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THESIS

IMPACT OF M777 HOWITZER USAGE ON UNSCHEDULED MAINTENANCE REQUIREMENTS

by

Trevor Klemin

June 2023

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13. ABSTRACT (maximum 200 words)

Howitzers are essential to combined arms warfare since they allow commanders to engage enemy targets from greater distances while sending projectiles on high-angle trajectories over friendly forces and terrain features. The M777A2 howitzer is used by the U.S. Army and Marine Corps for frontline operations where untimely failures can have immediate consequences. To safeguard against such failures, testing is performed to establish predictable maintenance requirements that can be synchronized with operations' planning. Unfortunately, random component failures still burden these weapons with surprise losses to combat effectiveness. To improve predictable maintenance requirements, we analyze maintenance records from six M777A2 howitzers during a six-year period to determine if component failures and repair costs are correlated with howitzer usage. The maintenance data comes from the Army Global Combat Support System (G-Army). The usage data comes from DA Form 2408-4 gun cards, which are maintained by the crew of each howitzer. We use a nonparametric technique to evaluate the frequency of component failures and the changes in repair costs relative to usage. We failed to find a relationship between usage and component failures, but we did associate repair costs with usage increases where sharp rises occur around 750 and 1,250 cumulative rounds fired.

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IMPACT OF M777 HOWITZER USAGE ON UNSCHEDULED MAINTENANCE REQUIREMENTS

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ABSTRACT

Howitzers are essential to combined arms warfare since they allow commanders to engage enemy targets from greater distances while sending projectiles on high-angle trajectories over friendly forces and terrain features. The M777A2 howitzer is used by the U.S. Army and Marine Corps for frontline operations where untimely failures can have immediate consequences. To safeguard against such failures, testing is performed to establish predictable maintenance requirements that can be synchronized with operations' planning. Unfortunately, random component failures still burden these weapons with surprise losses to combat effectiveness. To improve predictable maintenance requirements, we analyze maintenance records from six M777A2 howitzers during a six-year period to determine if component failures and repair costs are correlated with howitzer usage. The maintenance data comes from the Army Global Combat Support System (G-Army). The usage data comes from DA Form 2408-4 gun cards, which are maintained by the crew of each howitzer. We use a nonparametric technique to evaluate the frequency of component failures and the changes in repair costs relative to usage. We failed to find a relationship between usage and component failures, but we did associate repair costs with usage increases where sharp rises occur around 750 and 1,250 cumulative rounds fired.

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LIST OF ACRONYMS AND ABBREVIATIONS

CBM	conditions-based maintenance
EFC	equivalent full charge
G-Army	Army Global Combat Support System
MCF	mean cumulative function
PNPP	power nonhomogeneous Poisson process
SE	standard error
SMX	scheduled maintenance
UMX	deadlining unscheduled maintenance
USMC	United States Marine Corps

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EXECUTIVE SUMMARY

An essential component to combined arms warfare is the howitzer. Howitzers allow commanders to engage enemy targets from greater distances while sending projectiles on high-angle trajectories over friendly forces and terrain features such as mountains. The range of these weapons depends on the design of the howitzer and the type of munition fired. Some howitzers are self-propelled while others are towed. One of the primary types of towed howitzers used by the U.S. Army and U.S. Marine Corps is the M777A2. This thesis examines the mechanical reliability and repair costs of the M777A2 relative to usage.

The mechanical reliability of a weapon system is paramount to frontline combat operations. Predictable maintenance requirements can be synchronized with operations' planning and budget processes. However, random component failures burden the military with unexpected losses to combat effectiveness and budget shortfalls. To reduce the occurrence of component failures, improved reliability estimates allow components to be replaced before failing. This enables leaders to plan operations around upcoming maintenance requirements while minimizing shocks from surprise component failures. To facilitate improved reliability estimates, we analyze the occurrence of component failures and the overall cost of repairs against two metrics of usage for the M777A2 howitzer.

This thesis analyzes maintenance records and usage data from six M777A2 howitzers observed over a six-year period. We evaluate whether the occurrence of critical component failures and the cost to repair these failures is correlated with howitzer usage. The maintenance data comes from the Army Global Command Supply System (G-Army). The usage data comes from DA Form 2408-4 gun cards, which are maintained by the gun crews of each howitzer and contain two separate metrics of usage that correspond to firing events. We use a nonparametric technique to evaluate whether these usage metrics correlate with the occurrence of component failures or the costs of repairing said failures.

We found no relationship between howitzer usage and the rate at which components fail. As these howitzers fired more and more rounds over the six years of observation, the

available data did not reveal an increasing or decreasing rate of component failure. That said, analyzing data from a larger sample size may yet discover a correlation.

However, we did find the cost of repairing component failures increases as the cumulative usage of the howitzer increases. Since cumulative usage data is maintained for each howitzer on the weapon's gun card, these results allow leaders to refine future cost estimates based upon the total lifetime usage. Although the failure rate of a howitzer remains constant, the data show the costs of repairing those failures increases. We observed significant rises in costs at 750 and 1,250 cumulative rounds fired.

For future analysis, we need to analyze individual component failure rates instead of failures of the complete system (Freeman et al. 2019). To do this, we have two recommendations. First, add specific part numbers to the automated report in G-Army to feasibly allow the computation of failure rates by component. Second, clarify the reports' description of the maintenance action. Currently, maintenance clerks describe maintenance actions in a free-text cell, which makes it impractical to analyze in aggregate because of the variety of spellings and descriptive abilities of the population of clerks. Standardizing these descriptions can be achieved by adding a drop-down menu with pre-set component names.

Our second recommendation is to acquire data on a larger sample of howitzers. The digital gun cards are centrally maintained online by Army Materiel Command while the maintenance records are centrally maintained in G-Army and can be accessed with the appropriate permissions. Acquiring these permissions to analyze larger datasets will improve the quality of results and may yield additional insights on specific component failures.

References

Freeman LJ, Medlin RM, Johnson TH (2019) Challenges and new methods for designing reliability experiments. *Quality Engineering* 31(1), https://doi.org/10.1080/08982112.2018.1546394.

I. INTRODUCTION

An essential component of combined arms warfare is the howitzer. Howitzers allow commanders to engage enemy targets from greater distance while sending projectiles on high-angle trajectories over friendly forces and terrain features. The range of these weapons depends on the design of the howitzer and the type of munition fired. Some howitzers are self-propelled while others are towed. One of the primary types of towed howitzers used by the U.S. Army and U.S. Marine Corps (USMC) is the M777A2.

The M777A2 howitzer entered service with the USMC in 2004, was first delivered to the U.S. Army in 2006, and has since been purchased by the armed forces of Canada, Australia, and India (Army Technology [AT] 2023). Additionally, 152 M777A2s have been delivered to Ukrainian forces as of early 2023 (Anderson and Cancian 2023). In total, more than 1,200 have been ordered worldwide at a price of $3.7 million apiece (AT 2023). The M777A2 is a towed howitzer, which means it gets to its firing position by either being towed with a truck or sling-loaded via helicopter.

In terms of capability, the M777A2 howitzer fires a wide selection of projectiles that are 155 mm in diameter. Standard munitions weigh about 95 lbs apiece and can reach targets nearly 21 miles away (Picatinny Arsenal Public Affairs Office [PAPAO] 2023). Depending on the type of munition, M777A2 projectiles can travel up to 39,000 feet above the firing point at almost 2.5 times the speed of sound (PAPAO 2023). The breech chamber is designed to sustain expansion pressures of 60,000 lbs per square inch (PAPAO 2023). Figure 1 shows the M777A2 in action with the USMC.

Figure 1. M777A2 Being Fired. Source: Atlamazoglou (2023).

Weapon systems such as the M777A2 are tested to estimate their component failure rates before being fielded to the military. Component failures occurring on predictable bases are added to a schedule for routine maintenance, which we call scheduled maintenance (SMX). SMX allows the military to predict maintenance costs and maximize operational readiness by synchronizing operations' planning with upcoming maintenance requirements.

However, randomly occurring component failures burden the military with both unexpected costs and surprise losses to operational readiness. When these failures inhibit the safe and effective use of the howitzer, we refer to them as deadlining unscheduled maintenance (UMX) events. Previous work emphasizes the need to increase the rigor of weapon system testing to improve estimated failure rates and thereby operational readiness (Freeman et al. 2019). Successfully improving failure-rate estimates may decrease UMX events while increasing SMX requirements. Fewer UMX events, even at the cost of added SMX, allow the military to better synchronize operations and budgets with upcoming maintenance requirements.

This thesis analyzes the frequency of UMX events and their associated repair costs for six howitzers to determine a correlation with the usage of each howitzer. To do this, we analyzed maintenance records from 2016 through 2021 for six M777A2 howitzers. Figure 2 shows the total cumulative number of UMX and SMX repairs over time for these six howitzers, which demonstrates a relatively constant rate of SMX and an increasing rate of UMX events.

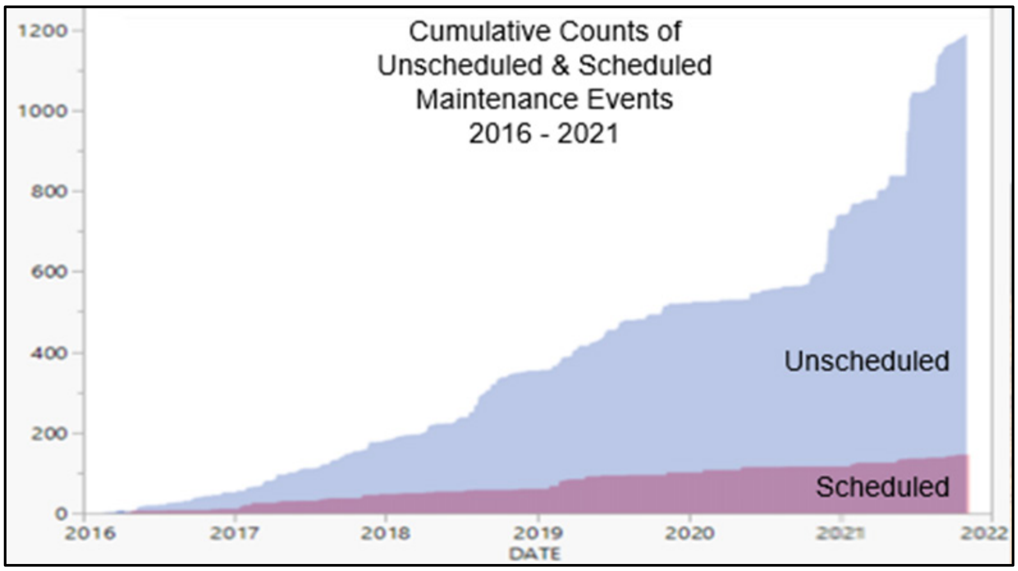


Figure 2. Cumulative Counts of Unscheduled and Scheduled Maintenance Events for Six M777A2 Howitzers.

This thesis explores the relationship between the occurrence of UMX events and costs with the usage of the howitzers. We use two separate metrics of usage, both of which are recorded on DA Form 2408-4 gun cards, which are maintained by the crew of each howitzer. A gun card records various information each time the weapon system is fired and is subsequently entered into an online database (Tulsa 2022). By combining the usage data with the UMX data, we analyze potential relationships to improve estimated failure rates.

We have two study issues. First, we model the frequency of UMX events against both usage metrics to determine if failure rates vary relative to usage. Second, we model the cost of repairing an UMX event against both usage metrics to determine whether costs change with usage.

To conduct this analysis, we next review literature focusing on predicting maintenance costs and applicable modeling techniques. Then we discuss the data available and how it is formatted to facilitate our analysis. Next, we describe both predictor and response variables and outline our methodology. Lastly, we provide the results of our work and recommend areas for future study.

II. LITERATURE REVIEW

There are many techniques to build predictive maintenance models, but we did not find a definitive method or predictor of UMX events for any weapon system. Nonetheless, the literature contains insights to shape our analysis. These insights include common issues with data quality, sample size, the use of parametric and nonparametric techniques, and the applicability of usage data to facilitate accurate predictions (Freeman et al. 2019).

An emerging practice within the field of maintenance is conditions-based maintenance (CBM). Rather than performing specified maintenance on a rote timetable or waiting for a component to fail before conducting a repair, CBM uses predictive metrics to forecast failures and recommends appropriate maintenance actions before any failures occur. The data used to predict these failures vary by type of equipment. However, the potential benefits of this system cannot be ignored - so long as reliable metrics can be identified. Colegrove et al. (2022) highlights the advantages of CBM with application towards unmanned undersea vehicles to improve the mean time between failures for the U.S. Navy. Although the predictive metrics and methodologies are not specified, they identify the overarching architecture required, the minimum functional capabilities to be maintained, and highlight the potential benefits of CBM. They assert that predicting maintenance requirements will improve overall operational readiness, which underscores our motivation for studying M777A2 howitzers (Colegrove et al. 2022).

Research by Stuetelberg and Thomas (2021) identifies benefits of CBM in commercial fleets, and the authors propose ways the U.S. Marine Corps (USMC) can adapt to attain similar benefits. They found that commercial fleets implemented CBM on crucial pieces of equipment directly tied to generating revenue as either high-value components or low-density components critical to overall production. They also predict cost savings and increased operational readiness if the USMC successfully adopts a CBM program, but they caution that such a shift in maintenance operations requires significant upgrades to maintenance monitoring systems and information technology (Stuetelberg and Thomas 2021).

Hartmann (2001) evaluates maintenance records over a four-year period obtained from the German Army to predict maintenance requirements. Although he found the Weibull distribution effective in simulating supply delivery times and repair times, his resulting predictions of maintenance requirements were unreliable because the analyzed maintenance data was missing 53% of applicable records. Hartmann (2001) discovered data-generating maintenance activities were failing to accurately capture the maintenance records, so procedural steps needed to be taken before meaningful analysis could be completed. This highlights the need for both the right type of data and a complete record of data to enable an effective analysis (Hartmann 2001).

Foley (2015) used a Poisson generalized linear regression model to predict mechanical failures in USMC ground vehicles. He analyzed maintenance records for nearly 3,200 medium tactical vehicles over a three-year period with vehicle mileage as an explanatory variable. His analysis of maintenance data revealed inaccuracies in recorded vehicle serial numbers, regional codes, maintenance defect codes, and odometer readings, which limited the insights that could be gained from his analysis. He attempted to leverage usage-data to explain mechanical failures, but this is another example of how incomplete and inaccurate records are obstacles for an insightful analysis (Foley 2015).

Mimms (1992) developed a program for the USMC to predict maintenance requirements and operational readiness rates using an empirical Bayes approach. His model predicted the amount of time equipment would be in each state of maintenance and developed internal reliability estimators based upon the input data. As in subsequent efforts, the data required to accurately run his model was inconsistently recorded and even incorrectly captured in the maintenance system of record, which limited the quality of his findings (Mimms 1992). This again highlights the need for consistent and accurate data to appropriately train and validate a model.

Chia (2010) used a regression model to predict maintenance costs for operating and maintaining mine resistant ambush protected vehicles using maintenance records over a two-year period. Although able to determine differences in costs between the branches of service, the paucity of data prevented the analysis from detecting statistically significant factors causing these differences (Chia 2010). Chia’s work highlights the need for an extensive series of data to ensure sufficient observations to detect relationships between variables.

Van Houten (1994) built a principal components and logistic regression model to predict aircraft mishaps from monthly maintenance records over a four-year period. He accounted for sixteen predictor variables overall, but his model did not uncover significant relationships between the available maintenance data and the occurrence of aircraft mishaps (Van Houten 1994).

Kovich and Norton (2008) developed a linear regression model and a time series analysis to forecast unscheduled maintenance requirements for infrastructure on U.S. Air Force installations. They used records for a seven-year period including eight predictor variables for two outcome variables. Their model accounted for a substantial portion of variability in the outcome variables (Kovich and Norton 2008).

Exponential and lognormal distributions are often used to estimate mean time to failure or repair. Almog (1979) compared these two distributions on the same maintenance data and concluded the lognormal distribution was the more accurate descriptor. However, the author noted that when the exponential distribution was used, the practical difference between the use of either distribution was small.

Continuing this line of effort, Camozu (1982) confirmed Almog's (1979) finding that the lognormal distributions are preferred to the exponential distribution when modeling mean time to repair. The author continued his analysis and compared results of the lognormal distribution with the gamma distribution in 46 scenarios. He found the gamma distribution was accepted 28 percent more often than the lognormal distribution. However, he noted that applying any of these distributions carries the assumptions that, (1) occurrences are independent from one another and are (2) identically distributed (Camozu 1982).

The relationship between equipment age and the cost of spare parts was investigated by Fan et al. (2005). The authors examined the case of the M1 Abrams tank, which first entered service in 1980, but they did not find any statistically relevant evidence suggesting costs of spare parts increased as the equipment aged. (We note that the M1

Abrams is still in service, albeit in updated models, so applying this finding to original-issue or out-of-service equipment may yield different results.) The authors also discouraged using cost as a dependent variable because budget constraints limit spending, and these limits are unobservable to a researcher. Spare parts are often not purchased until additional funds are released, at which point parts are still prioritized and some denied until sufficient funds are available. In other words, the costs used to train a model represent what was spent instead of what needed to be spent. They did not find a mechanism within the Army that tracks unfunded maintenance requirements. Lastly, they suggest the best cost-predictors for spare parts are equipment location and the frequency and intensity of operations, which further motivates our work (Fan et al. 2005).

Spurred by increasing maintenance expenditures in the USMC during the early 2000s, Romero and Elliott (2009) examined parametric cost-estimating models to predict future budget requirements. The authors acquired data on maintenance expenditures, equipment age, frequency of operations, equipment inventory levels, and procurement costs over a six-year period to conduct their study. The authors found that incomplete and inaccurate data would prevent reliable results, and they made recommendations to improve data collection. To quantify frequency and intensity of operations, the authors recommended that planners use data from operators as opposed to support personnel or maintenance records. Their reasoning was that operators have more familiarity with metrics of usage and have a vested interest in accurately logging operations because it ties directly to after action reports, ammunition accountability, and resupply. To illustrate this point, the authors pointed to artillery chiefs, who record rounds fired into a centrally managed database that can be accessed by planners and analysts. In contrast, mileage is entered into the system of record by supporting maintenance personnel as a mere box-check requirement without any natural incentives for accuracy (Romero and Elliott 2009).

Another method used to predict maintenance requirements is machine learning. Therrio (2018) used a support vector machine to model maintenance requirements for major components of a naval propulsion system. He analyzed 25 variables with nearly 600,000 observations from a vessel's propulsion system. After training his model on part of the data, his predictions on the validating data set had error rates of less than 0.5 percent (Therrio 2018).

Posadas et al. (2020) also applied machine learning to forecast demand for spare parts and demand for maintenance on the F/A-18E/F jet aircraft. They used historical parts demand and maintenance data from a ten-year period to train and evaluate their model. They applied four parametric and six non-parametric machine learning techniques to detect underlying relationships to explain demand for either parts or maintenance. The authors found, however, that the effectiveness of their techniques was limited by data sparsity, particularly when attempting to forecast demand for parts (Posadas et al. 2020). They found greater success simply forecasting the occurrence of a maintenance failure. They recommended using additional data to increase the fidelity of their models (Posadas et al. 2020).

Freeman et al. (2019) discuss the need for improved reliability experiments to increase accuracy of estimated failure rates and to positively impact operational readiness. The authors address reliability modeling of the M109 Paladin, a self-propelled howitzer, and point to flaws in modeling complex systems comprised of many components; as one subsystem is repaired or even replaced, the overall system variance in reliability changes. Additionally, because complex systems are integrated and inter-system dependent, issues arise from assuming failure events are independent and identically distributed as is required when using techniques such as the Poisson, lognormal, or Weibull distributions. They propose tracking operating conditions at the subsystem and component level to predict failures for individual components as opposed to the failure events of the whole system. They also propose modeling failure occurrences from usage (Freeman et al. 2019).

Noting the inherent weakness of modeling techniques that rely on assumptions of independence, Nelson (1988) developed a nonparametric technique called the mean cumulative function (MCF). The MCF can be graphically represented and can estimate both the cumulative cost and the total number of repairs required per unit of age (Nelson 1995). He further explains its applicability when analyzing left-truncated data, which is where the number of total failures or total cost before the observation period are unknown

(Nelson 1990). He explains how the MCF produces standard reliability metrics using recurrence data and can be adapted to include confidence intervals (Nelson 1988).

The primary driver of corrosion within a large caliber gun barrel, such as that belonging to the M777A2 howitzer, is the type of munition fired (Hasenbein 2003). Hasenbein (2003) explains how an artillery "round" is comprised of a charge and a projectile, and both have an impact on the longevity of the barrel. The charge is the propellant that ignites inside the combustion chamber of the barrel, rapidly expands into a high-pressured gas, and expels the projectile through the opposite end of the barrel. The projectile is what kills the target. Projectiles are designed in different weights and have driving bands and obturator bands of various levels of quality, all of which wear the barrel at different rates.

The charge impacts barrel life in two ways: the temperature at which the propellant burns and the amount added to the combustion chamber to expel the projectile (Hasenbein 2003). Different propellants are designed to burn at different temperatures and chemical compositions, all of which corrode the barrel at different rates. However, the more dominant effect on barrel-wear is from the quantity of charge loaded into the combustion chamber, which varies based upon the firing trajectory, range to target, and the type of projectile being fired. More charge equates to higher pressured gas, which leads to more stress on the barrel (Hasenbein 2003).

Because each round fired may have a different type of projectile and a different quantity of charge, merely counting the number of rounds fired is insufficient to measure the amount of stress applied to the barrel. This is where the equivalent full charge (EFC) metric becomes pertinent (Hasenbein 2003). Hasenbein (2003) explains that the EFC is calculated to capture the stress on the barrel from the entire round, both charge and projectile, and that a barrel is designed to last only to a specific number of cumulative EFC rounds fired, at which point the barrel must be replaced (Hasenbein 2003). This explains the significance of metering howitzer usage by both the number of rounds and the number of EFC rounds fired.

III. DATA AND METHODOLOGY

In this chapter we describe our data, its sources, and outline our methodology. The data were obtained from six howitzers belonging to the same active duty Army fires battalion. By using howitzers from the same battalion, we reduce the possibility of confounding variables since these guns are maintained by the same organization, conduct the same exercises, and are tactically deployed in the same environment.

A. DATA

The maintenance data was obtained from the U.S. Army Global Command Supply System (G-Army), which is the sole system of record in the Army for ordering parts and updating the maintenance status for each piece of equipment. The data includes a record for each opened workorder with the following fields: date the component failure is discovered; whether the equipment is deadlined; whether the workorder is for SMX or UMX; the serial number of the relevant weapon system; and when a part is ordered, received, and installed. The data includes all maintenance events from February 2016 through November 2021. The number of UMX events for each howitzer is depicted in Figure 3.

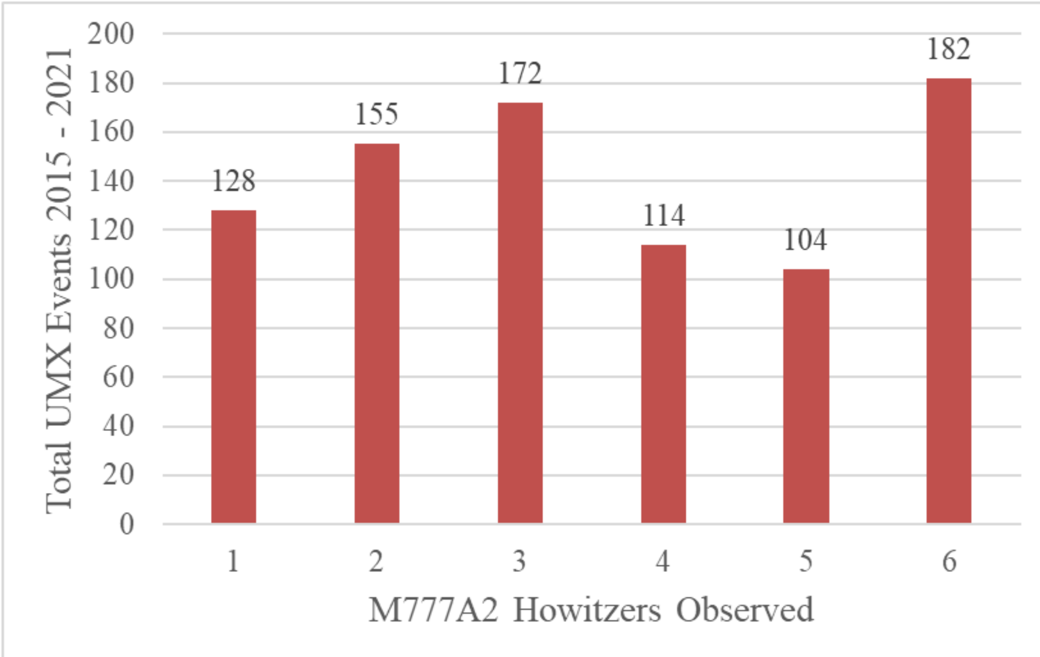


Figure 3. Total UMX Events by Howitzer 2015-2021.

To measure usage, we use the number of rounds fired and the number of EFC rounds fired, which are both recorded on DA Form 2408-4 gun card. The information on the gun card is recorded by the gun crew of each howitzer and is entered into an online database. Table 1 shows an example gun card's header; note that it tracks the serial number of both the gun barrel (aka, "tube") and the entire weapon system (aka, "cannon"). (The howitzers we analyzed were all on their first tube.) It also provides the maximum EFC lifespans of both the tube and weapon system.

Table 1. Example DA Form 2408-4 Gun Card Header.
Adapted from Tulsa (2022).

1. Tube Serial 9101P	2. Cannon Type, Model or Series M256 Cannon, 120mm Gun		3. ORGANIZATION (UIC/UNIT) WAGRC0 (IN BN 02 CO C ARMOR HB	4. SPECIAL LIFE DATA Condemn the cannon tube when 1500 EFC rounds have been fired. Comdemn the cannon when it reaches 4500 EFC rounds.
5. End Item Identification SN: LA23042U (Tank, Combat, FT: M1A1/M1A2)			6. RDS/EFC COMPUTATION	
7. Cannon Serial 8199	8. Retubings 1	9. Rebushings	ZONE | EFC FACTORS	
Cumulative EFC RDS fired for Cannon: 229.000				

Tubes:	Status	Tube Serial	EFC Rounds
	Active	9101P	37.000
	Previous	9538	192.000

Once the crew returns from the firing range, the gun card entries are transcribed to an online database centrally managed within Army Materiel Command (Tulsa 2022). Example usage data is shown in Table 2 and includes the type of projectile, charge, number of rounds fired, number of EFC rounds fired, and cumulative round counts. Of the four firing events depicted in Table 2, note how the number of rounds fired vary from one to five whereas the number of EFC rounds fired ranges from 0.05 to 1.25. Because of the magnitude at which these two metrics vary, we will analyze the UMX event data against each usage metric separately.

Table 2. Example DA Form 2408-4 Weapon Record Data. Adapted from Tulsa (2022).

10. Date	Projectile Type	Zone or Charge	Rounds Fired	EFC RDS Fired	Cumulative RDS fired	Remaining Life (EFC RDS)	Remarks: Recoil Exercise (RE), Gage or Velocity Reading, Safety Inspection (SI)	Signature
10-03-2012	PROOF FIRING	PROOF PROOF 1.25	1	1.25	1	2,648.750	Proofed at ___ by ___	
10-18-2012		NA					BORESCOPE. BORESCOPE AND STARGAGE INSPECTIONS PERFORMED AT APG. S/G = 6.102" SERVICEABLE.	
10-18-2012		NA					BORESCOPE. MAGNETIC PARTICLE INSPECTION AND BLACKLIGHT BORESCOPE PERFORMED AT ___. SERVICEABLE.	
08-12-2013		NA					BORESCOPE. PERFORMED BY ___ AT ___. SERVICEABLE.	
08-12-2013		NA					PULLOVER GAGE: 6.105. ACTUAL P/O = 6.102" PERFORMED BY GEORGE FRANCK AT YPG. SERVICEABLE.	
12-17-2013	M107, HE	M232/M232A1 3	1	0.1	2	2,648.650	Fired at ___ by test director ___.	
12-17-2013	M107, HE	M231 1	1	0.05	3	2,648.600	Fired at ___ by test director ___.	
12-17-2013	M795, HE	M203/M203A1 8-S	5	5	8	2,643.600	Fired at ___ by test director ___.	

The maintenance data is left-truncated because we do not know how many failures the howitzers experienced prior to the observation window (Nelson 1990). However, the usage metrics maintain cumulative counts and are analogous to the mileage on a personally owned vehicle. A vehicle's mileage never resets, it increments each time the vehicle is driven, and SMX requirements are metered according to the car's mileage. Likewise, the cumulative rounds and EFC rounds fired never reset, and they both increment every time the howitzer is fired. This allows us to analyze whether the rate UMX events occur is correlated with usage. Figures 4 and 5 show the total cumulative rounds and EFC rounds fired, respectively, at the start and end of the observation window.

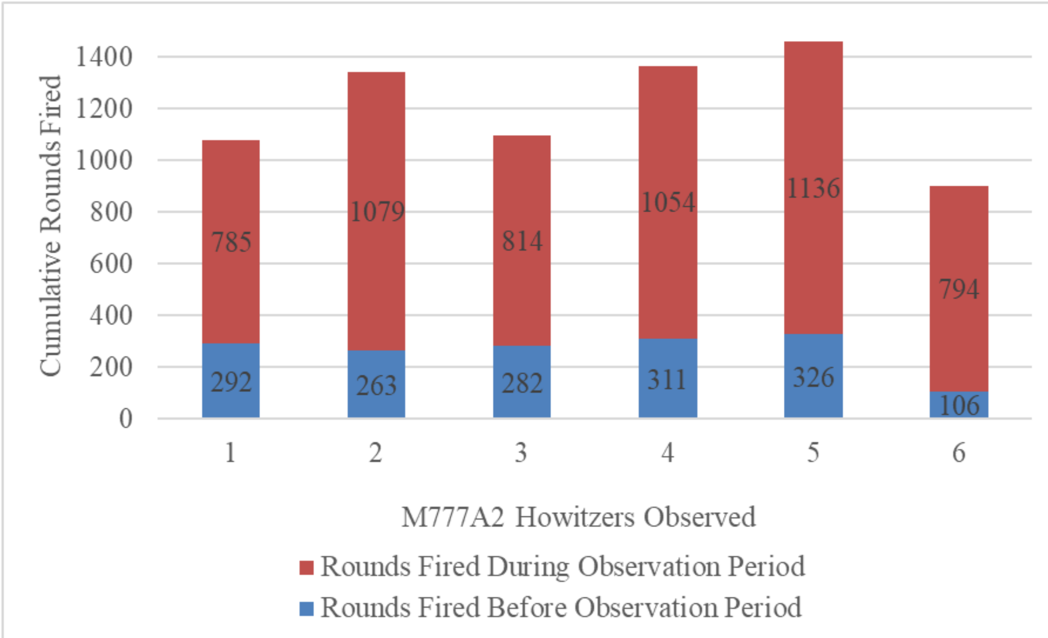


Figure 4. Cumulative Rounds Fired Before and After Observation Period By Howitzer.

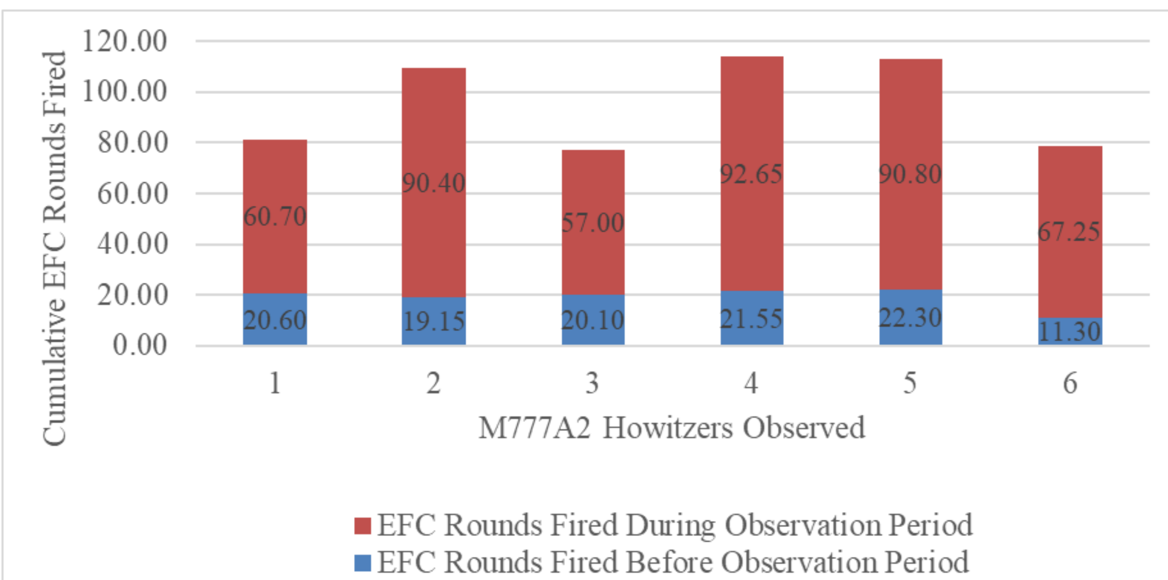


Figure 5. Cumulative EFC Rounds Fired Before and After Observation Period By Howitzer.

B. METHODOLOGY

In this section we explain how we formatted the data into a single dataset, the explanatory and response variables, how we apply the MCF, and the hypotheses that we consider. Then we provide an overview of the software used to conduct the analysis.

1. Data Formatting

We find that UMX events tend to be clustered where the closing of one event often leads to the initiation of a new event. This tendency may have several contributing factors, but we find it plausible that troubleshooting an initial mechanical failure leads to discovering additional faulty components, which results in new maintenance records. We assume that firing the howitzer is the dominant force leading to equipment failure. By metering gun life in cumulative rounds fired, we consider a cluster of UMX events occurring between firing events as a single UMX event. For example, if ten UMX events are recorded between two firing events, then each component failure is assumed to have been caused by the preceding firing event. Consequently, these ten maintenance records are combined into a single UMX event. Their costs are summed together because all ten are associated with the same level of usage, i.e., cumulative rounds fired or cumulative EFC rounds fired.

We combine the maintenance records with the firing data into a dataframe and orient each UMX event to a cumulative level of usage. This is analogous to recording the maintenance actions on a vehicle to its mileage; the dataset does not include a row for each mile driven, but instead only has a row for each maintenance action and the associated mileage when that action occurred. By doing this, we create a record within the dataset for each UMX event, which includes the serial number of a howitzer, two cumulative levels of usage, and the cost of that UMX event.

2. Variables

The two explanatory variables are the cumulative rounds fired and the cumulative EFC rounds fired. Each of these variables is paired with the UMX data independently to determine which, if any, effects the frequency of UMX events or costs. The cumulative rounds fired is an integer representing the total rounds fired by a howitzer. The same process is used for the cumulative EFC rounds fired, but the EFC round count is measured to two decimal places.

We examine two response variables: the occurrence of an UMX event and cost of the UMX event. The occurrence of an UMX event is binary and is described as a function of usage. A value of zero means that no UMX event occurred while a value of one indicates that an UMX was observed at that point of usage. Likewise, the cost of the UMX event is a dollar amount recorded to two decimal places. Each response variable is evaluated independently of the other.

3. MCF

To examine the relationship between the explanatory and response variables, we use the mean cumulative function (MCF). The MCF is a nonparametric estimator of the cumulative frequency of discrete events per unit of usage or time (Nelson 1988). If a system does not change its frequency of events over time, the MCF should be well approximated by a line, the slope of which gives the frequency and is often denoted λ and interpreted as the rate of a homogeneous Poisson process. If the frequency of events is increasing over time, the MCF is sometimes approximated by a model of the form $\alpha\, t^{\beta}$, where t represents usage or time, and β is a parameter that is greater than 1. In this case the occurrence of events may be described as a power non-homogeneous Poisson process (PNPP) with an increasing rate. If β is equal to zero, the rate is constant and a homogeneous Poisson process is obtained as a special case. The MCF can also be used to describe the mean cumulative cost per unit of usage (Nelson 1988). We apply the MCF once against each metric of usage. For instance, we use *cumulative rounds fired* for one analysis, and we use *cumulative EFC rounds fired* for the second analysis.

The first analysis describes the number of UMX events at a moment in usage (Nelson 1988). We get this by summing the number of UMX events at a given level of usage and dividing by the number of howitzers observed at that level (Nelson 1988). The result is an estimate of the expected number of UMX occurrences per howitzer at the given level of usage (Nelson 1988).

The second analysis describes the average cost of repair per howitzer per unit of usage (Nelson 1988). This number is computed by summing the total costs at a given level of usage and dividing by the number of howitzers observed at the given level of usage (Nelson 1988). The result is an estimate of the expected cost of repairs per howitzer at the given level of usage.

When plotted, the resulting curve visually describes the evaluated system (Nelson, 1988). The change in slope of the MCF curve allows us to describe the weapon system as improving, stable, or deteriorating as depicted in Figure 6 (Nelson, 1988).

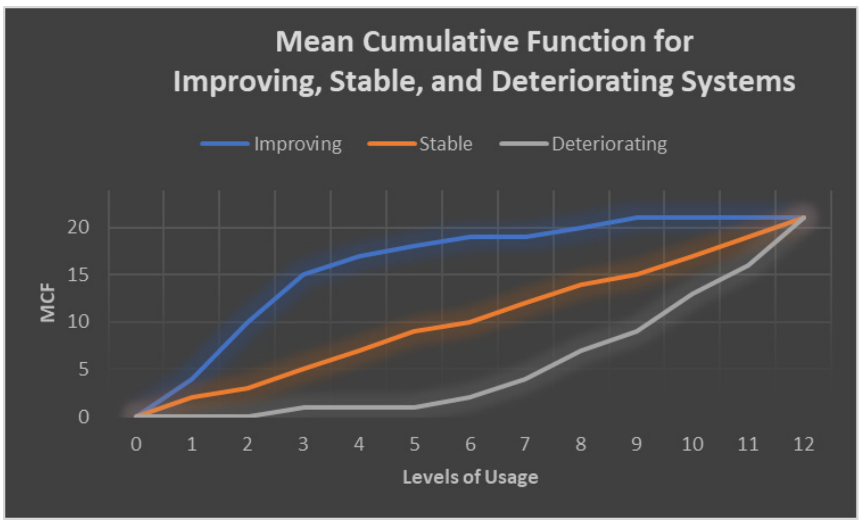


Figure 6. Example Graphical Representation of the Mean Cumulative Function.

If the slope of the MCF curve is decreasing as cumulative usage increases, then the howitzers can be described as improving because the rate UMX events occur is diminishing as overall usage increases. However, if the MCF curve is linear, the howitzers are described as stable because the rate at which UMX events occur is unchanging as overall usage increases. Lastly, if the MCF curve increases as overall usage increases, the howitzers will be described as deteriorating because UMX events are more common per unit increase of usage.

Apart from observing the changing slope of the MCF curve, the key quantifiable metric is the β parameter from a fitted power nonhomogeneous Poisson process (PNPP) equation. A 95 percent confidence interval is obtained by taking the fitted equation's β estimate plus/minus twice its standard error (SE). If the β parameter's 95 percent confidence interval includes one, then the MCF curve is said to be stable. If the β parameter's 95 percent confidence interval is entirely less than one, we can conclude that the MCF curve is improving. If the β parameter's 95 percent confidence interval is entirely more than one, we can conclude that the MCF curve is deteriorating.

It is important to consider that our data is left-truncated (i.e., each howitzer had a period of usage before maintenance events were recorded). As shown in Figures 4 and 5, all six howitzers fired at least 106 rounds and at least 11.30 EFC rounds before the observation period began, and the number of UMX events that occurred before the observation period are completely unknown (Nelson 1990). Consequently, the resulting MCF curve will intersect the x-axis at the number of cumulative rounds where the first observed UMX event occurred, which is no less than 106 rounds fired and no less than 11.30 EFC rounds fired. As shown in Figure 7, the MCF curve for the number of UMX events per unit cumulative rounds fired intersects the horizontal axis at about 250. This implies that the first observed UMX event was at 250 rounds fired.

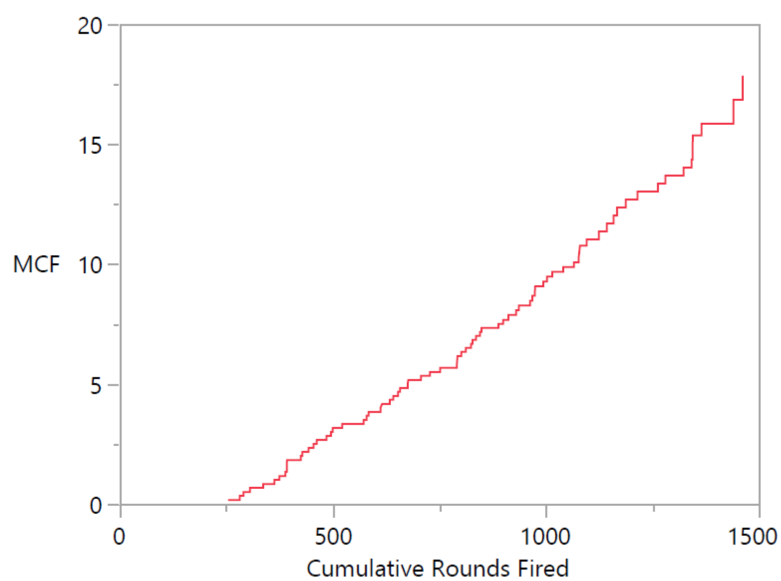
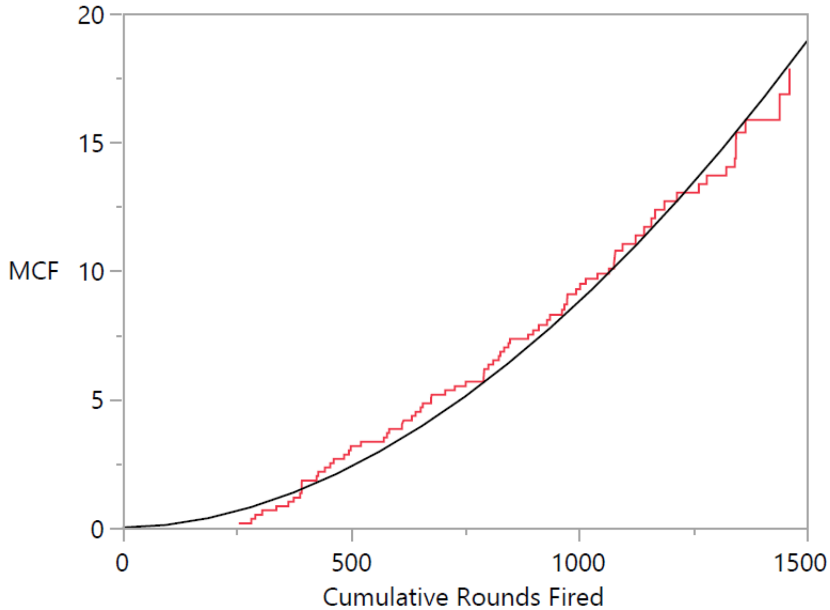


Figure 7. MCF for UMX Events vs. Cumulative Rounds Fired.

We use the software JMP to visualize the data and fit the PNPP curve. When fitting the PNPP curve, JMP starts the curve at the origin. This introduces bias into the fitted model as JMP attempts to fit a curve from the origin to the intercept. Figure 8 illustrates a distorted curve that begins at the origin while the MCF curve begins at 250 cumulative rounds fired.



Fitted Recurrence Model

Power Nonhomogeneous Poisson Process

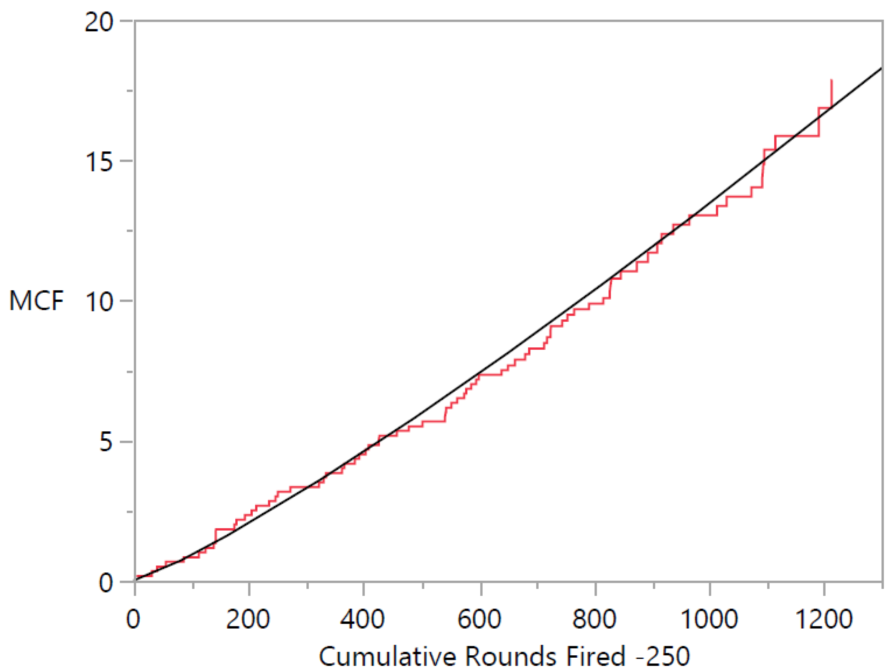
Parameter Estimates

Parameter	Estimate	Std Error
θ Intercept	317.58367	51.354376
β Constant	1.8936416	0.207188

Figure 8. MCF for UMX Events vs. Cumulative Rounds Fired with a Distorted PNPP Curve.

The MCF curve in Figure 8 appears linear, which suggests a failure to reject the null hypothesis. An approximate 95 percent confidence interval for β is obtained as 1.89 ±

2(.21) = (1.47, 2.31) which is entirely greater than one, suggesting the howitzers are deteriorating and that the MCF curves upwards. The inflated value of the β parameter is due to truncation. To eliminate this distortion, we shift our MCF curve to the left so that the intercept is at the origin. We do this by subtracting the value of the intercept, in this case 250, from every recorded value of cumulative rounds fired. Figure 9 illustrates the adjusted MCF curve with the appropriately fitted PNPP curve. The new 95 percent confidence interval for β is $1.17 \pm 2(.13) = (.91, 1.43)$, which includes one and justifies not rejecting the null hypothesis at the .05 test level.



Fitted Recurrence Model

Power Nonhomogeneous Poisson Process

Parameter Estimates

Parameter	Estimate	Std Error
θ Intercept	108.87764	28.641556
β Constant	1.1715761	0.1299702

Figure 9. Adjusted MCF for UMX Events vs. Cumulative Rounds Fired with Correctly Fitted PNPP Curve.

Again, we only adjusted the MCF curve to correctly estimate the β parameter. If we want to infer the mean number of UMX events for cumulative rounds fired, we must reference Figures 7 or 8.

4. Hypotheses

The null hypothesis is there is no relationship between the explanatory variables and the response variables. This is made evident by a linear MCF curve and verified if the β parameter has a 95 percent confidence interval that includes one. If we fail to reject the null hypothesis, then the available evidence is insufficient to suggest a relationship between the explanatory and response variables.

Conversely, the alternative hypothesis is that β is not equal to one. If the β parameter has a confidence interval that is entirely less than one, it means the howitzer is improving with usage. If the β confidence interval is above one, then the system is said to be deteriorating in some respect, such as an increasing rate of failures or cost.

5. Software Utilization

To answer our study issues, we analyze our dataset using the recurrence analysis tool in JMP, which is a SAS software product (SAS 2021). This tool plots the MCF curve and fits a PNPP equation to estimate the β parameter and SE. Together these allow us to visually evaluate the results and to numerically justify our assessment of the null hypothesis.

To apply the model, we assign an explanatory variable to the "age" role and a response variable as a "cost" role (SAS 2021). For example, cumulative rounds fired would be assigned as the "age" while the financial expenditure for each UMX repair would be assigned as the "cost." The serial number for each howitzer is assigned to the "system ID" role (SAS 2021). These designations allow JMP to generate the MCF curve, which is used to determine the mean expected cost or number of UMX failures per unit usage. Next, we fit a PNPP model to the adjusted MCF curve to generate the β parameter and SE, which allows us to mathematically evaluate the null hypothesis (SAS 2021).

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IV. RESULTS

Here we review the results of our analyses and answer both study issues.

A. FIRST STUDY ISSUE

The first study issue is whether the occurrence of UMX events is correlated with usage. Since we have two usage metrics, we begin by evaluating the occurrence of UMX events relative to cumulative rounds fired. Figures 7, 8, and 9 illustrate this analysis. As depicted in Figure 9, the correctly fitted PNPP curve has a β parameter confidence interval that includes one, so we fail to reject the null hypothesis at the .05 test level. This data does not suggest the occurrence of UMX events is correlated with cumulative rounds fired.

Now we examine whether the occurrence of UMX events is correlated with cumulative EFC rounds fired. Figure 10 shows the MCF curve, and immediately we can see its linear characteristic closely resembles the MCF for cumulative rounds fired illustrated in Figure 7.

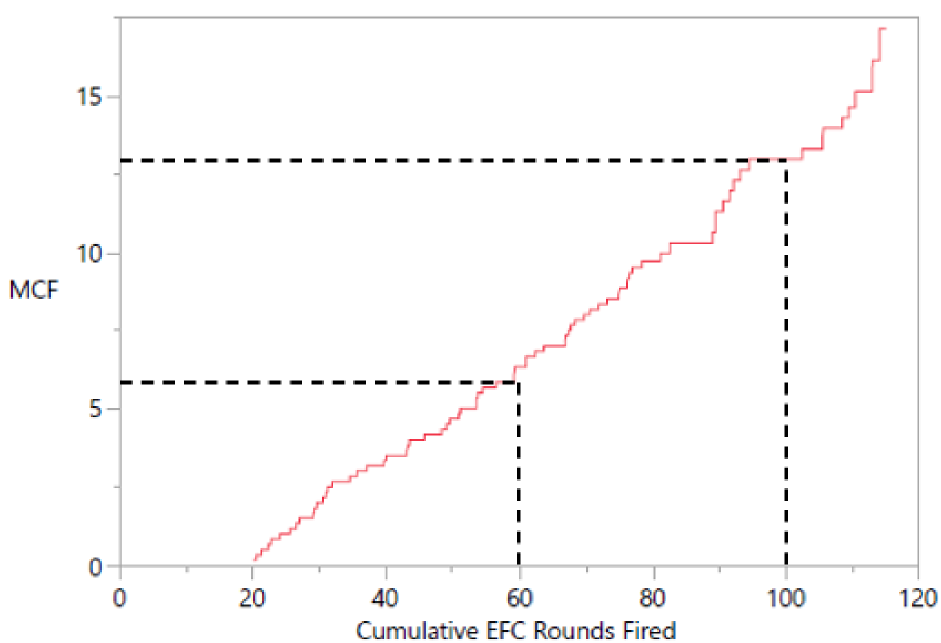
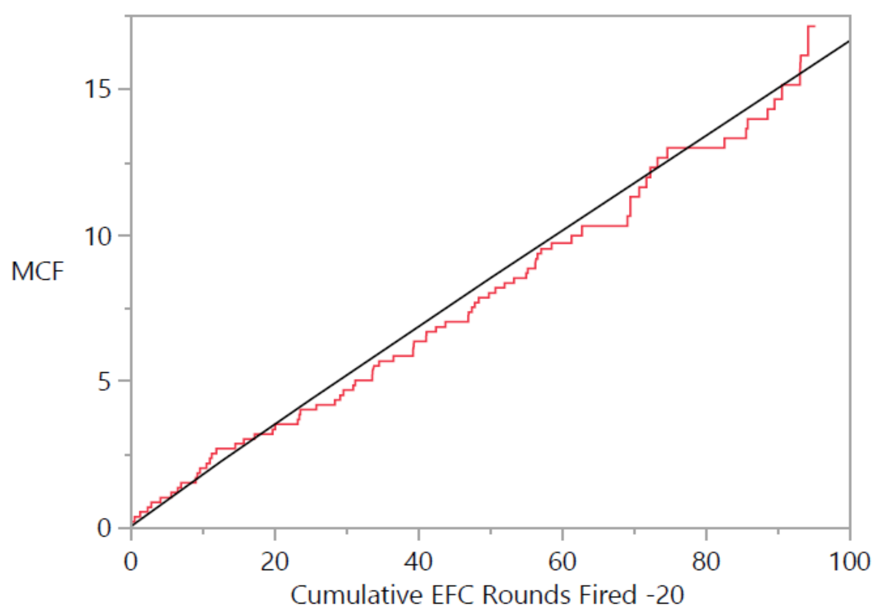


Figure 10. MCF for UMX Events vs. Cumulative EFC Rounds Fired.

For these six howitzers, we can expect to experience six UMX events per howitzer while cumulative EFC rounds fired increases from 20 to 60. And as the cumulative EFC rounds fired increases from 60 to 100, we can expect another seven UMX events to occur for each howitzer. The rate UMX occur appears relatively constant.

Additionally, after adjusting the MCF curve to the left 20 units and fitting the PNPP equation, we see the β parameter's 95 percent confidence interval is (0.75, 1.19), which includes one. Thus, this evidence fails to suggest any relationship exists between the occurrence of UMX events and cumulative EFC rounds fired at the .05 test level. Figure 11 shows the adjusted MCF curve and the β parameter estimate. Consequently, we fail to reject the null hypothesis for both metrics of usage. This evidence suggests these usage metrics do not have any impact on the occurrence of UMX events.



Parameter Estimates

Parameter	Estimate	Std Error
θ Intercept	5.4861662	1.7505726
β Constant	0.9681384	0.1079694

Figure 11. Adjusted MCF for UMX Events vs. Cumulative EFC Rounds Fired with PNPP Curve and β Estimate.

B. SECOND STUDY ISSUE

Our second study issue is whether the cost of repairing UMX events is correlated with usage. Since we have two usage metrics, we begin by evaluating the cost of UMX events relative to cumulative rounds fired. Figure 12 depicts an unusual stepping pattern that appears to be increasing as cumulative rounds fired increases.

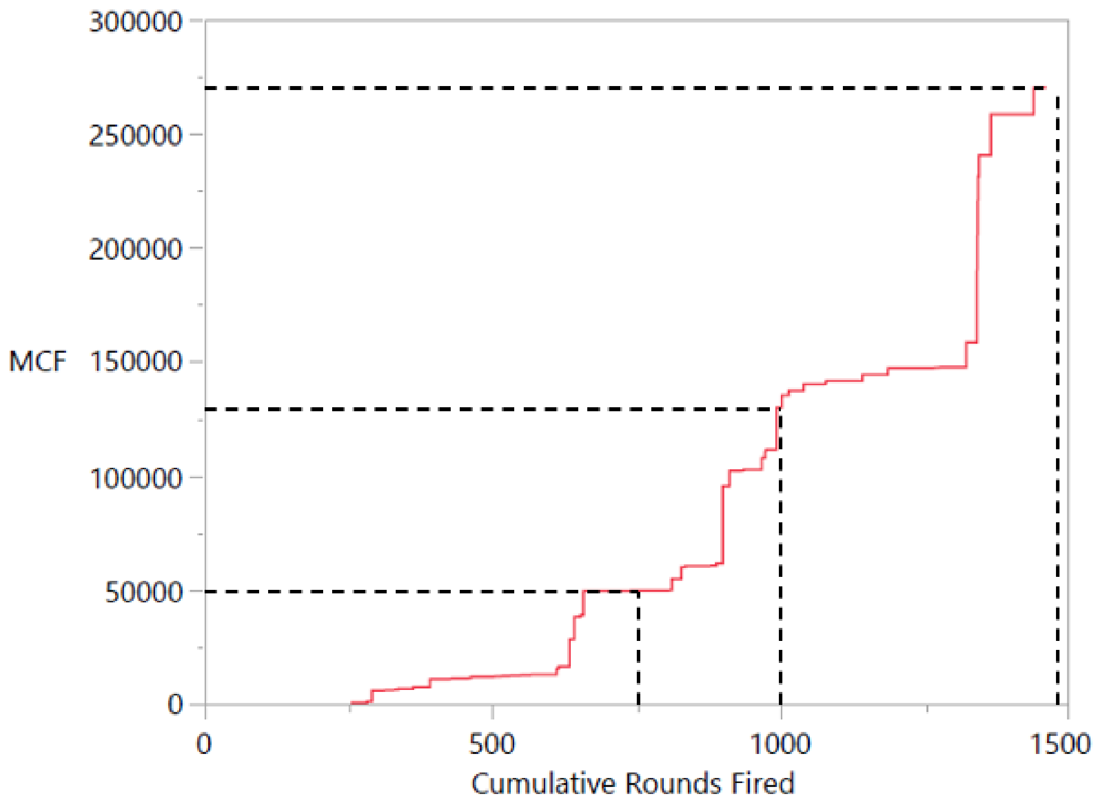
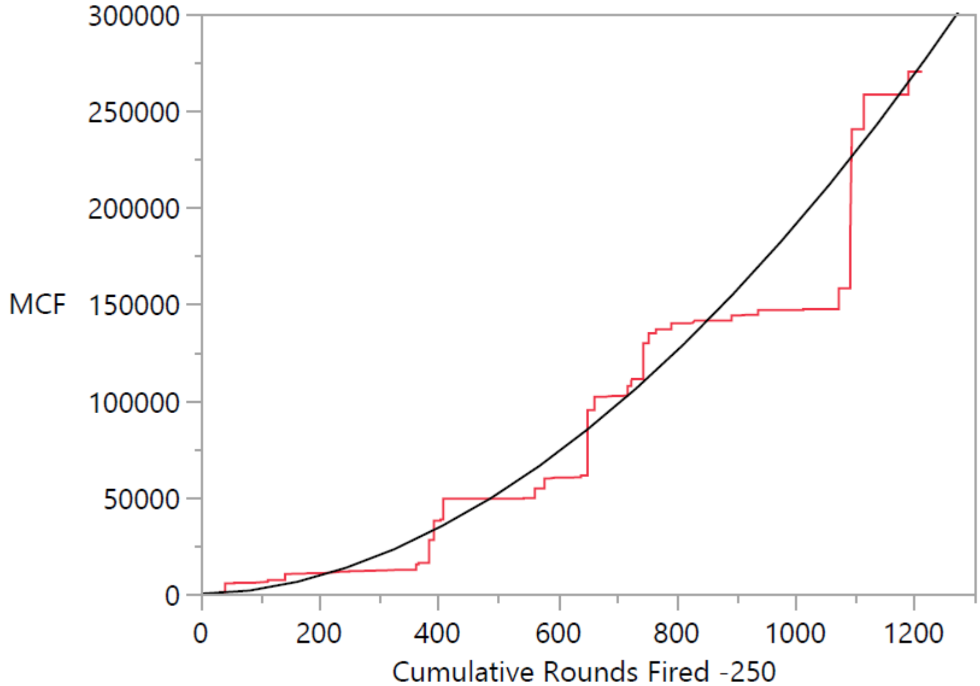


Figure 12. MCF of UMX Costs vs. Cumulative Rounds Fired.

For instance, usage from 250 to 750 cumulative rounds fired incurs an expected cost of approximately $50,000 per howitzer. However, the expected cost of maintenance from 1,000 to 1,500 cumulative rounds fired increases to approximately $125,000 per howitzer. This data suggests costs increase markedly after 750 cumulative rounds fired and again around 1,250 cumulative rounds fired.

After adjusting the MCF curve to the left 250 rounds to align the intercept with the origin, we fit the PNPP model and estimate the β parameter. Figure 13 shows an increasing curve with an approximate 95% confidence interval for β at (1.87, 1.88) that is well above one. This confirms that these howitzers are deteriorating and UMX costs increase at an increasing rate as more rounds are fired. We reject the null hypothesis and conclude that UMX costs are positively correlated with cumulative rounds fired.



Fitted Recurrence Model

Power Nonhomogeneous Poisson Process

Parameter Estimates

Parameter	Estimate	Std Error
θ Intercept	1.5409222	0.0090446
β Constant	1.8778114	0.0016925

Figure 13. Adjusted MCF of UMX Costs to Cumulative Rounds Fired with PNPP Curve and β Estimate.

Our next analysis compares UMX costs with cumulative EFC rounds fired. Figure 14 demonstrates this MCF curve is increasing.

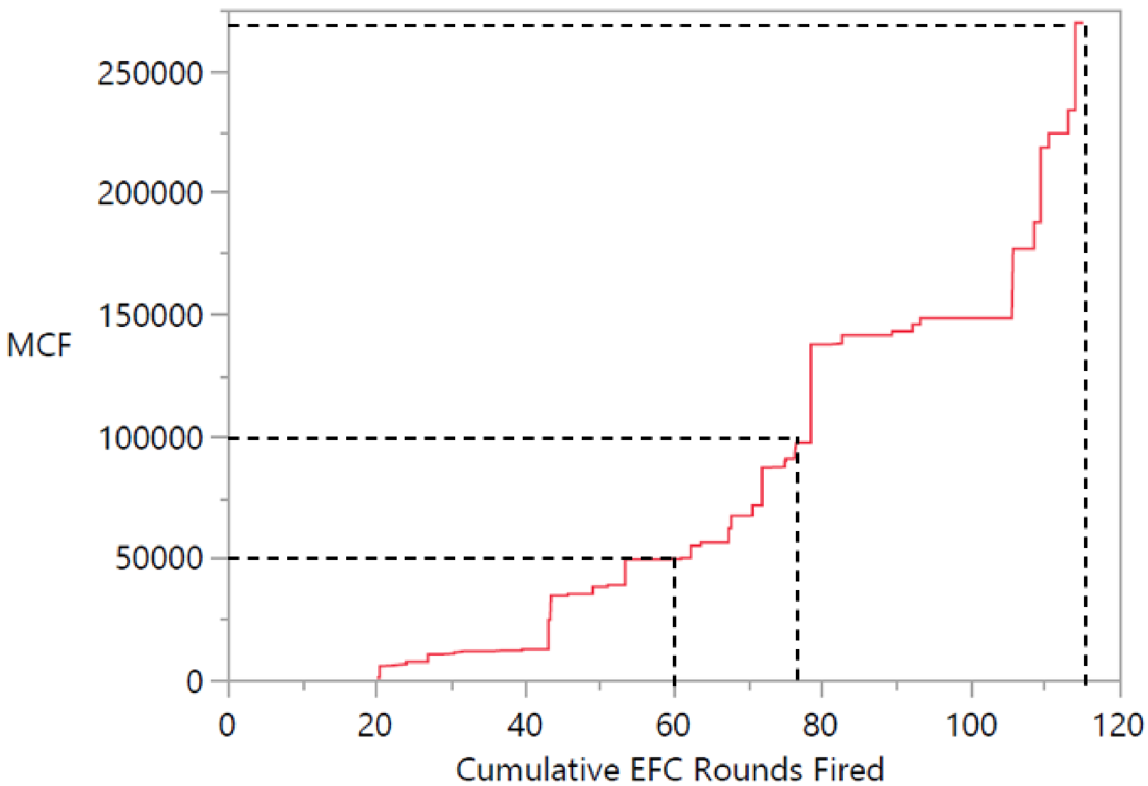
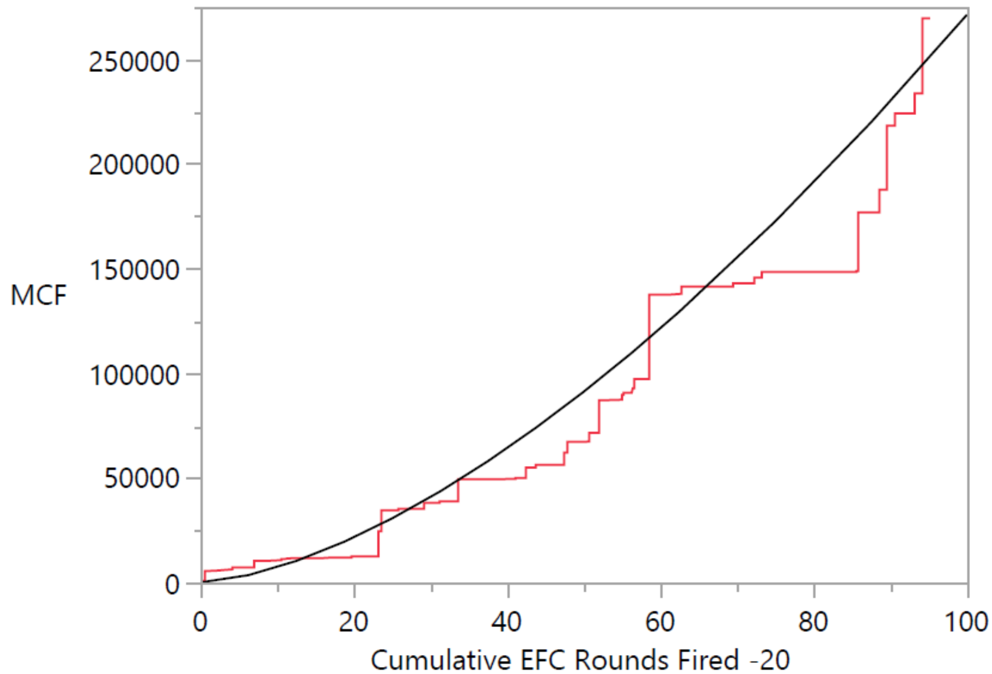


Figure 14. MCF for UMX Costs vs. Cumulative EFC Rounds Fired.

Total costs for UMX events average $50,000 per howitzer during the first 40 EFC rounds fired (from 20 to 60 cumulative EFC rounds fired). However, the last 40 EFC rounds fired (from 78 to 118) show an increase to over $150,000 per howitzer. This data suggests there are definite cost increases around 80 and 110 cumulative EFC rounds fired.

When we adjust the MCF curve to plot the PNPP curve and estimate the β parameter, Figure 15 confirms the M777A2 howitzers are deteriorating.



Fitted Recurrence Model

Power Nonhomogeneous Poisson Process

Parameter Estimates

Parameter	Estimate	Std Error
θ Intercept	0.0352208	0.0002484
β Constant	1.5733914	0.0014291

Figure 15. Adjusted MCF of UMX Costs vs. Cumulative EFC Rounds Fired with PNPP Curve and β Estimate.

UMX costs are also increasing relative to the cumulative EFC rounds fired. The approximate 95 percent confidence interval for β is (1.571, 1.573) which is well above one, leading us to reject the null hypothesis at the .05 test level. We therefore conclude that the data demonstrate a positive correlation between UMX costs and cumulative EFC rounds fired. For study issue two, we reject the null hypothesis: these usage metrics are positively correlated with UMX costs.

V. CONCLUSIONS AND RECOMMENDATIONS

If weapon systems experience component failures on predictable bases, their impacts can be mitigated by adding routine inspections and maintenance actions. Expanding SMX allows military organizations to better synchronize maintenance requirements with operational requirements and budgets. However, UMX events occurring randomly shock budgetary constraints and hinder operational readiness. Freeman et al. (2019) discuss the need for improved reliability experiments to increase the accuracy of calculated failure rates, and they suggest using nonparametric techniques and usage data. Incidentally, Nelson (1988) developed the MCF, which is a nonparametric method for modeling reliability relative to usage. Freeman et al. (2019) motivated us to improve estimated failure rates and Nelson gave us the tools to do it.

We used the MCF to analyze whether the occurrence of UMX events and the costs of repairing those events are correlated with either of two usage metrics, cumulative rounds fired and cumulative EFC rounds fired. We found the rate UMX events occurred was unrelated to either usage metric and we failed to reject the null hypothesis for study issue one. However, the costs of repairing UMX events increase as these howitzers accumulate more total usage. Cumulative rounds fired demonstrated spikes in costs after 750 and 1,250 rounds, while cumulative EFC rounds fired showed sharp increases in costs around 80 and 110 EFC rounds. We reject the null hypothesis for study issue two at the .05 test level and conclude this evidence shows strong correlation between usage and UMX costs.

Improved maintenance data and accessibility may provide valuable insights such as refining failure rates for specific components (Freeman et al. 2019). Detailed analysis on specific components or parts could be completed if the part-numbers were added to the automated G-Army report. This would allow researchers to develop models predicting failures of specific components instead of attempting to model the entire weapon system as a single entity. Additionally, rather than having a free-text cell for maintenance clerks to describe mechanical failures, inputting a drop-down menu of predetermined components or types of actions would increase the potential for refining the predictive maintenance program for the Army. Lastly, researchers may yet discover a relationship between usage and the occurrence of UMX events if a larger sample of data could be analyzed.

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