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QUANTITATIVE ASSESSMENT OF BARREL WEAR FROM SOLID COPPER BULLETS

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QUANTITATIVE ASSESSMENT OF BARREL WEAR FROM SOLID COPPER BULLETS

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A THESIS APPROVED FOR THE
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Quantitative Assessment of Barrel Wear from Solid Copper Bullets Abstract

Forensic firearm analysis is based on the principle that firearms impart individual characteristics on bullets and cartridge cases during the firing process, and these individual characteristics can be used to trace a bullet or cartridge case back to the firearm that shot it. For bullets, these characteristics are created by the features inside the barrel. However, these features are subject to change and wear, and this can lead to the inability to identify the firearm that shot a specific bullet. There are many ammunition types on the market, and each type may affect barrel features differently. Literature in the field primarily focuses on the effect of conventional ammunition (i.e., jacketed lead core). One study has been conducted on solid copper bullets, and it indicates that they may have a greater effect on barrel individual characteristics than conventional ammunition. The goal of this research was to determine how solid copper bullets affect barrel rifling characteristics after the successive firing of 500 rounds through a new Glock 19 Gen 5 with a Glock Marksman Barrel. From the 500 bullets, 68 were collected for further analysis. The first ten and last ten bullets were used to profile the barrel characteristics at the beginning and end of the study while every tenth bullet was collected to track any changes in the features. Three-dimensional scans of the land engraved areas (LEAs) were generated using the Cadre Forensics Versa system. Cadre Forensics' implementation of the Congruent Matching Profile Segments algorithm was used to compare the depths of the LEAs. The data were analyzed using the Kwiatkowski-Phillips-Schmidt-Shin time series test, and it showed that the data exhibit a significant decreasing trend. Based on the algorithm scores and visual examinations of the LEA scans and depth profiles, this study demonstrates that solid copper bullets have a significant effect on the individual characteristics within firearm barrels.

Dedicated to my husband and my parents. Thank you for always believing in me.

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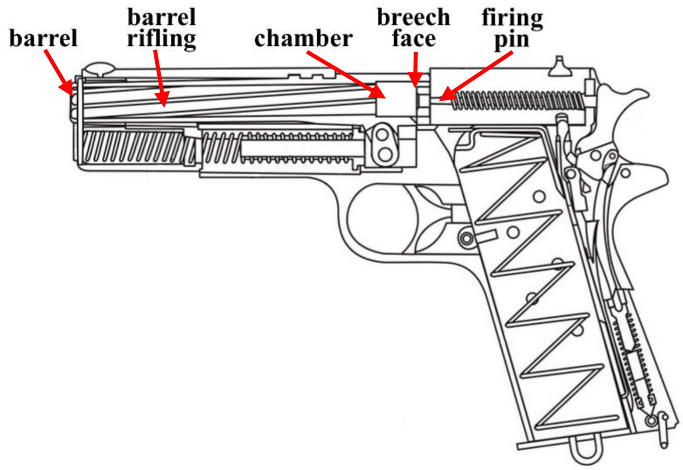
Introduction

Forensic firearm examiners are tasked with determining if a piece of firearm evidence, specifically a fired cartridge case or bullet, was fired from a suspect firearm. To do this, test shots are fired from a suspect firearm to create known exemplars of that firearm's characteristics. Firearm examiners then compare the unknown evidence to these exemplars. The goal of comparisons is to either identify the correct firearm that shot the evidence or eliminate a firearm from the suspect list. While the correct firearm can be identified, forensic firearm examiners are not responsible for establishing who shot the firearm. Other responsibilities of firearm examiners include distance determinations and serial number restorations, but firearm identification is the bulk of their work.

An important discussion in firearm examination is the extent in which individualizing features of firearms change over time. Demonstrating if and how these features evolve can provide examiners with a better understanding of how to conduct analysis. The bullet or cartridge case material, different firearm manufacturing techniques, and the number of rounds consecutively fired are all factors that can affect the appearance and longevity of identifying characteristics. Current literature primarily focuses on the individual characteristics of several essential elements of a firearm. Many articles discuss the breech face, chamber, and barrel because these parts leave the most individual characteristics on firearm evidence (Figure 1). Such research supports the field of firearm examination by helping solidify the examination standards supported by the Association of Firearm and Tool Mark Examiner (AFTE) Theory of Identification.

Figure 1: *Parts of a firearm*



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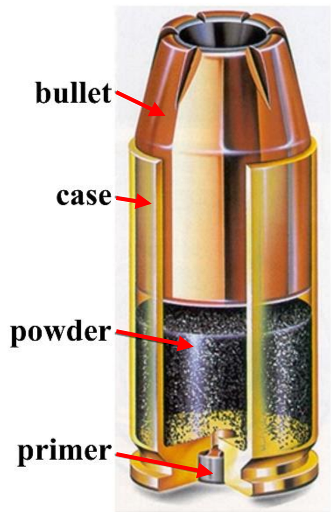
Throughout the literature, one factor that needs additional research is the effect of consecutively firing solid copper bullets on the individual characteristics of firearm barrels. Extensive research has been conducted on full metal jacket ammunition and how it changes the surface features in barrels, but the current knowledge on other types of ammunition is limited. Because solid copper bullets are more expensive than conventional ammunition, they are not yet widely used (Remington, 2023). Therefore, solid copper bullets are not often seen in crime laboratories. If bullet material influences the persistence of individual characteristics, examiners should be aware of what bullet material has the greatest effect. Research on how individual characteristics change after firing solid copper bullets can increase an examiner's knowledge of the lifespan and value of these characteristics.

Basics of Firearm Examination

When two objects come in contact with one another, the harder object often leaves marks on the softer object; this is the basis of firearm and toolmark examination (Monturo, 2019). Toolmark analysis examines the markings left on the softer object by the tool. Firearm examination is a sub-discipline of toolmark analysis where the firearm is considered the tool and the ammunition components receive the toolmarks. The primary role of firearm examiners is to analyze cartridge components, i.e., bullets and cartridge cases, to determine if they were fired by a specific firearm (Figure 2; Association of Firearm and Tool Mark Examiners [AFTE], n.d.-a). Any part of the firearm that comes in contact with cartridge cases or bullets may provide important details for examination (Monturo, 2019).

Figure 2: *Components of a cartridge*



Adapted from "What is Firearm and Tool Mark Identification?," by Association of Firearm and Tool Mark Examiners, n.d.-a (https://afte.org/about-us/what-is-afte/what-is-firearm-and-tool-mark-identification). Copyright 2022 by AFTE.

There are two types of characteristics important to examination, class characteristics and individual characteristics, and the firearm manufacturing process creates both on many pieces in the firearm (AFTE, n.d.-a). Class characteristics are defined as “measurable features of a specimen which indicate a restricted group source. They result from design factors and are determined prior to manufacture” (AFTE, 2013d, p. 38). These characteristics can exclude a tool from examination based on its manufactured features. Specific models of firearms will share the same class characteristics, such as the direction of rifling twist in barrels, because they were manufactured in the same manner (Heard, 2008). Individual characteristics are not chosen before manufacture. Instead, they are markings randomly created during manufacture or through use, and this makes them unique to a specific tool (AFTE, 2013g).

Using class and individual characteristics, firearm examiners can make a conclusion about the source of a toolmark. Four possible conclusions are described by AFTE: identification, inconclusive, elimination, and unsuitable (AFTE, 2013j). A conclusion of identification means that the characteristics of two objects exhibit sufficient agreement while an elimination means that the objects have sufficient disagreement. According to the AFTE Theory of Identification, sufficient agreement exists when “the likelihood another tool could have made the mark is so remote as to be considered a practical impossibility” (AFTE, 2013k, p. 124). A comparison can be inconclusive if the objects’ features are insufficient for either an identification or elimination. Objects unsuitable for analysis, such as small bullet fragments, would result in an unsuitable conclusion. These conclusions can be reached using several analysis techniques.

There are two primary techniques used in firearm examination. Conventional analysis requires the examiner to use a comparison microscope to analyze surface features on bullets or cartridge cases (Heard, 2008). Conclusions can be made once a sufficient number of similarities or differences have been found, but these conclusions are subjective and based on the examiner's experience (AFTE, 2013k). The second technique involves Consecutive Matching Striae (CMS). CMS are striations or surface variations that line up across two different toolmarks (AFTE, 2013e). Quantitative Consecutive Matching Striate (QCMS) is a numerical method of calculating the number of uninterrupted CMS sequences (Chu et al., 2013). The QCMS criteria require specific amounts of CMS for both two and three-dimensional toolmarks. At least two groups of five or one group of eight CMS must be present for two-dimensional toolmarks, while three-dimensional toolmarks need a minimum of two groups of three or one group of six CMS. To reach a conclusion, the number of CMS for two toolmarks must exceed that of the "best known non-matching quantitative CMS value" (AFTE, 2013i, p. 93).

Firearm Operation

Firearm examination is possible because of the operation mechanism of firearms. The cycle of operation for a semiautomatic pistol begins with feeding and chambering (Monturo, 2019). These steps work together to properly load ammunition in the chamber. Before a pistol can be fired, it must be cocked and reach full battery. Moving the slide on a pistol backward cocks the hammer, and bringing the slide back forward locks the bolt and puts the firearm into battery. In semi-automatic pistols, this process must be done manually to fire the first round. Then, it occurs automatically between each shot as the slide moves back to eject the fired cartridge case and chamber a new round. Once the pistol is in battery, it is ready to fire. Firing is a multi-step process that starts with pulling the trigger; the movement of the trigger releases the firing mechanism. The firing pin or striker then moves out of the breech and impacts the primer on the back of the cartridge case.

The primer contains a shock-sensitive explosive that ignites when the firing pin strikes the primer cap (Figure 1; Monturo, 2019). Sparks from the explosive then ignite the gunpowder in the cartridge case. Pressure and gases from the burning gunpowder fill the case, pushing the bullet out of the case and through the barrel (Figure 1). The case is then extracted from the chamber and ejected out of the firearm. These steps are important to firearm examiners because they create the individual characteristics on bullets and cartridge cases that are used in analysis.

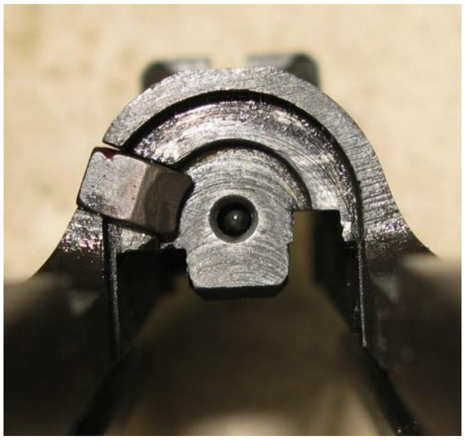
The firing pin leaves an impression on the primer cap. Pressure inside the chamber pushes the cartridge case back, and an impression of the breech face characteristics is also left on the primer cap. Internal case pressure causes the case to expand against the chamber; this is called obturation, and it results in chamber marks on the sides of the case. Extraction and ejection can leave faint marks on the case as well. Additionally, the barrel leaves individual characteristics on the bullet as it scrapes against the barrel's rifling.

The breech face and barrel characteristics are used more frequently in analysis for two reasons. First, firearm class characteristics are provided by these areas (e.g., breech face pattern, number of lands and grooves, and direction of twist). Second, individual characteristics left on cases and bullets by the breech face and barrel, respectively, are consistent across many rounds (Monturo, 2019). Therefore, the breech face and barrel are often the subject of firearm research.

Breech Face Characteristics

The breechblock (sometimes referred to as the bolt) is the part of the firearm that helps lock the breech during firing to keep gases from escaping (AFTE, 2013c). The breech face is the side of the breechblock that rests against the end of the chamber and supports the cartridge case. Internal pressure from firing pushes the case backward; this causes the head of the cartridge case to press on the breech face and receive an inverted impression of it (Monturo, 2019). There are different breech face manufacturing techniques that result in several breech face patterns. For example, milling produces circular breech face marks, broaching results in parallel marks, and abrasive blasting creates granular patterns (Figure 3; Monturo, 2019). These patterns can be used as class characteristics during examination. Individual characteristics of breech face patterns can be found in the size, shape, length, or spacing of the features within the pattern.

Figure 3: *Breech face with concentric marks*



From "Forensic Firearm Examination," by C. Monturo, 2019, p.119. Copyright 2019 by Elsevier Inc.

Firearm examiners consider cartridge cases important for several reasons. The class characteristics left by the breech face can help determine the potential number of firearms used at a crime scene (Monturo, 2019). Evidence cartridge cases with three different breech face patterns would have to have been fired from three different firearms. Furthermore, class characteristics can eliminate suspect firearms. If the breech face pattern on an evidence cartridge case is different from the pattern on a test-fired case from a suspect firearm, then that firearm can be eliminated from further analysis (Monturo, 2019). Individual characteristics in the breech face pattern on cases are unique to the firearm that created them. Therefore, cartridge cases can also be used to identify a firearm if no bullets were recovered from the scene (Monturo, 2019).

Research on Breech Face Characteristic Persistence

Research Before 2000

Research on firearm individual characteristics has been conducted for the last four decades. One of the earliest articles focused on the breech face impressions of 900 consecutively fired cartridge cases (Kirby, 1983). Kirby's study involved the test firing of a .455 caliber Smith & Wesson revolver. The ammunition used for the study was .455 Colt cartridges with lead alloy bullets and brass cartridge cases. The first five cases were reserved to establish the class and individual characteristics of the breech face, and they served as the controls for comparison. Every fifth case was analyzed against these controls. The individual characteristics were consistent in all 900 cases. While there were a few differences in the smaller striations, Kirby attributes this to the shot variation of normal firing. He summarizes his findings by indicating that there should not be a minimum number of cases needed for test firing evidence revolvers.

Other early research worked to establish that firearm breech faces exhibit identifying characteristics that can be used in examination (Matty, 1984). During the mid-1980s, Raven P-25 breech faces were made with mills, which leave circular marks. To determine if the concentric marks left by the mills could be unique enough for identification, six bolts were collected after milling. The first three bolts were manufactured consecutively, and the second three were made an hour later. After comparing the breech faces, it was concluded that they all exhibited significant differences in the minute striations left by the mill. Two casts were made of each breech face to test the marks' concentricity. Turning one of the casts 180 degrees out of phase still resulted in matching striations for each set. This article proved that even consecutively manufactured breech faces can be differentiated and that the milling process does result in uniform, circular marks that can be used for examination. Matty's research was confirmed ten years later when Raven Arms was bought by Phoenix Arms (Thompson, 1994). Four bolts were randomly selected from a group of 60,000, and casts were made of the breech faces. Thompson's study resulted in the same findings as Matty's original article.

In 1986, Tsuneo Uchiyama published an article examining the individual characteristics of breech faces on firearms with close serial numbers. The study involved test firing five Browning Baby, twenty-six Raven P-25, and two Titan pistols, all of which were .25 caliber. Uchiyama states that identifying the separate Browning pistols was difficult for the examiner because the patterns were nearly uniform. Based on this uniformity, a different examiner may not find any differences to fit their preconception of an identification. The breech faces of Raven pistols did not have a sufficient amount of concentric lines to definitively conclude how similar the patterns were. Some cartridge cases had several striations that matched one case but other striations matched a different case. Furthermore, the spacing between the circular lines was not always similar across the cases, increasing the difficulty of the comparisons. The two Titan pistols had deep and prominent concentric markings that differed even though they were successive serial numbers. Uchiyama concluded that his research was not reliable enough to create any recommendations for the number of similar striations that equate to an identification.

Research After 2000

In 2008, Gouwe et al. published an article discussing the impact of test firing 10,000 rounds on the persistence of breech face characteristics. A Glock Model 22 was selected from the Indianapolis-Marion County Weapons Reference File, and the Indianapolis Police Department provided 10,000 .40 Smith & Wesson cartridges. During the test firing, the pistol was not cleaned, and every tenth cartridge case was kept for examination. The researchers analyzed the cases in two ways: conventional analysis as described by the Theory of Identification and quantitative analysis using Consecutive Matching Striae (CMS). Both techniques yielded the same result that identifications could be made for all 10,000 cases. The authors concluded that the CMS technique provides stronger arguments in legal circumstances because CMS is less subjective and quantitative in nature.

In another article, researchers studied consecutive firing on five different types of Turkish-manufactured pistols (Sarıbey et al., 2009). The five pistols tested were the Canik 55, Kanuni 16, Sarılmaz Kılınç 2000, Yavuz 16, and Şahin 08, and they were fired 1,000; 2,000; 2,500; 3,500; and 5,000 times, respectively. MKE 9mm Parabellum cartridges were fired from each firearm. For each pistol, every 250th case was set aside to analyze. Additionally, the first ten cases were used to determine the initial class and individual characteristics of each pistol. Across the five pistols, the first and final cases could be positively identified to each other. The authors reported that the class characteristics remained intact for all five pistols, and while there were some variations in the individual characteristics for each firearm, none were significant enough to prevent identifications.

Chamber Characteristics

In pistols, the chamber is integrated at the rear of the barrel (Figure 4; Heard, 2008). The barrel and chamber are separated in revolvers, with several chambers located in a revolving cylinder behind the barrel (Figure 4). However, the chamber in both pistols and revolvers is the part of the firearm that receives the cartridge and aligns it at the back of the barrel. Pistol chambers are manufactured in a similar method to barrel manufacture (Monturo, 2019). A drill cuts the general opening for the barrel and chamber. Then, a reamer brings the barrel to the correct caliber by cutting away small amounts of metal (see the section *Barrel Characteristics* for more information). The barrel reamer only finishes the barrel; the chamber is made in a separate step. There are two types of chamber reamers used in chamber manufacture: rough reamers and finishing reamers. The rough reamer cuts the chamber out of the barrel, and the finishing reamer smooths the surface and brings the chamber to the desired caliber. Finishing reamers leave concentric markings in the chamber. During firing, an impression of these markings is left on the cartridge case, and they are analyzed as individual characteristics. Unlike breech faces and barrels, there are no class characteristics in a firearm chamber.

Figure 4: *Chambers*

Note. Pistol chamber (top) and revolver chamber (bottom) noted in red. From "Forensic Firearm Examination," by C. Monturo, 2019, pp. 119, 186. Copyright 2019 by Elsevier Inc.

Research on Chamber Characteristic Persistence

Research on chamber features is not as common because they are not often used in forensic laboratories as a method of identification. When cartridge cases are found at the crime scene, firearm examiners typically use breech face patterns because those markings are more distinct and plentiful. However, if the breech face markings are insufficient for identification, chamber marks can be useful in conducting examinations (Stowe, 2012). One of the few articles about chamber characteristics focuses on their longevity after extensive firing. Stowe conducted her research to provide information on how chamber characteristics on cartridge cases change through use and how they can be analyzed in a forensic laboratory.

Stowe (2012) compared the longevity of chamber characteristics in an expensive and inexpensive firearm: a Browning Hi-Power and Hi-Point Model C, respectively. The study also compared the effects of aluminum, brass, and nickel-plated brass cases on chamber characteristics. Both firearms fired 408 cartridges per case material for a total of 1,440 rounds (1-480 aluminum, 481-960 brass, and 961-1,440 nickel-plated brass). Two additional test fires were shot for each case type once the 1,440 rounds had been fired. The final test fires were collected to compare each case type’s first case to one fired after all 1,440 rounds.

For both the Browning and the Hi-Point pistols, all 480 aluminum and brass cases could be identified to each other (Stowe, 2012). Chamber marks varied in consistency across the cases, making identifications for later cases more difficult. For the brass cases, only cases 270 and 320 (750 and 800 in total sequential order, respectively) could not be identified due to a lack of chamber marks. The nickel-plated brass cases could not be identified for either pistol. Although chamber marks were present on these cases, they were not sufficient for identification. Casts were made of both chambers before and after the experiment, and there were no significant changes to the markings on the casts for both pistols. The final two test fires of the aluminum cases could be matched to each other for both pistols, but the brass and nickel-plated brass cases could only be matched from the Hi-Point pistol. None of the final test-fired cases could be identified to the first case for each type.

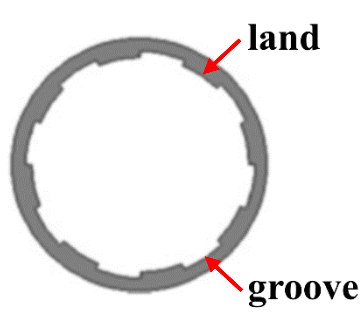
Stowe's (2012) research demonstrated that chamber marks in the chamber remained even after firing over 1,400 rounds. However, the chamber marks on cases could only yield identifications up to approximately 900 rounds. The case material does impact the transfer of chamber marks; harder metals limit the ability to make identifications. Nickel-plated brass was the hardest metal of the three case types tested, and it showed the least consistency in chamber mark presence and appearance. The research is significant because it shows the importance of using the "same cartridge case material type as the evidence cartridge cases [when] test firing" (Stowe, 2012, p. 307). Understanding how different metals affect the individual characteristics of firearms is crucial to effective analysis. If different case materials affect chamber characteristics, then it is possible that different bullet types can have different effects on barrel characteristics.

Barrel Characteristics

The barrel is the piece of a firearm that a projectile travels through upon firing (AFTE, 2013a). Barrels can be smooth (shotguns) or rifled (handguns and rifles). Rifling is the spiral grooves cut into the inner surface of a barrel. They serve to create a stabilizing spin in the bullet's trajectory to improve accuracy and muzzle velocity (Monturo, 2019). Barrels begin as solid steel rods, so the bore must be created before rifling can be added. The bore of the barrel is the internal hole running the entire length of the barrel (AFTE, 2013b). Specialized drill bits are used to manufacture the bore because the bore must be straight and centered in the barrel. After the bore is drilled, it is finished using a barrel reamer. Compared to drilling, which removes larger chunks of metal, reaming removes smaller pieces to smooth the barrel and ensure it does not become too wide for the desired caliber. The reamer leaves concentric marks on the interior surface of the bore (Monturo, 2019).

Once the bore is manufactured to the correct size, it can be rifled (Monturo, 2019). There are many different rifling techniques, but three of the most common methods are button rifling, broach rifling, and hammer forging. Button rifling does not remove any metal. Instead, sections of the bore are flattened by the raised portion of the button. The depressed sections created during rifling are called grooves while the remaining raised sections are the lands; lands and grooves are always equal in number (Figure 5; AFTE, 2013f, 2013h). Compared to button rifling, broach rifling removes pieces of metal from the bore to form the grooves (Monturo, 2019). Most techniques, including button and broach rifling, create traditional rifling where the lands and grooves are distinct with square edges (Figure 6). In hammer forging, the barrel is hammered around a mandrel, and the rifling features on the mandrel are imprinted on the bore. Hammer forging is used when manufacturers want to create polygonal rifling. Polygonal rifling has softer edges between the lands and grooves, and it can make firearm examination more difficult because class characteristics are harder to determine (Figures 5, 6, and 7).

Figure 5: *Lands and grooves of traditional rifling*



Adapted from "Handbook of Firearms & Ballistics," by B. J. Heard, p. 162. Copyright 2008 by John Wiley & Sons Ltd.

Figure 6: *Rifling shape in a barrel*

Note. Traditional (top) and polygonal (bottom). Adapted from "Handbook of Firearms & Ballistics," by B. J. Heard, p. 162. Copyright 2008 by John Wiley & Sons Ltd.

Figure 7: *Rifling shape on a bullet*

Note. Traditional (left) and polygonal (right). From "Forensic Firearm Examination," by C. Monturo, 2019, p. 200. Copyright 2019 by Elsevier Inc.

Bullets are valuable pieces of evidence for firearm examiners because they exhibit the class and individual characteristics consistent with a specific firearm's barrel (Monturo, 2019). Forensic analysis of bullets begins with examining the class characteristics found on the bullet, i.e., those left on the fired bullet by the barrel. Barrel class characteristics include the number of lands and grooves, the width of the lands and grooves, the direction of twist, the type of rifling, and the caliber. Comparisons of class characteristics require the suspect firearm to be test fired. Test fires allow firearm examiners to ensure the class characteristics of the evidence bullet could have been produced by the barrel of the suspect firearm. If a bullet found at a crime scene has six lands and grooves, then it must have been fired through a barrel with six lands and grooves.

Unique surface contours that appear during or after manufacture are considered individual characteristics (Monturo, 2019). These contours allow firearm examiners to identify a common source between toolmarks. The width, height or depth, and the relative position of the characteristics can be used in comparisons. Heard (2008) states that the drilling and reaming steps conducted before rifling result in more prominent individual characteristics than those left by the rifling process. Any wear or imperfections on the rifling tool (e.g., the broach or button) can produce noticeable characteristics in the barrel grooves, but they are not the source of striations used in bullet comparisons. These characteristics are called subclass characteristics (Monturo, 2019). Subclass characteristics can be found on any piece made by the flawed tool. Since several manufactured pieces can have the same subclass characteristics, these features cannot be used to make identifications. However, more specific groups can be formed by subclass characteristics than by class characteristics.

Once analysis of class characteristics has been conducted, the individual characteristics can be examined (Monturo, 2019). It is important to note that the individual characteristics used for comparisons are only found in the bullet grooves. The barrel lands create the bullet grooves, or land engraved areas (LEAs). Regardless of the rifling technique used, the machining tools only form the barrel grooves. During firing, the bullet may come in contact with the barrel grooves, and this creates the bullet lands, or groove engraved areas (GEAs). Therefore, markings found in the barrel grooves and GEAs are susceptible to subclass characteristics and are not generally used for analysis. Conversely, surface variations on the barrel lands are left by the reaming process and rarely contain subclass characteristics. These reaming markings are subsequently found on the LEAs and are used for examination.

When examining two bullets, the firearm examiner can conclude the bullets were fired by the same firearm if the bullets have a significant number of similar striations in the LEAs (Heard, 2008). In theory, proper maintenance could allow the specific striations to last the lifetime of the firearm. However, variations in individual characteristics are inevitable, and they can cause bullets fired from the same gun to appear different, particularly if they were not fired close together in sequence. The potential for bullets fired from the same firearm to differ in striation patterns has practical applications in forensic science and is the subject of current research.

Research on Barrel Characteristic Persistence

Jacketed Lead Core, Lead Alloy, and Frangible Bullets

Research Before 2000. Early research on barrel characteristics began in the 1980s. Two exemplary studies were published in 1983 researching how long consecutively fired bullets could be identified to one another before the individual characteristics were altered past the point of possible identification. The study conducted by Shem and Striupaitis (1983) used a Raven Arms Model P-25 firearm and .25 caliber full metal jacket ammunition. A total of 501 bullets were fired through the firearm. The first bullet and every tenth round were collected for analysis. The bullets were analyzed under a comparison microscope to compare the striations left by the barrel. Coarse individual characteristics began to change after a few hundred rounds while the finer individual characteristics had a much faster rate of change. A region of pronounced striations appeared in one of the land engraved areas (LEA) on each bullet. It was this LEA that led Shem and Striupaitis to their identifications because the other LEAs only had a few individual striations that were present throughout the entire study. Although the individual characteristics began to evolve, the authors concluded that identifications were possible for all 501 rounds. They noted that a study on a larger number of bullets may result in the inability to positively identify the first and last bullet to each other.

The second study was published by a team of Japanese researchers from the Tokyo Metropolitan Crime Laboratory in conjunction with the US Army Crime Laboratory (Ogihara et al., 1983). In this study, 5,000 rounds of .45 caliber full metal jacket ammunition were fired from a .45 caliber Colt Pistol Model M1911A1. Every tenth bullet was retained for examination. The width of each land impression on the bullet was recorded to determine if there was a significant change in land size; there was no significant difference in the averages of the six land widths. As for the striations in the lands, there was varying consistency in the number of bullets that could be identified. Identifications were possible in land 1 for all 5,000 bullets; lands 2, 3, and 4 resulted in identifications for 3,000 bullets. Identifications could be made until the 4,000th bullet in land 5 but only the 2,500th bullet in land 6. Because all 5,000 bullets could be identified by the striations in land 1, the other lands did not need as many similar striations to reach a conclusion.

However, a third article was published in 1983 that yielded conflicting results (Kirby, 1983). Kirby researched the longevity of individual characteristics left on cartridge cases and bullets after firing 900 rounds. While identifications were possible for all 900 brass cartridge cases, the bullets could not be positively identified after the 50th one. Finer individual characteristics were too evolved by this point. Some of the coarser characteristics were still present, but they were not sufficient for identification. Kirby summarizes that these findings are not generalizable because lead alloy bullets were used. Lead alloy bullets are softer and have a lower chamber pressure compared to full metal jacket bullets. These factors can cause variations in the number of striations left on the bullets. The diameter of the bullets was not taken before test firing began, so the bullets may have been too small to properly receive striations. A final consideration for these results is that the firearm was not cleaned during the experiment. A build-up of lead or powder residue on the bore could affect the consistency of the barrel to mark the bullets.

Research After 2000. More recent research is continually analyzing consecutively fired bullets to improve the field and expand the knowledge of firearm examiners. In 2013, Cary Wong published his research on the comparison of 1,000 bullets fired from a Ruger P89 9mm Luger pistol. Winchester full metal jacket bullets were used. The first ten bullets were kept for comparison, as well as every 25th bullet starting at bullet 25. Wong used quantitative consecutive matching striae (QCMS) to evaluate the similarity between striations on the bullets based on their depth, width, length, and relationship to other features. Bullets fired closer together had higher QCMS values, so it was easier to reach an identification. Some striations faded or disappeared entirely over the course of the study. However, sufficient identifying characteristics were present on every bullet.

Other studies from the last decade researched different aspects of consecutively fired bullets. One study created test sets for examination practice using ten consecutively rifled barrels (Hamby et al., 2009). The barrels were for a Ruger P-85 9mm Luger. The study used Winchester 9mm full metal jacket ammunition. Two hundred and forty test sets were created, and each test set had a control and unknown group. The control group included two bullets known to be fired from each of the ten barrels. The unknown group included 15 bullets with at least one per barrel; a few barrels had up to three bullets in a group. The 240 test sets were sent to firearm examiners and trainees around the world. They were tasked with identifying the unknown bullets to one of the known bullets, and therefore, one of the ten barrels. Out of the 7,605 total unknown bullets included in the test sets, three were unsuitable for examination because of damage. Five additional unknown bullets were marked inconclusive by two trainees. The participants were able to correctly identify the matching known bullet and barrel to each of the remaining 7,597 unknown bullets. Hamby et al. summarized the article by saying that given good bullet conditions, there is a low estimated error rate for identification.

Some researchers have conducted studies to test different bullets. Tsuneo Uchiyama (2008) created a study to compare three types of bullets: full metal jacket (FMJ), jacketed hollow point (JHP), and frangible. Frangible ammunition is designed to break open on impact to reduce ricochet; the Delta Frangible Ammunition company made its frangible ammunition out of "tungsten and copper powder in a nylon polymer matrix" (AFTE, n.d.-b). The firearm used in this study was a Hi-Point C9 chambered in 9mm Luger (Uchiyama, 2008). A total of 100 rounds were fired and collected: 20 Remington FMJ, 56 Speer Gold Dot JHP (nineteen 115 grain, nineteen 124 grain, and eighteen 147 grain), 20 frangible, and 4 Federal FMJ. Quantitative consecutive matching striae (QCMS) was used to determine the agreement between bullets based on the presence of matching striation sequences. Even when examining bullets fired back-to-back, identifications were difficult across the different types of bullets. Uchiyama suggests this is due to the different diameters of the bullet types, with the larger bullets having more contact with the barrel. The frangible bullets had the largest diameter and also had the most striations present. The Remington bullets had the smallest average diameter as well as the shallowest and fewest striations. However, Uchiyama concluded that the barrel characteristics did not significantly wear during the study because the frangible bullets could all be identified to each other.

Solid Copper Bullets

In their 2021 article, authors Chris Garcia and Mike Giusto discussed the lack of research on solid copper bullets in relation to barrel wear. They created a study to analyze how the successive firing of solid copper bullets altered the striation patterns in three different barrels. The barrels used were for a Glock Model 17, a Taurus Model PT 92 AF, and a Beretta Model M9, and they all were broach rifled. Five hundred rounds were fired through each barrel, and the bullets were analyzed for similar individual characteristics. Barrel casts were made throughout firing to allow for comparison of striations on the lands and grooves. Garcia and Giusto used the Quantitative Consecutive Matching Striae (QCMS) technique to quantitatively measure striation similarities, but specific QCMS numbers were not given in the study.

Throughout the study, both the Glock and Beretta barrels had striation patterns appear and disappear (Garcia & Giusto, 2021). For the Glock Model 17, identifications could only be made between the first 26 bullets. Even so, some bullets that were consecutively fired, such as bullets 21 and 22, yielded inconclusive results. By the 51st bullet, striations that were present on earlier bullets were completely missing. Identifications were possible for the Beretta barrel until bullet 246; at this point, the authors noted that there were insufficient consecutive matching striae to make an identification. Compared to the first barrel casts, the later casts for both the Glock and Beretta barrels showed important identifying features disappearing and new scratches and markings appearing. As for the Taurus barrel, identifications could not be made after bullet 11, and barrel casts exhibited significant changes to the striation marks.

Since both the Glock and Beretta barrels were new, the authors concluded that the inability to identify all 500 bullets for each barrel could be caused by a “breaking-in period” (Garcia & Giusto, 2021, p. 33). The Taurus barrel had been fired before the study, so Garcia and

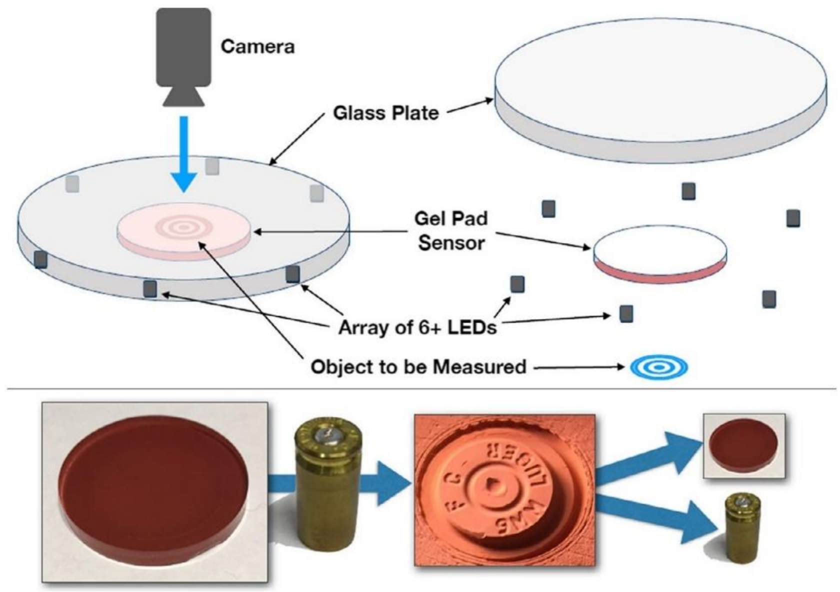
Giusto attributed its insufficient comparisons to prior use and manufacturing errors. Based on the quick deterioration of individual characteristics seen on the fired bullets and barrel casts of all three barrels, the study concluded that solid copper bullets are more abrasive than other types. Additional tests were conducted by firing 45 rounds of full metal jacket (FMJ) bullets through a Smith & Wesson Model 5906 and a different Beretta M9. Compared to the primary study, identifications could be made between all 45 FMJ bullets from both new barrels. Garcia and Giusto recommend additional research, such as testing barrels with different rifling manufacturing techniques (Garcia & Giusto, 2021).

Advancements in Examination

Since the beginning of the discipline, two-dimensional analysis using comparison light microscopes has been the standard of firearm examination. Conventional examination has often been criticized for being too subjective, so researchers have created techniques that attempt to quantify firearm analysis results (Chu et al., 2013). However, current quantitative techniques, such as Quantitative Consecutive Matching Striae (QCMS) criteria, still rely on examiners to subjectively determine and count CMS runs. An additional problem encountered with traditional light microscopy is that different lighting conditions can affect the ability to see important features (Weller et al., 2015). A team of forensic scientists and researchers spent the last few years working on a three-dimensional system that not only introduces a more objective quantitative algorithm but also reduces limitations associated with two-dimensional microscopy. The product of their work was the Cadre Forensics TopMatch-GS 3D System, which is an instrument that employs a “feature-based surface comparison algorithm” to quantitatively compare characteristics of forensic firearm evidence (Weller et al., 2015, p. 200).

The TopMatch system creates three dimensional scans in two steps. The first step is scan acquisition, which uses the GelSight 3D sensor to capture the topography of the primer region of a cartridge case. The sensor is a silicone pad covered in elastic paint that allows the sensor to take the shape of any object pressed against it. It is sensitive enough to conform to very faint textures, including human fingerprints or paper currency. The paint also prevents external light from reflecting off the case while the scan is collected. LED lights positioned around the sensor are sequentially illuminated to cast shadows on the cartridge case from different angles; at the same time, a set of images are taken to capture the shading on the case. The TopMatch algorithm reconstructs a three-dimensional model of the case from the shadowed pictures; reference standards of case dimensions are used to help make the model. This method is called photometric stereo or "shape from shading" (Figure 8; Weller et al., 2015, p. 200). The second stage of the TopMatch System is scan comparison. In this stage, the algorithm is used to analyze and compare any surface features across multiple cartridge cases. It gives a score for the degree of similarity between two cases that is based on the quality and quantity of the identified features. The similarity score ranges between 0 and 1 with higher numbers indicating greater similarity between features.

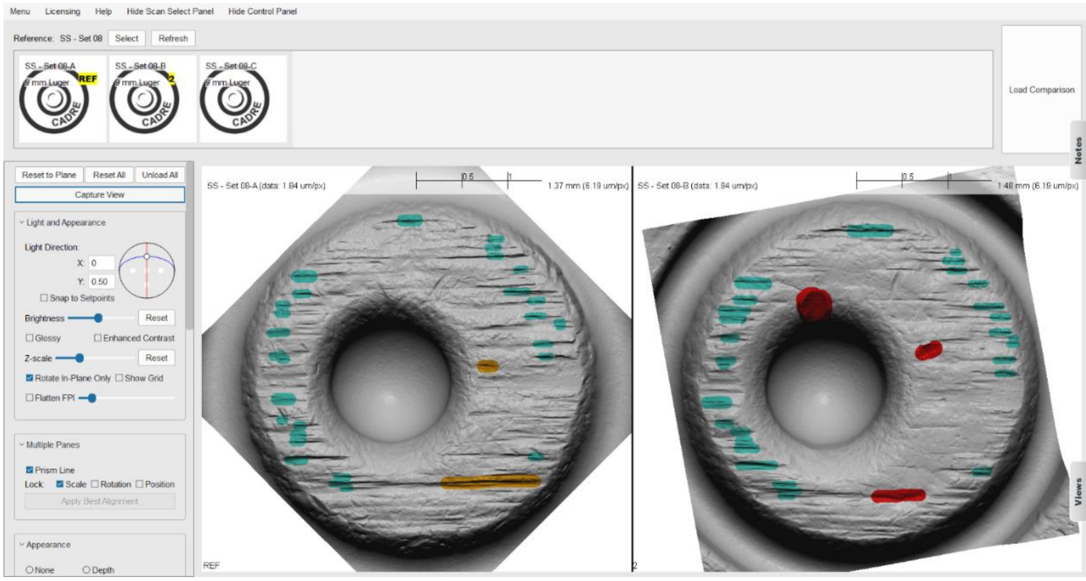
Figure 8: *GelSight 3D sensor setup*



Note. (Top row) The sensor is fixed to a glass plate. The cartridge case is pressed upward into the sensor, and the camera captures the images from above. (Bottom row) The head of a cartridge case is pressed into the sensor to create a three-dimensional scan. From “Results of the 3D virtual comparison microscopy error rate (VCMER) study for firearm forensics,” by C. Chapnick, T. J. Weller, P. Duez, E. Meschke, J. Marshall, and R. Lilien, 2021, *Journal of Forensic Sciences, 66*(2), p. 559 (https://doi.org/10.1111/1556-4029.14602). Copyright 2020 by the American Academy of Forensic Sciences.

Cadre Forensics also developed the Virtual Microscopy Viewer (VMV) software to allow examiners to upload and compare scans (Duez et al., 2018). Similar to physical microscopy, the position of the cases and the direction of the virtual light source can be manipulated to aid in comparing features. However, there are two features of the VMV software that traditional comparison microscopes cannot achieve. The Z axis of each cartridge case can be adjusted to view the depth of the surface features, and the scans can be viewed in enhanced contrast mode to visualize softer features not easily seen with the system’s default graphics. The VMV software also allows the user to make annotations for similar or different features (Figure 9).

Figure 9: *Virtual Microscopy Viewer cartridge case annotations*



Note. Matching features are annotated in teal, and different features are in yellow and red. Own work.

Validation of the Cadre Forensics 3D System

The Cadre Forensics research team has published several peer-reviewed studies validating their software. The first study involved five test sets that incorporated over 700 cases fired by 290 firearms (Weller et al., 2015). Sets one through three were created to simulate real-world cartridge cases seen in crime laboratories, and the firearms used in these sets varied in the quality of breech face impressions left on case heads. The third set was designed to specifically test the TopMatch system's ability to analyze the aperture shear marks on Glock pistols. Sets four and five included well-marking firearms to test how the system functions in perfect cartridge case conditions. Within each test set, every cartridge case was compared in an all-vs-all approach. Among the first three test sets, the TopMatch algorithm correctly identified approximately 75% of the cases. The other 25% had markings unsuitable for comparisons; the authors noted that any measurement system would likely result in an inconclusive conclusion for these cases. Sets four and five both resulted in a score of 100% accuracy.

Two other articles have been published to validate the VMV software. In the first study, two test sets were created to measure how well firearm examiners could virtually analyze cartridge cases (Duez et al., 2018). Both test sets included seven cases; the first three cases were known matches, and cases four through seven were unknown cartridge cases. Fifty-six analysts from 15 laboratories participated in this study. The participants used the VMV software to analyze and annotate the cases to determine if any resulted in identifications. The cases in test set one were fired by one firearm. For test set two, one firearm test-fired cases one through three, five, and seven while a second firearm shot cases four and six. Every participant correctly identified the cases in set one. Only two participants incorrectly marked identifications in set two, but the authors noted that these two individuals were trainees.

The second VMV study focused on determining the error rate of virtual microscopy (Chapnick et al., 2021). This research included forty test sets consisting of three cartridge cases. Two of the three cases were fired by the same firearm and the third was unknown. The unknown case was a known match (KM) to the two control cases in 17 sets, while it was a known non-matched (KNM) in the other 23 sets. Each participant was given 16 random sets, and they were tasked with determining if the third case in each set was a KM or KNM. The participants annotated each test set to support their conclusions. There were 1,184 comparisons conducted for the study: 693 KNM and 491 KM. Only three comparisons resulted in a false positive for an error rate of 0.43% (3/693), and there were no false negatives reported (0/491). The studies published by Cadre Forensic researchers have shown that the TopMatch and VMV systems are reliable tools for firearm examiners.

The majority of research in firearm analysis has shown that, under certain circumstances, individual characteristics on fired cartridge cases and bullets can persist through hundreds of rounds and allow for identifications. Breech face characteristics tend to yield identifications after at least 1,000 rounds. Nevertheless, researchers have noted that changing the cartridge case material may affect the quality of breech face impressions. As demonstrated in Stowe's (2012) article, cartridge case material significantly affects how long chamber individual characteristics will last. For aluminum and brass cases, identifying characteristics are present up to approximately 900 rounds. The nickel-plated brass case comparisons resulted in no identifying characteristics being shared by any of the cases.

Research on the effects of consecutive firing on barrel characteristics is primarily conducted on full metal jacket ammunition. In these studies, identifications have been possible up to 5,000 or more rounds in certain conditions. However, only one article has tested solid copper bullets. Garcia and Giusto's (2021) research not only focused solely on solid copper bullets, but it included additional tests to compare solid copper bullets to full metal jacket ones. Their findings showed that solid copper bullets are not able to be identified after 500 rounds, with some immediately consecutive bullets not having matching characteristics. While this research is important, the conditions of the study were not the same for each firearm model. The barrels were cleaned at different intervals, and only two of the three barrels were new.

Due to the low prevalence of solid copper bullets, their effect on barrel rifling and individual characteristics is not fully understood. However, following state legislative bills and military precedent, there is growing pressure for civilians to switch from lead ammunition to lead-free varieties, including solid copper ammunition (California Department of Fish and

Wildlife, 2019; Lallanilla, 2013). As lead-free ammunition becomes more common, crime laboratories will likely see an increase in the submission of solid copper bullets.

Firearm examination is historically two-dimensional in nature, but three-dimensional techniques are growing in popularity. Novel three-dimensional systems are capable of comparing firearms evidence in new ways and using algorithms to quantify these comparisons. While the Cadre Forensics team has only published articles validating their software and algorithm with cartridge case comparisons, the technology can be used to analyze fired bullets as well. The sensitivity of the GelSight sensor is capable of creating a three-dimensional scan of features on fired bullets. The Cadre Forensics TopMatch-GS 3D System is revolutionizing the way firearm examination is conducted because it provides an objective method of comparing ammunition components.

Reports such as the 2009 National Academy of Sciences review of current forensic science disciplines calls for comparison-based disciplines to increase the objectivity of conclusions (National Research Council, 2009). Therefore, the Cadre Forensics system is preferred over traditional subjective visual comparisons because the algorithm similarity score quantifies the similarity of the striations. Furthermore, past research using traditional visual comparison has issues with bias because the researchers knew if the cartridge cases and bullets were shot by the same firearm. Changes in barrel characteristics may be overlooked to support the examiner’s conclusion. The use of an algorithm will avoid such occurrences of bias. The goal of this study was to expand on previous research using solid copper bullets by applying a 3D instrument and algorithm for quantitative data to analyze any changes occurring to barrel characteristics.

Methods

Materials

Bullets

Previous research has shown that solid copper bullets have a significant effect on barrel characteristics, but more research is needed to fully understand their impact (Garcia & Giusto, 2021). Therefore, solid copper bullets were the focus of this study. This study required 500 solid copper bullets, and the specific bullets that were used are Barnes Ammunition VOR-TX 9mm Luger 115 grain (Barnes Bullets, n.d.). The barrel characteristics were profiled at the beginning and end of the study by collecting the first and last ten fired bullets. Changes in the features were demonstrated through the collection of every tenth bullet, for a total of 68 bullets. Prior to firing, each bullet was engraved with its shot number to ensure the bullets stayed in the correct order. The engravings are on the nose of each bullet because the curved nose does not come into contact with the barrel during the firing process. The bullets were collected and stored consecutively to further ensure the bullets were examined in firing order.

Firearm

A Glock 19 Gen 5 chambered for 9mm Luger ammunition was used for this study, and it was chosen for two reasons. The first reason is that Glock firearms are one of the most popular handguns in the United States, regardless of caliber. Every year, the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) releases the Annual Firearms Manufacturers and Export Report. The 2020 report shows that Glock was the third largest pistol manufacturer (Bureau of Alcohol, Tobacco, Firearms and Explosives, 2021). Glock manufactured 445,442 pistols, including 231,540 9mm pistols. Gunbroker.com, one of the largest firearm auction websites, releases an annual report of the highest selling handguns; in 2020, Glock 19 pistols came in first (Gunbroker.com, 2020). The second reason for selecting a Glock 19 Gen 5 9mm is that 9mm is considered the most common caliber. The ATF helps law enforcement agencies at the local, state, federal, and international levels trace the sale and possession of firearms recovered from crime scenes (Bureau of Alcohol, Tobacco, Firearms and Explosives, 2022a). At the end of every year, the ATF releases a report on the amount of firearms recovered and traced for each caliber. In the 2021 report, 9mm firearms were recovered the most, totaling 197,634 out of 452,513 firearms (Bureau of Alcohol, Tobacco, Firearms and Explosives, 2022b). The firearm for this study was handled and stored in accordance with the University of Central Oklahoma's Policy on Firearms for Classroom and Field Instruction.

Barrel

Glock barrels traditionally have polygonal rifling (Monturo, 2019). Polygonal rifling does not have prominent lands and grooves, so the number, width, and location of lands and grooves are hard to determine on fired bullets. Therefore, bullet comparisons can be difficult because both class and individual characteristics are harder to identify (Heard, 2008). New Glock Gen 5 barrels, however, come with a specialized barrel called the Glock Marksman Barrel (GMB). Compared to older Glock barrels, GMBs have enhanced rifling features within the polygonal profile that allow for easier identifications between bullets (Christen & Jordi, 2019). Additionally, research has shown that identifications are possible after firing 500 rounds of solid brass ammunition through a GMB, even though changes to the details were observed. The results of this study determined how solid copper bullets affected the enhanced rifling of GMBs, specifically if identifications were possible after 500 rounds.

Bullet Collection, Storage, and Cleaning

There are several recovery methods on the market, including water recovery tanks, fiber-based traps, and rubber-based traps. Each recovery system was evaluated to determine which would be the most efficient for the purposes of this study, and a rubber-based method was selected. Water recovery tanks are limited to smaller calibers due to their size (Werner et al., 2018). While a water recovery tank could be used for 9mm Luger ammunition, bullets are frequently deformed by the impact of entering the water. Hollow point bullets showed the most significant damage in a water tank compared to cotton or fiber recovery methods. Since the VOR-TX bullets selected for this study are hollow point, a water tank was not recommended. Cotton-based recovery methods were also not recommended because special precautions must be taken to prevent the cotton from igniting. Therefore, a ballistic rubber trap was preferred.

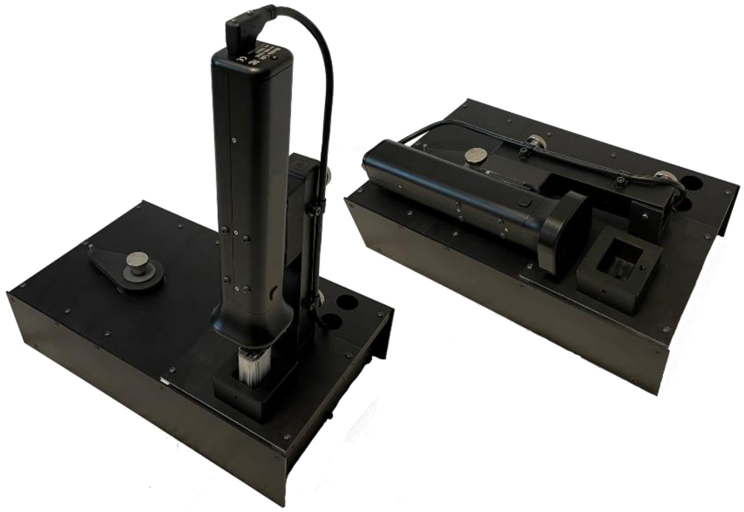
The Super Target Systems portable bullet trap was used for bullet recovery. The collection chamber is made of ballistic steel, and the inside was filled with ballistic rubber mulch to catch the bullets and prevent damage such as fragmentation or expansion (Super Target Systems, n.d.-a). Super Target Systems sells the bullet trap with a “self-healing ballistic rubber” front panel that is designed to slow the bullets down (Super Target Systems, n.d.-b). This front panel is approximately one inch thick and very dense. Some damage was observed on hollow point test fires when the rubber panel was installed on the bullet trap. Due to the deformities on these test fires, concerns were raised that the front panel would damage the striations on the bullets. To prevent any damage, a section of the front panel was removed, and the front of the trap was covered with cardboard so that the rubber mulch would not fall out of the collection chamber.

The bullets were fired one at a time into the collection chamber and returned to the cartridge boxes in the order that they were fired. This ensured the bullets were stored in the proper order in case any engravings were damaged. Furthermore, it protected the bullets from potential damage caused by contacting each other in the chamber. The cartridge boxes containing both the unfired and fired bullets were stored in a locked cabinet in the laboratory when they were not needed. To remove any debris from the fired bullets, they were cleaned with alcohol and cotton swabs following standard practice.

Bullet Scanning

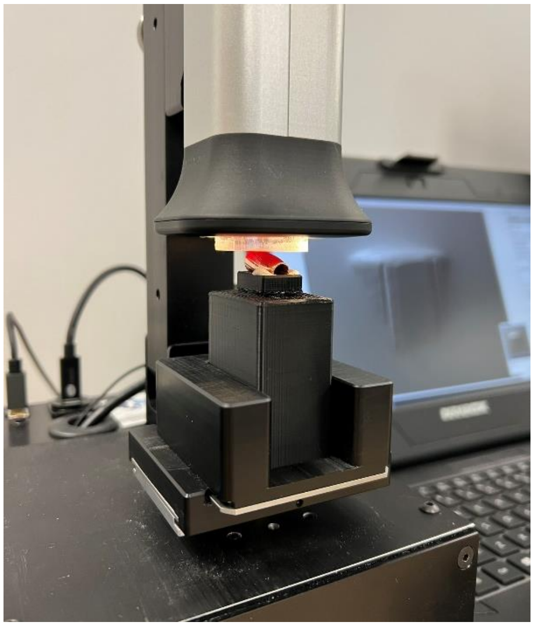
Current methods of examination (i.e., conventional analysis and QCMS) are still subjective. The Cadre Forensics Versa system provides an objective and quantitative approach to firearm analysis by collecting three-dimensional scans of bullets and other surfaces with toolmarks (Figures 10 and 11; Cadre Forensics, n.d.). The bullets were scanned individually and manually rotated to scan each land engraved area (LEA). As previously discussed, firearm examiners use LEAs for comparisons because they contain prominent markings and are not as susceptible to subclass characteristics as the groove-engraved areas (GEAs). Therefore, only the LEAs were scanned. GMBs have six lands, so there were six scans per bullet for a total of 408 individual LEA scans. Two systems were used to complete the scanning process in a timely manner. Bullets were randomly selected to scan on each system to offset any effects caused by differences between the two systems.

Figure 10: *Cadre Forensics Versa Scanner*



From Cadre Forensics, https://www.cadreforensics.com/

Figure 11: *Versa Scanner set-up*

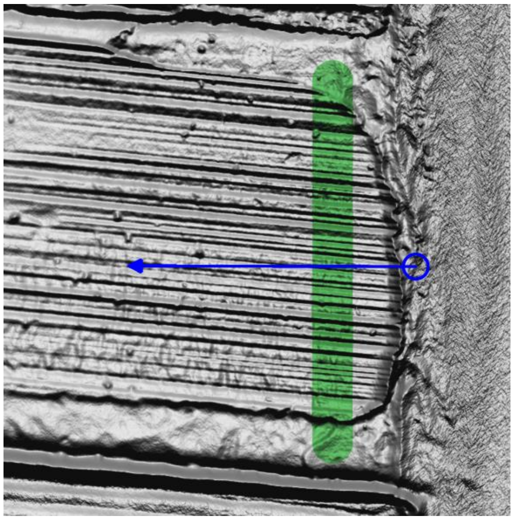


Note. A bullet is mounted on the bullet holder, and the bullet holder is positioned on the Versa scanner. A live view of the LEA scan is shown in the background. Own work.

Bullet Comparison

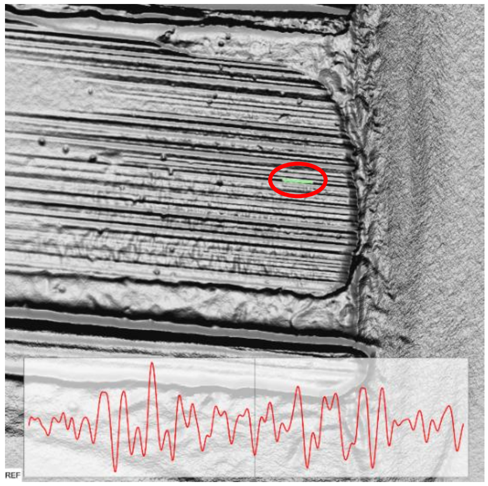
Prior to comparison, the bullets were masked to define the regions of interest that the algorithm should compare. The TopMatch software allows examiners to manually adjust the regions of interest by using the mouse to mark the desired features, such as the aperture shear on cartridge cases or LEAs on bullets (Figure 12; Weller et al., 2015). The algorithm then plots the depth profile of the striations within the masked region, and these depth profiles are used for comparisons (Figure 13). Depth profiles can be effective at illustrating changes in features by showing if certain striations are softening or disappearing. During a bullet comparison, the depth profile of an LEA on one bullet is compared to the six LEA depth profiles on a different bullet to find the orientation that yields the highest similarity scores.

Figure 12: *Mask of land engraved area on Bullet 001*



Note. The green mark is the LEA mask. The blue arrows helps with orientation by pointing toward the nose of the bullet. Own work.

Figure 13: *Depth profile of land engraved area on Bullet 001*



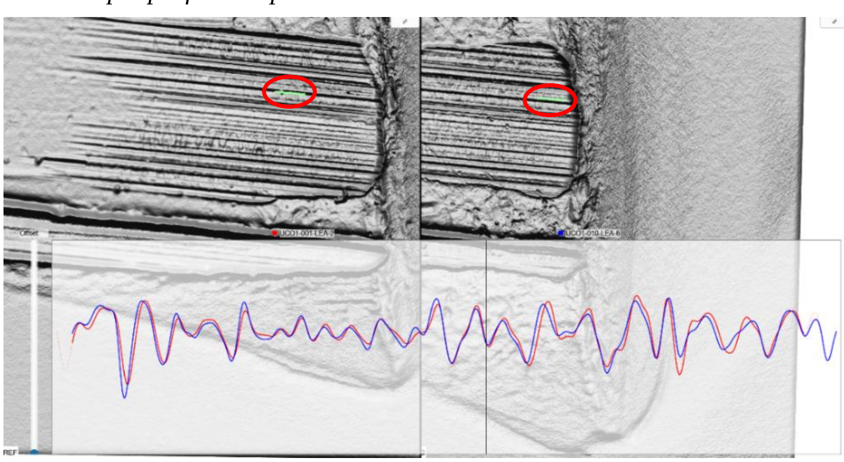
Note. The green line on the scans (circled in red) is shown on the depth profile by the location black line. Own work

The bullet comparison algorithm implemented by Cadre Forensics is based on the Congruent Matching Profile Segments (CMPS) method developed at the National Institute of Standards and Technology (Chen et al., 2019). All comparisons were performed using TopMatch version 1.7 beta which included version 1.0 of the CMPS algorithm as implemented by Cadre. Cadre's CMPS method divides a depth profile into segments, and segments on one profile are compared to those on another. There are two factors that decide if two segments can be correlated. First, segments must demonstrate similarities in striation depth and spatial relationship. Second, the segments themselves must be in the same position on the two bullets. If both of these factors are in agreement, then the two segments are correlated, and the algorithm moves on to the remaining segments. When a potential LEA pair is found, the algorithm compares the segments on the rest of the LEAs in sequence to determine if the correct bullet orientation has been found for that comparison. If the bullets are in the proper orientation, then the algorithm gives a similarity score for each LEA pair as well as an overall score for the comparison.

The algorithm similarity score for an LEA pair is the number of segments found to be in congruence, and the overall similarity score for a bullet comparison is the average of the six LEA scores. For example, an LEA on bullet A is compared to the six LEAs on bullet B. One LEA pair yielded 12 congruent segments, and this was the highest number of congruent segments for the LEA on bullet A when compared to bullet B. The similarity score for this LEA pair would then be 12. When the remaining five LEA pairs confirm that this is the correct orientation for the two bullets, the number of congruent segments for each pair is used as the pair's similarity score. If the six LEA pair similarity scores are 12, 8, 11, 10, 11, and 9, then the overall similarity score for the bullet comparison is 10.167. Higher scores are associated with identifications, but there is not a threshold for identification.

While the algorithm uses depth profiles to generate similarity scores, visual examinations of the depth profiles were conducted to support the algorithm's scores. If the algorithm gives a high score for an LEA pair, it is expected that the LEAs will have similar depth profiles (Figure 14). In this figure, the LEAs are visibly similar, but the depth profiles also show significant agreement. This supports the algorithm's score of 12 for this pair.

Figure 14: *Depth profile comparisons*



Note. The red depth profile is for the bullet on the left. The blue depth profile is for the bullet on the right. The green lines on the scans (circled in red) have a similar depth as shown by the location of the black line on the depth profiles. Own work.

Traceability

To ensure the software provided accurate measurements, a sinusoid reference standard was scanned every fifteen bullets. The sinusoid standard is created with known wavelengths and wave amplitudes. It is calibrated by an external, accredited laboratory following the standards established by the ISO/IEC 17025 and the National Institute of Standards and Technology. A calibration certificate is provided, and it details the known measurements of the wavelengths and amplitudes for the specific sinusoid standard a laboratory receives. Prior to using the scanner, the sinusoid standard is scanned under different operating conditions. These values are used to calculate a 95% confidence interval that defines acceptable minimum and maximum values for the wavelengths and amplitudes. During this study, if a scan of the standard resulted in measurements that fell outside of the confidence interval, troubleshooting steps would have been taken to identify and correct the issue prior to scanning additional samples. Only the fifteen bullets between the inaccurate standard scan and the previous standard scan would have been rescanned. However, each scan of the sinusoid reference standard produced values that fell within the accepted confidence interval, so troubleshooting steps were not necessary.

Data Analysis

The algorithm similarity scores were used as the primary data for this study. As the barrel individual characteristics changed over time, it was expected that bullets fired 10 shots apart would have a higher similarity score while those fired several hundred shots apart would have a smaller similarity score. For statistical analysis, the Kwiatkowski-Phillips-Schmidt-Shin time series test was applied to the similarity scores for bullet 001 to determine if there was a trend in the data and if the trend is significant. To visualize the trend, the similarity scores for bullet 001 were plotted. The same statistical analyses were applied to the similarity scores for bullets 002-

009 to show that the results were consistent and not simply due to shot variation within the first ten bullets. Visual comparisons of LEA pairs were conducted to support the best alignment determined by the algorithm. Analysis of the depth profiles was also used to reinforce the algorithm's results.

Results and Discussion

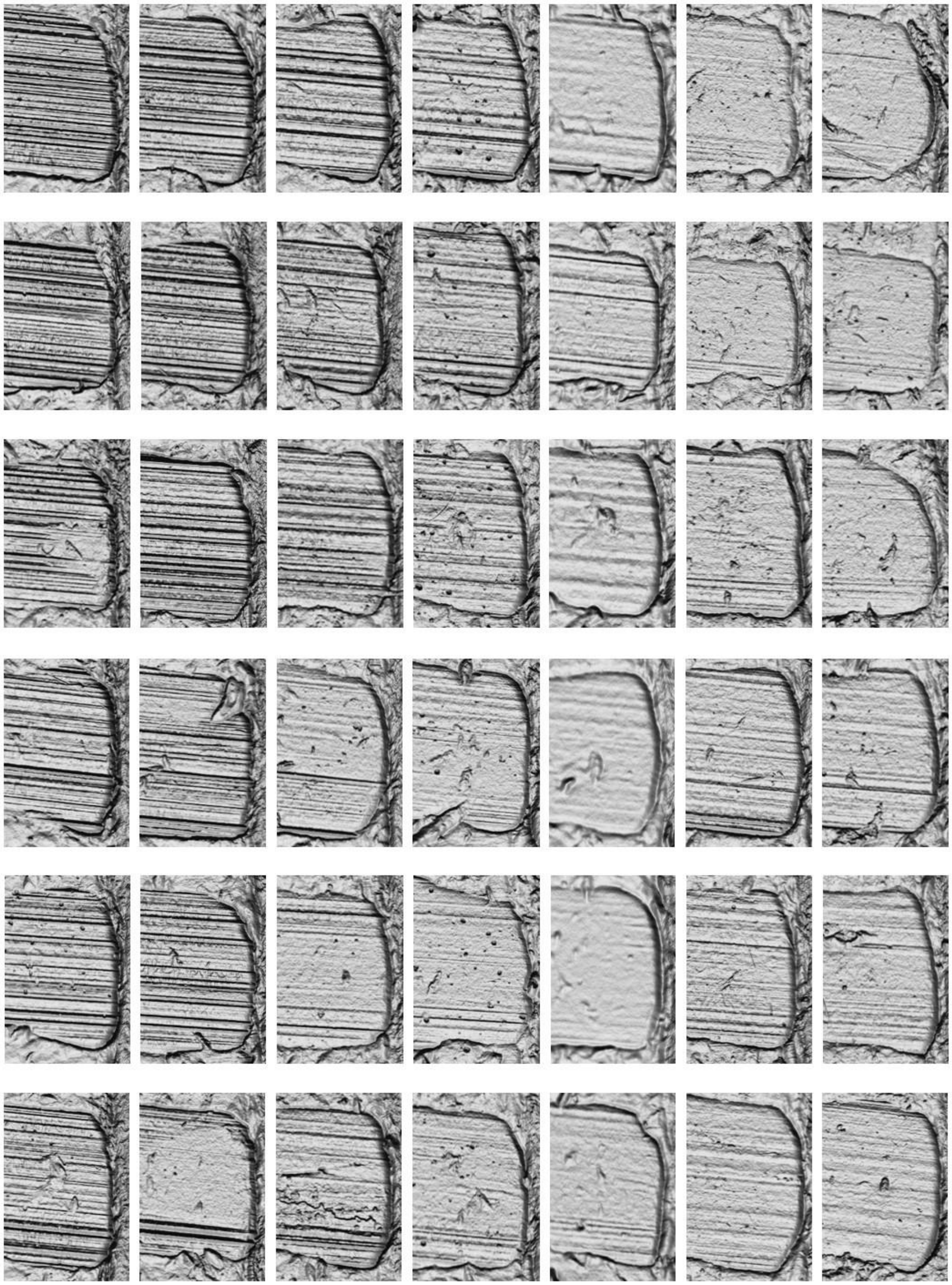
Visual Examinations

The three-dimensional scans for bullets 001, 010, 100, 200, 300, 400, and 500 were visually examined and compared to evaluate the condition of the land engraved areas (LEAs), including the quality and quantity of striations, and to track any changes that occurred throughout the course of the study (Figure 15). In this figure, the columns depict bullets 001, 010, 100, 200, 300, 400, and 500, while the rows show the corresponding LEAs on each bullet based on the best alignment determined by the algorithm. For example, the first column on the left shows the six LEAs for bullet 001 while the top row compares a corresponding LEA on the seven bullets.

All six LEAs on bullet 001 have very prominent striations, but these features show significant wear; by bullet 500, the striations have almost disappeared entirely. Furthermore, the LEAs appear to be changing at different rates. The striations in the first three LEAs shown in Figure 15 begin softening between bullets 200 and 300, and more noticeable changes appear by bullet 400. For the last three LEAs, changes to the striations start earlier in the firing sequence, with more pronounced striations wearing within the first 100 bullets.

However, it is still possible to confirm the algorithm's LEA alignment using these scans. The striations seen at the bottom of the LEAs in the second row can be seen in all seven bullets even as the rest of the features soften. This agreement was used to determine the correct order for the LEAs on each bullet. When the five remaining LEAs were compared in sequence, more striations were found to be in agreement, and the algorithm's alignment was confirmed.

Figure 15: *Land engraved area comparisons*



Note. Each column depicts the six LEAs for a bullet, representing bullets 001, 010, 100, 200, 300, 400, and 500, when moving from left to right. Within each row are the corresponding LEA pairs for the seven bullets.

Even though some striations on bullet 001 were still visible on bullet 500, and were used to validate the algorithm's LEA alignment, manual comparisons of bullet 001 and bullet 500 did not result in an identification. When the bias of the algorithm's alignment was removed, an identification could not be confidently reached because the quality and quantity of the striations on bullet 500 had changed too much. Additional striations appeared on several of the later bullets. While this could be due to shot variation, it affected the interpretation of the features.

It should be noted that the nose of bullet 300 exhibited severe damage; the petals of the hollow point bullet peeled back preventing it from being scanned in the bullet holder. It had to be held during the scanning process, and this likely contributed to the poorer quality scans seen in Figure 15. However, the scores for bullet 300 are consistent with those of the surrounding bullets. Holding the bullet during scanning did not seem to have affected the results of the study or the ability to verify the algorithm's results.

Algorithm Data

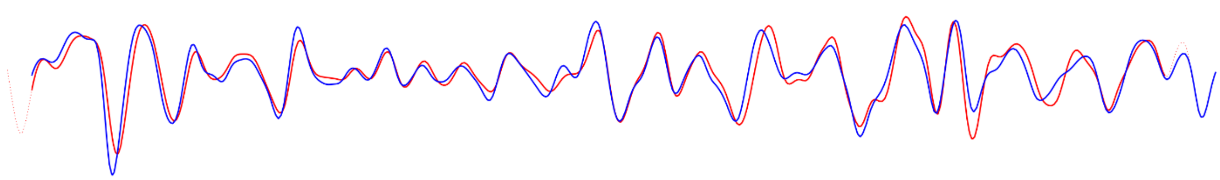
As previously discussed, the Cadre Forensics implementation of the CMPS algorithm was applied to the depth profiles generated from the bullet scans. The scores from the LEA comparisons were averaged to determine an overall similarity score. As with the visual comparisons, bullet 001 was compared to bullets 010, 100, 200, 300, 400, and 500. The scores from these comparisons decrease as expected based on the features observed in the scans in Figure 15 (Table 1).

Table 1: *Similarity scores*

Comparison	Overall Similarity Score
Bullet 001 vs Bullet 010	8.833
Bullet 001 vs Bullet 100	6.000
Bullet 001 vs Bullet 200	4.500
Bullet 001 vs Bullet 300	3.667
Bullet 001 vs Bullet 400	3.667
Bullet 001 vs Bullet 500	3.500

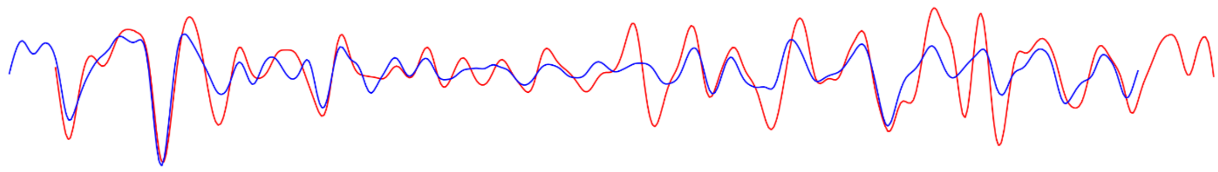
To have a better understanding of the similarity scores, the depth profiles for the comparisons mentioned above were analyzed. In three of the six comparisons, LEA 2 on bullet 001 had the highest score in the alignment generated by the algorithm, so it was used for depth profile analysis. The profiles for bullet 001 and bullet 010 show a high degree of similarity (Figure 16). Some agreement is present in the depth profiles for bullet 001 compared to bullets 100 and 200, but most of the features are starting to become softer and less pronounced (Figures 17 and 18). Only a few striations on bullets 300 and 400 line up with those on bullet 001 (Figures 19 and 20). However, these features are more shallow than the respective features on bullet 001. Finally, the depth profile for bullet 500 is almost completely flat, and there is no agreement between the profiles for bullet 001 and bullet 500 (Figure 21). The similarity observed in each of the depth profiles can be correlated to the similarity in the scans in Figure 15 and the similarity scores in Table 1.

Figure 16: *Bullet 001 vs bullet 010 depth profile comparison*



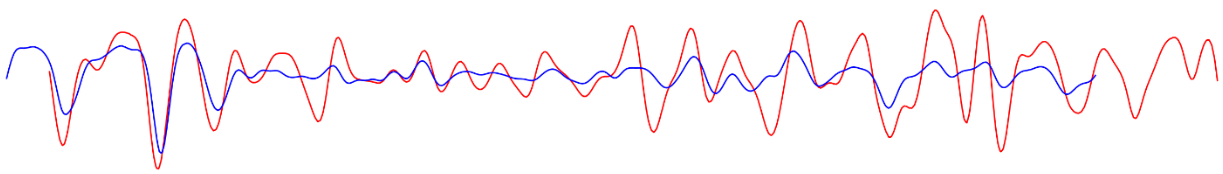
Note. The red depth profile is for bullet 001, and the blue depth profile is for bullet 010.

Figure 17: *Bullet 001 vs bullet 100 depth profile comparison*



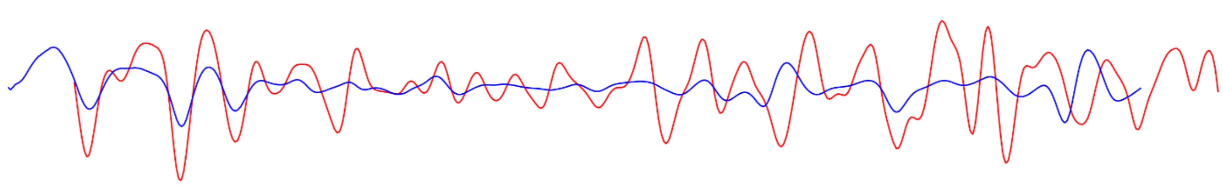
Note. The red depth profile is for bullet 001, and the blue depth profile is for bullet 100.

Figure 18: *Bullet 001 vs bullet 200 depth profile comparison*



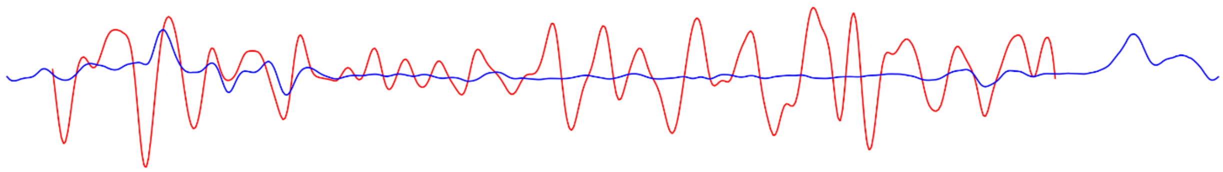
Note. The red depth profile is for bullet 001, and the blue depth profile is for bullet 200.

Figure 19: *Bullet 001 vs bullet 300 depth profile comparison*



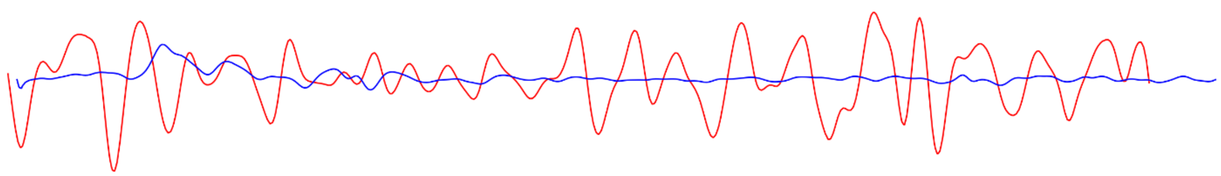
Note. The red depth profile is for bullet 001, and the blue depth profile is for bullet 300.

Figure 20: *Bullet 001 vs bullet 400 depth profile comparison*



Note. The red depth profile is for bullet 001, and the blue depth profile is for bullet 400.

Figure 21: *Bullet 001 vs bullet 500 depth profile comparison*



Note. The red depth profile is for bullet 001, and the blue depth profile is for bullet 500.

Statistical Analysis

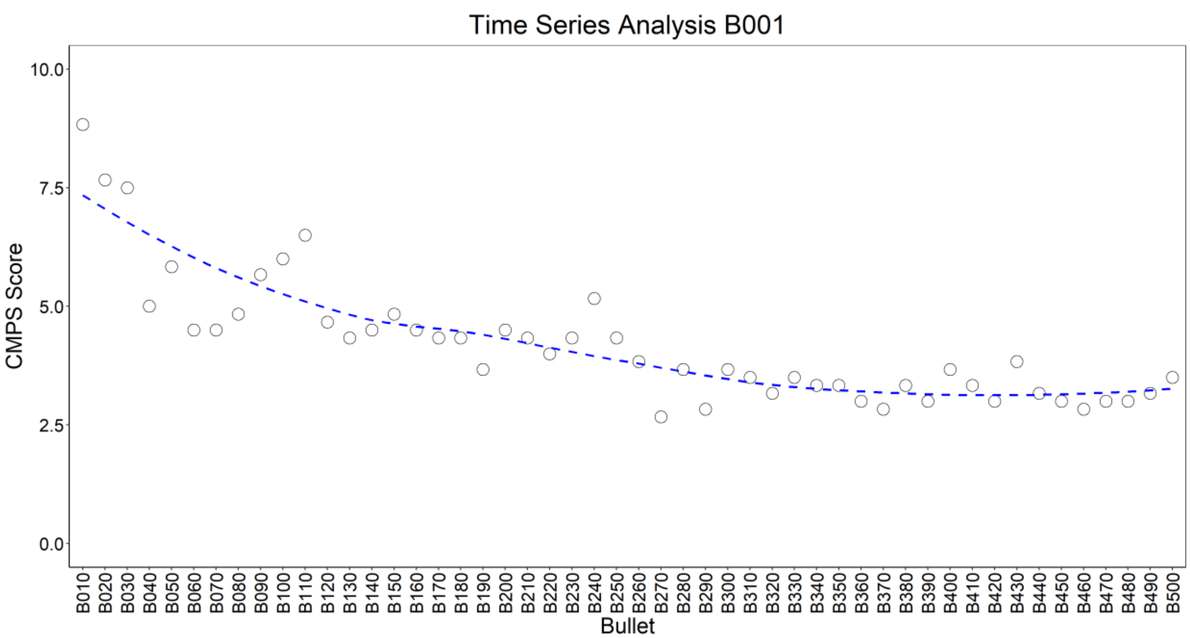
The data for this study were analyzed as a time series. Time series tests are applied to data that are collected at evenly spaced time intervals and may exhibit variations due to the collection interval (National Institute of Standards and Technology, n.d.-a). The bullets collected for this study were ten shots apart and therefore fall under the parameters of a time series analysis. It should be noted that bullets 002-009 and 491-499 were collected to profile the individual characteristics at the beginning and end of the study and were not included in statistical analyses.

The time series data in this study were tested to provide evidence of stationarity. In a stationary time series, the statistical properties of a collection of data, such as the mean or standard deviation, do not vary over time (National Institute of Standards and Technology, n.d.-b). Conversely, statistical properties in a nonstationary time series do vary over time, and the distribution of the variation is time-dependent. It was hypothesized that the data for this study would be nonstationary. The firing number of a bullet may affect the quality and quantity of individual characteristics in the LEAs therefore affecting the similarity scores for that bullet. For example, bullets fired later in the firing sequence would have fewer or less detailed individual characteristics and lower similarity scores than bullets fired earlier. In this hypothesis, the similarity scores vary over time and are nonstationary.

There are several time series statistical tests that could have been used to determine the data's stationarity, but the Kwiatkowski-Phillips-Schmidt-Shin (KPSS) was selected because its null hypothesis is that the data are stationary. The KPSS test is a type of statistical hypothesis test, and acceptance or rejection of the null hypothesis is based on the *p* value. The *p* value is the statistical probability that the data would be observed if the null hypothesis were true. Put more simply, the *p* value is the likelihood that variations in the data are coincidental. Calculated *p* values can range from 0 to 1. Higher *p* values indicate that variations could still be observed under the conditions of the null hypothesis and are due to chance. Lower *p* values, however, suggest that differences in the data likely could not be observed under the conditions of the null hypothesis.

A *p* value close to zero is often called significant if it falls under a defined significance threshold. A significance level of 0.05 corresponds to a 95% confidence interval, and this is the default value for statistical testing (Di Leo & Sardanelli, 2020). Therefore, the significance threshold for this study was set to 0.05, and a *p* value less than 0.05 would not only reject the null hypothesis but indicate that the variation in the data is significant and non-random. The KPSS test was applied to the similarity scores for bullet 001 using the kpss.test function within the tseries R package (Trapletti & Hornik, 2023). The *p* value is less than 0.01, which is below the threshold of 0.05. Therefore, the KPSS test demonstrates that the data are nonstationary, and the observed decrease in the similarity scores is a significant trend. The scores for bullet 001 were plotted to further illustrate the decreasing trend, with the compared bullet on the X axis and the corresponding similarity score on the Y axis (Figure 22). Because the results from bullet 001 could be due to shot variation, the same statistical analyses were applied to bullets 002-009. The KPSS test *p* values and the plots for these bullets are located in Appendix A and Appendix B, respectively. A plot of the similarity scores for bullet 001 including bullets 002-009 and bullets 491-499 is in Appendix C.

Figure 22: *Time Series Plot for Bullet 001*



Note. The dotted blue line is a trend line, or line of best fit, and it was added to aid in visualizing the trend.

Limitations

The data from this study suggest that solid copper bullets do have an effect on the persistence of barrel individual characteristics. However, the barrel used in this study was new, so the quick decrease in the presence of individual characteristics could be attributed to "breaking in" the barrel. Some research studies have discussed a potential breaking-in period to be the cause of rapid changes to features, especially when solid copper bullets are fired (Garcia & Giusto, 2021). This breaking-in period has been defined as the time in which an unknown number of bullets need to be fired through a new barrel in order for the striations to mark consistently (Smith, 2021). While there are only a few articles that discuss a breaking-in period, it should not be ruled out as a potential reason for the change in barrel individual characteristics observed in this study.

Other limitations of this study are based on the study design. First, the sample size included only 500 bullets while comparable research includes 1,000 or more bullets. Due to the small sample size, the results of this study may not be as generalizable as those that include a larger sample size. Furthermore, these results may be limited because the barrel used for the study was a Glock Marksman Barrel (GMB). The GMB barrel is only found in newer models of Glock firearms. Therefore, not only could these results be limited to Glock firearms, but they may only be generalizable to newer Glocks with GMBs. Additional research would need to be conducted to determine how solid copper bullets affect older Glock models as well as other firearm brands. Similarly, there are other brands that sell solid copper ammunition, and a different brand may produce different results than the Barnes Ammunition VOR-TX bullets.

Conclusion

When compared to the data from studies conducted on both solid copper bullets and other ammunition types, the results of this study support the conclusion that solid copper bullets are more abrasive and have a greater effect on barrel rifling individual characteristics. The TopMatch algorithm was an effective tool to determine the corresponding LEA pairs, and it provided quantitative, objective data on the similarity between the fired bullets. However, bullet 500 could not be identified with the algorithm or through visual comparisons. The similarity score for bullet 001 and bullet 500 was 3.500 while the similarity score between bullet 001 and bullet 010 was 8.833. The land engraved areas on bullet 500 were significantly less detailed than those on bullet 001 as supported by visual examinations.

These results are important for firearm examiners because they demonstrate that examiners must be conservative when using individual characteristics to reach an elimination. If a substantial period of time has passed between a crime and the recovery of a firearm, it is possible that the individual characteristics in the barrel have changed since the crime occurred. As demonstrated by this research, only 500 rounds of solid copper bullets were needed to cause statistically significant changes to the barrel's features. If bullet 001 and bullet 500 were compared by an examiner, it is likely they would not reach an identification.

Continued work on this project could analyze each land engraved area to determine if they wear at the same rate. Recall, the quantity of striations on each land engraved area for a single bullet varied. Therefore, supplemental analysis would demonstrate if the features in the barrel lands wear differently and how this is visualized on fired bullets. Future research may include an analysis on the effect of additional shots of solid copper bullets through the same barrel. For example, 500 additional bullets could be fired to see how bullet 1000 differs from bullet 001 and bullet 500. A comparison study could be conducted on the effect of 500 rounds of conventional ammunition fired through a new Glock Marksman Barrel. This would help determine if this study is simply an observation of the breaking-in period or a true effect of solid copper bullets.

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Appendix A: *p* values for bullets 002-009

Bullet 002: $p < 0.01$

Bullet 003: $p < 0.01$

Bullet 004: $p < 0.01$

Bullet 005: $p < 0.01$

Bullet 006: $p < 0.01$

Bullet 007: $p < 0.01$

Bullet 008: $p < 0.01$

Bullet 009: $p < 0.01$

Appendix B: Time series plots for bullets 002-009

Figure 23: *Time Series Plot for Bullet 002*

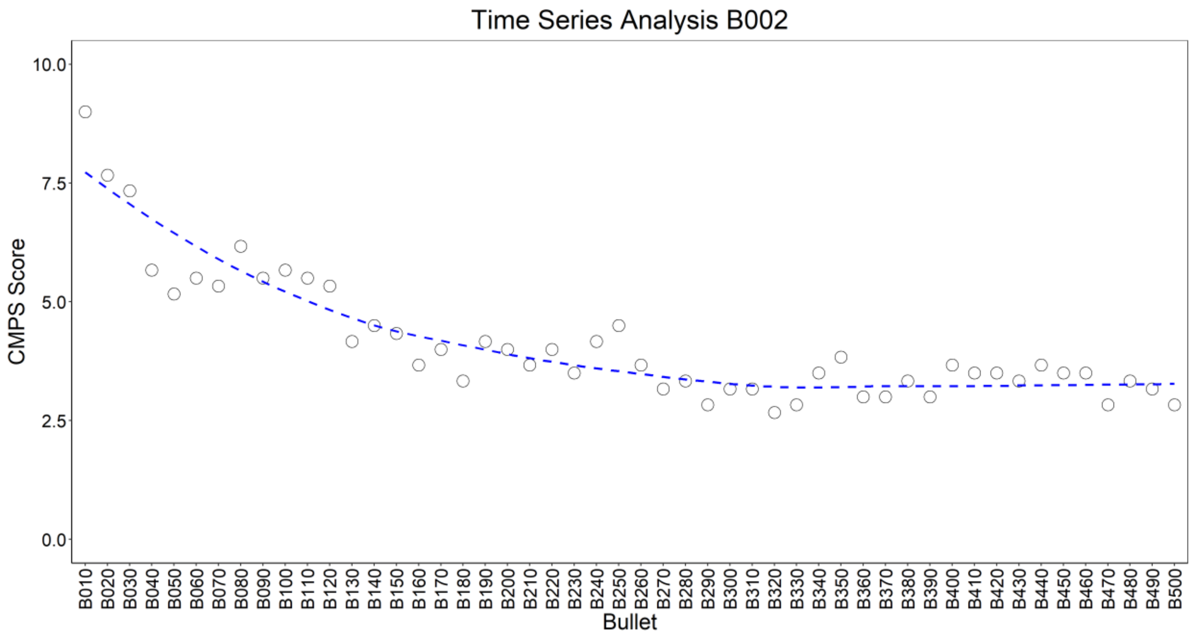


Figure 24: *Time Series Plot for Bullet 003*

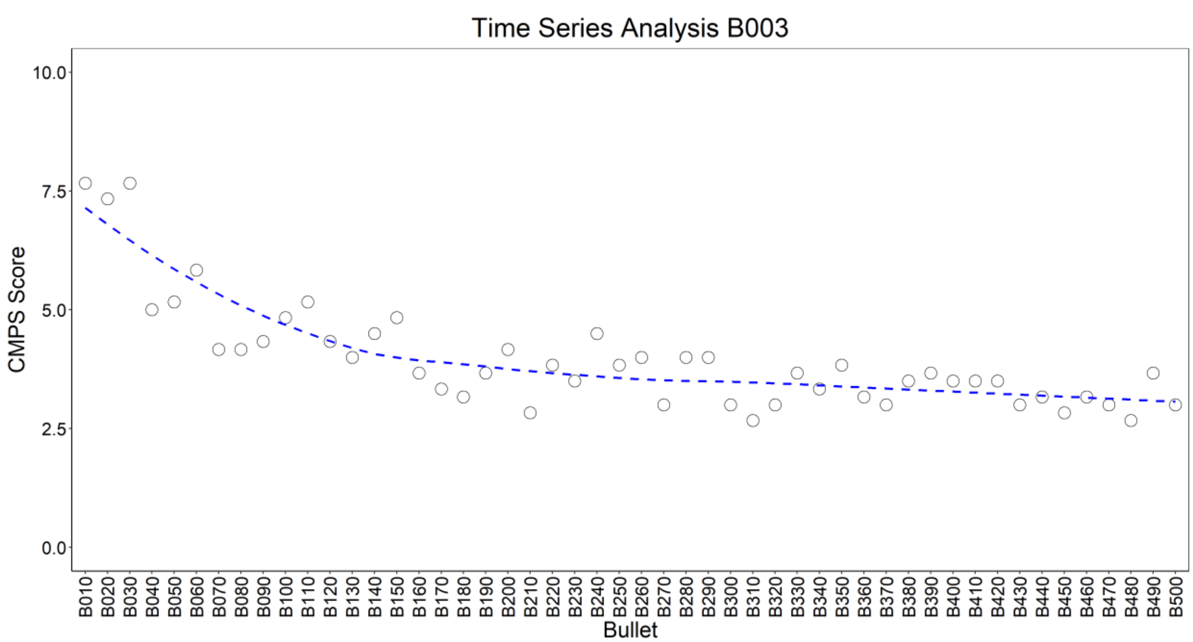


Figure 25: *Time Series Plot for Bullet 004*

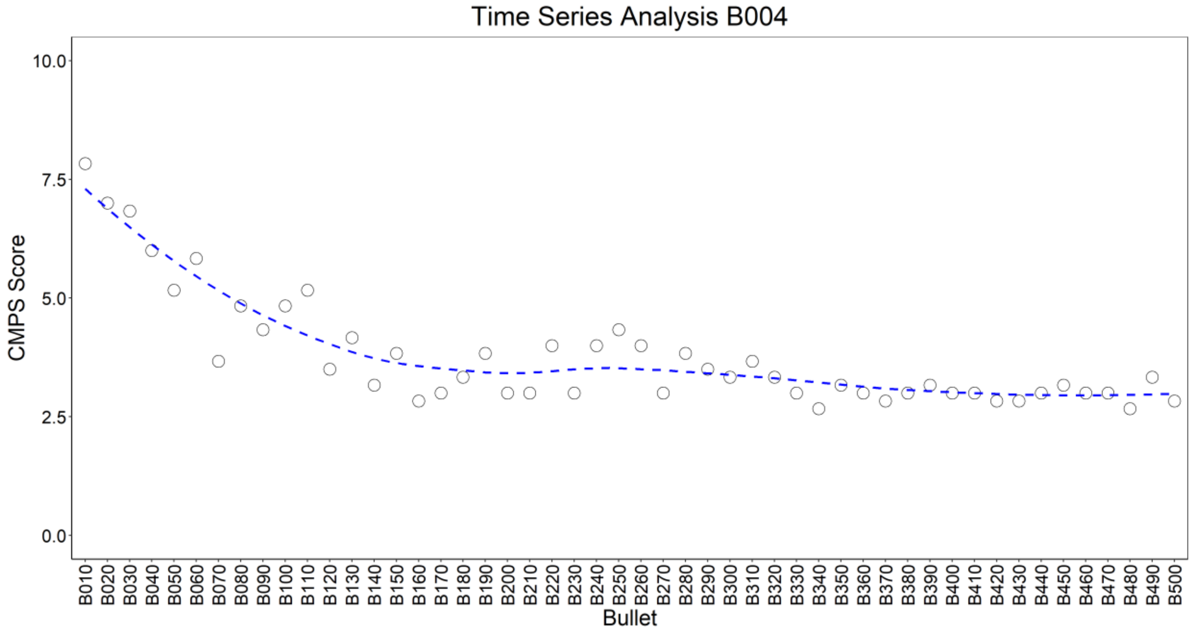


Figure 26: *Time Series Plot for Bullet 005*

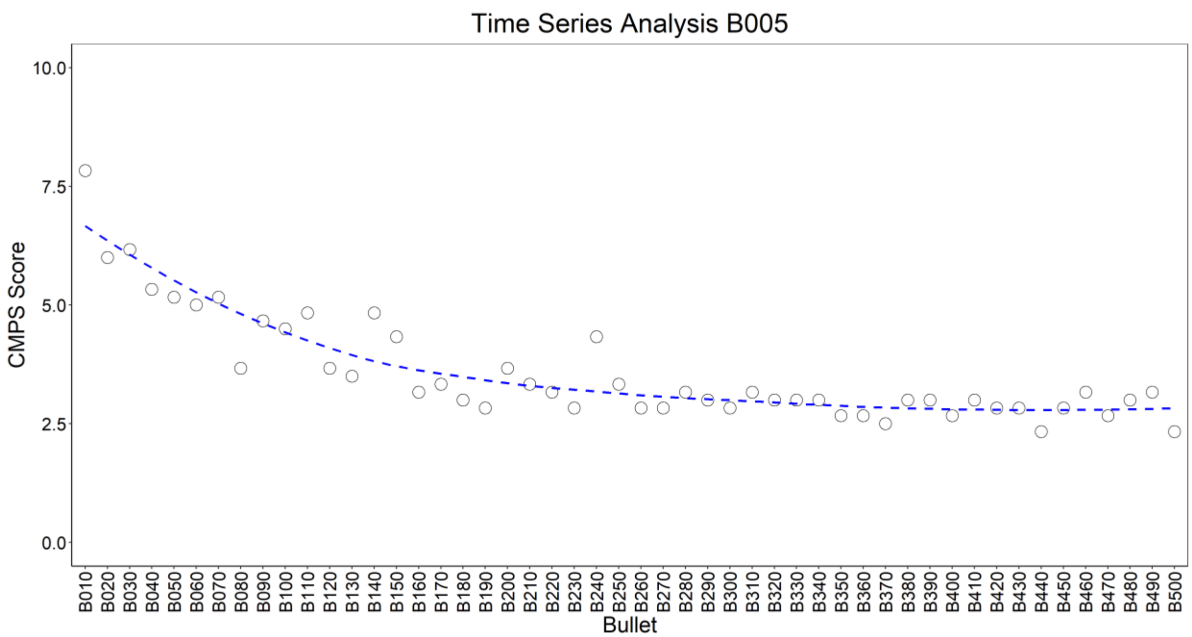


Figure 27: *Time Series Plot for Bullet 006*

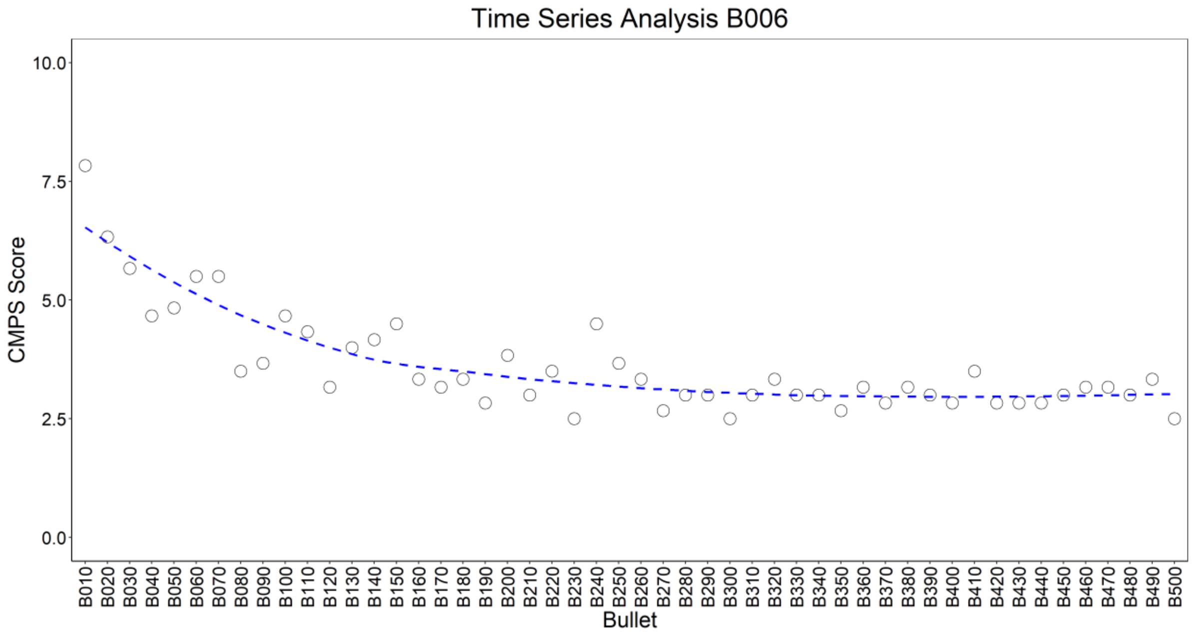


Figure 28: *Time Series Plot for Bullet 007*

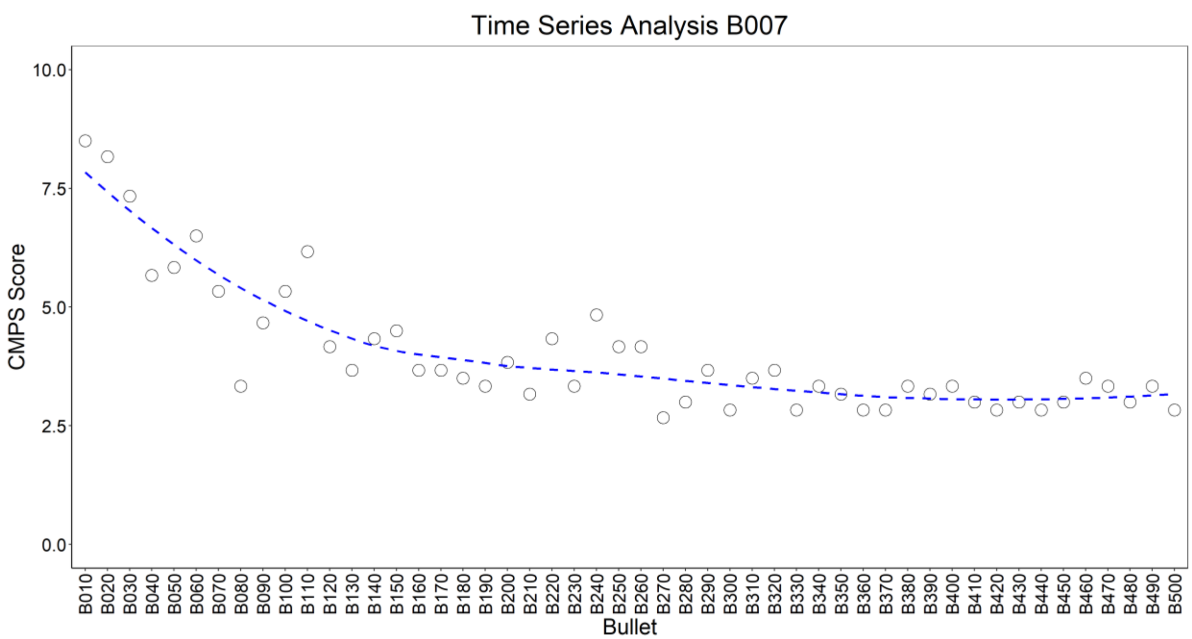


Figure 29: *Time Series Plot for Bullet 008*

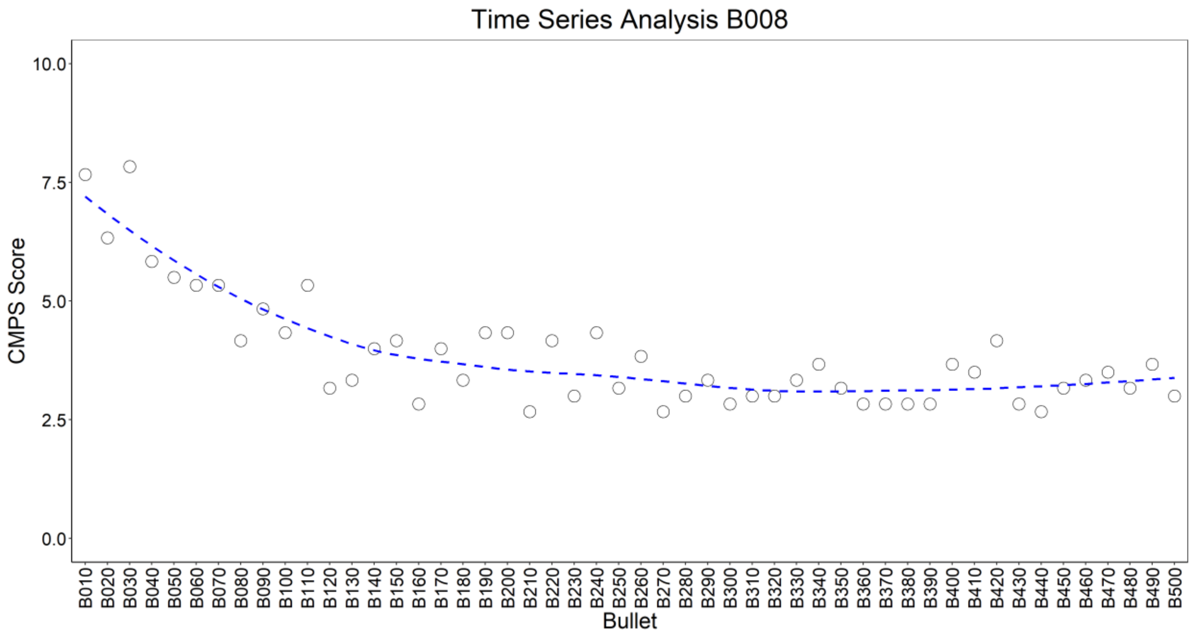
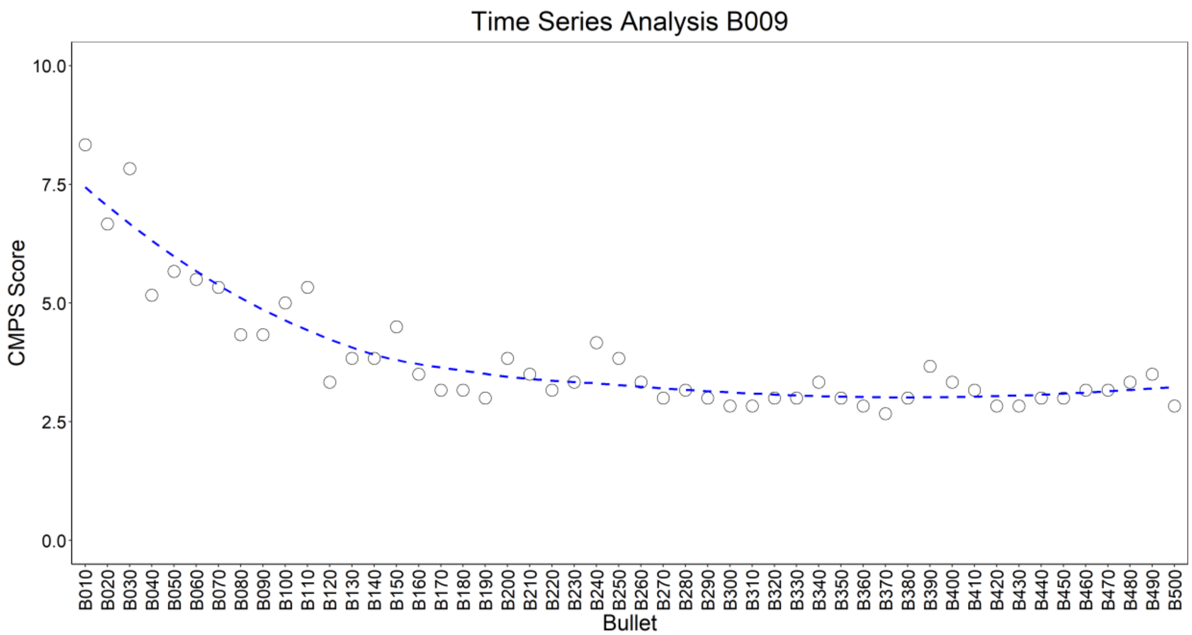


Figure 30: *Time Series Plot for Bullet 009*



Appendix C: Expanded time series plot for bullet 001

Figure 31: *Expanded Time Series Plot for Bullet 001*