Comparative Analysis of Traditional and UAV Bridge Inspections Performed by New Mexico State University

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Resumen

Este trabajo de investigación presenta un análisis comparativo entre la inspección asistida por UAV y las metodologías tradicionales de inspección de puentes, centrado en la evaluación de su rendimiento. Se pretende identificar las diferencias en los resultados de la inspección y evaluar la eficacia de las inspecciones asistidas por UAV.

Se definieron tres objetivos específicos para alcanzar la meta de la investigación. En primer lugar, se compararon los resultados de la inspección a nivel elemental entre las dos metodologías. Se analizaron los resúmenes del estado elemental de cada inspección, y el análisis estadístico reveló una variación máxima del 16,1% y un error del 20,5% en comparación con los valores tradicionales.

En segundo lugar, se calculó el rendimiento de cada metodología de inspección utilizando la filosofía Lean. Las mediciones in situ durante la inspección se recogieron y clasificaron según los principios Lean. Se comprobó que las inspecciones asistidas por UAV requerían aproximadamente el doble de tiempo que las inspecciones tradicionales.

Por último, se examinó la relación entre los resultados de la inspección y el rendimiento. La inspección asistida por UAV permitió inspeccionar elementos antes inaccesibles, como los pilotes, lo que se tradujo en un aumento del tiempo de inspección.

Esta investigación contribuye a comprender el rendimiento y los resultados de las inspecciones asistidas por UAV en comparación con los métodos tradicionales. El estudio subraya la importancia del análisis estadístico, las mediciones de productividad Lean y la consideración de las zonas inaccesibles en las inspecciones de puentes.

Palabras clave: UAV, inspección tradicional, rendimiento, condición de elemento, Lean

Abstract

This research paper presents a comparative analysis between UAV-assisted inspection and traditional bridge inspection methodologies, focused on evaluating their performance. Aiming to identify the differences in inspection results and assess the efficiency of UAV-assisted inspections.

Three specific objectives were defined to achieve the research goal. Firstly, the inspection results at the elemental level were compared between the two methodologies. The elemental condition summaries from each inspection were analyzed, and statistical analysis revealed a maximum variation of 16.1% and an error of 20.5% compared to traditional values.

Secondly, the performance of each inspection methodology was calculated using the Lean philosophy. On-site measurements during the inspection were collected and classified according to the Lean principles. Founding that UAV-assisted inspections required approximately twice as much time as traditional inspections.

Lastly, the relationship between inspection results and performance was examined. The UAV-assisted inspection allowed for the inspection of previously inaccessible elements such as piles, resulting in increased inspection time.

This research contributes to understanding the performance and results of UAV-assisted inspections compared to traditional methods. The study emphasizes the importance of statistical analysis, Lean productivity measurements, and the consideration of inaccessible areas in bridge inspections.

Keywords: UAV, traditional inspection, performance, element condition, LEAN

Comparative Analysis of Traditional and UAV Bridge Inspections Performed by New Mexico State University

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Final graduation project to opt for the degree of
Bachelor's Degree in Construction Engineering

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ESCUELA DE INGENIERÍA EN CONSTRUCCIÓN

Dedication

I dedicate this research to my family.

To my dad, Hugo Navarro Serrano P.E who supported me since I was a child to fall in love with construction engineering and accompanied me throughout this process.

To my mom Giselle Montero Carmona who was always there to support me and encourage me throughout my career.

To my brothers Ernesto, Felipe, and sister Carolina for always having faith in my academic life and motivating me to aim higher and higher.

To all my friends in college who reminded me to enjoy the little moments of life as well.

To TEC, School of Construction Engineering, and AEICO for giving me the opportunity to expand my skills and knowledge for my professional and personal life.

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Extended summary

The conventional approach to bridge inspection involves the physical presence of trained professionals who visually assess the various components of the bridge. However, this method presents challenges when dealing with tall bridges or areas that are difficult to access, requiring additional measures such as temporary structures or specialized equipment. Nonetheless, these solutions also have their own limitations and drawbacks.

The difficulties faced in traditional bridge inspections have underscored the importance of exploring alternative methods that can enhance the efficiency and efficacy of the inspection process, particularly in situations where access to specific areas is challenging. In this context, the utilization of unmanned aerial vehicles (UAVs) has emerged as a promising solution. Several studies [1,2,3] have demonstrated the potential of UAV-based inspections in overcoming the limitations associated with height and restricted accessibility, enabling a more thorough evaluation of bridge elements. By employing UAVs, inspections can be conducted with greater ease and precision, allowing for comprehensive assessments that were previously hindered by physical constraints.

This research a comparative analysis between UAV-assisted inspection and traditional bridge inspection methods, with a primary focus on evaluating their performance. The objective is to identify the differences in inspection results and to evaluate the efficiency of UAV-assisted inspections in order to contribute to a better understanding of their effectiveness compared to traditional methods.

Three specific objectives were outlined to achieve the research goal. A thorough comparison of the inspection results at the elemental level between the two methods was conducted. The elemental condition summaries obtained from each inspection were carefully analyzed and a comprehensive statistical analysis was performed. The results showed a maximum variation of 16.1% and an error of 20.5% compared to the traditional values, highlighting the differences and discrepancies in the inspection results.

On-site measurements were meticulously collected during the inspection process and categorized according to lean principles. The results showed that UAV-assisted inspections took approximately twice as long as traditional inspections, shedding light on the productivity and efficiency aspects of the two methodologies.

Lastly, the study examined the relationship between inspection results and performance. A notable benefit of UAV-assisted inspections was the ability to access previously inaccessible elements, such as piles, resulting in an increase in overall inspection time. By examining this relationship, this research provides valuable insights into the trade-offs between accessibility and inspection efficiency.

The study highlights the importance of statistical analysis, lean productivity measurements, and consideration of inaccessible areas in bridge inspections as critical factors to be considered for efficient and reliable inspection practices.

Introduction

Traditional bridge inspection involves on-site inspections by trained professionals who visually evaluate the various elements of the bridge. However, this approach is challenged in the case of high bridges or limited access to the substructure. In such situations, additional measures such as the use of temporary structures or specialized equipment are often employed to gain access to these hard-to-reach areas. But these solutions have their own limitations.

A disadvantage of using temporary structures or specialized equipment is the need for trained personnel to work at heights, which introduces safety risks and requires additional resources to ensure worker safety. In addition, the implementation of these measures can significantly increase the time required to conduct inspections. Setting up and dismantling temporary structures or operating specialized equipment can be time-consuming, resulting in longer inspection times.

These challenges highlight the need for alternative approaches that can improve the efficiency and effectiveness of bridge inspections, particularly in cases where access to certain areas is problematic. UAV-based inspection has emerged as a promising solution to address these limitations. Studies of unmanned aerial vehicles (UAVs) [1,2,3] have shown that they can overcome the limitations of height or limited access, thereby providing a more comprehensive assessment of bridge elements.

Overall, the integration of UAV technology into bridge inspections has the potential to revolutionize the field by improving access to critical areas, increasing inspection efficiency, and ensuring the safety of personnel involved in the process. By leveraging the capabilities of UAVs, bridge inspections can be conducted more effectively, resulting in better maintenance and helping with management of bridge infrastructure deficiencies showed by the ASCE Report [4].

The purpose of this research is to evaluate the performance of UAV-assisted inspections in comparison to traditional inspections conducted by New Mexico State University. To accomplish this, the following objectives were defined:

- To identify the differences in elemental level results between the two methods. This was accomplished by recompiling the elemental condition summary data from the reports of each inspection.
- To calculate the performance of each methodology according to the LEAN philosophy. This was done using on-site measurements during the inspections.
- To relate the inspection results to their performance. By using the results of the reports and on-site LEAN measurements.

It is important to consider that the specific conclusions drawn from this research are based on the findings of the study conducted with New Mexico State University. The applicability and generalizability of these conclusions may vary depending on factors such as bridge types, environmental conditions, and specific inspection protocols. Further research and real-world implementation are needed to validate and refine the findings in different contexts and bridge settings.

No automated systems or algorithms for damage detection and quantification were used in this study, as the initial implementation of UAV inspections was focused on observation. The use of the lean philosophy had a diagnostic scope to identify how activities and time were distributed during the experiment. In terms of this research, the data collected from the bridges was considered as the same group and not as independent data. Due to this, no t-student test was applied. Also, this research is only focused on comparing the results between the methods applied to one bridge and no multiples.

Thanks to the staff of the Bridge Inspection Program at NMSU for their collaboration and willingness to support the research. To Dr. Zhang for being the primary advisor for this research and to Dr. Jauregi for arranging the opportunity to conduct this research for the benefit of both parties.

Chapter 1: Theoretical Framework

According to the Report Card for America's Infrastructure made by ASCE in 2021, the bridges in the USA have an overall grade of C where 42% are at least 50 years old. After 2018 the bridges rated as Fair passed the number of bridges rated as Good [4]. This number could increase in a couple of years due to the rise of the bridge's average age to 44 years. To prevent this, the DoTs are working on improving the bridge maintenance programs, which start with the routine inspections of the bridges every 2 years according to the National Bridge Inspections Standards (NBIS) [5]. A good quality inspection can help with the early detection of damages in bridges and lead to preventive actions such as maintenance or repair.

1.1 Bridge Inspections

Routine inspections are the first step in the early detection of bridge damage. They allow DOTs to be alerted to sudden damage and critical findings that put the public using these roads at risk in the short or medium term. Inspections help preserve the condition of the country's infrastructure by identifying damage at an early stage and preventing it from increasing. Currently, there are different methodologies to perform bridge inspections, which seek to address the difficulties that may arise during these inspections.

1.1.1 Bridge Inspection Types

There are two main groups where bridge inspections can be classified: traditional and advanced. The traditional inspection is the most frequent one and it contains visual and physical inspections. The visual inspection looks up for damages on the bridge observing the substructure and superstructure elements. When the visual inspections are not enough to quantificate the damage, physical inspections are needed. It mainly contains the damage measurements on the different elements on the bridge.

During the 2010s advanced inspections began to spread thanks to technological advances. Some examples of these advances are Non-Destructive Evaluation (NDE) and Unmanned Aerial Systems (UAS). The NDE improved the data obtained from the inspections with their ability to evaluate the interiors from the bridge elements without having to apply destructive testing. The NDE method may vary depending on the bridge material; they are frequently used on steel bridges due to their relationship with fatigue inspections. And for concrete bridges, the Ground Penetration Radar (GPR) is the method more applied by DoTs according to the survey made by Dorafshan and Maguire in 2018 [6]. Even though NDE can provide more detailed information about the bridge status, various authors [3,7] agree that the NDE performance relapses on the inspectors' experience and how capable is to interpreted the results.

Research has found a way to overput this outcome by combining NDE and UAS in various ways, from using Infrared Thermography (IR) with UAV for detecting and quantifying delamination on bridge decks [7] to GPR combined with Ultrasonic Surface Wave Testing using the RABIT for decks inspections [8].

1.1.2 Traditional Bridge Inspections Challenges

The construction industry is getting behind with technological advances compared to other industries. When they have been upgrading their performance and implementing automatization during the last years, construction is just starting to implement certain types of automatizations. In traditional bridge inspections, the biggest challenge is access to difficult areas. According to the Bridge Inspectors Reference Manual, the only two ways to access difficult areas are doing it through equipment and access vehicles [9].

Using an Under Bridge Inspection Truck (UBIT) can increase the duration of the inspection due to all the work needed for its use. According to the Manual on Uniform Traffic Control Devices for Streets and Highways (MUTCD) [10], users must be informed and guided throughout traffic control. Vehicle control includes traffic rearrangement, closure of the UBIT lane, and all signage required to alert drivers. In the case of New Mexico renting a UBIT for a day can cost around $1,747 [11] increasing the inspection price. Other problems involved with UBITs are the exposure to hazards during their use. The most common accident during the use of UBIT is the overturning of the unit. This hazard not only threatens the safety of inspectors and operators but also that of the public.To prevent it, DoTs must invest in safety training for their inspector, especially safety equipment. This can also affect the bridge by adding weight due to the UBIT or traffic congestion due to the closed lane with the UBIT in it.

Another problem that the use of UBIT implies is the economic losses caused by traffic stoppage, in which both merchandise and employees will have to spend more time to reach their destinations, according to the New York Times, these losses represent more than $100 billion a year [12]. An example of the vehicle control required for the use of UBIT is shown in Figure 1.

Figure 1. *Traffic control due to a UBIT inspection.*

[13]

Reducing inspection time is a critical aspect that can greatly benefit the bridge inspection process. By improving data processing and using advances in technology such as UAVs, semi-automated or automated inspection approaches can be developed to speed up the overall inspection process.

By incorporating these technologies and strategies, the inspection process can be accelerated, allowing Department of Transportation (DoT) agencies to inspect a greater number of bridges in a given time frame. This, in turn, contributes to more efficient infrastructure management and maintenance practices, leading to improved overall safety and longevity of bridge structures.

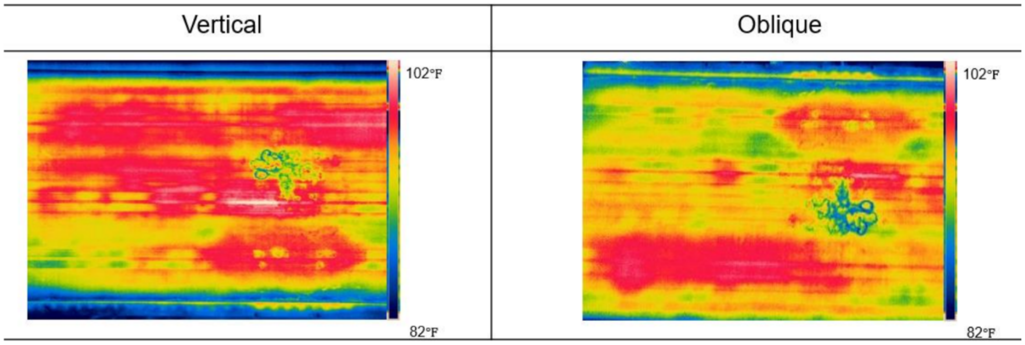
1.2 UAS and UAVs

The Federal Aviation Administration FAA defines UAS as an unmanned aircraft and the equipment necessary for the safe and efficient operation of the aircraft [14]. The UASs contain the Unmanned Aerial Vehicle UAV, payload system, and other systems attached to the UAV like sensors. At their beginnings, UASs were only for military purposes. Still, after the 2010s they increased their application in different industries like communication and broadcasting, agriculture, the energy sector, and construction [15].

1.2.1 UAVs Sensors

One of the advantages of UAS is the implementation of sensors in the vehicle to enrich the information obtained during the inspection. Usually, these sensors are restricted to non-contact types like thermal infrared sensors TIR and Light Detection and Ranging LiDAR. TIR sensors measure the thermal properties of the materials and combined with an UAVs is able to identify delamination on concrete decks [7] as observed in Figure 2. On the other hand, LiDAR sensors project light onto objects and generate information that can be transformed into 3D modeling; this can improve the quality of bridge virtual twins for bridge management systems or Bridge Information Modeling BrIM [16].

Figure 2. *Delamination images obtained by using TIR sensor on UAVs depending on the angle.*



[8]

Other types of sensors help the UAV with navigation issues during the flight. When going under the bridge the UAV can lose the GPS signals and be unable to fly correctly. The main concern with losing the GPS signal in the drone is losing control of the device. Not being able to control the drone increases the chances of collision with the bridge, inspectors, or bridge users in general. All of these scenarios could lead to economic and physical loss for the organization. To prevent the UAV to crash into the bridge, sensors like Radio Detection and Ranging RADAR, Sound Navigation and Ranging SONAR, or magnetic sensors can help the UAV to predict its position and the near elements [6].

1.2.2 FAA regulations

Due to UAVs flighting into controlled airspace, the FAA stands some regulations that need to be fulfilled to attend a UAS flight. Some regulations related to the specific aircraft space, the UAS, and the pilot are shown in Chart 1. Of all these regulations those that most restrict the implementation of UAVs in bridge inspections are highlighted with underline.

The total weight of the UAS limited to 25 kg could limited the UAVs implementation because it limits the sensor capacity depending on the weight of each of them. That the vehicle has to be on the pilot's visible range limits the localization of the pilot during the flight under the deck. The UAV can not fly over people nonrelated to the operation; this restricts the flights over the deck to only when the bridge has been closed. The maximum altitude permitted is 133 meters above the top of the structure, on big bridges, this can lead to not being able to take images from the entire bridge at once. The UAV can only fly during the daytime, this limits the ability to take a full analysis of thermal infrared images due to the changes in temperature during the day.

CHART 1. FAA REGULATIONS RELATED TO UAVs

Pilots	UVAs	Aircraft space
● Must have at least 16 years old. ● Be able to read, speak, write, and understand English. ● Be in a physical and mental condition to safely fly a drone. ● Pass an initial aeronautical knowledge exam: "Unmanned Aircraft General – Small (UAG)". ● Take a recurrent aeronautical knowledge test every two years.	● Drone speed can not exceed 160 km/h. ● UAS has to be registered and certified by the FAA. ● Total weight UAS is limited to 25 kg. ● Requires a waiver for the following operations: operate from a moving vehicle or aircraft, operate at night, operations over moving vehicles or human beings. ● UAS has to be on the pilot’s visible range during all the flight.	● Special restrictions when flying near stadiums, sport events, Airports, Security Sensible Airspace, restricted or special use airspace and over Washington, DC. For this ● Maximum altitude permitted is 133 m above the top of the structure.

[17]

1.3 UAV-aided bridge inspections

Even though around 34 DoTs around the USA have been involved with UAV-aided Bridge Inspections, none of them have been able to integrate the use UASs into routine bridge inspections [6]; between 2018 and 2020 the DoTs using UAVs passed 6% to 21% [18]. The UAVs are applied to various areas by DoTs, from recollecting traffic data to UAV-aided bridge inspections. Recently most UAVs used on bridge inspections are 94% used for recollecting images, and 61% for observational damage description.

The implementation of UAVs on bridge inspections offers different improvements and can help with automatizing the data processing using different algorithms and technological advantages like Artificial Neural Networks ANN and Machine Learning. It also offers more efficient inspection and the ability to increase productivity with the help of Lean Philosophy by eliminating non-value added activities from the process. To qualify inspections with less capital needed, this can be studied by comparing total cost and applying values like Net Present Value NPV and Return on Investment ROI to verify that the investment is truly worth it.

1.3.1 Data processing

One of the advantages of implementing UAVs in bridge inspection is related to the possibility of automating the processing of the data obtained. The data processing includes the selection of high-quality images, the detection of damage within these images, and the quantification of the damage. Several authors have successfully coded algorithms capable of performing one or more of these tasks [2,3,7,19].

Although automated data processing is not within the scope of this research, it is important to highlight the advances that can be integrated after the implementation of UAV-assisted bridge inspections. The functionality and scope of each type of algorithm are detailed below.

1.3.1.1 Algorithms for high-quality image selection

These algorithms work by selecting the images that qualify with the standard established by the user. Evaluates the different image properties such as sharpness, brightness, noisiness, and exposure [18]. Those algorithms are considered the first stage of autonomous data processing. Normally from a UAV-aided inspection around 2,000 images can be collected, but that does not mean that all 2,000 images can give crucial information. Some images can be blurred or with low quality due to low light, which is why a high-quality image selection is crucial for efficient data processing.

1.3.1.2 Algorithms for damage detection on images

The purpose of these algorithms is to filter the images with damages out of the stack of images obtained from the bridge inspection. To obtain information from images the pixel values are interpreted as a vector. There are various methods to work this information to detect damage.

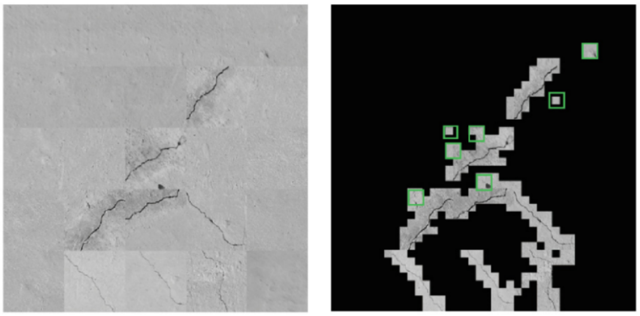
Edge detection algorithms evaluate the image properties and apply first and second derivatives to the pixels value and determine if is an edge or not, but the accuracy can be compromised by blurry images [18]. Other Gradient-based edge detection methods use the discontinuation values for pixels and calculate the gradient using the first-order partial derivatives to determine edge pixels [20] without relaying on the image quality. The Grayscale image processing method integrates conversion from RGB to LAB values while applying a grayscale filter, where L is for lightness, A is for green and red components, and B is for blue and yellow components; to preserve the original gradient value [21].

1.3.1.3 Algorithms for damage quantification

Even though the algorithms can detect damage there is still a need to quantify damage and report it. For this, a manual measurement needs to be done, but studies have found that using algorithms with Convolutional Neural Networks CNN combined with Deep Learning can be as accurate as manual measurements [2,3,7]. Figure 3 shows the input and output results of a damage detection algorithm. It identifies the segments that the algorithm detected the crack pattern.

Deep Learning is a subset of Machine Learning composed of neural networks with at least three layers or more that attempt to simulate the behavior of human brains by learning from a large amount of data [22]. CNN work by cutting the input image into pieces and analyzing the pooling values to avoid redundant information, fuse the similar one, and eliminate the unnecessary. Research has demonstrated successful results in delamination damage detection and quantification when applying these algorithms [7] with an accuracy of 99.25% when compared to manual methods.

Figure 3. *Crack detection by an algorithm based on Machine Learning.*



[7]

1.3.2 Productivity analysis

The main improvement that UAVs offer is an increase in productivity; even though there are not many records of data on productivity specifically, a diagnosis can be obtained by various methods. Productivity can be described as the ratio between the output of production and the input of production factors [23]. A productivity diagnosis can help find out if the process is effective and efficient by getting the maximum goals using the minimum resources possible.

1.3.2.1 Lean Philosophy

The Lean philosophy, also known as the Toyota Production System, changed the production philosophy around the 1970s in Japan's first oil crisis when Toyota maintained sustained even when the Japanese economic growth collapsed [24]. This philosophy looks to eliminate all the activities classified as non-value added and use this time for more value-added activities.

Lean classifies activities into three groups: value-added, required non-value added, and non-value added. The value-added activities are directly related to the production or development of the final product and affect its performance. On the other hand, required non-value and non-value activities do not contribute to the process or affect the final performance. The difference between required non-value and non-value activities is that required non-value activities are needed to finish the final product.

From a bridge inspection perspective reviewing old reports, measurement of damage on bridge elements, and writing reports are classified as value-added activities. Because the quality of the final product depends on the activities' performance and can lead to non-value activities. If the inspector does not review the report correctly, he or she will not identify the previous damages correctly. Then when performing the inspection it will require more time to identify them. This can generate non-value activities like wasting time looking for the correct measurement tools due to a lack of planning or overlooking the elements to find damages.

Lean philosophy is more than categorizing activities it can help to diagnose inefficient processes and evaluate if new methods increased productivity. When changing the methologloy used in bridge inspections field is necessary to measure if the new method is improving efficiency and effectiveness. Authors have already implemented the Lean philosophy into traditional routinary inspections [25] and worked with the methodology and application of UAVs into inspections [1], and found a successful way to implement these methodologies into bridge inspections.

Chapter 2: Methodology

The purpose of the research is to perform a comparative analysis between traditional and UAV-assisted inspections performed by the Bridge Inspection Program at New Mexico State University. This analysis focused on the data obtained and the productivity of each methodology. The research was able to quantify the differences between the data obtained and the productivity through the experiment in a controlled scenario. The controlled scenario consisted of applying both inspection methodologies to the same bridge and then comparing their results. The NMSU Bridge Inspection Program inspectors were divided into two teams, A and B. Team A was responsible for conducting the inspection using the traditional method. While Team B performed the UAV based inspection.

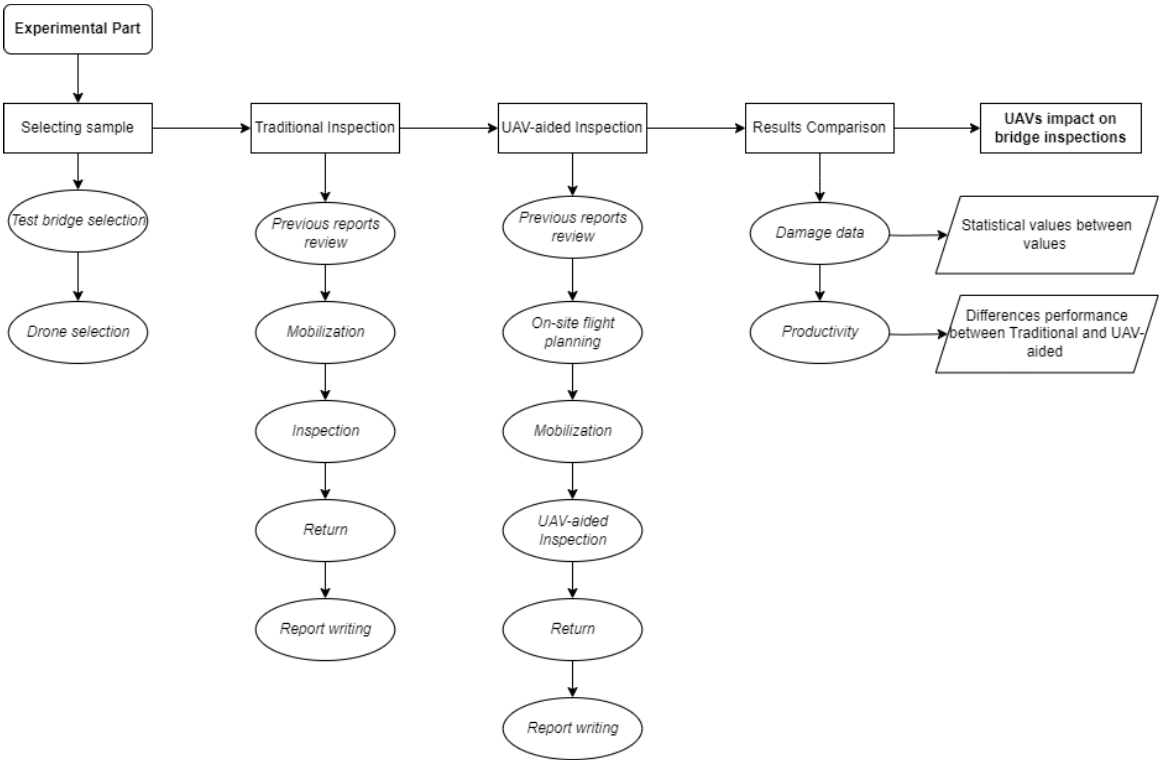
The research was conducted using a two-part experiment. The investigation was designed to test two bridge inspection methods on the same bridge. The results of quantifying the damage and productivity of each method were used to compare them.

2.1 Experiment

The experiment used both methods on the same bridge to compare their performance in a controlled scenario following the flowchart show in Figure 4. Team A performed the traditional inspection, while Team B performed the UAV-assisted inspection. Both inspections quantified the damage at the element level of the bridge and recorded the times of each activity.

By comparing these values, it was possible to determine the impact of the implementation of UAVs in bridge inspections in terms of productivity and data obtained during the inspection. The experiment consisted of four phases: selecting the sample, performing the traditional inspection, performing the UAV-assisted inspection, and comparing the results.

Figure 4. *Experimental flowchart process.*



2.1.1 Test Bridge Selection

In the selection of the sample bridge, a number of characteristics were taken into account. Since it was the first implementation of UAVs in bridge inspections, the area around the bridge had to be an open space to reduce the difficulties of control of the drone during the flights. Bridges in more rural areas were also considered since they had little traffic and did not require vehicular control. This is to avoid flying over third parties, which is prohibited by the FAA, and their exposure to them. Additionally, easy access to the bridge abutments was considered, so that the drone could always be within the range of vision of the pilot when inspecting under the bridge. Finally, it was considered to be a bridge representative of the bridge population in the state of New Mexico. In this way, the performance projection could be made to bridges with similar characteristics.

In addition to all of these characteristics, the need to use UAVs to inspect bridges was considered. This requirement had to do with the inaccessibility of the substructure during traditional inspections. This includes bridges that have other types of service in the substructure other than highways. For these types of bridges, access to the substructure is affected by the presence of water, the difference in elevation between the ground and the bridge, or the passage of railroads. In these cases, it can be difficult to quantify the damage to the components because they are inaccessible.

2.1.2 Traditional Bridge Inspection

This phase included activities related to inspecting the bridge using the traditional methodology performed by the A-Team. On-site LEAN productivity measurements were conducted throughout this phase. The LEAN productivity measurements performed include five stages: a review of previous reports, mobilization to the bridge, inspection, return, and report writing. All these stages were measured during on-site measurements.

For the review of the previous reports phase, all the work before mobilization is considered. The annotations and evaluations of the previous inspection are reviewed to define the activities to be carried out. In the mobilization phase, all transportation activities to the bridge were considered, from filling the gas tank to the loss of exits.

The inspection phase was from arrival at the bridge to departure. The activities where the information for the elaboration of the reports was collected were considered in this stage. From the measurement of cracks, review of joints, and discussion between inspectors to determine the damage of an element. For the return phase, the same activities are considered for the mobilization phase, except that they were carried out after the bridge inspection. The reporting phase evaluated the activities of image processing, inspection annotations, modification of the previous report, Dropbox update, among others.

The template used for taking the measurements considered the stage, the initial hour, the final hour, the total time in minutes, notes for the activity, and the overall time for the stage.

2.1.3 UAV-aided Bridge Inspection

At this stage, Team B inspected the bridge with the help of UAVs. LEAN productivity measurements were taken on site. For this inspection the LEAN measurements considered 6 stages: a review of previous reports, preflight, mobilization, UAV-aided inspection, return, and report writing.

The review of previous reports used the same times as for the traditional bridge inspection. Pre-flight includes activities associated with UAV logistics. From flight planning and launch site selection to UAV testing 4 days prior to inspection.. Like the traditional bridge inspection, mobilization contemplated all the activities between the office and the arrival at the bridge.

For the UAV-assisted inspection, all activities related to the inspection of the bridge and the adjustment and takeoff of the UAVs were contemplated. For the return, all transportation activities between the bridge and the return to the office were used. Finally, the report writing considered all the activities for the elaboration of the inspection report, image processing, mailing, and editing previous reports, among others.

2.1.4 Results comparison

This phase was divided into a comparison of the LEAN productivity results and the quantification of the damages. For the productivity outcomes, all activities obtained from the field measurements were categorized into the following categories: Value Added VA, Required Non-Value added, and Non-Value added. Then calculate the total time per each stage. This number was required for estimating the percentage for each activity category.

The total time invested in each type of activity and the percentage of the total time of the stage was obtained. After performing this process in each stage, the total time of the process was calculated, considering each stage and its types of activities. By adding the times of each type of activity and obtaining how much percentage of the total time they represent. Finally, the percentage difference of each type of activity was calculated. This was used to determine whether productivity was increased or decreased by the use of UAVs.

For data quantification, the condition summary elements of each report were recompiled for comparison of damage estimates. Statistical analyses including error percentages, coefficient of variation, and standard deviation were performed on all differing damages. Performing a statistical analysis of the damage quantification results is a valuable step in evaluating the performance of UAV-assisted inspections compared to traditional inspections.

Chapter 3: Results

The research study that was conducted in this investigation was designed to look at two different categories of results: LEAN productivity results and bridge damage quantifying results. The inspections were conducted by Teams A and B in the southern part of Albuquerque in Bernalillo County. The productivity results were classified and their respective percentages were calculated. This analysis allowed the identification and quantification of the key elements that contribute to productivity improvements in the context of the implementation of UAVs in bridge inspections.

On the other hand, the results of the quantification of the bridge damage were obtained through the creation of a comparative table and through statistical calculations. This table provided a comprehensive overview of the major differences in damage quantification at the element level according to the National Bridge Elements established by the Federal Highway Administration and the National Highway Institution [26].

The combination of these two sets of results provides valuable insights of how both the operational efficiency and structural condition rating of the bridge can benefit from this implementation.

3.1 Test Bridge Selection

Considering all the characteristics and the need to implement UAVs presented in the methodology, Bridge No. 7510 was selected as the sample bridge for the experiment. It is a 12-span continuous concrete bridge located in New Mexico District 3 in Bernalillo County, built in 1975. The characteristics met by the sample 7510 bridge are shown in Chart 2 and Figure 5 and 6 show photographs of the bridge.

CHART 2. ADHERENCE TO THE CHARACTERISTICS OF THE BRIDGE 7510 AS SAMPLE BRIDGE

Sample Bridge Characteristics	Bridge 7510 Characteristics
Area around the bridge is an open area	The space around the bridge is open and there is no significant vegetation to interfere with the flight of the UAV
Bridge is located in a rural area	The bridge is considered an urban collector with an ADT of 3,631 cars per day
Access to abutments	Easy access to abutments through surrounding land
Representative bridge	Similar characteristics are found on most of the bridges that cross the Rio Grande
Need to use UAV	River flow prevents access to spans 2 - 11

Figure 5. *Bridge 7510 profile view looking North.*

Figure 6. *Bridge 7510 profile view looking South.*

3.2 Traditional Bridge Inspection

Productivity measurements began a day before the inspection day with a review of previous reports. Upon arrival at the site, inspection of the superstructure and wear surface from Abutment 1 to Abutment 2 began. Then the substructure was inspected. Due to lack of access to all spans, only spans 1 and 12 were inspected as shown in Figure 7. In the end, the team went back to the office and prepared the report with the quantification of the damage that was observed Table 1 shows the summary of the quantification of the condition of the elements: deck, girders, abutments, pile caps and piles. LEAN productivity measurements were taken throughout all of these processes.

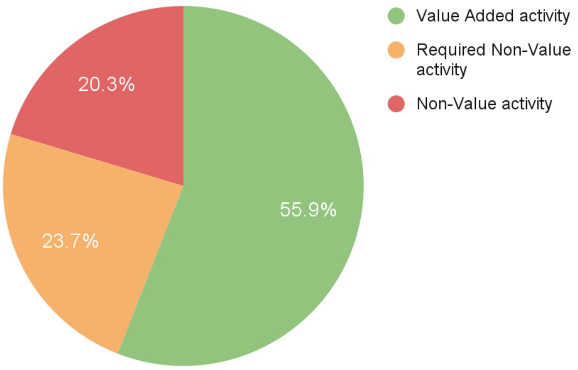
Figure 7. *Team A inspecting accessible spans.*

TABLE 1. ELEMENT CONDITION SUMMARY FROM TRADITIONAL INSPECTION

Element	Condition State 1 Good	Condition State 2 Fair	Condition State 3 Poor
Deck	-	3 112 m²	-
Girder	1 207 m	3 m	-
Abutment	-	6 m	30 m
Pile cap	185 m	3 m	6 m
Pile	176 each	-	-

Table 3 shows the Lean productivity results of the inspection stage related to this methodology and figure 8 shows the distribution of activities according to their LEAN classification. This section focused on the results of the Inspection stage because it is the only stage where the differences between the methods are found. See Appendix 2 for the results for each stage.

Figure 8. *Traditional Inspection activities divided by LEAN classification.*



3.3 UAV-aided Bridge Inspection

As with the traditional inspection, the UAV-assisted inspection began with a review of previous reports. Before the inspection day, on-site flight planning was conducted to determine the launch zones, the number of flights, the flight path, and the practice flight. It also included the logistics of the drone flight, such as the definition of the marking zones and the application for the flight permit. Figure 9 details the pre-planning for the inspection. The red color is the launch area used, the green color was used to highlight the path of the first and third flights. Blue was used to highlight the second flight path, and yellow shows the flight through the substructure.

The training flight took place on Bridge No. 6255 located in Doña Ana County in Las Cruces. This bridge consists of 2 sets of 4 continuous steel spans. The test flight was conducted on this bridge due to some logistical issues that the team was having. This bridge was chosen for training because it also crosses the Rio Grande, but the waterway was closed. This improved the access to the substructure so that the pilot could practice flying under the bridge shown in Figure 10.

Four flights were made on the day of the inspection. The first and third flights were made along the south and north sides of the bridge, the flights were at deck level to observe the cracking behavior at the deck edges and to observe the exterior girders as shown in Figure 11 and 12. The second flight focused on observing the deck from an oblique top view as shown in Figure 13.

The last trip focused on observing the substructure, the UAV flew at the lowest possible height without touching the water and without colliding with the girders to enter the span, in Figure 14 is possible to see the view from the drone before entering the span. The condition of Spans 2-11, which could not be observed during the traditional inspection, was observed during this flight. The observations were limited to the visual detection of any cracks or spalling.

Figure 9. *On-site flight planning.*

Figure 10. *UAV flying through the spans during practice flight.*

Figure 11. *Deck-side and outer girder on South view.*

Figure 12. *Cracks on deck-side and outer girder on North view.*

}

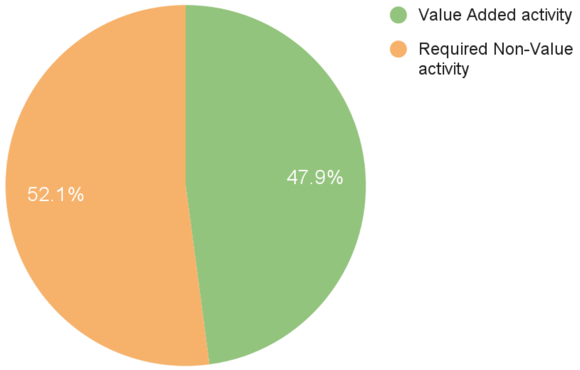
Figure 13. *Transversal cracks on deck identified during the second flight.*

Figure 14. *Closement to the span near abutment 2.*

TABLE 2. ELEMENT CONDITION SUMMARY FROM UAV-AIDED INSPECTION

Element	Condition State 1 Good	Condition State 2 Fair	Condition State 3 Poor
Deck	-	3 062 m²	51 m²
Girder	1 206 m	2 m	2 m
Abutment	-	6 m	30 m
Pile cap	185 m	3 m	6 m
Pile	140 each	32 each	-

Figure 15. *Proportion of UAV-aided inspection activities by type of activity.*



3.4 Results comparison

In this section, we present all the data compiled for the comparison of the two methodologies, including the LEAN productivity measurements and the results of the Element Condition Summary. To compare the productivity results, Table 3 shows the total duration of each inspection and the time spent on different types of activities.

To compare the results of the Element Condition Summary, Chart 3 was prepared. The deck, beam, abutment, pile cap, and pile element notes from each inspection are summarized in this table. The purpose of this comparison was to identify variations in the qualitative nature of the damage observed in each inspection.

For a quantitative analysis of the damage, the statistical values derived from the results are presented in Table 4. It is important to note that since the objective of the research was to compare UAV-assisted inspections with traditional inspections, the traditional inspection results were considered as theoretical values against which the UAV-assisted inspection results were compared. This approach allowed for a meaningful assessment of the extent to which UAV-assisted inspections were consistent with traditional inspection results.

TABLE 3. LEAN PRODUCTIVITY RESULTS OF THE INSPECTION STAGE FOR BOTH METHODS.

Methodology	Total time [hours:minutes]	Value Added activities [hours]	Required Non-Value added activities [hours]	Non-value added activities [hours]
Traditional	0:59	0:33	0:14	0:12
UAV	1:59	0:57	1:02	0:00

CHART 3. COMPARISON OF TRADITIONAL INSPECTION AND UAV INSPECTION ELEMENT NOTES

Element	Traditional Inspection	UAV Inspection
Reinforced Concrete Deck	Underside appears sound throughout. Sides of deck have moderate vertical and horizontal cracks.	Underside appears sound throughout with minical cracking. East bound deck edge has vertical and horizontal cracks with water staining and underside has minimal horizontal cracking
Open Girder/Beam Prestressed Concrete	Significant cracks on girder ends 2 and 5 at each abutment.	Few cracks on all girder ends at abutment but girder 3.
Reinforced Concrete Abutment	The faces of backwalls are water stained.	Water stained has now developed into efflorecense.
Reinforced Concrete Pier Cap	Some piers have moderate vertical cracks.	Debris on top of caps.
Reinforced Concrete Pile	Piles are in good condition	All piles at span 1 and 2 are fully delaminated.

TABLE 4. STATISTICAL VALUES FOR THE QUANTIFICATION OF DAMAGES IN THE INSPECTIONS

Element	Traditional Inspection Value		UAV Inspection Value		Average	Standard Variation	Coefficient of Variation	% error
Deck	3 112	m²	3 062	m²	3 087	35	1.1%	1.6%
Girder	1 207	m	1 206	m	1 207	1	0.1%	0.1%
Abutment	30	m	30	m	30	0	0.0%	0.0%
Pile cap	185	m	185	m	185	0	0.0%	0.0%
Piles	176	each	140	each	158	25	16.1%	20.5%

Chapter 4: Results analysis

4.1 Test Bridge Selection

Based on the considerations outlined in Chart 2 in Chapter 2, Bridge N° 7510 was selected as a sample bridge. Visual evidence that the surrounding area met the specified requirements can be seen in Figures 5 and 6. This ample space provided the UAV pilot with enhanced mobility along the bridge, as there were no significant hazards obstructing the flight path and risking collision. In addition, the bridge had unobstructed access to the abutments, as the presence of minimal vegetation did not impede the UAV's passage through the spans near the abutments. The bridge's location in a rural area had minimal impact on nearby traffic. This made it easy for the inspectors to mobilize along the deck.

Importantly, this particular bridge stood out for its ability to represent the required scenario for the study. Throughout New Mexico, there are numerous bridges that span the Rio Grande, which pose a challenge to the inspection of their substructures due to the presence of water. Consequently, most substructures require a specialized inspection approach such as water inspections or UBITs.

4.2 Traditional Bridge Inspection

The traditional inspection attempted to replicate the typical scenario where not all members of the substructure are accessible. The deck could be completely inspected except for the upper part because it is covered by the wearing surface. A condition state (CS) of 2 Fair was assigned in Table 1 to the entire 3 112 m² deck, which has moderate width cracks that are unsealed. The inspection of the girders revealed that partial examination was feasible, thanks to the accessibility of spans 1 and 12. Based on the assessment, these elements were assigned condition states (CS) of 1 (Good) and 2 (Fair). CS 2 was attributed due to the identification of delamination and cracks in the areas that were accessible for inspection.

Regarding the substructure elements, the abutments were the only components that could be thoroughly inspected during the assessment. The assigned CS of 3 (Poor) was due to the presence of spalls exceeding 2.51 cm in size. On the other hand, CS 2 (Fair) was assigned when spalls measured 2.51 cm or less, and efflorescence was present without significant accumulation.

In the case of pile caps and piles, only the ones that were accessible for inspection were taken into consideration. The inspection results revealed that the pile caps exhibited condition states (CS) across all three categories: 1 (Good), 2 (Fair), and 3 (Poor). The majority of pile caps were classified under CS 1 since their condition could not be verified due to inaccessibility. Pile caps falling into CS 2 exhibited unsealed longitudinal and vertical cracks. Additionally, severe delamination was identified in the pile cap of piles 4 and 8, resulting in their assignment to CS 3. Finally, in the traditional inspection, the accessible piles were observed and showed no damage, so all piles were assigned a CS 1.

During the comprehensive inspection process, LEAN productivity measurements were recorded carefully for the activities of each stage. Looking at Table 3, the inspection stage had a total duration of 59 minutes, which included 33 minutes of value-added activities, 14 minutes of required non-value-added activities, and 12 minutes of non-value-added activities. These values are also shown as percentages in Figure 8, highlighting that just over 50% of the activities have a direct impact on the efficiency and effectiveness of the inspection and reporting process.

In this scenario, 10 of the bridge's 12 spans were inaccessible for inspection without the use of special equipment. Inspectors are faced with two scenarios because the vast majority of spans cannot be observed. They can use the accessible spans to estimate how the remaining spans will perform. This action is based on the assumption that the behavior is the same on all the spans along the bridge.

On the example bridge, this condition is not fulfilled because the span spacing becomes smaller the closer the spans are to the center of the bridge. With these distance changes, the positive moments in the spans change magnitude, so it cannot be guaranteed that they all have equal damage.

The most recommended scenario is to quantify only the detected damage, indicate good condition for the elements not inspected, and document the recommendation to the DOT to perform a special inspection to verify the elements' condition. The problem with this solution is that if the condition of the bridge is not alarming, the DOT postpones these specialized inspections and does not monitor the condition of the elements correctly.

4.3 UAV-aided Bridge Inspection

The processes employed for UAV-assisted inspections were adjusted based on the methodologies proposed in the work of Junwon Seo, Luis Duque, and Jim Wacker [1]. These adaptations were implemented to mitigate potential errors that could impact the UAV's performance during inspections. The on-site flight planning process played a crucial role in the successful implementation of UAVs in inspections, allowing inspectors to familiarize themselves with UAV flight planning while adhering to the regulations set forth by the Federal Aviation Administration (FAA).

Flight planning in the field allowed inspectors to proactively anticipate challenges that might arise during flights, such as the presence of obstructive vegetation that would impede access to certain spans. It also facilitated the identification of FAA-designated restricted areas, allowing inspectors to take necessary precautions and avoid flying over these areas.

Conducting practice flights was an integral part of the process, allowing the inspectors to verify the proper functioning of the UAV and test the planned flight paths. The test flight was conducted on a bridge with similar characteristics. The absence of water during the flight made it easier to manipulate the UAV through the spans as observed in Figure 10. In particular, the test flight revealed a new threat to flight operations, namely the transit of wild animals. During the test flight, a group of birds began to fly in close proximity to the UAV, intermittently disrupting its flight. In response to this situation, measures were taken to anticipate such occurrences during the inspection, including the decision to procure an air horn to scare off the birds should they appear on the day of the inspection.

The four flights conducted on the day of the inspection proved to be successful, providing valuable insights into the condition of elements that were previously inaccessible during the traditional inspection. The first and third flights yielded significant observations regarding the behavior of cracks along the edges of the deck, highlighting their propagation or concentration patterns along the deck and offering insights into the condition of the exterior girders, as depicted in Figures 11 and 12.

Despite having access to the deck during the traditional inspection, it was considered necessary to make a second flight specifically to obtain oblique photographs. This type of photography allows for the identification of crack patterns that may indicate the presence of map cracking, which is critical to a full understanding of the structural condition.

Upon completing the traditional inspection and assessing the remaining elements, the quantification of damages was conducted for the deck, girders, abutments, pile cap, and piles. With regards to the deck, the observations made during flights one and three provided valuable insights into the behavior of cracks along the edges. The damages depicted in Figures 11 and 12 allowed for the assignment of a condition state (CS) of 3 (Poor) to the deck due to the presence of wide cracks.

Similar wide cracks were observed along the edges of all girders as they approached the abutments, with the exception of girder 3. Accordingly, a CS of 3 (Poor) was assigned to the cracks in these girders based on the documented evidence. No additional damage to the abutments or pile caps was discovered during the inspection, thus confirming the results obtained in the traditional inspection.

In the final phase, quantification was carried out for all the piles, resulting in the assignment of condition states (CS) of 1 (Good) and 2 (Fair). The CS 2 was attributed to the presence of evidence of delamination in all the piles within span 8, where the spall size measured less than 2.51 cm. This finding contributed to the assessment of the piles and their condition.

The UAV-assisted inspection process, as indicated in Table 3, had a total duration of 1 hour and 59 minutes. Among the activities performed, 57 minutes were classified as value-added activities, while required non-value-added activities accounted for one hour and 2 minutes. No non-value-added activities were detected during the inspection. In terms of percentage distribution according to Figure 15, the required non-value-added activities constituted 52.1% of the total time, while value-added activities accounted for 47.9% of the duration. These metrics highlight the relative proportions of different types of activities in the UAV-assisted inspection process, indicating that a significant portion of the time was allocated to required non-value-added activities, highly related to UAV logistics.

4.4 Results comparison

Upon examining Table 3, it becomes apparent that the UAV-assisted inspection had a duration nearly twice that of the traditional inspection. Furthermore, the duration of required non-value-added activities significantly increased, reaching almost four times the duration of such activities in the traditional inspection. This increase can be attributed to the logistical considerations involved in UAV inspections.

Several factors contribute to the extended duration of required non-value-added activities in UAV inspections. For example, the installation of signage at both bridge approaches, as well as payload installation and drone setup, are necessary tasks that do not directly contribute to the final inspection output. In addition, UAV batteries must be changed, which in this study lasted approximately 15 to 20 minutes per battery change.

The increase in total duration and value-added activities observed in the UAV-assisted inspection can be attributed to the expanded scope of the inspection itself. In contrast to the traditional inspection, where only span 1 and 12 elements could be inspected, the UAV-assisted inspection allowed for the inspection of all elements across the entire bridge.

This expanded scope of inspection significantly increases the workload and the time required to conduct the inspection. As a result, the total duration of the UAV-assisted inspection is naturally longer, and a greater number of value-added activities are performed. The increased coverage and inspection of all items provide a more comprehensive assessment of the bridge's condition but also require additional time and resources.

Analyzing Chart 3, it is evident that the notes taken during the UAV-assisted inspection provide more detailed descriptions of the observed characteristics of the elements. This level of detail is possible because of the close observation possible during the flights. However, it is important to note that the detailed descriptions do not inherently indicate more severe damage or a higher Condition State (CS) for the elements. The increased level of detail simply allows for a more accurate and comprehensive assessment of the observed conditions.

To perform a comparative analysis of the damage quantifications, the data from Tables 1 and 2 with the highest representation of each element were used. Specifically, the elements with the highest representation in terms of Condition State (CS) were selected for comparison. For the deck, the data corresponding to CS 2 Fair, which represents the element with the highest observed condition state, were considered. In the case of the beams, the data corresponding to CS 1 "Good" were taken into account, since it represents the element with the highest observed condition. Similarly, for the abutments, the values corresponding to CS 3 Poor were selected as they reflect the highest condition of the element. Finally, for the pile cap and piles, the data corresponding to CS 1 were used, since it represents the element with the highest observed condition state.

Several measures were used to analyze the statistical properties of the results obtained from the inspections. First, the mean of the quantification results for each element was calculated to determine the central tendency of the data. In addition, the standard deviation was calculated to assess the variability or spread of the values around the mean. Among the elements, the deck had the largest standard deviation, indicating a higher degree of variability in the quantification results. However, when considering the sample size in relation to the standard deviation result, the greatest variability was observed in the piers. This indicates that the quantification results of the piers have a wider range of values, possibly indicating a greater diversity in their condition.

To assess the representativeness of the sample data, the coefficient of variation was calculated for each element. The coefficient of variation is the ratio of the standard deviation to the mean, expressed as a percentage. It serves as a measure of the relative variability within the data. Notably, all of the sample data had relatively low coefficients of variation, with none exceeding 30%. This indicates a relatively homogeneous distribution of values within each element's quantification results. Although the piles exhibited the highest variation with a coefficient of variation of 16.1%, this is still within the acceptable range of variation.

Furthermore, the inaccuracy of UAV-assisted inspection results was evaluated by calculating error percentages and comparing them with traditional inspection values, which were considered theoretical. The highest error was observed for piles, which deviated 20.5% from the values obtained using traditional inspection.

The statistical analysis shows that the piles showed the highest variation when moving from the traditional inspection to the UAV-assisted inspection methodology. This result can be attributed to the fact that the UAV allowed a more comprehensive observation of the true condition of these elements, which was not possible during the traditional inspection. Consequently, the quantification results for the piles obtained by the UAV-assisted inspection differed from the automatically assigned CS 1 Good in the traditional inspection.

It is also noteworthy that the piles represented the largest number of inaccessible elements during the traditional inspection. As a result, their condition was automatically assigned without direct visual inspection. However, the use of UAV-assisted inspection allowed the true condition of these previously inaccessible elements to be assessed, leading to other quantification results.

Although the piles have the highest error percentage among the elements when comparing the two inspection methods, it is important to emphasize that this sample remains representative due to its low variation. Despite the deviation from traditional inspection values, the low coefficient of variation indicates a relatively homogeneous distribution of quantification results for the piles.

This suggests that the UAV-assisted inspection provides a more accurate assessment of the condition of the piles, highlighting the importance of this methodology for the accurate evaluation of elements that were previously inaccessible or subject to automatic assignment of condition states.

Overall, the statistical analysis underscores the benefits of UAV-assisted inspection in providing more detailed and accurate assessments of the elements, particularly the piles, which experienced the most significant change from the traditional inspection method.

Chapter 5: Conclusions and Recommendations

Conclusions

The purpose of this research was to evaluate the performance of UAV-assisted inspections compared to traditional inspections performed by New Mexico State University. In order to carry out the research, an experiment was conducted where the bridge 7510 was inspected under traditional and UAV-assisted methodologies.

From these inspections, quantification results were recompiled at the elemental level and LEAN productivity measurements were performed on site. For the elemental level results, the quantities obtained for the deck, girders, abutment, pile cap and piles in each inspection were compared with statistical analyses to support the relationship between the samples.

The sample with the largest deviations from the results of the traditional inspection was the piles. The standard deviation was 25, the obtained coefficient of variance was 16.1% and the percentage error of the sample was calculated to be 20.5%. Despite these variations, the sample has a coefficient of variance of less than 30%, so the sample is considered representative and homogeneous.

In the case of the Lean measurements, the activities of each inspection stage were classified to determine the distribution of activities. With these values, a comparison was made between the two methodologies and it was observed how the results varied according to the methodology. UAV-assisted inspection was found to require twice as much time as traditional inspection.

Based on the results obtained in this research, it is concluded that:

1. The research found that the quantification results obtained from UAV-assisted inspections are similar to those obtained from traditional inspections. The statistical analyses done show that the samples are representative and homogeneous. This support the relationship between the samples, indicating that UAV-assisted inspections can generate results comparable to the traditional inspections.
2. LEAN productivity measurements taken during the inspections indicate that UAV-assisted inspections have a different distribution of activities than traditional inspections. The data shows that UAV-assisted inspections require additional activities that could double the inspection time. This is related to flight planning, payload installation, and battery changes. However, despite these additional activities, the overall value-added activities still contribute to the efficiency and effectiveness of the inspection process.
3. The element level quantification results showed that the UAV-assisted inspections were able to provide more detailed and comprehensive data compared to traditional inspections. The UAV-based methodology allowed inspection of previously inaccessible areas, resulting in a better understanding of the condition of the bridge elements. This increased level of detail can contribute to more accurate assessments of damage and deterioration, helping to develop effective maintenance and repair strategies.

Recommendations

Consideration of the presence of wildlife around the bridge is an important aspect to consider in future research on UAV-assisted inspections. The disruption caused by birds during the practice and UAV inspection flights highlights the need for strategies to mitigate such disruptions and ensure the safety and effectiveness of the inspection process. By addressing the challenges posed by wildlife presence and incorporating strategies to mitigate their impact, future research can enhance the reliability and applicability of UAV-assisted inspections in real-world bridge inspection scenarios.

Further research is recommended to try to evaluate the compatibility of the data considering it as two different assets of data where a t-student test is needed. This is also needed when applying the UAV-aided method to multiple bridges.

References

[1] J. Seo, L. Duque, and J. Wacker, “Drone-enabled bridge inspection methodology and application,” *Autom. Constr.*, vol. 94, pp. 112–126, 2018.

[2] Q. Zhang and A. H. Alavi, “Automated two-stage approach for detection and quantification of surface defects in concrete bridge decks,” in *Nondestructive Characterization and Monitoring of Advanced Materials, Aerospace, Civil Infrastructure, and Transportation XV*, 2021.

[3] Q. Zhang, K. Barri, S. K. Babanajad, and A. H. Alavi, “Real-time detection of cracks on concrete bridge decks using deep learning in the frequency domain,” *Engineering (Beijing)*, vol. 7, no. 12, pp. 1786–1796, 2021.

[4] ASCE, “2021 Report Card for America’s Infrastructure,” Dec. 2020.

[5] Federal Highway Administration, “National Bridge Inspection Standards,” *Federal Register*, vol. 87. pp. 27396–27437, 06-May-2022.

[6] S. Dorafshan and M. Maguire, “Bridge inspection: human performance, unmanned aerial systems and automation,” *Springer Link*, 21-May-2018.

[7] Q. Zhang *et al.*, “Automated unmanned aerial vehicle-based bridge deck delamination detection and quantification,” *Transp. Res. Rec.*, 2023.

[8] FWAH, “RABIT Bridge Inspection Tool,” 2014. [Online]. Available: https://www.fhwa.dot.gov/research/tfhrc/programs/infrastructure/structures/ltbp/ltbpresearch/rabit/index.cfm.

[9] “Bridge Inspector’s Reference Manual,” *State.mn.us*, 2012. [Online]. Available: https://www.dot.state.mn.us/bridge/pdf/insp/birm/birmchapt0-cover.pdf. [Accessed: 20-Mar-2023].

[10] “2009 MUTCD with Revisions 1, 2, and 3 incorporated, dated June 2022 (PDF) - FHWA MUTCD,” *Dot.gov*. [Online]. Available: https://mutcd.fhwa.dot.gov/pdfs/2009r1r2r3/pdf_index.htm. [Accessed: 03-May-2023].

[11] “Equipment rentals in Las Cruces, NM.” [Online]. Available: https://www.bigrentz.com/rental-locations/new-mexico/las-cruces.

[12] A. Frakt, “Atascado y estresado: cómo afecta el tráfico a tu salud,” *The New York times*, The New York Times, 07-Feb-2019.

[13] “Aspen a-30,” *Aspen Aerials, A Time Manufacturing Company*. [Online]. Available: https://aspenaerials.com/bridge-inspection/a-30/. [Accessed: 03-Jun-2023].

[14] “Small unmanned aircraft systems (UAS) regulations (Part 107),” *Faa.gov*. [Online]. Available: https://www.faa.gov/newsroom/small-unmanned-aircraft-systems-uas-regulations-part-107. [Accessed: 20-Mar-2023].

[15] First Element: Status, “Study analysing the current activities in the field of uav,” *Europa.eu*. [Online]. Available: https://ec.europa.eu/docsroom/documents/1707/attachments/1/translations/en/renditions/pdf. [Accessed: 20-Mar-2023].

[16] K. Whitehead *et al.*, “Remote sensing of the environment with small unmanned aircraft systems (UASs), part 2: scientific and commercial applications,” *J. Unmanned Veh. Syst.*, vol. 02, no. 03, pp. 86–102, 2014.

[17] “Airspace restrictions,” *Faa.gov*. [Online]. Available: https://www.faa.gov/uas/getting_started/where_can_i_fly/airspace_restrictions. [Accessed: 20-Mar-2023].

[18] E. Jeong, J. Seo, and J. Wacker, “Literature review and technical survey on bridge inspection using unmanned aerial vehicles,” *J. Perform. Constr. Facil.*, vol. 34, no. 6, 2020.

[19] E. Jeong, J. Seo, and J. P. Wacker, “UAV-aided bridge inspection protocol through machine learning with improved visibility images,” *Expert Syst. Appl.*, vol. 197, no. 116791, p. 116791, 2022.

[20] A. Avramović and B. Reljin, “Gradient edge detection predictor for image lossless compression,” in *Proceedings ELMAR-2010*, 2010, pp. 131–134.

[21] B. Lei, N. Wang, P. Xu, and G. Song, “New crack detection method for bridge inspection using UAV incorporating image processing,” *J. Aerosp. Eng.*, vol. 31, no. 5, p. 04018058, 2018.

[22] E. Bisong, “What is deep learning?,” in *Building Machine Learning and Deep Learning Models on Google Cloud Platform*, Berkeley, CA: Apress, 2019, pp. 327–329.

[23] M. Björkman, “What is productivity?,” *IFAC Proc. Vol.*, vol. 25, no. 8, pp. 203–210, 1992.

[24] T. Ohno, *Toyota production system: Beyond large-scale production*. London, England: Taylor & Francis, 2021.

[25] E. Masoud, “Application of Lean Philosophy to Routine Inspection of Bridges,” University of Delaware, 2017.

[26] W. Wilson, “Specification for the national bridge inventory bridge elements,” *Dot.gov*. [Online]. Available: https://www.fhwa.dot.gov/bridge/nbi/131216_a1.pdf. [Accessed: 13-May-2023].

Appendix

The following documents are included in the Appendix:

1. LEAN on-site measurement report template
2. LEAN on-site measurement report for traditional inspection
3. LEAN on-site measurement report for UAV inspection

NEW MEXICO STATE UNIVERSITY

BRIDGE INSPECTION PROGRAM

Productivity Lean Measurements

Date:		**Team:**	
Location:		**Stage:**	
Bridge:		**Methodology:**	

N°	Activity	Start time	End time	Total time	Notes
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16					
17					
18					
19					
20					

Stage total time: **0**

NEW MEXICO STATE UNIVERSITY

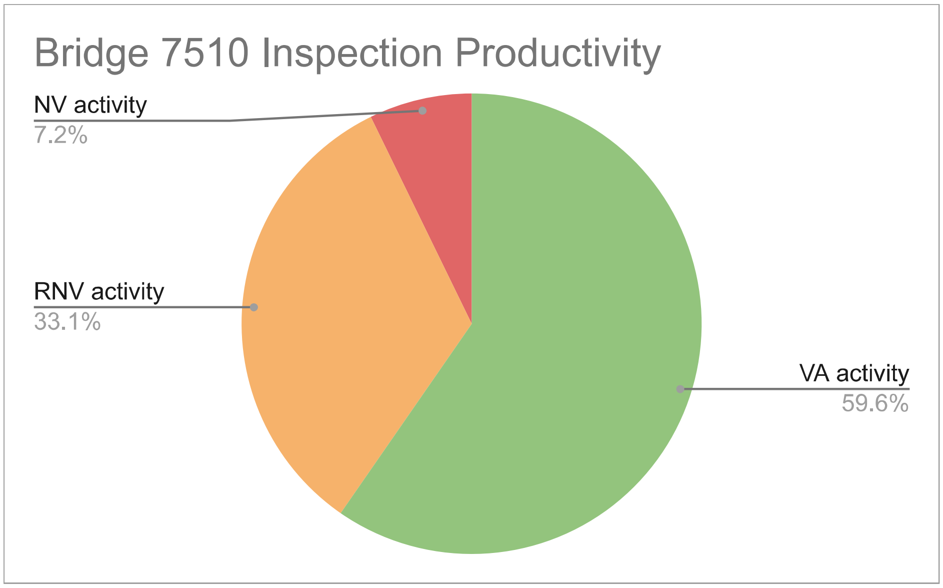
BRIDGE INSPECTION PROGRAM

Productivity Lean Measurements

On site summary metrics

Bridge:	7510	**Team:**	A
Location:	Bridge Inspection Program Office	**Methodology:**	Tradtitional

Phase	Total phase time	VA activities	RNV activities	NV activities
Previous report review	0:14	0:12	0:02	0:00
Movilization	0:20	0:00	0:20	0:00
Inspection	0:59	0:33	0:14	0:12
Return	0:19	0:00	0:19	0:00
Report Writting	0:54	0:54	0:00	0:00
Total times	**2:46**	**1:39**	**0:55**	**0:12**



NEW MEXICO STATE UNIVERSITY

BRIDGE INSPECTION PROGRAM

Productivity Lean Measurements

Date:	5/9/2023	**Team:**	A
Location:	Bridge Inspection Program Office	**Stage:**	Previous report review
Bridge:	7510	**Methodology:**	Tradtitional

N°	Activity	Start time	End time	Total time	Notes	Classification
1	Looking for old reports	12:41	12:43	0:02		Value added activity
2	Looking emails	12:43	12:45	0:02		Required non value activity
3	Review report and photos	12:45	12:55	0:10		Value added activity
4						
5						

Stage total time: **0:14**

Value added activities summary

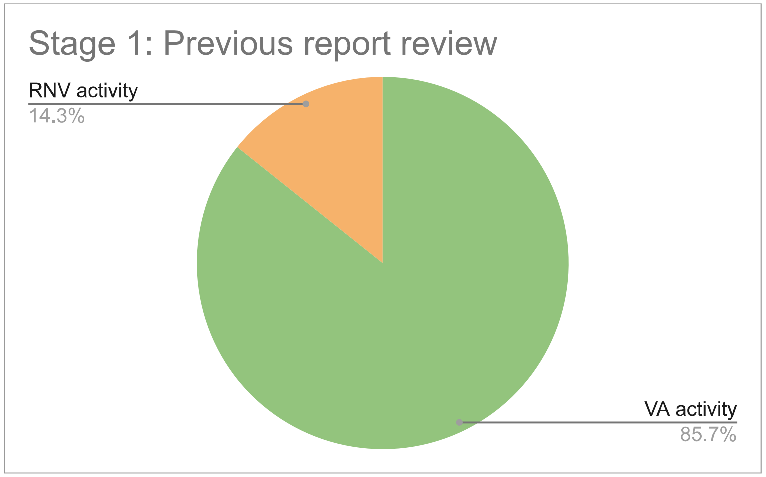
Activity	Activity time
Looking for old reports	0:02
Review report and photos	0:10
Total VA activities time	**0:12**
% VA activities	**85.7%**

Required non value added activities summary

Activity	Activity time
Looking emails	0:02
Total VA activities time	**0:02**
% VA activities	**14.3%**

Non value added activities summary

Activity	Activity time
	0
Total VA activities time	**0:00**
% VA activities	**0.0%**



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BRIDGE INSPECTION PROGRAM

Productivity Lean Measurements

Date:	5/9/2023	**Team:**	A
Location:	Route from NMSU to bridge site	**Stage:**	Movilization
Bridge:	7510	**Methodology:**	Tradtitional

N°	Activity	Start time	End time	Total time	Notes	Classification
1	Driving to the bridge	9:44	10:04	0:20		Required non value …
2				0:00		
3				0:00		
4				0:00		
5				0:00		

Stage total time: **0:20**

Value added activities summary

Activity	Activity time
	0

Total VA activities time **0:00**

% VA activities **0.0%**

Required non value added activities summary

Activity	Activity time
Coordinating next stop	0:20

Total VA activities time **0:20**

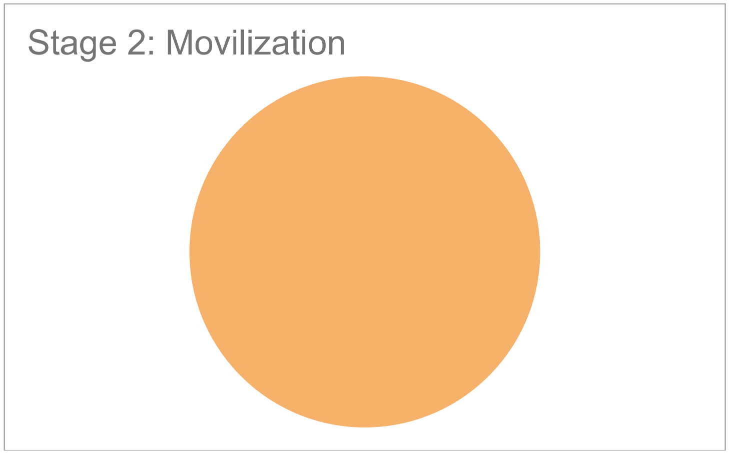
% VA activities **100.0%**

Non value added activities summary

Activity	Activity time
	0:00

Total VA activities time **0:00**

% VA activities **0.0%**


Stage 2: Movilization

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BRIDGE INSPECTION PROGRAM

Productivity Lean Measurements

Date:	5/9/2023	**Team:**	A
Location:	Bridge site	**Stage:**	Inspection
Bridge:	7510	**Methodology:**	Tradtitional

N°	Activity	Start time	End time	Total time	Notes	Classification
1	Getting ready	10:04	10:07	0:03		Required non value a…
2	Planning inspection	10:07	10:10	0:03	Should have done this by the previous report review	Non value activity
3	Inspecting deck	10:10	10:18	0:08		Value added activity
4	Inspecting substructure 1	10:18	10:28	0:10		Value added activity
5	Heading to the other abutment	10:28	10:39	0:11		Required non value a…
6	Inspecting substructure 2	10:40	10:55	0:15		Value added activity
6	Re taking photos	10:55	11:04	0:09	One team member accidently deleted some photos	Non value activity
			Stage total time:	**0:59**		

Value added activities summary

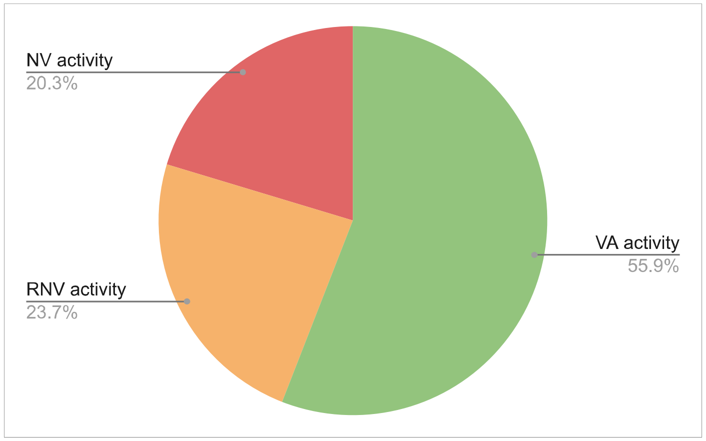
Activity	Activity time
Inspecting deck	0:08
Inspecting substructure 1	0:10
Inspecting substructure 2	0:15
Total VA activities time	**0:33**
% VA activities	**55.9%**

Required non value added activities summary

Activity	Activity time
Getting ready	0:03
Heading to the other abutment	0:11
Total VA activities time	**0:14**
% VA activities	**23.7%**

Non value added activities summary

Activity	Activity time
Planning inspection	0:03
Re taking photos	0:09
Total VA activities time	**0:12**
% VA activities	**20.3%**



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BRIDGE INSPECTION PROGRAM

Productivity Lean Measurements

Date:	5/9/2023	**Team:**	A
Location:	Route from bridge to BIP office	**Stage:**	Return
Bridge:	7510	**Methodology:**	Tradtitional

N°	Activity	Start time	End time	Total time	Notes	Classification
1	Driving back	11:04	11:23	0:19		Required non value acti…
2						
3						

Stage total time: **0:19**

Value added activities summary

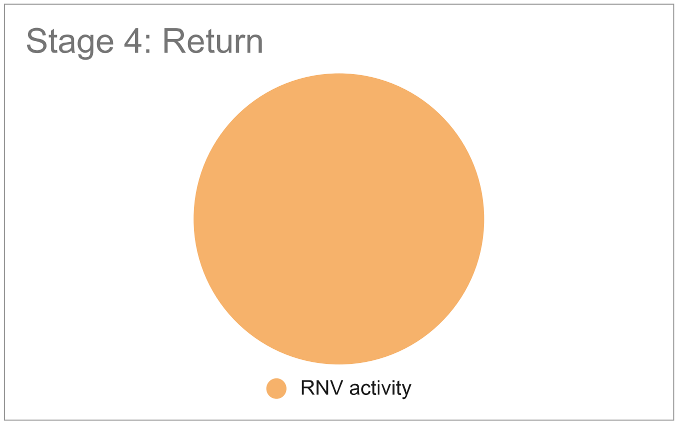
Activity	Activity time
	0
Total VA activities time	**0:00**
% VA activities	**0.0%**

Required non value added activities summary

Activity	Activity time
Getting ready to head out	0:19
Gas stop	
Driving	
Total VA activities time	**0:19**
% VA activities	**100.0%**

Non value added activities summary

Activity	Activity time
	0
Total VA activities time	**0:00**
% VA activities	**0.0%**



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BRIDGE INSPECTION PROGRAM

Productivity Lean Measurements

Date:	5/3/2023	**Team:**	A
Location:	Bridge Inspection Program Office	**Stage:**	Report writting
Bridge:	7510	**Methodology:**	Tradtitional

N°	Activity	Start time	End time	Total time	Notes	Classification
1	Report editing	16:20	17:14	0:54	Includes photo page and report editing	Value added activity
2				0:00		
3				0:00		
4				0:00		
5				0:00		

Stage total time: **0:54**

Value added activities summary

Activity	Activity time
Report editing	0:54

Total VA activities time **0:54**

% VA activities **100.0%**

Required non value added activities summary

Activity	Activity time
Instructions from Bridge inspector	0:00

Total VA activities time **0:00**

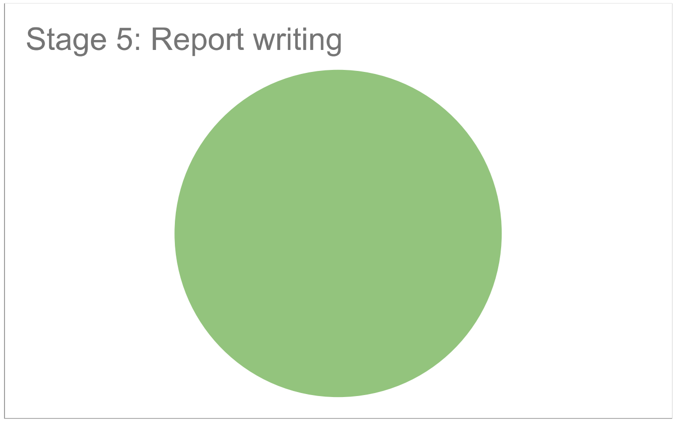
% VA activities **0.0%**

Non value added activities summary

Activity	Activity time

Total VA activities time **0:00**

% VA activities **0.0%**



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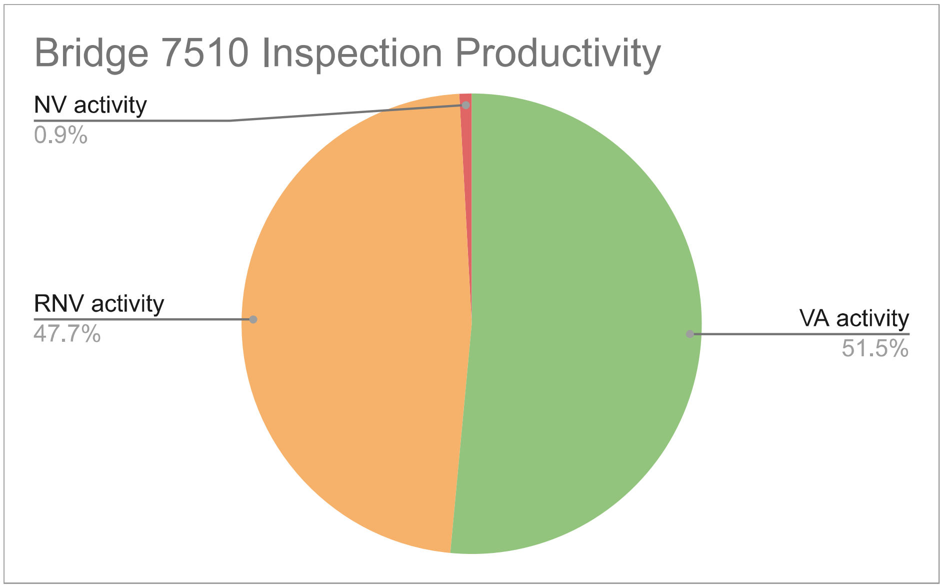
BRIDGE INSPECTION PROGRAM

Productivity Lean Measurements

On site summary metrics

Bridge:	7510	**Team:**	B
Location:	Bridge Inspection Program Office	**Methodology:**	UAV inspection

Phase	Total phase time	VA activities	RNV activities	NV activities
Previous report review	0:13	0:05	0:02	0:02
Movilization	0:15	0:00	0:15	0:00
Inspection	1:59	0:57	1:02	0:00
Return	0:19	0:00	0:19	0:00
Report Writting	1:13	0:59	0:14	0:00
Total times	**3:59**	**2:01**	**1:52**	**0:02**



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BRIDGE INSPECTION PROGRAM

Productivity Lean Measurements

Date:	5/9/2023	**Team:**	B
Location:	Bridge Inspection Program Office	**Stage:**	Previous report review
Bridge:	7510	**Methodology:**	UAV inspection

N°	Activity	Start time	End time	Total time	Notes	Classification
1	Looking for old reports	8:31	8:36	0:05		Value added activity
2	Waiting for surface setup	8:36	8:38	0:02		Non value activity
3	Printing old reports	8:39	8:42	0:03		Required non value activity
4	Packing for leaving	8:42	8:45	0:03		Required non value activity
5						

Stage total time: **0:13**

Value added activities summary

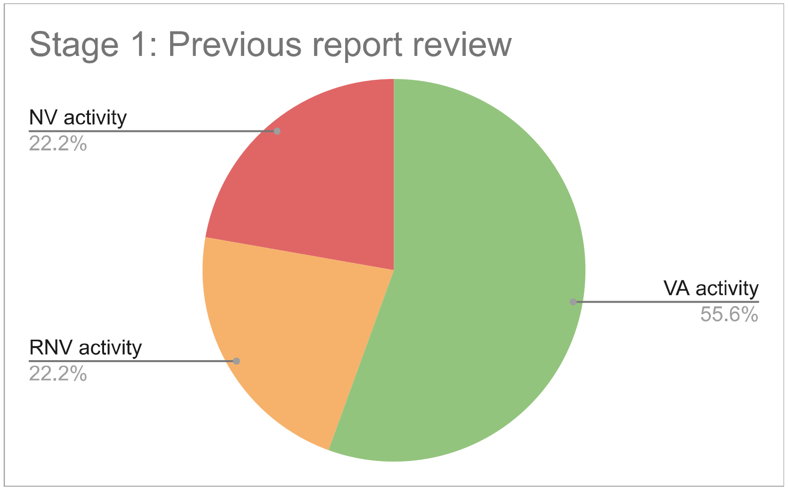
Activity	Activity time
Looking for old reports	0:05
Total VA activities time	**0:05**
% VA activities	**38.5%**

Required non value added activities summary

Activity	Activity time
Printing old reports	0:02
Packing for leaving	0:03
Total VA activities time	**0:02**
% VA activities	**15.4%**

Non value added activities summary

Activity	Activity time
Waiting for surface setup	0:02
Total VA activities time	**0:02**
% VA activities	**15.4%**



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BRIDGE INSPECTION PROGRAM
Productivity Lean Measurements

Date:	5/9/2023	**Team:**	B
Location:	Route from NMSU to bridge site	**Stage:**	Movilization
Bridge:	7510	**Methodology:**	UAV inspection

N°	Activity	Start time	End time	Total time	Notes	Classification
1	Driving to the bridge	7:15	7:30	0:15		Required non value …
2				0:00		
3				0:00		
4				0:00		
5				0:00		
			Stage total time:	**0:15**		

Value added activities summary

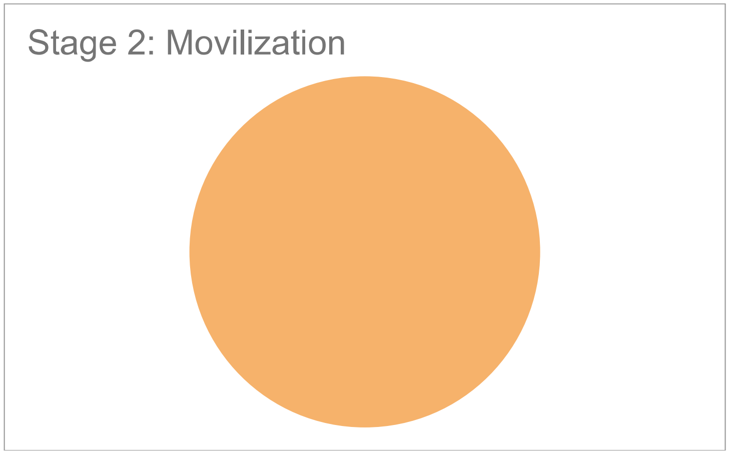
Activity	Activity time
	0
Total VA activities time	**0:00**
% VA activities	**0.0%**

Required non value added activities summary

Activity	Activity time
Coordinating next stop	0:15
Total VA activities time	**0:15**
% VA activities	**100.0%**

Non value added activities summary

Activity	Activity time
	0:00
Total VA activities time	**0:00**
% VA activities	**0.0%**



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BRIDGE INSPECTION PROGRAM

Productivity Lean Measurements

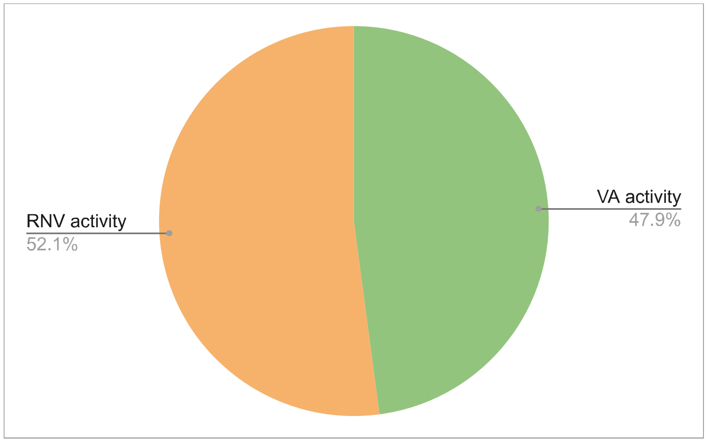
Date:	5/9/2023	**Team:**	B
Location:	Bridge site	**Stage:**	Inspection
Bridge:	6997	**Methodology:**	UAV inspection

N°	Activity	Start time	End time	Total time	Notes	Classification
1	Setting up signage	7:30	7:53	0:23		Required non value a…
2	Taking equipment to the payload	7:53	8:00	0:07		Required non value a…
3	Setting up the drone	8:00	8:20	0:20		Required non value a…
4	Making first flight	8:23	8:35	0:12		Value added activity
5	Change batteries	8:35	8:40	0:05		Required non value a…
6	Making second flight	8:40	8:51	0:11		Value added activity
7	Change batteries	8:51	8:53	0:02		Required non value a…
8	Making third flight	8:54	9:08	0:14		Value added activity
9	Change batteries	9:09	9:14	0:05		Required non value a…
10	Making fourth flight	9:14	9:34	0:20		Value added activity

Stage total time: **1:59**

Value added activities summary

Activity	Activity time
Making first flight	0:12
Making second flight	0:11
Making third flight	0:14
Making fourth flight	0:20
Total VA activities time	**0:57**
% VA activities	**47.9%**



Required non value added activities summary

Activity	Activity time
Setting up signage	0:23
Taking equipment to the payload	0:07
Setting up the drone	0:20
Change batteries	0:05
Change batteries	0:02
Change batteries	0:05
Total VA activities time	**1:02**
% VA activities	**52.1%**

Non value added activities summary

Activity	Activity time
Total VA activities time	**0:00**
% VA activities	**0.0%**

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BRIDGE INSPECTION PROGRAM

Productivity Lean Measurements

Date:	5/9/2023	**Team:**	B
Location:	Route from bridge to BIP office	**Stage:**	Return
Bridge:	7510	**Methodology:**	UAV inspection

N°	Activity	Start time	End time	Total time	Notes	Classification
1	Driving back	11:04	11:23	0:19		Required non value acti…
2						
3						

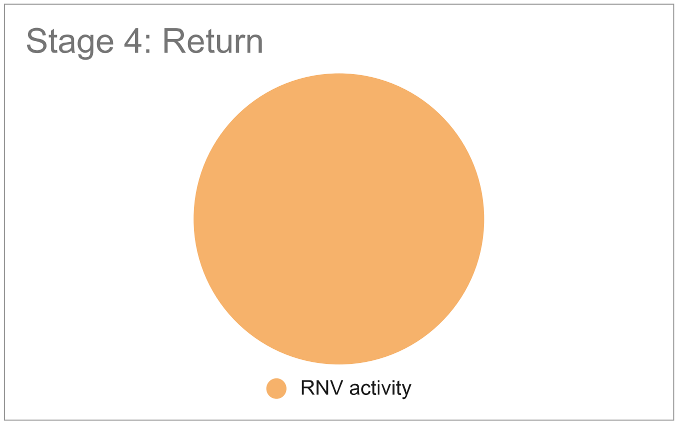
Stage total time: **0:19**

Value added activities summary

Activity	Activity time
	0

Total VA activities time **0:00**

% VA activities **0.0%**



Stage 4: Return

Required non value added activities summary

Activity	Activity time
Getting ready to head out	0:19
Gas stop	
Driving	

Total VA activities time **0:19**

% VA activities **100.0%**

Non value added activities summary

Activity	Activity time
	0

Total VA activities time **0:00**

% VA activities **0.0%**

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BRIDGE INSPECTION PROGRAM

Productivity Lean Measurements

Date:	5/9/2023	**Team:**	B
Location:	Bridge Inspection Program Office	**Stage:**	Report writting
Bridge:	7510	**Methodology:**	UAV inspection

N°	Activity	Start time	End time	Total time	Notes	Classification
1	Report editing	16:20	17:14	0:54	Includes photo page and report editing	Value added activity
2				0:00		
3				0:00		
4				0:00		
5				0:00		
			Stage total time:	**1:13**		

Value added activities summary

Activity	Activity time
Report editing	0:54
Total VA activities time	**0:59**
% VA activities	**80.8%**

Required non value added activities summary

Activity	Activity time
Instructions from Bridge inspector	0:00
Total VA activities time	**0:14**
% VA activities	**19.2%**

Non value added activities summary

Activity	Activity time
Total VA activities time	**0:00**
% VA activities	**0.0%**