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Corridor-Wide Surveillance Using Unmanned Aircraft Systems Phase II: Freeway Incident Detection using Unmanned Aircraft Systems (Part A)

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16. Abstract

During the second phase of this study, the team collected field data with unmanned aerial vehicles (UAVs) at different elevations and distances from the road to analyze the performance of a background subtraction algorithm for vehicle detection. Validation analyses were carried out and their results indicated that a detection rate with an accuracy of up to 92% can be reached using the background subtraction algorithm. The results of the ANOVA test confirmed that the drone's distance from the road was the only main factor associated with vehicle detection percentage (at the 95% confidence level). It was also determined that, depending on drone type, elevation can affect the detection rate based on the interaction plots created. The experiences from the field activities that took place during this phase of the project were incorporated into the previously developed protocol for the use of UAVs in corridor surveillance. The protocol was also updated with the steps that must be followed for several scenarios and these can be incorporated in future studies on the use of drones in transportation applications.

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Executive Summary

The use of unmanned aerial vehicles (UAVs) in transportation-related areas has been growing in recent years. UAVs have been used to monitor traffic operations and collect traffic information while offering several advantages over traditional equipment. The mobility of UAVs makes it possible to cover more road areas and it eliminates the hassle of installing equipment that requires closing lanes temporarily, such as when using pneumatic tubes. In addition, traffic incident reporting can benefit from UAV platforms by reducing the response time and improving the efficiency of incident management. During the second phase of this study, the team collected field data with UAVs at different elevations and distances from the road to analyze the performance of a background subtraction algorithm for vehicle detection. Validation analyses were carried out and their results indicated that a detection rate with an accuracy of up to 92% can be reached using the background subtraction algorithm. It was also determined that situations where the drone was located at lower values for the distance of the road showed higher detection rates. This can be interpreted as positioning the drone closer to the road, though not to distract drivers, being associated with higher percentages of vehicles detected by the background subtraction algorithm. The results of the ANOVA test confirmed that the drone's distance from the road was the only main factor associated with the vehicle detection percentage (at the 95% confidence level). Based on the interaction plots created, it was also determined that elevation can affect the detection rate depending on drone type. The experiences from the field activities conducted during this phase of the project were incorporated into the previously developed protocol for the use of UAVs in corridor surveillance. The protocol was also updated with the steps that must be followed for several scenarios and these can be incorporated into future studies on the use of drones in transportation applications.

Chapter 1. Introduction

For several decades, daily operations of incident identification mostly relied on reporting by calling 911 (drivers or passengers involved in crashes or witnesses passing by) or observing by freeway service patrol vehicles. Automatic freeway incident detection is a novel approach that is expected to reduce response time and improve the efficiency of incident management. Unmanned aerial vehicle (UAV) platforms have been used to obtain video data and develop methodologies for incident detection (Liu et al., 2015; Lee et al., 2015). Liu et al. (2015) targeted low-volume roads and Lee et al. (2015) performed pilot tests for real-time incident monitoring. Traffic Management Centers (TMCs) also use video data to monitor freeway traffic operations and incident detection (FHWA, 2016). However, TMCs are cautious about using video data due to constraints and risks, especially privacy concerns of road users. The FHWA report *Transportation Management Center Video Recording and Archiving Best General Practices* (2016) identifies technologies that can lower image resolution to remove private information, such as the license plate number of the vehicles. In addition, sensing technologies (e.g., thermal sensors) can collect images for extracting traffic information without capturing private information. Limited studies report on the benefits of automatic incident detection with thermal images.

In recent years, UAVs have been used to monitor traffic operations and collect traffic information, which supplies additional information that is hard to obtain by using conventional sensing technologies. Compared to traditional stationary sensors, UAV technologies allow users to select locations and different angles and elevations while collecting traffic information. Also, the mobility of UAVs makes it possible to cover long distances of freeways so both temporal and spatial dimensions can be collected, which makes it possible to apply cutting-edge learning methods to perform traffic analysis. These characteristics make the use of UAVs cost-effective as compared to conventional sensing technologies (Jin et al., 2016). Furthermore, it has the potential of reducing secondary traffic incidents, thus improving the overall safety of the freeway corridor being studied.

This report details the efforts and the research outcomes of the second phase of the study. Based on the results from Phase I, the team collected field data at different elevations and distances from the road to analyze the performance of a background subtraction algorithm in vehicle detection. The experiences from the field activities helped develop protocols for data collection using UAVs for several purposes. As such, the objectives for the second phase of the study were the following:

1. To advance the current state of the art in freeway automatic incident detection using image data from UAVs and analyze the efficiency of a vehicle detection algorithm.
2. To develop a protocol for the integration and implementation of unmanned aircraft systems (UAS) in traffic incident management at district TMCs.
3. To identify barriers and challenges to implementing emerging technologies in automatic incident detection and provide suggestions for future research studies.
4. To strengthen the mutual collaboration and lessons learned associated with incident management with local TMCs for the benefit of reducing recurrent and non-recurrent traffic congestion and improving corridor safety for all present and future road users.

It is expected that the outcomes from this phase of the study will advance automatic incident detection in traffic management and will fill the gaps in the existing literature related to analyzing temporal and spatial images. This report is organized as follows: Chapter 2 summarizes the literature review performed for this phase, including topics on freeway concepts, unmanned aircraft systems and their applications, incident management and traffic congestion, and background subtraction algorithms; Chapter 3 explains the methodology for the study, including the steps taken and lessons learned at each of the data collection activities; Chapter 4 details the results of the analyses; Chapter 5 discusses the protocol for using UAS in traffic monitoring; and Chapter 6 offers conclusions and recommendations.

Chapter 2. Literature Review

This section presents the literature review performed for the second phase of the research project. The topics of focus were freeway concepts, UAS applications and specifications, data collection techniques, flight plans, background subtraction algorithms, incident detection, traffic congestion, the use of UAS in other areas, and experimental design. This review follows and complements the literature review that was done for the first year of the research project.

Freeway Concepts

To properly understand and select the study site, it is important to define the components of the freeway. The Highway Capacity Manual (HCM, 2016) was used as the primary source for defining the concepts. A freeway is defined as a separated highway with full control of access having two or more lanes in each direction for the exclusive use of motorized traffic. A freeway facility is composed of various uniform segments that can be analyzed to determine capacity and level of service. The types of segments found in freeways are basic, merge, diverge, and weaving segments. Merge segments are those areas where two or more traffic streams combine to form a single traffic stream. Diverge segments consist of a single traffic stream that divides into two or more separate traffic streams. Weaving segments are the areas where two or more traffic streams traveling in the same direction cross paths along a significant length of the freeway without the use of traffic control devices. These three types of freeway segments are depicted in Figure 1. All other areas are considered basic freeway segments.

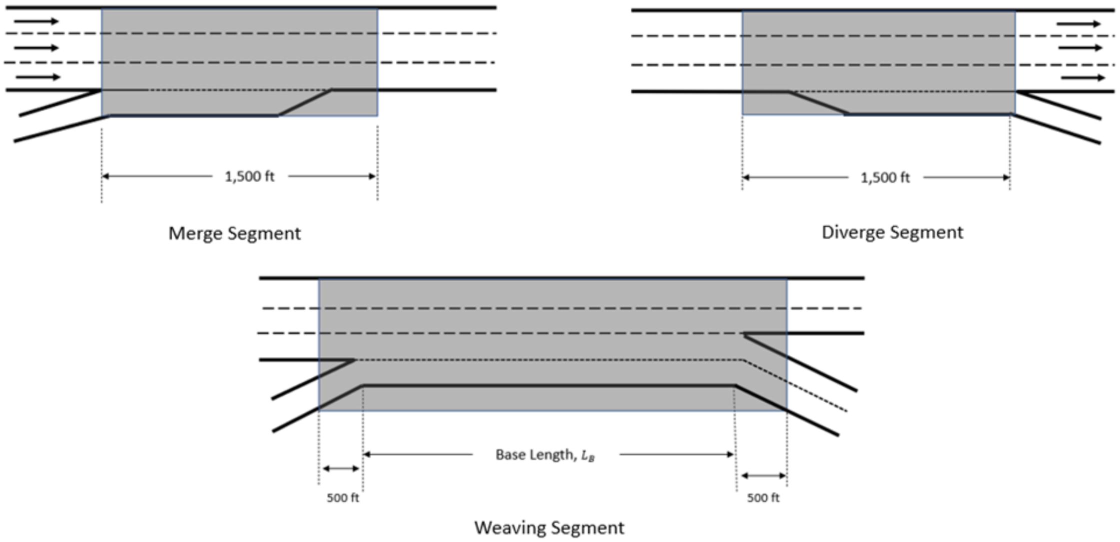


Figure 1. Merge, diverge, and weaving freeway segments and influence areas (adapted from HCM, 2016).

A freeway section is defined as extending from gore point to gore point and is mostly directly compatible with the freeway performance databases used by the agencies. Segments are defined as portions of freeway sections and can be identified by the facility operations influence area. The influence area for the basic freeway segments can be identified as any other segment along the freeway that is not within the defined influence area of the weaving, merge, and diverge segments. The influence areas for weaving, merge, and diverge segments are also shown in Figure 1.

All segments are unlikely to have the same conditions; therefore, it is less likely they have the same capacity. The capacity of the freeway facility relies on identifying the critical segment(s) where a breakdown begins. The critical segment is defined as the bottleneck segment that will break down the earliest, given that the traffic conditions do not change. The capacity in the context of freeway facilities can be described as governed by the position and severity of active bottlenecks along its length. Both characteristics vary over time and space, depending on the time-varying demand flow rates in each facility segment. A bottleneck that is active at one time may hide another, less severe bottleneck further downstream by suppressing demand flows to that downstream bottleneck. There is no simple definition for freeway facility capacity, other than it is variable over time and influenced by the timing and location of active bottlenecks (HCM, 2016).

Unmanned Aircraft Systems

One of the most important aspects when working with unmanned aircraft systems (UAS) is to comply with FAA 14 CFR Part 107. Therefore, one focus of the first-year study was to understand UAS specifications, regulations, and protocols required by FAA 14 CFR Part 107. The regulations include the certification needed to fly the UAS, limitations and restrictions, and waivers for special applications.

14 CFR Part 107

The use of UAS is regulated by the Federal Aviation Administration (FAA), which categorizes drone pilots as recreational, commercial, government or public safety use, and educational users. Every drone operator must understand under which category they fall. Commercial users fall under the 14 CFR Part 107 guidelines. These guidelines state that every drone operator must comply with the remote pilot certification. The FAA’s website provides all the necessary tools to understand the requirements of Part 107 and the process for obtaining the remote pilot certification. If a drone operation requires deviating from the 14 CFR Part 107 regulations, the remote pilot in command can ask for a waiver depending on the situation. A list of the waivers available is shown in Table 1.

Table 1. Available Waivers for Flight Operations (Source: FAA, 2022a)

FLIGHT OPERATIONS	WAIVERS
Fly from a moving aircraft or a vehicle in populated areas	107.25 - Operation from a Moving Vehicle or Aircraft
Fly during periods of civil twilight or at night without anti-collision lighting	107.29(a)(2) and 107.29(b) - Operation at Night
Fly beyond your ability to determine orientation with unaided vision	107.31 - Visual Line of Sight Aircraft Operation
Use a visual observer without following all the requirements	107.33 - Visual Observer
Fly multiple UAS with only one remote pilot	107.35 - Operation of Multiple Small UAS
Fly over a person with a UAS that does not meet the operational categories 1, 2, 3, or 4	107.39 - Operation over Human Beings
Fly a small UAS: over 100 mph groundspeed, over 400 ft above ground level (AGL), with less than 3 statute miles of visibility, and/or within 500 ft vertically or 2,000 ft horizontally from clouds	107.51 - Operating Limitations for UAS
Fly from a moving aircraft or a vehicle in populated areas	107.25 - Operation from a Moving Vehicle or Aircraft

UAS Selection

An important factor that repeats itself in most, if not all, of the research literature with UAS is the proper selection of the aircraft according to their use. There are several applications of UAS in surface transportation, including road and bridge inspection, traffic surveillance, incident management and investigation, and emergency management. Therefore, it is highly important to understand the strengths and limitations of the aircraft that will be used for a specific application.

Different drone manuals, such as DJI Phantom 3 and 4, DJI Mavic 2 Enterprise Advanced, Autel Evo Series, and others, were analyzed during the first year of the research project. Although these drones have some aspects in common, they perform differently, thus emphasizing the importance of evaluating several UAS to gain insight into their processes. Some of the things that were found in common were the different flight modes, the Return-to-Home feature, warning lights, battery safety, storage, and maintenance. For the different aspects, several quotes from local and national small UAV suppliers were evaluated in terms of the drone specifications and capabilities required for the research project. Some of these specifications include camera resolution, battery life, stability to adverse weather conditions, and software for thermal detection, among other attributes. Based on the reviews of manuals, two UAS were selected for this project: the DJI Mavic 2 Enterprise Advanced and the Autel Evo 2 Pro 6K, both shown in Figure 2. Tables 2 and 3 show the specifications and features of each drone.

(a) DJ Mavic 2 Enterprise Advanced *(b) Autel Evo II Pro 6K*

Figure 2. UAVs used for the project tasks.

Table 2. DJI Mavic 2 Enterprise Advanced Features (Adapted from DJI, 2022)

AIRCRAFT		**THERMAL CAMERA**	
Takeoff weight (no accessories)	909 g	Sensor	Uncooled vox microbolometer
Max takeoff weight	1100 g	Focal length	9 mm (approx.)
Dimension (LxWxH)	Folded: 214x91x84 mm		35 mm format equivalent: 38 mm (approx.)
	Unfolded: 322x242x84 mm	Sensor resolution	640x512 @ 30 Hz
Diagonal distance	354 mm	Accuracy of thermal temperature	±2°C or ± 2%, whichever is greater
Max ascent speed	6 m/s	Digital zoom	16 x
Max descent speed	5 m/s	Pixel pitch	12 µm
Max speed (no wind)	72 kph (S-mode)	Spectral band	8-14 µm
	50 kph (P-mode)	Photo format	R-JPEG
Max service ceiling above sea level	31 min	Video format	MP4
Max wind speed resistance	10 m/s	Metering method	Spot meter, area measurement
Internal storage	24 GB	FFC	Auto/Manual
VISUAL CAMERA		**BATTERY**	
Sensor	1/2" CMOS, effective pixels: 48 M	Capacity	3850 mAh
Lens	FOV: 84"	Voltage	15.4 V
	35 mm format equivalent: 24 mm	Max charging voltage	17.6 V
	Aperture: f/2.8	Battery type	LiPo
	Focus: 1 m to ∞	Energy	59.29 Wh
ISO range	Video: 100-12800 (auto)	Net weight	297 g
	Photos: 100-1600 (auto)	Charging temperature	5°C - 40°C
Digital zoom	32x	Operating temperature	-10°C - 40°C
Max image size	8000x6000	Heating temperature	-20°C - 6°C
Still photography modes	Single shot interval: 2/3/5/7/10/15/20/30/60 s	Heating methods	Manual heating, Auto heating
	Panorama: sphere	Heating duration	500s (max)
Video resolution	3840x2160 @3Ofps	Heating power	55W (max)
	1920x1080 @3Ofps	Charging time	90 min
Photo format	JPEG	Max charging power	80W
Video format	MP4		

Table 3. Autel Evo II Pro 6K Features (Adapted from Autel, 2022)

AIRCRAFT		VISUAL CAMERA		BATTERY	
Takeoff weight	1191 g	Image sensor	1" CMOS	Battery	7100 mAh
Max takeoff weight	1999 g	Pixels	20 MP	Battery type	LiPo 3S
Aircraft battery	7100 mAh	Perspective	82*	Battery energy	82Wh
Max flight time	40 min	Lens	EFL: 28.6 mm, Aperture: f/2.8-f/11	Max charging power consumption	93W
			Focus Distance: 1 m to any distance (auto)		
Max level flight speed	45 mph (20 m/s)	ISO range (video)	100-6400 (auto)	Charging temperature	5-45 °C
Max ascent speed	8 m/s	ISO range (photo)	100-12800 (auto)	Charging time	90 min
Max descent speed	4 m/s	Zoom	1-8x (max 3x lossless)	Transmission power (2.4 G)	13.2
Operating environment	14-104 °F	Video format	MP4 / MOV	Weight	365 g
Working frequency	2.4-2.48935 GHz	Video resolution	6K	Storage temperature	-10-30 °C
		Max bitrate	120 Mbps	Storage humidity	65±20 %RH

UAS for Data Collection Techniques

The sale of drones is expected to reach over $63.6 billion by 2025 (Insider Intelligence, 2022). UAS are being used in a wide range of areas because of their ability to be equipped with thermal cameras, sensors, and other devices that can provide extensive information. The development of drone technologies and their use has drawn significant attention to engineering applications (Ciampa et al., 2019).

The traffic and transportation industry constantly follows the development of technologies that can bring potential benefits. Bubalo et al. (n.d.) proposed the use of UAS technology as an alternative to data collection techniques for the monitoring and evaluation of a comparative analysis of the parameters (i.e., flow, density, and speed) of the traffic flow. The authors used video recordings to measure the parameters with two methods related to the position of the UAS: stationary and moving. The first method used fixed frames from the stationary UAS whereas the second method used a series of images from the moving UAS. It was determined that using UAS technology for the transportation area brings great importance to traffic surveillance, control, and traffic analysis, and it has a future for wider applications and traffic planning (Bubalo et al., n.d.).

Flight Planning

When operating a drone, it is important to establish what is called a flight plan. The term *flight planning* can be used to describe all the logistics that are considered when performing a drone flight operation. Measure (2020) defined a drone flight plan as a predetermined combination of instructions, including the coordinates, speed, altitude, direction, heading, gimbal and camera actions, and many more that are involved to guide the drone to complete a flight. Flight planning can help the pilot and other crew members reduce the time spent in the field. The flight plan can be created in various ways; the pilot can manually make one and place the information in the drone's remote control manually or by using the pre-planned flight feature or instead can use flight-planning software, either mobile or web-based (Measure, 2020).

UAS Applications

Among the leading commercial uses of UAS are construction planning, management, and inspections (Pozner, 2020). An industry that has benefitted the most, and has reached a growth of drone use on the job site of 239% in 2018, was the construction industry (Drone Deploy, n.d.). Since the application of drones in the construction industry and inspection is growing, it was important to review the literature on these current uses. This review shows some insight into how to integrate the use of drones into the transportation area.

Kim et al. (2020) developed a multilevel goal model for decision-making in UAS visual inspection in construction and infrastructure projects. The study documented the job responsibilities and established the goals for UAS operators. It also identified three key personnel (inspector, operator, and observer) along with their tasks, goals, decision criteria, and situation awareness requirements. For example, the inspector establishes the objectives of the work whereas the operator is the UAS pilot who interacts with the inspector. The operator also develops the flight plan and determines the most efficient way to collect the data. On the other hand, the observer helps and communicates with the operator during the flight procedures. It was determined that understanding the information needed by every member, as well as how they will use that information, provides all the team members with the necessary details for their roles to efficiently complete the project. UAS operation decision-making includes preparing the flight, collecting the data, analyzing the data, documenting the results, and addressing feedback (Kim et al., 2020).

Duque et al. (2018) summarized the findings of the current drone techniques for the inspection, monitoring, and analysis of infrastructures. Federal organizations such as the United States Department of Transportation (US DOT), the United States Department of Agriculture-Forest Service (USDA-FS), and others have investigated the ways the capabilities of drones can be integrated into current bridge inspection practices. The results stated that the recent findings are satisfactory, and this has led engineers to perform visual inspections more efficiently and in less time in comparison to traditional inspection techniques (Duque et al., 2018). In addition, the study established some considerations that need to be verified in selecting the most suitable drone for the inspections. Among these considerations is the selection of a drone with more than 20 minutes of flight time and that a camera can be positioned on top of the drone. The authors also recommended using a camera resolution with low illumination and high-resolution videos as well as drones with good payload capacity, drone lights attached, and long remote range.

The use of UAS should be considered as an assistive tool for routine bridge inspections to improve the quality of inspections. This can be obtained by collecting information and details that typically are not easily obtained without expensive access methods or when the interruption of the bridge's services is required (Ciampa et al., 2019). One of the advantages and benefits of using drones in bridge inspections is the ability to access areas that normally would require restricting the capacity in a structure with load restrictions (Tomiczek et al., 2019).

Most of the research on UAS in inspections has focused on the capabilities and efficiency that integrating drones brings to inspections. Hubbard and Hubbard (2020) documented the safety benefits and a methodology that can be applied to a wide range of areas in both the public and private sectors. This methodology assesses the benefit and cost ratio (B/C) related to safety in numerous DOT applications, such as high mast pole inspections, culvert inspections, or mechanically stabilized earth wall inspections that are usually inspected by the same team that examines the bridges. Safety for workers is an important consideration and this study documents the contribution that drones can provide to this aspect (Hubbard and Hubbard, 2020). The research work explains the number of ways the four-phase bridge inspection can be enhanced with drones. In the first phase, pre-inspection activities, drones can provide videos that will help the inspection team to have a preview of the facilities to be inspected. This preview helps get everything ready and ensures that the team makes the best use of the time on the field. Pre-inspection flights can identify potential hazards, environmental risks, and other conditions that could represent a dangerous situation. With all the information gathered in the pre-inspection activities, the team can develop risk management strategies. During bridge inspection, the second phase, and with the findings in the first phase, the team can focus their field time on the components that are distressed or need additional attention. The drone's capabilities allow the team's inspectors to gather information and data from a safe location. In the third phase, post-inspection, the inspectors review all the information gathered in the previous phases and prepare the required report. The data obtained with the drone can be stored and used to track any changes in the conditions of the bridge. The data can be also used in before-and-after studies. Finally, the fourth phase is damage assessment. In this phase, responders operate the drone to obtain information on the bridge components securely; this provides more safety to the personnel and can reduce costs. The benefit-cost analysis done for the case study in the research work indicated that using drones with the proposed methodology in the four-phase bridge inspection provides a B/C ratio greater than one. This suggests that incorporating drones for bridge inspections is an appropriate investment.

Ciampa et al. (2019) performed a literature review on the practical issues of the use of drones for construction. The authors stated that damage assessment in construction projects using drones is a significant factor. Drones can help engineers from the beginning of the damage's occurrence and allow the planning of experimental investigations for diagnostics. Incorporating the abilities of thermal cameras into the drone is a great non-destructive method that can be useful for detecting the type of materials of the structures, the presence of steel rebar, water leakages, humidity, and more. This is especially useful when inspecting historical structures and areas where catastrophic disasters were experienced.

Incident Detection and Traffic Congestion

A key step to reducing incidents that are related to congestion is the early detection of these events (Chakraborty et al., 2018). Yang and Yan (2015) stated in their research that the efficiency of incident detection algorithms depends on the influence of factors such as the type of traffic incident and the traffic parameters. Traffic incidents can be classified as recurrent or non-recurrent based on their time characteristics. Recurring incidents occur when the road capacity does not meet the traffic demand and these usually happen often or repeatedly at certain times such as peak hours. This type of incident can be resolved by traffic demand management or improving road conditions. Non-recurrent incidents are often sudden and unexpected and cause a rapid decrease in the capacity of the road, thus creating serious impacts on the traffic flow.

The traffic parameters that influence the detection algorithms are traffic flow speed, vehicle occupancy, and lane occupancy (Yang and Yan, 2015). Not a single road, especially high-speed facilities, is immune from human errors. Any incident on the road can lead to congestion and even secondary incidents. For accurate incident detection, it is required to detect congestion on the road (Bansal, 2018).

The non-recurrent congestion that develops because of incidents is an important traffic factor for the efficiency of urban road networks. For this type of congestion, the change in speed over a period of time is a useful indicator of traffic conditions. Since there are more vehicles in the peak hour periods, an incident occurring will have a greater effect than if it happens during off-peak periods (Li et al., 2019).

The effective management of freeway facilities requires an understanding of the condition where incidents occur (Song et al., 2020). Congestion is a variable that can influence the likelihood of a traffic incident. Incidents are expected to increase due to the number of vehicles on the road, and they can also decrease due to the reduction of the speed of vehicles (Retallack and Ostendorf, 2019).

Background Subtraction Algorithms

During the literature review process, it was found that several studies have implemented different techniques of vehicle detection to accomplish the objective of developing an automated data collection method to implement a traffic data extraction and analysis system. Two kinds of vision-based vehicle detection methods are available. The first method is based on intrinsic properties, which consist of machine learning methods that can identify specific features of an object. The second method is based on motion detection, which consists of detecting the movement of an object (Leduc, 2008). The latter was selected for the study. A variety of motion detection methods are available, such as background subtraction, frame differencing, and virtual coil method, among others. In this part of the project, the background subtraction method was selected.

The background subtraction method consists of comparing the divergence (i.e., separation) between a present image and a background image by pixels and setting a threshold to determine whether it is background or not (Gupte et al. 2002). Two main categories of background subtraction methods exist: recursive and non-recursive. The recursive methods use a unique value to account for the background and the non-recursive methods use a buffer to represent the background (Setifra and Larabi, 2014). Due to its several algorithms with their fast implementations, background subtraction becomes a very important step in many computers' vision and video surveillance systems, which assume static cameras. Many robust background subtraction algorithms try to outperform the others in both quantitative and qualitative manners. This competition can sometimes confuse the users thus making the selection of an algorithm difficult. To overcome this issue, Setifra and Larabi (2014) reviewed the background subtraction process by defining it and exploring the most used algorithms. The review performed by the authors determined that there are some post-processing techniques used to remove non-relevant (or unneeded) content that is extracted from background subtraction methods. It was also stated that, although there are several techniques to compare the accuracy of background subtraction algorithms, visual inspection is often appreciated. Therefore, human intervention, including knowledge about the scene and its interpretation, can be helpful. The authors indicated that future work should focus on the use of background subtraction algorithms for following processing, such as tracking and object classification.

Multiple studies have worked with a mixture of these motion detection-based algorithms to spot vehicles. Most of these studies obtained video recordings of the traffic flow with cameras mounted on stationary structures. In one of these studies, videos taken from a structure facing the road were processed using background subtraction, Prewitt filter, and morphological operations to detect and count vehicles (Javadzadeh et al., 2015). Studies have worked on vehicle detection and tracking algorithms in real-time traffic (Cao et al., 2016). Adi et al. (2018) developed a system of vehicle counting on toll roads. This system included processes of video acquisition, frame extraction, and image processing for each frame. Video acquisition was conducted in the morning, at noon, in the afternoon, and in the evening. The system employed background subtraction and morphology methods on gray-scale images for vehicle counting. The best vehicle counting results were obtained in the morning with a counting accuracy of 86.36%, whereas the lowest accuracy was in the evening, at 21.43%. Differences in morning and evening results were caused by different illumination in the morning and evening. This caused the values in the image pixels to be different (Adi et al., 2018).

Machine vision systems that use traffic videos to detect and count vehicles with the aim of better-managing traffic in congested areas have been developed (Javadzadeh et al., 2015). The authors stated that their proposed method can be considered superior to other systems since it can be used without the need for any special hardware other than the camera, thus allowing the system to be implemented at a low cost. An approximate detection accuracy of 88% was obtained on several frames of traffic surveillance video, which was considered effective in detecting the movement of vehicles. The authors made several suggestions to improve their proposed method, including using different edge detection or segmentation methods or identifying the rows of pixels with greater numbers of edges than other areas of the image (Javadzadeh et al., 2015).

AlSaadj et al. (2019) presented, compared, and analyzed different background subtraction methods from the literature using the BGSLibrary. The algorithms were tested on images taken from a drone in different weather conditions throughout the year; this was done to determine if the background subtraction methods faced any difficulties. The tests consisted of extracting and evaluating the foreground mask of 30 background subtraction algorithms on three different aerial datasets. It was determined that heat waves affected many of the algorithms as they failed to detect any moving targets during these weather conditions. In addition, AlSaadj et al. (2019) stated that one of the main challenges faced by the algorithms is the small size of the targets in the images.

Najiya and Archana (2018) proposed a modeling framework to identify traffic streams and extract the bidirectional traffic flow parameters from UAV videos. The authors stated that their proposed method was able to obtain a 90% accuracy in vehicle counts in both directions of the traffic stream. It was also established that their system was efficient for both light conditions (day and night) and that this accuracy was not affected by the movements of the UAV. However, a decrease in accuracy was observed when the traffic was heavily congested, and the UAV was positioned at higher elevations. As such, the authors suggested that future works should focus on improving the modeling framework developing for dense traffic conditions (Najiya and Archana, 2018).

If vehicle detection and tracking can be realized and popularized in daily life, the vehicles can be unified. For the drivers, congestion notifications can be sent to prevent traffic rush; the optimal route can be suggested to save energy; and risk warnings can be sent to avoid vehicle crashes. Information about real-time public transportation can be shared with everyone to promote public transportation and, hence, reduce environmental pollution. In addition, infrastructure can be optimally distributed according to the feedback to save construction expenses as well as maintenance costs. Therefore, vehicle detection systems can be considered sustainable and efficient, and able to aid in solving transportation-related problems.

Chapter 3. Methodology and Field Activities

The research methodology for the second phase of the project is described in this section. Figure 3 shows the steps for this methodology. The first step was the literature review, which was previously discussed in the second chapter. The second step was the selection of sites to perform the video data collection; afterward, the dates of the field activities can be selected. The experiment design was developed that included the variables (and their values) to be studied. After all these steps were done and the information gathered, the flight plan was prepared and executed. After all the video data was collected, the next step was to analyze the videos by running them through the background subtraction algorithm. The final step is to report the conclusions and recommendations based on the results of the analyses.

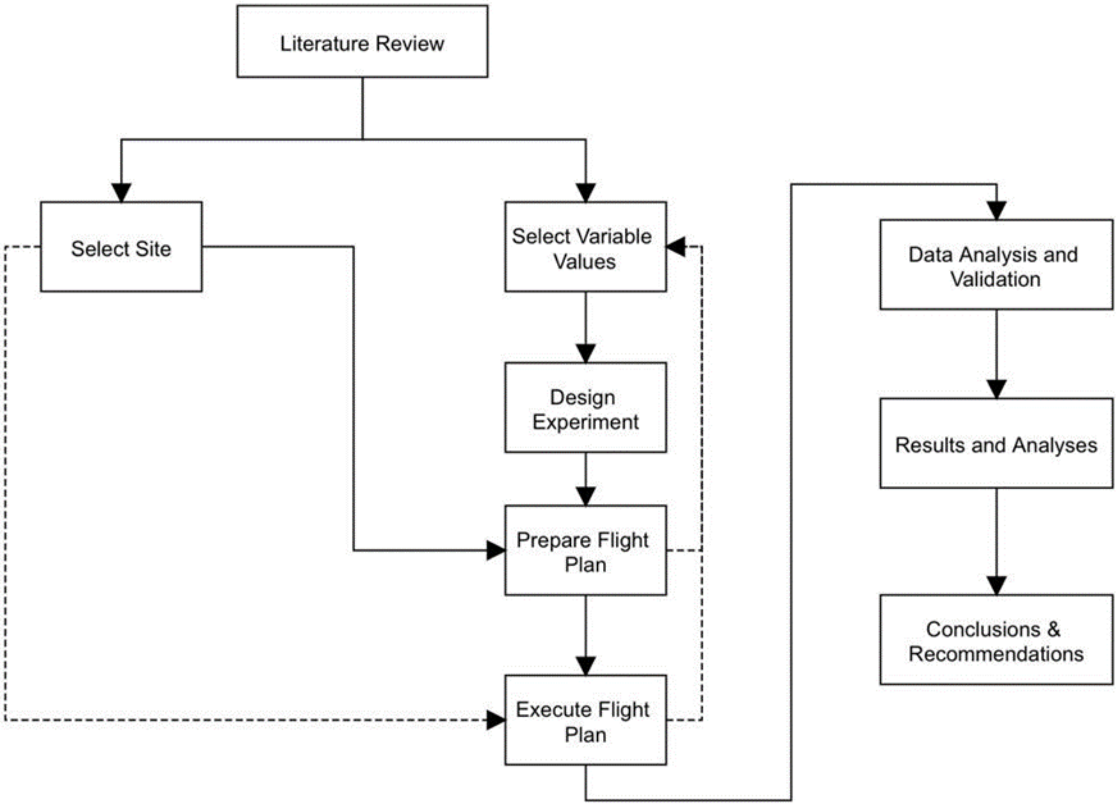


Figure 3. Methodology flowchart.

Site Selection

In the first step of the methodology, potential sites are initially identified; this can be done with programs such as Google Maps and Google Earth, which allow easy observation of the site characteristics. The requirements for a site to be selected in this study were the following:

- If the site is under a controlled airspace area that allows the flight operations of UAVs.
- If the site has an area where the crew members (i.e., remote pilot and observer) can be located and that can serve as the ground station.
- If the site does not have towers that can create magnetic interference or any other type of structure that can represent an obstacle to flight operations.

- If the site is free of other potential hazards, such as trees, power lines, etc.

After the sites were identified, they were evaluated and those that complied with the requirements were selected and described in terms of their roadway geometric characteristics. A total of four sites were selected where six field activities (described in the Execute Flight Plan section) were performed. Figure 4 shows the location of the sites (with some aerial photos obtained) whereas Table 4 includes information on some of the sites' characteristics.

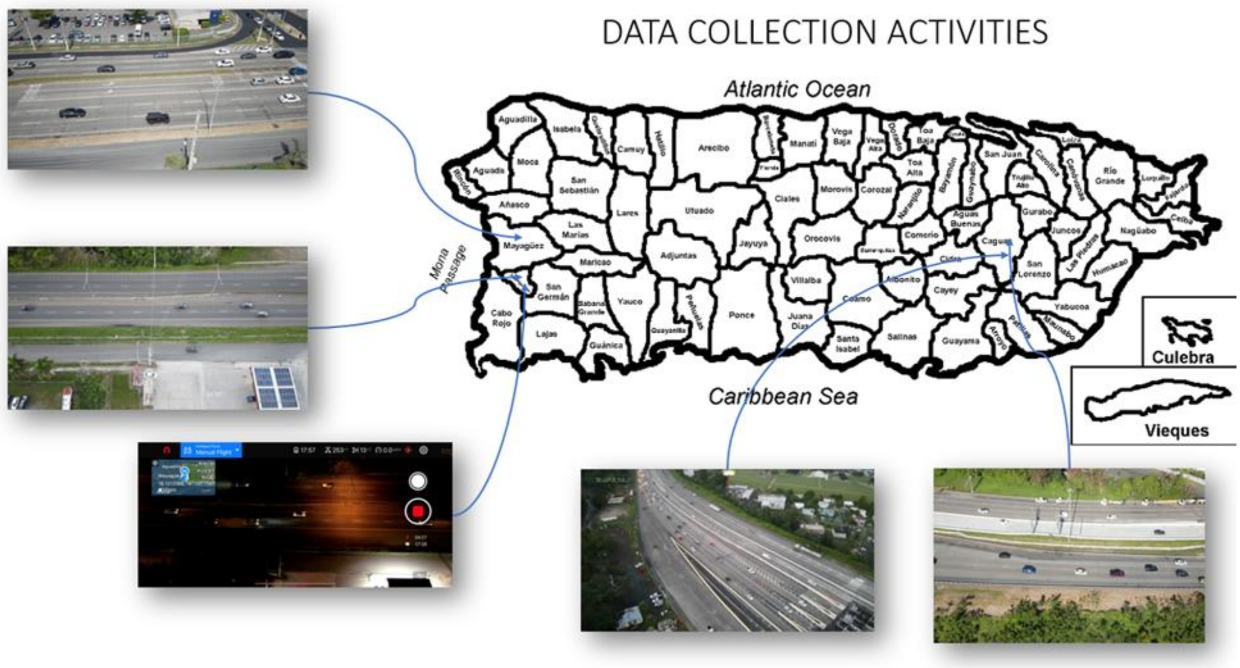


Figure 4. Location map for data collection activities.

Table 4. Description of Sites Selected

DATE (S)	ROUTE AND LOCATION (TOWN)	ROADWAY CHARACTERISTICS						
		Lanes (total)	Lane width (ft)	Speed limit (mph)	Pavement surface	Type of facility	Type of segment	Segment length (ft)
8/27/2021	PR-2 Km. 160, Mayaguez	9	11	55	Concrete	Signalized intersection	Three-leg intersection	250
11/29/2021 and 12/10/2021	PR-52 Km 14.5, Caguas	13	12	65 (55 DTL and toll lanes)	Concrete	Freeway	Basic, toll plaza	800
1/26/2022 2/2/2022 2/9/2022	PR-2, Km 167-168, Hormigueros	7	12	55	Asphalt	Multilane highway	Basic	500
3/23/2022 and 3/24/2022	PR-52 Km 14.0, Caguas	8	12	55	Concrete	Freeway	Basic	500

Selection of Variables and Their Values

Based on the research outcomes from the first phase of the project, it was determined for the second phase to study some factors that can affect vehicle detection. The factors that were selected to investigate were drone elevation (or altitude), drone's distance from the road, illumination conditions, and type of drone. Table 5 shows the range of values that were initially identified to be studied.

Table 5. Values for Preliminary Variables Identified

VARIABLES	VALUES
Drone Elevation	250 ft – 350 ft
Distance from the Road	50 ft – 100 ft
Illumination	Day – Night
Drone	Mavic - Evo

It is important to mention that some of these values were replaced with other values as field activities took place; these changes are discussed in detail in the subsequent section Execute Flight Plan.

Experiment Design

In any experiment, there are one or more independent variables or factors that are changed purposely to observe the effects and changes they have in the response variables. The statistical design of experiments is an efficient procedure for the planning of any experiment. This procedure ensures that the data are obtained and analyzed to yield valid and objective conclusions (NIST, n.d.).

The split-plot design is a special case of a factorial treatment structure. This type of experimental design was selected for this project. The split-plot design is used when some factors are harder (or more expensive) to vary than others. Much of the cost of running a split-plot experiment is tied to changes in the hard-to-change factors (Jones and Nachtsheim, 2009). A split-plot design consists of two experiments with different experimental units of different "sizes" (Meier, n.d.). One randomization is conducted to determine the assignment of block-level treatments to whole plots (Jones and Nachtsheim, 2009). It is difficult to analyze due to the random errors of split blocks and whole blocks consisting of a lack of repeatability and too much variability.

Based on the type of variables for this experiment, it was recommended to use a split split-plot design (Figure 5). The procedure to collect the videos was developed using that type of design.

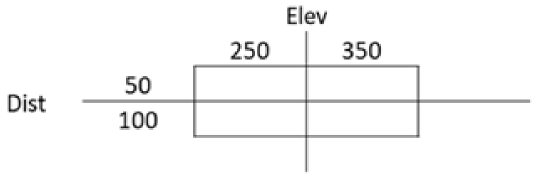


Figure 5. Split split-plot design with experiment variables.

Preparation of Flight Plans

For every video data collection activity, a flight plan was developed using the general procedure previously developed during the first phase of the project (see Chapter 5 of this document). The general procedure was adjusted for each flight operation based on the purpose of the activity. The flight plan must include several details such as the name of the client (i.e., for whom the project is), the name of the project, the duration, and who is the Remote Pilot in Command (RPIC). In the purpose area, the pilot must briefly describe the project and list the procedure to be followed. The location, date, airspace classification, operating altitude, if waivers and/or authorization are needed, and a list of the persons (crew members) that will be part of the flight operation activity must also be established in the flight plan in the corresponding areas. In addition, a map of the location must be provided; within that map, the pilot must delimit both the project area and the UAS operating area. Finally, the take-off, landing, and backup areas must be identified within the project area on the map. Figure 6 shows a template developed for the flight plan activities.

FLIGHT PLAN			
General Information			
Client		Duration	
Project		RPIC	
Project Description			
Purpose			
Location			
Flight Dates			
Airspace Classification			
Operating Altitude			
Waivers/Authorizations			
Crew Members			
Location Map			
Project Area			
UAS Operating Area			
Take-off, Landing, and Backup Areas			

Figure 6. Flight plan template.

Execute Flight Plan

As part of the research, six flight activities were performed in arterial and freeway segments. For all of them, the protocol was used and continued to be updated with the lessons learned from each activity. Each activity had a different purpose; therefore, there were different scenarios. Five of the scenarios served as test sites to understand the capabilities of the two drones available to the crew and to prepare for the study site. The test sites also helped select the variable of drone elevation and distance from the road for the study site, Figure 7. Each scenario and the lessons learned are described below; for most of these scenarios, two different drones were used that vary in terms of battery life, resolution, weight, lens, and digital zoom capacity.

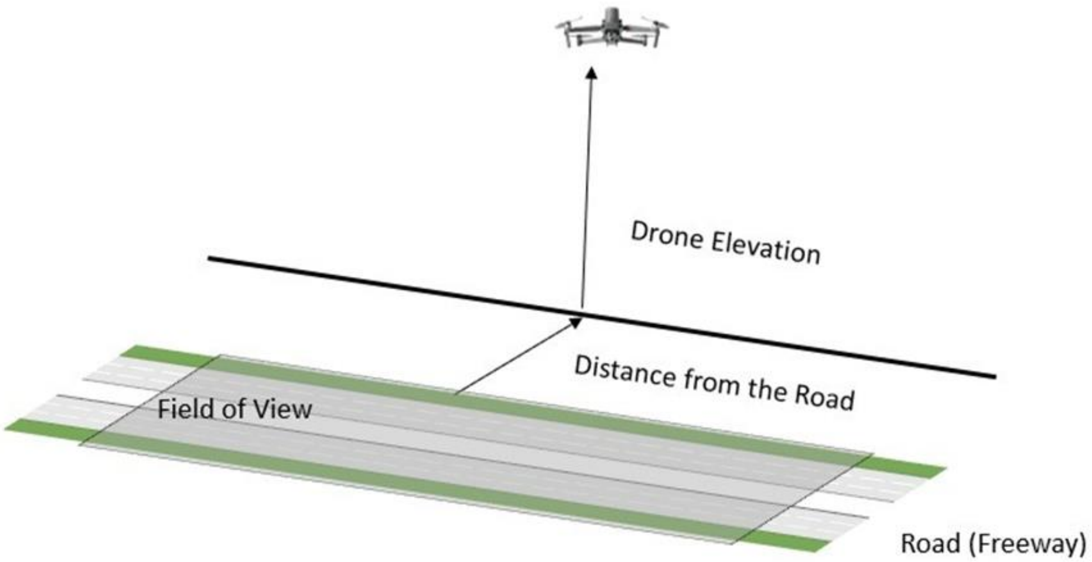
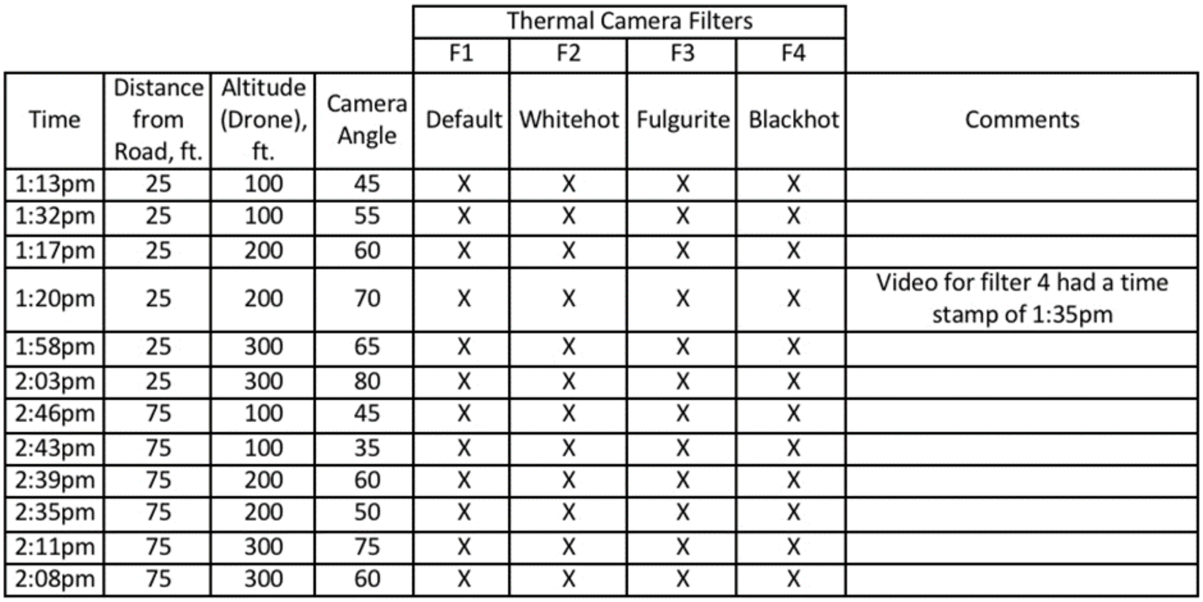


Figure 7. Flight operation variables.

Activity 1: Thermal Filters at Different Levels of Altitude, Distance from the Road, and Camera Angle

The purpose of the first scenario was to test the thermal filters of a drone at different elevations, distances from the road, and camera angles. For each set of variables previously selected, shown in Table 6, 30-second videos were collected. This scenario occurred at an intersection on highway PR-2 km 160.1, in front of a shopping center. This section is considered a principal arterial with six lanes (three per direction) and a two-lane left-turn lane to enter the shopping center. The team consisted of three people: the RPIC, the visual observer, and one person taking notes who oversaw following all the experiment and flight operation steps.

Table 6. Data Collection Sheet for Activity 1



				Thermal Camera Filters				
				F1	F2	F3	F4	
Time	Distance from Road, ft.	Altitude (Drone), ft.	Camera Angle	Default	Whitehot	Fulgurite	Blackhot	Comments
1:13pm	25	100	45	X	X	X	X	
1:32pm	25	100	55	X	X	X	X	
1:17pm	25	200	60	X	X	X	X	
1:20pm	25	200	70	X	X	X	X	Video for filter 4 had a time stamp of 1:35pm
1:58pm	25	300	65	X	X	X	X	
2:03pm	25	300	80	X	X	X	X	
2:46pm	75	100	45	X	X	X	X	
2:43pm	75	100	35	X	X	X	X	
2:39pm	75	200	60	X	X	X	X	
2:35pm	75	200	50	X	X	X	X	
2:11pm	75	300	75	X	X	X	X	
2:08pm	75	300	60	X	X	X	X	

When the team arrived at the location, the reference points for two values for distance from the road (25 ft and 75 ft) were measured approximately. The team moved to the back area of a parking lot adjacent to the highway section to minimize potential distractions for drivers and provide more safety for the equipment and the team. Then the procedure that was established in the flight plan was followed, which was:

1. Review the before-flight checklist developed in the first phase of the project (see Table 8 in Chapter 5 of this document).
2. Lay out the equipment at the site.
3. Turn on the drone and move to the first distance from the road established.
4. Elevate the drone to the first altitude established.
5. At that altitude, place the camera at the first angle established.
6. Record videos for at least 30 seconds using each of the four thermal filters selected (default, white hot, fulgurite, and black hot).
7. When all four videos are taken (one for each filter), move the camera to the second angle and record the next set of videos.
8. Repeat steps 1 through 6 with the next DFR value or the altitude until all the videos are taken with previously determined variables.

In the first scenario, the RPIC encountered a situation with the SD card used in the drone. The video recording required more space than anticipated, prompting the note-taker to get a new SD card during the flight. Another situation that arose during the flight was related to the weather conditions. The conditions for that day were favorable for flying the drone; nonetheless, the heat index exceeded 100°F. The hot temperature added to the switching of the thermal camera filters reduced the battery's capacity.

Activity 2: One Hour Video Using Two Drones

In the second scenario, the purpose was to record a one-hour video during the AM peak hour using 15-minute intervals. Due to the battery capacity, two drones were used, alternating between 15-minute periods. Therefore, the team consisted of four people: two RPICs (one for each drone) and two visual observers (one for each drone). The location of this scenario was on a segment on freeway PR-52 km 14.0, near the Caguas North Toll Plaza, with six lanes (three per direction) and a dynamic toll lane (DTL) that consists of two lanes along the median. It is important to note that although the drones would alternate, and most of the time only one drone was in the air, there were short times that both drones would be in operation. This operation required two visual observers, as only one observer would not have been enough, even if this person could see both drones simultaneously. The flight plan was the following:

1. Verify the before-flight checklist.
2. Set up and calibrate drones for flight.
3. Specify elevation, distance from the road, and camera angle (the camera angle was determined during mid-flight).
4. RPIC #1 would deploy Drone #1 to the specified point and record a 15-minute video.
5. RPIC #2 will start deploying Drone #2 near the specified point when Drone #1 had recorded 12 minutes; once there, it will remain on standby until the 15-minute mark.
6. Once finished recording, RPIC #1 would apply the Return-to-Home function and land the drone. There they would replace the battery and recalibrate the compass.
7. Repeat the process until the desired data is collected.
8. Properly pack up the equipment and check for any damage.

The drones were set up and calibrated to operate at a 250 ft altitude and 100 ft distance from the road. From the previous activity, it was determined that the camera angle should be selected mid-flight to obtain the best view of the road. During this activity, there was a vehicle incident at the entrance of the DTL near the operation area (Figure 8). One RPIC decided to use the drone under operation to record the bottleneck that produced the incident. Although the incident was at a distance less than the maximum permitted by the FAA (2,000 ft horizontal distance), the default value on the drone was set to a conservative value of 1,000 ft. This situation prompted the team to recalibrate the drones and change the default settings to the maximum allowed (2,000 ft) for future field activities. It was also observed that it was difficult for the visual observer to maintain eye contact with the drone since the incident occurred near a horizontal curve in a mountainous area.

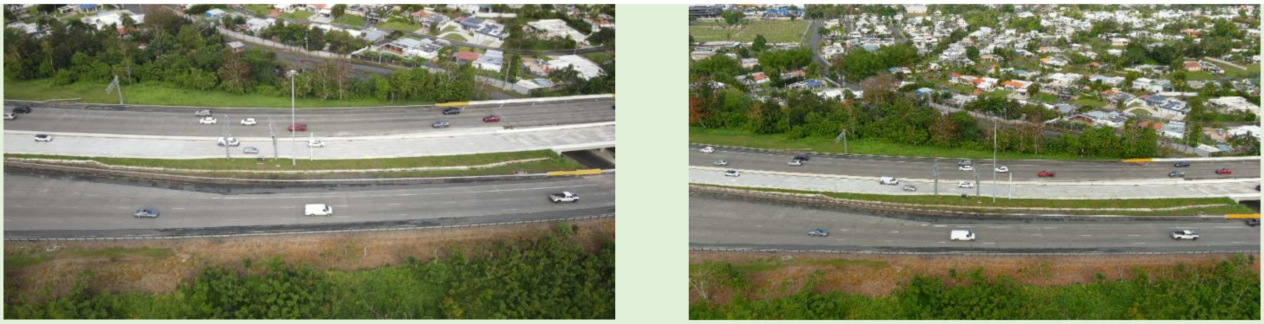
Figure 8. Bottleneck incident during activity 2.

Activity 3: Two Drone Simultaneous Operations at Different Elevations

This activity aimed to record two-minute videos from a freeway segment using two drones simultaneously but positioned at different elevations; 200 ft and 300 ft elevations were selected. This was performed to compare if different elevations influence vehicle detection programs. This scenario was at the same location as scenario 2 (previous activity), and the UAS team consisted of four people: two remote pilots and two visual observers. The flight plan was the following:

1. Verify the before-flight checklist.
2. Set up and calibrate drones for flight.
3. Select the road segment and specify the elevation (high level, low level), distance from the road, and camera angle (determined during mid-flight according to the best view of the highway).
4. RPIC #1 pilots Drone #1 to the specified location to start recording a two-minute video.
5. RPIC #2 pilots Drone #2 to the specified location and records two-minute videos simultaneously with Drone #1.
6. Safely apply the Return-to-Home command to land the drones.
7. Properly pack up the equipment and check for any damage.

For this scenario, the drone set for the lower elevation (200 ft) was deployed first, and a tree was selected as the point of reference. Once this drone was in position, the second drone (300 ft altitude) was deployed and positioned using the lower drone as its point of reference. After the field activity was over, both RPICs agreed that selecting a point of reference from the surroundings on the day of the flight might not be ideal. It was determined to verify the efficiency of traffic cones as points of reference for future activities. Figure 9 shows images from 200 ft and 300 ft elevations, taken with the DJI Mavic and Autel Evo 2 drones, respectively.



(a) 200 ft Elevation / 250 DFR (DJI Mavic)

300 ft Elevation / 300 DFR (Autel Evo 2)

Figure 9. Time-stamped images from activity 3.

Activity 4: Two Drone Simultaneous Operations at Different Elevations and Distances from the Road

Similar to the third scenario, the purpose of the activity was to record five-minute videos using two drones simultaneously but positioned at different elevations and distances from the road. The length of the videos recorded was increased to five minutes. The location for this scenario was highway PR-2 km 167.9 in the Municipality of Hormigueros, PR. The segment was a principal arterial with four lanes (two lanes per direction) plus a frontage road in the eastbound direction. The UAS team consisted of four people: two RPICs and two visual observers.

The flight plan was almost the same one followed in the previous activity. After the checklist was reviewed and the drones were set up and calibrated, based on the lessons learned from the previous activity, the team selected the points of reference (for the distance from the road) using traffic cones. The team measured the two distances from the edge of the service road—50 ft and 100 ft—using an odometer (see Figure 10); the coordinates of these two locations were recorded using GPS in case the activity had to be repeated. The drones were then deployed to specified elevations according to the flight plan and recorded five-minute videos.

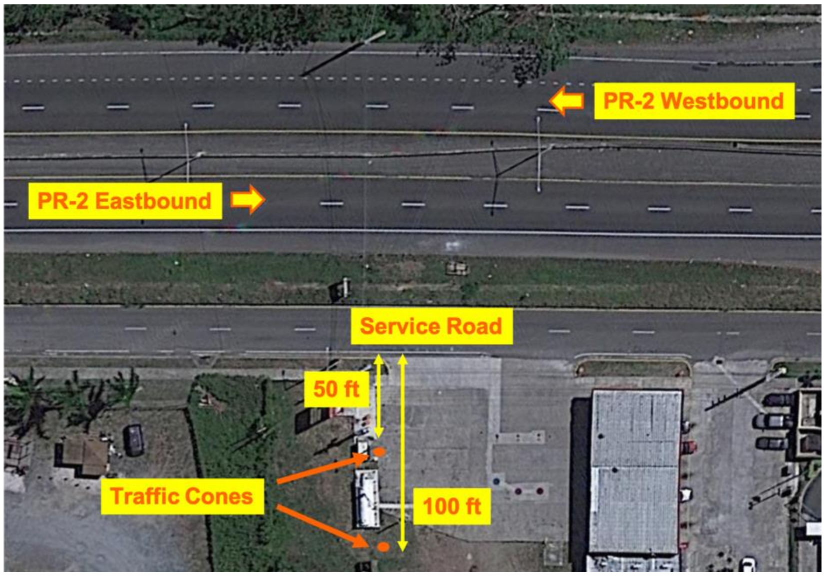


Figure 10. Reference points using traffic cones.

Activity 5: Two Drone Operations at Different Elevations and Distances from the Road on Different Light Conditions

This activity aimed to take videos from an arterial segment using two drones positioned at different elevations and distances from the road. Since only one drone would be deployed at a time, the UAS team consisted of two people: an RPIC for each drone, each serving as the visual observer for the other drone. The location for this scenario was the same as the previous one: highway PR-2 km 167.9.

The flight plan followed was similar to the previous scenario. After reviewing the checklist, placing the traffic cones, and setting up and calibrating the drones, the first drone was deployed according to an elevation and distance from the road established to record a five-minute video. This action was performed until all videos were recorded for the different combinations. Then the same steps were performed using the second drone. It is important to mention that this was done when sunset was going to take place.

This activity helped to highlight the importance of safety when collecting data during night conditions. Although 14 CFR Part 107 allows for drone operation 30 minutes after sunset, the visibility conditions diminish quickly (see Figure 11). Therefore, it is recommended to verify that the flashing beacons of the drones are working correctly before this type of activity. The points of reference must be located during daylight conditions.

During this scenario, the team encountered a problem: it was suspected that a wind gust tilted one of the drones. The drone could not be straightened mid-flight, requiring the RPIC to land the drone and recalibrate it to continue with the operation. In addition, after approximately 30 minutes, there was a drastic change in the weather condition. Even when the weather was frequently monitored—as required on the checklist—it suddenly started to rain, which weather mobile applications failed to predict. Therefore, it was decided to cancel the rest of the data collection activity.

Figure 11. Image taken after sunset for activity 5.

Activity 6: Two Drone Simultaneous Operations at Different Elevations and Distances from the Road on a Freeway Segment

The objective of this scenario was to collect video data during the morning peak hour on a freeway segment considering three variables: drone elevation, distance from the road, and type of drone. Data analyses were then performed to determine if any of these variables influenced the percentage of vehicles detected using a background algorithm (citation paper Bryan). The location for this last scenario was a segment of freeway PR-52 km 14.9 near the Caguas North Toll Plaza. The freeway segment has six lanes (three per direction) plus the two median DTLs. For this activity, two drones were deployed simultaneously to collect the same data, but each was positioned at different altitudes and distances from the road. The UAS team consisted of four people: two RPICs and two visual observers. The flight operation followed the design split-split plot structure shown in Figure 12. As seen in the figure, the two values for the variable distance from the road were 150 and 250 ft, and the values for elevation were 100, 200, and 300 ft.

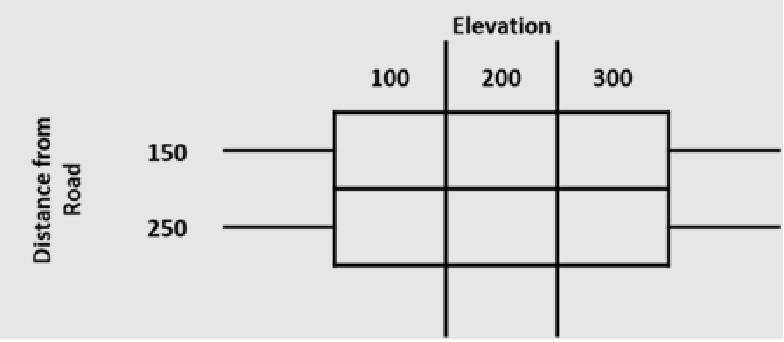


Figure 12. Split-split plot experiment design structure for activity 6 (values in feet).

The flight plan for this scenario was the following:

1. Verify the before-flight checklist.
2. Set up and calibrate both drones for flight.
3. Locate the point of reference previously identified.
4. Specify the elevation, distance from the road, and camera angle (determined during mid-flight).
5. RPIC #1 pilots Drone #1 to the specified variables and records video.
6. RPIC #2 pilots Drone #2 to the specified variables and records video.
7. Repeat until all sets of variables are done.
8. Safely apply the Return-to-Home command to land the drones.
9. Properly pack up the equipment and check for any damage.

For this scenario, the RPICs determined the reference point before the flight using Google Earth instead of traffic cones; this saved time and was convenient for complex places (e.g., forests or lakes). The coordinates were recorded in case the activity had to be repeated.

During the data collection, RPICs observed that the freeway segment could not be entirely seen for the 150 ft distance from the road value. It was then decided to substitute it with a value of 300 ft distance from the road. The team also observed that at the 100 ft elevation, the presence of tall vehicles such as trucks could obstruct the view of other cars farther away, as seen in Figure 13.

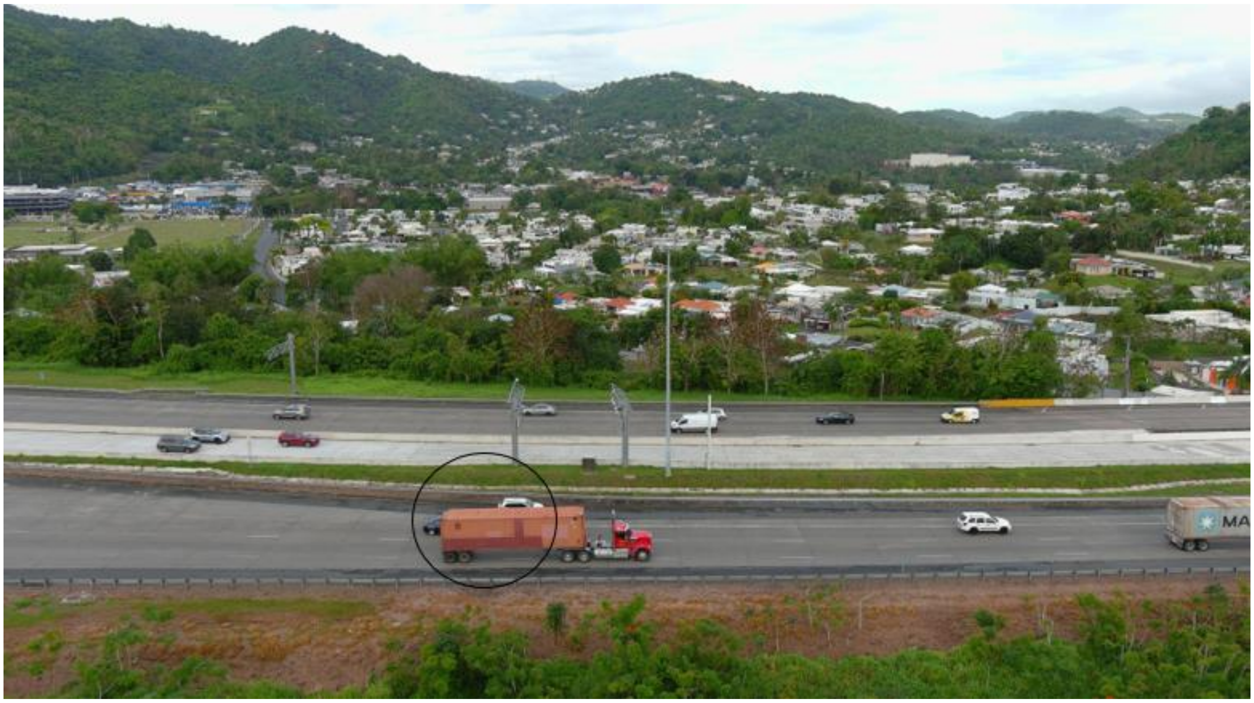


Figure 13. View from 250 ft drone distance from the road and 100 ft elevation.

Data Validation

Vehicle detection using a background subtraction-based algorithm was developed and provided by our fellow research team at the University of South Florida (USF). A background model is built using a Gaussian Mixture-based Background/Foreground Segmentation Algorithm. To distinguish the foreground (moving objects) from the static background, input frames are supplied into the background model. The result is a binary image, with the moving items represented by the foreground mask. Two additional morphological modifications, opening and dilation, are applied to the binary image. The opening removes noise by conducting an erosion operation, followed by a dilation operation. After opening, closing is used to fill in any minor holes in the objects in the foreground. A contour area threshold is used to further filter out noise; if a contour does not meet the threshold value (e.g., is less), then it is eliminated. The bounding boxes of any identified vehicles are then produced using the coordinates of the contour. The bounding boxes surrounding each car detected can be appreciated in Figure 14.

Figure 14. Sample frame from data collection.

To verify the results from the background subtraction algorithm, vehicle counts are manually taken (i.e., observed) for each frame of the video and are compared to how many bounding boxes are presented in the image. A bounding box consists of border coordinates that enclose an image in the frame, in the shape of a box (square); in this case, the images that are enclosed with these bounding boxes are the vehicles detected by the algorithm.

Data collection activities required the team to take 5-minute videos. However, these videos were cropped into 30-second videos and then run through the algorithm to save time and resources. A 30-second video contains between 890 and 930 frames, hence, the reduction in video duration. The steps to run the algorithm are the following:

1. Take a 30-second video sample from the original 5-minute video.
2. Import video.
    - When importing the video to the algorithm, it is essential to verify that we are using the correct folders in the directory where the videos are saved. Also, the name of the subject video must be identical to the one input in the script, otherwise the algorithm will not run.
3. Establish threshold inputs.
    - The *varThreshold* helps set which pixel is determined to be in the background. This value sets the magnitude of certainty to determine the background, and therefore the foreground as well.
    - The *morphological transformation* (or kernel inputs) is an operation based on the image shape; it takes the original shape and transforms it into a structuring element. The input for the kernel determines the magnitude of the transformation into structuring elements. The higher the value, the more transformation is performed to the image, and it can be related to more noise in the video.
    - The input for the *contour area* sets the minimum area required for a bounding box to be counted as a vehicle. This value is useful when the elevation of the drone varies. For lower elevations, a higher threshold value for the contour area is needed. This is because at lower

elevations the images of vehicles in the video appear to be bigger when compared to higher elevations, hence the need for a higher minimum threshold.

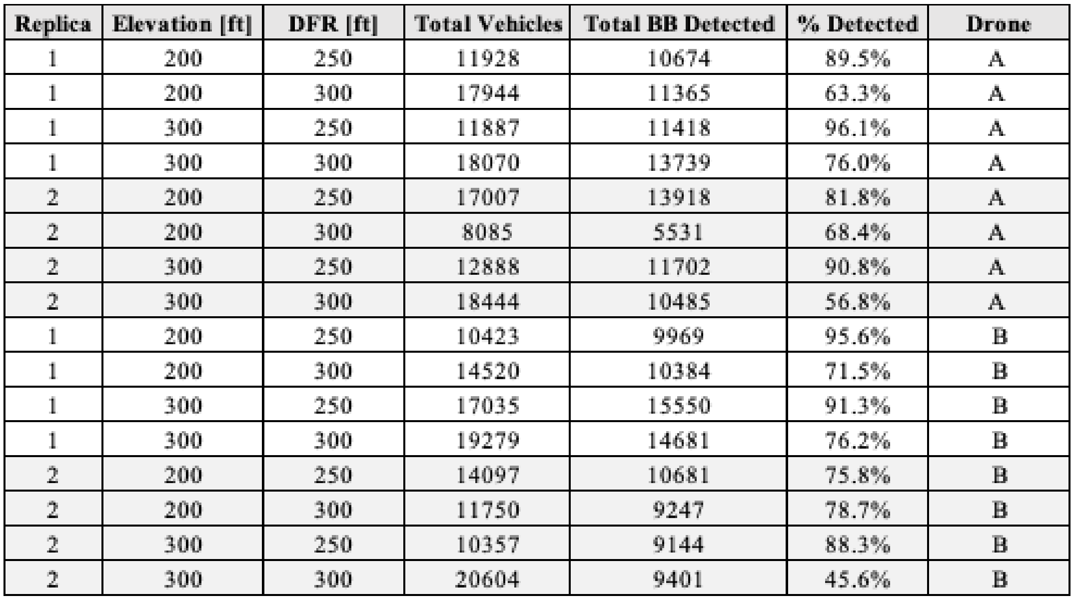
4. Run the algorithm and perform manual counts.
    - When running the algorithm each frame is evaluated. The vehicles and bounding boxes in each frame are counted. Both counts, per frame, are input on a spreadsheet in their respective columns.
5. Verify the results.
    - After all vehicle counts per frame, from both the algorithm and the manual counts, are input on the spreadsheet, these are compared by calculating the "percentage of vehicles detected." These percentages, which are calculated both per frame and total, take the values of the manual counts as the real number of vehicles in the image.

The algorithm is designed to indicate the cumulative value of vehicles detected per frame. To obtain the number of vehicles detected by the algorithm after the first frame, we simply calculate the difference in values between consecutive frames. It is important to understand that the output obtained represents the bounding boxes created by the vehicle detection algorithm and the results, per frame, can be interpreted as the density of vehicles in the given road segment.

Chapter 4. Statistical Analyses and Results from Field Activities

The research for the second year focused on determining the efficiency of the algorithm considering certain variables. Among these factors are drone elevation, distance from the road, DFR replica, and drone type. Two replicas were taken for the dataset; the first replica represents the data taken on the first day of data collection (for the study site), while the second replica represents the data taken on the following day. Each replica consists of data collection for the four established treatments. It should be noted that there were no differences in weather and traffic conditions for these days (sunny skies, dry pavement, non-peak traffic). The results of the data collected and analyzed are shown in Table 7.

Table 7. Results from the Data Validation Process



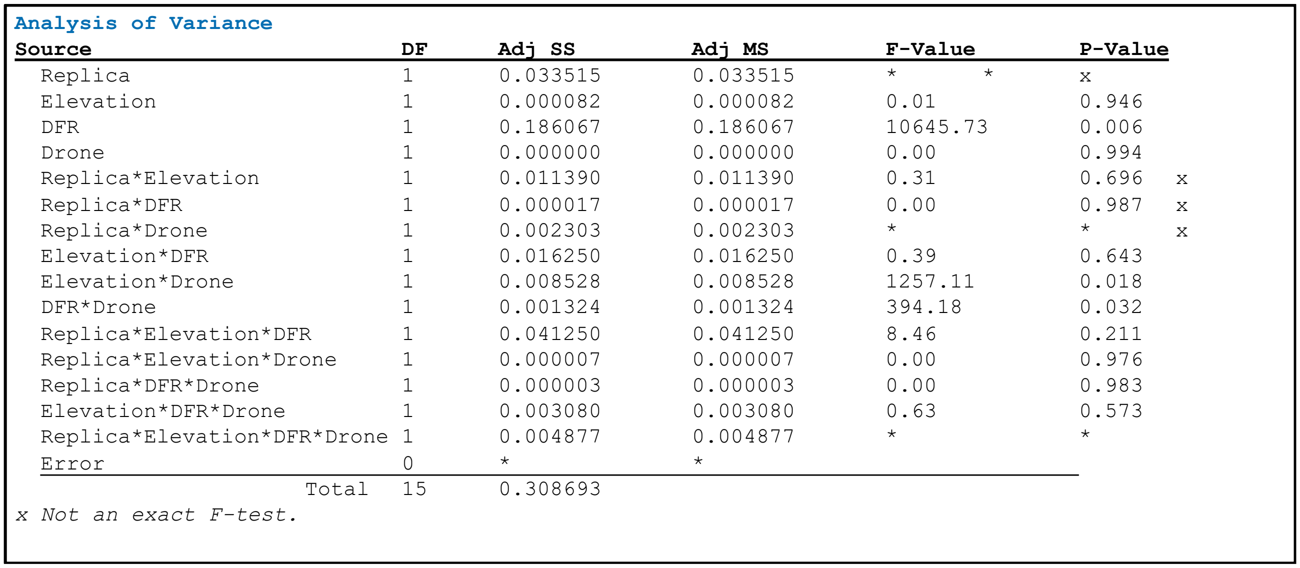
Replica	Elevation [ft]	DFR [ft]	Total Vehicles	Total BB Detected	% Detected	Drone
1	200	250	11928	10674	89.5%	A
1	200	300	17944	11365	63.3%	A
1	300	250	11887	11418	96.1%	A
1	300	300	18070	13739	76.0%	A
2	200	250	17007	13918	81.8%	A
2	200	300	8085	5531	68.4%	A
2	300	250	12888	11702	90.8%	A
2	300	300	18444	10485	56.8%	A
1	200	250	10423	9969	95.6%	B
1	200	300	14520	10384	71.5%	B
1	300	250	17035	15550	91.3%	B
1	300	300	19279	14681	76.2%	B
2	200	250	14097	10681	75.8%	B
2	200	300	11750	9247	78.7%	B
2	300	250	10357	9144	88.3%	B
2	300	300	20604	9401	45.6%	B

The dataset consisted of videos captured using different UAVs. The video clips for the dataset were taken at a rate of 30 frames per second, which translates to approximately 900 frames per 30-second video clip. Every frame was evaluated in terms of vehicles in the road segment and vehicles detected with the bounding boxes ("Total BB Detected" in Table 7).

In Table 7, it is observed that the vehicle detection algorithm proved to have high performance (over 90%) in some of the treatments. However, in some treatments, the percentage of vehicles detected was lower. High vehicle detection, up to 96%, was obtained with treatment #3—drone at 300 ft elevation and 250 ft DFR. Treatment #4, the combination of 300 ft elevation and 300 ft DFR, of the second replica (Drone B), was the treatment with the lowest percentage of vehicle detection (45.6%). The average detection rate for treatments 1, 2, 3, and 4 were 86%, 70%, 92%, and 64%, respectively, with treatment #3 with the best performance and treatment #4 with the lowest detection rate.

While the analysis and validation of the data were being carried out, factors that may cause a reduction in vehicle detection capability were theorized. Among these factors were identified the color of the vehicle, the gap (space) between vehicles or traffic density, some structures such as utility poles, and occlusion due to tall vehicles such as trucks.

To evaluate the efficiency of the vehicle detection algorithm, an analysis of variance (ANOVA) was developed. This was performed to identify or classify the variables into systematic and random factors. Systematic factors have a significant statistical influence on the efficiency in which vehicles are detected. The results of the ANOVA can be observed in Figure 15.



```
Analysis of Variance
Source                          DF     Adj SS        Adj MS        F-Value        P-Value
  Replica                       1      0.033515      0.033515      *       *      x
  Elevation                     1      0.000082      0.000082      0.01           0.946
  DFR                           1      0.186067      0.186067      10645.73       0.006
  Drone                         1      0.000000      0.000000      0.00           0.994
  Replica*Elevation             1      0.011390      0.011390      0.31           0.696  x
  Replica*DFR                   1      0.000017      0.000017      0.00           0.987  x
  Replica*Drone                 1      0.002303      0.002303      *              *      x
  Elevation*DFR                 1      0.016250      0.016250      0.39           0.643
  Elevation*Drone               1      0.008528      0.008528      1257.11        0.018
  DFR*Drone                     1      0.001324      0.001324      394.18         0.032
  Replica*Elevation*DFR         1      0.041250      0.041250      8.46           0.211
  Replica*Elevation*Drone       1      0.000007      0.000007      0.00           0.976
  Replica*DFR*Drone             1      0.000003      0.000003      0.00           0.983
  Elevation*DFR*Drone           1      0.003080      0.003080      0.63           0.573
  Replica*Elevation*DFR*Drone   1      0.004877      0.004877      *              *
  Error                         0      *             *
                      Total     15     0.308693
x Not an exact F-test.
```

Figure 15. Analysis of variance results.

Performing the ANOVA test determines whether a variable has a statistically significant influence in terms of detection rate by looking at the p-values. A variable with p-values less than 0.05 indicates that it is statistically significant at the 95% confidence level (i.e., the influence of this variable on vehicle detection rate is significant). From the ANOVA results, it can be observed that the variables that influence vehicle detection are DFR, the relationship between drone and elevation, and the relationship between drone and DFR. DFR is considered to be the main variable affecting the vehicle detection rate. From the dataset, it was observed that at a closer distance from the road (DFR value of 250 feet), a higher detection percentage was obtained. In terms of elevation, the results indicated that there was no significant statistical influence. However, when validating the data manually, higher heights were easier to work with. This is because vehicles can be better appreciated from this type of vantage point as the separation between vehicles is clearer.

As mentioned above, the data collection was done in the morning peak hour, so the traffic density at times was relatively high. This implies that the separation between vehicles was smaller, which caused the vehicle detection algorithm to group within the same bounding box up to three vehicles. Another probable cause for the reduction in vehicle detection could be the obstruction of the roadway; in our case, this was caused due to utility poles and overhead signs located on the dynamic toll lane (DTL). While running the UAV-captured videos through the algorithm, it was observed that these structures caused an effect in which vehicles passing through the obstructed lanes were undetected or partially detected. On occasion, vehicles that were initially detected, either were no longer detected on the following frames or the bounding box was split in two. The occlusion of vehicles was visible in the data collection activities. Occlusion was observed more frequently when operating at lower altitudes and when trucks were present on the roadway. Lower altitudes provide less favorable vantage points. Small vehicles traveling alongside trucks, often, were obstructed from view. Some of these vehicles were obstructed completely and others partially; partially occluded vehicles formed part of the bounding box area designated for the truck, hence, not being detected, and counted as one vehicle: the truck and the obstructed car.

Figure 16 represents the efficiency at which vehicles are detected considering elevation, DFR, and drone type (main effects plot). The lines observed in the left and right plots demonstrate that the detection efficiency is not affected by elevation and drone, as they are almost horizontal lines. However, when observing the mean percentage of vehicles detected with DFR (center plot), a difference of approximately 20% in detection between treatments is observed. This is interpreted as higher detections are associated with smaller distances from the road. Treatments with a DFR of 250 ft averaged a percentage of detection of approximately 88% when compared with treatments with a DFR of 300 ft, which experienced on average about 67% detection rate.

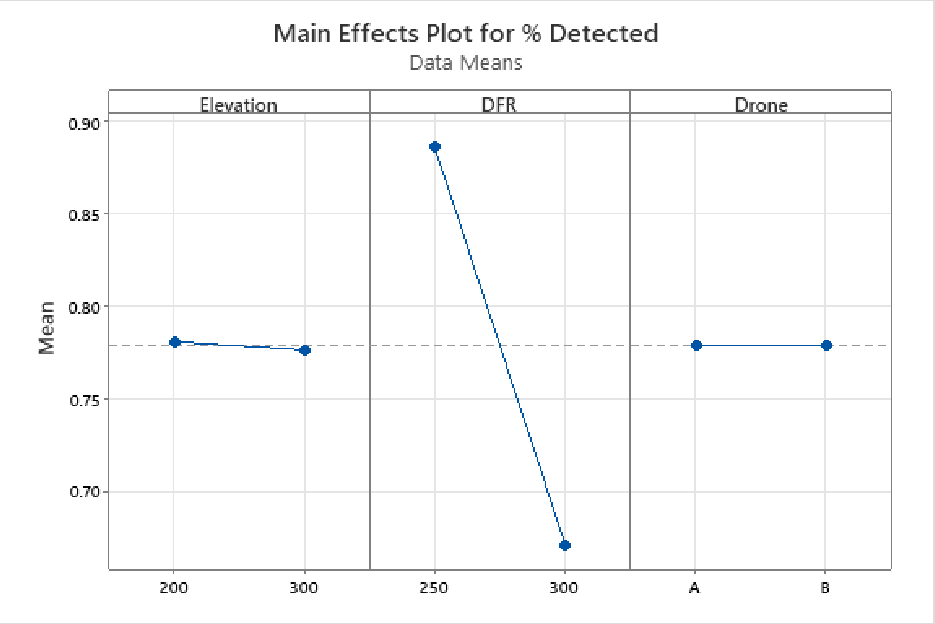


Figure 16. Main effects plot for percentage of vehicles detected.

Figure 17 shows the interaction plot between drone and elevation in terms of the percentage of vehicles detected. An interaction plot displays the levels of one variable for the means of each level of another variable. The interaction plot indicates that similar efficiency can be obtained for the different drones but at different elevations: one type of drone is associated with 80% of vehicles detected at a 300 ft elevation whereas this percentage is obtained with the other drone at 200 ft elevation. However, from Figure 16 it was observed that elevation does not influence the efficiency of the detection rate. This phenomenon may be associated with the different specifications and features that each drone possesses.

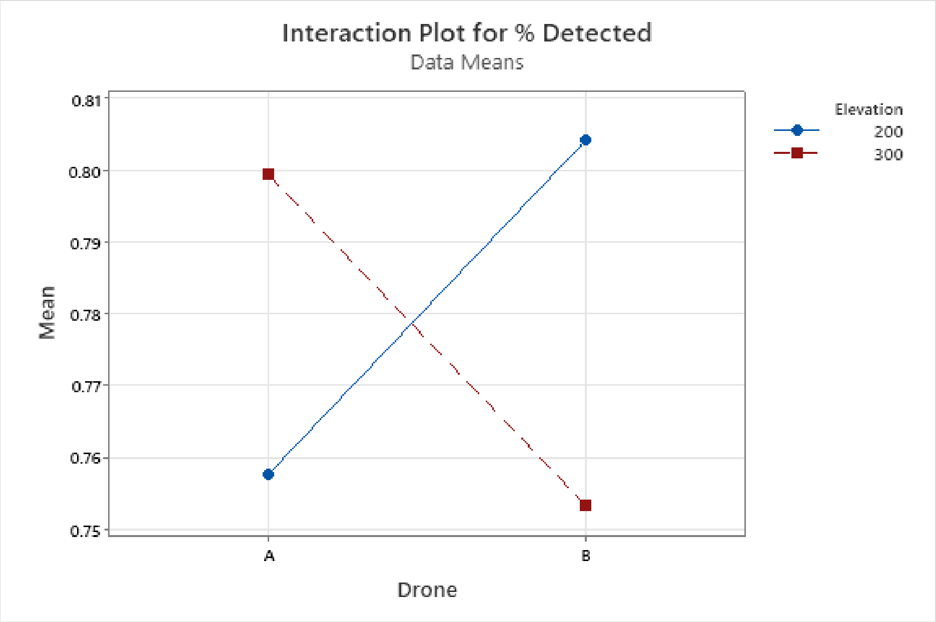


Figure 17. Interaction plot for percentage of vehicles detected: drone type versus elevation.

The interaction plot for the relation between drone and DFR is presented in Figure 18. The difference in detection rate is about one percent and both lines are similar: for both types of drones, the percentage of vehicles detected decreases with an increase in distance from the road. This indicates that these relationships are marginal.

Figure 18**. Interaction plot for percentage of vehicles detected: drone type versus DFR.**

Chapter 5. Protocol for Using UAS for Traffic Monitoring Activities

The protocol developed during the first year was updated with the lessons learned during the flight activities of the second year. It was developed with the purpose of integrating the UAS into transportation studies and applications, focusing on freeway facilities for incident detection and management. The protocol contains information from the Federal Aviation Administration (FAA) and the lessons learned in the research field activities that took place as part of the study. It also considers the experiences in climatic conditions applicable in the tropical region and other locations in the United States, including Puerto Rico, as well as the collective experience of experts in surface transportation traffic operations and safety-related areas. With all this collective judgment and knowledge, checklists were created into three major categories: before, during, and after the flight.

Once a person obtains the pilot certificate and is knowledgeable of FAA's rules and restrictions, they are prepared to start operating the drone. The operation of the drone can be divided into three parts: before, during, and after the flight. Each part is described in more detail with checklists and an explanation of every item in the following sections.

Before the Flight

Before operating the UAS, the Remote Pilot in Command (RPIC) must have a prompt or checklist to ensure the safety of each member of the team. This list, shown in Table 8, should be reviewed by all members of the team before the flight.

Table 8. Checklist for Before the Flight

	ITEM	
BEFORE	1	Remote Pilot in Command Credentials and Information
	2	Airspace Clearance
	3	Evaluate Site Area
	4	Weather Conditions
	5	Emergency Contingency
	6	Flight Plan
	7	Drone Inspection

Item #1: Remote Pilot in Command Credentials and Information

The before-the-flight checklist begins with the pilot reviewing that all the documentation is valid according to 14 CFR Part 107 requirements; this includes both the Remote Pilot Certificate and the registration of the drone that will be used. The pilot is responsible for verifying that the drone has the FAA registration up to date and that this registration is visible to third parties. An example of the Remote Pilot Certificate is shown in Figure 19; Figure 20 shows the FAA page for registering a drone.

I UNITED STATES OF AMERICA XI

DEPARTMENT OF TRANSPORTATION ▪ FEDERAL AVIATION ADMINISTRATION

IV NAME

XXXXXXXXXXXX

V ADDRESS XXXXXXXXXXXXX
XXXXXXXXXXXXXXXXXXXX

VI NATIONALITY USA

IVa D.O.B. XXXXXXXXX

SEX	HEIGHT	WEIGHT	HAIR	EYES
X	XX	XXX	XXXXX	XXXXX

IX HAS BEEN FOUND TO BE PROPERLY QUALIFIED TO EXERCISE THE PRIVILEGES OF

II REMOTE PILOT

III CERTIFICATE NUMBER XXXXXXX

X DATE OF ISSUE XXXXXXXX

XIV

VIII ADMINISTRATOR

Figure 19. Remote pilot ID card (Source: Gleim Aviation)

Welcome to the FAADroneZone

I fly under Part 107 or as a Public Aircraft

I need to register a drone that is less than 55 lbs, apply for a waiver/authorization under Part 107, or report a UAS/drone accident.

I fly under The Exception for Recreational Flyers

I need to register a drone under The Exception for Recreational Flyers.

Register a drone that weighs 55 lbs. or more.

Already registered? Log In to your existing account.

For general information about drones, rules for flying, and how to become a drone pilot, visit the FAA website.

Figure 20. Drone registration website (Source: FAA, 2022b).

Item #2: Airspace Clearance

The next three items on the list are related to the area where the drone flight will take place, beginning with an inspection of the airspace clearance to verify any regulations or restrictions. For this part, it is important to understand the FAA airspace classifications, shown in Figure 21.

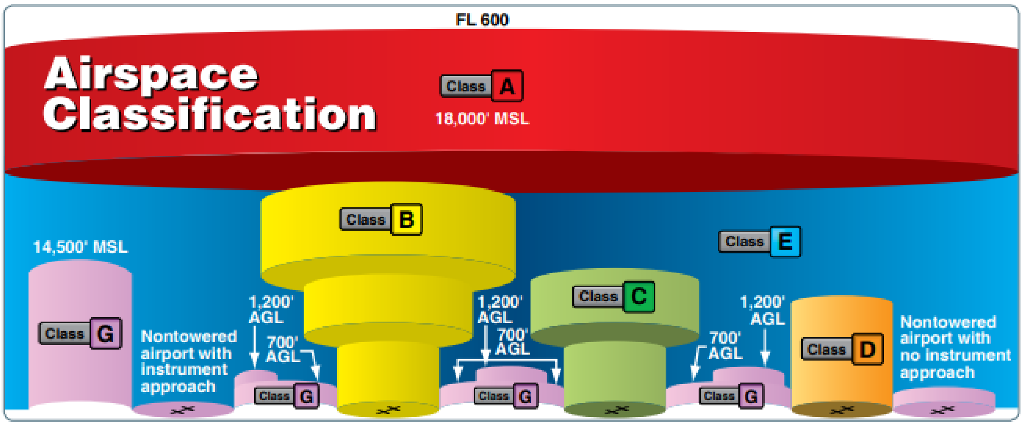


Figure 21. Airspace classification (Source: FAA).

There are six FAA airspace classifications. Class A is for airplanes traveling at 18,000 ft or more above the Mean Sea Level; UAVs are not allowed in this class. Classes B, C, and D are controlled airspaces around airports; the horizontal restrictions for each of these classes depend on the size of the airport. Authorization is needed to fly a drone in these airspaces. Most of the airspace in the United States is Class E and it is still controlled airspace, thus requiring authorization. It is also important to note that other airspaces besides airports are restricted, such as those around military buildings. The only airspace where no authorization is needed to operate a drone is Class G, which is uncontrolled airspace.

To obtain information about the airports in the area and the controlled airspace, the pilot can access the SkyVector website. Figure 22 shows the restricted airspace on the island of Puerto Rico due to the location of airports, military bases, and other controlled areas.

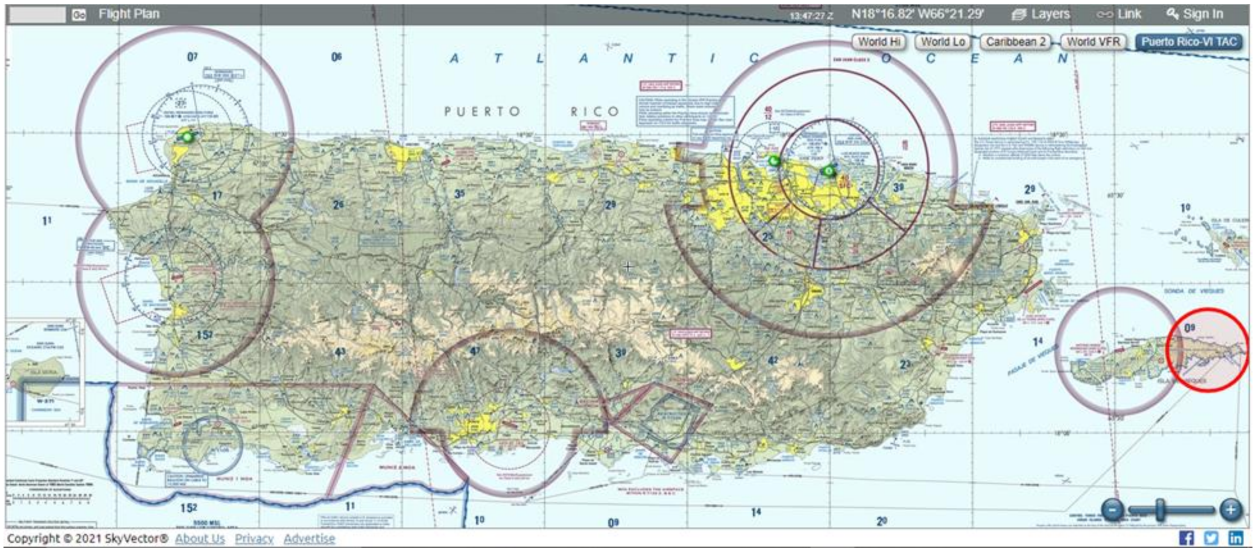
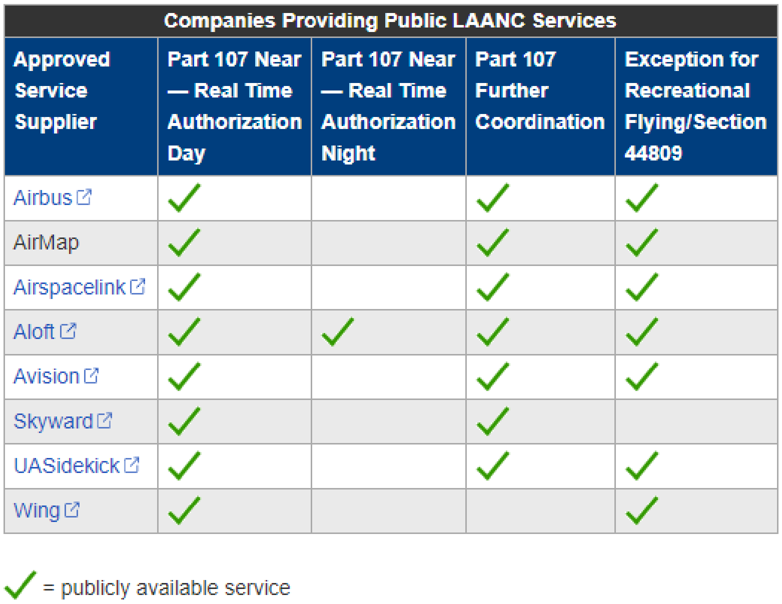


Figure 22. Puerto Rico airspace classification map (Source: SkyVector).

As mentioned before, in the event of any airspace restrictions, an operational waiver can be obtained if it can be demonstrated that a safe flight can be achieved. Low Altitude Authorization Notification Capability (LAANC) provides these airspace authorizations. LAANC is a collaboration between the FAA and the industry to automate any application and the process of approval in the event of an authorization request. According to the FAA website, LAANC can provide drone pilots with access to controlled airspace at or below 400 ft as well as awareness of where they can and cannot fly.

Through automated applications developed by FAA Approved UAS Service Suppliers (USS), pilots apply for an airspace authorization. The FAA's website provides a list of their approved service suppliers and the type of LAANC services, shown in Figure 23.



Companies Providing Public LAANC Services				
Approved Service Supplier	**Part 107 Near — Real Time Authorization Day**	**Part 107 Near — Real Time Authorization Night**	**Part 107 Further Coordination**	**Exception for Recreational Flying/Section 44809**
Airbus	✓		✓	✓
AirMap	✓		✓	✓
Airspacelink	✓		✓	✓
Aloft	✓	✓	✓	✓
Avision	✓		✓	✓
Skyward	✓		✓	
UASidekick	✓		✓	✓
Wing	✓			✓

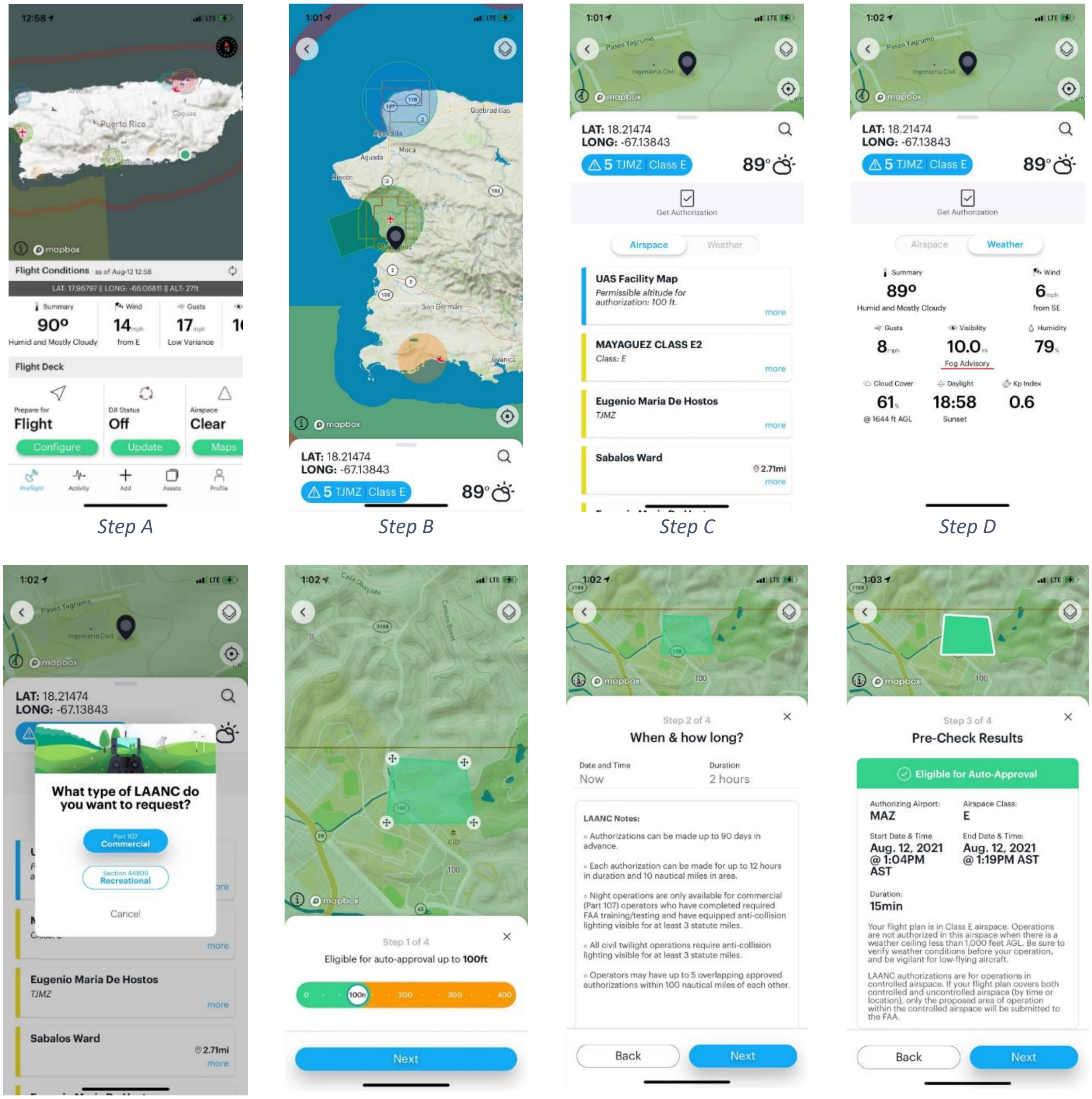
✓ = publicly available service

Figure 23. Companies providing public LAANC services (Source: FAA).

The research team used the supplier Aloft for the required authorizations. The mobile application of Aloft free version is available in the app store for iOS users and the Google Play Store. The steps taken were the following:

A. First download or, if already downloaded, verify if the application needs an update. Sign up or log in with the Part 107 Remote Pilot credentials.
B. Once the mobile application is open, search on the map for the location where the flight operation will take place.
C. After the location is selected, scroll up to the bottom part of the display where there are several tabs. The *Airspace* tab shows the classification and the name(s) of the controlled airspace near the location.
D. The *Weather* tab displays the present conditions for the selected area.
E. Click on the *Get Authorization* icon and select the type of LAANC request; for this study, the “Part 107 commercial” was selected.
F. Proceed to select the desired area in the map of the drone operation; this will display the maximum elevation where it would be approved to operate the drone immediately, both in words and using a colored bar. In the bar, the green area shows the elevation that is eligible for auto-approval. A higher elevation can be selected by scrolling on the bar, which will fall on the orange area, thus requesting a waiver to operate the drone that will not be approved automatically.
G. Afterwards, select the date, time, and duration of the drone operation being requested.
H. If the request is approved automatically, a text message is sent to the number provided while signing up that contains the information of the authorization.

Figure 24 shows a series of screenshots of the process using the Aloft mobile application. In Step F, it is observed that the maximum elevation eligible for auto-approval was 100 ft (green area on the bar); scrolling to the right on the orange area would have resulted in a waiver request that would have taken time to be approved.



UAS Facility Map
Permissible altitude for authorization: 100 ft.

MAYAGUEZ CLASS E2
Class: E

Eugenio Maria De Hostos
TJMZ

Sabalos Ward

Summary: 89° Humid and Mostly Cloudy
Wind: 6 mph from SE
Gusts: 8 mph
Visibility: 10.0 mi Fog Advisory
Humidity: 79%
Cloud Cover: 61% @ 1644 ft AGL
Daylight: 18:58 Sunset
Kp Index: 0.6

Step 1 of 4
Eligible for auto-approval up to 100ft

Step 2 of 4
When & how long?
Date and Time: Now
Duration: 2 hours

LAANC Notes:
- Authorizations can be made up to 90 days in advance.
- Each authorization can be made for up to 12 hours in duration and 10 nautical miles in area.
- Night operations are only available for commercial (Part 107) operators who have completed required FAA training/testing and have equipped anti-collision lighting visible for at least 3 statute miles.
- All civil twilight operations require anti-collision lighting visible for at least 3 statute miles.
- Operators may have up to 5 overlapping approved authorizations within 100 nautical miles of each other.

Step 3 of 4
Pre-Check Results
Eligible for Auto-Approval
Authorizing Airport: MAZ
Airspace Class: E
Start Date & Time: Aug. 12, 2021 @ 1:04PM AST
End Date & Time: Aug. 12, 2021 @ 1:19PM AST
Duration: 15min

Your flight plan is in Class E airspace. Operations are not authorized in this airspace when there is a weather ceiling less than 1,000 feet AGL. Be sure to verify weather conditions before your operation, and be vigilant for low-flying aircraft.

LAANC authorizations are for operations in controlled airspace. If your flight plan covers both controlled and uncontrolled airspace (by time or location), only the proposed area of operation within the controlled airspace will be submitted to the FAA.

Step A *Step B* *Step C* *Step D*

Step E *Step F* *Step G* *Step H*

Figure 24. Process to obtain LAANC authorization with Aloft mobile app: steps A–H.

Items #3 and #4: Evaluate Site Area and Weather Conditions

Even if an authorization or waiver is obtained for a flight operation, the area still must be evaluated to identify any potential hazards that can interfere with the flight operations, such as trees, cables from utility poles, and transmission towers. If any potential hazards are identified, then a contingency plan must be developed to execute the flight. Also, before any drone operation, the weather conditions must be verified to commence the operations. This should be done several days in advance and on the day of the flight. There are several weather applications available that the pilot can use to monitor the conditions and to prepare according to the weather predictions. It is also important to identify an area to protect the team from the sun and heat due to high temperatures, as well as an available seating area to rest if the drone operation will take a long time.

Items #5 and #6: Emergency Contingency and Flight Plan

For the emergency contingency plan, at least one member of the team must oversee having the emergency contact information of all the team members, emergency responders, information on the drone manufacturer, and a first aid kit available.

For the flight plan, the team must have a written document that describes the purpose of the operation and the following details: airspace classification, location, list of crew members, and both the primary and alternative launch and land sites. The flight plan can be obtained from available templates, or one can be created based on the requirements of the operation. It should also have at least one alternative procedure in case of an unexpected situation, such as an obstruction, changes in weather conditions, or an emergency. The flight plan also indicates how the experiment is going to be performed. It must be revised by the remote pilot in command as they are the person who oversees the flight operations. A template of the flight plan document developed by the research team was shown in Figure 6 (Chapter 3) of this document.

Item #7: Drone Inspection

The remote pilot in command (RPIC) must verify that the drone has all the updates necessary and if not, this must be done with sufficient time days before the flight. Afterward, the pilot proceeds to inspect all the parts of the drone to make sure everything is ready to go ahead with the flight. The pilot must be familiar with the equipment that is being used. Table 9 shows some recommendations observed after researching some manufacturers and drone manuals.

Table 9. Recommendations from Manufacturers of Drone Manuals

MANUALS	Be familiar with the manufacturer’s manual(s). Make sure the crew members understand the basic operations of the equipment.
PROPELLERS	The propellers are a fundamental part of the equipment. Make sure a thorough inspection is conducted to ensure they are in perfect condition for every flight. If the propellers are not in excellent condition, make sure to notify the RPIC and replace them immediately.
BATTERIES	Inspect all batteries before every flight. Make sure they are in peak conditions. Search for any damaged or swollen batteries; report immediately any damage.

	Estimate the number of batteries needed for the operation and have additional batteries as a preventive plan.
	Make sure all the batteries are fully charged before the flight.
	If possible, have an on-the-go charging station ready.
REMOTE CONTROL	Make sure the remote-control battery is fully charged.
	Verify that the available data storage space is enough to carry out the flight operation requirements.
CAMERA	Make sure the lenses are clean and in peak condition.
SOFTWARE	Before every flight, verify if the software of the equipment needs an update.

	Make sure all the necessary updates are installed.
STORAGE	Verify the available space to store the data that would be collected.
	Have backup storage space available.

During the Flight

While operating the UAS, the remote pilot in command must have a prompt or checklist to ensure the safety of each member of the team during the flight; this list should be reviewed by all members of the team and is shown in Table 10.

Table 10. Checklist for During the Flight

	ITEM	
DURING	1	Interference/Manual Operations
	2	Challenges Encountered
	3	Data Collection
	4	Battery Level
	5	Crew Members

Items #1 and #2: Interference/Manual Operations and Challenges Encountered

Every drone must always have at least one visual observer. The visual observer must be always attentive to the drone for any interference. At least one crew member must oversee keeping watch of all the personal belongings and all the equipment during the operation. The pilot can alter the flight plan if they encounter challenges such as a change in weather conditions, visibility problems, technical difficulties, or any other unexpected situation. The team must always maintain proper contact during the flight and use communications devices if they are far away from each other. As part of good crew resource management, a crew member must prepare for the weather conditions (e.g., have water available on a hot day). The pilot should have a backup plan in case the weather conditions change drastically. Most importantly, the crew members must be prepared for any situation that can represent a risk to the flight operation.

Items #3: Data Collection

It is essential to have a layout of the procedure detailing what data will be collected and how it will be collected. At least one crew member must monitor this procedure and make sure everything is followed according to plan. An example of a layout of data collection is shown in Table 11.

Table 11. Example of Data Sheet for the Procedure

				Treatments				
Time	Distance from Road, ft	Altitude (drone), ft	Camera Angle					Comments

For the flight operation shown in Table 11, the thermal filters for the drone's camera (i.e., treatments) were investigated at different levels of drone altitude, distance from the road, and camera angle; as such these were incorporated in the table. It is recommended to always have a column for comments to record any situation that could affect the study, such as strong wind gusts, recharging the batteries, and so on.

Items #4 and #5: Battery Level and Crew Members

The pilot must always monitor the battery level of the drone during the flight to ensure the safety of the operation, especially in tropical conditions since hot temperatures can reduce the battery use time. The pilot and the team must follow the procedure established for data collection. In case of an incident, the pilot can deviate from the procedure if needed. The crew members must be prepared for the weather conditions during the operations. In case the pilot feels that they are not able to fly the UAS (e.g., due to a heat stroke), they must warn the crew members so that they can ensure the safety of the pilot as well as the equipment. Figure 25 shows the response of the crew members in case the pilot becomes incapacitated during the flight. There should always be a person who oversees the safety of all the members during the operations.

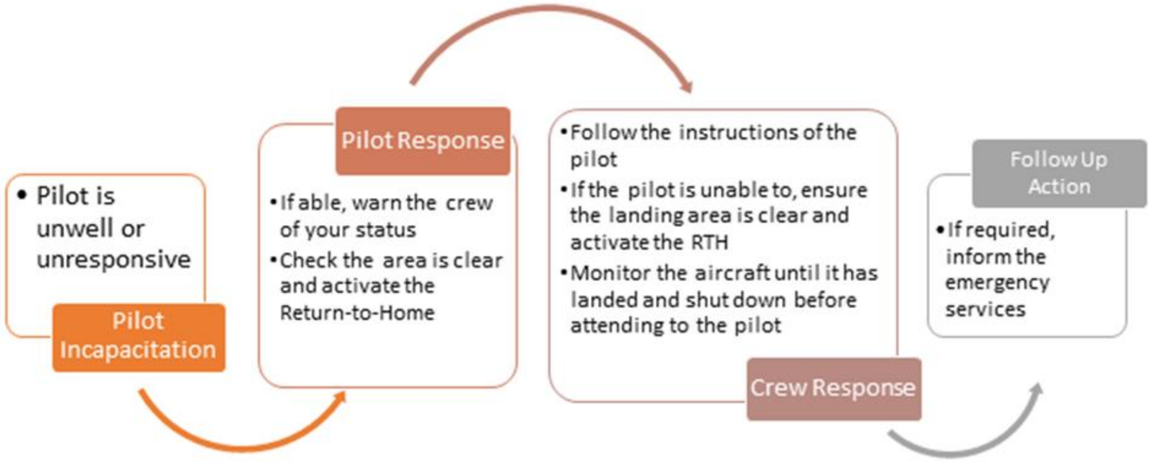


Figure 25. Crew members' response if pilot becomes incapacitated.

After the Flight

After operating the UAS, the remote pilot in command must have a prompt checklist to ensure the safety of each member of the team. This list should be reviewed by all members of the team and is shown in Table 12.

Table 12. Checklist for After the Flight

	ITEM	
AFTER	1	Drone Inspection
	2	Storage Considerations
	3	Incidents
	4	Flight Report
	5	Data Analysis

Items #1 and #2: Drone Inspection and Storage Considerations

When finalizing operations, all the equipment used, as well as its components, must be checked and stored. It is suggested to keep a log of all the equipment and components used for each flight and provide the appropriate maintenance. The manufacturer's manuals include recommendations for correct maintenance procedures; they also indicate how to properly store the equipment.

Items #3 and #4: Incidents and Flight Reports

In case of any incidents that could affect the drone operation, such as the drone impacting another object or a broken propeller, a report must be completed with a detailed explanation of what occurred. The report must include the people involved and their recollections of the incident. It is important to know that if the cost to replace or repair the damage caused by the incident exceeds the limits established in 14 CFR Part 107, the incident must be reported to the FAA. The RPIC must use the *FAADroneZone* website (FAA, 2022b) to file the report. After every drone flight operation, the remote pilot will draft a report that details everything done during the flight.

Item #5: Data Analysis

Unmanned aerial vehicles could be used to transmit data in real time; however, data can also be recorded so that it can be analyzed later. The videos can be analyzed using several programs as well as manually by a visual observer. The data collected from the videos could then be used for different study purposes. It is recommended to analyze the data as soon as possible to determine if the purpose of the study was achieved and that there is no need to repeat the data collection process (i.e., return to collect additional data).

Chapter 6. Conclusions and Recommendations

The second year of the research project *Corridor-wide Surveillance Using Unmanned Aircraft Systems* focused on two main tasks: evaluating the performance of vehicle detection and updating the protocol for using UAS for traffic monitoring activities according to the lessons learned in the field activities.

For the evaluation of the performance of the vehicle detection algorithm, a framework was developed that consisted of four steps. The first step entails defining and developing a proper flight plan for the data collection activities, once the data collection sites are identified. The team developed a flight plan template for this purpose, which was helpful for the data collection activities. The second step in the framework is the data collection stage; this stage involves going to the field and taking videos using UAS for them to be analyzed later. In this step, the checklists developed for before, during, and after the flight operations (and detailed in Chapter 5 of this document) are essential. After the data is collected, the videos are run through a vehicle detection algorithm (third step); for this phase of the project, the algorithm used was based on background subtraction methods. Finally, the data validation process comes to play in the fourth step: vehicles illustrated in the frame are manually counted and compared with how many vehicles are being detected by the algorithm as indicated by bounding boxes.

A series of data collection activities took place in several highway segments in Puerto Rico. These activities helped update the protocol (especially with the lessons learned) and in developing the methodology for the final collection activity. The purpose of the last data collection event was to test the performance of a background subtraction algorithm for vehicle detection. The performance of the algorithm, which was developed by the USF NICR team, was based on the percentage of vehicles detected. The variables of drone elevation and distance from the road were examined as it was hypothesized that these could influence vehicle detection rates. The results of the validation analyses show that a high detection rate with an accuracy of up to 92% can be reached using the background subtraction algorithm. Treatments where the drone was located at lower values for distance of the road (DFR) showed higher detection rates, meaning that positioning the drone closer to the road, though not to distract drivers, is associated with higher percentages of vehicles detected by the background subtraction algorithm evaluated. The results of the ANOVA test confirmed this, as DRF was the only main factor to be significant at the 95% confidence level. The interaction plots indicated that, depending on drone type, the elevation can affect the detection rate. However, results showed decreased detection rates in some treatments. Some factors that can be responsible for this observance could be related to high traffic densities, colors of vehicles that blend with the pavement, and obstructions to the roadway.

The protocol developed for the use of UAVs in traffic monitoring offers convenient information in the form of checklists to aid the RPIC and the team members for three stages during a flight operation: before, during, and after the flight. The field activities conducted during this phase of the project helped in updating this protocol based on the lessons learned. In addition, the protocol details the steps that must be followed for several scenarios that can be incorporated into future studies on the use of drones in transportation applications.

During the data collection activities, the team identified relevant issues that researchers and transportation professionals should be aware of when using drones for collecting roadway and traffic data. These issues and their respective recommendations are:

- There could be both connectivity and visibility problems between the drone, remote control, and the RPIC, either due to great distances or due to road alignment changes such as horizontal curves.

It is therefore recommended to perform visibility and communication (connectivity) tests before conducting any studies.

- Depending on the capabilities of the drone, it can experience difficulties transmitting a clear image at long distances. To mitigate this situation, the RPIC and the visual observer(s) must place themselves in a strategic area where the drone is close to both the area of interest and themselves.
- When operating a drone in a long or curved segment or mountainous terrain, one should consider that the drone must always be visible to at least two crew members. A minimum of two visual observers is recommended for these types of highway segments. In addition, it is recommended to use portable two-way radios (i.e., Walkie-talkies) or other communication devices for continuous contact between the team members.
- The entire team should use safety vests and helmets per federal regulations when operating alongside a freeway corridor.
- Hot temperatures reduce the battery life of drones. It is recommended to have additional batteries or a charging station on site.
- Wind gusts may affect the stability of the drone during operation. If a drone is tilted mid-flight, it might be necessary to land the drone and recalibrate it before resuming flight operations. It is also recommended to check the wind speed and the presence of wind gusts for the day when the flight operations will take place.
- Be prepared to cancel the flight operation due to unexpected weather conditions. Even if weather apps are checked daily, their predictions can vary.
- When investigating the distance from the road and the drone's elevation to collect traffic data, it is best to set a range of values for these variables before data collection. It is recommended to try different combinations on test sites before collecting data on the study site to narrow down the most appropriate combinations.
- The camera angle is determined once the drone is placed in its position to get the best possible view of the highway.
- For night conditions, it is best to determine the points of reference during daylight. The team members should verify that the flashing beacons on the drone are functional before deployment.
- Every flight operation has lessons learned. It is recommended to document all experiences and review them with the team members to improve future operations.

From the experiences of the two main tasks (algorithm performance evaluation and update of the protocol), the other objectives established for the second phase of the project were achieved. The research team was able to identify the challenges of using UAVs for traffic monitoring; these barriers were documented, and recommendations were offered. Finally, the collaboration between the research team and key personnel from the Traffic Management Center in Puerto Rico strengthened as a result of these two entities being in constant communication for the data collection activities.

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