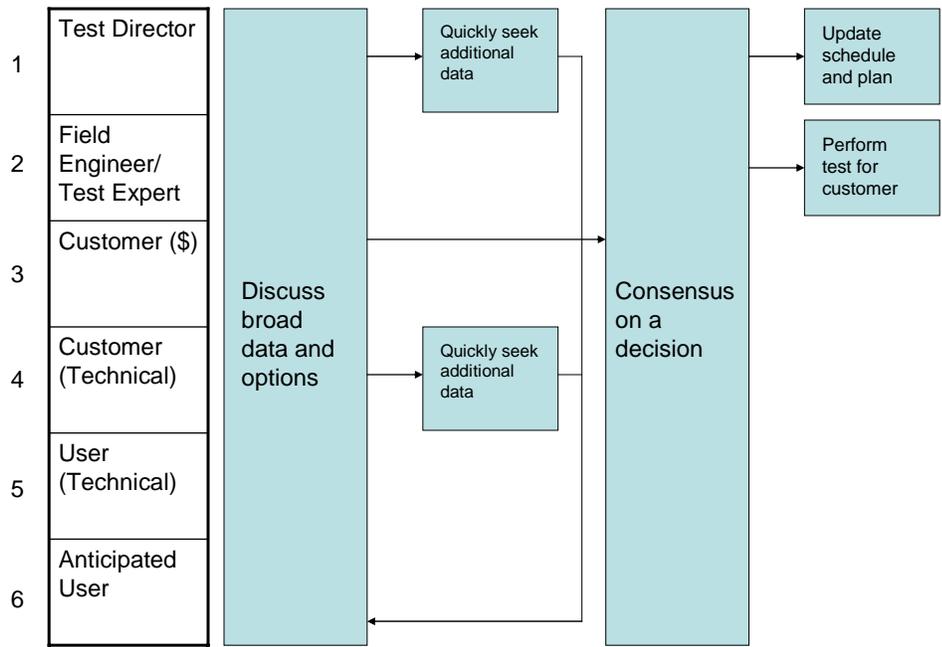


Figure 3. Swim lane diagram for Transformation Plan A.

The Transformation Plan A swimlane diagram, on the other hand, is very useful for planning and execution. There is no easy visual handle for recognition of the plan but the artistic design is sacrificed for utility and function. The swimlane diagram acts as a simplified transformation test plan or guide which aids the decision community to set up and follow this alternative plan.

4.3 Transformation Plan B

Plan B was optimized for situations in which time and money are not significant concerns, but in which relevance and precision are the highest concerns. For Plan B, all historical data related to the test project at hand is accumulated for consideration. Examples of historical data include: course profilometer data, TIRs or final reports from

past test projects, and previously collected performance data. ATC then presents the organized project data to the decision community. It is then decided by the PM that the available data is not sufficient to produce a satisfactory test plan optimized for the user's intended environment. During conferences held by the decision community, ATC is given input as to the PM's additional data needs. It is also possible that other groups such as the US. Army Tank-Automotive and Armaments Research and Development Command (TARDEC) or the U.S. Army Materiel Systems Analysis Activity (AMSAA) could be approached and assigned to collect data or information outside of ATC's expertise.

An ATC Test Engineer or the Technical PM would act as the lead data integrator, should other agencies become involved, in order to compile and organize the additional data which will be sent to the ATC Test Director for analysis. If the need arises, an existing vehicle or the test prototype will be instrumented and run over various ATC courses to gather empirical data of interest. If possible, modeling and simulation should be used as an alternative or to obtain results for extreme condition cases. Use of modeling and simulation in most cases helps to reduce cost and time spent collecting additional data. When the additional data collection is complete the ATC Test Director will again compile and organize the new data, perform any preliminary analyses assigned by the PM, and present the findings to the decision community for further discussion. The decision community will then decide on an appropriate test plan based on the combination of the historical information and the additional data.

Two different plan models were developed to visually describe this alternative transformation plan. The first is a free-form diagram of the plan; it is shown below in Figure 4.

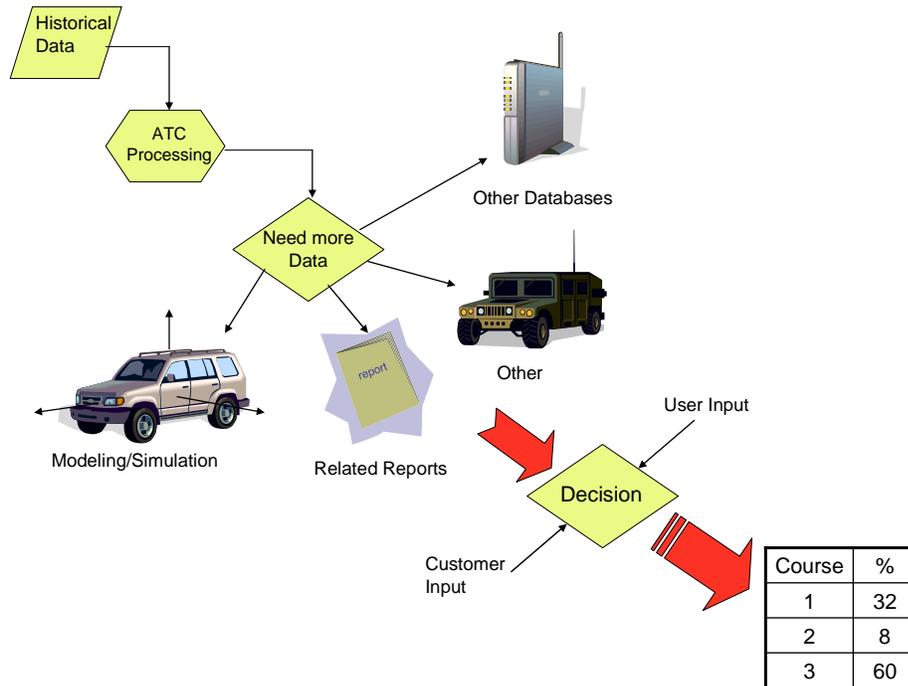


Figure 4. Graphic model of Transformation Plan B.

The Plan B free form diagram, like Plan A's, is a helpful model for quick visual recognition of the transformation plan. The diagram illustrates that the plan centers on additional information gathering. In addition this diagram also shows a number of potential sources for additional information which will help in transformation execution. It, however, is also not helpful for describing the steps to creating the resultant test course matrix. The second model was developed as a swimlane diagram. It is shown below in Figure 5.

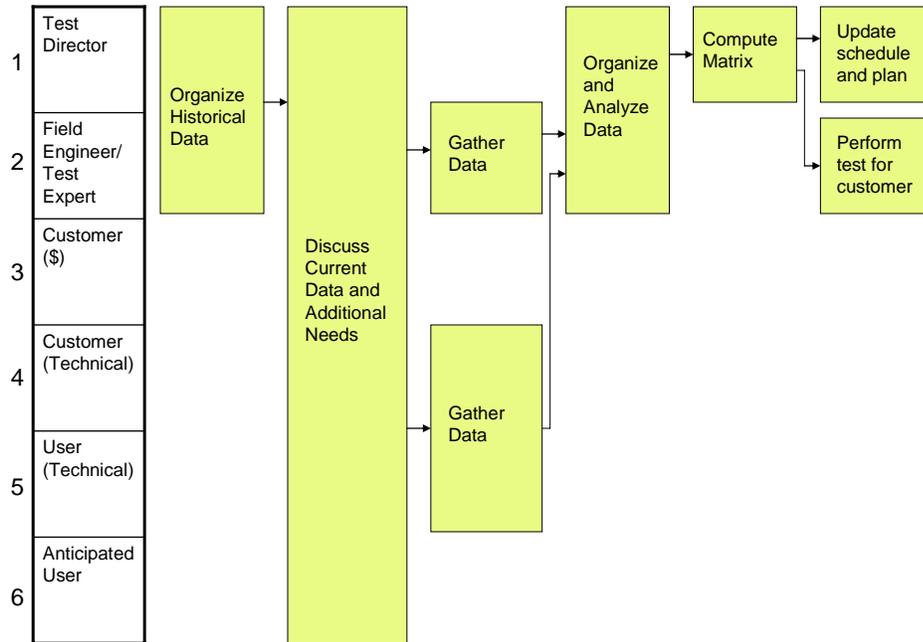


Figure 5. Swim lane diagram for Transformation Plan B.

The Plan B swimlane diagram is very useful for planning and describing work flow. This diagram is very methodical and precise in describing Plan B, and so would be very helpful to the decision community for planning and program scheduling. Like most swimlane diagrams, however, there is no easy visual handle for recognition of the plan. In addition, although the swimlane diagram shows a very detailed process it does not provide any help to the decision community about possible options for data gathering.

4.4 Transformation Plan C

Plan C is optimized for test accuracy and relevancy to the intended use environment. Here, the Decision Community forms a consensus on a ranked list of important data channels, such as velocity or vertical acceleration, that must be considered when making the automotive test plan. Those data channels at the top of the list will be

the primary sources for optimizing the test plan. The data channels are data that has already been captured for the intended vehicle or one similar to it on ATC test courses and the intended use environment. The test plan will then be optimized by test engineers at ATC by minimizing the error between a compilation of ATC test courses and the intended environment. The specifics of the optimization process and algorithm will be discussed in depth later in Section 4.4. Once ATC has developed the optimized road course test matrix, it will be presented to the Decision Community for review and approval. Two different models were developed to visually describe this alternative transformation plan. The first is a free-form diagram of Plan C; it is shown below in Figure 6.

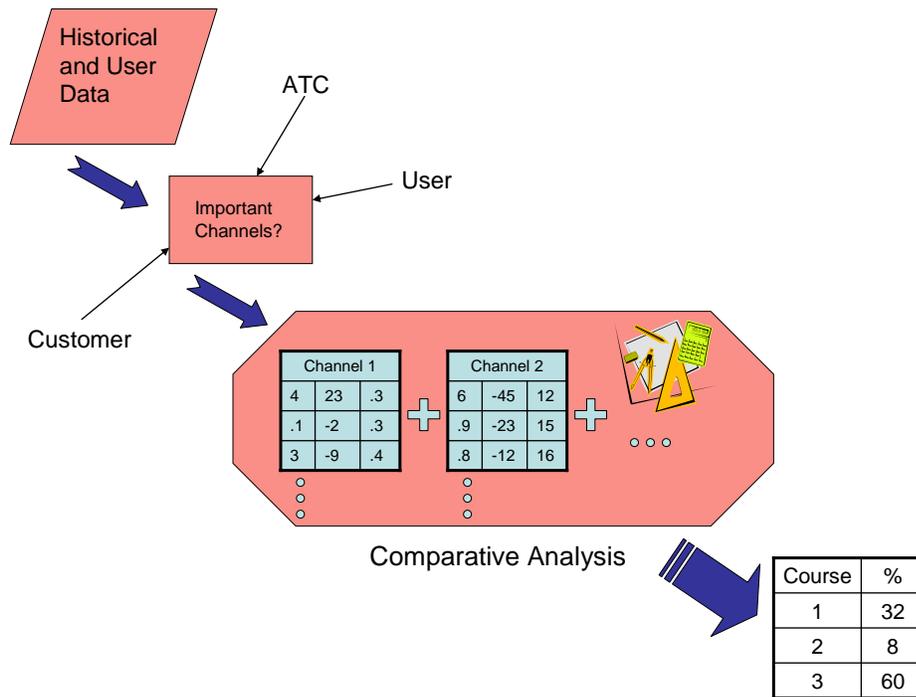


Figure 6. Graphic model of Transformation Plan C.

The Plan C free form diagram, unlike Plan A and Plan B, is not very useful as a quick visual representation of this transformation plan. The diagram illustrates the transformation plan's emphasis on choosing important channels as a work flow rather than as an artistic representation. This diagram is not as detailed as the previous diagrams and does not help the decision community transform the desired channels into a resulting test matrix. The Plan C free form diagram is useful as a rough description of the transformation plan but must be further described in order to provide additional benefits to a decision community. The second model was developed as a swimlane diagram. It is shown below in Figure 7.

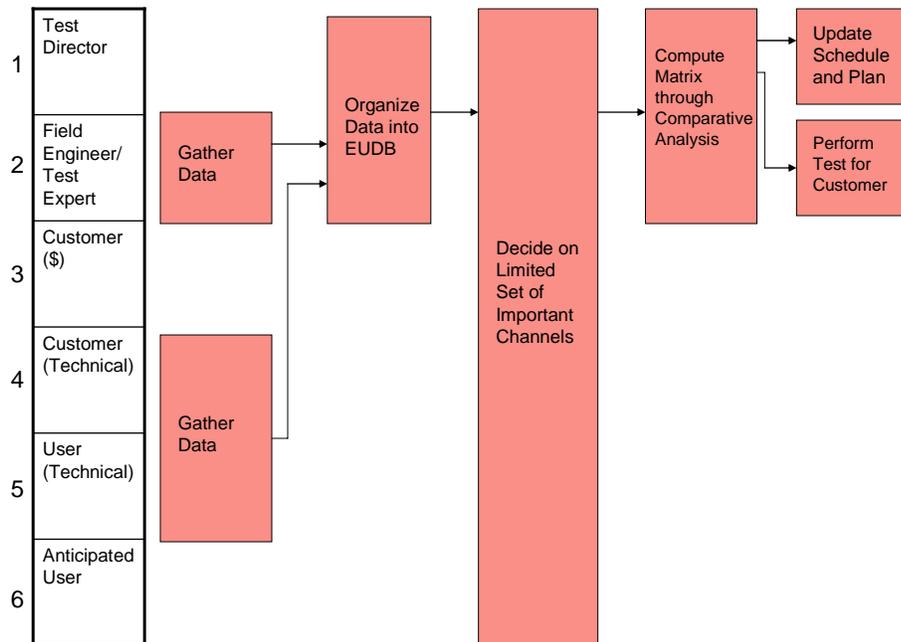


Figure 7. Swim lane diagram of Transformation Plan C.

The Plan C swimlane diagram eclipses the free form diagram in utility. This diagram, like Plan B, is very methodical and precise in describing Plan C and so is much

more helpful to the decision community for planning and plan execution than the free form diagram. Like most swimlane diagrams, there is no easy visual handle for recognition of the plan, but from minimal inspection the essence and many details of Plan C become clear.

4.4.1 Optimization Problem Formulation

In Transformation Plan C two different sources of data are compared in order to optimize a road course test matrix. These sources are data captured from ATC road courses, notated as x_{nij} , and data captured from the desired or intended use environment, notated as y_{ij} . The subscript n represents the particular road course on which the data was captured. The subscript n can be given a number value based on an index of numbered courses making mathematical representation easier or it can be given as a series of letters more easily denoting a particular course, i.e. x_{P1ij} for data taken from the Perryman 1 course. The intended use environment variable, y_{ij} , is not given an n subscript because the data set describing the goal test environment is expected to incorporate the entire intended use spectrum as if it were one ideal road course. If more than one data set is provided for multiple intended use environments, they must be synthesized into one corporate data set that describes the extent of possible road conditions the vehicle may encounter.

The subscript i , found in both parameters, represents the particular data channel for which the data was recorded. In similar fashion, the subscript j can be given either numbered representation for mathematical simplicity or alphabetical representation for easier identification. Examples of different data channels are road speed (subscript RS or

V), engine coolant temperature (ET), transmission temperature (TT), vertical acceleration (VA), and roll rate (RR).

The subscript j , also found in both variables, represents the particular element found in the vector. As described later, j is equivalent to a bin value found on the histogram in a database maintained by ATC. J is the total number of elements, j , found in a vector for a particular data channel, i , for a particular road course, n . It is imperative that for each objective function, $f_i(w)$, the same bin size, number, spacing, and units are used. If the J vector dimension is not common throughout the road courses as well as the intended use profile for a particular objective function, whether single objective or multi-objective, the optimization algorithm will not work.

Most of the data representing x_{nij} and y_{ij} can be found on an ATC maintained database called the Engineering Unit Database (EUDB). Any data captured at ATC is automatically uploaded to the EUDB. It is also standard procedure to upload data captured outside of ATC onto the EUDB if the instrumentation present in the vehicle was provided by ATC. The y_{ij} data can either be found in the EUDB or in any number of other formats, but in either case the data must ultimately be converted and inputted into the intended optimization solver program.

The data on the EUDB is presented in histogram format but it can be easily copied over to Matlab or Excel. When copied, the result is a vector with matrix dimensions of $1:J$, J being the total number of histogram bins on the EUDB. Histogram bin sizes are based on the data acquisition resolution set in the ADMAS computer before a vehicle is tested. Each bin represents a set range of values for a particular data channel. They may be in units of mph for road speed, degrees Fahrenheit for engine temperature, g

for lateral acceleration, or others. The bin size could be in 1-mph increments or 10-mph increments, based on the ADMAS data acquisition resolution, which can be different for each data channel. The resolution will be mirrored in the EUDB histogram. For example, the ADMAS software for a road speed data channel is usually set for 1 mph increments; therefore the data found in the EUDB will be plotted as a histogram with bin sizes of 1 mph starting at 0 mph up to a maximum speed, usually 70 mph, for a total of 71 bins. The total number of bins will determine the vector size, or J.

The bin values and subsequently the elements, j, in each vector are the number of counts or data points captured during the length of the data file that fit in each particular bin. For instance, a road speed vector for a specific set of runs on one road course that starts [324, 34, 83,...] means that for the amount of time the ADMAS was collecting data the vehicle accumulated 324 counts while at 0 mph, 34 counts while at 1 mph, 83 counts while at 2 mph and so on. The number of counts is directly related to time based on the rate at which the ADMAS collected data. Multiplying the number of counts in a bin by the inverse of the acquisition speed in hertz produces the total time in seconds or minutes the vehicle spent at a particular speed. Therefore, a key containing the data resolution and the data acquisition rate must be kept from the original ADMAS computer set up in order to convert the histogram bin size and bin values into real and useful units. Once the histogram data is copied into Matlab or Excel an example of the resulting vector is shown below.

```
%01 Nov 09:17 start time
%ADMAS File 141633
%Laps 1-10 on MTA Gravel - 10.3 miles
V_MG=[ 2, 6, 6, 36, 66, 36, 37, 50, 36, 34, 29, 26, 29, 24, 21, 15, 17...
```

The unalterable discrete data sets, x_{nij} and y_{ij} , are input parameters and not the actual variables optimized in the algorithm. As stated before, all discrete data sets used in a single objective optimization must maintain the same vector dimensions. If a single data set's dimensions are altered in any way the optimization will not function. x_{nij} and y_{ij} are broad notations and are broken down into different data channels for both and additionally into different road courses for x_{nij} . For example the data set for road speed on Perryman 1 is denoted as $x_{p1,v,j}$ and the data set for the intended use road speed profile is $y_{v,j}$. Each data set is discrete and so the optimization must be conducted with care so as to not introduce extraneous error. Instead of forming polynomial regressions for each data set in order to create an equation to use in the optimization algorithm, it is better to employ matrix or discrete mathematics when optimizing.

An objective function, $f_i(w)$, is formed by combining ATC road course data sets for a single data channel into a synthesized test profile using weights and calculating the error between the resultant test profile with the intended use profile for that data channel. The variables that will be optimized in the algorithm are the weights used to combine the sum of the ATC road courses to form the resultant test profile. W is actually the set of weights, w_n , n again representing the road course in the optimization. N represents the total number of courses being considered in the optimization. In multi-objective optimization cases, the w_n variables are shared for each objective function and cannot be denoted w_{ni} for different data channels. In order to obtain valid optimization results showing tradeoffs the w_n variables must be the same in each objective function.

For a single data channel we multiply each x_{nij} by w_n , sum those, and then subtract y_{ij} to obtain an error vector. The optimization program will then adjust each

weight until it can converge upon a minimized error vector, ideally a zero vector. In order to maintain positive and real solutions the L2 norm is used to measure the error vector.

The optimization algorithm used in Plan C also includes two very important constraints. The first constraint needed requires that the sum of the weights for each available road course, $\Sigma(w_n)$, must equal 1. The purpose of the first constraint is to ensure that the resulting optimized weights are percentages. The second constraint needed requires that each optimized weight, w_n , be greater than zero. The second constraint ensures that the optimized road course test matrix is feasible, since it is impossible to run a negative percentage of time on a course in order to achieve the desired road course profile.

The above problem description can easily and simply be conveyed in a classic single objective optimization problem statement, shown below.

$$\begin{aligned} \text{Minimize } f_i(w) &= \sqrt{\sum_{j=1}^J \left(\sum_{n=1}^N w_n \cdot x_{nij} - y_{ij} \right)^2} \\ \text{Subject to : } &\sum_{n=1}^N w_n = 1 \\ &w_n \geq 0 ; n = 1:N \end{aligned}$$

When creating a multi-objective optimization problem the form of the solution changes. For single objective optimizations the solution is most commonly a single non-dominated optimal point. This point is either a local or a global maximum or minimum depending on the problem conditions. In multi-objective optimization problems, the solution becomes a set of non-dominated solutions. For two objective optimization problems, the solution set can be graphed on a two-dimensional function space plot called the Pareto curve or Pareto frontier.

The Pareto curve provides an easy means to display the tradeoffs made between the two objective functions. An example of a Pareto curve is shown in Figure 8. Points close to the center of the curve are called non-compensating solutions [6]. For non-compensating solutions the function value for either objective function will not be as optimal as it would be if solved alone but neither function was disregarded in the solution. For points close to either extreme of the Pareto curve, the solution value will significantly favor one objective function over another. This is called a compensating solution because the optimal value on one objective function compensates for the poor performance of the other objective function. As more objective functions are added to the optimization problem it becomes increasingly difficult to visually plot the Pareto space due to the increase in dimensions. However, the concepts of tradeoffs and compensating versus non-compensating solutions still apply. Dominated solutions in either case should be avoided. An example Pareto curve showing trade-offs between two objective functions along with compensating and non-compensating solutions are shown below in Figure 8.

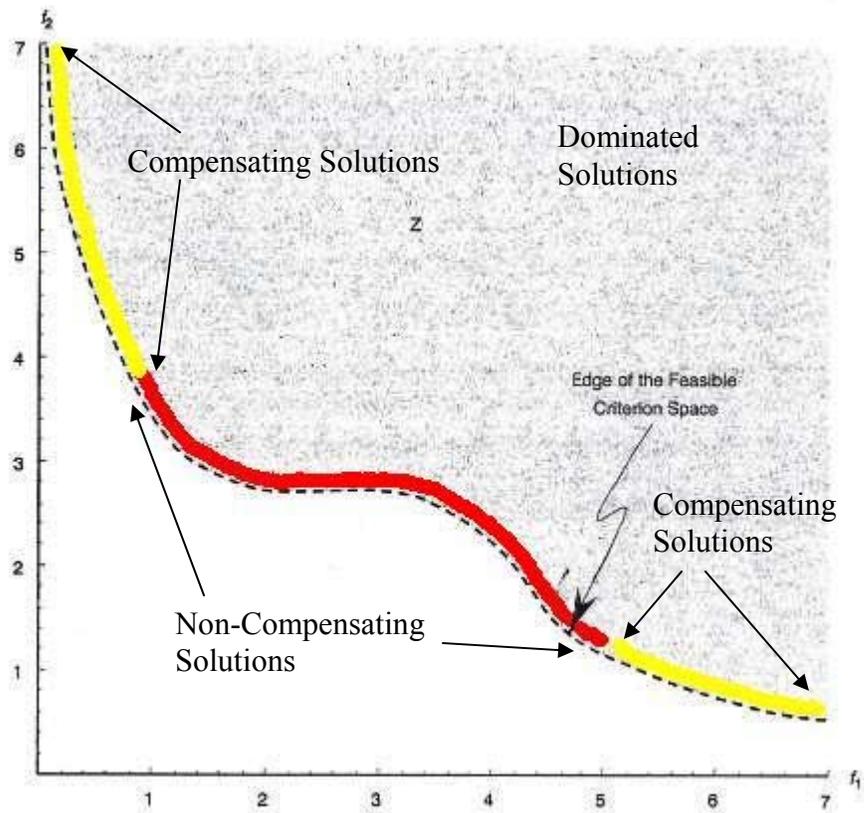


Figure 8. Example of a Pareto curve in two-dimensional function space [7].

There are many ways to form multi-objective optimization problems. The most common representation of a multi-objective optimization is shown below in the context of this research. The additional objective functions are present in order to minimize other data channels along with the original data channel.

$$\text{Minimize } f_1(w) = \sqrt{\sum_{j=1}^J \left(\sum_{n=1}^N w_n \cdot x_{n1j} - y_{1j} \right)^2}$$

$$\text{Minimize } f_2(w) = \sqrt{\sum_{j=1}^J \left(\sum_{n=1}^N w_n \cdot x_{n2j} - y_{2j} \right)^2}$$

$$\text{Minimize } f_i(w) \dots$$

$$\text{Subject to : } \sum_{n=1}^N w_n = 1$$

$$w_n \geq 0; n = 1:N$$

The above optimization problem formulation can become difficult, however, to implement in an analytical programming scheme like Matlab. While the Matlab function *fminimax* can be used to solve multi-objective optimization problems, the algorithm can be inflexible when attempting to find tradeoffs between objective functions. One way to simplify the algorithm is to convert the multi-objective problem into a single objective problem using the other objective functions as specific constraints. This is the method used for the multi-objective optimization problems in this research. The additional objective functions become nonlinear constraints in the problem formulation. They are nonlinear because of the L2 norm calculation. The single objective problem is then solved at stepped intervals tied to potential optimum points for the constrained objective functions creating a discrete rather than continuous Pareto curve. This converted multi-objective optimization problem is depicted below where k_i is the independent step value for each additional objective function and I is the total number of objective functions included in the optimization.

$$\begin{aligned} \text{Minimize } f_1(w) &= \sqrt{\sum_{j=1}^J \left(\sum_{n=1}^N w_n \cdot x_{n1j} - y_{1j} \right)^2} \\ \text{Subject to : } f_i(w) &= \sqrt{\sum_{j=1}^J \left(\sum_{n=1}^N w_n \cdot x_{nij} - y_{ij} \right)^2} \leq k_i; \quad i = 2 : I \\ &\sum_{n=1}^N w_n = 1 \\ &w_n \geq 0; \quad n = 1:N \end{aligned}$$

4.4.2 Optimization Algorithm Implementation

The optimization algorithm used in this plan is the culmination of many weeks of research and trial and error. The first attempt to create an optimization algorithm for Transformation Plan C focused on the use of polynomial regression fits for the available

data sets. It was thought that by converting the discrete data sets into polynomial equations would make the optimization process smoother and faster. Converting the discrete sets into continuous equations would free the optimization from the constraints of identical matrix dimensions and would support efforts to increase the quality of the optimization by simplifying statistical reliability calculations. As work progressed in this vein the optimization algorithms needed in Matlab became too complex. A unique set of variables had to be created for each road course for a single data channel. It became extremely difficult and time consuming to track all of the separate variables in Matlab and the *fmincon* function did not handle the large and complex objective function well. Errors introduced into the optimization due to the conversion of discrete data to continuous equations translated to optimal solutions so that realistic optimum points chosen by hand were found to be more optimal than calculated points. As a result the decision was made to attempt to optimize the road course test matrix using the original discrete data sets.

After continued work using the discrete data sets a successful optimization algorithm was formed. There are a number of preprocessing steps that must be conducted before the Matlab algorithm can run. First the data for the desired channels must be loaded into an M-file on Matlab. All ATC vehicle data is kept on the EUDB. ATC data can be easily obtained by forming a histogram of the desired data channel for a vehicle using the EUDB software. Once the histogram is constructed the data points can be copied from viewing them in an edit screen. The values should then be pasted as a labeled vector in the M-file. The matrices should be located on the same file as the optimization algorithm for programming ease. It is also important to denote on the M-

file when the data was collected in the field, what file it was from, how many miles the vehicle ran, and any other pertinent information. These can all be found on the EUDB.

A sample vector for road speed on the Munson gravel course is shown below.

```
%01 Nov 09:17 start time
%ADMAS File 141633
%Laps 1-10 on MTA Gravel - 10.3 miles
V_MG=[ 2, 6, 6, 36, 66, 36, 37, 50, 36, 34, 29, 26, 29, 24, 21, 15, 17...
```

The mileage accumulated for each data file and road course becomes very important later when it will be required to convert the percentage of time spent on a course to the percentage of miles spent on each course. The data vectors for each road course will be inserted into the M-file along with the `x_goal` data set. When data sets are found corrupted at extremities or when certain files were collected using a different histogram bin size, the larger files must be cut or otherwise converted so that all vectors remain the same length for processing.

The next step for preprocessing is to convert each data set into a frequency distribution. This is accomplished by simply dividing the vector by the sum of each of its individual values. Converting the histogram values to a frequency distribution does not introduce error into the optimization, it is only a helpful way to normalize the data and convert it into a useable means for creating an optimized road course test matrix. This is accomplished in Matlab as follows:

```
V1=(Va)/sum(Va);
```

Once the data sets are converted the optimization algorithm can be constructed. The `fmincon` function used for both the single and multi-objective optimizations in this research has predetermined structure for inputs and outputs. The inputs required for `fmincon` are the initial guess, the equivalent constraints, the inequality constraints, and the lower and upper bounds on the solution. The constraints used here must be linear. Any

non-linear constraints must be programmed in a separate M-file and inputted into the *fmincon* function call in another way. Except for the initial guess, any inputs that are not a part of the optimization problem can be left as blank square brackets. An example of the inputs is shown below.

```
x0=[.1,.1,.1,.1,.1,.1,.4]; %Initial guess for W_n's
A=[]; %A Matrix Values for A*X <= B
B=[]; %B Matrix Values for A*X <= B
Aeq=[1,1,1,1,1,1,1]; %Aeq Matrix Values for Aeq*X = Beq
beq=[1]; %Beq Matrix Values for Aeq*X = Beq
lb=[0,0,0,0,0,0,0]; ub=[1,1,1,1,1,1,1]; %lower and upper
bounds - satisfies the inequality constraint in Section
4.4.1
```

Now that the required inputs are set the *fmincon* function itself can be written. There are a number of output options that can be employed when using *fmincon*. They are activated when written at the beginning of the function call. In addition to providing the optimum point *fmincon* can print the following information if requested: the value of the objective function at the optimum point, an exit flag describing the exit condition of *fmincon*, the number of iterations taken, the number of function evaluations made, the norm of the final step, the algorithm used in the optimization, the first-order optimality, the Lagrange multipliers at the optimum point, the gradient of the objective function at the optimum point, and the Hessian matrix of the objective function at the optimum point. An example of a *fmincon* function call requesting all of these outputs is shown below.

```
[X,FVAL,EXITFLAG,OUTPUT,LAMBDA,GRAD,HESSIAN]=FMINCON(...
```

Next any additional parameters that will be required for the *fmincon* function call must be inserted. This includes the converted road course data vectors. The data and any other inputs required for the objective function need to be inserted in the *fmincon* function call so that it can be carried over the separate M-file containing the objective

function calculation. An example of a working *fmincon* function call used in this research is provided below.

```
[X,FVAL,EXITFLAG,OUTPUT]=fmincon(@objfunctions,x0,[],[],Aeq,beq,lb,ub,options,V1,V2,V3,V4,V5,V6,V7,V_goal)
%objfunctions will call the file objfunctions.m where the
objective function is programmed
```

The final step in the optimization algorithm is to program the objective function M-file. First the new M-file name must match the one used in the *fmincon* function call. Then the file must pull through all of the same inputs that were programmed in the initial M-file. The objective function can then be written using all of the variables and parameters that were pulled from the initial file. A working objective function M-file is shown below.

```
Function f=objfunctions(x,V1,V2,V3,V4,V5,V6,V7,V_goal) %V1
through V7 are discrete frequency distribution profiles for
road speed on seven different courses
a1=x(1);a2=x(2);a3=x(3);a4=x(4);a5=x(5);a6=x(6);a7=x(7);
%x(n)'s are the weight variables, they are changed to a1
through a7 to simplify the objective function programming
f=norm((a1*V1+a2*V2+a3*V3+a4*V4+a5*V5+a6*V6+a7*V7)-V_goal);
%'norm' is a Matlab code to perform the L2 norm, ie. Square
the sum and square V_goal then take the square root of it
```

At this point everything is complete for the single objective optimization algorithm. If only one data channel is desired for optimization, this Matlab code will provide an optimum solution for a time percentage road course test matrix. One necessary post processing step to take will be to convert the time percentage into a distance percentage since all DTPs require a road course test matrix to be in miles and percentage of miles.

In order to convert the w_n vector from the time domain into the distance domain additional information from the EUDB data files is needed. Imbedded in the EUDB data files are the values for total distance traveled for each run and the average speed of each

run. In cases when more than one data file is used for a single course, n , the total distance must be calculated by summing the individual distances traveled for each data run on the particular course. Conversely the average speed for multiple runs must be averaged instead of summed for the overall average speed on the course. For a single course n , the distance domain weight, d_n , can be calculated using the below equation where D_n represents the total distance traveled on the course for the data being used and V_n represents the average vehicle speed observed on the course.

$$d_n = \frac{V_n w_n}{D_n}$$

The final steps that can be taken for optimizing the road course test matrix are to conduct a multi-objective optimization based on the single objective with nonlinear constraints equation mentioned prior. For a multi-objective optimization a third Matlab m-file must be created for the nonlinear constraints. An example of the necessary Matlab code is shown below.

```
function[C,Ceq]=M915_ttemp_NLConstr(x,V1,V2,V3,V4,V5,V6,...
V7,V_goal,T1,T2,T3,T4,T5,T6,T7,T_goal,k)
a1=x(1);a2=x(2);a3=x(3);a4=x(4);a5=x(5);a6=x(6);a7=x(7);
C(1)=norm((a1*T1+a2*T2+a3*T3+a4*T4+a5*T5+a6*T6+a7*T7)-...
T_goal)-k;
Ceq=[];
```

In this instance it is a two objective function optimization problem because there is only one nonlinear constraint equation, labeled C(1), the first objective function remaining in the original objective function m-file. It is important to note that in order for the optimization algorithm to function all of the parameters must be passed through to every m-file in use even if the parameters will not be used in a particular file. There are no equivalent nonlinear constraint equations so Ceq is left blank with open and closed brackets. It is also evident that k has been passed through to the file so that it can be used

in the objective function constraint equation. The same w_n vector, in the same form of $x(n)$ as in the single objective code previously, will be used for each objective function because it is the set of variables being concurrently optimized.

The objective function m-file will be nearly identical to the single objective optimization set-up. Similar to the nonlinear constrain equation, all of the parameters must be passed into the file. This file should contain the highest priority objective function. Even though the trade-off relationship between objective functions can be distinguished on the Pareto curve, placing the primary objective function in this file will help simplify the analysis of results later in the process. An example of the objective function Matlab m-file is shown below.

```
Function f=objfunctions(x,V1,V2,V3,V4,V5,V6,V7,V_goal,...
T1,T2,T3,T4,T5,T6,T7,T_goal,k)
a1=x(1);a2=x(2);a3=x(3);a4=x(4);a5=x(5);a6=x(6);a7=x(7);
f=norm((a1*V1+a2*V2+a3*V3+a4*V4+a5*V5+a6*V6+a7*V7)-V_goal);
```

The final m-file that will need alterations is the main data file. In order to complete the multi-objective optimization algorithm in Matlab a *for* loop must be created surrounding the *fmincon* function call for each k_i . Since, in the example, it is only a two objective optimization problem only one *for* loop will be needed. An example of the optimization algorithm code for a main data m-file is shown below.

```
x0=[.1,.1,.1,.1,.1,.1,.4];
Aeq=[1,1,1,1,1,1,1];
beq=[1];
lb=[0,0,0,0,0,0,0]; ub=[1,1,1,1,1,1,1];
options=optimset('LargeScale','off');

for k=.45:-.01:0.25

[X,FVAL,EXITFLAG,OUTPUT]=fmincon(@objfunctions,x0,[],[],Aeq
,beq,lb,ub,@M915_ttemp_NLConstr,options,V1,V2,V3,V4,V5,V6,V
7,V_goal,T1,T2,T3,T4,T5,T6,T7,T_goal,k)
```

```

C1=norm((X(1,1)*T1+X(1,2)*T2+X(1,3)*T3+X(1,4)*T4+X(1,5)*T5+
X(1,6)*T6+X(1,7)*T7)-T_goal);

figure(1)
plot(FVAL,C1,'k*')
box on
grid on
hold on
axis tight
xlabel('Road Speed Obj Function Value');
ylabel('Transmission Temp Obj Function Value');

end

```

The vector C1 is identical to the second objective function in the nonlinear constraint m-file. It is placed in the *for* loop in order to simplify plotting the Pareto curve. The plotting commands below C1 simply plot the discrete Pareto curve based on the step size values, k, and the primary objective function values. The end result will be a figure such as the two dimensional discrete Pareto curve shown below in Figure 9. A full example of the Matlab optimization algorithm is provided in Appendix C.

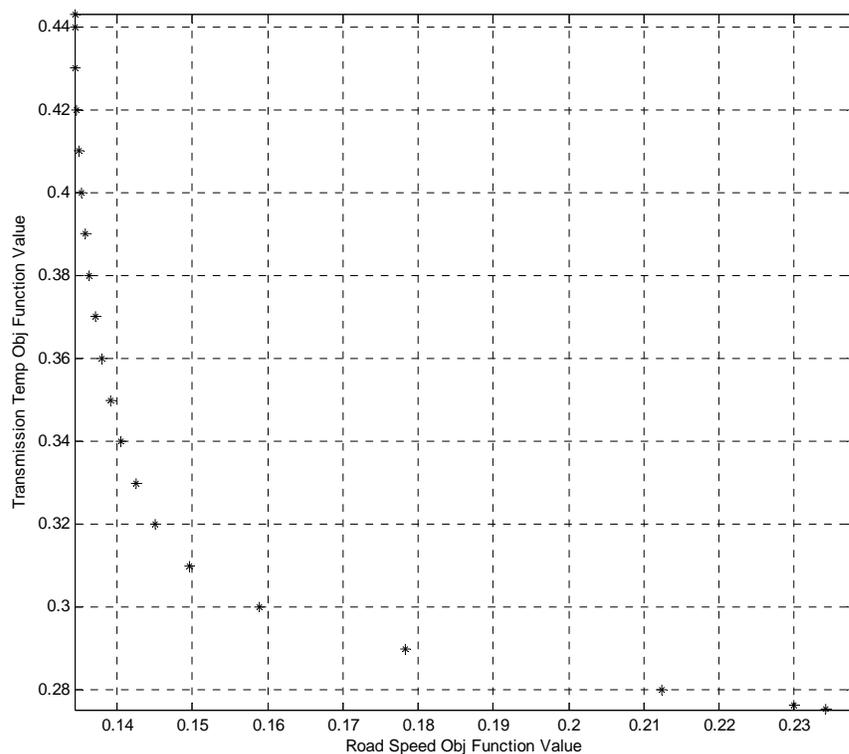


Figure 9. Sample discrete Pareto curve for a two objective optimization problem.

4.4.3 Optimization Algorithm Validation

The Matlab implementation of Transformation Plan C was validated by comparing a simplified example of the implementation to the same example implemented using Excel. In each case the example was developed and solved first in Microsoft Excel and then in MathWorks MatLab 7.3.0. The first example was a single objective optimization problem, the second example was developed as a multi-objective optimization problem.

4.4.3.1 Single Objective Optimization Example

Data. For the first example two sets of data were created to simulate two independent road courses, $x_{1,lj}$ and $x_{2,lj}$. These data sets were created with vectors already normalized into the frequency domain. The first objective function used was road speed and is in units of miles per hour. A third data vector was created to simulate the goal road speed profile, or y_{lj} . The data sets are displayed below in Table 4.

		Course 1 ($x_{1,lj}$)	Course 2 ($x_{2,lj}$)	Goal (y_{lj})
Road Speed (mph)	20	0.25	0.4	0.3
	30	0.5	0.4	0.5
	40	0.25	0.2	0.2

Table 4. Single objective optimization data for validation example.

Excel. The Microsoft Excel optimization validation example can be conducted either by hand in a trial and error fashion or using an optional optimization solver add-in. In this example both methods were performed. For the first method an Excel table was constructed in order to quickly perform a gross approximation of the minimum point. The results are provided below in Table 5. The approximation shows that the minimum

point should be found in close proximity to a point defined by a Course 1 weighting variable, w_1 , as 0.7 and a Course 2 weighting variable, w_2 , as 0.3.

Weight Variables		L2 Norm Error
Course 1	Course 2	
0	1	0.14142
0.1	0.9	0.1239
0.2	0.8	0.10677
0.3	0.7	0.09028
0.4	0.6	0.07483
0.5	0.5	0.06124
0.6	0.4	0.05099
0.7	0.3	0.04637
0.8	0.2	0.04899
0.9	0.1	0.05788
1	0	0.07071

Table 5. Hand calculated approximation for single objective optimization solution.

The second and more exact method used in Microsoft Excel was an add-in function called Solver. The Solver add-in is a sub-program that is used to perform single objective optimizations on discrete data sets. The solution for the single objective validation example was found using the Solver add-in. The problem is set up in an Excel worksheet first. Separate cells are denoted for each variable and parameter. Initial numeric guesses are inserted into the variable cells designated for w_1 and w_2 . The objective function must be placed in another cell and all variables must be referenced in the equation. The Excel objective function equation cell contained the formatted equation below.

$$E5=\text{SUMPRODUCT}(L3:L5,L3:L5)$$

The cells L3 through L5 made up the vector of the calculated road course profile vector subtracted by the goal profile vector, which is the error equation. The

SUMPRODUCT is an Excel equation code which multiplies two vectors together and then sums their elements. Since cells L3 through L5 are used twice, the end result performs the first part of the L2 Norm conversion. The final solution must be square rooted in order to make the Excel objective function match the intended objective function described earlier in Section 4.4.1.

Before the Solver can be initiated, the constraint cells must be designated. Both nonlinear and linear constraint equations can be used in the Solver program. The equality or inequality condition must be set after the Solver is initiated. The first constraint cell contained the equation for the sum of w_n , which will later be set to equal zero. The inequality constraints bounding the limits of w_n did not have to be ascribed to cells because the conditions on the variables were easily handled in the Solver program.

The final step in the process was to initiate the Solver add-in. Once the Solver set-up prompt appears the objective function, variable, and constraint cells were referenced. On the same screen the equality and inequality constraint equations were constructed. The Excel spreadsheet used is shown below in Figure 10 and the Solver set-up prompt for the validation example is shown in Figure 11.

	A	B	C	D	E	F	G	H	I	J	K	L
1							Fractions	0.5	0.5			
2				Identification	Value		MPH	course 1	course 2	calculated	goal	difference
3		Design Variables	x1	W 1	0.5		20	0.25	0.4	0.325	0.3	0.025
4			x2	W 2	0.5		30	0.5	0.4	0.45	0.5	-0.05
5		Objective Function	F1	ABS of Error in comb	0.00375		40	0.25	0.2	0.225	0.2	0.025
6			C1	W1 >= 0	0.5							
7			C2	W2 >= 0	0.5							
8		Constraints	C3	W1 <= 1	0.5							
9			C4	W2 <= 1	0.5							
10			C5	W1+W2=1	1							
11												

Figure 10. Microsoft Excel spreadsheet used for the Solver optimization example.

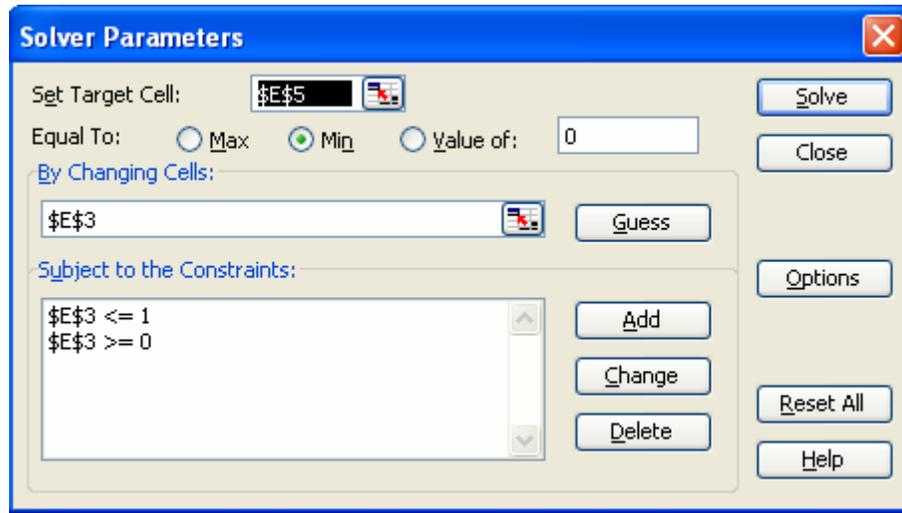


Figure 11. Excel Solver optimization prompt.

The objective function cell was referenced for “Set Target Cell:”. The two-dimensional optimization problem could be greatly simplified by making w_2 dependent on w_1 . This was accomplished by inserting $(1 - w_1)$ whenever w_2 was needed in the Excel spreadsheet. The variable cell for w_1 was referenced for “By Changing Cells:”. The lower and upper bounds on w_1 were added to “Subject to the Constraints:” on the prompt. The equality constraint was not needed because the dependent relationship set up by using w_1 and $(1 - w_1)$. The resulting Excel optimization solution is shown below.

Microsoft Excel 11.0 Answer Report
Worksheet: [excel opt algorithm 2.xls]Sheet2
Report Created: 1/24/2007 9:57:01 AM

Target Cell (Min)

Cell	Name	Original Value	Final Value
\$E\$5	ABS of Error in comb Value	0.0114	0.002142857

Adjustable Cells

Cell	Name	Original Value	Final Value
\$E\$3	W 1 Value	0.2	0.714285714

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
\$E\$3	W 1 Value	0.714285714	\$E\$3>=0	Not Binding	0.714285714
\$E\$3	W 1 Value	0.714285714	\$E\$3<=1	Not Binding	0.285714286

Matlab. The same programming code techniques described in Section 4.4.2 above were used for the single objective optimization validation example solved using Matlab. The actual m-file contents for the main data file are provided below. The main data file is the file that must be run in order for the algorithm to provide a solution.

```
function simple_example

close all;
clear all;

% Road Speed
% course 1 profile x_(1,1,j)
V1=[.25,.5,.25];

% course 2 profile x_(2,1,j)
V2=[.4,.4,.2];

% goal profile y_(1,j)
V_goal=[.3,.5,.2];

% Optimization Algorithm
x0=[0,0]; % initial guess
Aeq=[1,1]; % linear constraint argument: 1*w(1)+1*w(2)
beq=[1]; % equivalent constraint: Aeq must =1
lb=[0,0]; ub=[1,1]; % lower and upper bounds
options=optimset('LargeScale','off');

[X,FVAL,EXITFLAG,OUTPUT]=fmincon(@exampleobjfunc,x0,[],[],Aeq,beq,lb,ub,[],options,V1,V2,V_goal) % '@exampleobjfunc'
will make a function call to the objective function file
with out the other file having to be explicitly run
```

The second file that was needed was the objective function file. This file is a separate imbedded file that needs to be in the same working folder as the main data file so it can be accessed but it should not be explicitly run. The actual objective function m-file code used for the validation example is provided below.

```

function f=exampleobjfunc(x,V1,V2,V_goal) % parameters
brought from main date file
a1=x(1);a2=x(2); % weight variables w(1) and w(2)
f=norm((a1*V1+a2*V2)-V_goal); % objective function

```

The result of the optimization problem set up above is a series of outputs. The actual Matlab solution to the single objective optimization validation example is shown below.

```

Optimization terminated: magnitude of directional derivative in search
direction less than 2*options.TolFun and maximum constraint violation
is less than options.TolCon.
No active inequalities.

```

```

X =

```

```

    0.7145    0.2855

```

```

FVAL =

```

```

    0.0463

```

```

EXITFLAG =

```

```

    5

```

```

OUTPUT =

```

```

    iterations: 5
    funcCount: 18
    lssteplength: 1
    stepsize: 0.0073
    algorithm: 'medium-scale: SQP, Quasi-Newton, line-search'
    firstorderopt: 9.1246e-005
    message: [1x172 char]

```

Validation Analysis. The solution from the Excel Solver was a time frequency weight of 0.7143 for Course 1 and 0.2857 for Course 2. After taking the square root of the objective function value at that point, the result is an error of 0.0463. The solution for the single objective optimization problem from the Matlab algorithm was a time

frequency weight of 0.7145 for Course 1 and 0.2855 for Course 2. The objective function value for error at the Matlab optimum was also 0.0463.

The two solutions are very close, only differing by 0.02% for the Course 1 weight and by 0.02% for Course 2. These are insignificant inconsistencies between the Excel solution the Matlab solution. In general the inexpensive Excel Solver is less powerful and not as accurate as the Matlab software. Even so, the proximity of both reasonable solutions suggests that the Matlab algorithm is accurate and viable for single-objective optimizations.

4.4.3.2 Multi-objective Optimization Example

4.4.3.2.1 Data

For the second example another additional data sets were created to simulate two independent road courses for a second objective functions, transmission temperature. The transmission temperature vectors were labeled $x_{1,2j}$ and $x_{2,2j}$ for course 1 and course 2 respectively. These data sets were also created with vectors already normalized into the time frequency domain. A final data vector was created to simulate the goal transmission temperature profile, or y_{2j} . The y_{2j} goal transmission temperature vector was made to match the y_{2j} goal road speed vector in order to simplify the algorithm computations and the validation analysis. The second objective function data sets are displayed below in Table 6.

		Course 1 ($x_{1,2j}$)	Course 2 ($x_{2,2j}$)	Goal (y_{2j})
Transmission Temperature (°F)	200	0.25	0.2	0.3
	300	0.3	0.6	0.5
	400	0.45	0.2	0.2

Table 6. Second objective function optimization data for validation example.

4.4.3.2.2 Excel

The Excel Solver could not solve multi-objective optimization problems. As a result, a method similar to the rough approximation conducted for the single objective optimization was used. For a two objective optimization problem there is no single optimal point. The solution, instead, is a set of optimum points created by trade-offs between the two objective functions. Plotting these points creates the Pareto curve which is the most useful method for displaying the optimization problem solution.

The Excel Pareto curve points were found by setting the variables, w_n , at extremes and then solving for the L2 Norm error at stepped intervals within those extreme points for each objective function. Table 7 below displays the road speed results for each interval taken between w_1 equaling 0% and equaling 100%. Table 8 below displays the transmission temperature results for the same w_1 values.

Weight Variables		Calculated Profile Vector			Differences			L2 Norm Error
Course 1 (w_1)	Course 2 (w_2)	20 MPH	30 MPH	40 MPH	20 MPH	30 MPH	40 MPH	
0	1	0.4	0.4	0.2	0.1	-0.1	0	0.14142
0.1	0.9	0.385	0.41	0.205	0.085	-0.09	0.005	0.1239
0.2	0.8	0.37	0.42	0.21	0.07	-0.08	0.01	0.10677
0.3	0.7	0.355	0.43	0.215	0.055	-0.07	0.015	0.09028
0.4	0.6	0.34	0.44	0.22	0.04	-0.06	0.02	0.07483
0.5	0.5	0.325	0.45	0.225	0.025	-0.05	0.025	0.06124
0.6	0.4	0.31	0.46	0.23	0.01	-0.04	0.03	0.05099
0.7	0.3	0.295	0.47	0.235	-0.005	-0.03	0.035	0.04637
0.8	0.2	0.28	0.48	0.24	-0.02	-0.02	0.04	0.04899
0.9	0.1	0.265	0.49	0.245	-0.035	-0.01	0.045	0.05788
1	0	0.25	0.5	0.25	-0.05	0	0.05	0.07071

Table 7. Road Speed L2 Norm error approximations.

Weight Variables		Calculated Profile Vector			Differences			L2 Norm Error
Course 1 (w_1)	Course 2 (w_2)	200 °F	300 °F	400 °F	200 °F	300 °F	400 °F	
0	1	0.2	0.6	0.2	-0.1	0.1	0	0.14142
0.1	0.9	0.205	0.57	0.225	-0.095	0.07	0.025	0.12062
0.2	0.8	0.21	0.54	0.25	-0.09	0.04	0.05	0.11045
0.3	0.7	0.215	0.51	0.275	-0.085	0.01	0.075	0.1138
0.4	0.6	0.22	0.48	0.3	-0.08	-0.02	0.1	0.12961
0.5	0.5	0.225	0.45	0.325	-0.075	-0.05	0.125	0.15411
0.6	0.4	0.23	0.42	0.35	-0.07	-0.08	0.15	0.18385
0.7	0.3	0.235	0.39	0.375	-0.065	-0.11	0.175	0.21668
0.8	0.2	0.24	0.36	0.4	-0.06	-0.14	0.2	0.2514
0.9	0.1	0.245	0.33	0.425	-0.055	-0.17	0.225	0.28732
1	0	0.25	0.3	0.45	-0.05	-0.2	0.25	0.32404

Table 8. Transmission Temperature L2 Norm error approximations.

The Pareto curve was plotted by designating the L2 Norm error values for transmission temperature as the y-coordinates and the error values for road speed as the x-coordinates. The result is shown below in Figure 12.

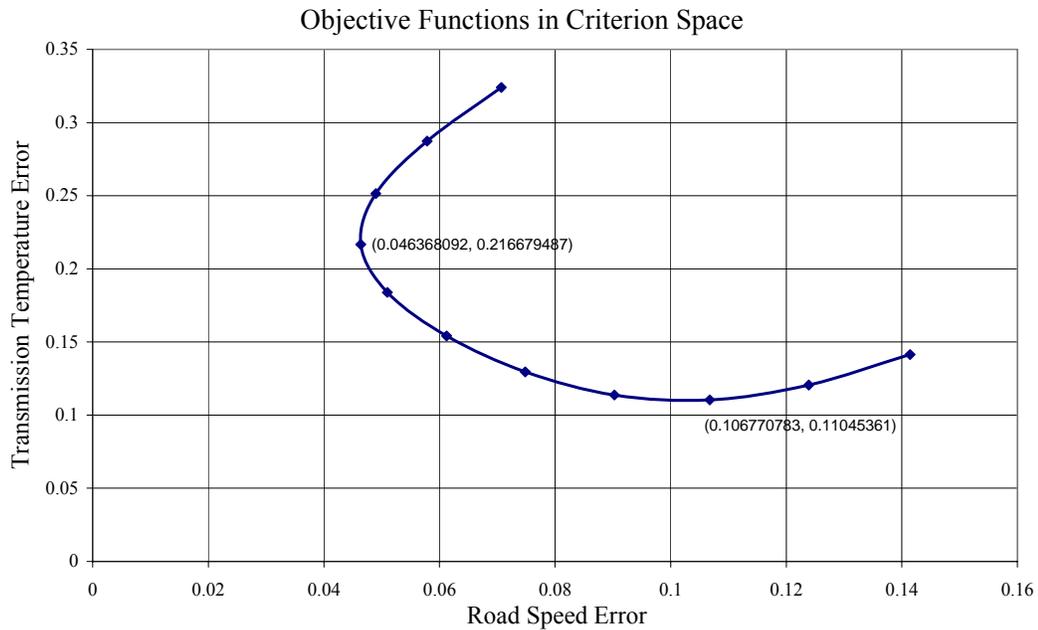


Figure 12. Excel generated Pareto curve for two objective validation example.

Another plot that is useful for confirming the validity of the Pareto curve are separate plots of the objective functions in the design space [8]. When each objective function is plotted independently for the range of potential optimal points, visual inspection and comparison to the Pareto curve can provide further confirmation that a valid solution set has been found. Figure 13 below provides the independent plots of both objective functions in the design space.

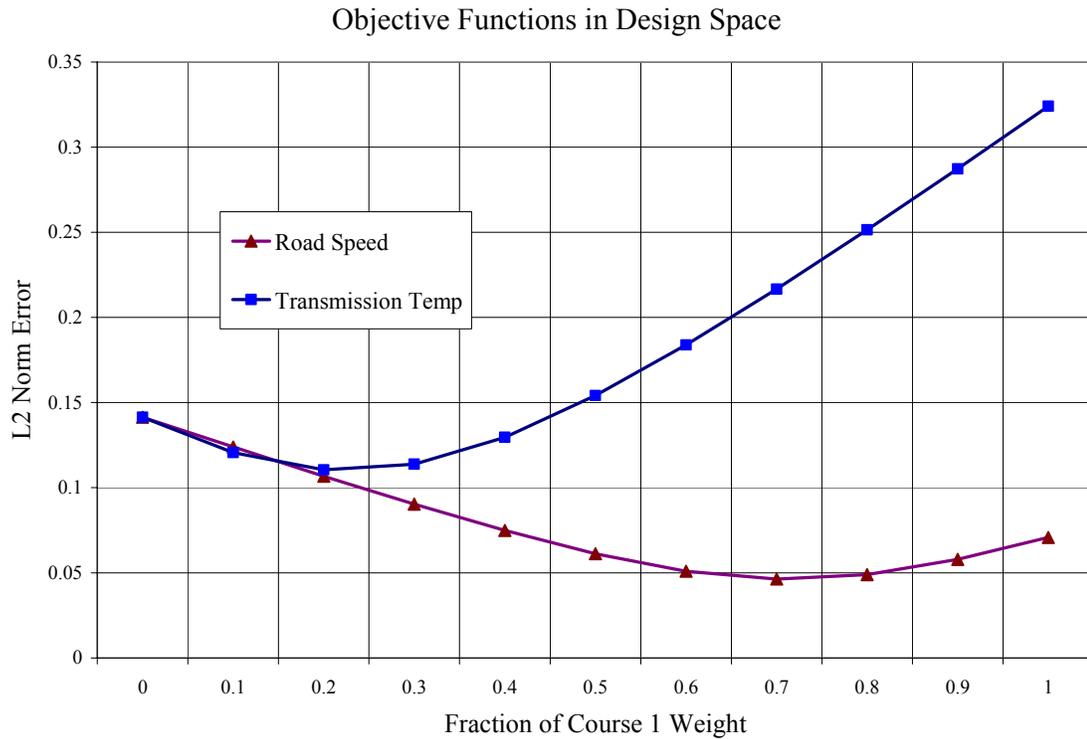


Figure 13. Independent objective function performance in the design space.

From Figure 13 it is clear that the road speed objective function reaches a minimum point somewhere between a w_1 value of 0.65 and 0.8. It is already known that the optimal point for road speed is approximately 0.715. It is also evident that the transmission temperature objective function reaches its minimum point somewhere close to a w_1 value of 0.2. From the plot we gather that a trade-off will not occur until after the

transmission temperature objective function reaches its optimal point, before that point both objective functions experience better performance as w_1 increases. Similarly trade-offs will cease after the road speed objective function reaches its minimum point. Therefore, it is expected that the valid Pareto curve will show trade-off characteristics between the two objective functions for the w_1 interval of approximately 0.2 to 0.715. We also gather from Figure 13 that when w_1 approaches 0.715 the optimal point becomes a stronger compensating solution because the road speed objective function's performance significantly compensates for the transmission temperature objective function's poor performance. When the value of w_1 approaches 0.2 on the other hand, we can expect a non-compensating solution due to the relative closeness of both objective functions performances.

4.4.3.2.3 Matlab

The same programming code techniques described in Section 4.4.2 above were used for the multi-objective optimization validation example solved using Matlab. The actual m-file contents for the multi-objective main data file are provided below.

```
function simple_example_multi

close all;
clear all;

% Speed
%course 1 profile
V1=[.25,.5,.25];

%course 2 profile
V2=[.4,.4,.2];

%goal profile
V_goal=[.3,.5,.2];

% Transmission Temp
%course 1 profile
T1=[.25,.3,.45];
```

```

%course 2 profile
T2=[.2,.6,.2];

%goal profile
T_goal=[.3,.5,.2];

% Optimization Algorithm
x0=[0,0];
Aeq=[1,1];
beq=[1];
lb=[0,0]; ub=[1,1];
options=optimset('LargeScale','off');

for k=0.3:-.01:0

[X,FVAL,EXITFLAG,OUTPUT]=fmincon(@exampleobjfunc_multi,x0,[
],[],Aeq,beq,lb,ub,@exampleNLConstr,options,V1,V2,V_goal,T1
,T2,T_goal,k)

    C1=norm((X(1,1)*T1+X(1,2)*T2)-T_goal);

    figure(1);
    plot(FVAL,C1,'k*');
    hold on
    xlabel('Road Speed Obj Function Value');
    ylabel('Transmission Temp Obj Function Value');
end

```

The second file required for the optimization was the objective function file. This file is nearly identical to the single objective optimization example with the exception of the additional parameters that must be passed to each imbedded file. The actual objective function m-file code used for the validation example is provided below.

```

function
f=exampleobjfunc_multi(x,V1,V2,V_goal,T1,T2,T_goal,k)
a1=x(1);a2=x(2);
f=norm((a1*V1+a2*V2)-V_goal);

```

The third file that was required to conduct the multi-objective optimization was the nonlinear constraint file. This file was called out similarly to the objective function sub-file in the *fmincon* function call on the main data file. The nonlinear constraint file provides the additional objective functions used in the multi-objective optimization

algorithm. The actual m-file code for the transmission temperature objective function constraint is provided below.

```
function
[C,Ceq]=exampleNLConstr(x,V1,V2,V_goal,T1,T2,T_goal,k)
a1=x(1);a2=x(2);
C(1)=norm((a1*T1+a2*T2)-T_goal)-k;
Ceq=[];
```

The end result of the two-objective optimization problem described above is a series of outputs including a set of numeric solutions found at each k interval as well as a discrete Pareto curve plot for the objective functions. The set of optimal solutions to the multi-objective optimization validation example is shown below in Figure 14.

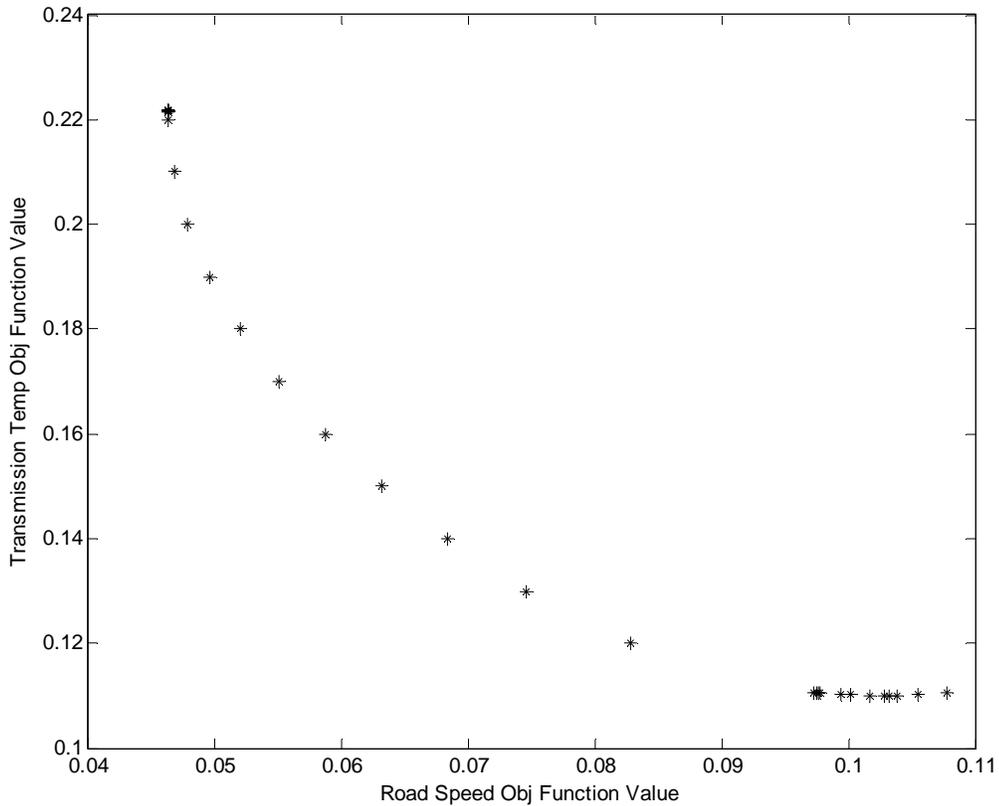


Figure 14. Discrete Pareto curve plot for the multi-objective optimization validation example.

4.4.3.2.4 Validation Analysis

The most important evidence to support the Matlab algorithm validation results from a comparison of the resulting Pareto curves. Inherent to the programs optimization function, Matlab will only plot the set of non-dominated optimal solutions. Based on the Excel Pareto curve in Figure 12, the set of non-dominated solutions occurs approximately between the points (0.0464, 0.2167) and (0.1068, 0.1105) in the criterion space. The discrete point (0.0464, 0.2167) refers to a road speed L2 Norm error of 0.0464 and a transmission temperature L2 Norm error of 0.2167 which corresponds to a w_1 weight of 0.7. In Figure 12, this point corresponds to the single objective road speed function optimum. The discrete point (0.1068, 0.1105) refers to a road speed L2 Norm error of 0.1068 and a transmission temperature L2 Norm error of 0.1105 which corresponds to a w_1 weight of 0.2. In Figure 13, this point corresponds to the single objective transmission temperature function optimum. A non-dominated Excel Pareto curve, shown below in Figure 15, can now be compared to the Matlab Pareto curve.

Objective Functions in Criterion Space

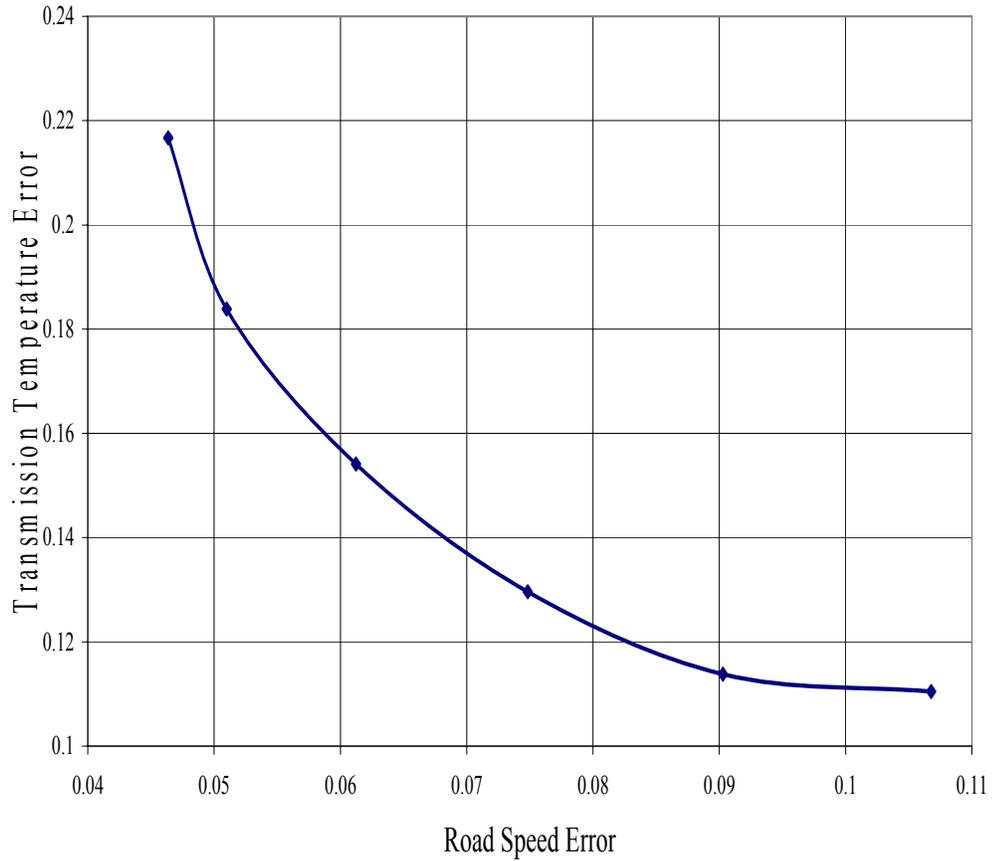


Figure 15. Non-dominated Excel Pareto curve.

The new Excel Pareto curve shown in Figure 15 was plotted using the same dimensions and scale as the Matlab plot in order to simplify the comparison. A synthesized plot including both Excel and Matlab Pareto curves is shown in Figure 16. The discrete Matlab solution set has been plotted over the Excel curve. Clearly both Pareto curves are nearly identical, validating the Matlab algorithm. One reason for minor inconsistencies between the shapes of the two plots result from a minimal set of discrete points available for the Excel plot relative to the number of points plotted on the Matlab curve. Another reason can be explained by the differences in solution methods. The

hand calculated Excel Pareto curve does not give exact end points to the non-dominated set of solutions and is only as exact as the significant figures and finite step size of the hand calculations can allow. With a decreased step size and resulting increase of discrete optimum points in the criterion space, the two curves should become increasingly similar.

Objective Functions in Criterion Space

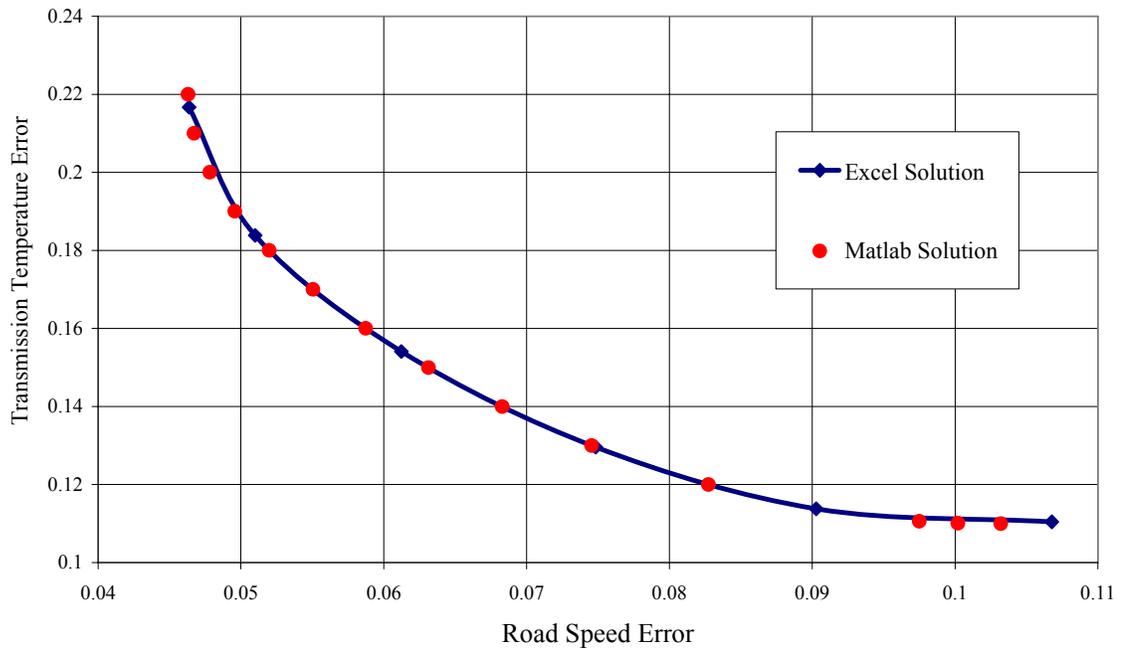


Figure 16. Synthesized plot of Matlab generated Pareto curve and Excel generated Pareto curve.

4.5 Transformation Plan D

Alternative Transformation Plan D is one that can easily be added to other transformation plans as an extension but is not a full transformation plan itself. Plan D acts as a subcomponent or module that can be implemented as requested or needed. The plan is in essence a feedback loop, providing comparative outputs and data to the test center to monitor the road test course matrix’s validity. Plan D can be implemented at

the end of another transformation plan for informational purposes only or in the middle of another transformation plan in order to provide an iterative process for achieving better matrix results.

This feedback loop allows the test center to perform two levels of validation. The first lower level evaluation involves comparing test data or simulated test results to the intended output of the optimization algorithm. By correlating data that was actually obtained from the vehicle performing the intended road test course matrix with that of the anticipated result from the optimization model, we can determine if the optimization algorithm is accurately assessing the road course information. This evaluation is more beneficial to the test center than to the PM, because it helps with internal quality control of product which is the test matrix.

The second level of evaluation requires comparison of test data to the original intent. This higher level evaluation is more appropriate for the PM to consider. While it can be expected that the optimization worked properly, the degree to which the test correlates to the original environment largely depends on where the vehicle is tested and how much resources the PM wants to invest.

Once the evaluation has been completed, the decision community meets to discuss the evaluation results and to determine the satisfaction level or stopping criteria for further iterations of the test matrix. If the evaluation is satisfactory then the matrix will be adopted and testing will commence or continue. If the evaluation is not satisfactory then either optimization algorithm or even transformation plan will be adapted or replaced until the PM or decision community is satisfied or until the stopping criteria have been met.

Two different models were developed to visually describe this alternative transformation plan. The first is a free-form diagram of Plan D; it is shown below in Figure 17.

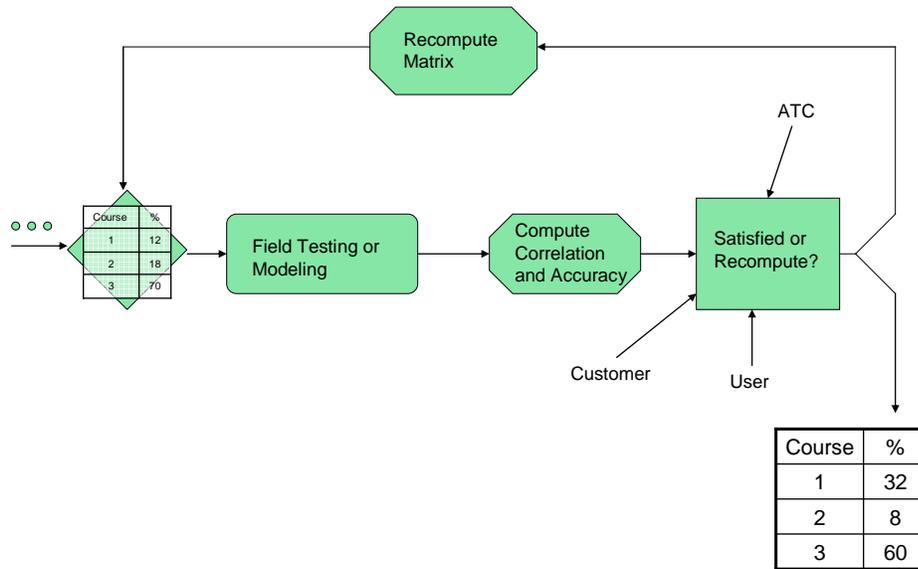


Figure 17. Graphic model of Transformation Plan D.

The Plan D graphic diagram is useful in identifying the well-known feedback loop intrinsic to this transformation plan. While the diagram is simple and straight forward, the notation in the action boxes is terse and can lead to confusion. The etcetera dots on the left side of the diagram are meant to convey the fact that this plan can be inserted into any other transformation plan, but without notation or a more clear depiction it causes confusion as well. The second model was developed as a swimlane diagram. It is shown below in Figure 18.

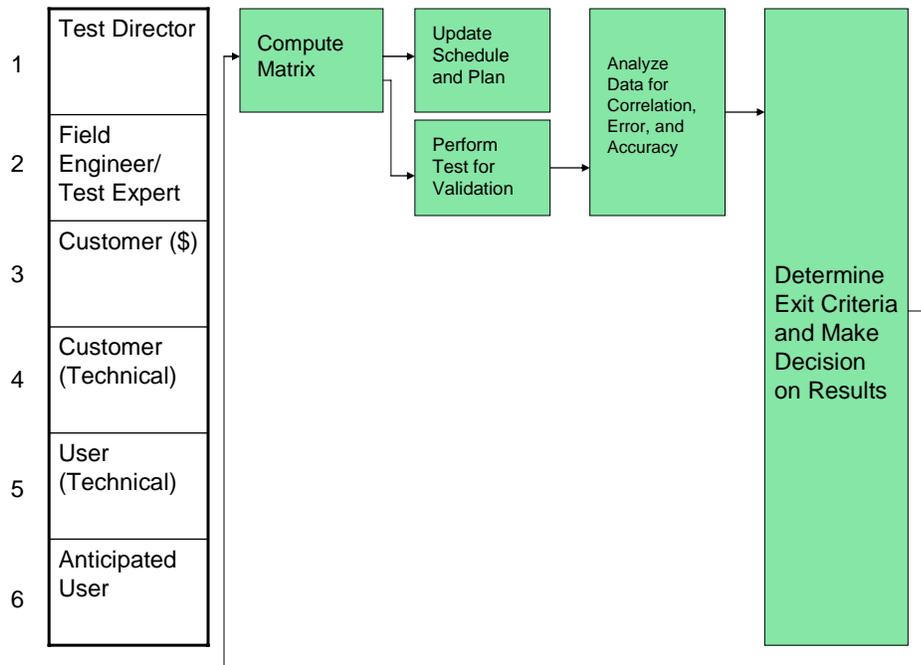


Figure 18. Swim lane diagram of Transformation Plan D.

The Plan D swimlane diagram is also uncomplicated and direct. The features of the process steps, the parties involved, and the flow of information are clear and comprehensible.

4.6 Summary and Discussion

Military automotive vehicle testing for many years has been guided by the recycling of past test plans for vehicles similar in form and function to the current vehicles undergoing tests. The original test plans were developed by military leaders speculating on the intended environments where the vehicles would be used during their life. While using recycled automotive test plans minimizes any effort required to determine the desired endurance road course test matrix, changing intended use environments and extending a system’s operation well beyond its original intended

lifetime has caused an ever widening gap between the test environment and the actual use environment. As a result, efforts have been made to determine alternative methods by which an automotive project's Decision Community can create more relevant road course test matrices given any set of variable circumstances or scenarios.

The first alternative to this traditional transformation plan is called Transformation Plan A. Transformation Plan A is appropriate for a scenario in which little time is available to decide on a test plan. In this plan, the entire test project decision community meets to discuss the road course test matrix. Government requirements and PM desires are discussed against the User's needs and the test center's capabilities. Ultimately the Decision Community must make a consensus on the resulting road course test matrix. A drawback of Transformation Plan A is that the only information available to make the decision on the road course test matrix is what was brought by the meeting attendees. The benefits, however, are that the test matrix is formed in the span of one meeting and that the Decision Community has the opportunity to create a more relevant test plan based on their current knowledge.

The second alternative is Transformation Plan B. This transformation plan is appropriate for scenarios in which additional time is available and when additional information beyond the Decision Community is necessary. If no road course test matrix is acceptable to everyone, then the Decision Community tasks individuals or groups to obtain additional information. Sometimes further professional opinion and insight is needed, sometimes only past or current documents need to be consulted. Time is still finite, however, and after a limited time the Decision Community must again meet and form a consensus on the automotive test plan. The drawbacks of this plan are the

potential for less relevant road course test matrices than those from Transformation Plans C and D and the additional time required to form a decision. However, the advantage is the likelihood of a road course test matrix that is more relevant to the actual use environment than the traditional transformation plan or Transformation Plan A results.

A third alternative to the traditional transformation plan is Transformation Plan C. Transformation Plan C is appropriate for occasions in which ample time is available and when a very relevant road course test matrix is desired. This plan is characterized by a significant effort conducted by the test center in order to gather and analyze data from the desired use environment and data from the test center's road courses. These two sets of data are then converted into an optimized road course test matrix using sophisticated analytical multi-objective optimization techniques and software. Transformation Plan C ensures a high probability of use environment relevancy but includes the large disadvantage of the required time and effort to develop a result.

The final alternative transformation plan that was considered is Transformation Plan D. This plan is appropriate for scenarios when the road course test matrix relevancy significantly eclipses the issue of time. In such cases, the Decision Community requires uncompromised accuracy of the road course test matrix and ample time is available to conduct the optimization. Transformation Plan D is characterized by a key additional step in the optimization process. After an optimized road course test matrix has been found, the test center will conduct validation runs using a test vehicle. After the instrumented test vehicle has performed a few cycles following the new test plan, the captured data will be compared to the desired use environment data. If the differences between the data are outside of limits specified by the Decision Community, the test

center will perform additional optimizations using the newest data until the road course test matrix is found to be satisfactory. While Transformation Plan D requires the greatest time and effort expenditure off all of the transformation plans, it also ensures the highest relevance of the test environment to the actual use environment.

Each transformation plan has been optimized for a certain set of circumstances. The end result is a set of versatile methods by which Decision Communities can choose how to develop new and relevant automotive test plans depending on known trade-off characteristics. These known trade-off characteristics are represented in a graphical format below in Figure 19. The graphic representation provides a quick and simplified reference clearly displaying the anticipated relative performances of each transformation plan.

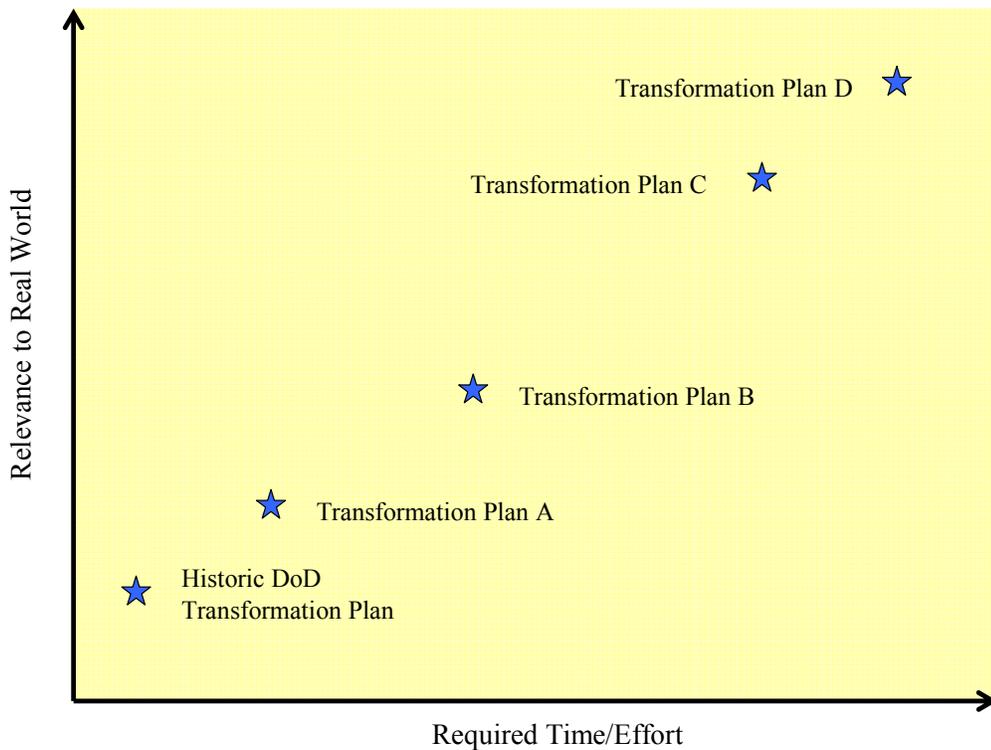


Figure 19. Theoretical plot showing expected trade-offs for proposed transformation plans.

Another graphic representation used in this section to describe the different transformation plans is the swimlane diagram. The swimlane diagram, used in many manufacturing and decision production systems, provides a detailed representation of the individuals or groups involved, the actions taken, and the flow of decisions and information for the individual transformation plans. Swimlane diagrams are very useful for clearly depicting the Decision Community network, the process required to successfully employ a transformation plan, and the required tasks of each group or individual during each step of the process. However, the disadvantages of swimlane diagrams are their poor high level representation of the transformation plan and its distinguishing characteristics.

CHAPTER 5: M915 TRUCK TRACTOR TRANSFORMATION PLANS

The first practical application of the newly developed transformation plans was conducted on a military line haul tractor test project at ATC. The 3,000 mile endurance portion of the automotive test was divided into three subsets, each following a separate transformation plan. Three road course test matrices were independently developed for each 1,000 mile endurance subtest. The test project was cancelled before the endurance subtest began, however the different transformation plans and their resulting road course test matrices were evaluated and compared based on predetermined performance criteria. The purpose of this practical exercise was to validate the comparative performance assumptions made in Section 4.6 and to confirm the effectiveness, strengths, and weaknesses of each transformation plan.

5.1 Problem Situation

The M915 series Truck Tractor is a line haul type tractor commonly used to pull a variety of tanker, flat bed, goose neck, and container trailers. The M915 vehicle curb weight (VCW) is approximately 19,000 pounds, while its gross vehicle weight (GVW) is 52,000 pounds. The M915 Truck Tractor in combination with a trailer has a gross combination vehicle weight (GCW) of 105,000 pounds. The first prototype M915 Truck Tractor was tested at ATC in 1978 for the Initial Production Evaluation of the XM915 [9]. Designed almost 30 years ago, the M915A1, shown below in Figure 20, was first produced by AM General. At the time the Department of the Army intended the M915 to be used by soldiers primarily on flat, well maintained paved roads and to a far

lesser degree on improved secondary gravel roads or in hilly to mountainous environments. By 1983, a standard test plan and road course test matrix was developed to simulate the intended use environment, which is still used today on most M915 test projects [10]. The M915 Truck Tractor has gone through many improvements and variations, the latest version being the M915A3 Truck Tractor, shown below in Figure 21. While the M915's primary components and functionality has changed minimally, the M915's actual use environment has changed drastically with the U.S. military's recent involvement in areas of conflict such as Afghanistan and Iraq.



Figure 20. Early model M915A1 Truck Tractors [11].



Figure 21. Modern M915A3 Truck Tractor used for line haul operations [12].

PM's and other DoD customers are required to obtain safety confirmations for any aftermarket add-on subsystems they intend to field on automotive assets for the U.S. Army's benefit. Safety confirmation reports are provided to military units who will be using or operating the new subsystem to ensure soldiers are made aware of potential safety hazards accompanying the new subsystem and ways to mitigate safety risks. In order to obtain a safety confirmation for components that will be used on automotive assets, the integrated subsystem must undergo a 3,000 mile endurance test at ATC to the satisfaction of DTC's current safety standards.

The M915 test project used for this practical application was initiated by a Program Manager – Heavy Tactical Vehicles (PM HTV) request to install a new fire suppression system that would be used on many M915A3s in the Operation Iraqi Freedom (OIF) and Operation Enduring Freedom (OEF) theatres. While the test plan included non-automotive subtests relating to the subsystem's functionality and performance, the DoD required that an automotive endurance test be conducted to ensure

the subsystem could withstand the daily vibration and handling loads caused by normal operation of the M915 in theatre.

Operational data was provided on the M915 from fourteen instrumented M915A3s operating in Kuwait for OIF. Data was collected for vehicle road speed, vehicle acceleration, engine load, throttle position, fuel consumption rate, roll, pitch and yaw rates, engine coolant temperature, transmission oil temperature, engine speed, and transmission output speed values. The data was recorded for approximately one month and then uploaded onto the EUDB for analysis. The fourteen M915A3 data files cumulatively comprise the actual use environment that will be used for the Transformation Plans goals and form the basis for performance comparisons.

5.2 Transformation Plans

In conjunction with a joint ATC/DTC effort to determine a more accurate representation of the M915A3 Truck Tractor's operational environment, DTC, AEC, and the test sponsor, PM HTV, agreed to allow the vehicle to be tested in three distinct phases, each consisting of 1,000 endurance miles each. The three phases represented Transformation Plans A and C, and were used to obtain actual endurance test data which was used to assess the individual and comparative performance of the transformation plans. The Transformation Plan A was implemented as phase 1. Two forms of Transformation Plan C, labeled C-1 and C-2, were conducted in phases 2 and 3 respectively.

5.2.1 Phase 1

Following Transformation Plan A outlined in Chapter 4, the decision community collectively agreed to follow the standard M915 Truck Tractor Road Course Distance Matrix. The standard road course matrix for the M915 was first developed in 1983 for the Initial Production Test of the M915A1 [9]. Since that time the standard M915 road profile has been used on every M915, M915A1, M915A2, and M915A3 test project. The standard M915A3 Truck Tractor road course test matrix intended for this test based on the results of Transformation Plan A is shown below in Table 9.

Test Course	Per Course, %	Distance, miles
Paved	75.0	750
Secondary Roads	20.8	625
MTA Gravel	8.3	83
MTA BB/G	3.3	33
CTA-C	9.2	92
Cross-Country	4.2	42
PTA-1	4.2	42
Total	100.0	1000

Table 9. Transformation Plan A M915A3 Truck Tractor Road Course Test Matrix.

BB/G = Belgian Block and Gravel.
CTA = Churchville Test Area.
MTA = Munson Test Area.
PTA = Perryman Test Area.

5.2.2 Phase 2

Transformation Plan C-1 was conducted using a single-objective optimization algorithm. Following the basic Transformation Plan C outlined in the Section 4.4 above, the decision community agreed to follow ATC's suggestions based on their optimized road course distance matrix. In September 2005, data was collected for three different M915A3 configurations on all ATC endurance test courses. These configurations were

the M915A3 Truck Tractor only, the M915A3 Truck Tractor with an empty M872 Flatbed Trailer, and the M915A3 Truck Tractor with an M872 Flatbed Trailer loaded to its maximum gross vehicle weight rating (GVWR). Data was recorded for ten laps on each endurance road course for each M915 configuration. The data was then uploaded onto the EUDB to store the data and to make it available for analysis.

Based on input from the PM, the TSM, and the AEC representative, the M915 road course test matrix was optimized for a single channel, road speed. The Decision Community desired a test that would maximize its relevance to the road speed profile found from OIF. The Decision Community had evidence that the unique speed profile found in theatre was responsible for increased part failures there.

A vehicle's road speed profile is generally a very subjective measure due to the influence of the driver. However, for this research the road speed is considered an objective data channel due to the manner in which the samples have been obtained. ATC employs professionally trained drivers to conduct endurance and reliability tests. These drivers are trained to maintain test course posted speed limits for many thousands of accumulated miles. Maintaining course speed limits helps to protect the driver from vehicle instability due to excessive speed on test courses as well as providing a compelling structure for test conduct reinforcement. Following these speed limits on course also increases the test's repeatability. Years of test data have been gathered on vehicles running the same courses that can then be compared to the results from new vehicles having operated on the courses following nearly the same road speed profile.

The OIF road speed profile was also treated as unbiased data, however some issues must be noted. The vehicles used for data capture in theatre were selected at

random but could not be instrumented without the drivers knowledge. The onboard data acquisition system could not be sufficiently concealed from vehicle operators. Consequently, driver habits might have been altered during the data acquisition. The OIF data captured was intended to represent a random sampling of operating conditions in theatre giving a sufficiently impartial road speed channel data set and actual use profile. Driving conditions in OIF vary to a great extent based on the particular type of vehicle. However, variations in driving conditions from driver to driver are insignificant when considered broadly, as in this research. The extended duration of the data acquisition effort, the thousands of miles represented, and the large number of vehicles instrumented provide additional factors to counter any initial change in drivers habits. As a result, road speed data can be used as a sufficiently unbiased measure of test course and actual use environment characteristics for any vehicle that has been tested in this manner. The resulting M915A3 Truck Tractor road course test matrix that optimizes road speed relevance is shown in Table 10.

Test Course	Per Course, %	Distance, miles
Paved	43	430
Secondary Roads	51	510
PTA-A	13	130
CTA-C	38	380
Cross-Country	6	60
MTA 2" Bumps	6	60
Total	100.0	1000

Table 10. Transformation Plan C-1 M915A3 Truck Tractor Road Course Test Matrix.

5.2.3 Phase 3

After further consideration, the Decision Community decided a road course test matrix optimized for road speed alone would not be sufficient for a thorough investigation of theatre vehicle failures. As a result, a new road course test matrix was optimized for both road speed and transmission oil temperature data channels as a different implementation of Transformation Plan C. It should be noted that transmission temperature does not commonly experience large fluctuations for different road courses. The transmission oil temperature is predominately affected by the engine’s power output, i.e. engine load. Transmission oil temperatures tend to remain constant unless the engine experiences great loads, like extended operation over hilly or mountainous terrain or when hauling a heavy trailer while sustaining high speeds. Though the transmission oil temperature may not change in this exercise, the data channel is still of some interest due to the nature of the OIF operating environment. The resulting approved Transformation Plan C-2 road course test matrix for Phase 3 is shown in Table 11.

Test Course	Per Course, %	Distance, miles
Paved	25	250
Secondary Roads	57	570
MTA Gravel	12	120
MTA BB/G	33	330
CTA-C	12	120
Cross-Country	18	180
MTA 2” Bumps	2	20
PTA-1	16	160
Total	100.0	1000

Table 11. Transformation Plan C-2 M915A3 Truck Tractor Road Course Test Matrix.

5.3 Transformation Plan Results and Discussion

There are two primary results obtained from each Transformation Plan. The first is the road course test matrix in units of miles and percent miles. The second is a series of histograms showing the relation of the synthesized road course test matrix to the desired actual use environment profile for important channels. These results will be displayed by phase. Charts showing the M915A3 profiles of important data channels for each road course are displayed in Appendix A.

5.3.1 Phase 1 Results

The road course test matrix for Transformation Plan A used in Phase 1 is shown above in Table 9. No special calculations or conversions had to be conducted on the matrix because it was taken from previous M915 test plans and was already in the proper format. Additional time and effort was needed, however, to create a synthesized histogram comparing the Transformation Plan A road course test matrix to that of the actual use environment profile. The first comparative histogram was created for the road speed data channel and is shown below in Figure 22.

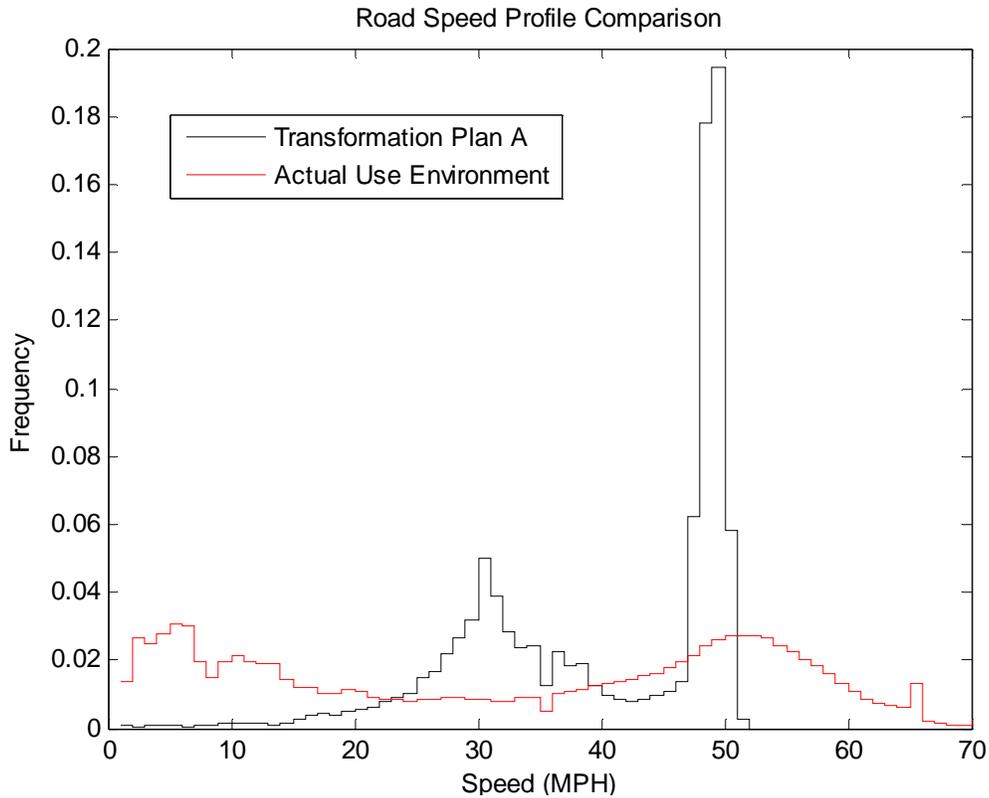


Figure 22. Transformation Plan A M915 road speed profile comparison.

Clearly Transformation Plan A is not an ideal match for the actual use environment with regards to road speed. In Section 5.4, we will determine explicitly the correlation of the two profiles. In addition to road speed, similar profile comparisons were made for the transmission temperature, engine coolant temperature, and engine load data channels. These comparisons are shown below in Figures 23 through 25.

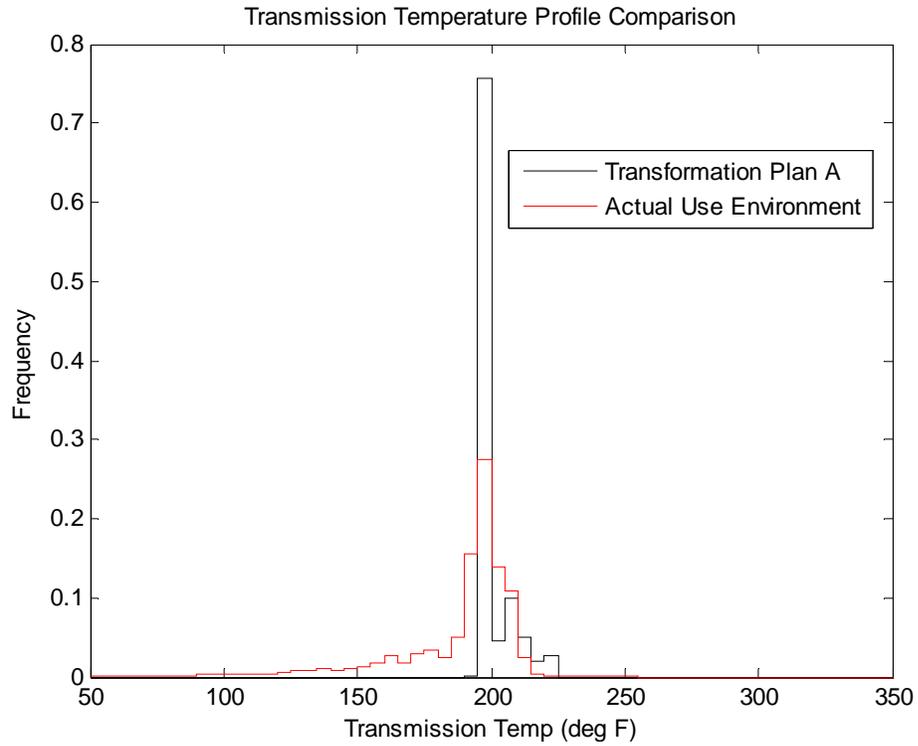


Figure 23. Transformation Plan A M915 transmission temperature profile comparison.

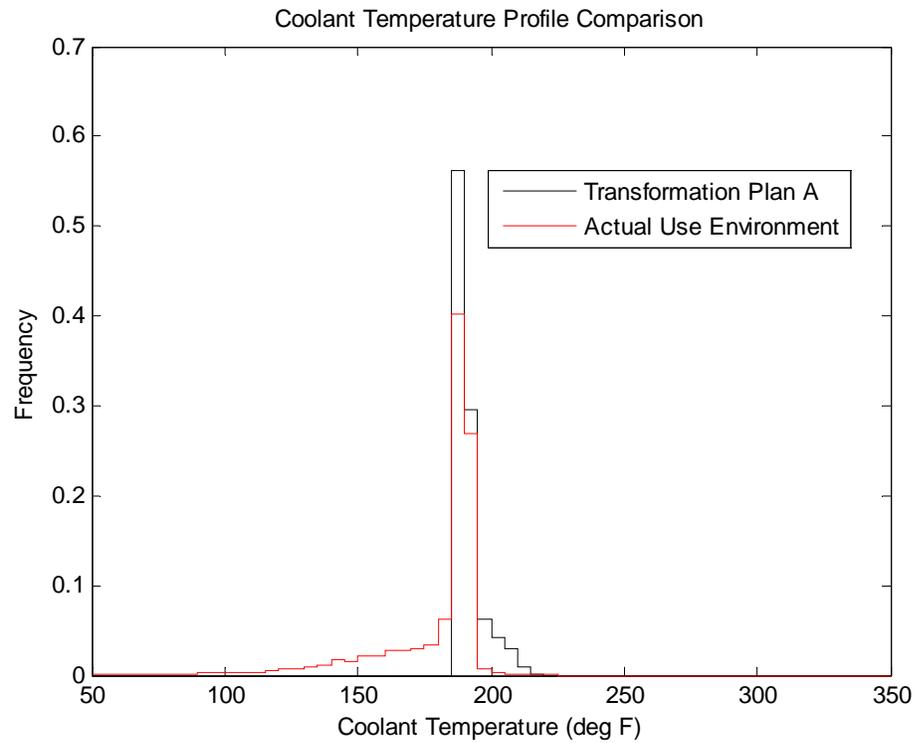


Figure 24. Transformation Plan A M915 engine temperature profile comparison.

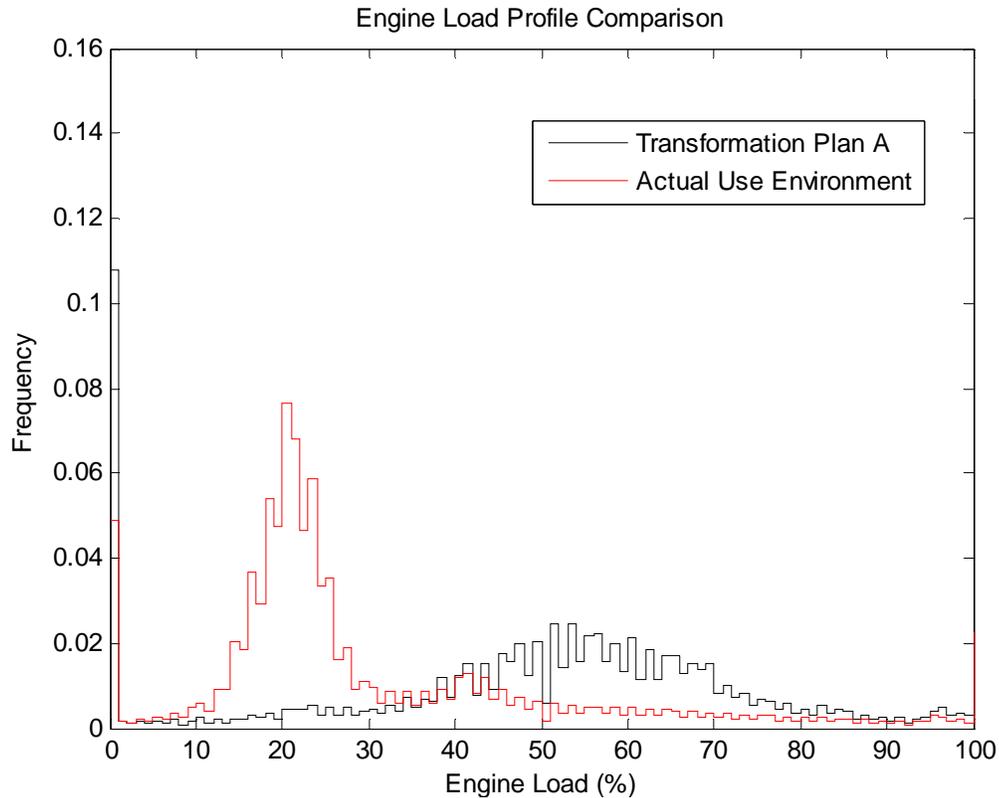


Figure 25. Transformation Plan A M915 engine load profile comparison.

Of the four comparisons, the transmission temperature and coolant temperature data channels appear to have the highest correlation with the actual use profile for those data channels. However, it is clear that no data channels are an ideal match to the desired test and use environment.

5.3.2 Phase 2 Results

A significant amount of time and effort were required to produce the road course test matrix shown above in Table 10 for Transformation Plan C-1 in Phase 2. The Decision Community previously requested that the road course test matrix be optimized for the road speed data channel. The data was obtained from the EUDB and inserted into Matlab as separate vectors for each road course including the actual use environment data from OIF. The single objective optimization algorithm was run and a resulting time

frequency solution vector for each road course weight was created. The time frequency weighting vector was then converted into a distance percentage weighting vector. Finally, with a road course test matrix in its proper format, the same data channel histogram comparisons could be made. The histograms are shown below in Figures 26 through 29.

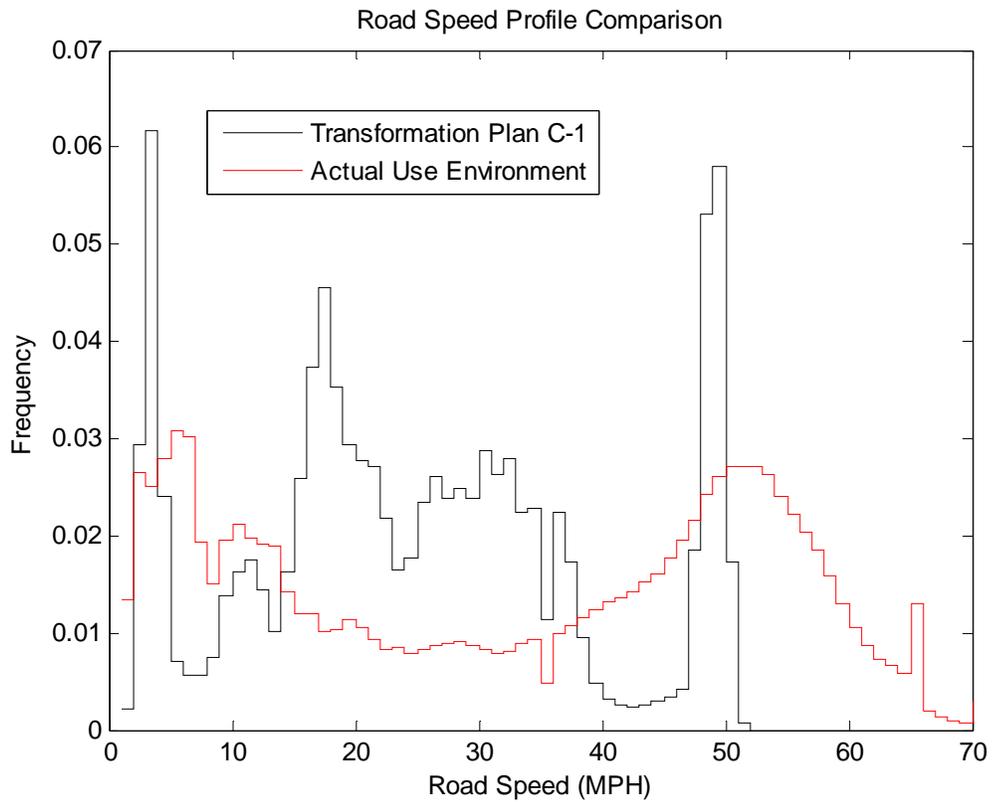


Figure 26. Transformation Plan C-1 M915 road speed profile comparison.

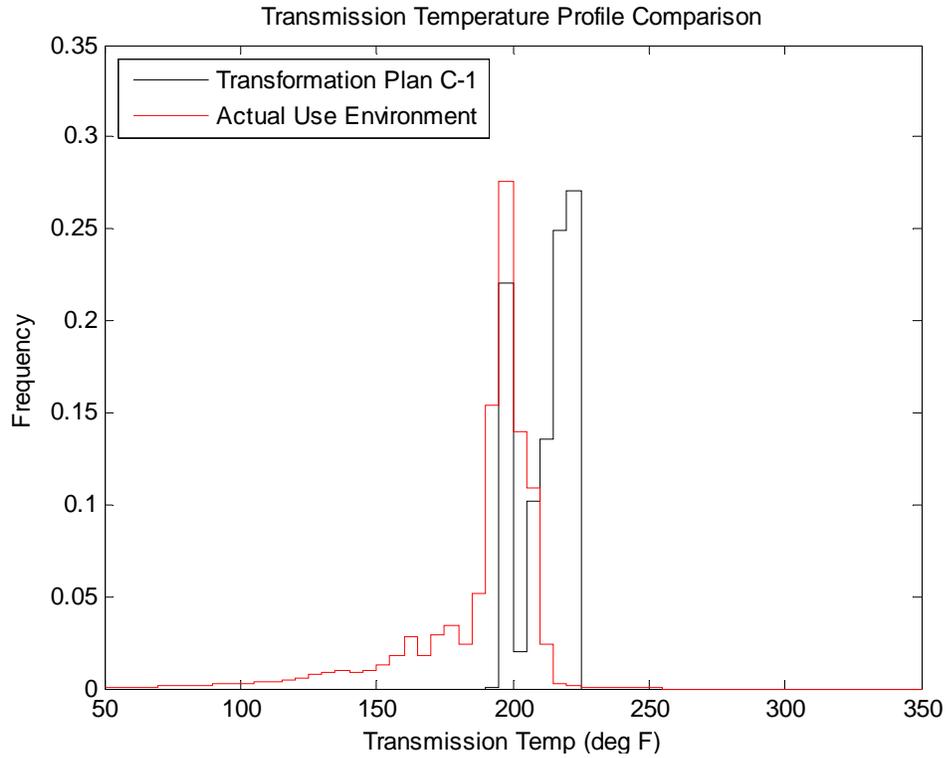


Figure 27. Transformation Plan C-1 M915 transmission temperature profile comparison.

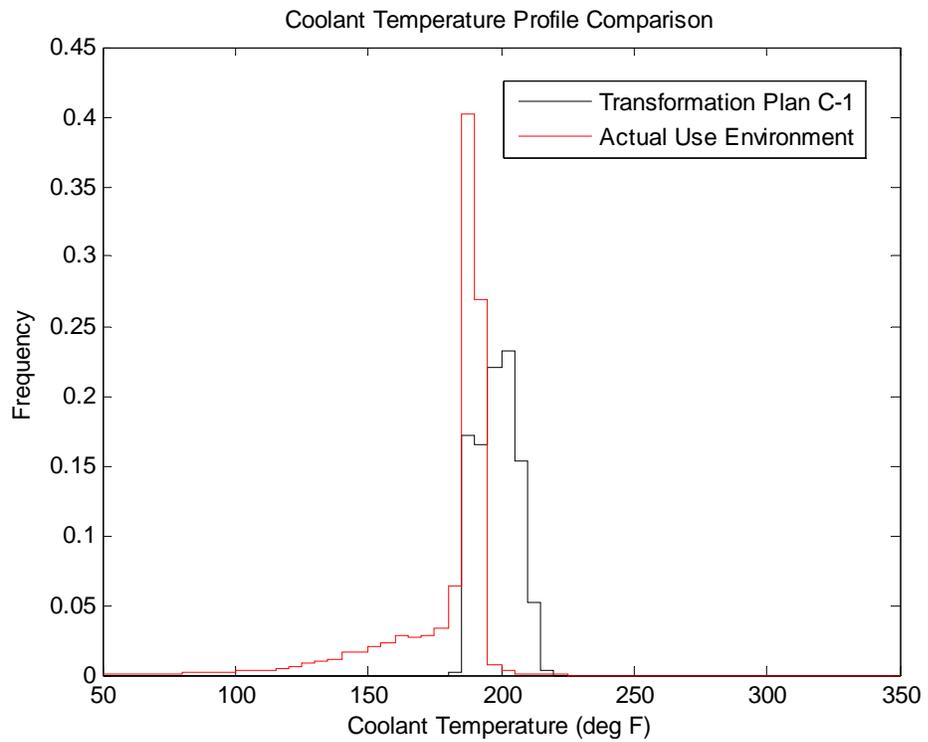


Figure 28. Transformation Plan C-1 M915 engine temperature profile comparison.

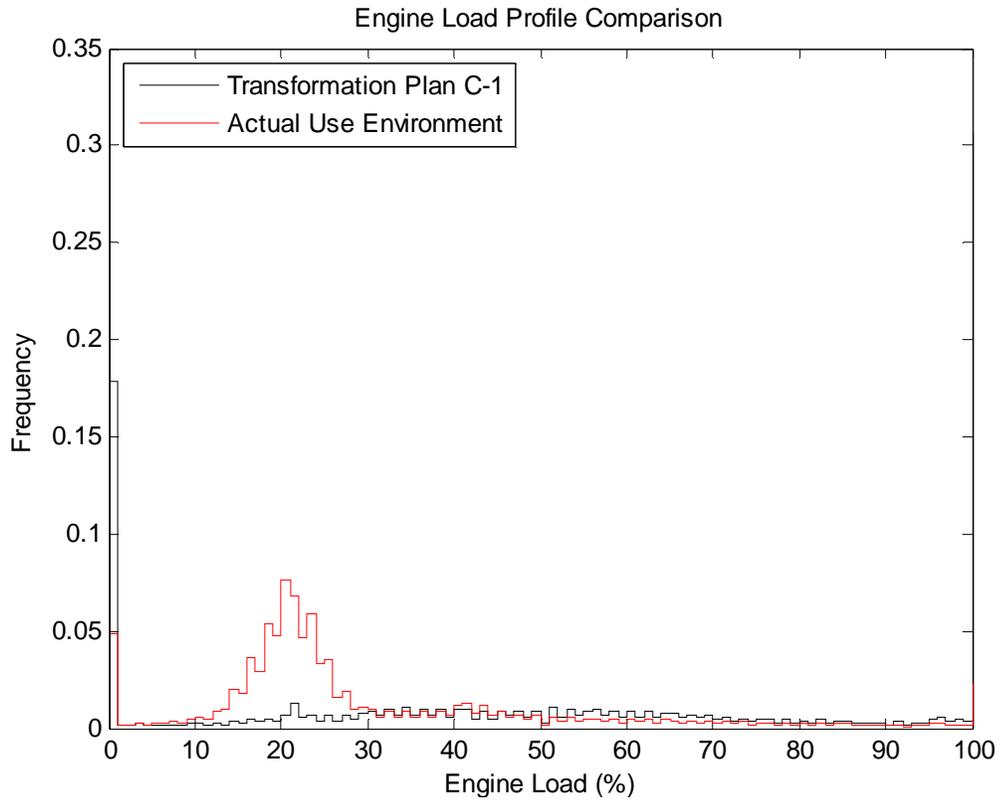


Figure 29. Transformation Plan C-1 M915 engine load profile comparison.

The road speed histogram comparison reveals little regarding the potential correlation between the Transformation Plan C-1 road course test matrix and the actual use environment data. The Transformation Plan C-1 synthesized profile does follow significant peaks in the actual use environment data but at the same time the Plan C-1 data also produces its own false peaks in the middle of the road speed spectrum.

Initially, little can be taken from the transmission temperature and engine coolant temperature comparison histograms. They both appear to be similar in shape to the respective actual use environment profiles but at a lower magnitude. The engine coolant data channel, however, appears to be highly correlated to the actual used environment data. Besides a discrepancy in the relative peaks of the two plots in the 15 to 25 percent range, the synthesized Transformation Plan C-1 road course test matrix follows the actual

use environment profile very closely. Explicit results will have to be analyzed in Section 5.4.

5.3.3 Phase 3 Results

The last phase of the M915A3 test project required a multi-objective optimization for the road course test matrix based on Transformation Plan C-2. Because a majority of the Matlab code was written for the single objective optimization in Phase 2, there were only minor additions and changes that had to be made for the process to produce a set of feasible results akin to a Pareto curve. Additional data sets had to be obtained from the EUDB for the second data channel. The Matlab code also required conversion from a relatively simple single objective optimization set up to a more complicated multi-objective optimization including a *for* loop and an additional m-file for the non-linear constraint equation. The Decision Community decided before hand that the second data channel to be optimized was the transmission temperature. With a working Matlab algorithm, a Pareto curve was established providing a range of possible solutions to the Decision Community.

Matlab initially produced a road speed and transmission temperature Pareto curve that was not to scale. The unscaled Pareto curve, shown below in Figure 30, is simply the default setting in Matlab in order to provide a visually appealing graph. The road speed and transmission temperature L2 norm error axes were then manually set in order to show proper scaling of the Pareto curve. The properly scaled Transformation Plan D Pareto curve is shown below in Figure 31.

ATC presented the results of Transformation Plan C-2 including the above Pareto curves to the Decision Community in order to facilitate a decision on the final road course test matrix. ATC determined that the L2 Norm error value for the road speed data channel remained significantly lower than the transmission temperature L2 Norm error value even at the transmission temperature's lowest optimized point. This fact was made very apparent by the scaled Pareto curve. Upon inspection of the properly scaled Pareto curve and after discussing the results, the Decision Community decided to choose a compensating solution favoring the transmission temperature data channel. The decision was based on the realization that the road speed L2 Norm error varied little and was significantly lower than the transmission temperature L2 Norm error, which varied more. In this particular case the transmission temperature data channel can be minimized without significantly penalizing the road speed data channel. The time frequency weighting vector corresponding to the desired Pareto point was then obtained and converted into a distance percentage weighting vector for the road course test matrix, as shown above in Table 11.

The Transformation Plan C-2 road course test matrix was then used to create a synthesized test profile. The synthesized test profile was then compared to the actual use environment for the road speed, transmission temperature, engine coolant temperature, and engine load data channels. These comparison histograms are shown below in Figures 32 through 35.

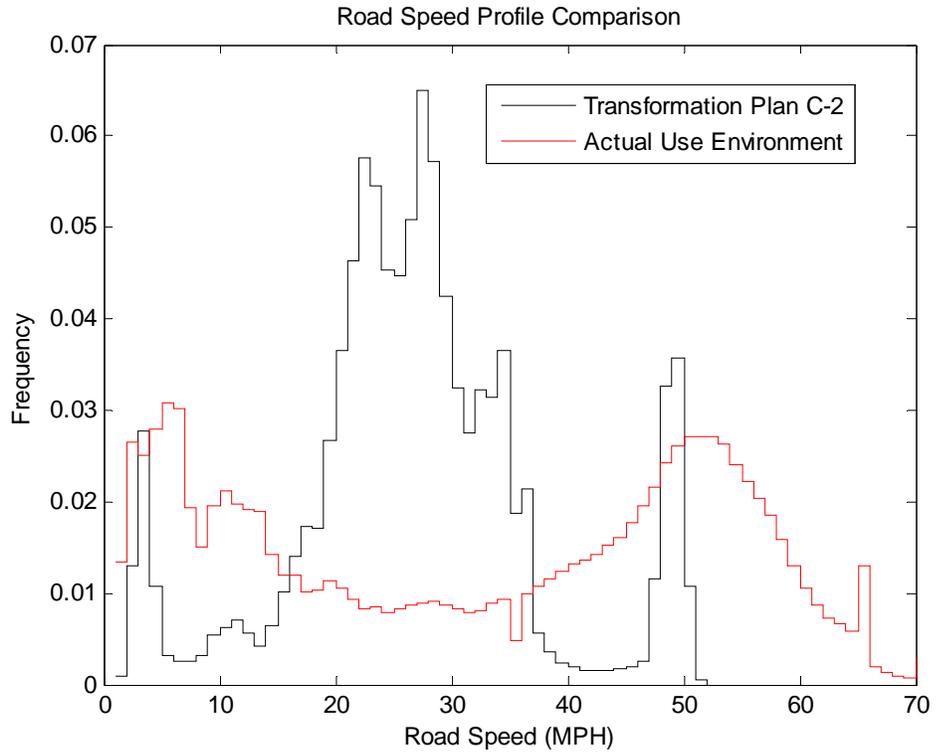


Figure 32. Transformation Plan C-2 M915 road speed profile comparison.

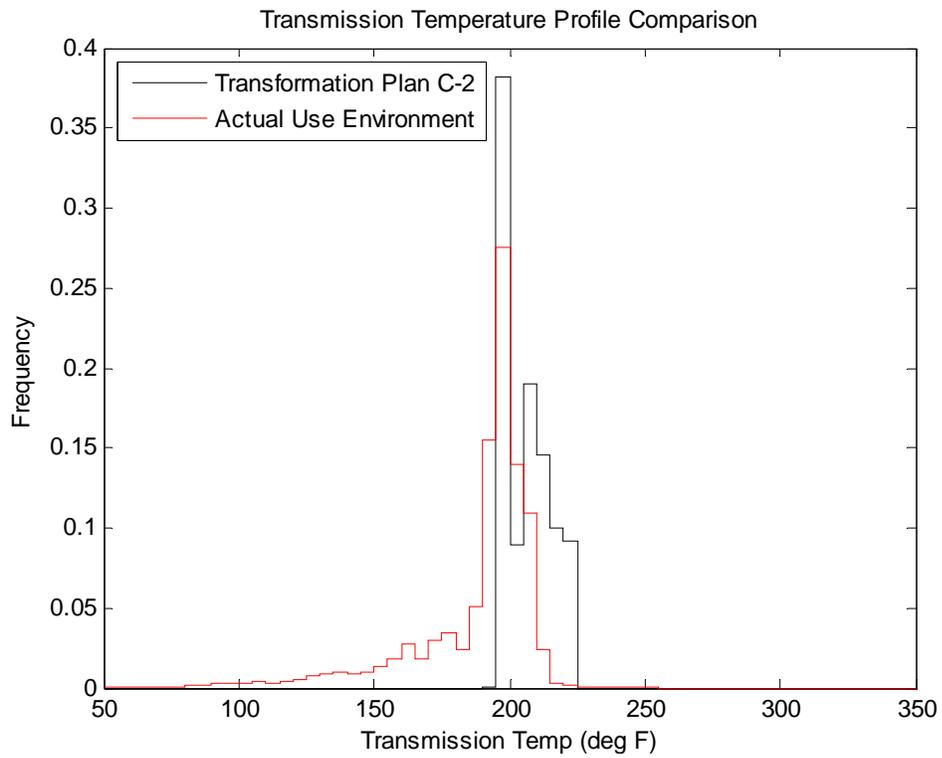


Figure 33. Transformation Plan C-2 transmission temperature profile comparison.

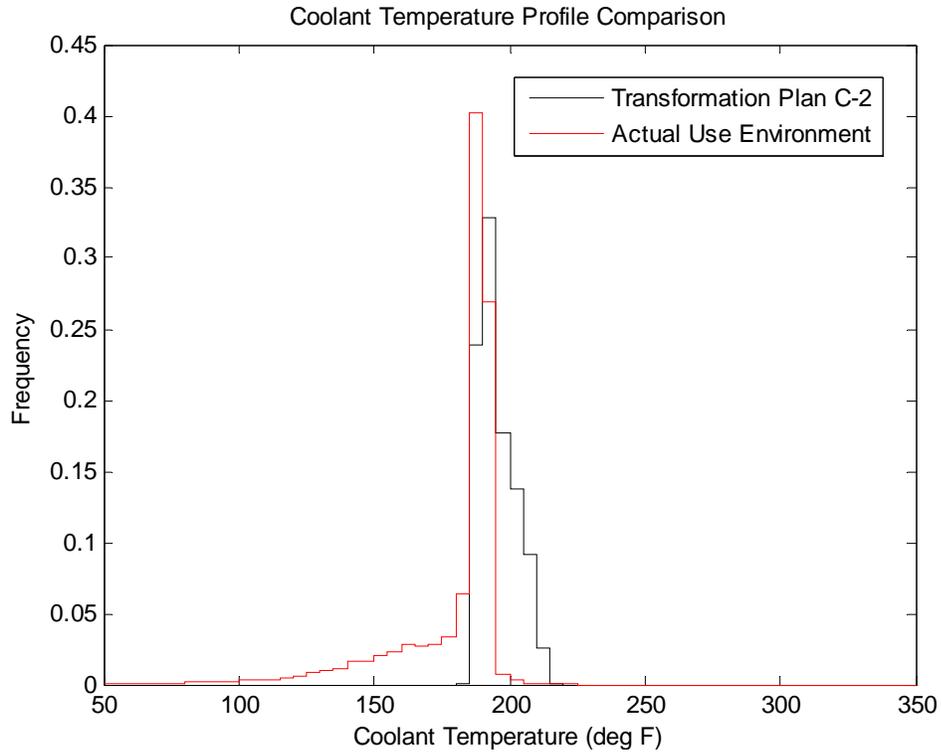


Figure 34. Transformation Plan C-2 M915 engine temperature profile comparison.

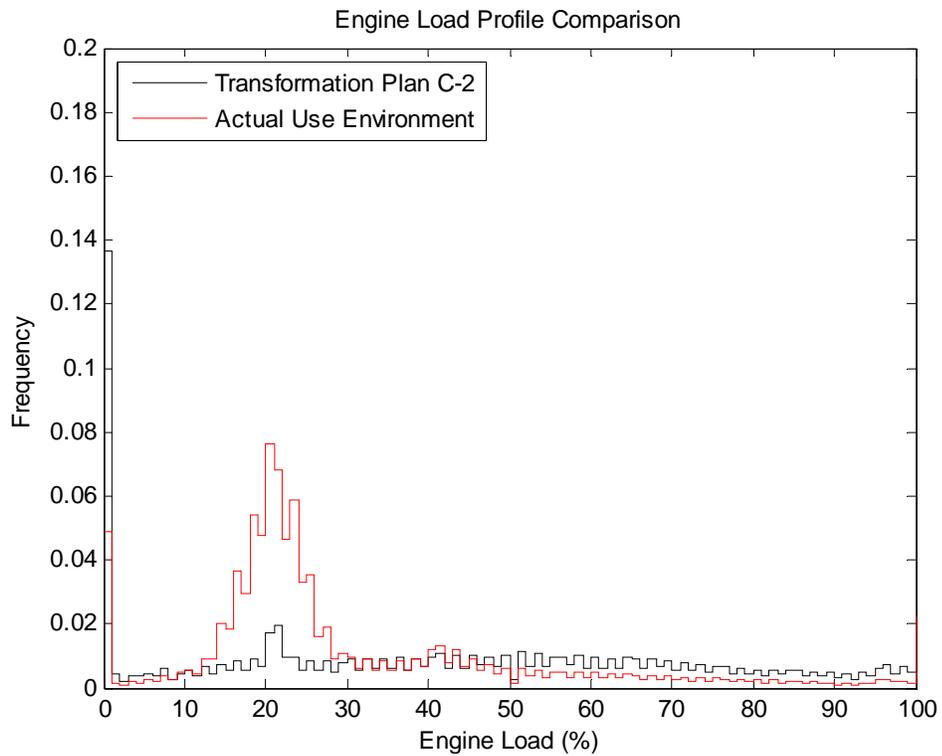


Figure 35. Transformation Plan C-2 M915 engine load profile comparison.

From the comparison histogram, the Transformation Plan C-2 result for the road speed data channel does not appear to be very similar to the actual use environment profile. The transmission temperature and the engine coolant temperature profiles also seem to have less correlation to the actual use profile than previous Transformation Plan results. The one channel however that is clearly highly correlated with the actual use environment profile is the engine load data channel.

A final plot was generated comparing the performance of each data channel to the Pareto points obtained in the optimization and shown above in Figures 30 and 31. The new comparison plot is shown below in Figure 36. The x-axis represents Pareto points 1 through 17, and are equivalent to the y-axis objective function values (transmission temperature L2 Norm error) found on the Transformation Plan C-2 Pareto curve. As a result, the transmission temperature error trend is linear in Figure 36.

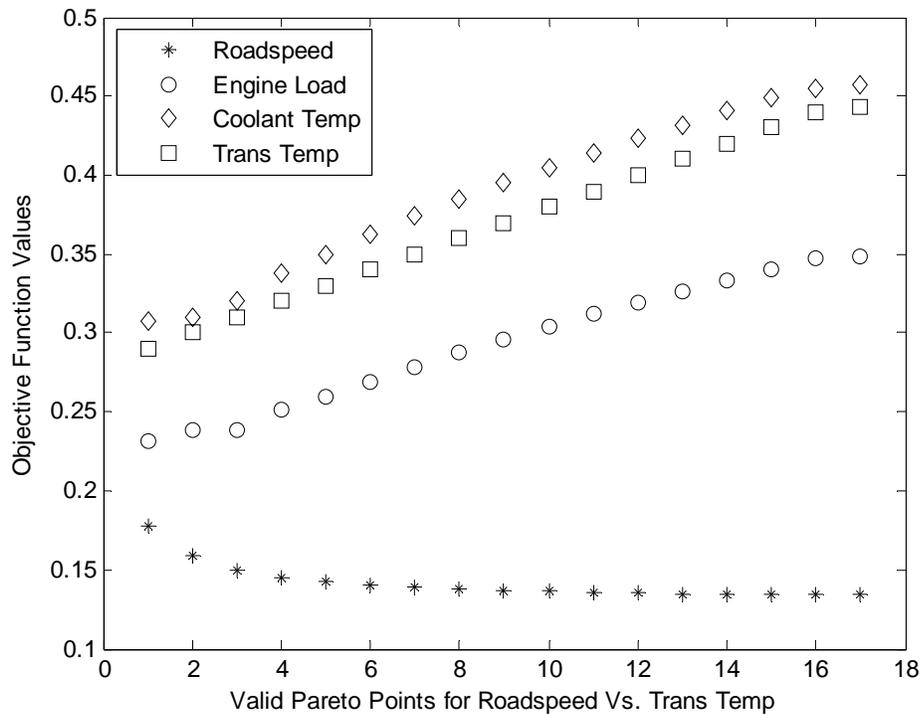


Figure 36. Data channel performance comparison plot for Pareto points.

Inspection of the comparison plot reveals that the road speed data channel behaves significantly different from the other data channels. In addition, the transmission temperature, engine coolant temperature, and engine load data channels plots are highly correlated in shape. Though these data channels differ in actual performance, their behavior is nearly identical. If any of these three data channels were optimized against one another, there would likely be no trade-offs between the objective functions and hence no Pareto curve. In other terms, for the range of Pareto solutions given above, minimizing one data channel will, in turn, minimize the other data channels as well, excluding the road speed data channel. The comparison plot also reveals that, for these four data channels chosen for comparison and optimization, the road speed data channel will always have a lower L2 Norm error value when optimized against any of the other data channels. In Section 5.4, actual quantitative indices will be analyzed to determine Transformation Plan C-2's performance and relevancy.

5.4 Transformation Plan Performance Analysis

Performance metrics were employed in order to explicitly compare the advantages and disadvantages of each transformation plan for the M915 Truck Tractor test. The performance metrics can be dichotomized into two groups: error-related and effort-related indices. The following error-related metrics were utilized: correlation coefficient (R), and the L2 Norm error value (E). The following effort-related metrics were used: cost to implement transformation plan, number of iterations required for satisfactory road course test matrix, time to implement transformation plan, expertise required, effort required, and customer satisfaction with results. Considering all of the metrics together

provides a better understanding of the tradeoffs for each transformation plan even though some metrics can be highly subjective. The ultimate goal is to provide guidelines to help decision makers early in a military system's acquisition process determine which transformation plan is most beneficial for the particular set of circumstances.

5.4.1 Error-related Performance Indices

The two error-related performance indices used were the correlation coefficient and the objective function value, or L2 Norm error. The Pearson product-moment correlation coefficient is a basic indicator for variable dependence. The correlation coefficient is not critical measure of performance due to its simplicity, however, it does provide some insight for the data comparisons. Using the correlation coefficient tailored for sample data sets, the correlation coefficient equation can be described as follows:

$$r_{xy} = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{(n-1)s_x s_y}$$

where \bar{x} and \bar{y} are the sample means of x_i and y_i , s_x and s_y are the sample standard deviations of x_i and y_i , and the sum is from $i = 1$ to n [13]. In this case the correlation coefficient provides a rough estimate for the accuracy of the road course test matrix compared to the actual use environment profile taken from vehicles supporting OIF and obtained through ATC's EUDB. Correlation coefficient values range from -1 to $+1$. The closer the correlation coefficient value is to $+1$ the better the correlation is between two sets of data. Correlation coefficient values greater than $+0.7$ are desired to confirm a high degree of correlation. Negative correlation coefficient values confirm that two data sets are inversely correlated, meaning one value is high when the other is low. In other words, the two data trends are contradictory. To illustrate this point, consider the example data set for road speed used in Table 5 in Section 4.4.3.1. Using the rough

optimum estimate of 70% of Course 1 and 30% of Course 2, a synthesized data set was made to describe the expected road speed profile seen during testing. For a perfect correlation coefficient of +1, the goal profile was plotted against itself producing points on a straight line with slope of +1. To depict a positive correlation coefficient, the optimized data profile was plotted against the goal speed profile. The result is series of points that follow a fitted linear trend line with slope equivalent to its correlation coefficient value of 0.9964. A final data profile was fabricated to show a negative correlation coefficient. The data set was created by choosing bin values opposite to the goal speed profile. The three data sets are shown below in Table 12, and they are plotted along with trend lines and correlation coefficient values in Figure 37.

Road Speed (mph)	Goal Speed Profile	Correlation Comparison Profiles		
		Perfect	Optimized Realistic	Negative
30	0.3	0.3	0.295	0.4
40	0.5	0.5	0.47	0.1
50	0.2	0.2	0.235	0.5
Correlation Coefficient		1	0.99637	-0.99998

Table 12. Example speed profiles for correlation coefficient trends.

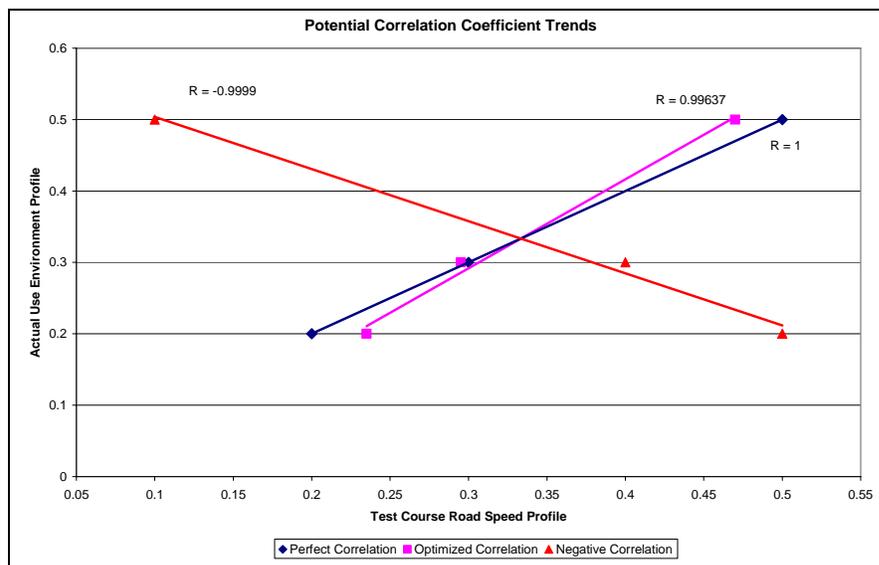


Figure 37. Example correlation coefficient trends.

The objective function value used in Transformation Plan C was used to measure the error of the other transformation plan road course test matrices. The objective function is the L2 Norm of the error between the test course profile data and the desired real world data. A simplified Transformation Plan C objective function used for comparing test results is provided below. The L2 Norm error is labeled as E which stands for function value.

$$E = \sqrt{\sum_{j=1}^J \left(\sum_{n=1}^N w_n \cdot x_{nj} - y_{1j} \right)^2}$$

This objective function provides a more thorough and sophisticated analysis of the dependence and accuracy of the different sets of data in each transformation plan. Unlike the correlation coefficient, it is most desirable to minimize the E value. Because E is just a handle for the L2 Norm error, all E values will be positive. A perfectly optimized function will have an E (the L2 Norm error) value of 0. Specific E values are difficult to analyze alone. Rather a function’s performance based on an E value must be analyzed by comparison to another function’s E value. The values of the correlation coefficient and the objective function for each transformation plan used with the M915 Truck Tractor test are provided below in Table 12.

M915A3 Transformation Plan Performance Metrics - Selected Channels								
Transformation Plan	Road Speed		Transmission Temperature		Coolant Temperature		Engine Load	
	R	E	R	E	R	E	R	E
	A	0.1907	0.2674	0.7960	0.5231	0.9690	0.2020	0.1625
C-1	0.0925	0.1346	0.4036	0.4410	0.5087	0.4439	0.2229	0.3444
C-2	-0.2486	0.1783	0.7786	0.2900	0.7824	0.3082	0.2886	0.2310

Table 13. Correlation Coefficient and Objective Function value results from M915 Truck Tractor transformation plans.

For Transformation Plan A, it is clear that the engine coolant temperature data channel is the most correlated with its subsequent actual use environment data channel and has the smallest error compared to the other three data channels. The next best correlated data channel is the transmission temperature. However, it should be noted that the transmission temperature data channel has the highest error of the set. The road speed and engine load data channels are equally unrelated to their respective actual use environment profiles with low correlation coefficient values. Error values for these data channels are relatively close with engine load slightly better.

Transformation Plan C-1 was optimized for the road speed data channel. The road speed error value has decreased and is now lower than the other data channel errors; however, the road speed correlation coefficient value has decreased as well. The transmission temperature and engine coolant temperature correlation coefficient values have decreased significantly while it has increased for the engine load data channel. The engine load and transmission temperature error values have decreased compared to Transformation Plan A while the engine coolant temperature error has increased for the new road course test matrix. Overall, the road speed data channel has the least error, with engine load second and transmission and engine coolant temperature data channels nearly equivalent have the most error for Transformation Plan C-1.

The goal of Transformation Plan C-2 was to optimize the transmission temperature data channel then the road speed data channel. From Section 5.3.3, we learned that for any solution on the Pareto curve the road speed error will be below the other data channel errors. The road speed error is greater than in Transformation Plan C-1 because a Pareto solution was chosen to favor the transmission temperature, but

still remains lower than the Transformation Plan A error. The next lowest error value belongs to the engine load data channel, which has decreased from its Transformation Plan C-1 value but is still higher than in Transformation Plan A. While the correlation coefficient value for engine load remains very low, the transmission and engine coolant temperature data channels have risen above 0.7 regaining a strong correlation with their actual use environment profiles. Because a non-optimal solution with regards to the road speed data channel has been chosen, the road speed correlation coefficient decreased to a negative value, signaling a divergence from the actual use environment profile. The transmission temperature error has reached its lowest value in Transformation Plan C-2, which is expected due to the optimization; however the engine coolant temperature error in Plan C-2 is higher than in Plan C-1 but lower than in Plan A.

Overall trends in the error-related performance data can best be seen in a series of plots. For each data channel, correlation coefficient and L2 Norm error value trends have been graphed from Transformation Plan A through Transformation Plan C-2. These plots are shown below in Figures 38 and 39.

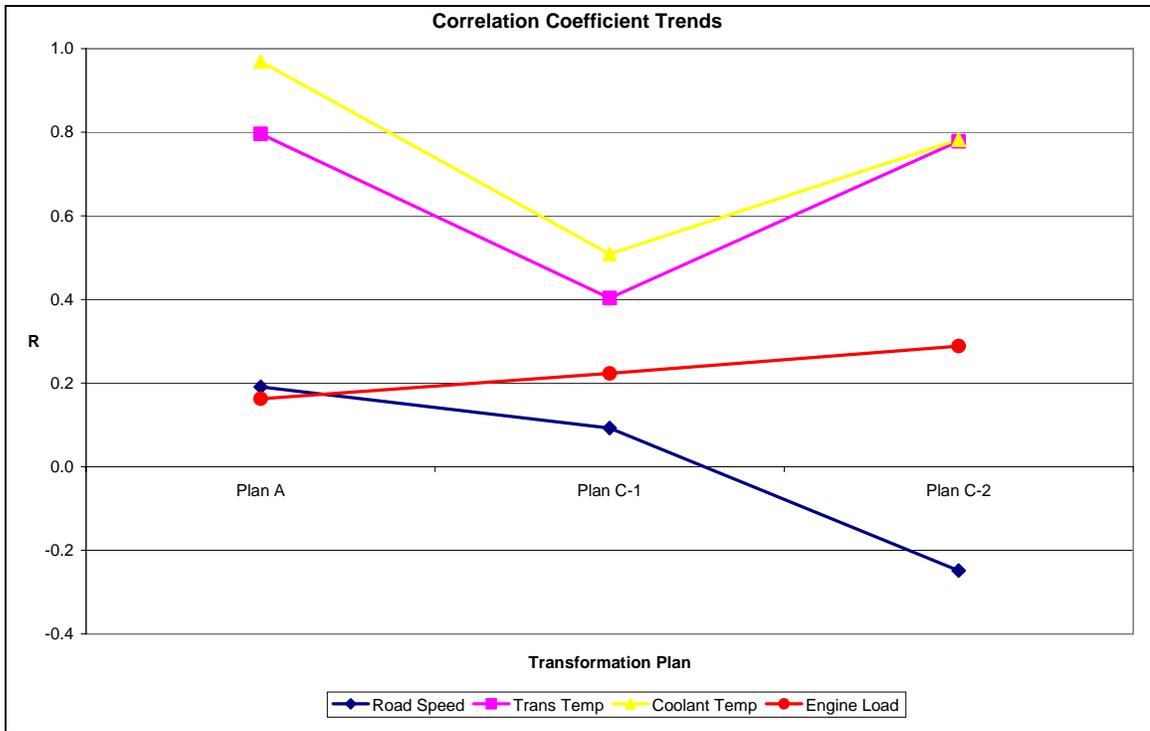


Figure 38. M915 correlation coefficient trends across transformation plans.

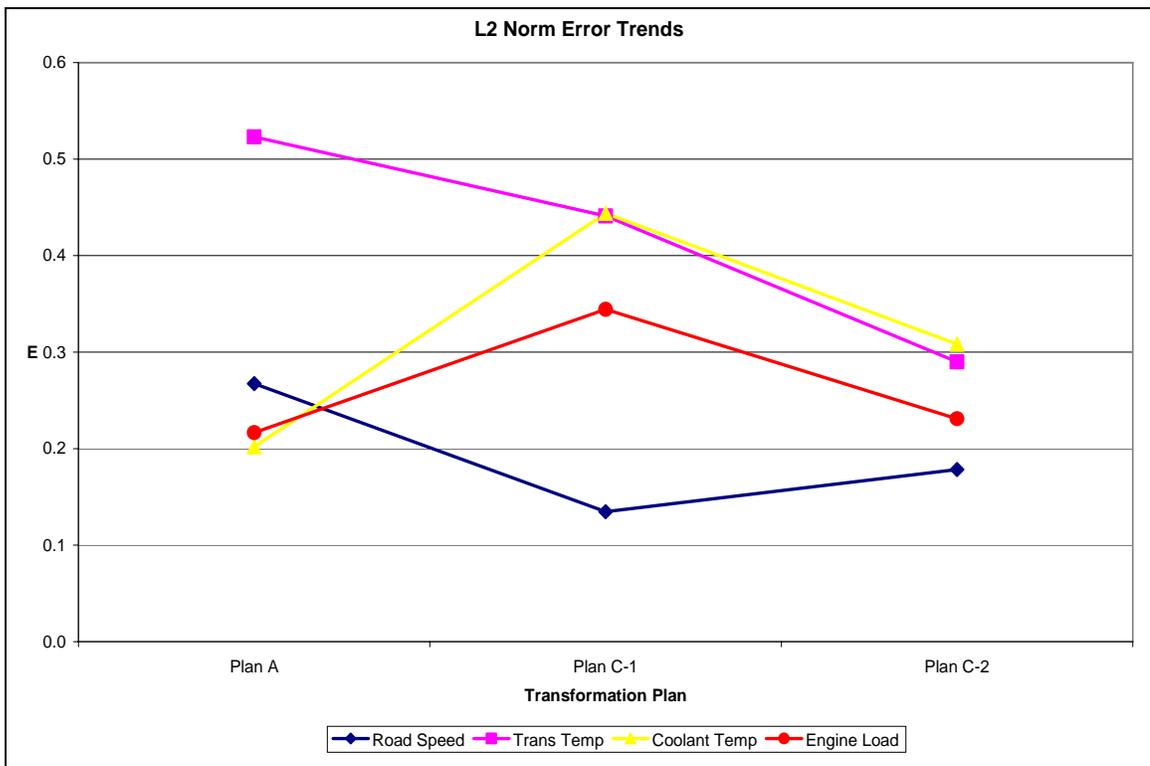


Figure 39. M915 L2 Norm error trends across transformation plans.

The road speed data channel correlation coefficient steadily regresses from Transformation Plan A to Plan C-2 ultimately ending in a detrimental negative correlation coefficient, as seen visually in Figure 38. The road speed L2 Norm error decreases from Plan A to Plan C-1; while increasing slightly for Transformation Plan C-2, the road speed error remains significantly lower than the rest of the data channels for Plans C-1 and C-2.

The transmission temperature and engine coolant temperature data channels were found to be significantly correlated to the goal profiles in Plans A and C-2 but both dipped below acceptable positive correlation limits for Transformation Plan C-1. For L2 Norm error in Transformation Plan A, the engine coolant temperature outperformed all other data channels while the transmission temperature had the worst error. For Transformation Plan C-1, the transmission and engine coolant temperature errors converged to a point much worse for the engine coolant temperature but better for the transmission temperature. For Transformation Plan C-2, the two temperature error values decreased similarly from their Plan C-1 value but still retained the highest error values.

The engine load correlation coefficient increased from Transformation Plan A through Plan C-2, however the R value never reached acceptable limits climbing only as high as 0.2886 in Transformation Plan C-2. In Transformation Plan A, the L2 Norm error for engine load was lowest. The engine load error increased significantly for Transformation Plan C-1 and then decreased in Plan C-2, retaining the second lowest error for both transformation plans.

Two data sets were plotted in a similar fashion to Figure 37 above to illustrate an anomaly found in the R and E results. The road speed data channel has the lowest L2

Norm error for Transformation Plans C-2 but at the same time has the lowest correlation coefficient value. Conversely, the engine coolant data channel in Plan C-2 has the highest E value but also has the highest R value. The synthesized engine coolant temperature and road speed data channels were plotted against their actual use environment profiles in order to show the actual correlation comparison. These plots are shown below in Figures 40 and 41.

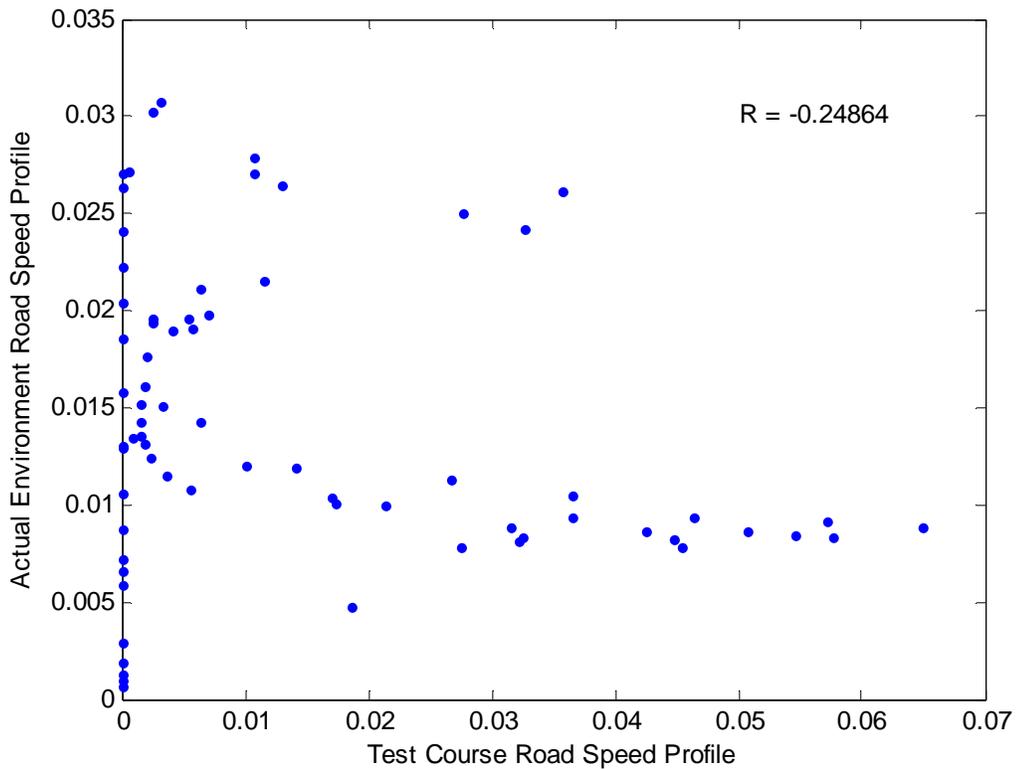


Figure 40. Transformation Plan C-2 road speed correlation plot.

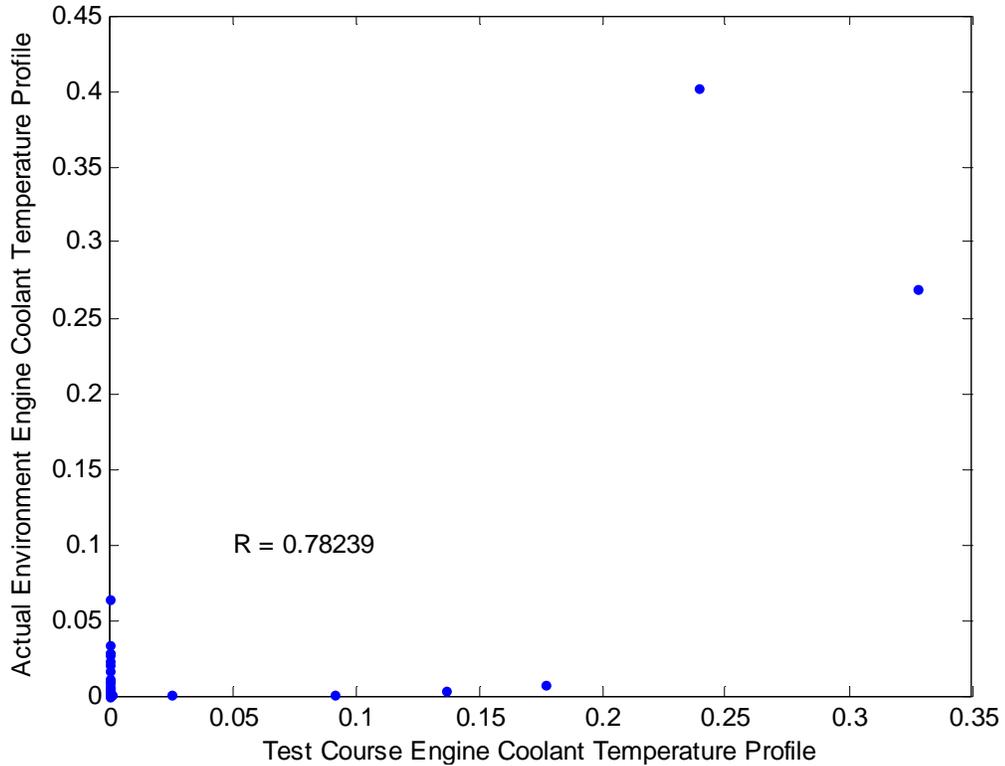


Figure 41. Transformation Plan C-2 engine coolant temperature correlation plot.

The road speed correlation, from Figure 40, is visibly poor. It is difficult to distinguish any trend in the points. Figure 32, in Section 5.3, provides some insight regarding the poor performance in correlation and the high performance in L2 Norm error. While the composite Transformation Plan C-2 road speed profile rarely matches the values of the actual use environment profile, the difference between the two profiles varies a maximum of approximately 3.5%. The engine coolant temperature appears to be highly correlated with its actual use profile based on Figure 41. Most of the points are centered on a single vertical line. However, we find that the error reaches a maximum of approximately 20% based on Figure 34 in Section 5.3. Composite data channel profiles with widely disbursed correlation points but at small intervals will have poor R values but relatively good E values, while profiles with highly linear correlation point distributions but with high outliers result in good R values but poor E values.

In addition to the correlation coefficient and L2 Norm objective function metrics, effort-related performance indices such as the cost to implement the transformation plan and the iteration count needed to determine an acceptable result were also considered for the performance analysis.

5.4.2 Effort-related Performance Indices

Cost of implementation and effort required are effort-related performance measures because it was difficult to keep exact accounts of all costs and to quantify effort. The cost of implementation primarily consists of the labor costs to determine and publish the DTP which includes the road course test matrix used for endurance or reliability testing. Implementation costs can also include travel costs for Decision Community meetings and material or equipment costs for necessary software or hardware specific to a particular transformation plan requirement. An implementation schedule and cost breakdown for each transformation plan is shown below in Figure 41. Table 14, below, provides a breakout of costs and iterations required for each transformation plan.

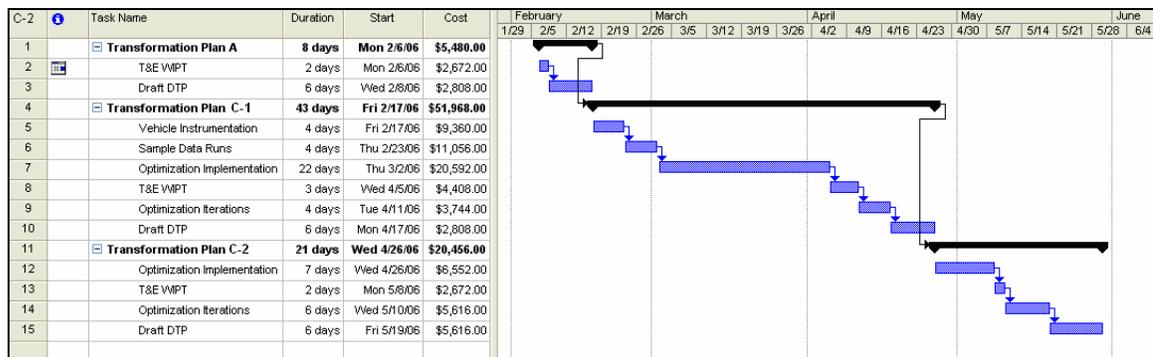


Figure 42. Gantt chart of M915 Transformation Plan implementation costs.

		Transformation Plan		
		A	C-1	C-2
Recurring Costs	Test Director	\$4,144	\$9,360	\$15,867
	Field Engineer	\$1,336	\$0	\$0
	Instrumentation Engineer	\$0	\$0	\$0
	Driver	\$0	\$0	\$0
	Travel	\$800	\$1,600	\$800
	Fuel	\$0	\$0	\$0
	Instrumentation	\$0	\$0	\$0
Initial Setup Costs	Test Director	\$0	\$28,080	\$6,552
	Field Engineer	\$0	\$7,488	\$0
	Instrumentation Engineer	\$0	\$2,944	\$0
	Driver	\$0	\$1,296	\$0
	Travel	\$0	\$0	\$0
	Fuel	\$0	\$400	\$0
	Instrumentation	\$0	\$800	\$0
Recurring Costs		\$6,280	\$10,960	\$16,667
Initial Setup Costs		\$0	\$41,008	\$6,552
Actual Total		\$6,280	\$51,968	\$23,219

Table 14. M915 Transformation Plan implementation cost breakdown.

Transformation Plan A did not require any special equipment or materials. During Plan A, a two-day Temporary Duty (TDY) travel for two ATC employees, one engineer and one test director, to attend a T&E WIPT to decide on a final DTP was required. The labor cost required to publish an accurate draft of the DTP for Plan A was relatively little, it was completed by one test director in 6 working days. The road course test matrix required one iteration for approval. Transformation Plan A required approximately \$6,300 in labor costs to implement.

The cost of implementation for Transformation Plan C-1 was significantly higher compared to Transformation Plan A. Material and equipment costs included a license for Matlab, optimization text books, vehicle fuel, and data acquisition systems for vehicle data retrieval. Travel costs included a three-day TDY trip for two ATC employees.

Labor costs included two test directors for the duration of the data acquisition and DTP publishing efforts, as well as three engineers and two drivers during the data acquisition effort. The DTP publishing phase took significantly more time than in Plan A because a large amount of time was needed to create a working optimization algorithm in Matlab and then additional time was needed to help the PM determine a preferred data channel for the optimization. Overall, Transformation Plan C-1 required approximately 9 weeks in order for an approved draft DTP to be published. Three road course test matrix iterations were required before an approved matrix was decided upon. Overall, an estimated \$52,000 was spent implementing Transformation Plan C-1 for the M915 Truck Tractor.

When Transformation Plan C-2 was implemented, many of the costs for Plan C-1 could be reduced or eliminated completely because the test directors and engineers were familiar with the data and the optimization algorithm and additional data was not required. No additional materials or equipment were needed for Plan C-2, these costs were sunk during Plan C-1. Plan C-2 required a two-day TDY travel for one engineer and one test director from ATC. Two test directors remained on the project in order to optimize the multi-objective road course test matrix, however, less time was required to perform the optimization and to draft the approved DTP. The Plan C-2 draft DTP was approved in 3 weeks after starting. Transformation Plan C-2 required the most road course test matrix iterations with five changes before approval. An estimated \$23,000 was spent implementing Transformation Plan C-2.

Transformation Plan C-1 superficially required the highest cost to implement. In reality Plan C-1 had the highest cost because it was the first optimized transformation

plan implemented. Initial setup costs associated with Plan C-1 for the M915 Truck Tractor would have nearly identically transferred to Plan C-2 had it been implemented first. When considering the estimated recurring costs of the three Transformation Plans, Plan C-1 is clearly less expensive than Plan C-2. Transformation Plan A requires no initial setup cost and will always maintain the lowest implementation cost due to the short time line and minimal labor involvement. The initial setup cost for any optimized transformation plan will be high due to the necessity to instrument vehicles, gather data, and then process the data into an optimization algorithm. Initially the working optimization algorithm required 4 weeks to implement. The majority of the optimization algorithm code can be easily reused for subsequent test projects, helping to minimize the time required to form later optimized road course test matrices.

Vehicle test projects with existing repositories of ATC test course data will require little time and effort to individualize a road course test matrix. However, previously untested vehicle systems will require initial setup costs. Overall, implementing the first optimized transformation plan required a high initial investment cost, approximately \$47,600 for the M915 Truck Tractor, while continuation costs become marginal and range from approximately \$11,000 for Transformation Plan C-1 to \$17,000 for Transformation Plan C-2.

5.4.3 Transformation Plan Performance Summary

The three major performance indices discussed in Section 4.6, solution quality, cost to implement, and time required, were discussed in depth the above sections. A table was created to provide a concise summary of the performance results. The information is provided below in Table 15.

		Transformation Plan		
		A	C-1	C-2
Solution Quality	Correlation	Low, Irregular	High, Irregular	High, Irregular
	Error	High, Irregular	Very Low	Very Low, Performance Tradeoffs
	Confidence in relevance	Low	High	Very High
Cost	Investment	None	High	High
	Continuation	Very Low	Medium-Low	Medium
	Effort	Very Low	Medium	Medium-High
	Variation	Very Low	Irregular	Irregular
Time	Investment	None	Very High	Very High
	Continuation	Very Low	Medium-Low	Medium-High

Table 15. M915 Transformation Plan performance results summary.

Based on the objective and subjective results from the implementation of Transformation Plans A, C-1, and C-2 for the M915 truck tractor, the actual performance of the separate plans differed from their expected performance as depicted in Figure 19 in Section 4.6. Figures 43 and 44, below, provide a high level illustration of the findings of this Chapter.

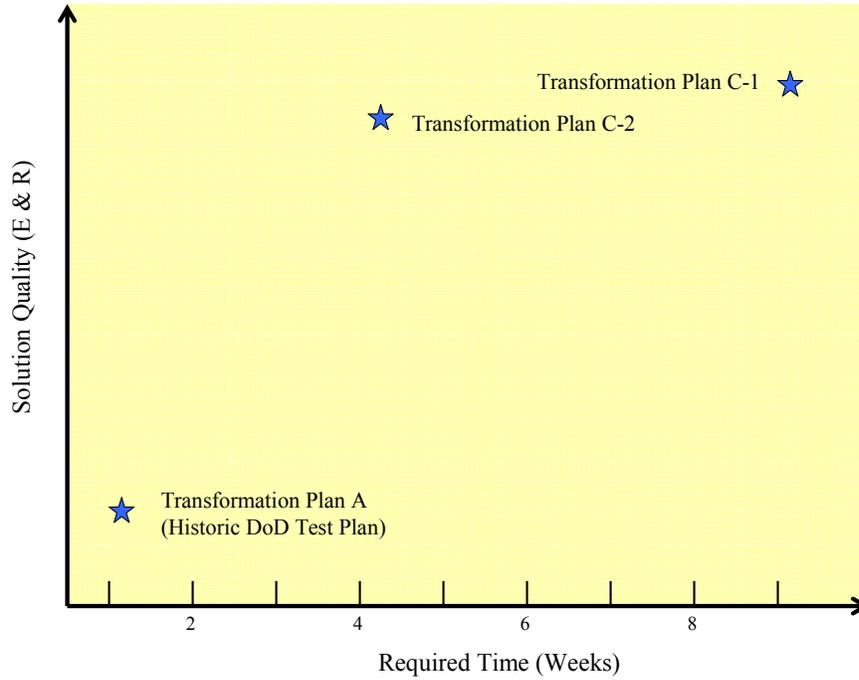


Figure 43. Actual time and solution quality trade-offs for three proposed M915 transformation plans.

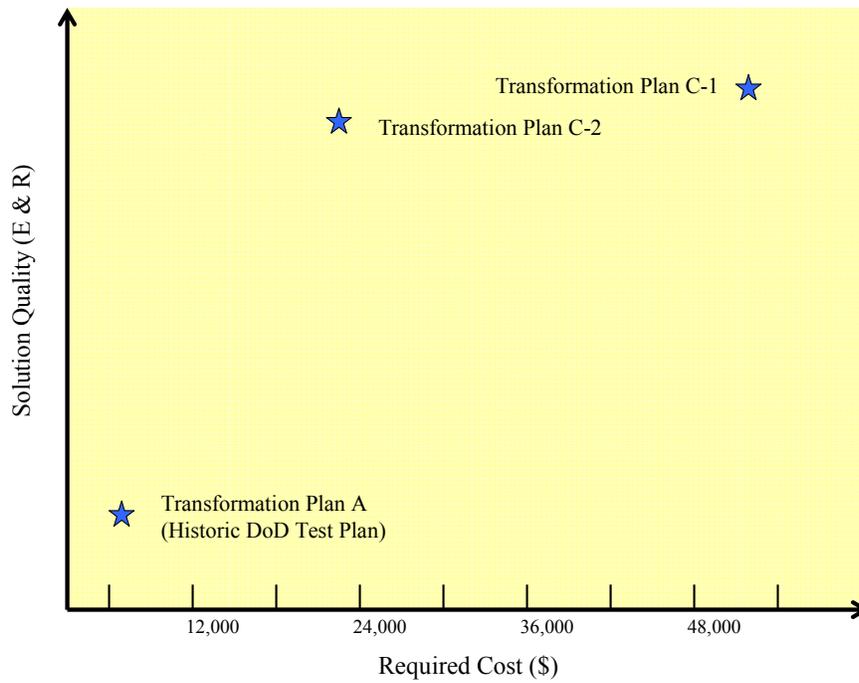


Figure 44. Actual cost and solution quality trade-offs for three proposed M915 transformation plans.

CHAPTER 6: HMMWV TRANSFORMATION PLAN DEVELOPMENT

This chapter continues our investigation of the practical applications of the newly developed transformation plans conducted on a military light duty all-terrain vehicle test project at ATC. The 3,000 mile endurance portion of the automotive test was divided into three subsets, each following a separate transformation plan. Three road course test matrices were independently developed for each 1,000 mile endurance subtest. The test project was cancelled before the endurance subtest began, however the different transformation plans and their resulting road course test matrices were evaluated and compared based on predetermined performance criteria. The purpose of this practical exercise was to validate the comparative performance assumptions made in Section 4.6 and to confirm the effectiveness, strengths, and weaknesses of each transformation plan.

6.1 Problem Situation

The HMMWV is actually a family of vehicles retaining a common body style and chassis but ranging widely in function. The HMMWV was designed as a tactical 1 1/4-ton, 4x4, multipurpose vehicle offering superior mobility in rugged, off-road terrain. The HMMWV replaced numerous aging U.S. Army vehicles, including the M151 1/4-ton utility vehicles, also known as the Jeep, the M274 1/4-ton Mule, the M561 1-1/2-ton Gama Goat, and the M880 1 1/4-ton pick-up truck [14]. The first HMMWV models designed in the early 1980's consisted of three major types, a personnel carrier, an equipment carrier, and an armament carrier. Since initial fielding in 1983, 29 distinct models in all have been developed. One of the latest HMMWV models used currently in OIF and OEF is the armored M1114 HMMWV. The M1114 has a heavier suspension

than most HMMWV models so that it can carry the additional payload of the external armor. The M1114 is equipped with a roof mounted turret upon which many types of weapon systems can be mounted. Though initially designed to operate in less hazardous tactical environments, the M1114 has had to taken on a hybrid combat and tactical role in recent foreign conflicts. The M1114's VCW is approximately 5,500 pounds, while its maximum GVW is 12,100 pounds.

The first prototype HMMWV's were tested at ATC in 1982 for a competitive production evaluation. The first HMMWV model, the M998, shown below in Figure 45, continues to be produced in an A2 version by AM General. At the time the Department of the Army intended the HMMWV family of vehicles to be used by soldiers in a variety of environments, but to operate especially adeptly in rugged, cross county conditions. In addition to handling extremely difficult terrain at low speeds, the Army still wanted the HMMWV to perform well on maintained paved roads, improved secondary gravel roads, and in hilly to mountainous environments. By 1983, a standard test plan and road course test matrix was developed to simulate the intended use environment, which until 1988, was used on all HMMWV test projects.

The HMMWV has gone through many improvements and variations, the latest versions being the M1114 Armament Carrier, shown below in Figure 46, the M1151 Advanced Armament Carrier, and M1152 Advanced Shelter Carrier. While the HMMWV's primary components and functionality has changed minimally, the HMMWV's actual use environment has changed drastically with the U.S. military's recent involvement in areas of conflict such as Afghanistan and Iraq.



Figure 45. Early model M998A0 HMMWV [15].



Figure 46. Modern M1114A2 HMMWV [16].

PM's and other DoD customers are required to obtain safety confirmations for any aftermarket add-on subsystems they intend to field on automotive assets for the U.S. Army's benefit. Safety confirmation reports are provided to military units who will be using or operating the new subsystem to ensure soldiers are made aware of potential safety hazards accompanying the new subsystem and ways to mitigate safety risks. In order to obtain a safety confirmation for components that will be used on automotive

assets, the integrated subsystem must undergo an endurance test at ATC to the satisfaction of DTC's current safety standards.

The M1114 HMMWV test project used for this practical application was initiated by the Program Executive Office for Combat Support and Combat Service Support (PEO CS&CSS). The Program Executive Officer (PEO) requested to install a new component that would be used on many M1114 HMWVs in the OIF and OEF theatres. While the test plan included non-automotive subtests relating to the component's functionality and performance, the DoD required that an automotive endurance test be conducted to ensure the subsystem could withstand the daily vibration and handling loads caused by normal operation of the M1114 HMMWV in theatre and that the added weight of the component would not significantly compromise the safety of the HMMWV crew.

Operational data was provided on the M1114 HMMWV from three instrumented vehicles operating in Kuwait for OIF. Data was collected for vehicle road speed, roll, pitch, and yaw rates, tri-axial acceleration, and Global Positioning Satellite (GPS) location values. The data was recorded for approximately one month and then uploaded onto the EUDB for analysis. The three M1114 HMMWV data files cumulatively comprise the actual use environment that will be used for the Transformation Plans goals and form the basis for performance comparisons.

6.2 Transformation Plans

In conjunction with a joint ATC/DTC effort to determine a more accurate representation of the M1114 HMMWV's operational environment, DTC, AEC, and the test sponsor, PM LTV, agreed to allow the vehicle to be tested in three distinct phases,

each consisting of 1,000 endurance miles each. The three phases represented Transformation Plans A and C, and were used to obtain actual endurance test data which was used to assess the individual and comparative performance of the transformation plans. Transformation Plan A was implemented as phase 1. A single objective optimization was implemented as Transformation Plan C-1 in phase 2, while a multi-objective optimization was implemented as Transformation Plan C-2 in phase 3.

6.2.1 Phase 1

Following Transformation Plan A outlined in Chapter 4, the decision community collectively agreed to follow the OIF high speed HMMWV road course distance matrix. The OIF high speed HMMWV profile was developed in 2003 based on emerging needs from in theatre to test vehicles faster. The PM sponsored high speed profile was created based on the process outlined in Transformation Plan A, though before this research was conducted.

The standard road course matrix for the early HMMWV models was first developed in 1982 for the HMMWV Competitive Run-off Test. Since that time the standard HMMWV road profile has been used on every subsequent HMMWV model undergoing testing until a second road course test matrix was developed in 1988 for an IPT for a third generation of HMMWVs [17]. The standard HMMWV road course test matrix followed a 30/30/40 regimen, 30% of the endurance miles spent on primary paved roads, 30% spent on secondary roads, and 40% spent on cross country courses. Even after 1988, the original standard endurance test profile was used for the majority of HMMWV test projects. In 2003, however, there was a major shift from the original standard plan to the 1988 road course test matrix. The 1988 road course test matrix was adopted by PM LTV, AEC, and Commanders in theatre to represent the OIF high speed

HMMWV profile. The OIF high speed HMMWV/1988 endurance profile resulted in a 45/45/10 regimen and has been implemented in all major HMMWV endurance tests like the PQT of the HMMWV Modernization test since 2005 [18]. The OIF high speed HMMWV endurance profile representing Transformation Plan A is shown below in Table 16.

Test Course	Per Course, %	Distance, miles
Paved	45.0	450
Secondary Roads	45.0	450
MTA BB/G	45.0	450
Cross-Country	10.0	100
PTA-2	5.0	50
CTA B	5.0	50
Total	100.0	1000

Table 16. Transformation Plan A M1114 HMMWV Road Course Test Matrix.

6.2.2 Phase 2

Following Transformation Plan C outlined in the Section 4.4 above, the Decision Community agreed to follow ATC’s suggestions based on their optimized road course distance matrix. In September 2005, data was collected for one M1114 HMMWV loaded to GVW on all ATC endurance test courses. Data was recorded for ten laps on each endurance road course the HMMWV was capable of traversing. The data was then uploaded onto the EUDB to store the data and to make it available for analysis.

Based on input from the PM, the TSM, and the AEC representative, the HMMWV road course test matrix was optimized for a single channel, road speed. The Decision Community desired a test that would maximize its relevance to the road speed profile found from OIF. The Decision Community had evidence that the unique speed profile found in theatre was responsible for increased part failures there. As a result, the

M1114 HMMWV road course test matrix that optimizes road speed relevance is shown in Table 17.

Test Course	Per Course, %	Distance, miles
Paved	34.0	340
Secondary Roads	17.0	170
CTA-C	17.0	170
Cross-Country	20.5	490
PTA-1	28.5	285
PTA-2	0.5	5
CTA-B	20.0	200
Total	100.0	1000

Table 17. Transformation Plan C-1 M1114 HMMWV Road Course Test Matrix.

6.2.3 Phase 3

After further consideration, the Decision Community decided a road course test matrix optimized for road speed alone would not be sufficient for a thorough investigation of theatre vehicle failures. As a result, a new road course test matrix was optimized for both road speed and vehicle roll rate data channels as an implementation of Transformation Plan C-2. The resulting approved Transformation Plan C-2 road course test matrix for phase 3 is shown in Table 18.

Test Course	Per Course, %	Distance, miles
Paved	37	370
Secondary Roads	61	610
CTA-C	61	610
Cross-Country	2	20
PTA-1	2	20
Total	100.0	1000

Table 18. Transformation Plan C-2 M1114 HMMWV Road Course Test Matrix.

6.3 Transformation Plan Results and Discussion

The primary results obtained from each Transformation Plan are a road course test matrix in units of miles and percent miles and charts showing the relation of the synthesized road course test matrix to the desired actual use environment profile for important channels. These results will be displayed by phase. Charts showing the HMMWV profiles of important data channels for each road course are displayed in Appendix B.

6.3.1 Phase 1 Results

The road course test matrix for Transformation Plan A used in phase 1 is shown above in Table 16. No special calculations or conversions had to be conducted on the matrix because it was taken from previous M1114 HMMWV test plans and was already in the proper format. Additional time and effort was needed, however, to create a synthesized histogram comparing the Transformation Plan A road course test matrix to that of the actual use environment profile. The first comparative histogram was created for the road speed data channel and is shown below in Figure 47.

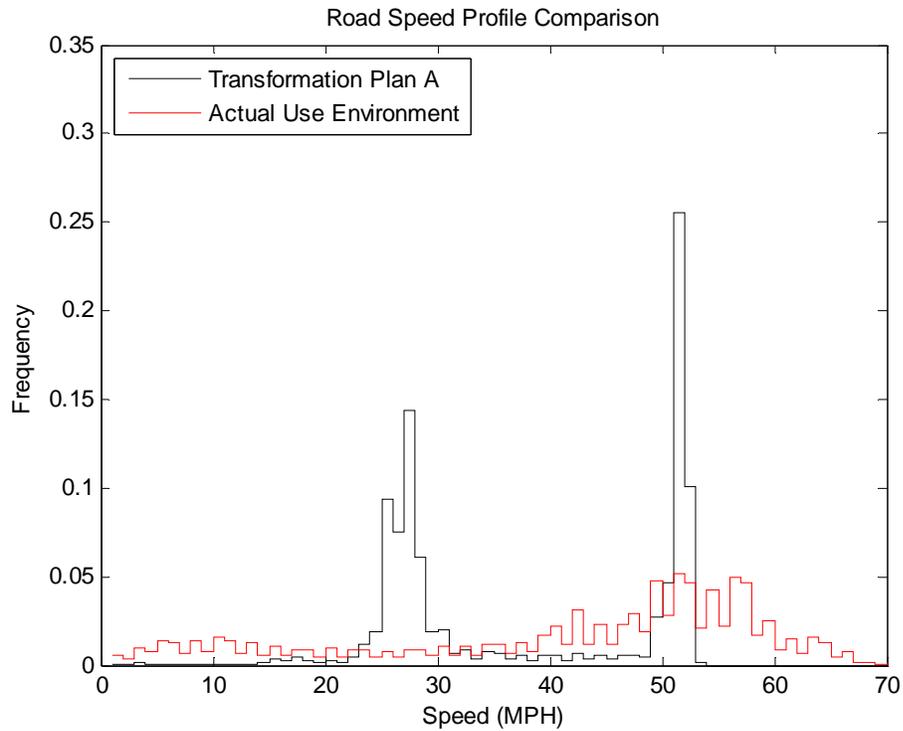


Figure 47. Transformation Plan A HMMWV road speed profile comparison.

Transformation Plan A is not appear to be ideal match for the actual use environment with regards to road speed. In Section 5.4, we will determine explicitly the correlation of the two profiles. In addition to road speed, similar profile comparisons were made for the roll rate, vertical acceleration, yaw rate, and pitch rate data channels. These comparisons are shown below in Figures 48 through 51.

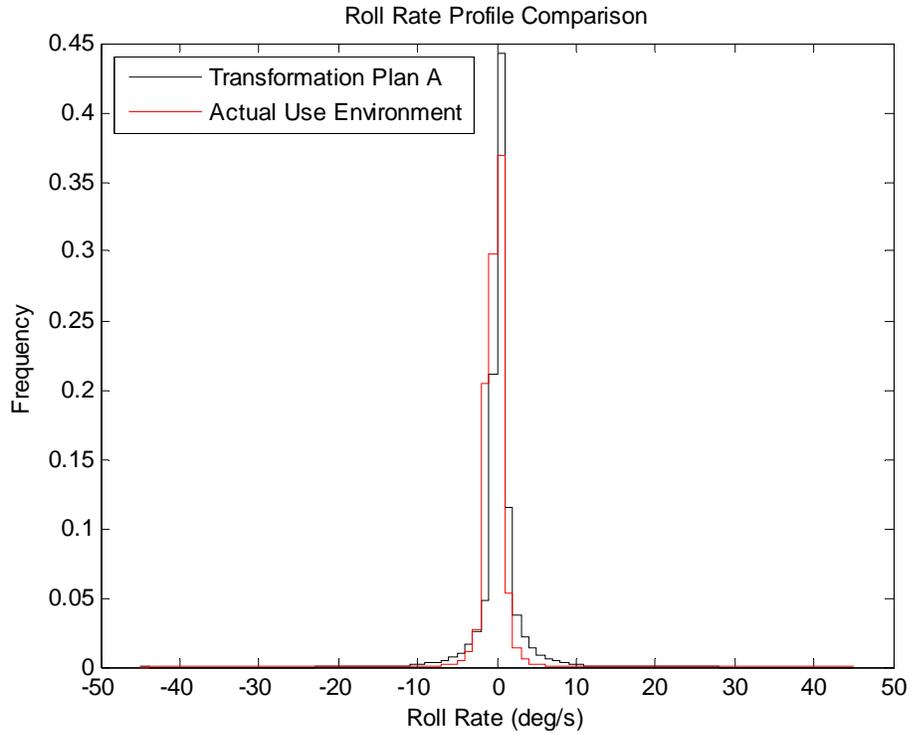


Figure 48. Transformation Plan A HMMWV roll rate profile comparison.

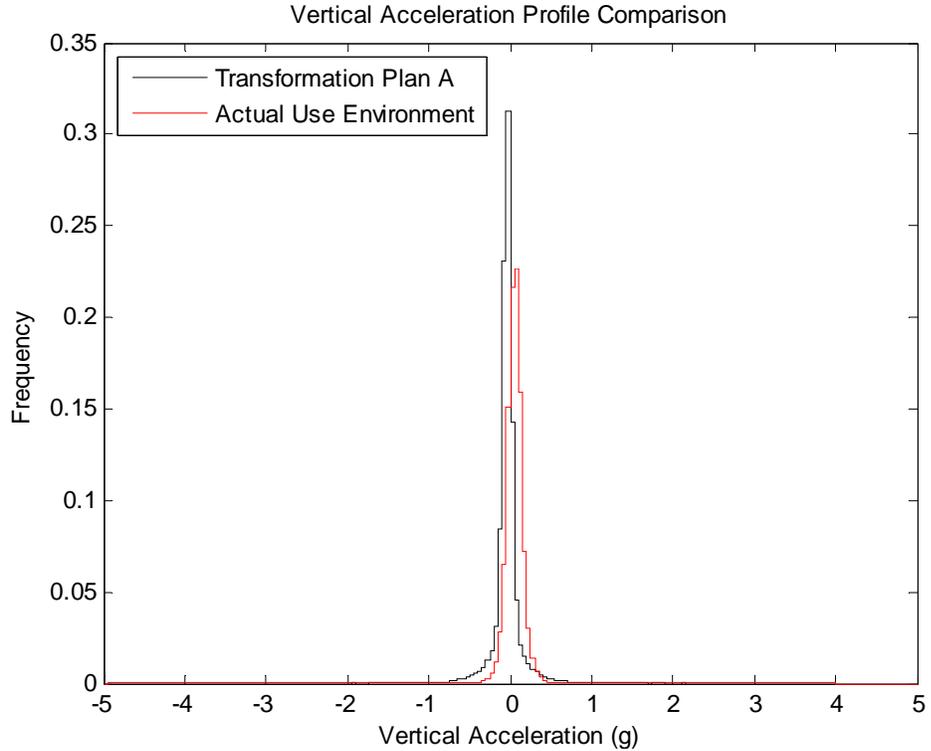


Figure 49. Transformation Plan A HMMWV vertical acceleration profile comparison.

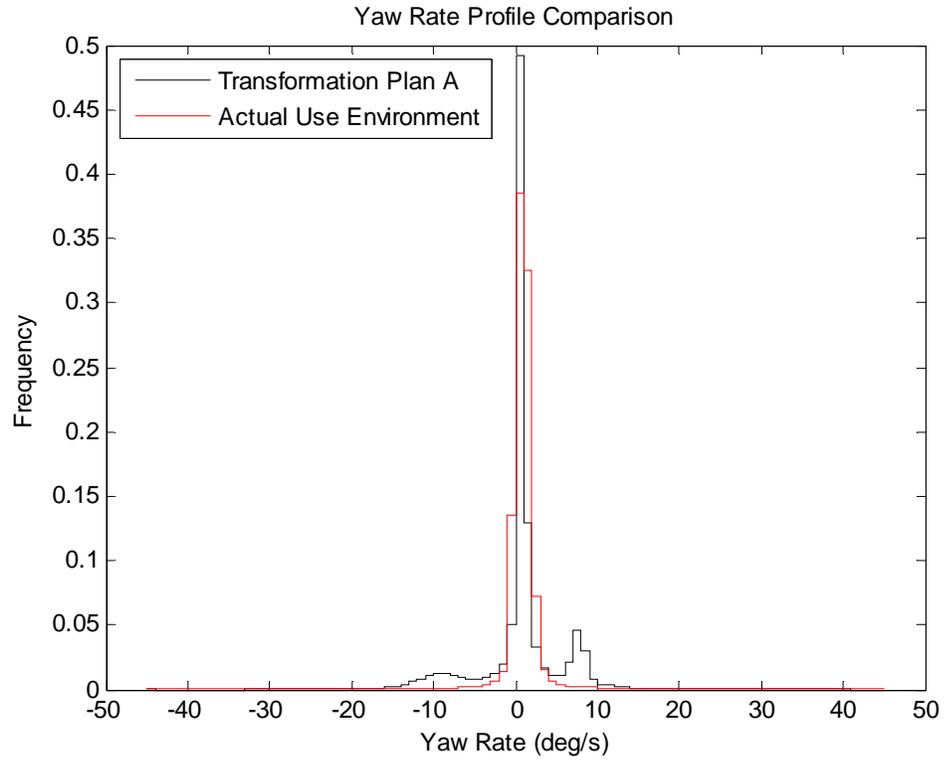


Figure 50. Transformation Plan A HMMWV yaw rate profile comparison.

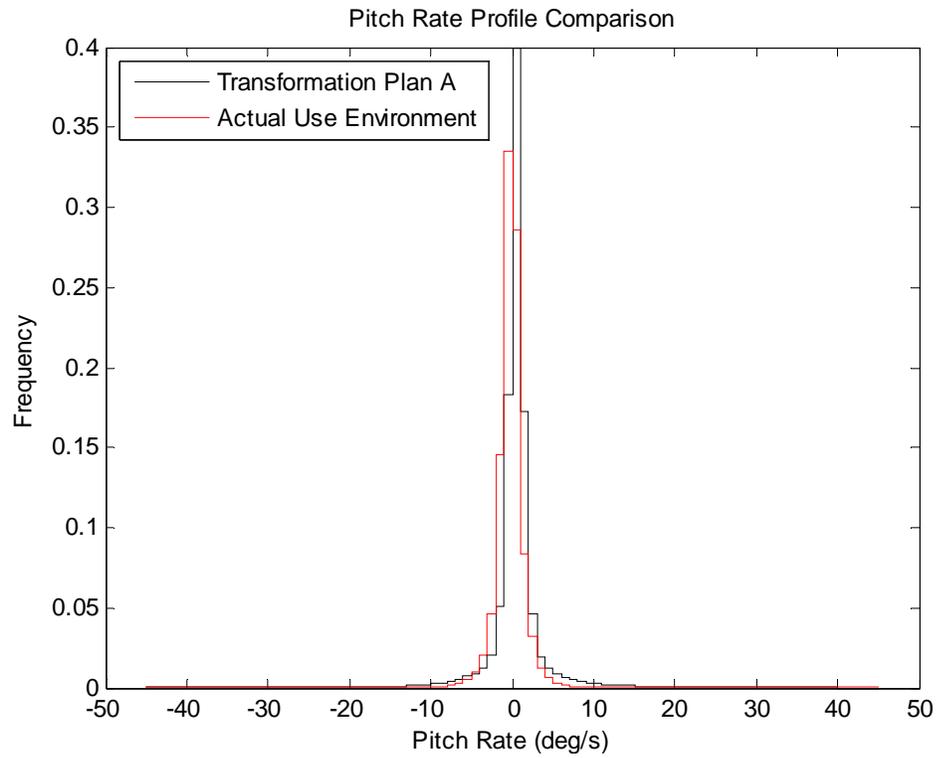


Figure 51. Transformation Plan A HMMWV pitch rate profile comparison.

From the histograms above, the remaining data channels all appear to be highly correlated to their actual use environment profiles. From visual inspection the vertical acceleration profile seems to have the largest discrepancies from its actual use environment. The results from these plots will be discussed further in Section 6.4.

6.3.2 Phase 2 Results

Approximately three days were required to alter the M915 optimization algorithm in order to produce the road course test matrix shown above in Table 17 for Transformation Plan C-1 in phase 2. The Decision Community previously requested that the road course test matrix be optimized for the road speed data channel. The data was obtained from the EUDB and inserted into a new Matlab file copied from the M915 optimization file as separate vectors for each road course including the actual use environment data from OIF. The single objective optimization algorithm was run and a resulting time frequency solution vector for each road course weight was created. The time frequency weighting vector was then converted into a distance percentage weighting vector. Finally, with a road course test matrix in its proper format, the same data channel histogram comparisons could be made. The histograms are shown below in Figures 52 through 56.

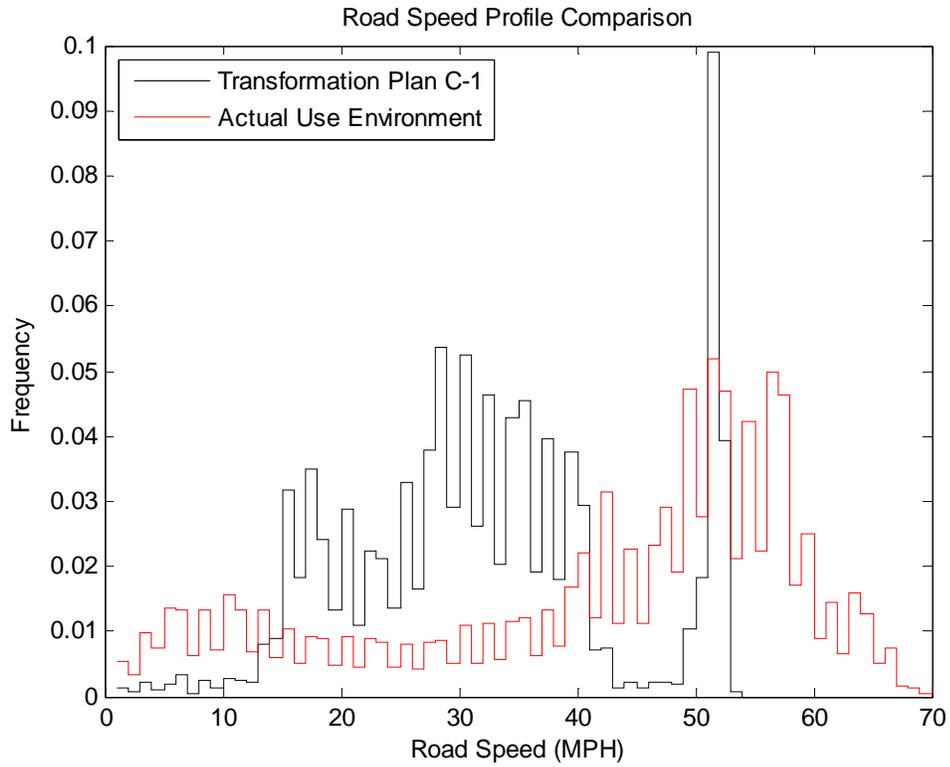


Figure 52. Transformation Plan C-1 HMMWV road speed profile comparison.

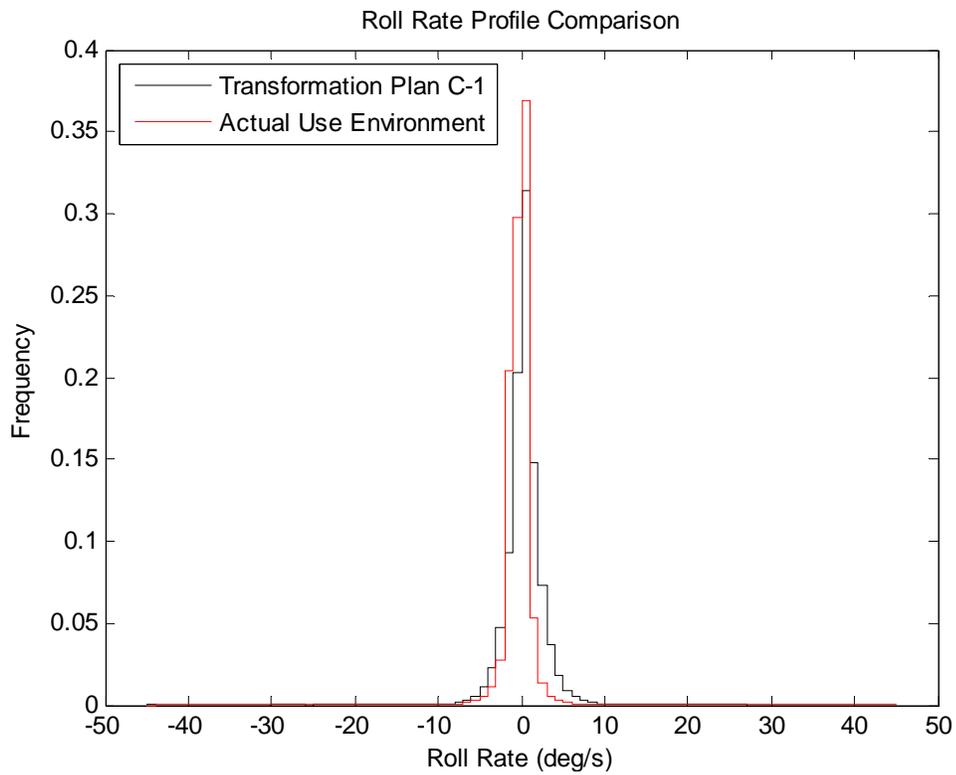


Figure 53. Transformation Plan C-1 HMMWV roll rate profile comparison.

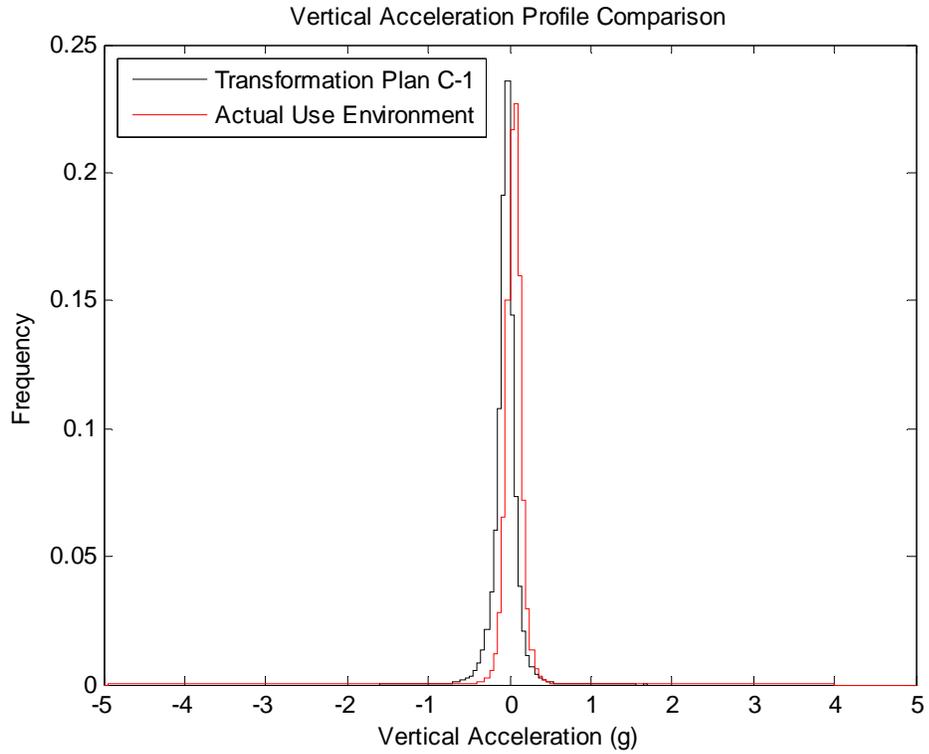


Figure 54. Transformation Plan C-1 HMMWV vertical acceleration profile comparison.

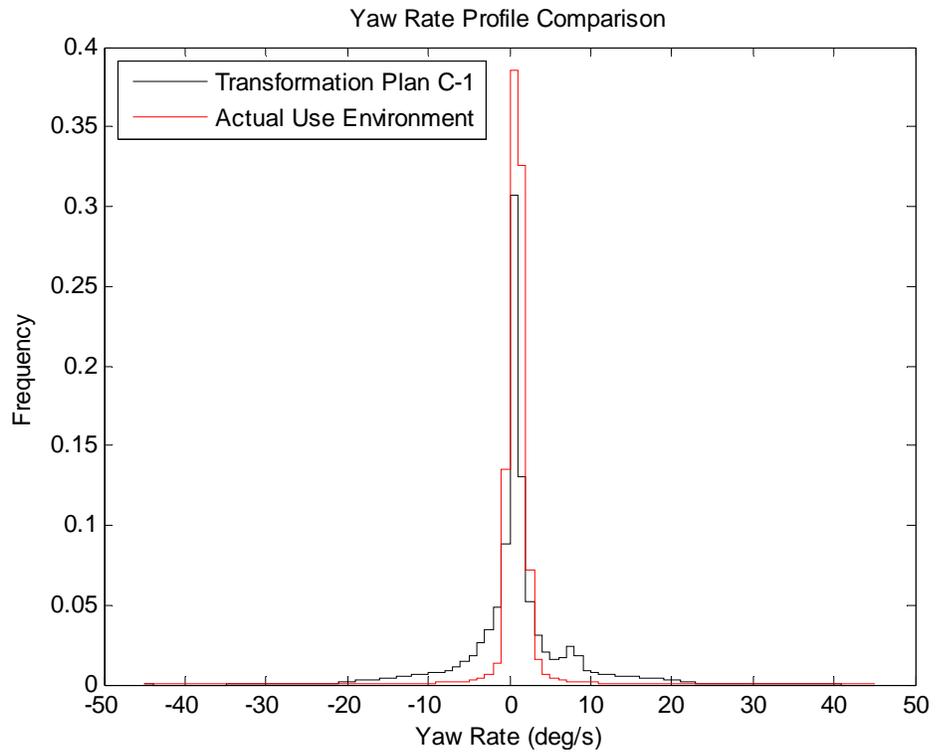


Figure 55. Transformation Plan C-1 HMMWV yaw rate profile comparison.

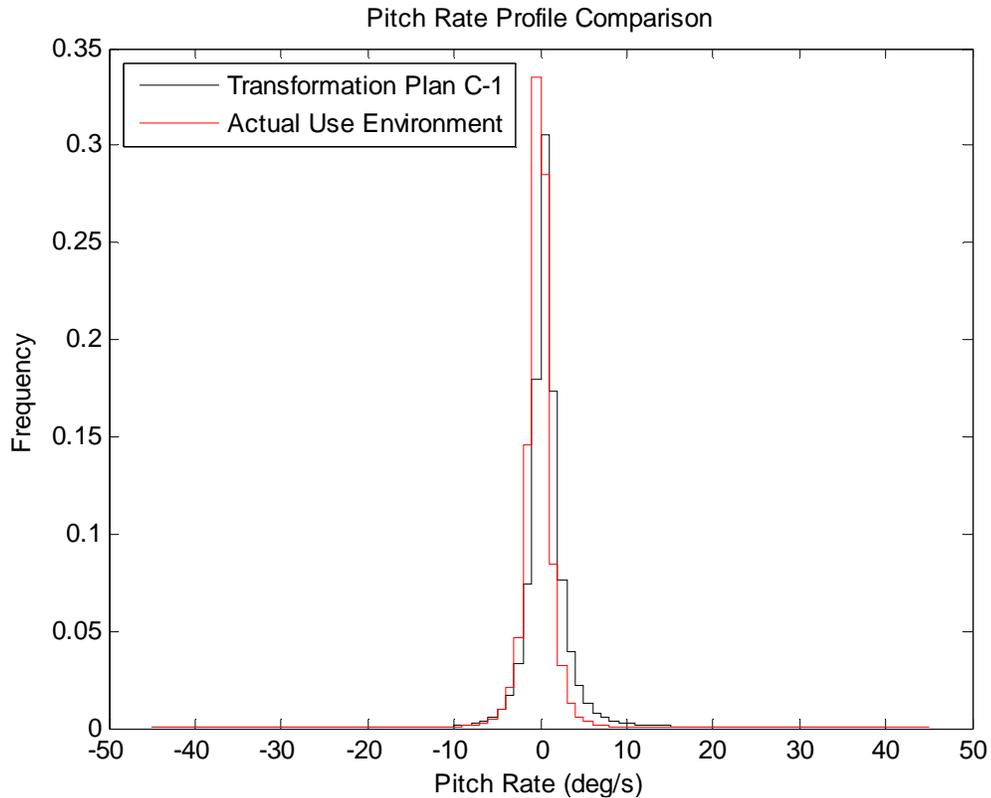


Figure 56. Transformation Plan C-1 HMMWV pitch rate profile comparison.

Compared to the road speed histogram comparison for Transformation Plan A, the histograms in the Transformation Plan C-1 road speed profile comparison appear to be much more similar in scale though there is still little distinguishable correlation between the two plots. Visual inspections of the remaining data channel comparisons reveal little change from that of Transformation Plan A results. An in-depth analysis will be made in Section 6.4.

6.3.3 Phase 3 Results

The last phase of the M1114 HMMWV test project required a multi-objective optimization for the road course test matrix based on Transformation Plan C-2. Only minor additions and changes were required to transform the M915 multi-objective optimization Matlab file into the HMMWV multi-objective optimization algorithm. The

process required approximately four days to complete the conversion and to produce a set of feasible results from a Pareto curve. The Decision Community decided before hand that the second data channel to be optimized was roll rate. With a working Matlab algorithm, a Pareto curve was established providing a range of possible solutions to the Decision Community.

Matlab initially produced a road speed and roll rate Pareto curve that was not to scale. The plot was then bounded to provide an evenly scaled Pareto curve. The unscaled and properly scaled Transformation Plan C-2 Pareto curves are shown below in Figures 57 and 58 respectively. In both plots, the chosen Pareto solution is highlighted.

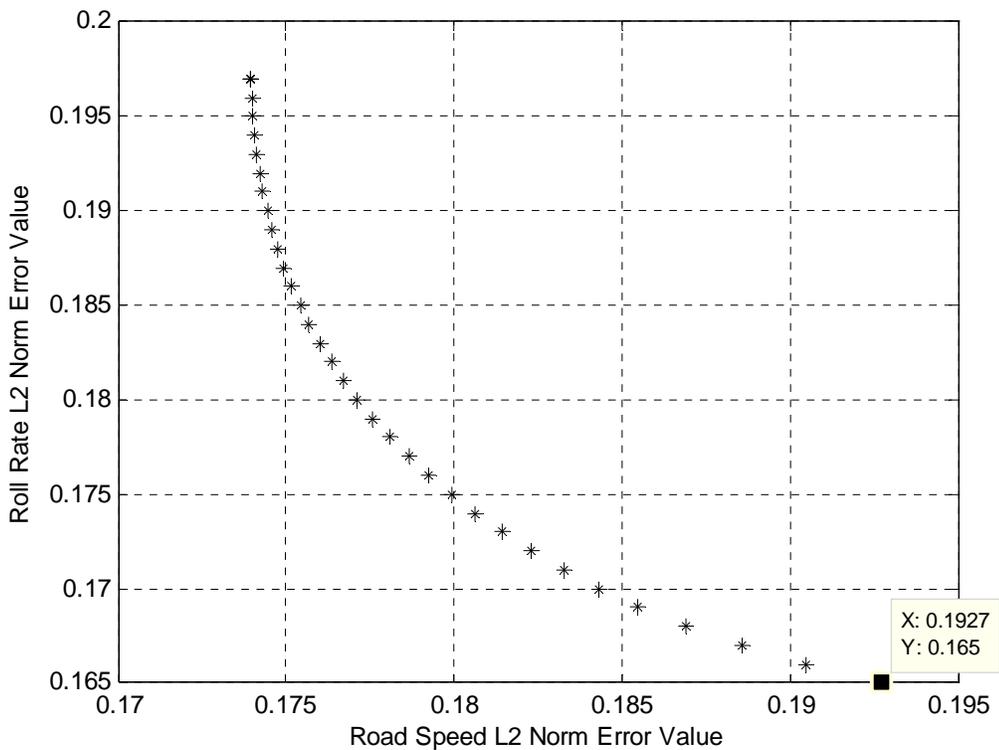


Figure 57. Unscaled HMMWV Transformation Plan C-2 Pareto curve.

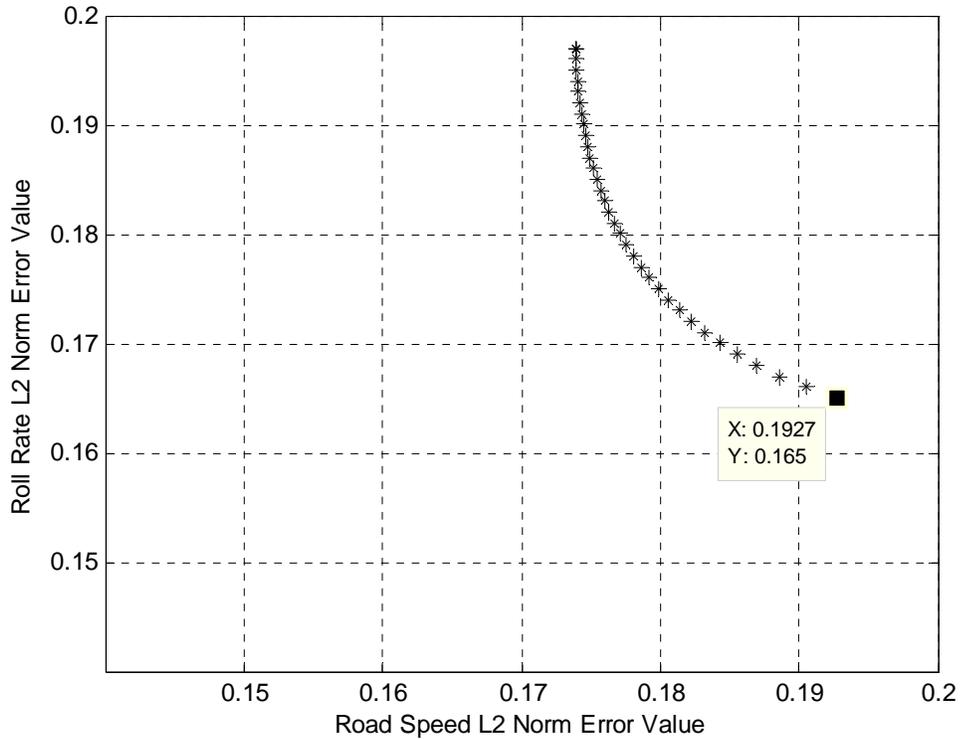


Figure 58. Properly scaled HMMWV Transformation Plan D Pareto curve.

ATC presented the results of Transformation Plan C-2 including the above Pareto curves to the Decision Community in order to facilitate a decision on the final road course test matrix. ATC determined that the L2 Norm error value for the road speed and the roll rate data channels provided a wide range for tradeoffs. The roll rate Pareto point error values varied slightly more, ranging from 0.165 to 0.197, while the road speed Pareto point error values ranged from 0.174 at the lowest and 0.193 at the highest. Upon inspection of the properly scaled Pareto curve and after discussing the results, the Decision Community decided to choose a compensating solution favoring the roll rate data channel, the point is highlighted in the above Figures. The decision was based on the rationalization that, in light of Transformation Plan C-1, the roll rate data channel retained higher importance for this phase and because the road speed L2 Norm error was within acceptable limits. The frequency weighting vector corresponding to the desired

Pareto point was then obtained and converted into a distance percentage weighting vector for the road course test matrix, as shown above in Table 18.

The Transformation Plan C-2 road course test matrix was then used to create a synthesized test profile. The synthesized test profile was then compared to the actual use environment for the road speed, roll rate, vertical acceleration, yaw rate, and pitch rate data channels. These comparison histograms are shown below in Figures 59 through 63.

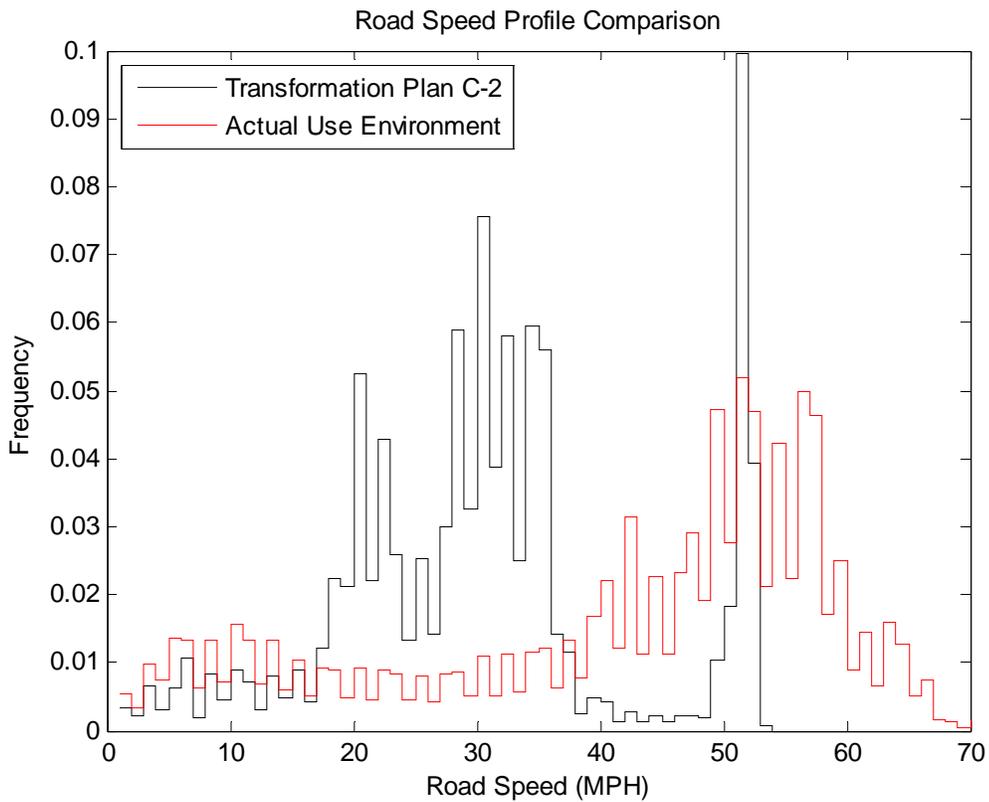


Figure 59. Transformation Plan C-2 HMMWV road speed profile comparison.

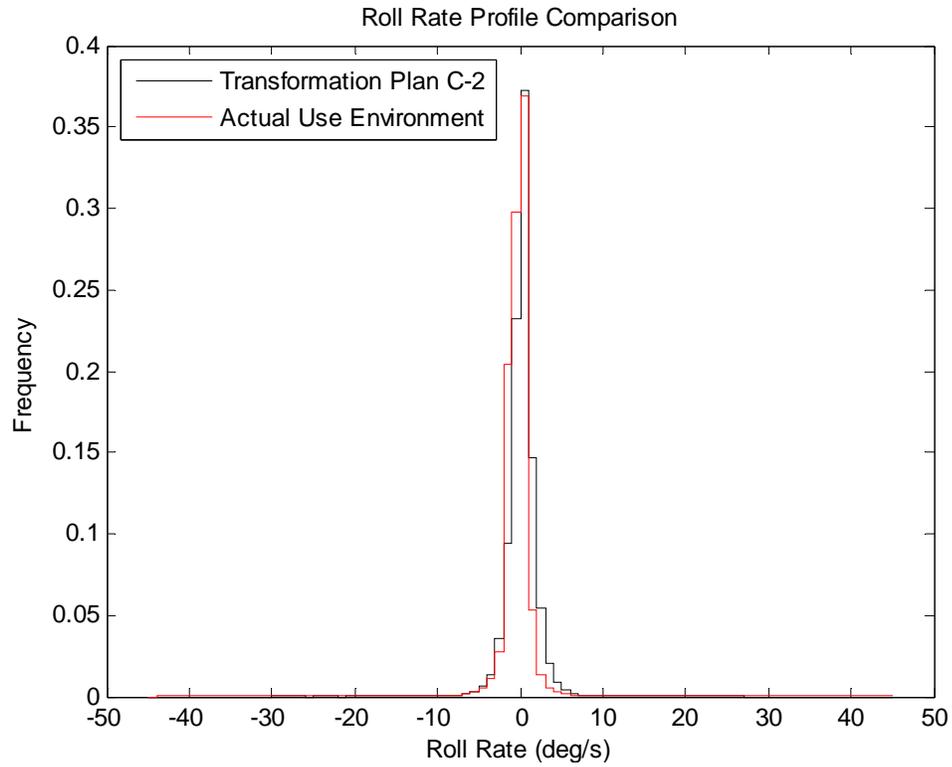


Figure 60. Transformation Plan C-2 HMMWV roll rate profile comparison.

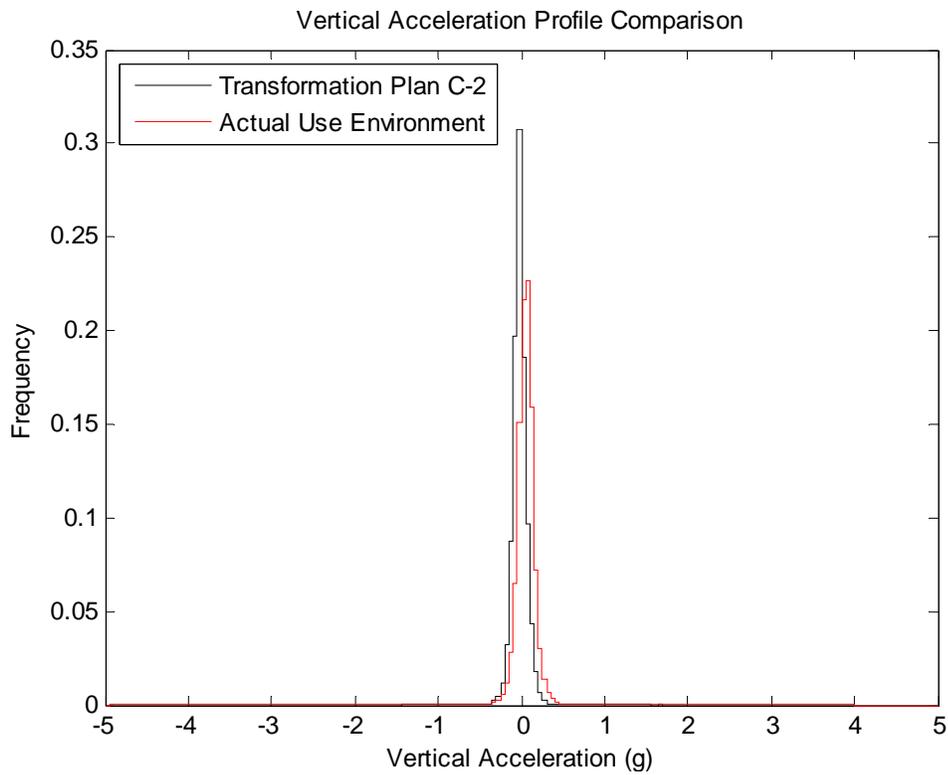


Figure 61. Transformation Plan C-2 HMMWV vertical acceleration profile comparison.

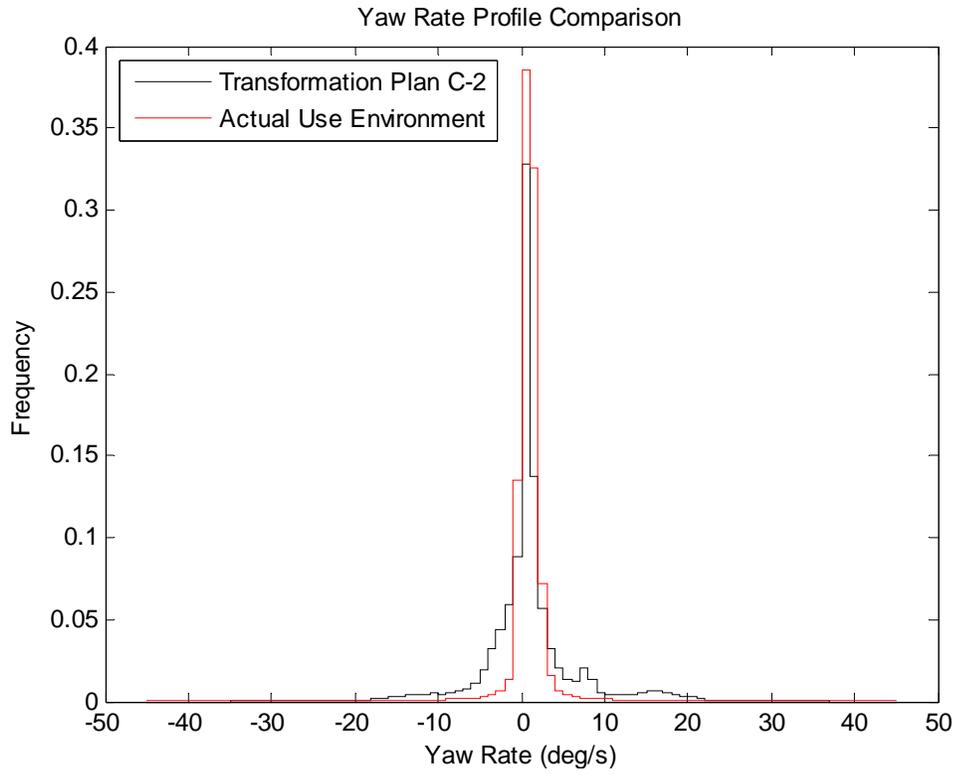


Figure 62. Transformation Plan C-2 HMMWV yaw rate profile comparison.

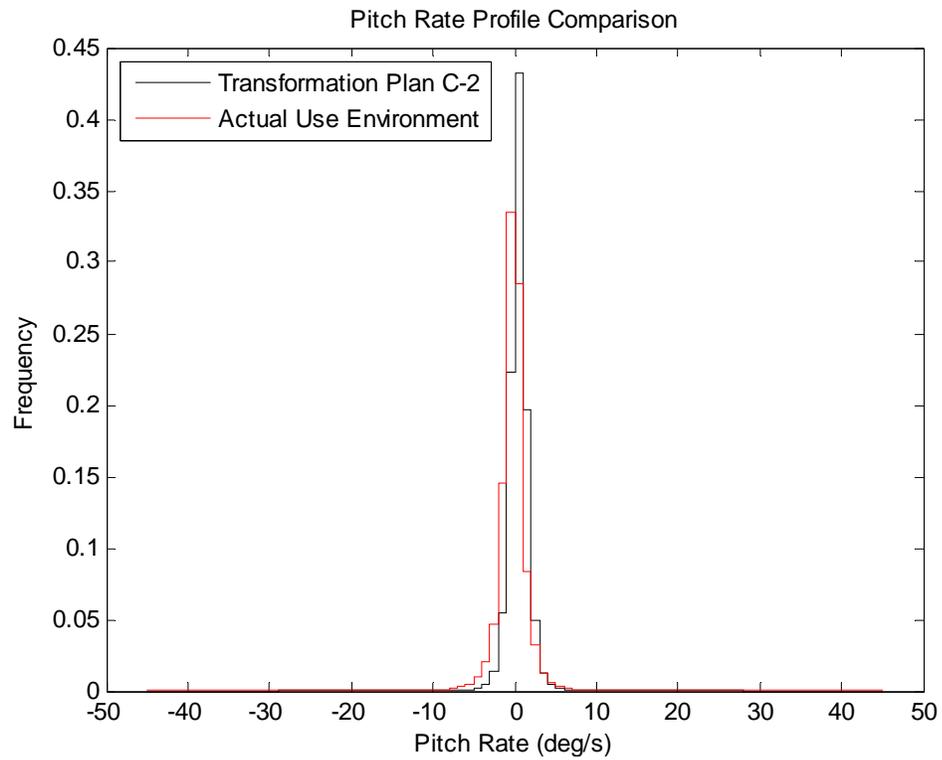


Figure 63. Transformation Plan C-2 HMMWV pitch rate profile comparison.

Upon visual inspection of the above comparison histograms nothing could readily be conferred regarding Transformation Plan C-2's performance in comparison to Plan A and Plan C-1. The road speed profile comparison remained uncorrelated. The ATC course roll rate profile looks highly correlated to its actual use profile but not significantly different from Plan A or C-1 plots. The remaining data channels appear to be sufficiently correlated to their actual use environments, though in-depth analyses will be conducted in Section 6.4.

A final plot was generated comparing the performance of each data channel to the Pareto points obtained in the optimization and shown above in Figures 57 and 58. The new comparison plot is shown below in Figure 64. The x-axis represents Pareto points 1 through 36, and are equivalent to the y-axis objective function values (roll rate L2 Norm error) found on the Transformation Plan C-2 Pareto curve. As a result, the roll rate error trend is linear in Figure 64.

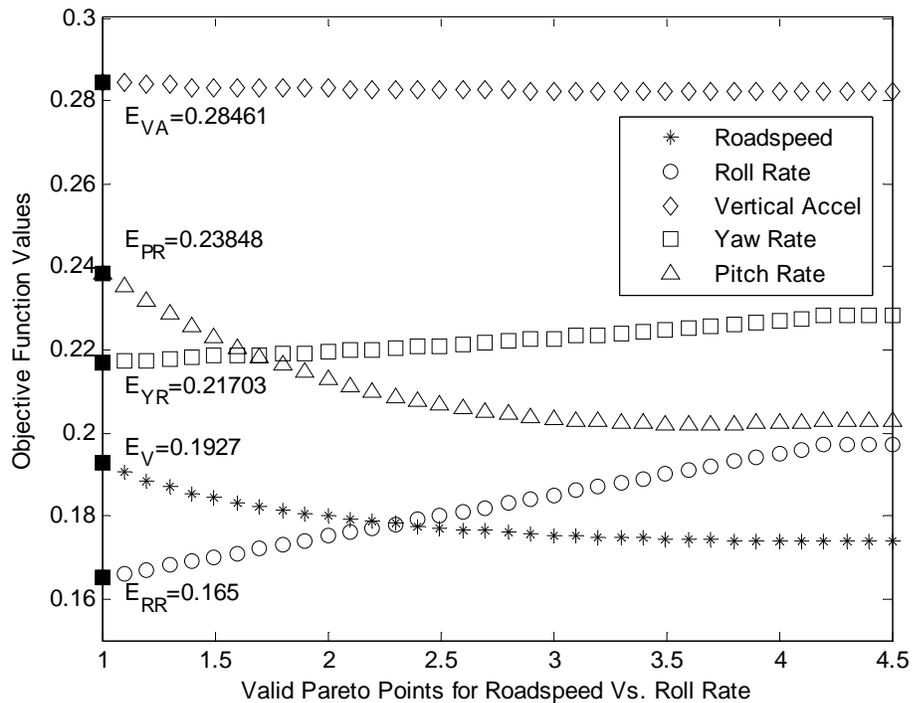


Figure 64. Data channel performance comparison plot for Pareto points.

Inspection of the comparison plot reveals that the road speed and roll rate data channels, as well as the pitch rate and yaw rate data channels, provide very distinctive trade-off characteristics. In addition, road speed and pitch rate errors follow similar decreasing polynomial trends while yaw rate and roll rate errors follow similar increasing linear trends. Incorporating either of these two sets in a multi-objective optimization would likely result in little to no tradeoffs in this range of error values. The vertical acceleration error is relatively constant through out the range of Pareto solutions and retains the highest error values of the five data channels. While for the HMMWV, the road speed data channel does not maintain a significantly lower E value than the remaining data channels, for the above range of error values both roll rate and road speed are guaranteed to be the best performing data channels. In Section 6.4 actual quantitative indices will be analyzed to determine Transformation Plan C-2's performance and relevancy.

6.4 Transformation Plan Performance Analysis

Performance metrics were employed in order to explicitly compare the advantages and disadvantages of each transformation plan for the M1114 HMMWV test. The performance metrics can be dichotomized into two groups: error-related and effort-related indices. The following error-related metrics were utilized: correlation coefficient (R), and the L2 Norm error value (E). The following effort-related metrics were used: cost to implement transformation plan, number of iterations required for satisfactory road course test matrix, time to implement transformation plan, expertise required, effort required, and customer satisfaction with results. Considering all of the metrics together

provides a better understanding of the tradeoffs for each transformation plan even though some metrics can be highly subjective. The ultimate goal is to provide guidelines to help decision makers early in a military system’s acquisition process determine which transformation plan is most beneficial for the particular set of circumstances.

6.4.1 Error-related Performance Indices

The two error-related performance indices used were the correlation coefficient and the L2 Norm error objective function value. These performance measures are discussed in depth in Section 5.4.1. The correlation coefficient provides a rough estimate for the accuracy of the road course test matrix compared to the actual use environment profile taken from vehicles supporting OIF and obtained through ATC’s EUDB. The L2 Norm error provides a more thorough and sophisticated comparative analysis of the dependence and accuracy of the different sets of data in each transformation plan. Correlation coefficient and L2 Norm error value results for the M1114 HMMWV test are provided below in Table 19.

		M1114 HMMWV Transformation Plan Performance Metrics									
		Road Speed		Roll Rate		Vertical Acceleration		Yaw Rate		Pitch Rate	
Transformation Plan		R	E	R	E	R	E	R	E	R	E
A		0.3441	0.3039	0.9175	0.2052	0.6424	0.3451	0.8812	0.2496	0.8756	0.2320
C-1		0.1358	0.1740	0.9302	0.1973	0.7228	0.2823	0.9373	0.2280	0.9000	0.2029
C-2		0.0887	0.1927	0.9468	0.1650	0.7622	0.2846	0.9334	0.2170	0.8885	0.2385

Table 19. Correlation Coefficient and L2 Norm error value results from M1114 HMMWV transformation plans.

In Transformation Plan A, the roll rate, yaw rate, and pitch rate data channels are significantly correlated to that of their actual use environment profiles. The vertical acceleration data channel is marginally correlated with its actual use profile with an R

value of 0.6424, but the Transformation Plan A road speed profile does not provide any adequate correlation to the road speed profile obtained from in theatre. The roll rate profile deviated the least from its actual use profile, at 0.2052, in Plan A with regards to the L2 Norm error. Pitch rate and yaw rate profile E values are slightly higher than the roll rate data channel at 0.2320 and 0.2496, respectively. The road speed error was higher still with a value of 0.3039, and the vertical acceleration retained the highest E value of 0.3451.

Transformation Plan C-1 was optimized for the road speed data channel. As a result, the road speed L2 Norm error has decreased approximately 43% to 0.1740 retaining the lowest error among the selected data channels. In like fashion, the errors of the remaining data channels have also decreased though not to the extent as which the road speed had descended. The roll rate profile retained the second lowest error, at 0.1973, the pitch rate the third lowest, at 0.2029, the yaw rate the fourth lowest at 0.2280, and the vertical acceleration retained the high error again at 0.2823.

The roll, pitch, and yaw rates retained excellent correlation to their actual use profiles in Transformation Plan C-1. The R value for vertical acceleration rose to 0.7228, firmly establishing the data channels correlation to its actual use profile for the Plan C-1 road course test matrix. As seen before in the M915 truck tractor implementation, while the road speed error has decreased significantly due to the optimization, its correlation has also decreased as well to nearly no distinguishable linearity between ATC profile data and that of the OIF data.

The goal of Transformation Plan C-2 was to optimize the roll rate data channel along with the road speed data channel. From Section 6.3.3, we learned that road speed

and roll rate experience significant tradeoffs within the range of Pareto solutions. In Transformation Plan C-2, the road speed error, 0.1927, has increased from the Transformation Plan C-1 error, 0.1740, because the Decision Community chose a Pareto solution which favored the roll rate data channel, though the road speed error remains significantly lower than the Transformation Plan A error, 0.3039. In Transformation Plan C-2, the roll rate error has become the lowest, at 0.1650. The vertical acceleration and pitch rate errors have increased from their Plan C-1 values, while the yaw rate error has decreased very little. The yaw rate error has become the third lowest, at 0.2170, while the pitch rate error rose to fourth lowest, at 0.2385. The vertical acceleration E value remains firmly the highest error.

The correlation coefficient for road speed has continued to decrease in Transformation Plan C-2 despite the increase in error, confirming the independence of the E and R measures. Despite the raise in the vertical acceleration error, the R value rose for Plan C-2, confirming sufficiently correlated profiles. While the yaw and pitch rate correlation coefficients have decreased slightly, these data channel profiles remain significantly correlated with their actual use profiles. Finally the roll rate R value has increased in value, retaining the highest degree of linear relation to its actual use profile, at 0.9468.

Overall trends in the quantitative performance data can best be seen in a series of plots. For each data channel, R and E value trends have been graphed from Transformation Plan A through Transformation Plan C-2. These plots are shown below in Figures 65 and 66.

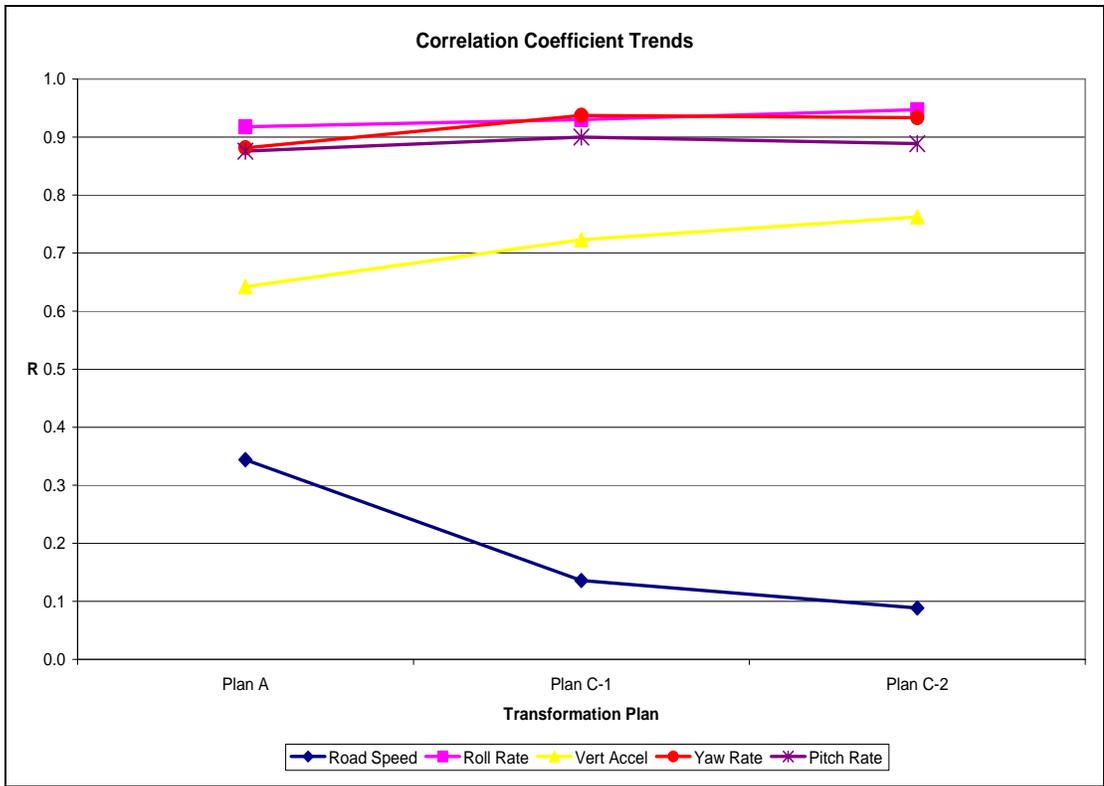


Figure 65. M1114 HMMWV correlation coefficient trends.

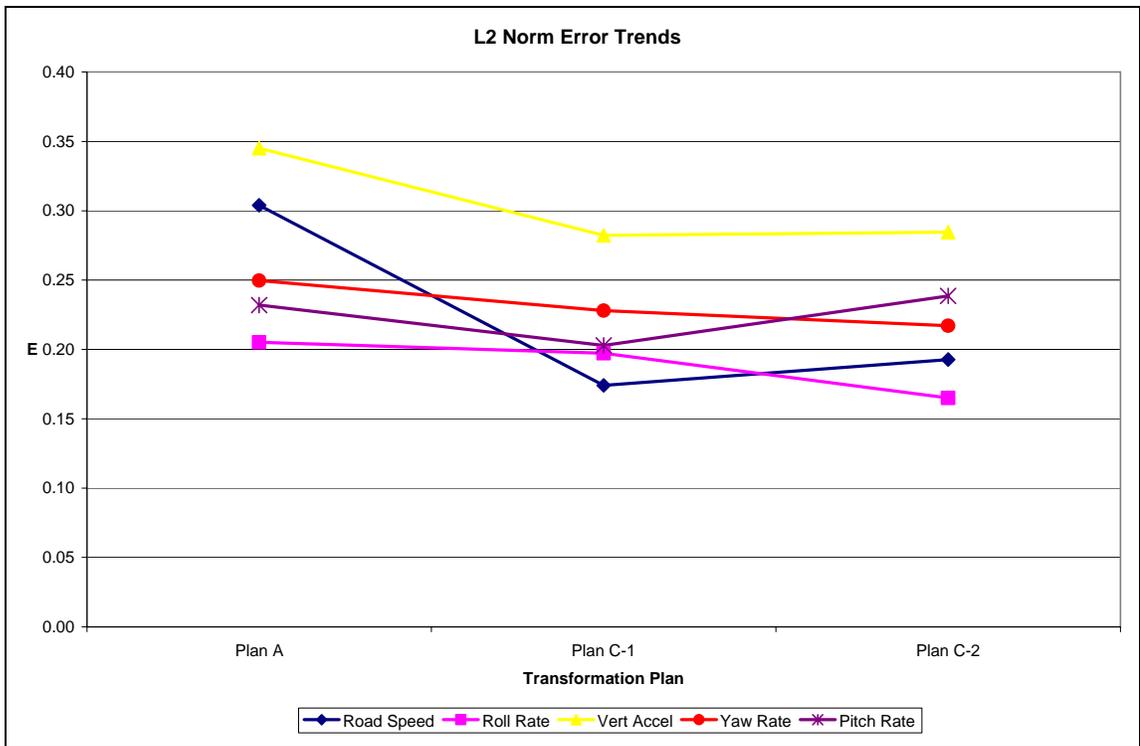


Figure 66. M1114 HMMWV L2 Norm error value trends.

The road speed data channel correlation coefficient steadily regresses from Transformation Plan A to Plan C-2 ultimately ending in a very low positive correlation coefficient, as seen visually in Figure 64. The road speed L2 Norm error decreases significantly from Plan A to Plan C-1; though an increase in error for Transformation Plan C-2 causes the road speed data channel to no longer retain the lowest error, the data channel's error remains small.

The roll, pitch, and yaw rate data channels were found to be significantly correlated to their goal profiles throughout each transformation plan. In addition, they shared very similar R trend lines. The L2 Norm errors for the three data channels started out relatively low in Transformation Plan A, and all decreased similarly for Transformation Plan C-1. However, the pitch rate error diverged from the still decreasing roll and yaw rate errors in Transformation Plan C-2.

The vertical acceleration correlation coefficient steadily increased from marginal correlation in Transformation Plan A to sufficient correlation in Plan C-2, the R value reaching acceptable limits in Transformation Plan C-1. The vertical acceleration L2 Norm error despite a significant decrease from Plan A to Plan C-1 retained the highest error among the remaining data channels for the duration of the HMMWV test. The data channel's error increased slightly from Transformation Plan C-1 to Plan C-2.

In addition to the correlation coefficient and L2 Norm error-related function metrics, effort-related performance indices such as the cost to implement the transformation plan and the iteration count needed to determine an acceptable result were also considered for the performance analysis.

6.4.2 Effort-related Performance Indices

Cost of implementation and effort required are subjective performance measures because it was difficult to keep exact accounts of all costs and to quantify effort. The cost of implementation primarily consists of the labor costs to determine and publish the DTP which includes the road course test matrix used for endurance or reliability testing. Implementation costs can also include travel costs for Decision Community meetings and material or equipment costs for necessary software or hardware specific to a particular transformation plan requirement. A Gantt chart showing the schedule and costs for implementing the transformation plans for the HMMWV are shown below in Figure 67. Table 20, below, provides a breakout of costs and iterations required for each transformation plan.

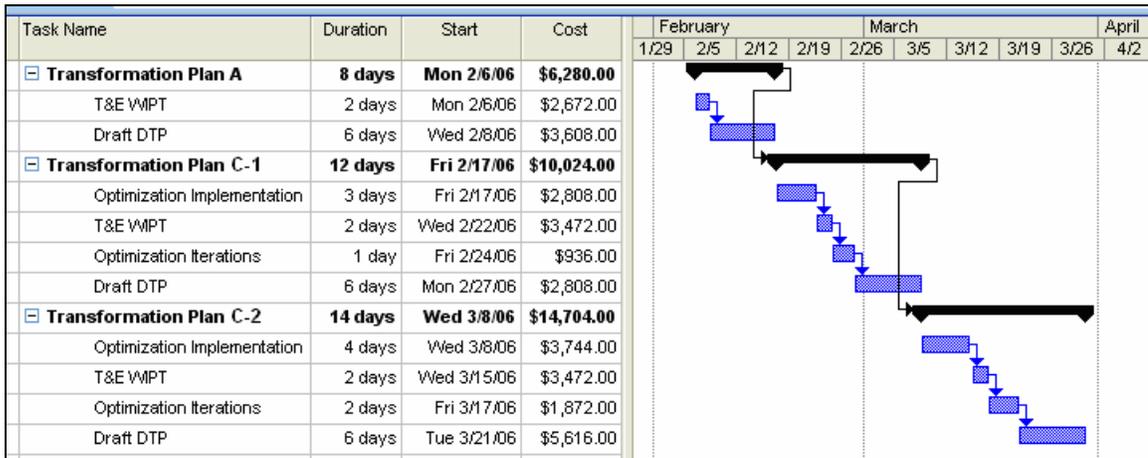


Figure 67. Gantt chart of HMMWV Transformation Plan implementation costs.

		Transformation Plan		
		A	C-1	C-2
Recurring Costs	Test Director	\$4,144	\$8,400	\$13,100
	Field Engineer	\$1,336	\$0	\$0
	Instrumentation Engineer	\$0	\$0	\$0
	Driver	\$0	\$0	\$0
	Travel	\$800	\$1,600	\$1,600
	Fuel	\$0	\$0	\$0
	Instrumentation	\$0	\$0	\$0
Initial Setup Costs	Test Director	\$0	\$0	\$0
	Field Engineer	\$0	\$0	\$0
	Instrumentation Engineer	\$0	\$0	\$0
	Driver	\$0	\$0	\$0
	Travel	\$0	\$0	\$0
	Fuel	\$0	\$0	\$0
	Instrumentation	\$0	\$0	\$0
Recurring Costs		\$6,280	\$10,000	\$14,700
Initial Setup Costs		\$0	\$0	\$0
Actual Total		\$6,280	\$10,000	\$14,700

Table 20. HMMWV Transformation Plan implementation cost breakdown.

Implementation of Transformation Plan A for the HMMWV did not change from that of the M915 truck tractor test. Transformation Plan A did not require any special equipment or materials. During Plan A, a two-day Temporary Duty (TDY) travel for two ATC employees, one engineer and one test director, to attend a T&E WIPT to decide on a final DTP was required. The labor cost required to publish an accurate draft of the DTP for Plan A was relatively little, it was completed by one test director in 6 working days. The road course test matrix required one iteration for approval. Transformation Plan A required approximately \$6,300 in labor costs to implement.

Implementation of the M1114 HMMWV Transformation Plans allowed additional data points to be gathered on recurring costs for the two transformation plans utilizing optimization steps. The cost of implementation for Transformation Plan C-1 was about

\$3,700 more than Plan A and approximately \$1,000 less than originally estimated in the M915 implementation. The implementation of Transformation Plan C-1 for the M1114 HMMWV required no material or equipment costs. Travel costs included a two-day TDY trip for two ATC employees. Labor costs included one test director for the duration of the optimization process and DTP publishing efforts. The Plan C-1 DTP publishing phase did not change from that in the M915 implementation. The Plan C-1 DTP publishing phase still required more time than in Plan A while the Decision Community determined a preferred data channel for the optimization and because standard pre-formatted DTPs could not be used. Overall, Transformation Plan C-1 required approximately 12 working days in order for an approved draft DTP to be published. Only one road course test matrix iteration was required before an approved matrix was decided upon. Overall, an estimated \$10,000 was spent implementing Transformation Plan C-1 for the M1114 HMMWV.

The implementation of Transformation Plan C-2 for the M1114 HMMWV also provided valuable insight regarding the recurring costs of more complex transformation plans. Plan C-2 cost approximately \$4,700 more than Plan C-1, and approximately \$8,400 more than Plan A to implement. However, when compared to original estimates in the M915 truck tractor implementation, the HMMWV Plan C-2 implementation was \$2,000 less. Like Plan C-1, no additional materials or equipment were needed, these costs were sunk during the M915 implementation phase, because all of the data for all of the vehicles was captured at one time and rolled into the first test's costs. Plan C-2 required a two-day TDY travel for one engineer and one test director from ATC. Two test directors remained on the project in order to optimize the multi-objective road course

test matrix. The Plan C-2 draft DTP was approved in 14 working days after initiation. Transformation Plan C-2 required the most road course test matrix iterations with three changes before approval. An estimated \$14,700 was spent implementing Transformation Plan C-2 for the M1114 HMMWV.

Implementation of these three transformation plans for the M1114 HMMWV provided valuable insight on the nature or providing such test plan options to PMs and other customers who repeatedly test conventional or long-standing vehicle systems. While previously untested systems would follow cost and effort trends seen in the M915 truck tractor Transformation Plan C-1 implementation, testing of vehicle types that presently exist in the U.S. Army's fleet but are being operated in new and different environments would likely follow the cost and effort trends found in the HMMWV transformation plan implementations. While small government test contracts might not have the ability to afford Plans C-1 or C-2, any transformation plan proposed in this research is certainly affordable for the average test project budget, most times between \$90,000 and \$300,000, which comes to ATC. Transformation Plan A requires no initial setup cost and will always maintain the lowest implementation cost due to the short time line and minimal labor involvement. Though, recurring Plans C-1 and C-2 are not significantly higher, only requiring at most and estimated \$8,500 and an additional 6 working days.

6.4.3 Transformation Plan Performance Summary

The three major performance indices outlined previously in Section 4.6, solution quality, cost to implement, and time required, were discussed in depth for the M1114

HMMWV in the above sections. A table was created to provide a concise summary of the performance results. The information is provided below in Table 21.

		Transformation Plan		
		A	C-1	C-2
Solution Quality	Correlation	Low, Irregular	High, Irregular	High, Irregular
	Error	High, Irregular	Very Low	Very Low, Performance Tradeoffs
	Confidence in relevance	Low	High	Very High
Cost	Investment	None	Low	Low
	Continuation	Very Low	Medium-Low	Medium
	Effort	Very Low	Medium-Low	Medium
	Variation	Very Low	Irregular	Irregular
Time	Investment	None	Low	Medium-Low
	Continuation	Very Low	Medium-Low	Medium

Table 21. HMMWV Transformation Plan performance results summary.

While many features of these transformation plans are unchanged, a few cost and time features of Plans C-1 and C-2 have been altered. The effort and investment costs and investment and continuation time requirements have been reduced for Plans C-1 and C-2 to reflect the findings from the M1114 HMMWV transformation plan implementations. Because the M1114 HMMWV test provided a clearer representation of a recurring test, the amended performance summary, Table 21, above represents most conventional system test projects while the M915 truck tractor performance summary, Table 15, in Section 5.4.3 represents prototype or previously unrecorded test projects. Based on the objective and subjective results from the implementation of Transformation Plans A, C-1, and C-2 for the M1114 HMMWV, the actual performance of the separate

plans differed from their expected performance as depicted in Figure 19 in Section 4.6. Figures 68 and 69, below, provide a high level illustration of the findings of this Chapter.

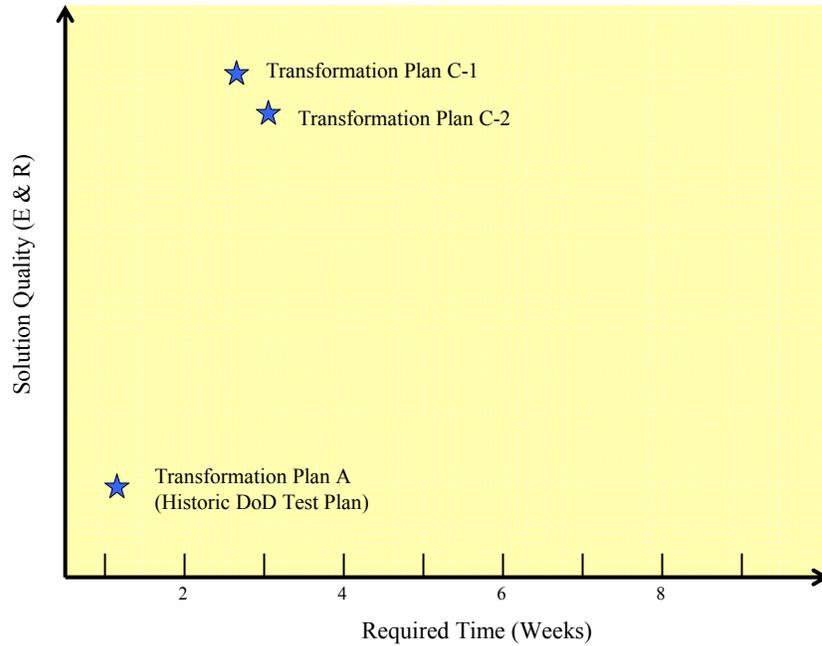


Figure 68. Actual time and solution quality trade-offs for three proposed HMMWV transformation plans.

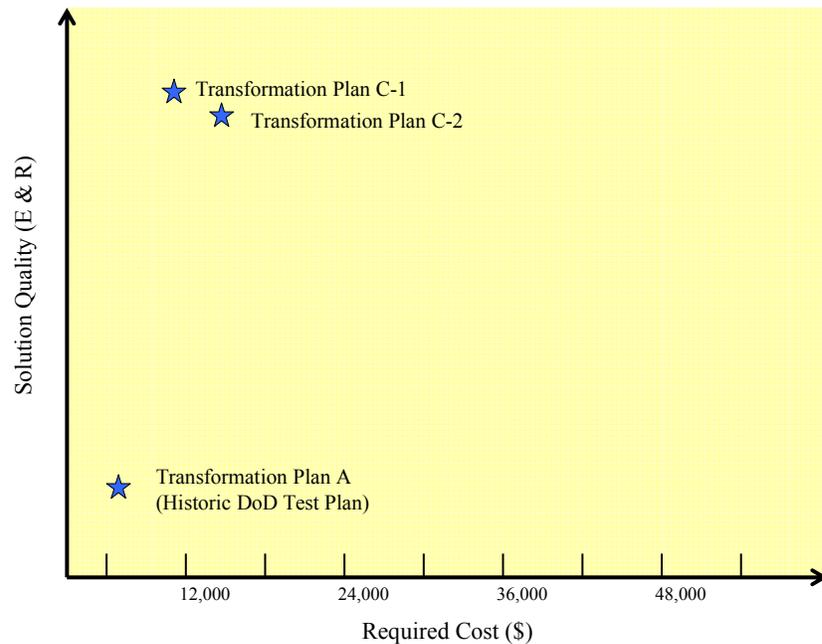


Figure 69. Actual cost and solution quality trade-offs for three proposed HMMWV transformation plans.

CHAPTER 7: SUMMARY AND CONCLUSIONS

This thesis attempts to aid military vehicle system representatives with design specific test strategies that have an increased relevance to current actual operating conditions while taking into account the PM's and the test center's abilities and constraints. A test's relevance often forms trade-offs with time, effort, and cost. By employing mathematical optimization techniques, exploring the wide array of options open to the PM, and weighing needs and desires against available data, time, and staffing, the PM or customer can more confidently choose the most relevant vehicle test plan that best suites his requirements and his constraints.

7.1 The Problem and a Solution

The rapid deployment of automotive systems has caused the Department of Defense test community and the Aberdeen Test Center in particular to reevaluate and redefine traditional test plans and practices in order to maximize the amount of valid and pertinent data obtained from shortened test schedules. However, the process of creating a detailed test plan can require significant time and effort. This process is called a transformation plan because it transforms information about customer requirements and operational data into a detailed test plan. ATC customers desire transformation plans that create highly relevant detailed test plans using the least amount of time and cost.

Unfortunately, test planning can become routine. Development programs simply reuse the detailed test plan that was used last time without investigating its relevance to new environments. This routine transformation plan reduces the time and effort involved but can lead to inappropriate test plans. Consider, for instance, using a test plan

developed soon after World War II for testing trucks that, sixty years later, will be driving not on the streets of European cities but instead on highways through Middle Eastern countryside.

To address this problem, a set of transformation plans were systematically developed that can be used to create highly relevant detailed test plans using the least amount of time and cost. The relative performance of these plans was evaluated as they were implemented for two common military vehicle systems. This work studied two specific cases: the M915 truck tractor and the M1114 HMMWV. A set of feasible transformation plans that are relevant to both cases were created. Both vehicle systems were soon to undergo automotive endurance testing at ATC, and, for both vehicles, data obtained from 30 days of operation in OIF was available in the EUDB.

The data available for each vehicle system was used in an optimization algorithm developed for two of the transformation plans. The optimization algorithm was used to mathematically determine optimized road course test matrices using both single and multi-objective optimization techniques by minimizing the L2 Norm error between the actual use data captured from OIF and ATC road course data for both vehicles. The M915 truck tractor road course test matrix was first optimized for a single channel, road speed, using Transformation Plan C-1, and then was optimized in combination with a second data channel, transmission temperature, in Transformation Plan C-2. In similar fashion, the M1114 HMMWV road course test matrix was optimized first for road speed relevance, and then in combination with the roll rate data channel for its two optimization transformation plans.

A third set of road course test matrices was created from Transformation Plan A for both vehicles. The transformation plans were then compared on the following objective and subjective performance metrics: the fit between the test plan and the operational conditions (measured using a correlation coefficient and an error measurement), the cost to implement the transformation plan, the computational effort, the time to execute the transformation plan, the expertise required, the effort required, and the customer's satisfaction with the results.

7.2 Conclusions

Automotive endurance or reliability testing is essential to the successful deployment of safe and effective military vehicular systems. As tactical and combat vehicles are designed for and by the U.S. Armed Forces, operating environment and reliability are fundamental pillars of the early design process. As the system reaches the prototype stage, developmental testing is required to prove the system concept and to discover weak aspects of the contractor's materials, manufacturing process, or the design itself. Test strategy or planning is of vital importance to successful developmental testing. In the sense of this research, a successful developmental test does not guarantee a system met certain criteria with few problems, rather it suggests that the test itself was an accurate representation of the vehicle's actual operating environment including all potential extremes the system might face.

Accordingly, this thesis centered on researching current vehicle test methods and evaluating them against newly developed test methods. The purpose of this investigation was to determine the best possible test methods applicable to automotive endurance

testing. As a result of this research, many conclusions can be drawn regarding the effectiveness of traditional test plans as well as new, optimization-based test plans. The first conclusion was that the testing community can easily implement new test planning processes based on objective data in addition to subjective opinion. This is evidenced by the ease with which relevant road course test matrices were developed for the M915 truck tractor and the M1114 HMMWV. For these plans vehicle data was needed, requiring an expenditure of resources such as time, effort, and money; however, the data was quickly and easily obtained due to ATC's level of expertise in this area. Once the basic single and multi-objective optimization algorithm was developed, the time needed to prepare a road course test matrix was significantly reduced, as is clear from the M1114 HMMWV Transformation Plans C-1 and C-2 implementation results. With a generalized working optimization model, only four days over the current transformation plan process are required to create an endurance test plan based solely on objective operating environment data rather than subjective human estimations.

The second conclusion that can be drawn from this research is that the vehicle data available drove the development of the optimization model. In the majority of situations in which optimization techniques are used to provide solutions to real technical problems, the process of optimization algorithm development begins with a problem statement, progresses next to objective function formulation, then a practical technique is chosen, and finally the data and necessary supporting equations are obtained to use in the finalized algorithm. The process could not be followed, however, in this research. The research began with data just obtained from OIF. Engineers were tasked to search for ways in which the new OIF data could be used. Once a problem area was identified, the

problem statement was generated. In our case, the objective functions could not be arbitrarily formed, they depended solely on the information that was at hand. The objective functions were thusly formed to be used specifically for the available discrete vehicle data. In similar fashion, the optimization technique was chosen and applied based on the constraints of the OIF and ATC data. This thesis has shown that optimization problems can be solved efficiently and effectively even in unorthodox ways. This fact should provide further impetus for engineers and researchers to consider using optimization practices for problems previously unconsidered because of uncommon or difficult circumstances.

A third conclusion stems from the importance of trade-offs when considering test plan solutions. Trade-off characteristics were most apparent during the Transformation Plan D implementation for the M915 truck tractor and the M1114 HMMWV. These two-objective optimization exercises both resulted in different but very interesting Pareto curves. The importance of Pareto curves were acknowledged, as they provided the PM and the Decision Community a means to deliberate over the true purpose and end result of developmental endurance testing. Such an active part taken in the testing process ultimately benefits the end user, the Soldier.

The difference in vehicle Pareto curves also showed how distinctive each vehicle type's mission is and how much that mission physically influences the vehicle itself. While the road speed relevance can easily be compensated by a high roll rate relevance, and vice versa, for the M1114 HMMWV, the OIF optimized M915 truck tractor test plan will always have more relevance to road speed than to transmission temperature or engine coolant temperature, because the road speed error is that much lower than the

others, as evidenced by their Pareto curves. Ultimately, in multi-objective optimization transformation plans, trade-off characteristics will have to be considered and important decisions made upon them.

A final conclusion that can be taken from this research is the importance of high-level system objectives optimization. The core of this research centers on the idea of customizable test strategies. Four transformation plans were researched and developed for this thesis because every test project is unique each with unique budgets, deadlines, priorities, missions, test criteria, governmental oversight, customers, end users, system functions, and stage of development. All of these considerations and many more, together, significantly affect the end result of the developmental test planning, execution, and evaluation process. While only four specific transformation plans were considered here, there are infinite varieties and solutions to this one problem; how to field a new automotive system with confidence in its performance and reliability. This research confirms that Decision Communities best serve this main objective by optimizing their particular test strategy. This is accomplished by actively considering and comparing their requirements, desires, and constraints with the test center's facilities, capabilities, and expertise and through discussion and the test center's professional guidance choosing the most relevant test plan given their constraints.

In general, these results show the extent to which a transformation plan impacts the end results of automotive developmental testing; determining the relevance the controlled test environment has to the actual operating environment. Utilizing mathematical optimization algorithms with discrete sets of data captured from both

environments can greatly improve the relevance of the developmental test, providing deliberate and objective substantiation to the transformation plan process.

7.3 Future Work

The ideas and propositions made in this thesis are the beginning of a long journey. Currently there are very few optimization models being implemented in testing and test strategy environments. Lack of training and misinformation regarding optimization and systems engineering have resulted in this absence. Due to improper test strategies, many costly design problems have arisen in deployed vehicles when they should have been discovered in the developmental testing stage. There are many ways and areas in which this research can be expanded to further our understanding of customized transformation plans as well as optimization. Three suggestions are made here starting from additional research of vehicle tests burgeoning to all manner of systems and testing conducted through ATEC.

ATC's new durability simulator is the first area where additional research could provide great benefits to the Army as well as to mechanical engineering in general. By the end of 2008, ATC will be operating a durability simulator capable of testing vehicles as large and as heavy as the Stryker. The durability simulator was a project initiated by ATEC in the pursuit to more quickly and more inexpensively test prototype systems with greater control and repeatability and consequently objectivity. The durability simulator works by attaching articulated actuators to a vehicle's hubs that can provide resistance to the vehicle's driving wheels, flexibility for vehicle maneuvering, and while introducing jounce and rebound patterns to the vehicle's suspensions system. The vehicle is "driven"

in place by a robot controlling throttle position, braking, and steering inputs. The robot follows an imaginary course created by ATC engineers based on data captured from existing road courses.

The potential to employ optimization techniques for the durability simulator is great. First, engineers must maximize the simulator's relevance to real driving conditions. While the purpose of the durability simulator is not to provide an identical representation of existing ATC test courses, engineers must ensure the simulator produces results that are grounded in and relevant to actual operation of the vehicle. It is hoped that the durability simulator will provide ATC a way to test vehicles in ways and on courses otherwise not available or too costly to produce. However, first the simulator must be calibrated, and optimization techniques would be an invaluable means to this end.

After the simulator is properly calibrated, optimization techniques and transformation plan research can be used to help determine the best test plans and strategy to follow. Similar to the field research conducted in this thesis, applying different transformation plans to simulated testing would be a great benefit to ATC and its customers. The conclusions found from this research, if applied to the durability simulator, would help customers optimize their test's relevance to the environment in which they are interested based on our data and their time and cost constraints.

The second area of research that these results could be expanded upon is other types of non-automotive testing. ATC, though the Army's primary automotive test facility, also specializes in testing water craft, tents, fire extinguishing systems, small arms, large caliber weapons, electronic equipment, robots and much more. ATEC, in

comparison, is responsible for testing all of the U.S. Army's systems and materials. Just as in the case with vehicle testing, a large number of these tests use test procedures that are decades old. In circumstances where test procedures are not old but instead painfully new, as in unmanned ground and air vehicles and in Netcentric systems, these results could be expanded to explore the best test strategies for new TOPs. Researching the application of optimization techniques and customizable transformation plans in these expanded areas would help to provide more streamlined, efficient, and accurate test services while saving the customer and the government time, money, and effort.

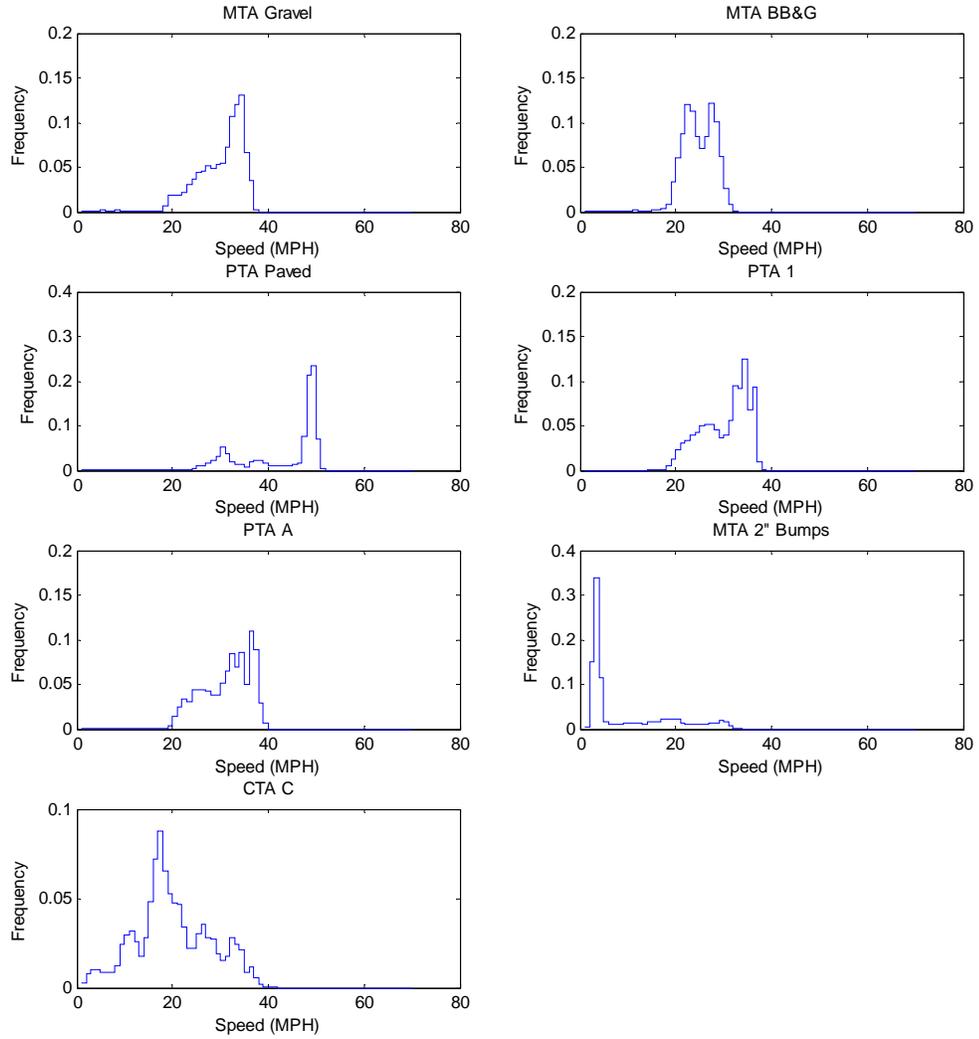
A third area in which this research should be continued is in the optimization of differing types of data. Systems are rarely tested for a single mode of failure or for a single performance characteristic. Often times, traditional test plans are so broad because the vehicle or system is so complex and is operated in so many different environments. The large question remains how to compare and optimize measures as different as drive shaft torque and operator comments. The former characteristic can easily be captured from instrumentation, however the latter is a very subjective measure and when converted into a numeric scale provides only a set of pseudo-data. By researching potential means to combining dissimilar data or pseudo-data sets, customers and engineers are given far more options and many more ways in which to objectively support their environment- or use-specific test plan.

A great wealth of valuable information can be gained from the exploration of each of these suggestions. Continued research in this field would help to stimulate the beneficial use of optimization in testing as well as provide great benefits to the government and to the field of mechanical engineering. Additional study of

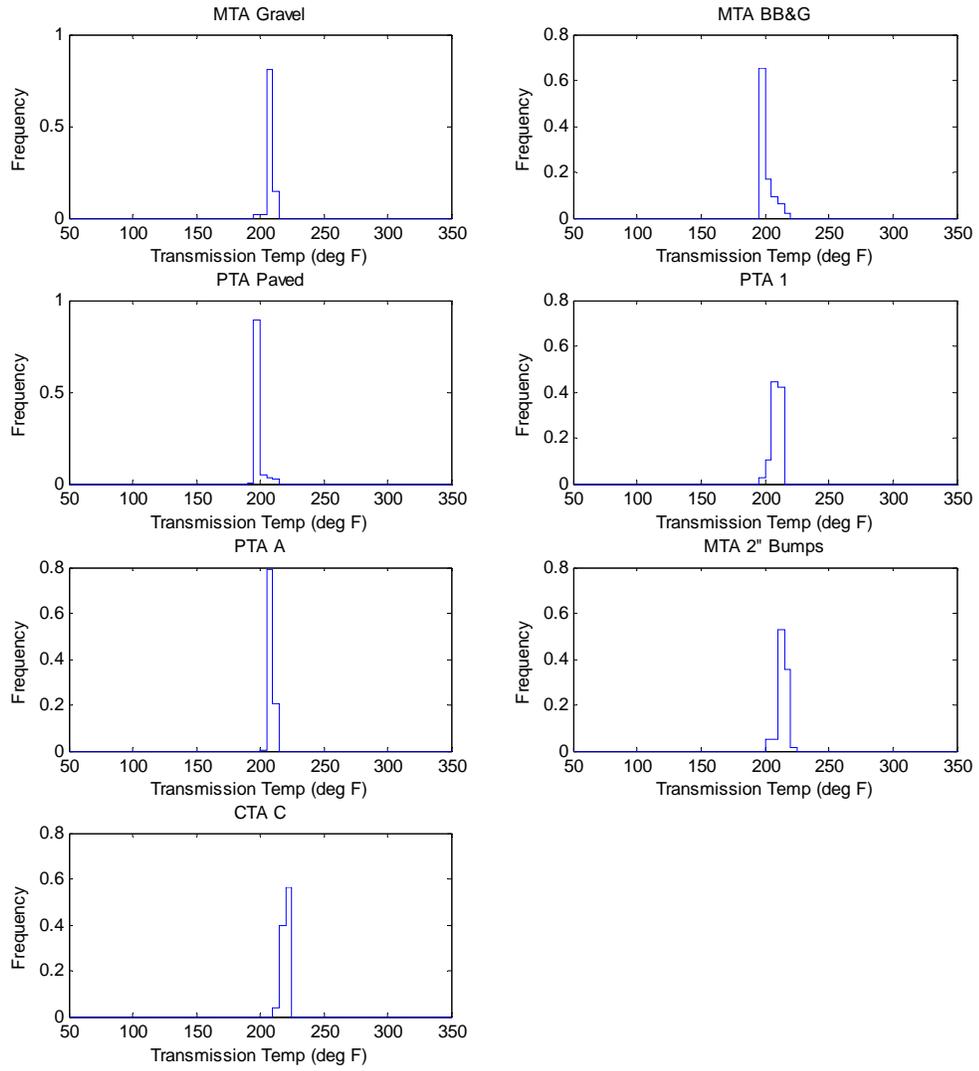
transformation plans and optimization techniques, implemented at any level, from ATC's Automotive Directorate to ATEC, promises to yield new and valuable knowledge of a process that is little known and understood.

APPENDIX A

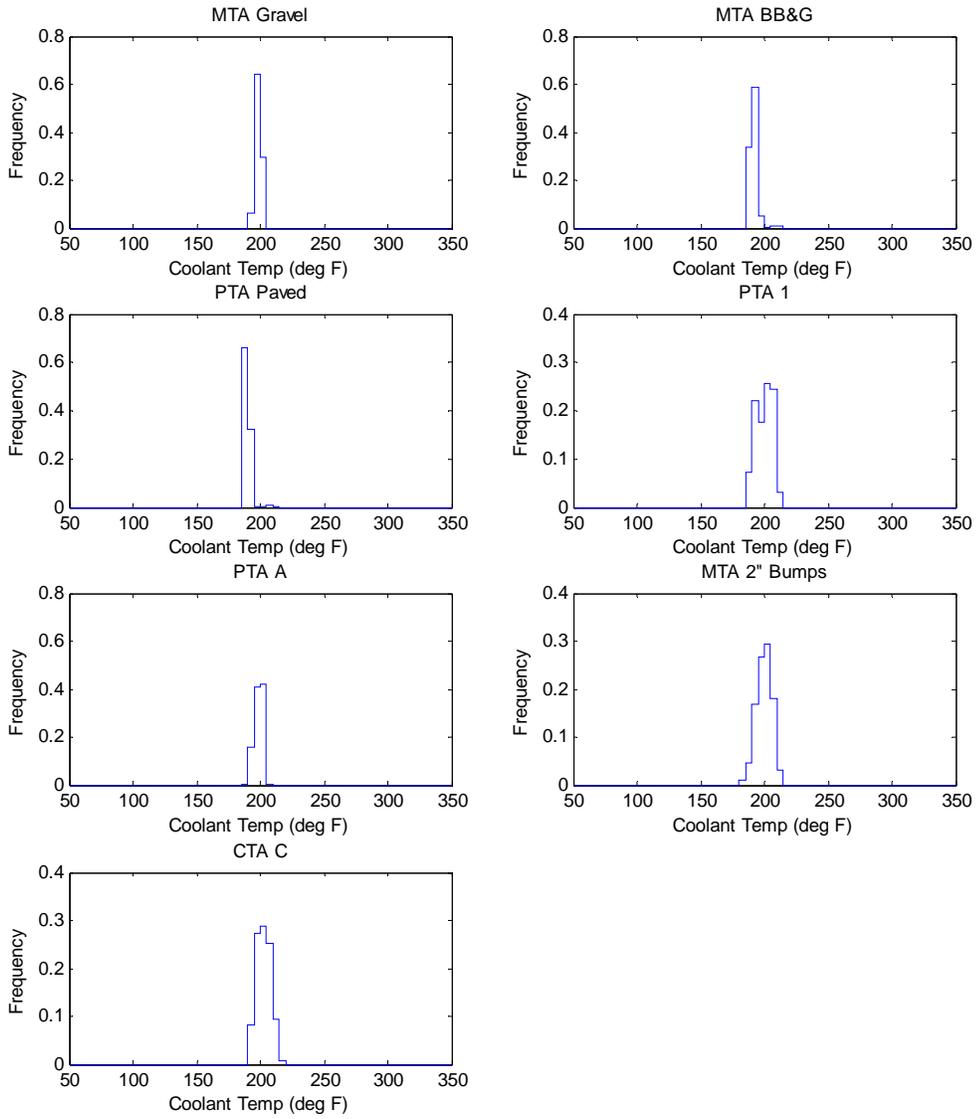
M915A3 Road Speed Profiles on ATC Courses



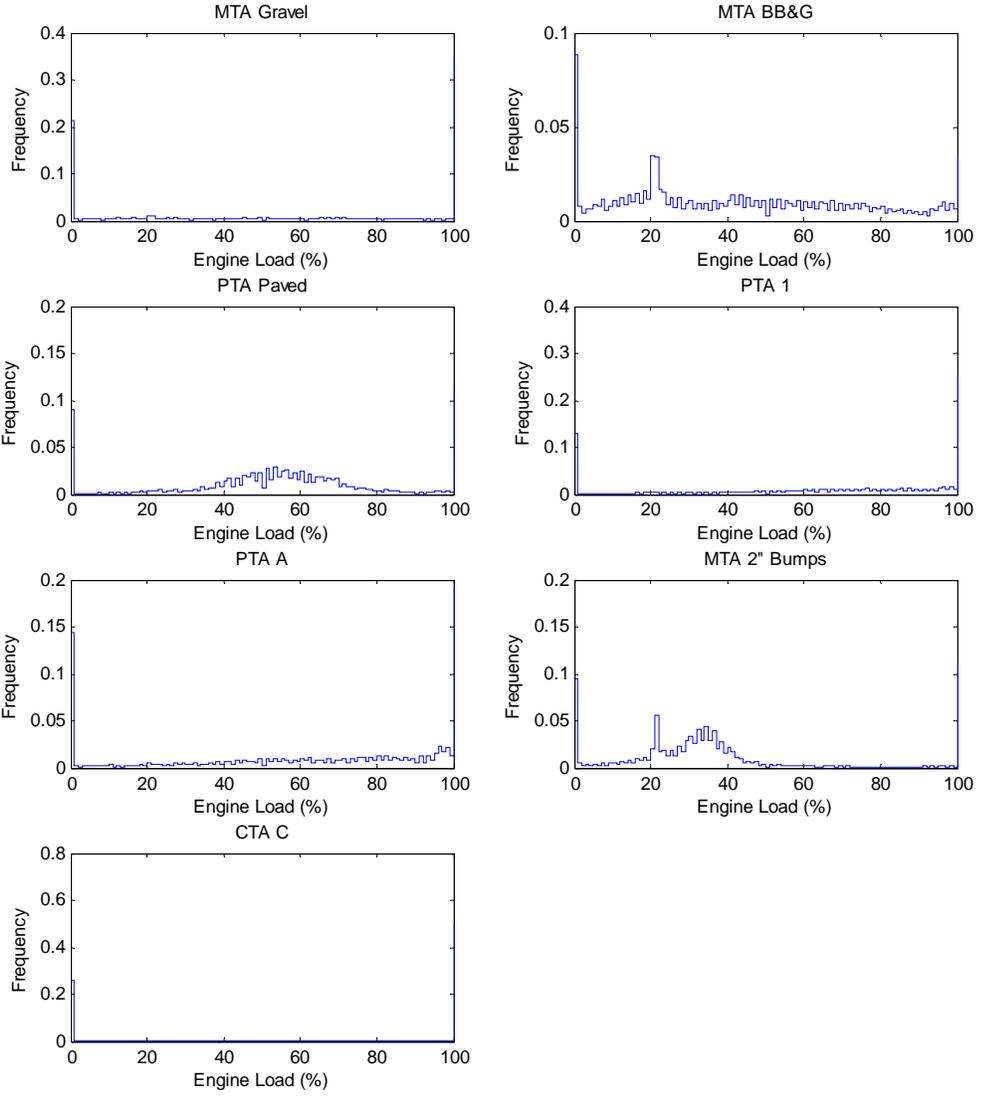
M915A3 Transmission Temperature Profiles on ATC Courses



M915A3 Coolant Temperature Profiles on ATC Courses

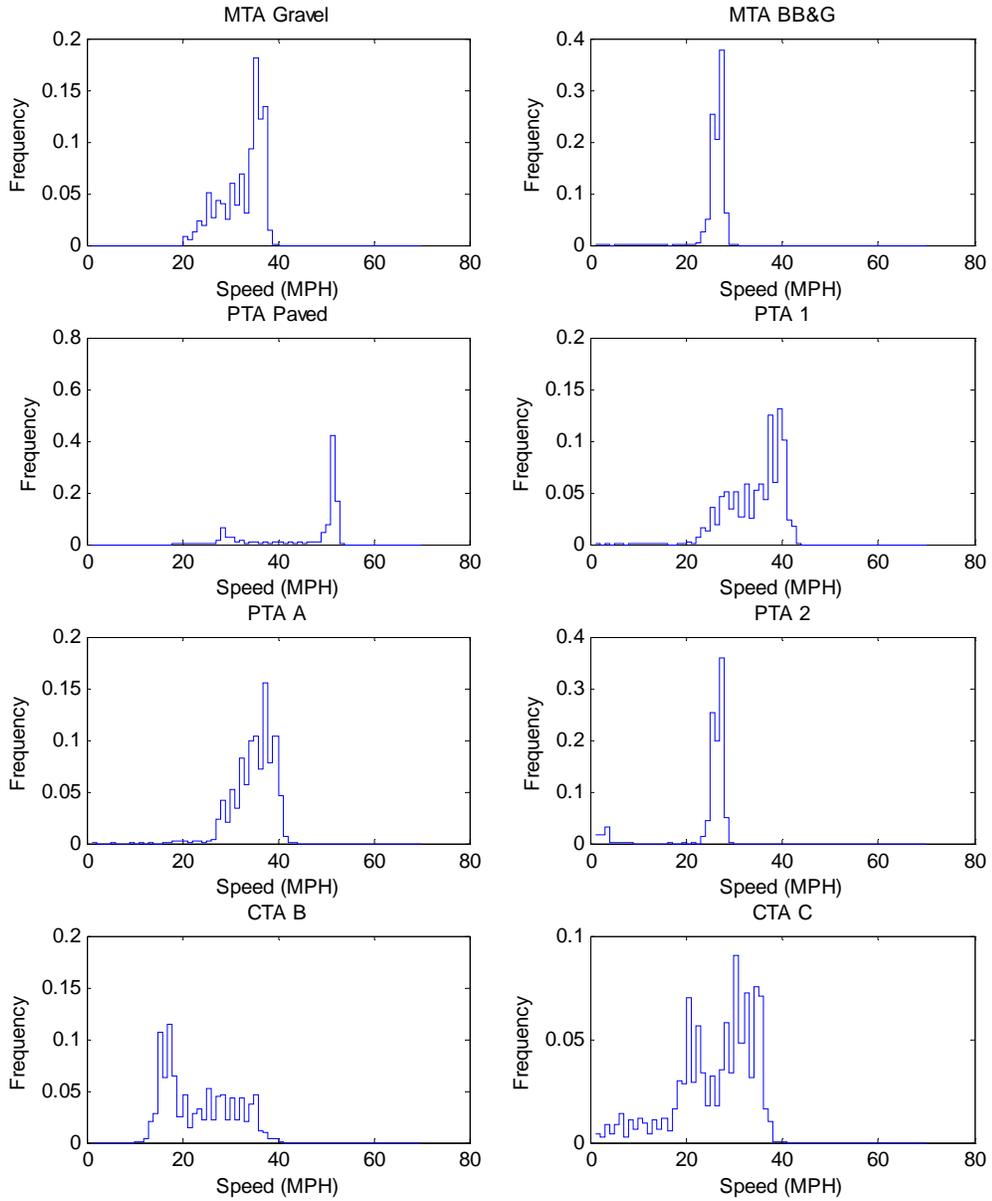


M915A3 Engine Load Profiles on ATC Courses

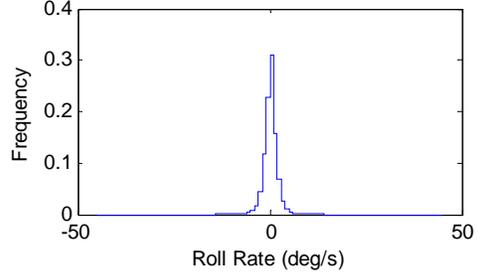
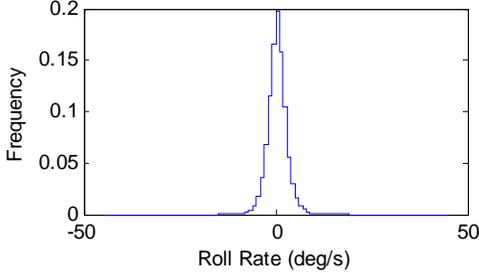
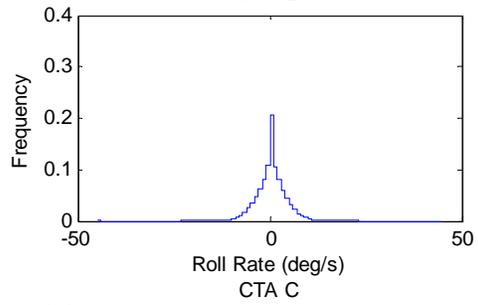
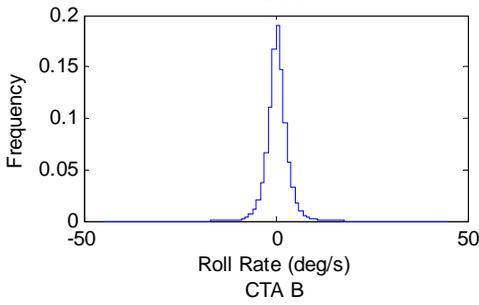
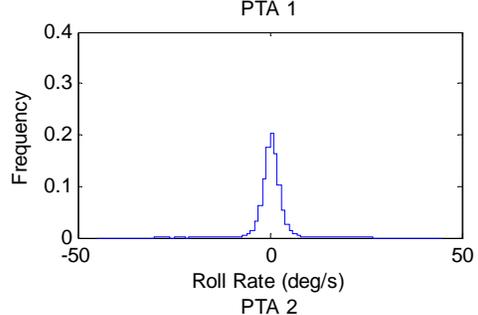
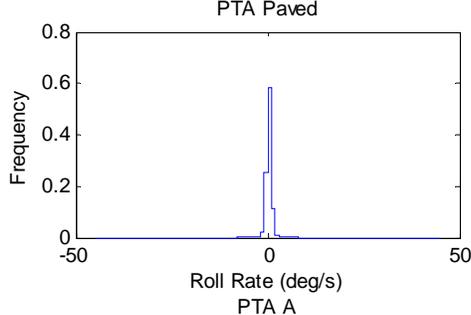
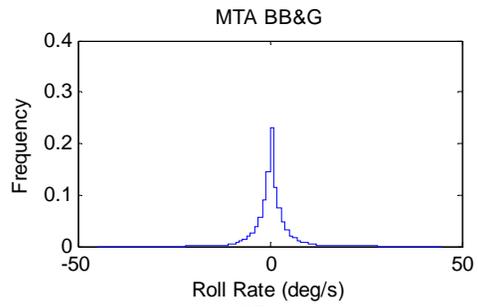
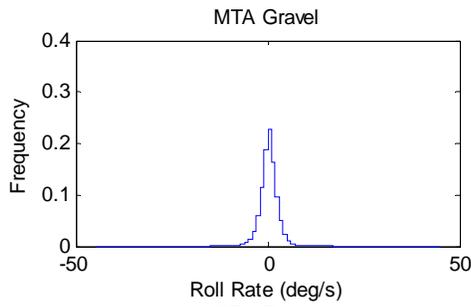


APPENDIX B

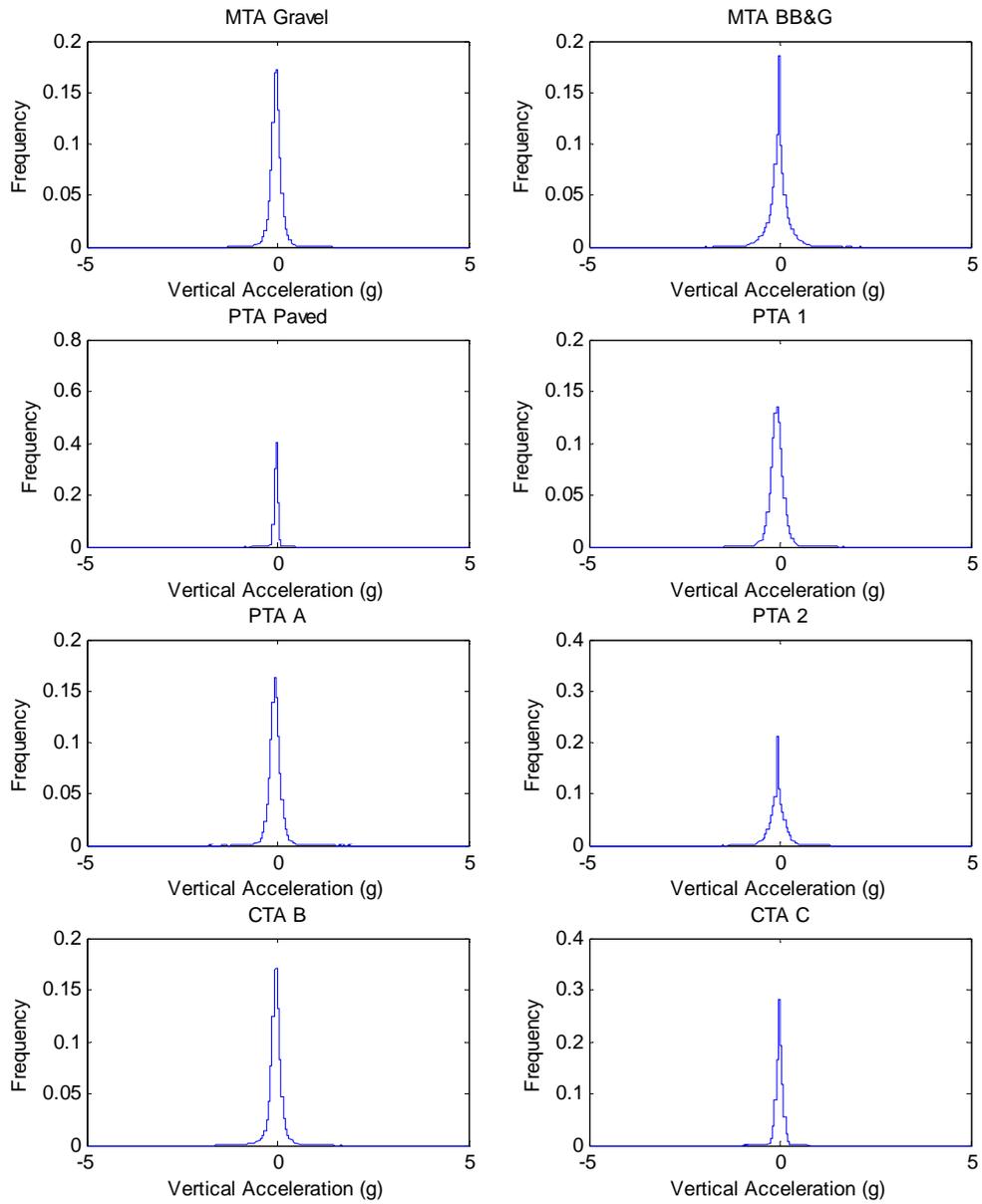
ATC Course Road Speed Profiles



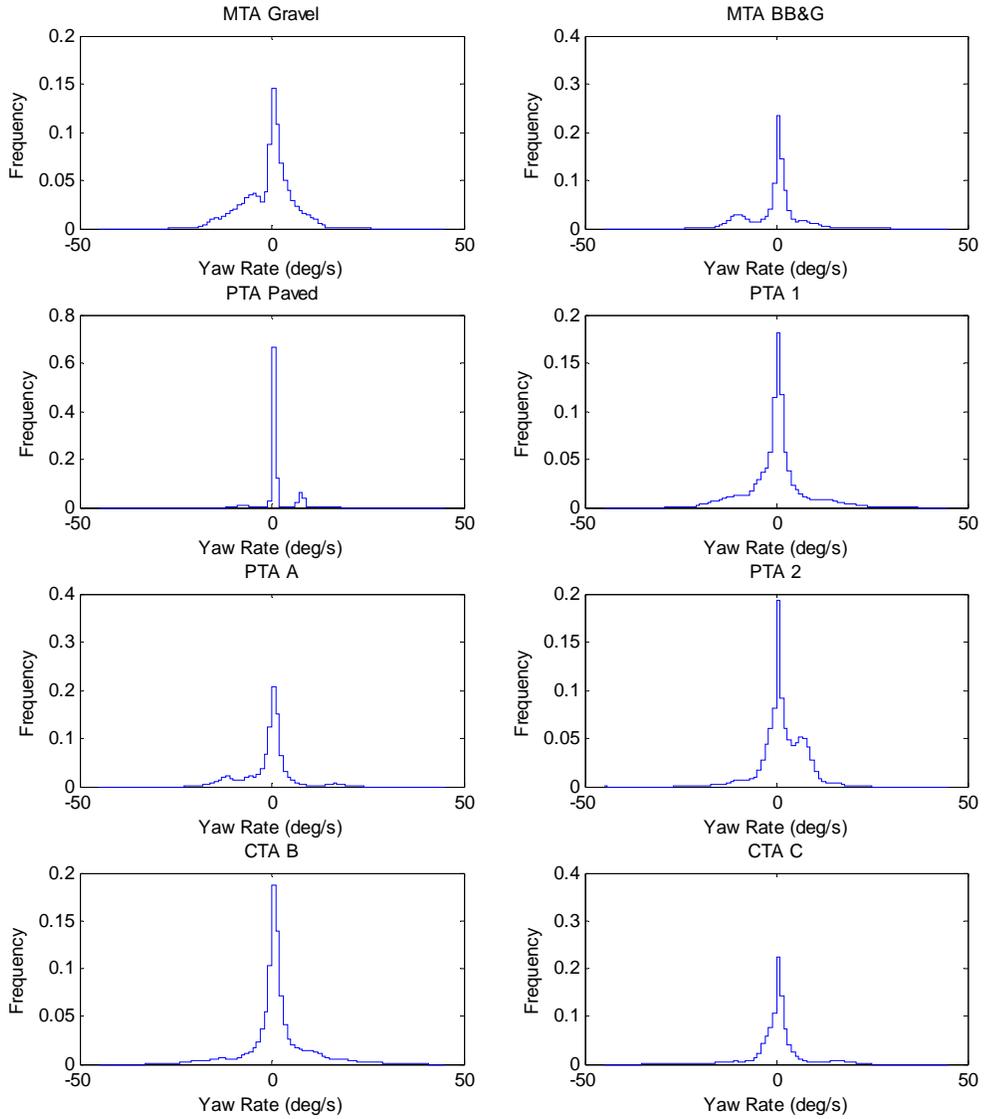
ATC Course Roll Rate Profiles



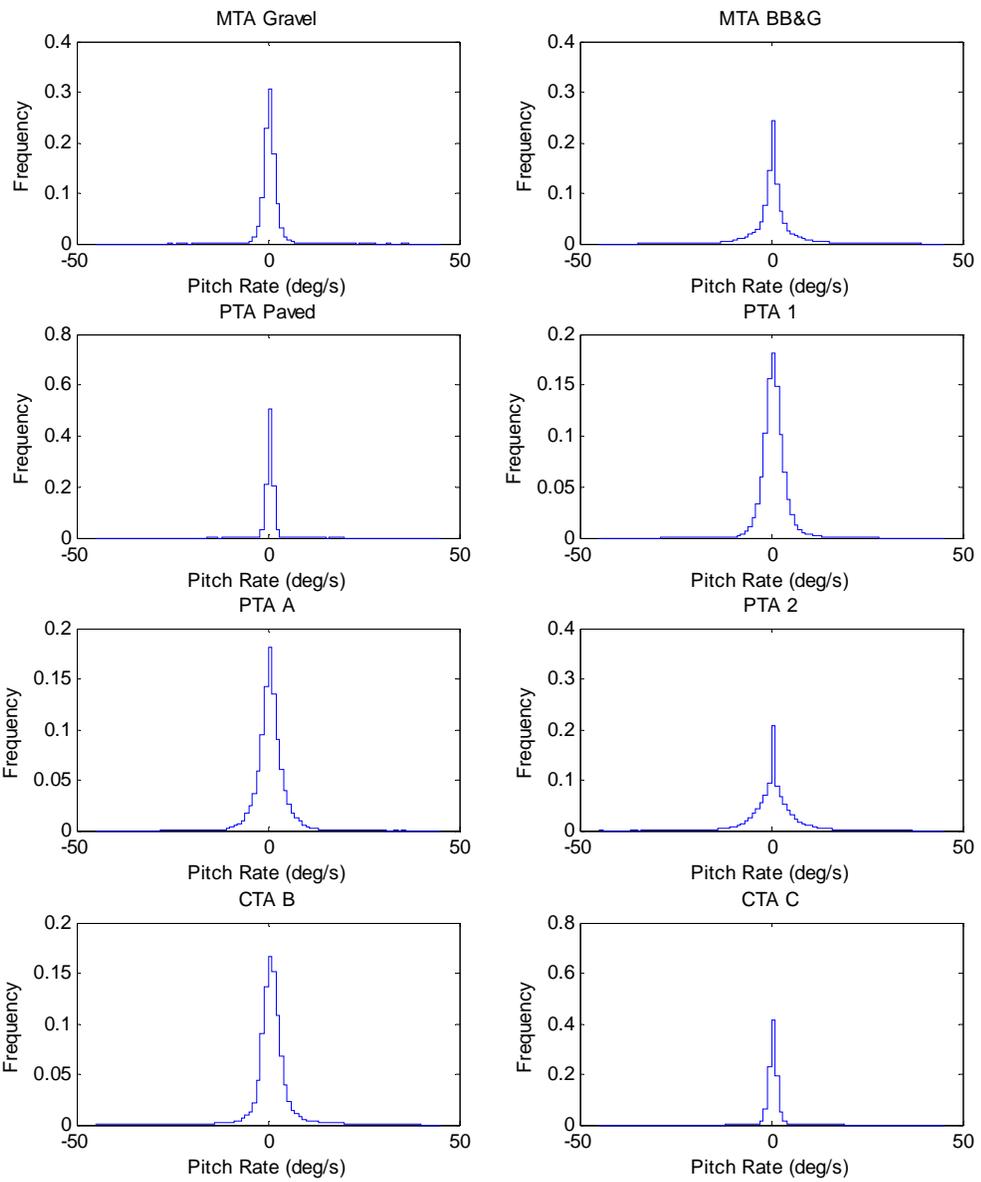
ATC Course Vertical Acceleration Profiles



ATC Course Yaw Rate Profiles



ATC Course Pitch Rate Profiles




```

stairs(bin1,E1)
title('MTA Gravel')
xlabel('Engine Load (%)')
ylabel('Frequency')
% legend('Data Histogram','Fitted Curve')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%01 Nov 10:19 start time
%ADMAS File 151656
%Laps 1-10 on MTA BB&G - 9.45 miles
Ec=[2579,231,113,184,191,256,225,346,167,227,320,225,352,259,403,296,414,267,458,343,1009
,988,490,440,241,360,208,356,177,279,323,178,275,186,278,172,314,183,272,224,317,393,248,
403,216,360,226,326,208,309,76,332,209,332,188,306,278,235,325,169,284,217,284,184,298,27
9,160,306,167,271,164,248,180,271,178,267,231,144,214,178,221,130,179,131,155,193,118,153
,128,152,95,146,85,174,156,227,286,169,263,190,989];

E2=(Ec)/sum(Ec); %Divide by Correction factor - Total counts
% figure(2)
subplot(4,2,2)
stairs(bin1,E2)
title('MTA BB&G')
xlabel('Engine Load (%)')
ylabel('Frequency')
% legend('Data Histogram','Fitted Curve')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%01 Nov 13:39 start time
%ADMAS Files 183807?, 214304, 222126
%Laps 1-2, 3-6, and 7-10 on PTA Paved - ?, 13.15, 13.1 miles
Ee=[4056,49,38,51,39,57,47,68,24,52,95,49,67,40,81,64,112,101,145,84,159,145,182,233,120,
196,140,218,126,179,192,170,252,172,367,227,330,303,586,367,612,767,378,762,460,882,810,1
015,638,1037,296,1269,735,1271,815,1120,1155,793,1015,690,1085,592,946,588,846,849,656,74
6,703,744,389,472,338,374,235,318,275,212,259,158,179,132,230,149,189,149,87,117,76,91,66
,88,42,71,98,153,196,120,146,115,4990];

E3=(Ee)/sum(Ee); %Divide by Correction factor - Total counts
% figure(3)
subplot(4,2,3)
stairs(bin1,E3)
title('PTA Paved')
xlabel('Engine Load (%)')
ylabel('Frequency')
% legend('Data Histogram','Fitted Curve')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%01 Nov 14:02 start time
%ADMAS Files 190148, 195207
%Laps 1-5 and 6-10 on PTA 1 - 12.35, 12.45 miles
Eg=[7855,135,75,108,138,137,102,142,68,125,132,73,162,127,145,137,227,136,247,205,266,249
,145,223,146,214,173,249,123,276,236,131,249,175,185,153,245,129,303,201,249,272,191,297,
211,334,243,385,300,445,98,482,272,455,303,412,510,421,536,405,582,392,582,351,640,665,34
5,581,431,640,450,712,427,664,502,659,722,448,556,407,623,412,709,532,715,747,515,786,522
,662,436,654,426,687,439,799,905,649,975,539,15130];

E4=(Eg)/sum(Eg); %Divide by Correction factor - Total counts
% figure(4)
subplot(4,2,4)
stairs(bin1,E4)
title('PTA 1')
xlabel('Engine Load (%)')
ylabel('Frequency')

```

```

% legend('Data Histogram','Fitted Curve')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%PTA A
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%01 Nov 15:50 start time
%ADMAS File 205009
%Laps 1-10 on PTA A - 11.3 miles
Ep=[3802,63,38,66,44,64,41,57,48,69,85,36,63,39,70,54,75,52,87,40,131,115,83,108,77,111,7
2,121,85,129,111,93,134,74,98,79,126,92,163,102,163,166,97,207,121,221,166,189,134,240,76
,265,159,254,175,239,234,144,228,170,252,197,283,147,234,230,136,273,154,215,203,250,154,
264,189,277,276,185,312,197,330,210,326,203,297,274,210,282,231,267,149,320,131,317,225,4
29,626,450,570,352,5119];

E5=Ep/sum(Ep);          %Divide by Correction factor - Total counts
% figure(5)
subplot(4,2,5)
stairs(bin1,E5)
title('PTA A')
xlabel('Engine Load (%)')
ylabel('Frequency')
% legend('Data Histogram','Fitted Curve')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%MTA 2" Bumps
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%01 Nov 11:13 start time
%ADMAS File 161129
%Laps 1-10 on MTA 2" Bumps - 4.05 miles
Eq=[3322,166,75,154,97,155,66,171,86,173,193,133,222,163,289,191,354,284,386,310,708,1944
,575,679,419,641,431,785,578,1031,1174,902,1424,1030,1558,1010,1376,721,960,559,750,611,3
82,361,198,225,163,210,96,145,38,121,86,109,68,89,87,53,88,54,77,53,66,32,49,66,53,74,38,
53,37,64,31,48,24,43,47,30,31,29,33,21,23,18,35,34,10,40,22,34,21,55,39,67,33,68,72,28,55
,42,3890];

E6=Eq/sum(Eq);        %Divide by Correction factor - Total counts
% figure(6)
subplot(4,2,6)
stairs(bin1,E6)
title('MTA 2" Bumps')
xlabel('Engine Load (%)')
ylabel('Frequency')
% legend('Data Histogram','Fitted Curve')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%CTA C
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%31 Oct 13:32 start time
%ADMAS Files 183220, 190805
%Laps 1-5 and 6-10 on CTA C - 5.75, 5.75 miles
Er=[11118,54,34,77,40,41,67,46,44,77,76,56,61,53,105,86,142,113,143,99,144,192,153,153,95
,187,82,133,80,138,114,62,103,62,86,59,115,70,107,88,144,134,68,130,82,156,71,116,82,132,
34,138,85,120,86,131,132,93,143,85,151,84,144,128,179,149,83,129,103,148,86,138,96,141,89
,125,133,86,125,85,100,71,131,92,139,125,81,93,80,75,59,112,59,75,61,138,132,53,69,88,213
51];

E7=Er/sum(Er);        %Divide by Correction factor - Total counts
% figure(8)
subplot(4,2,7)
stairs(bin1,E7)
title('CTA C')
xlabel('Engine Load (%)')
ylabel('Frequency')
% legend('Data Histogram','Fitted Curve')
SUPTITLE('M915A3 Engine Load Profiles on ATC Courses')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```



```

TT=norm((X(1,1)*T1+X(1,2)*T2+X(1,3)*T3+X(1,4)*T4+X(1,5)*T5+X(1,6)*T6+X(1,7)*T7)-
T_goal);

m=(k+.72)*100-100;
figure(6)
plot(m,FVAL,'k*')
hold on
plot(m,EL,'ko')
plot(m,CT,'kd')
plot(m,TT,'ks')
xlabel('Valid Pareto Points for Roadspeed Vs. Trans Temp')
ylabel('Objective Function Values')
legend('Roadspeed','Engine Load','Coolant Temp','Trans Temp','Location','NorthWest')

end

```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Conversion of Frequency RCTM to Distance RCTM For Transformation Plan D
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```

```

V_ave=[V1_ave,V2_ave,V3_ave,V4_ave,V5_ave,V6_ave,V7_ave];
D_total=Dot(V_ave,X);

```

```

RCTM_PlanD=V_ave.*X/D_total

```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Transformation Plan D Performance Metrics
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```

```

V_fit=X(1,1)*V1+X(1,2)*V2+X(1,3)*V3+X(1,4)*V4+X(1,5)*V5+X(1,6)*V6+X(1,7)*V7;
R_RSPEED=corrcoef(V_goal,V_fit)
RSPEED_fval=norm((X(1,1)*V1+X(1,2)*V2+X(1,3)*V3+X(1,4)*V4+X(1,5)*V5+X(1,6)*V6+X(1,7)*V7)-
V_goal)

```

```

T_fit=X(1,1)*T1+X(1,2)*T2+X(1,3)*T3+X(1,4)*T4+X(1,5)*T5+X(1,6)*T6+X(1,7)*T7;
R_TTEMP=corrcoef(T_goal,T_fit)
TTEMP_fval=norm((X(1,1)*T1+X(1,2)*T2+X(1,3)*T3+X(1,4)*T4+X(1,5)*T5+X(1,6)*T6+X(1,7)*T7)-
T_goal)

```

```

CT_fit=X(1,1)*CT1+X(1,2)*CT2+X(1,3)*CT3+X(1,4)*CT4+X(1,5)*CT5+X(1,6)*CT6+X(1,7)*CT7;
R_CTEMP=corrcoef(CT_goal,CT_fit)
CTEMP_fval=norm((X(1,1)*CT1+X(1,2)*CT2+X(1,3)*CT3+X(1,4)*CT4+X(1,5)*CT5+X(1,6)*CT6+X(1,7)*
CT7)-CT_goal)

```

```

E_fit=X(1,1)*E1+X(1,2)*E2+X(1,3)*E3+X(1,4)*E4+X(1,5)*E5+X(1,6)*E6+X(1,7)*E7;
R_ELOAD=corrcoef(E_goal,E_fit)
ELOAD_fval=norm((X(1,1)*E1+X(1,2)*E2+X(1,3)*E3+X(1,4)*E4+X(1,5)*E5+X(1,6)*E6+X(1,7)*E7)-
E_goal)

```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Transformation Plan D Road Speed Profiles
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```

```

TP_D_RS=X(1,1)*V1+X(1,2)*V2+X(1,3)*V3+X(1,4)*V4+X(1,5)*V5+X(1,6)*V6+X(1,7)*V7;

```

```

figure(11)
stairs(bingoal_RS,TP_D_RS,'k')
hold on
stairs(bingoal_RS,V_goal,'r')
title('Road Speed Profile Comparison')
xlabel('Road Speed (MPH)')
ylabel('Frequency')
legend('Transformation Plan D','Actual Use Environment','Location','NorthWest')

```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Transformation Plan D Transmission Temp Profiles
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```

```

TP_D_TT=X(1,1)*T1+X(1,2)*T2+X(1,3)*T3+X(1,4)*T4+X(1,5)*T5+X(1,6)*T6+X(1,7)*T7;

figure(12)
stairs(bingoal_TT,TP_D_TT,'k')
hold on
stairs(bingoal_TT,T_goal,'r')
title('Transmission Temperature Profile Comparison')
xlabel('Transmission Temp (deg F)')
ylabel('Frequency')
legend('Transformation Plan D','Actual Use Environment','Location','NorthWest')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Transformation Plan D Coolant Temp Profiles
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

TP_D_CT=X(1,1)*CT1+X(1,2)*CT2+X(1,3)*CT3+X(1,4)*CT4+X(1,5)*CT5+X(1,6)*CT6+X(1,7)*CT7;

figure(13)
stairs(bingoal_CT,TP_D_CT,'k')
hold on
stairs(bingoal_CT,CT_goal,'r')
title('Coolant Temperature Profile Comparison')
xlabel('Coolant Temperature (deg F)')
ylabel('Frequency')
legend('Transformation Plan D','Actual Use Environment','Location','NorthWest')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Transformation Plan D Engine Load Profiles
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

TP_D_EL=X(1,1)*E1+X(1,2)*E2+X(1,3)*E3+X(1,4)*E4+X(1,5)*E5+X(1,6)*E6+X(1,7)*E7;

figure(14)
stairs(bingoal_EL,TP_D_EL,'k')
hold on
stairs(bingoal_EL,E_goal,'r')
title('Engine Load Profile Comparison')
xlabel('Engine Load (%)')
ylabel('Frequency')
legend('Transformation Plan D','Actual Use Environment','Location','NorthWest')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Transformation Plan C Performance Metrics
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

CX=[0,0,.2487,0,.1073,.1679,.4760]; %Transformation Plan C time frequency weighting
vector from M915A3_road_speed_no_atef_52max.m

V_fit_C=CX(1,1)*V1+CX(1,2)*V2+CX(1,3)*V3+CX(1,4)*V4+CX(1,5)*V5+CX(1,6)*V6+CX(1,7)*V7;
R_RSpeed_C=corrcoef(V_goal,V_fit_C)
RSpeed_fval_C=norm((CX(1,1)*V1+CX(1,2)*V2+CX(1,3)*V3+CX(1,4)*V4+CX(1,5)*V5+CX(1,6)*V6+CX(
1,7)*V7)-V_goal)

T_fit_C=CX(1,1)*T1+CX(1,2)*T2+CX(1,3)*T3+CX(1,4)*T4+CX(1,5)*T5+CX(1,6)*T6+CX(1,7)*T7;
R_TTemp_C=corrcoef(T_goal,T_fit_C)
TTemp_fval_C=norm((CX(1,1)*T1+CX(1,2)*T2+CX(1,3)*T3+CX(1,4)*T4+CX(1,5)*T5+CX(1,6)*T6+CX(1
,7)*T7)-T_goal)

CT_fit_C=CX(1,1)*CT1+CX(1,2)*CT2+CX(1,3)*CT3+CX(1,4)*CT4+CX(1,5)*CT5+CX(1,6)*CT6+CX(1,7)*
CT7;
R_CTemp_C=corrcoef(CT_goal,CT_fit_C)
CTemp_fval_C=norm((CX(1,1)*CT1+CX(1,2)*CT2+CX(1,3)*CT3+CX(1,4)*CT4+CX(1,5)*CT5+CX(1,6)*CT
6+CX(1,7)*CT7)-CT_goal)

E_fit_C=CX(1,1)*E1+CX(1,2)*E2+CX(1,3)*E3+CX(1,4)*E4+CX(1,5)*E5+CX(1,6)*E6+CX(1,7)*E7;
R_ELoad_C=corrcoef(E_goal,E_fit_C)

```

```
ELoad_fval_C=norm((CX(1,1)*E1+CX(1,2)*E2+CX(1,3)*E3+CX(1,4)*E4+CX(1,5)*E5+CX(1,6)*E6+CX(1,7)*E7)-E_goal)
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%  
%Conversion of Frequency RCTM to Distance RCTM For Transformation Plan C  
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
D_total_C=Dot(V_ave,CX);
```

```
RCTM_PlanC=V_ave.*CX/D_total_C
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%  
%Transformation Plan C Road Speed Profiles  
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
TP_C_RS=CX(1,1)*V1+CX(1,2)*V2+CX(1,3)*V3+CX(1,4)*V4+CX(1,5)*V5+CX(1,6)*V6+CX(1,7)*V7;
```

```
figure(15)  
stairs(bingoal_RS,TP_C_RS,'k')  
hold on  
stairs(bingoal_RS,V_goal,'r')  
title('Road Speed Profile Comparison')  
xlabel('Road Speed (MPH)')  
ylabel('Frequency')  
legend('Transformation Plan C','Actual Use Environment','Location','NorthWest')
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%  
%Transformation Plan C Transmission Temp Profiles  
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
TP_C_TT=CX(1,1)*T1+CX(1,2)*T2+CX(1,3)*T3+CX(1,4)*T4+CX(1,5)*T5+CX(1,6)*T6+CX(1,7)*T7;
```

```
figure(16)  
stairs(bingoal_TT,TP_C_TT,'k')  
hold on  
stairs(bingoal_TT,T_goal,'r')  
title('Transmission Temperature Profile Comparison')  
xlabel('Transmission Temp (deg F)')  
ylabel('Frequency')  
legend('Transformation Plan C','Actual Use Environment','Location','NorthWest')
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%  
%Transformation Plan C Coolant Temp Profiles  
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
TP_C_CT=CX(1,1)*CT1+CX(1,2)*CT2+CX(1,3)*CT3+CX(1,4)*CT4+CX(1,5)*CT5+CX(1,6)*CT6+CX(1,7)*CT7;
```

```
figure(17)  
stairs(bingoal_CT,TP_C_CT,'k')  
hold on  
stairs(bingoal_CT,CT_goal,'r')  
title('Coolant Temperature Profile Comparison')  
xlabel('Coolant Temperature (deg F)')  
ylabel('Frequency')  
legend('Transformation Plan C','Actual Use Environment','Location','NorthWest')
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%  
%Transformation Plan C Engine Load Profiles  
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
TP_C_EL=CX(1,1)*E1+CX(1,2)*E2+CX(1,3)*E3+CX(1,4)*E4+CX(1,5)*E5+CX(1,6)*E6+CX(1,7)*E7;
```

```
figure(18)  
stairs(bingoal_EL,TP_C_EL,'k')  
hold on  
stairs(bingoal_EL,E_goal,'r')
```

```

title('Engine Load Profile Comparison')
xlabel('Engine Load (%)')
ylabel('Frequency')
legend('Transformation Plan C','Actual Use Environment','Location','NorthWest')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Transformation Plan A Performance Metrics
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

RCTM_PlanA=[.083,.033,.75,.042,0,0,.092]; %already in distance percentage domain
D_total_A=Dot(V_ave,RCTM_PlanA);

AX=RCTM_PlanA.*V_ave/D_total_A; %Plan A time frequency weights

V=[V1;V2;V3;V4;V5;V6;V7];
V_fit_A=AX*V;
R_RSpeed_A=corrcoef(V_goal,V_fit_A)
RSpeed_fval_A=norm((V_fit_A)-V_goal)

T=[T1;T2;T3;T4;T5;T6;T7];
T_fit_A=AX*T;
R_TTemp_A=corrcoef(T_goal,T_fit_A)
TTemp_fval_A=norm((T_fit_A)-T_goal)

CT=[CT1;CT2;CT3;CT4;CT5;CT6;CT7];
CT_fit_A=AX*CT;
R_CTemp_A=corrcoef(CT_goal,CT_fit_A)
CTemp_fval_A=norm((CT_fit_A)-CT_goal)

E=[E1;E2;E3;E4;E5;E6;E7];
E_fit_A=AX*E;
R_ELoad_A=corrcoef(E_goal,E_fit_A)
ELoad_fval_A=norm((E_fit_A)-E_goal)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Transformation Plan A Road Speed Profiles
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

figure(7)
stairs(bingoal_RS,V_fit_A,'k')
hold on
stairs(bingoal_RS,V_goal,'r')
title('Road Speed Profile Comparison')
xlabel('Speed (MPH)')
ylabel('Frequency')
legend('Transformation Plan A','Actual Use Environment','Location','NorthWest')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Transformation Plan A Engine Load Profiles
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

figure(9)
stairs(bingoal_EL,E_fit_A,'k')
hold on
stairs(bingoal_EL,E_goal,'r')
title('Engine Load Profile Comparison')
xlabel('Engine Load (%)')
ylabel('Frequency')
legend('Transformation Plan A','Actual Use Environment','Location','NorthWest')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Transformation Plan A Coolant Temp Profiles
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

figure(10)
stairs(bingoal_CT,CT_fit_A,'k')
hold on

```

```

stairs(bingoal_CT,CT_goal,'r')
title('Coolant Temperature Profile Comparison')
xlabel('Coolant Temperature (deg F)')
ylabel('Frequency')
legend('Transformation Plan A','Actual Use Environment','Location','NorthWest')

```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Transformation Plan A Transmission Temp Profiles
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```

```

figure(8)
stairs(bingoal_TT,T_fit_A,'k')
hold on
stairs(bingoal_TT,T_goal,'r')
title('Transmission Temperature Profile Comparison')
xlabel('Transmission Temp (deg F)')
ylabel('Frequency')
legend('Transformation Plan A','Actual Use Environment','Location','NorthWest')

```

```

figure(19)
plot(TP_D_RS,V_goal, '.')
R_TP_D_RS=corrcoef(TP_D_RS,V_goal);
title('Transformation Plan D Road Speed Correlation Comparison')
xlabel('Test Course Road Speed Profile')
ylabel('Actual Environment Road Speed Profile')
text(.05,.03,['R = ',num2str(R_TP_D_RS(1,2))])

```

```

figure(20)
plot(TP_D_CT,CT_goal, '.')
R_TP_D_CT=corrcoef(TP_D_CT,CT_goal);
title('Transformation Plan D Engine Coolant Temperature Correlation Comparison')
xlabel('Test Course Engine Coolant Temperature Profile')
ylabel('Actual Environment Engine Coolant Temperature Profile')
text(.05,.1,['R = ',num2str(R_TP_D_CT(1,2))])

```

function

```

f=objfunctions(x,V1,V2,V3,V4,V5,V6,V7,V_goal,T1,T2,T3,T4,T5,T6,T7,T_goal,k)
a1=x(1);a2=x(2);a3=x(3);a4=x(4);a5=x(5);a6=x(6);a7=x(7);
f=norm((a1*V1+a2*V2+a3*V3+a4*V4+a5*V5+a6*V6+a7*V7)-V_goal);

```

function

```

[C,Ceq]=M915_ttemp_NLConstr(x,V1,V2,V3,V4,V5,V6,V7,V_goal,T1,T2,T3,T4,T5,T6,T7,T_goal,k)
a1=x(1);a2=x(2);a3=x(3);a4=x(4);a5=x(5);a6=x(6);a7=x(7);
C(1)=norm((a1*T1+a2*T2+a3*T3+a4*T4+a5*T5+a6*T6+a7*T7)-T_goal)-k;
Ceq=[];

```

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