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The Application of Unmanned Aerial Systems In Surface Transportation - Volume II-D: Development of UAS Emergency Service Drone Network for Use in Surface Transportation

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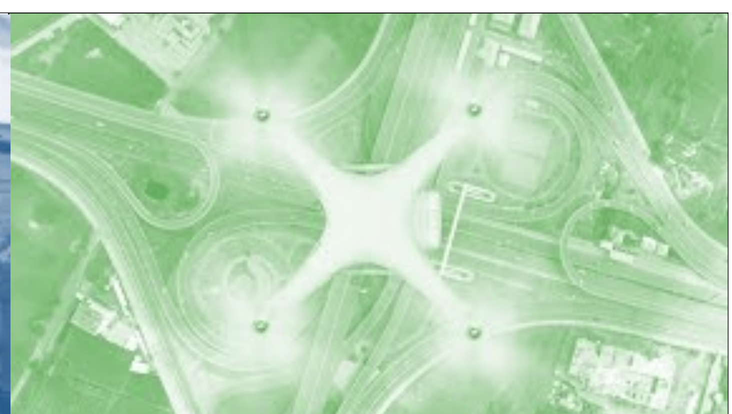

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16. Abstract

This report provides a literature review on applications of UAS for emergency response and presents a procedure to develop a UAS network for emergency response in Massachusetts. The literature review focuses on public policy and administration aspects of UAS and the growing interest in applying UAS for emergency response, including traffic incident management and emergency preparedness and response. An assessment of MassDOT needs for UAS in emergency response is provided. On the procedure of developing a UAS network for emergency response, the research team uses several geospatial datasets related to Massachusetts, including historical traffic incident (from 2013 to 2017) and natural disaster data (e.g., hurricanes and flood zones). A two-step method is proposed to minimize the cost and maximize the coverage of a UAS network for emergency response: (1) Identify incidents that are well-suited for using UAS; and (2) develop an optimization algorithm to determine UAS network parameters, including the number of UAS stations needed and their locations. We find that the UAS network parameters vary with the station coverage radius assumption and the target coverage rate. Moreover, the UAS network developed for traffic incidents can provide a satisfying coverage on the natural disaster events studied.

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Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Massachusetts Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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Executive Summary

Unmanned Aerial Systems (UAS) —commonly referred to as “drones”— have emerged over the last two decades as a promising technology with a wide range of applications for military and police forces, emergency and public services, commercial enterprises, and recreational users. This research focuses on UAS applications in emergency response. It aims to provide a comprehensive review of existing work of using UAS for emergency response and to develop a UAS network to facilitate such UAS applications. This report documents the research efforts, and consists of two main components: the first one is the literature and the second one presents a procedure to develop a UAS network for emergency response in Massachusetts. This procedure is very flexible and can be adapted for applications in other states.

This report begins with providing the background of the research task and objectives in Chapter 1. Chapter 2 summarizes the findings of the literature review, which focuses on the public policy and administration aspects of UAS applications in the United States, particularly in Massachusetts. The Chapter also looks at recent UAS applications for emergency response both nationally and internationally, key issues related to the planning of UAS emergency response networks, as well as the current UAS practices regarding emergency response of both MassDOT and the Massachusetts Emergency Management Agency (MEMA). The literature review suggests that current federal policies encourage the exploration of using UAS for different public purposes, and there has been growing interest in applying UAS for emergency response, including traffic incident management and emergency preparedness and response. Based on the literature review, an assessment of MassDOT needs for UAS in emergency response is performed and the results are also included in Chapter 3.

Chapter 3 presents the procedure to develop a UAS network for emergency response. It begins with introducing the geospatial datasets used, including historical traffic incident and natural disaster data (e.g., hurricanes and flood zones). Traffic incidents data from 2013 to 2017 is kindly provided by MassDOT and is used as one of the inputs for the proposed analysis procedure. Based on the data, a two-step method is proposed to minimize the cost and maximize the coverage of a UAS network for emergency response. The first step is to identify incidents that are well-suited for using UAS and the second one develops an optimization algorithm to determine UAS network parameters, including the number of UAS stations needed and their locations. This research further applies the developed algorithm to the applicable incidents identified, to find optimal UAS network parameters given some assumptions regarding the coverage area of each UAS station (i.e., station coverage radius). Not surprisingly, it is found that the UAS network parameters vary with the station coverage radius assumption and the target coverage rate. Specifically, the number of UAS stations needed increases with the target coverage rate but decreases with the station radius. The proposed procedure is designed to be generic and flexible. For practical UAS network decision-making with different traffic incident types and a heterogeneous fleet of UAS, the procedure can still be applicable with minor modifications.

Finally, Chapter 4 summarizes the key findings from this research task and briefly discusses future research needs.

In short, this report is an in-depth look at and analysis of Massachusetts “highway” incidents, particularly as they relate to the potential for drone use. This analysis was an important step in the MassDOT Drone Program’s incident response development and an aid to pre-planning for drone services of this type. By analyzing the incident types, severities, frequencies, and locations of highway incidents over the period April 2013 to October 2017, the research team has defined the concept of “key stations” that would “see” the largest number of incidents for a given drone launch point. 26 of these would be able to cover 95% of incidents statewide, and 13 of these would cover 81%. The key takeaways of this research are:

- “Key station” concept definition, station locations, and utility analysis;
- Decomposition of highway incidents over 4+ year period to serve as a reference for future drone utility assessments; and
- Overlay of “other disaster events” to investigate the coupling of environmental disasters (hurricanes, flooding) as they affect drone response capability and Massachusetts transportation infrastructure.

For the overall value of this research, while only an initial step in developing a robust statewide drone incident response capability, it provided key products and conclusions that will allow the drone team to build on the takeaways mentioned above. Since the delivery of the draft report, the research has been referenced and cited several times in support of subsequent drone team projects.

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List of Acronyms

Acronym	Expansion
BVLOS	Beyond-Visual-Line-Of-Sight
COA	Certificates of Waiver or Authorization
CA	Continuous Approximation
FAA	Federal Aviation Administration
FEMA	Federal Emergency Management Agency
NOAA	National Oceanic and Atmospheric Administration
NPG	National Preparedness Goal
NP-hard	Non-deterministic Polynomial-time Hardness
MVA	Multi-Vehicle Accident
PPD-8	Presidential Policy Directive 8
RF	Radio Frequency
SGI	Special Government Interest
UAS	Unmanned Aerial Systems

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1.0 Introduction

Unmanned aircraft systems (UAS) offer many potential opportunities to assist with surface transportation needs within the Massachusetts Department of Transportation (MassDOT), as well as at other state agencies. One promising application is to use UAS for emergency services and disaster relief. MassDOT and the Massachusetts Emergency Management Agency (MEMA) are both looking for information that will help them develop a better understanding of UAS emergency management support capabilities, including the ability to obtain rapid and critical post-disaster information to support both lifesaving and damage assessment services.

1.1 Objectives

The main objective of this research task is to conduct a literature search and detailed synthesis of the application of UAS in emergency response and disaster damage assessment services on surface transportation networks.

The research task (Task D of the MassDOT-funded UAS study) had two deliverables:

- Deliverable D1: Technical Memo on Literature Review
- Deliverable D2:
    a) A GIS-based hotspot map of previous incidents and natural disasters in Massachusetts.
    b) An initial UAS deployment network for emergency response.
    c) Python code used to compile data and create the initial UAS deployment network.
    d) A report describing the methods to identify applicable events for UAS missions, development of the UAS network, and the potential ways to use the UAS network for decision-making.

As Task D progressed, the research team received feedback from MassDOT and MEMA. Based on such feedback, the team deviated slightly from the original Scope of Work (Tasks D2 and D3) and revised Deliverable D2 to be more practical and implementation-focused.

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2.0 Literature Review and Assessment of MassDOT Needs

In this section, we first review relevant literature in three areas: policy and administration aspects of UAS applications (Part 2.1); existing applications of UAS for emergency response (Part 2.2); and UAS for emergency preparedness (Part 2.3). We also report our findings from a mid-stage project discussion with MassDOT officials and the questions they have regarding implementing UAS for emergency response in Massachusetts (Part 2.4). We close the section with some reflections from the review.

2.1 Policy and Administration Aspects of UAS Applications

Unmanned Aerial Systems (UAS) — commonly referred to as “drones” — have emerged over the last two decades as a technology with applications for military and police forces, emergency and public services, commercial enterprises, and recreational users. For any report providing advice on the possible use for emergency services, it is important to first provide an overview of the current legal, policy, and administrative environments surrounding UAS technologies with a particular lens toward use in emergency situations.

2.1.1 Summary of Current Federal UAS Policies

Increased demand for airspace, driven by the rapid emergence of UAS technology, pushed the United States Congress, in 2012, to pass the Federal Aviation Administration’s (FAA) Modernization and Reform Act of 2012 (Public Law PL 112-95). This Act requires the development of published rules for drone operation in domestic airspace by 2015 (*1*). The FAA regulations that emerged, allow the recreational small drone market to continue to proliferate and require commercial and public entities to seek FAA authorization before testing and utilizing drones for various applications.

There are several methods in place for private, commercial, and state or local entities to gain permission to operate UAS. The FAA publishes guidance online for model aircraft and small UAS weighing up to 55 pounds. Agencies in Massachusetts interested in operating UAS should be familiar with Part 107 Small UAS Rules, Certificates of Waiver or Authorization (COA), and Special Government Interest (SGI) expedition waivers (*2*).

2.1.1.1 UAS

Drones weighing 0.55 pounds or less typically reach a maximum height of 100 feet and cannot operate beyond visual line of sight (BVLOS) of the operator and wireless radio controller. These drones are frequently flown by hobbyists and other amateurs, including children. Due to the weight and size limit, it is unlikely that these drones will interfere with air traffic in surrounding air space and airports. These operators do not need to be certified

UAS pilots but should still know the rules published for hobbyists with drones as heavy as 55 pounds (*3*).

2.1.1.2 UAS Requiring a Certified Pilot; Small UAS Rule (14 CFR 107) - Part 107

Emergency and public service organizations throughout the country can operate drones under the Part 107 rules (*4*), or seek authorizations and waivers supporting regular and emergency UAS operations. In general, the FAA notes that "most of the restrictions… are waivable if the applicant demonstrates that … operation can safely be conducted under the terms of a certificate of waiver."

To operate under Part 107, the operator must attain a remote pilot certificate from the FAA, register the UAS as a 'non-modeler,' and follow the Part 107 rules briefly summarized below and in Table 2.1.

"To obtain a remote pilot certificate, an individual must be 16 years of age or older; be able to read, speak, write, and understand English; be in physical and mental condition to operate a small UAS; and pass an aeronautical knowledge exam at an FAA-approved knowledge testing center. The approved license must be accessible by the pilot and during all UAS operations and is valid for two years." (FAA Part 107)

Table 2.1: Summary of FAA Part 107 flight operation rules

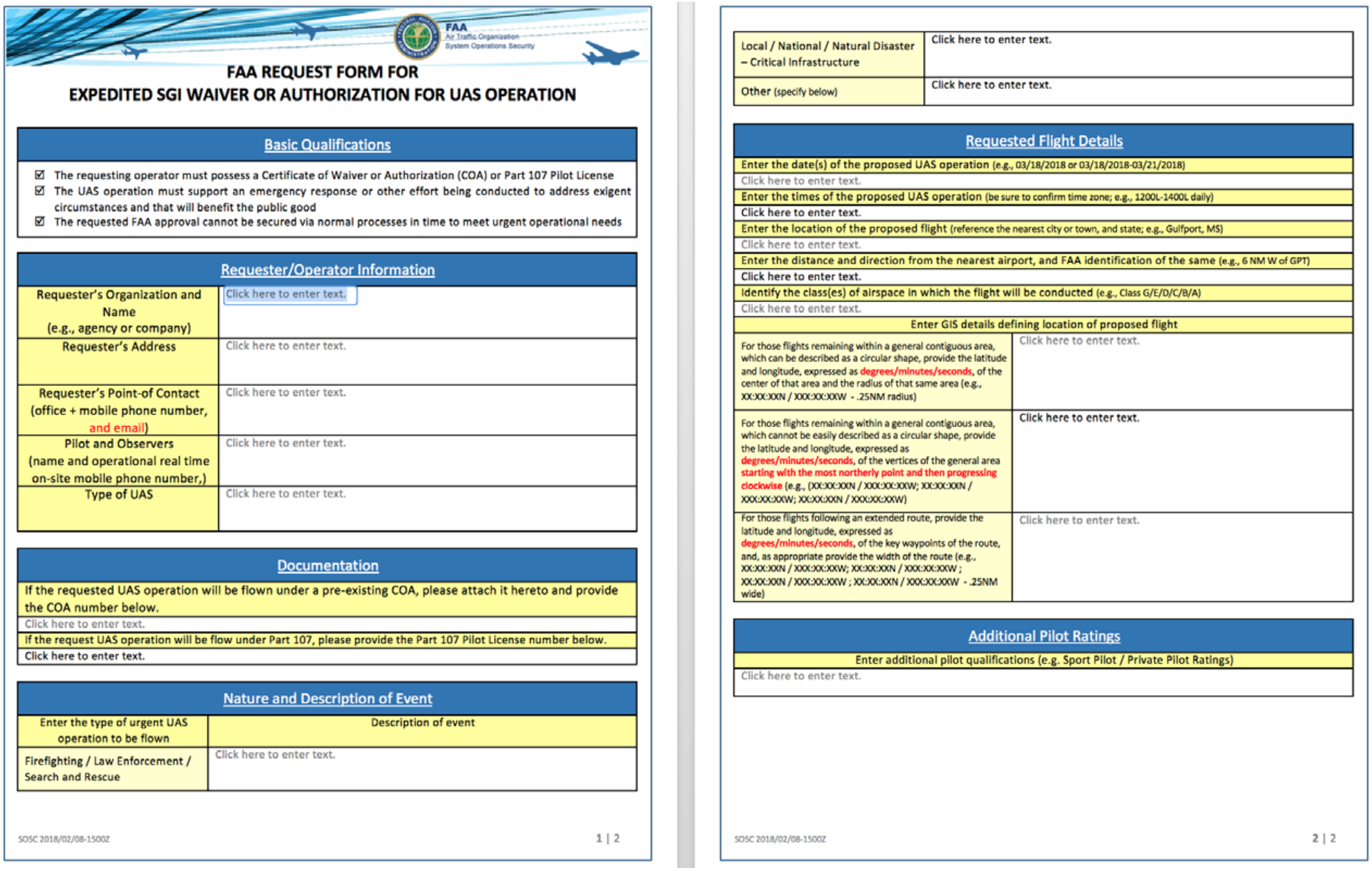
Rule #	FAA Part 107 Flight Operation Rules
1.	Fly in Class G airspace (otherwise unrestricted airspace below 1,200 feet)
2.	Keep the unmanned aircraft within visual line-of-sight
3.	Fly at or below 400 feet
4.	Fly during daylight or civil twilight
5.	Fly at or under 100 mph
6.	Yield right of way to manned aircraft
7.	Do not fly directly over people (without permission)
8.	Do not fly from a moving vehicle, unless in a sparsely populated area

2.1.1.3 Certificate of Authorization

State and local officials can apply to the FAA for a Certificate of Waiver or Authorization (COA) (*5*). The flight rules are identical to those in Part 107. Registering for a public COA includes reporting the type of UAS program and training completed to the FAA.

2.1.1.4 Special Government Interest (SGI)

The FAA may expedite approval for emergency drone operations under a Special Government Interest (SGI) process (*6*). To be eligible for an SGI waiver, an individual must be an existing Part 107 Remote Pilot with a current certificate *or* must have an existing Certificate of Waiver or Authorization (COA). If approved, an amendment will be added to the existing COA or Remote Pilot Certificate, which authorizes the pilot to fly under certain conditions. SGI waiver-seekers need to complete an Emergency Operations Request Form (Figure 2.1), and in return will receive the cooperation and coordination assistance of the FAA.



FAA

Air Traffic Organization

System Operations Security

FAA REQUEST FORM FOR

EXPEDITED SGI WAIVER OR AUTHORIZATION FOR UAS OPERATION

Basic Qualifications

- ☑ The requesting operator must possess a Certificate of Waiver or Authorization (COA) or Part 107 Pilot License
- ☑ The UAS operation must support an emergency response or other effort being conducted to address exigent circumstances and that will benefit the public good
- ☑ The requested FAA approval cannot be secured via normal processes in time to meet urgent operational needs

Requester/Operator Information

Requester's Organization and Name (e.g., agency or company)	Click here to enter text.
Requester's Address	Click here to enter text.
Requester's Point-of Contact (office + mobile phone number, and email)	Click here to enter text.
Pilot and Observers (name and operational real time on-site mobile phone number,)	Click here to enter text.
Type of UAS	Click here to enter text.

Documentation

If the requested UAS operation will be flown under a pre-existing COA, please attach it hereto and provide the COA number below.
Click here to enter text.
If the request UAS operation will be flow under Part 107, please provide the Part 107 Pilot License number below.
Click here to enter text.

Nature and Description of Event

Enter the type of urgent UAS operation to be flown	Description of event
Firefighting / Law Enforcement / Search and Rescue	Click here to enter text.
Local / National / Natural Disaster – Critical Infrastructure	Click here to enter text.
Other (specify below)	Click here to enter text.

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Requested Flight Details

Enter the date(s) of the proposed UAS operation (e.g., 03/18/2018 or 03/18/2018-03/21/2018)
Click here to enter text.
Enter the times of the proposed UAS operation (be sure to confirm time zone; e.g., 1200L-1400L daily)
Click here to enter text.
Enter the location of the proposed flight (reference the nearest city or town, and state; e.g., Gulfport, MS)
Click here to enter text.
Enter the distance and direction from the nearest airport, and FAA identification of the same (e.g., 6 NM W of GPT)
Click here to enter text.
Identify the class(es) of airspace in which the flight will be conducted (e.g., Class G/E/D/C/B/A)
Click here to enter text.

Enter GIS details defining location of proposed flight	
For those flights remaining within a general contiguous area, which can be described as a circular shape, provide the latitude and longitude, expressed as degrees/minutes/seconds, of the center of that area and the radius of that same area (e.g., XX:XX:XXN / XXX:XX:XXW - .25NM radius)	Click here to enter text.
For those flights remaining within a general contiguous area, which cannot be easily described as a circular shape, provide the latitude and longitude, expressed as degrees/minutes/seconds, of the vertices of the general area starting with the most northerly point and then progressing clockwise (e.g., (XX:XX:XXN / XXX:XX:XXW; XX:XX:XXN / XXX:XX:XXW; XX:XX:XXN / XXX:XX:XXW)	Click here to enter text.
For those flights following an extended route, provide the latitude and longitude, expressed as degrees/minutes/seconds, of the key waypoints of the route, and, as appropriate provide the width of the route (e.g., XX:XX:XXN / XXX:XX:XXW; XX:XX:XXN / XXX:XX:XXW ; XX:XX:XXN / XXX:XX:XXW ; XX:XX:XXN / XXX:XX:XXW - .25NM wide)	Click here to enter text.

Additional Pilot Ratings

Enter additional pilot qualifications (e.g. Sport Pilot / Private Pilot Ratings)
Click here to enter text.

SOSC 2018/02/08-1500Z 2 | 2

Source: U.S. Federal Aviation Administration, *Certificates of Waiver or Authorization (COA)*, March 9, 2018. *(5)*

Figure 2.1: FAA special government interest (SGI) waiver request form

2.1.1.5 Section 333 Exemptions
Commercial entity applications such as real estate appraisals, bridge inspections, and movie cinematography can all apply for permission to use the national air space. These authorizations are granted under Section 333 Exemptions (*7*). These commercial use exemptions applied to small UAS and are granted on a case-by-case basis. Typically, the FAA approval process for a Section 333 Exemption takes up to 90 days.

2.1.2 Summary of Massachusetts UAS Policies

No statewide law has been added to the federal rules. However, some towns and other governmental entities have implemented additional UAS restrictions, as summarized in Table 2.2. Some municipalities, such as the Towns of Chicopee and Holyoke, passed ordinances to restrict UAS usage in their jurisdictions, but these are likely an overreach as the FAA has preemptive authority on the national air space. In an earlier court case, a federal judge in Massachusetts overturned key parts of a Town of Newton ordinance, which restricted where drones could fly; the judge stated that the town would need to re-draft the ordinance to adhere to federal law (*8*).

Table 2.2: Summary of UAS codes in Massachusetts

Municipality	Ordinance
Town of Barnstable (*9*)	Banned UAS on beaches, following the lead of the Cape Cod National Seashore
Quabbin Reservoir (MA Dept of Conservation and Recreation) (*10*)	Restricts UAS in the Quabbin Reservoir without prior written approval
Cape Cod National Seashore (U.S. National Park Service) (*11*)	Bans UAS at Cape Cod National Seashore beaches
Town of Chicopee (*12*)	UAS cannot fly or take off/land on private property without prior written consent; reinforces 5 mile radius to local airfield
Town of Holyoke (*13*)	UAS cannot fly or take off/land on private property without prior written consent

2.1.3 Discussion: Key Policy and Administration Topics

Beyond the legal framework for operating UAS in Massachusetts, there are important ethical and administrative issues on how to best implement these systems as discussed below.

2.1.3.1 Privacy
Privacy has an evolving definition. In public service, UAS applications may inadvertently capture private information (*14*) (e.g., facial images, vehicle license plates) in different situations, such as field surveys and law enforcement use. To date, there is little relevant guidance on managing the data collected, including how to store the data, how long to keep

the data, and who should have access to the data (*15*). State and local officials should explore and develop policies for managing UAS collected data in an appropriate way.

2.1.3.2 Federalism

Many Americans support state and local initiatives to exercise authority over UAS use in their communities (*16*), including organizations such as the United States Conference of Mayors, and the National Governors Association (*17*). The National Conference of State Legislatures tracks UAS policies closely (*18*). The Drone Federalism Act of 2017 introduced in the 115th Congress in May 2017 sought to increase local control over the skies for UAS operations (*19*). Many of the concerns focus on recreational and commercial UAS, not emergency applications. While the United States Congress and the FAA support states using UAS for many applications, the development of UAS regulations at the local levels could introduce future change for potential UAS applications.

2.1.3.3 Safety

More UAS in the skies increase the likelihood of collisions both on the ground and in the air with vehicles, infrastructure, and people. Unmanned aircraft traffic management is "regarded as a key component of safe UAS integration into the national airspace system" (*20*). Currently, the FAA restricts UAS flights above people (without consent) or automobile traffic. Research also supports this restriction as it was found that UAS can contribute to driver distraction (*21*). Public safety will remain a constant concern in UAS applications. To enhance safety, one potential option could be to set a high standard on UAS pilot certificates. The FAA maintains a legal limit threshold for UAS operators, which includes an age requirement and an online test. Currently, someone without any UAS experience can be certified to operate drones. This is a low standard compared to US Air Force UAS operators who are all trained pilots (*22*). Massachusetts should consider mandating a higher level of training for its UAS pilots, especially those who may pilot a drone during an emergency.

2.1.3.4 Spectrum Allocation

All drones for commercial usage are controlled with communication systems utilizing radio frequency (RF) spectrum, which are currently allocated for AM/FM transmissions and used by the United States Department of Defense (*23*). There are ongoing discussions about reclassifying portions of the RF spectrum for emergency service use. If reallocation occurs outside the current frequency range, states will need to accommodate this change.

2.1.4 Recommendations

The FAA has the support of the United States Congress and the American people, suggesting that UAS technologies will become integrated into the national airspace in time. In this supportive environment, state policymakers are open to exploring the many applications of drones. The current guidelines are likely to remain valid at least in the short-term. Therefore, Massachusetts should consider taking steps to comply with, and master the FAA guidance of Part 107 (the Small UAS Rule) as small crafts are the most common drones available. MassDOT should also establish a system to allow the rapid filing of Special Government Interest flight waivers. Additionally, we recommend that Massachusetts create a pilot training and testing program beyond the standard requirement of an FAA 107 test to train a cohort of skilled and knowledgeable UAS pilots that can safely operate drones for emergency service. We also recommend that Massachusetts policymakers continually address cybersecurity issues related to UAS. The Commonwealth of Massachusetts should consider establishing a statewide data management system for UAS data to protect privacy. Such a management system should explicitly define what data can be used and how, who has access to the data, how to securely store the data, and when to delete it. This statement relates to a separate research task, Task F, of the larger MassDOT UAS study, examining potential applications of UAS in surface transportation (please see Volume II-F for the Task F report).

2.2 Existing Applications of UAS in Emergency Responses

Drones are increasingly being used for emergency response related to natural disasters. In addition, many agencies are interested in exploring the potential of UAS for traffic incidents. This section contains the research team's review of existing UAS applications in these two areas.

2.2.1 UAS Applications for Natural Disasters

Table 2.3: Summary of drone application in natural disasters 2005-2017

Year	Natural disaster	Country	Name of drone	Application				
				A	B	C	D	E
2005	Hurricane Katrina Response(USA)	UAS	AeroViroment Raven	✓	✓			
			Evolution	✓	✓			
			iSENSYS T-Rex	✓	✓			
			Silver Fox	✓	✓			
2005	Hurricane Katrina Recovery(USA)	UAS	iSENSYS IP3			✓		
2005	Hurricane Wilma (USA)	UAS	iSENSYS T-Rex		✓	✓		
2007	Berkman Plaza II(USA)	UAS	iSENSYS IP3			✓		
2009	Laquila Earthquake (Italy)		Custom		✓	✓		
2010	Haiti Earthquake (Haiti)		Elbit Skylark		✓			
2011	Christchurch Earthquake(NZ)		Parrot AR. Drone			✓		
2011	Tohoku Earthquake (Japan)		Pelican			✓		
2011	Fukushima Nuclear Emergency (Japan)		Honeywell T-Hawk		✓	✓		
2011	Evangelos Florakis Explosion (Cyprus)		AscTec Falcon		✓	✓		
			AscTec Hummingbird		✓	✓		
2011	Thailand Floods (Thailand)		FIBO UAV-1	✓				
			FIBO UAV Glid	✓				
2012	Finale Emilia Earthquake(Italy)		NIFTi			✓		
2013	Typhoon Haiyan((Philippines)		Unknown			✓		
2013	Lushan Earthquake (China)		HW18 (Ewatt HoverWings)	✓	✓			
2013	Yuyao Flooding(China)		River-map UAV		✓			
2013	Boulder Colorado floods(USA)	UAS	Falcon Fixed		✓			
2014	SR350 Mudslides Response(USA)	UAS	DJI Phantom		✓			
			AirRobot 100		✓			
			Precision Hawk		✓			
2014	SR350 Mudslides Recovery(USA)	UAS	AirRobot 180				✓	

			Precision Hawk		✓		✓	
2014	Balkans flooding (Serbia,Bosnia-Herzegovina)		ICARUS custom		✓		✓	
2014	Collbran landside (USA)	UAS	Falcon Fixed	✓	✓			
			Falcon Hover	✓	✓			
2014	Yunnan China Earthquake(China)		Parrot AR Type 2		✓			
2015	Dar Es Salaam flood(Tanzania)		Ebee		✓			
2015	Nepal Earthquake(Nepal)		Unknown	✓	✓			
2015	Islands of Vanuatu cyclone Pam		Indago quadcopters		✓			
			Alliance hexacopters		✓			
			fixed wing Trimble	✓				
2016	Ecuador earthquake		Unknown		✓	✓		
2017	Southern California “Skirball” Wildfires (USA)	UAS	DJI Matrice 100		✓		✓	
2017	Mexico Earthquakes		Unknown	✓			✓	
2017	Hurricane Maria(USA)	UAS	Flying Cow(or Cell on Wings)					✓
2017	Hurricane Irma(USA)	UAS	DJI Phantom 3	✓				
			Parrot Disco		✓	✓	✓	
2017	Hurricane Harvey(USA)	UAS	Unknown		✓	✓	✓	
2017	Flooding and Mudslide in Sierra Leone		Unknown		✓		✓	
2017	Mudslide in Mocoa(Colombia)		Aeryon SkyRanger	✓	✓			

Notes: A=Search, B=reconnaissance and mapping, C=structural inspection, D=estimation of debris, E=Communication

The team examined recent (2005-2017) applications of UAS in seven types of natural disasters: fire, earthquake, flood, hurricane, volcanic eruption, landslide, and search and rescue operations. In those emergency situations, drones offered unique advantages in five dimensions, including search, reconnaissance and mapping, structural inspection, estimation of debris, and communication. Table 2.3 provides a summary of drone applications in natural disasters in recent years. Different types of drones, fixed wing and rotary, in different shapes, sizes, and capacities, were used in those events. The takeaway from this part of the review is that the characteristics and thus the capabilities of drones vary significantly and that agencies should select drones based on the desired applications.

2.2.2 UAS Applications Specifically for Traffic Incidents or Emergencies

According to a 2012 report on energy security and traffic congestion, bottlenecks (40%) and traffic incidents (25%) are the two most significant causes of traffic congestion in the United States (U.S.) (*24*). Transportation agencies and first responders are always looking for innovative and cost-effective ways for resolving traffic incidents.

Stevens (*25*) has reviewed the applications of UAS for traffic incident management (UAS-TIM) across different state Department of Transportation (DOT) agencies in the U.S. and applications in other countries. It was found that over ten state DOTs looked at, or were looking at UAS-TIM. Among them, a few canceled the projects due to constraints from FAA regulation, while several (such as in Virginia, Ohio, Wyoming, and Utah) conducted test flights to ascertain the feasibility of UAS for transportation applications. None of the state DOTs have made UAS-TIM a routine practice. Outside the U.S., Norway and China tested applications of UAS for crash mapping, but the projects did not result in implementation. Lee et al. (*26*) reviewed research that used full-size fixed-wing UAS for traffic surveillance and found that most studies had not yet been implemented in the field due to safety concerns and regulatory issues.

While field tests of UAS for traffic management are limited, two applications are worth noting. In a joint project with the Metropolitan Transit Authority of Harris County and Houston TranStar, Stevens and Blackstock (*27*) conducted a demonstration project to examine UAS-TIM. Through several live demonstrations on highways, they showed that UAS can meet three needs (incident monitoring, situational awareness, and quick clearance and recovery) in traffic accident management. The two UAS platforms used in their study were: (1) a DJI Inspire 2 (untethered) UAS with DJI ZENMUSE X5S gimbal and camera system; and (2) a CyPhy Works Persistent Aerial Reconnaissance and Communications (PARC) tethered UAS with Long-Range Zoom Electro-Optical/Infrared (EO/IR). This study confirmed that UAS can perform all of the following:

- Real-time confirmation of traffic incidents
- Real-time monitoring of traffic incidents
- Real-time monitoring of alternate routes
- Real-time monitoring of traffic incident queuing
- Real-time monitoring of secondary crashes

Stevens and Blackstock (*27*) expected that their UAS will fit into the traffic incident management system as “other traffic management” to provide and receive data about road network conditions, traffic images, and incident information. However, the report (*27*) also pointed out that the demonstration did not result in regular use of UAS for TIM in the partner agencies. This same report (*27*) also raised questions regarding UAS’s crash scene mapping capability and whether the quality of UAS images can meet the requirements of court proceedings.

Lee et al. (26) conducted a pilot study that used quadcopter drones for incident monitoring. In their framework, after a traffic incident occurs, the highway patrol team arrives at the scene and quickly deploys drones with first person view (FPV) cameras to capture the incident scene. The drones send the videos to the ground station through a 2.4 GHz radio communications link. Through a commercial 4G/LTE network, the videos are then transmitted to the remote Traffic Control Center (TMC). They found that the drones were beneficial in that they could cover a wide area, which enabled queue length and delay measurement, and that they could do instant incident monitoring. Lee et al. (26) identified several challenges related to the applications of UAS for traffic surveillance and incident monitoring. One was the limited drone flying time. They recommended more expensive quadcopters that can stay in the air for more than an hour with up to 55 pounds of payload. Another one was limited video quality: it was fine for manual data processing but not sufficient for video analytics. Lee et al.'s work also found that full-size UAS have not often been implemented for traffic surveillance in the field much due to safety concerns and regulatory issues.

Overall, it is well recognized that drones have great potential for traffic incident management, including for providing situational awareness, monitoring traffic, and collecting data. At the same time, there are challenges associated with these applications, including the quality of UAS images, payload capacity, flight endurance, and tolerance to wind and turbulence (*27*, *28*).

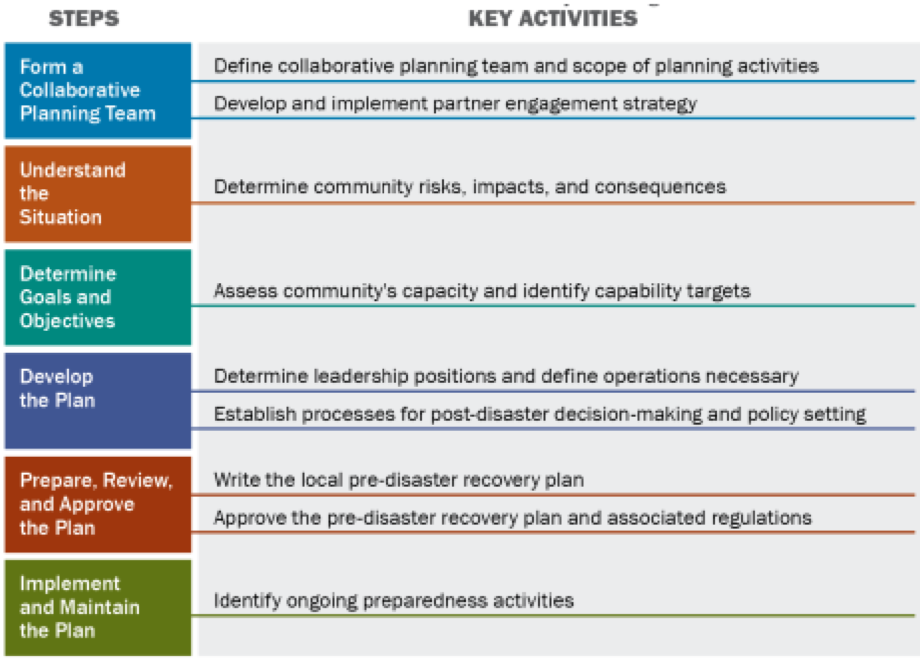
2.3 UAS for Emergency Preparedness

In this section, the research team reviews the planning aspects of UAS and UAS network design for emergency preparedness and response. We first provide an overview of federal disaster planning directives, a review of the literature available on UAS for disaster planning, and our recommendations to MassDOT on using UAS for both disaster and long-range transportation planning. After that, we review the literature on UAS network design, a critical component needed to enable UAS use, which can help plan and design a UAS network in Massachusetts for emergency preparedness.

2.3.1 Planning for Emergencies

Disaster planning in the United States is predicated at the federal level through Presidential Policy Directive 8 (PPD-8) (*29*), the Disaster Mitigation Act of 2000, and the Pre-Disaster Hazard Mitigation Act of 2010 (*30*). PPD-8 calls for the creation of a National Preparedness Goal (NPG) that supports preparedness efforts through guidance from the federal government to local governments via pre-disaster recovery planning (*31*). The intent of both the above statutes is essentially to provide a structure for the administration of disaster relief while controlling costs to the federal government from these efforts. States and local governments are able to seek federal funding for disaster relief and recovery upon meeting specific federal eligibility requirements, with development of a Federal Emergency Management Agency (FEMA)-approved hazard mitigation plan of the primary obligations.

For the federal government, effective pre-disaster planning is a process that integrates federal and local community planning objectives with the goal of facilitating decision-makers with the ability to reach sound decisions and investments. There are six (6) planning steps and nine (9) key recovery activities (Figure 2.2) that serve as guidance for pre-disaster planning activities (31). The six planning steps include (i) form a collaborative planning team, (ii) understand the situation, (iii) determine goals and objectives, (iv) develop the plan, (v) prepare, review, and approve the plan, and (vi) implement and maintain the plan.



Source: Federal Emergency Management Agency, *Pre-Disaster Recovery Planning Guide for Local Governments*, FD 008-03, 2017 (31, p. 27).

Figure 2.2: FEMA pre-disaster recovery guide for local governments

The plan-making process for preparing communities and organizations to adequately manage an emergency include operational plans (limited pre-disaster), policy plans (pre-disaster) and recovery plans (post-disaster). (*32*)

2.3.1.1 UAS for Disaster Planning

A critical component of all planning is the ability to acquire and analyze data. Planners have an extensive toolbox to draw from for various types of information that can be used to develop and test scenarios that are then presented to stakeholders for critique and refinement. Monitoring and appraisal of how plans are implemented is a tedious endeavor that only becomes more difficult over time, and a significantly cumbersome process when there is little or no current data available.

During disaster events, multiple parties have to make quick decisions to protect life and property. UAS can provide a low cost and quick turnaround option, that provides high-quality visual documentation of conditions as events unfold. UAS can be an important tool for disaster management for first responders, planners, and elected officials.

A uniform planned standard for the use of UAS across disciplines is not currently available. To date, no one has developed a comprehensive framework to explore the full extent of potential UAS applications as part of the pre-disaster planning process. As a result, present use of UAS for such planning is limited.

However, the potential of UAS for disaster applications is worth noting. Drones can provide transportation decision-makers with needed aerial support in areas and situations where it is too dangerous to deploy human assets to collect time-sensitive information. Kim and Davidson (*33*), conducted an analysis of how UAS can support critical transportation needs in disaster response scenarios by providing real-time video and photographic imagery of roads blocked by debris from downed trees, collapsed buildings, power lines, and so forth, to help determine which roads are passable for emergency response teams and which are possible evacuation routes.

2.3.1.2 Disaster Planning for MassDOT

Life shows that those with backup plans tend to recover and adapt from hardship at a faster rate than those that have not made hazard planning a priority. One of the lessons learned from Hurricane Maria in Puerto Rico in 2017 was that, when the hurricane made landfall, local and regional government agencies were all alone until the deployment of the Federal Emergency Management Agency and the Commonwealth of Puerto Rico rescue and recovery resources that took place only after weather conditions returned to normal.

For MassDOT, there could be significant problems if a hurricane like Maria ever made landfall in Massachusetts. The disruptions caused by recent snowstorm events (Nemo in 2013, and Juno in 2015) affected not only Massachusetts but the entire New England region. It is unrealistic to expect that there will be a plan for every single situation. However, without a contingency strategy in place, minor problems can escalate and affect multiple systems and networks beyond those under MassDOT's control.

The research team has the following recommendation to MassDOT: Incorporate the use of UAS as a planning and analysis tool for disaster management, with MassDOT's Aeronautics Division acting as the main entity within MassDOT to administer and deploy UAS resources. UAS can be used to identify crucial pressure points in the critical infrastructure in a relatively short period of time prior to and after extreme weather events. Such valuable information could make a dramatic difference for returning life to normal for millions of people. UAS will be additionally valuable if, and when, they become a part of a comprehensive disaster planning strategy.

2.3.2 UAS Network Design for Emergency Preparedness

In the application of UAS for emergency situations, one critical factor is the UAS network design. Often multiple emergent events happen simultaneously or in a very short time period, which then requires a resilient UAS network that can handle multiple events in an extensive area.

Erdelj et al. (*34*) identified several networking-related research challenges when using UAS for disaster management: (1) creating and maintaining the information relay network; (2) in-network data fusion; (3) handover issues; (4) UAS physical constraints compromising the communication; (5) automated network maintenance and UAS charging; (6) UAS network security and robustness; (7) UAS failure handling; and (8) privacy and trust issues.
To the best knowledge of the research team, existing investigations on the use of UAS networks for emergency preparedness has only been conducted in academia and there is no

example yet put into practice. Nevertheless, a review of the academic findings may shed light on optimal UAS network design if MassDOT is to implement this UAS application.

2.3.2.1 UAS network architecture design

Morgenthaler et al. (*35*) introduced UAVNet, an architecture and prototype implementation of an autonomously deployable temporary and flying Institute of Electrical and Electronics Engineers (IEEE) 802.11s Wireless Mesh Network. The central communication components are the wireless mesh nodes carried by UAS. The devices on the ground are divided into two groups: the end systems intending to communicate with each other and the monitoring and configuration devices, such as iPhones or iPads.

Erdelj et al. (*34*) presented a new perspective for classifying disasters and introduced a theoretical framework of wireless sensor-actor network architectures that can be effective in each of these cases for disaster management. In the example scenario, multiple deployed sensors, including drones and others, collect physical information (here, the water level at the monitored bank and vibration/displacement on the mountainside) and forward this for recording and storage at a centralized server location. The Wireless Sensor Network integrates different sensors with the monitoring displacements of landslides and triggers the alarm in the case of debris flow. The stand-by UAS can be called into active operational service. Schwab (*32*) designed another scenario in which the UAS form an independent network without support from the ground sensors. Multiple UAS stations that are strategically deployed over a wide geographical area can provide certain guarantees that some parts of the UAS infrastructure would operate even after a disaster occurs.

2.3.2.2 Optimization of UAS Network Operation

Bupe et al. (*36*) propose a fully autonomous system to deploy UAS as the first phase disaster recovery communication network for wide-area relief. An automation algorithm was developed to control the deployment and positioning of UAS based on a traditional cell network structure utilizing seven-cell clusters in a hexagonal pattern using MAVLink. The distributed execution of the algorithm is based on centralized management of UAS cells through assigning higher ranked UAS referred to as supernodes. The algorithm autonomously elects supernodes based on weighted variables and dynamically handles any changes in the total number of UAS in the system. This system represents a novel approach for handling a large-scale autonomous deployment of a UAS communications network. Bupe's proposed autonomous communication network was verified and validated using software simulations and physical demonstrations using identical quadrotor UAS.

Chowdhury et al. (*37*) proposed a Continuous Approximation (CA) model to determine the optimal locations for the distribution centers with their corresponding emergency supply inventories and service regions. The authors approximated drone transportation costs by considering a number of specific routing factors such as climbing, hovering, descending, turning, acceleration and deceleration, rotation, and constant speed cost.

Cong et al. (*38*) modeled a UAS network optimal path problem by finding the least cost tour on a specified set of arcs in a graph, which is related to the Chinese postman problem and the rural postman problem. By mapping the real traffic network into a virtual network, they were able to solve the problem by using mixed-integer linear programming. Their objective function aimed to minimize UAS battery usage, response time, and fixed UAS activation costs subjective to certain assignment constraints, such as different flying routes and UAS recharging depots.

2.3.3 Summary

UAS have great potential for emergency preparedness applications. However, a uniform planned standard for the use of UAS across disciplines is currently not available in Massachusetts. Therefore, the research team recommends that Massachusetts incorporate the use of UAS as a planning and analysis tool for both disaster and long-range transportation planning.

Additionally, to fully utilize the potentials of UAS for emergency preparedness and response, UAS network design is a critical issue. We found that there are growing research efforts in academia that investigated both the architectural design of the UAS network and ways to optimize the operation of UAS networks (such as to minimize cost). However, the UAS networks in the reviewed studies were often simplified in order to provide a theoretical framework. Therefore, it is challenging to directly implement those networks in practice.

2.4 Practice and Potential Needs of UAS in Massachusetts

In order to connect the literature review described above to the potential needs regarding UAS in Massachusetts, the research team attended a meeting at MEMA in Framingham in July 2018. Attendees included staff from MEMA and the MassDOT Aeronautics and Highway Divisions. At this meeting, among other things, the researchers learned that MassDOT is actively making progress toward the use of UAS for emergency response. Also, MEMA reportedly uses drones, through contractors, to assess disaster damage.

Building on the literature review findings and looking forward, it is clear that MassDOT could readily use UAS to respond to and/or assist investigations of traffic incidents, such as highway crashes and transit bus failures. For MEMA, important functions are to monitor infrastructure (such as coastlines or areas that are susceptible to flooding) before and after disasters to assess the damage, and monitoring transportation systems during an evacuation event, sometimes over a large geographic area. UAS can assist with these tasks.

Further, the discussions in the July meeting helped the research team to identify and clarify important questions and needs of the MassDOT and MEMA officials if UAS are to be used for emergency response. The key questions raised in the meeting include:

1. What are the parameters for a good drone mission? When – in what situations – should drones be used? And specifically, from a policy (privacy), FAA, and network perspective, where are the “good” drone missions?

2. Where, geographically in Massachusetts, should a fleet of UAS be located for rapid response to emergency incidents?
3. Who should own the emergency response drones? MassDOT? Or should a network of contractors be inventoried and utilized?
4. Who already has the UAS equipment and piloting capabilities to be called on in an emergency response situation? Currently, neither MassDOT nor MEMA has a full inventory of UAS licensed pilots and capabilities. And what additional training and testing systems assessing pilot skills are needed?

The remaining of the research project will address some of the questions raised above, detailed in the following sections.

2.5 Conclusions

In this synthesis effort, the research team examined the public policy and administration aspects of UAS applications, the recent applications of UAS for emergency and incident response, issues around planning and network design of UAS for emergencies or disasters, and the practice and needs of UAS for emergency and incident response at MassDOT and MEMA.
Our review suggests that current federal policies encourage exploration of UAS applications for different public purposes, including for emergency and incident response. The research team thus recommends that Massachusetts work on the policy and administration issues that are limiting the use of UAS for these purposes. Specific recommendations include **establishing a UAS data management system for privacy and developing a pilot training and testing program that goes beyond the standard FAA 107 testing** to establish and maintain a cohort of skilled UAS pilots who can safely and effectively respond in emergency situations.

We also find that nationally there are growing interests in using UAS for emergency and incident response. UAS use is increasingly used during or after natural disasters, particularly in instances of fire and flooding. One important lesson learned is that **the characteristics and capabilities of drones vary significantly, and agencies should select UAS equipment based on the desired applications and flying needs and parameters.**

There is also growing interest to use UAS for traffic incident management. Some field tests demonstrated that UAS have unique advantages in providing instant traffic monitoring and data collection. However, many UAS research projects and field testing in this area are in the early stages of exploration and adoption. So far, no agency has made the use of UAS for traffic incident management a routine practice.

Our review of the planning aspects of UAS for emergency preparedness and response shows that UAS can be very helpful in emergency and disaster management, but a uniform standard for UAS use across different areas (e.g., natural disaster, traffic incident, fire) is currently not available in Massachusetts. Therefore, we recommend that MassDOT consider the incorporation of UAS for emergency and disaster planning. Our review of UAS network design shows that there are research efforts in academia that examined the architecture design and operation optimization of the UAS network. However, they are from a theoretical perspective and lack validation from implementation.

Based on the outcome of the literature synthesis, arguably UAS have great potential for emergency and incident response. However, since many applications are still in the trial stage, the lessons learned from the literature synthesis are limited. Therefore, the research team recommends at this point, that it is important for Massachusetts to conduct a UAS trial program to study UAS' potential as well as issues that may arise in practice.

Finally, as summarized in Section 2.4, at a mid-stage of this project, a number of important questions were posed by MassDOT and MEMA focusing on how to develop a UAS emergency response network in the Commonwealth. This dialog was extremely helpful and helped the team to move from the broader literature review to a more refined and focused effort over the second half of the project. Limited by the scope of the project, we could not fully address all of the questions outlined in Section 2.4. Consequently, we focused on addressing two key questions below and leave the remaining ones for future research:

1. What are the parameters for a good drone mission? When – in what situations – can drones be used?
2. What are the design parameters of a UAS network for rapid response to emergency events in Massachusetts? Specifically, how many UAS stations are needed and where geographically to deploy them?

These two questions will be addressed in the following section.

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3.0 A UAS Network for Emergency Response in Massachusetts

In this section, as stated previously, our research team focuses on two of the key questions raised by MassDOT and MEMA:

1. What are the parameters for a good drone mission? When – in what situations – can drones be used?
2. What are the design parameters of a UAS network for rapid response to emergency events in Massachusetts? Specifically, how many UAS stations are needed, and where should they be deployed geographically?

In this second part of our research, our team undertakes two research tasks. First, we analyze historical traffic incident data to understand the features of incidents (e.g., frequency, location, and duration of various categories and subcategories of incidents) to address the first question of in what situations a UAS mission can be launched. Second, we then present an algorithm to decide the parameters of a UAS network for rapid emergency response within the Commonwealth. We developed the UAS networks for traffic incident response. We then show that the traffic incident-based networks can cover natural disasters as well, suggesting that the UAS networks can serve multiple purposes.

One important advantage of the algorithm we develop is that it provides a framework that can be improved upon or refined in the future. Users can use it for different types of events, refine the parameter ranges (such as the radius of UAS stations and candidate UAS station locations) based on need, and optimize the design based on the objective or budget. This tool can be useful for different divisions in MassDOT and other states.

3.1 Data

3.1.1 Geospatial data

3.1.1.1 Traffic incident data

MassDOT collected the traffic incident data. This data is critical in answering both questions above regarding when UAS should be used and where severe incidents are likely to occur that need a UAS response team. This incident database provided a total of 73,224 traffic incidents across the Commonwealth over the period of April 2013 to October 2017. Individual incident data include the starting and ending time, location (latitude/longitude), type, and severity. The incidents are categorized by six event types: Planned Roadway, Roadway/Traffic, Fire, Environmental/Hazmat, Law Enforcement/Security, and Property/Structural Damage. The six types are further classified into 107 sub-types. They are also categorized into five severity levels: Daily Operations, Level 1, Level 2, Level 3, and Level 4, with the higher level indicating more severe events.

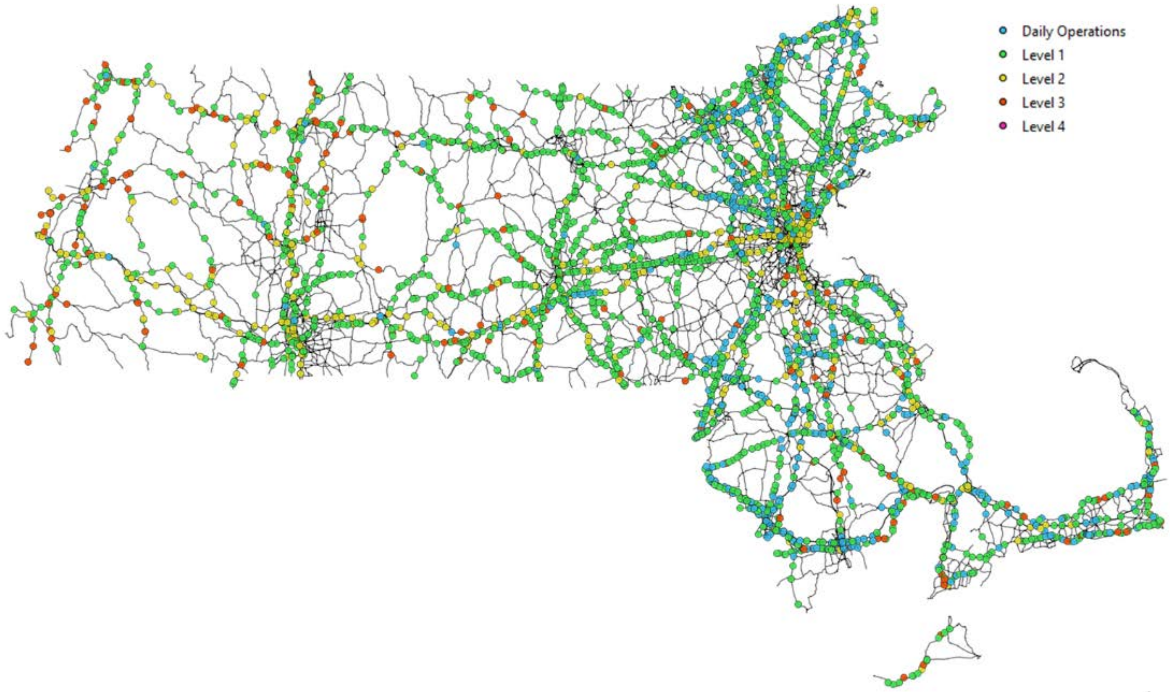


Figure 3.1: Illustration of historical traffic incident dataset (each point represents one incident and color indicates severity)

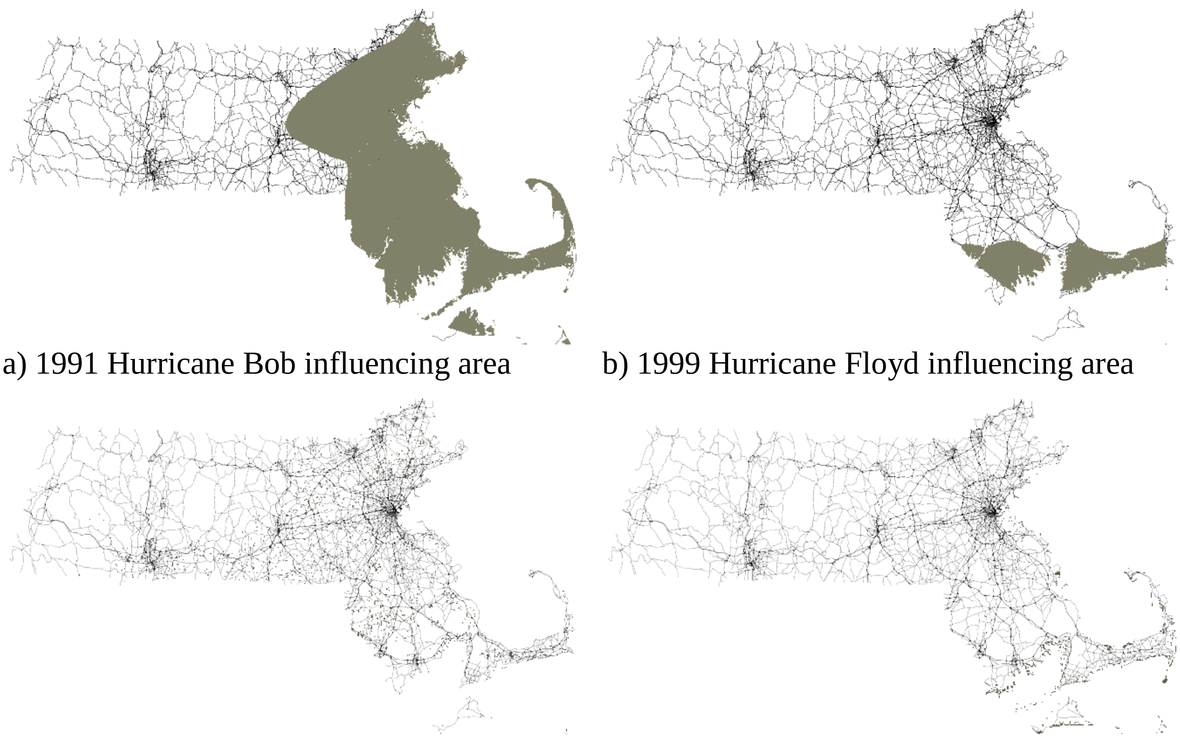
3.1.1.2 Disaster Data

Extreme weather-related events, such as damaging wind and flooding, are another aspect MassDOT and MEMA may want to consider when locating a rapid response UAS emergency network. While we readily admit historical location data on hurricane landfall in Massachusetts may not be the best predictor of future hurricane landfall, it could provide some useful information. The flood risk maps from the National Oceanic and Atmospheric Administration (NOAA) are a layer that may be useful, although future derivatives of what we implement here might want to consider richer data on road infrastructure elevation as it relates to these flood risk zones.

In our analysis, four datasets with hurricane and flood information were utilized: 1) the influencing area of 1991 Hurricane Bob with peak winds > 50 knots (NOAA damaging winds category); 2) the influencing area of 1999 Hurricane Floyd with peak winds > 50 knots; 3) NOAA 2% flood risk areas; 4) NOAA coastal flood risk areas.

Note that a variety of hurricanes that hit Massachusetts over the last 30 years (e.g., Gloria-1985; Bob-1991; Floyd-1999; Beryl-2006; and Hanna-2008) were also investigated. The two hurricane events that had peak wind speeds over 50 knots (Bob and Floyd) were chosen, given NOAA defines "damaging winds" as ones exceeding 50 mph (1 knot = 1.15 mph). The hurricane wind speed spatial data layer had to be built from wind recording station data that was taken at stations in a variety of Massachusetts towns. Not all towns had such data, so Geographic Information System (GIS) interpolation was used to create a wind speed surface for both the Bob and Floyd layers. Figure 3.3 and Figure 3.4 shows the analyzing and interpolating process. In Figure 3.3 and Figure 3.4, the wind speeds are scaled by color, with red indicating upper bound at 62-64 knots, green for the lower bound at 27-30 knots, and the transitioning colors indicate wind speeds in between . Towns with the upper bound speed (in red color) include Barnstable, Brewster, and New Bedford. Towns in intermediate speeds include Bourne, Edgartown, Milton, Plymouth, Taunton and Westfield. Towns with lower bound speed (in green color) include Beverly, Lawrence, Mount Washington, Nantucket, Norwood, Orange, Rockport, Salisbury, Southwick, Truro, Williamstown, and Worcester. Notably, Figure 3.4, most of the commonwealth is within the winds at 27-30 knots and the area at higher wind speed (62-64 knots) is in southern Massachusetts. The NOAA flood risk areas covered the entire state.

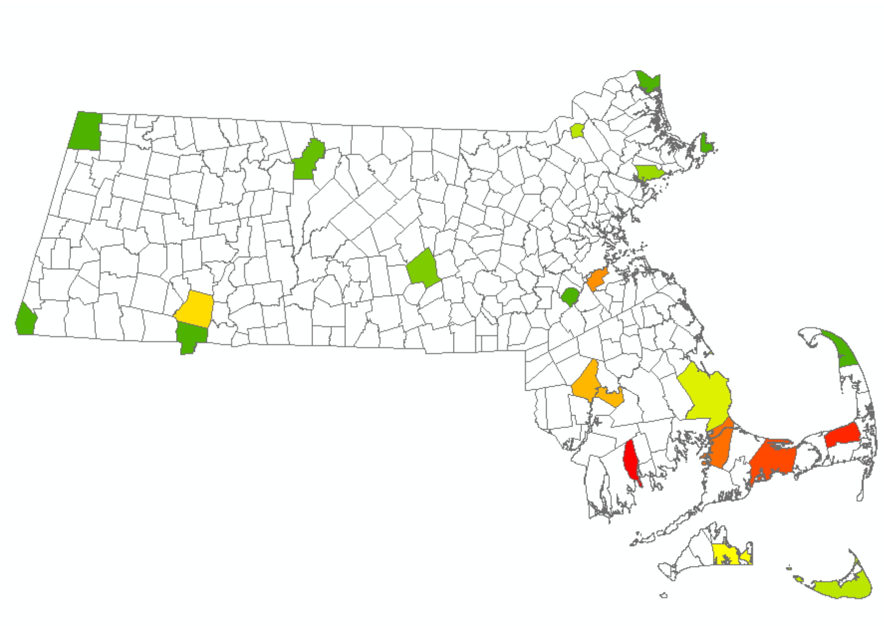
Using GIS data conversion tools, each of the four weather disaster layers was converted into a raster with a standard 500x500 meter cell size, where each cell obtains an indicator 1 (influenced) or 0 (not-influenced) that represents the status of the cell.



a) 1991 Hurricane Bob influencing area b) 1999 Hurricane Floyd influencing area

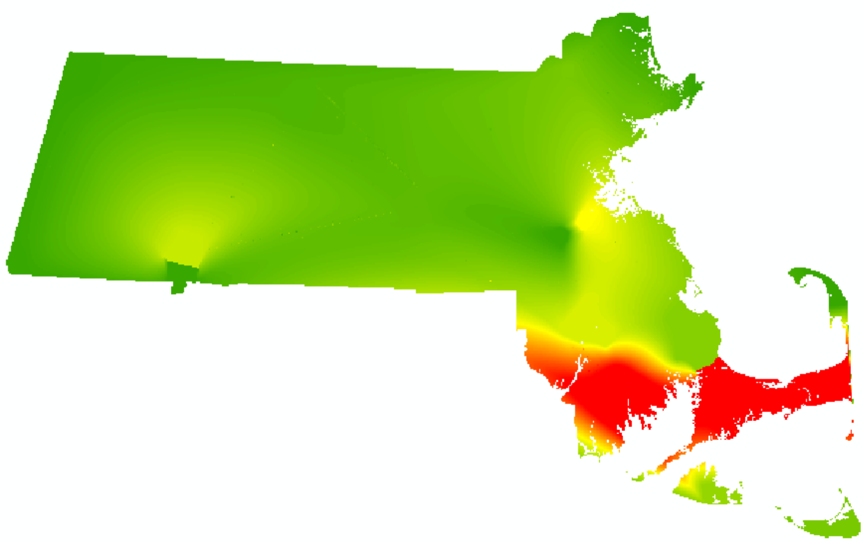
c) NOAA 2% flood risk areas d) NOAA coastal flood risk areas

Figure 3.2: Illustration of the four weather-related disaster data layers



Note: Red: 62-64 knots, green: 27-30 knots.

Figure 3.3: Towns with peak wind measurements for Hurricane Floyd (1999)



Note: Red: 62-64 knots, green: 27-30 knots.

Figure 3.4: Interpolated peak wind landscape for Hurricane Floyd (1999)

3.1.1.3 Maintenance facilities

We believe that the locations of MassDOT maintenance depots might be useful as potential UAS fleet deployment stations, given they are under the management of state DOT and could be easily upgraded to stage UAS supporting equipment, should MassDOT decide to purchase and maintain their own fleet. There are 125 maintenance depots across the commonwealth; see the figure below.

Lastly, the Massachusetts major roadway network GIS layer from MassGIS is used for visualizing the geo-location of all above-listed data.

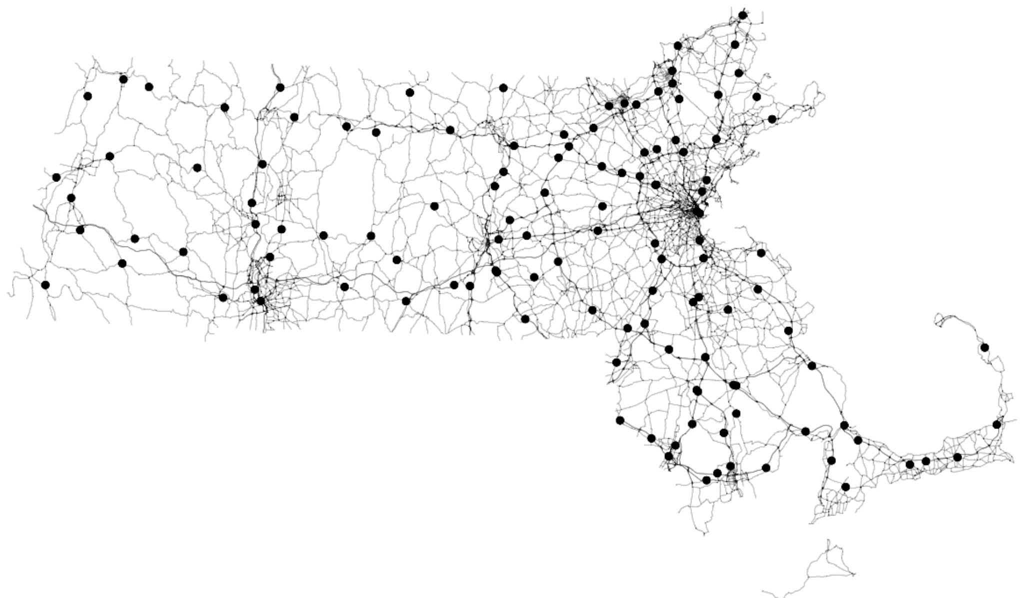


Figure 3.5: Illustration of MassDOT maintenance depot locations

3.1.2 Features of traffic incidents

In this subsection, we study the basic features of traffic incidents within the Commonwealth. This will help to answer the first question of when should UAS be used based on the event features, and also will help to identify historical traffic incident "hotspots" that would help locate UAS emergency response stations. We examine four aspects of the incidents, category (i.e., event type), frequency, severity, and duration. The aim is to reveal the most important features that are related to UAS missions.

Regarding event type, incidents under different layers (categories/subcategories) are demonstrated respectively. Incident categories are very general groupings of types of incidents such as "roadway/traffic", "planned roadway", "property/structural", "fire", "law enforcement", or "environmental or hazardous materials". These broad categories are further broken down into more subcategories such as "road debris", "potholes", "construction event", or "multi-vehicle accident (with or without injury)."

In the figures and discussions that follow, we examine the types of categories and subcategories and their frequencies, as well as the level of severity of their incidents. The review is done with the intention of trying to understand what kinds of high severity incidents exist, the temporal duration of these incidents, as well as the geographic location of these incidents. This historical information will assist in determining possible geographic locations of UAS emergency response base locations.

Figure 3.6 demonstrates the frequency of each incident category. More than 90% of the overall incidents between April 2013 and October 2017 fall under the Roadway/Traffic or Planned Roadway categories. Property/Structural Damage and Fire are prevalent but occur much less frequently, while the last two categories related to law enforcement or environmental or hazardous materials are relatively rare.

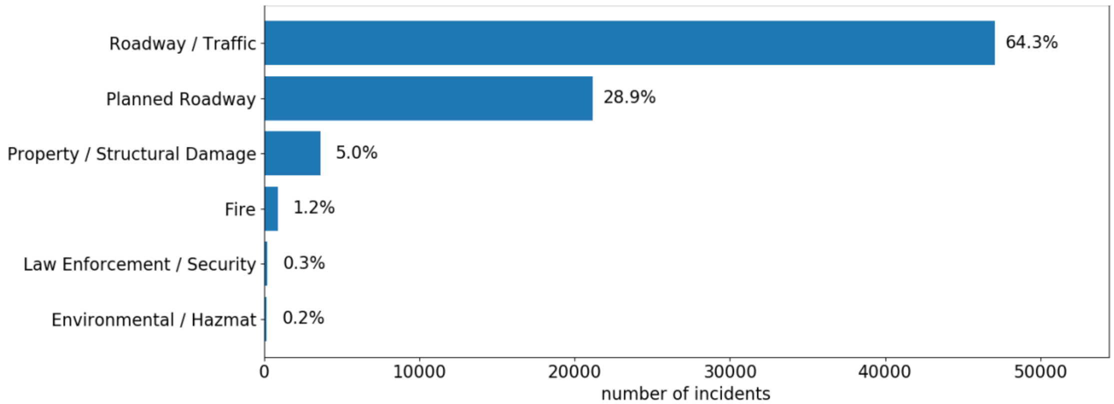


Figure 3.6: Frequency of each category

Figure 3.7 demonstrates the frequency of type of incident that occurs in the two most frequent incident broad categories (Roadway and Planned Roadway). Due to the limitation of figure size, only the top 10 most frequent incident subcategories are shown. Note that some of the most frequent incident subcategories are relatively minor. For example, the most prevalent subcategory, Debris/Rubbish, is likely not an event where a UAS network would need to be deployed to assess the situation. Similarly, pothole incidents, the fourth most prevalent in the dataset, also would not likely require UAS support. However, the subcategory MVA (Multi-Vehicle Accident) without injury or MVA with injury, while lower in terms of incident frequency, could be the kind of incident subcategory where a UAS response may be needed.

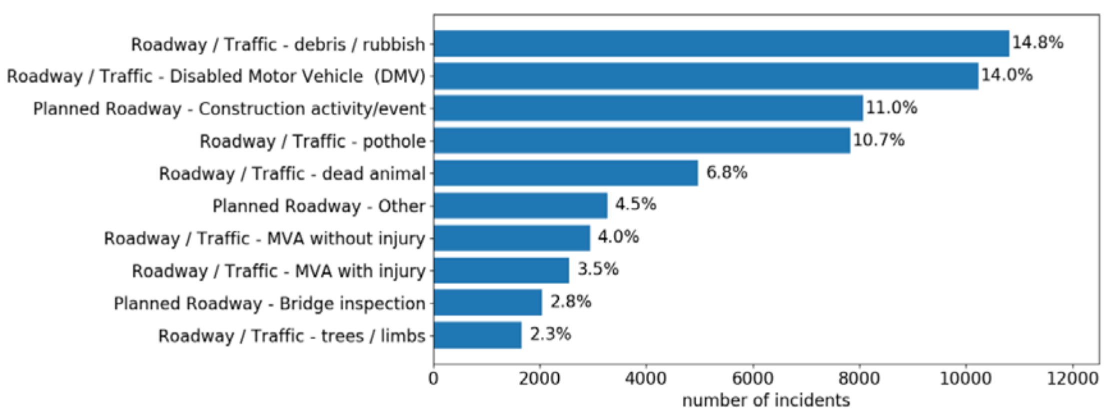


Figure 3.7: Frequency of top 10 incident subcategories under Roadway/Traffic or Planned Roadway

Figure 3.8 turns to an examination of incident severity levels in the overall dataset. While Level 1 and Daily operations are the most common severity categories, Level 2 and Level 3 take smaller proportions though they are much more severe. Level 4 is very rare (only four Level 4 incident in the dataset).

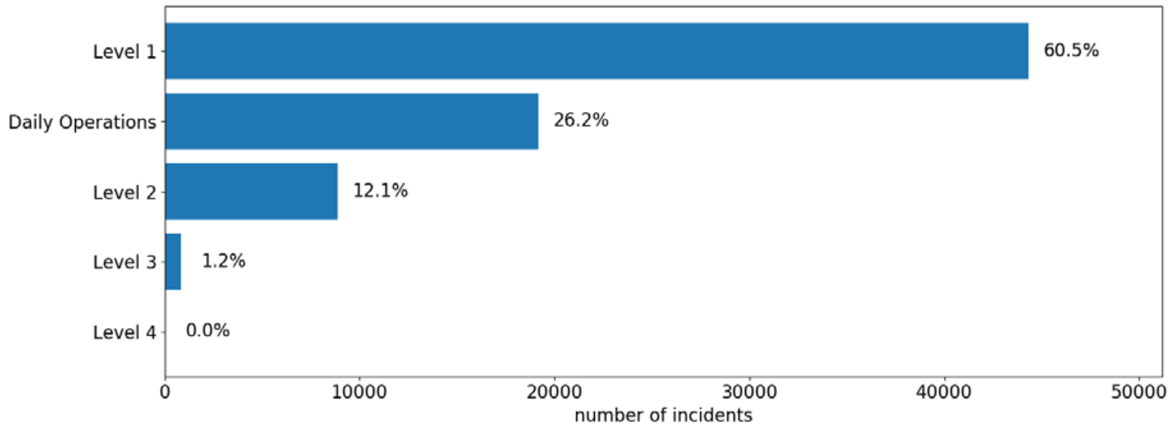


Figure 3.8: Proportion of each severity level

In addition to the frequency, severity level is another important factor for consideration of UAS missions. Thus, a cross-analysis is further conducted to investigate and discuss the severity distribution of the incidents.

Figure 3.9 shows the severity proportion of each category. The different colors indicate different severity levels: green for daily operations, light blue for Level 1, orange for Level 2, red for Level 3, and purple for Level 4. Most incidents in the fire category are at high severity levels (Level 3 or 4) despite the relatively low frequency. Regarding the two major categories, the Roadway/Traffic has a significant proportion of incidents at level 2 or higher severity, but the Planned Roadway incidents are mostly below level 2 severity, which suggests that this category may be one type where a UAS mission is not required.

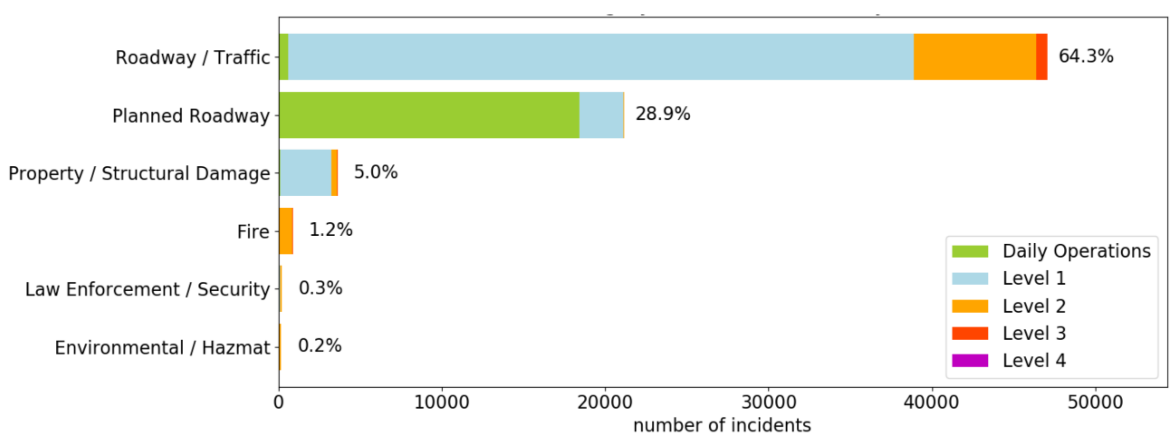


Figure 3.9: Severity proportion of each incident category

Similarly, Figure 3.10 shows the severity distribution of each subcategory. As mentioned earlier, the top six most frequent subcategories mostly consist of less severe incidents (Daily Operations or Level 1). Thus, these events may not be worth launching a UAS mission.

Meanwhile, MVA without injury and MVA with injury subcategories show a high Level 2+ (i.e., Level 2 or above) proportion, suggesting that these subcategories are likely candidates for UAS missions.

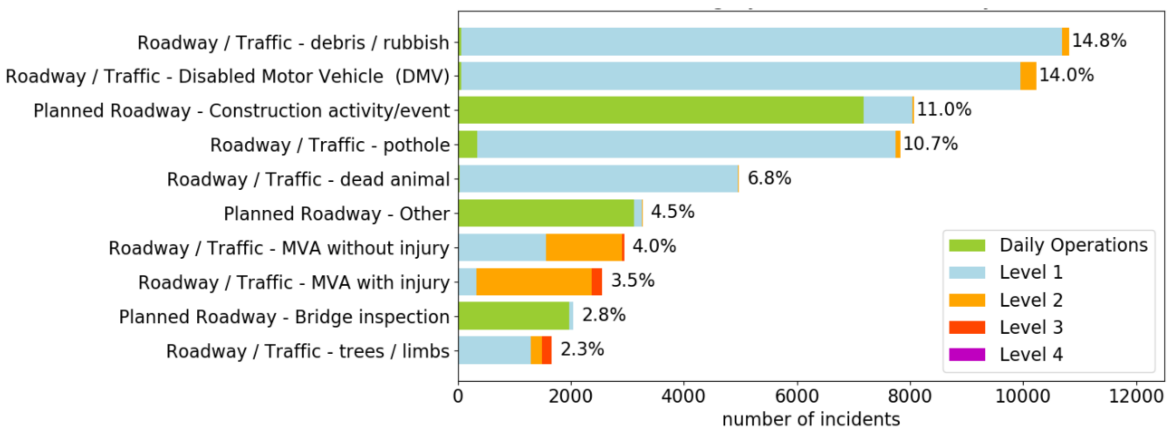


Figure 3.10: Severity distribution of top 10 incident subcategory

Another important feature of incidents is the event duration – the length of time from start to full operational cleanup of the incident – is another perspective that might help to answer the question of when and where a UAS mission should be flown. Figure 3.11 shows the overall duration distribution of incidents. We find that about 30% of incidents last over 1,000 minutes (about 16.5 hours), and some last a relatively short time (e.g. 5 minutes).

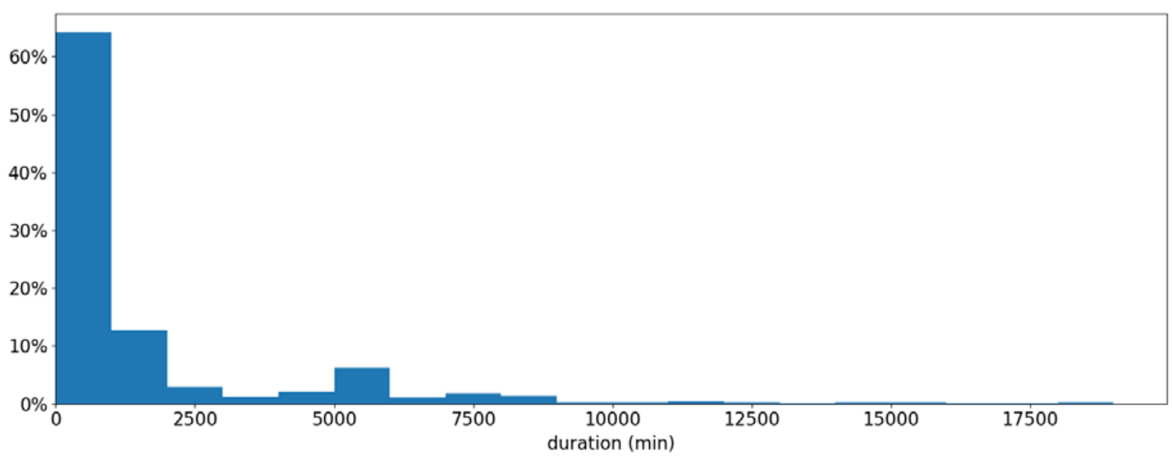


Figure 3.11: Overall duration distribution of incidents

3.2 Methods

To develop a UAS network for emergency response, we follow two steps:

- Step 1: to identify applicable incidents for UAS missions;
- Step 2: to decide the parameters of the UAS network, particularly, the station number and station locations.

These two steps will address the two questions raised above, respectively. Below, we elaborate on the two steps separately.

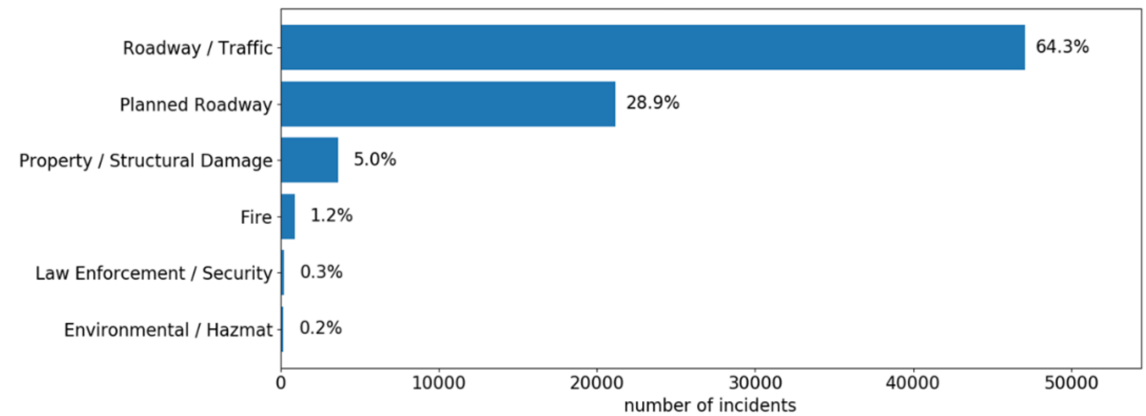
3.2.1 Identify Applicable Incidents for UAS Missions

In this subsection, we aim to identify events that are suitable for UAS missions. This will answer the Question 1 raised: "What are the parameters for a good drone mission? When – in what situations – can drones be used?"

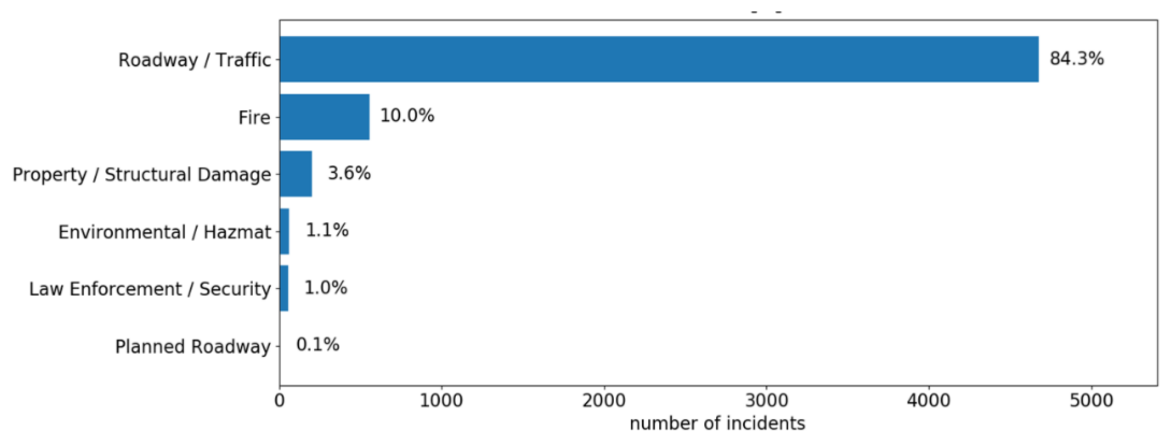
To this end, we consider two incident features, incident severity and duration[1]. The severity indicates whether an event is worth the efforts of flying a drone and the duration indicates whether it is feasible to use UAS. Specifically, for the severity filter, we consider events that are at severity level 2 or above. For the duration filter, we consider events the last between 30 minutes to five hours (300 minutes). The reason is that for events that last shorter than 30 minutes, the drones may not have enough time to prepare and respond; while for those lasting longer than five hours, drones may not be the most useful tools. In fact, it is found that most of the long-lasting events (>5 hours) fell into severity Level 1 or the level of Daily Operations. With the two filters, we identified the applicable incident set. The features of the applicable incidents (event type, frequency, severity, and duration) are shown on the next page.

Figure 3.12 shows the frequency of each category for the applicable incidents. It is found that most applicable incident categories are roadway/traffic incidents, fire, and property/structural damage. Note that the distribution of incident types in the filtered set is quite different from the no filter case.

[1] For real-time application, this would be the predicted duration.



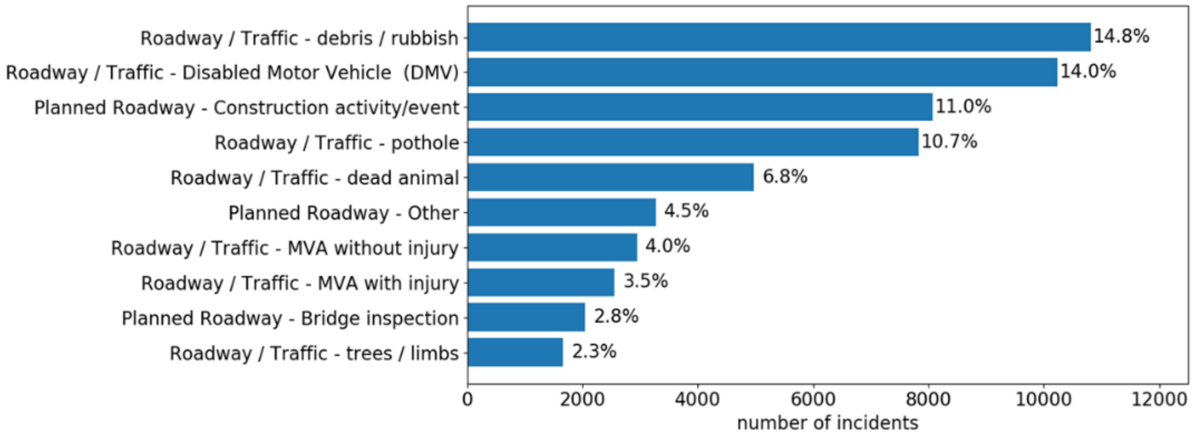
a) All incidents



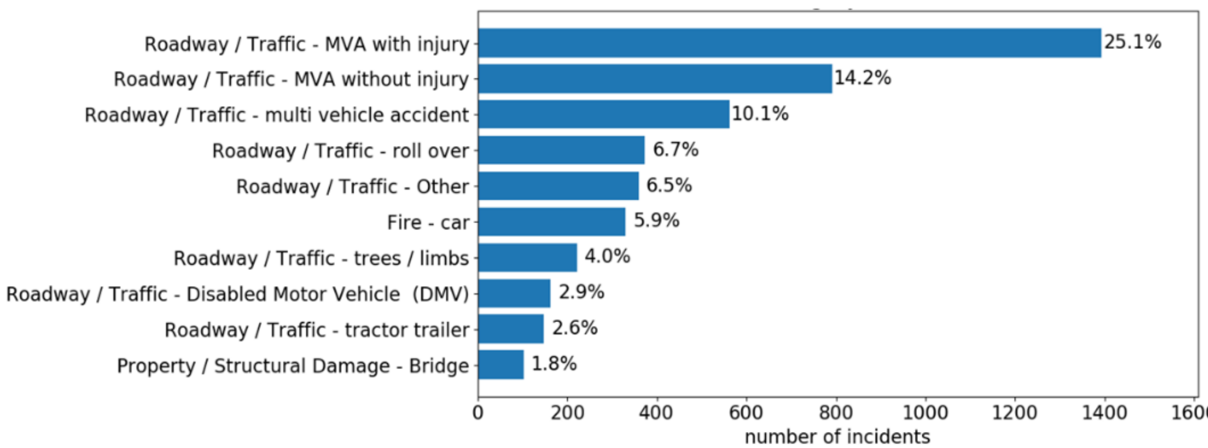
b) Applicable incidents (severity > Level 2; 30min < Duration <300min)

Figure 3.12: Frequency distribution of applicable incidents

Figure 3.13 demonstrates the frequency of the top 10 subcategories with filters. Specifically, multi-vehicle accidents, roll-over, car-on-fire are the most frequent applicable incident subcategories. This result is consistent with the observations in the raw data statistic as shown above.



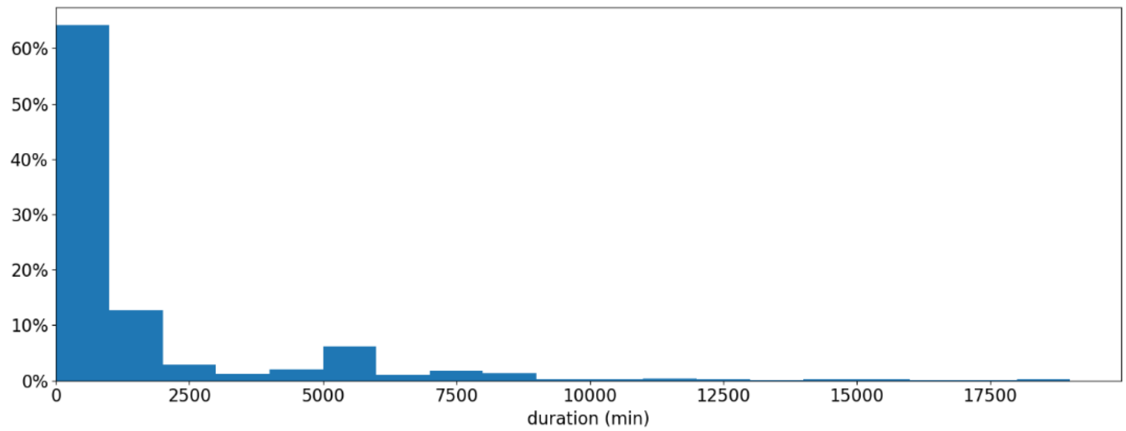
a) All incidents



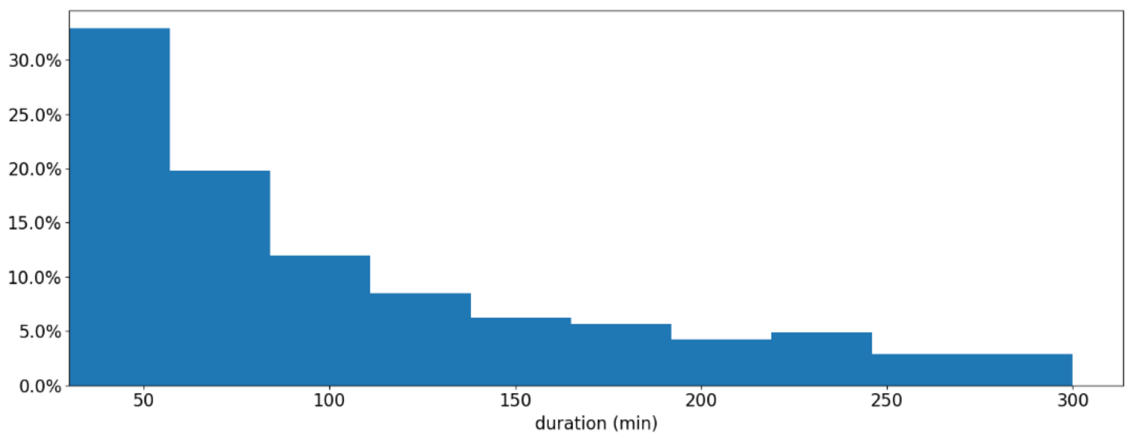
b) Applicable incidents (severity > Level 2; 30min < Duration <300min)

Figure 3.13: Frequency of top 10 subcategory of the applicable incidents

Furthermore, Figure 3.14 shows the duration distribution with filters. Most incidents that are applicable for UAS response are shorter 400 minutes.



a) All incidents



b) Applicable incidents (severity > Level 2; 30min < Duration <300min)

Figure 3.14: Duration distribution of the applicable incidents

In short, to identify the applicable incidents, we consider two filters:

- Severity level: level 2 or above.
- Duration range: between 30 minutes to five hours.

More filters can be further incorporated using the same procedure, such as the incident types. Notably, the setting of the filters will determine the applicable incident set, which should be further calibrated based on the operational features of the UAS, such as battery life and time needed to prepare missions, as well as the priority of the agency.

3.2.2 Develop the Optimal UAS Station Algorithm

In this section, we turn to determine the parameters of the optimal UAS network, which will address Question 2 above: “What are the design parameters of a UAS network for rapid response to emergency events in Massachusetts? Specifically, how many UAS stations are needed and where should they be deployed geographically?”

The objective of the UAS network is to provide comprehensive coverage of incidents with the lowest possible cost. To this end, we make two assumptions: (1) a UAS emergency response station will cover a fixed radius geographic area with radius r; and (2) the cost for each station is a constant. Based on that, the problem can be reformulated to "how to use the minimum number of circles to cover the desired number of events?" This problem is a classic discrete K-center problem in mathematics known to be "NP-hard"[2] (*39*) and the optimal solution cannot be analytically found. To address this problem, we develop a greedy algorithm to solve it. Figure 3.15 shows the flow chart of the approach. The inputs to the algorithm are summarized in Table 3.1, including incident locations, candidate locations for stations, radius of UAS station, and expected coverage of the network. The pseudo code of the algorithm is provided in the appendix. An example of the inputs used in our analysis is also provided.

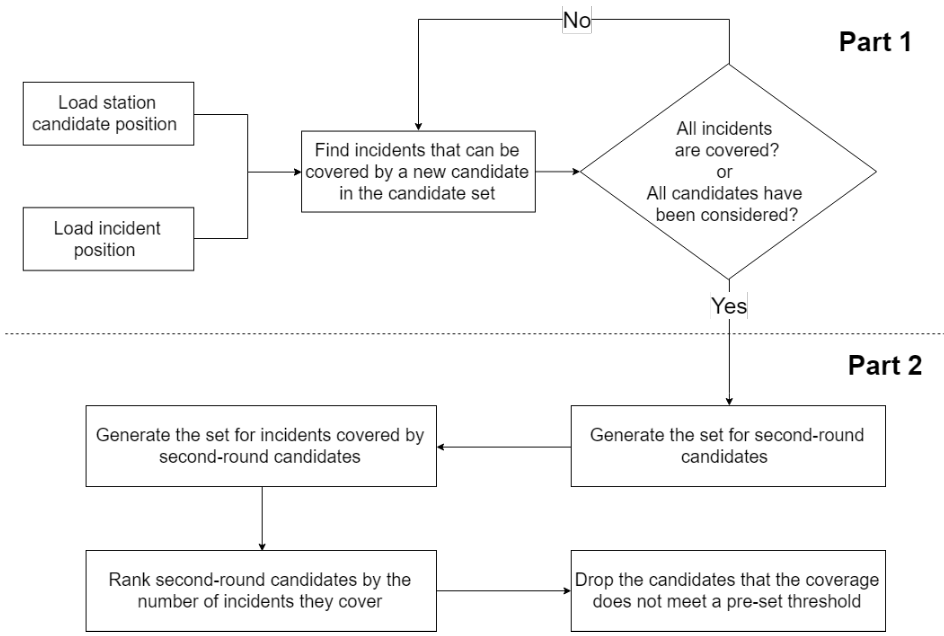


Figure 3.15: Flow chart of the optimal UAS station greedy algorithm

Table 3.1: Inputs of algorithm to optimize the UAS network

	Algorithm Inputs	**Example**
1	Incident points location	The 5541 applicable incident points
2	Candidate station location	MA maintenance depot locations
3	Radius of each UAS station r	$r = 5$ miles
4	Expected coverage of incidents	95%

[2] NP-hard problems are ones where there is no known polynomial algorithm. Consequently, the time it takes to find a solution grows exponentially depending on the scope or size of the problem.

3.3 Results

3.3.1 UAS network for traffic incidents

The proposed optimal UAS station algorithm is applied to the selected incidents with severity Level 2+ and duration in (30min, 300min), which results in a total of 5541 cases. The maintenance depots are used as the candidate locations for UAS stations. For the radius of UAS stations, we consider two different values, 5 miles and 10 miles. For expected coverage, we vary it from 90% to 95%. The summary of the inputs is provided in Table 3.2.

Table 3.2: Inputs Used in UAS Network Optimization

	Algorithm Inputs	**Inputs Used In Analysis**
1	Incident points location	The 5541 applicable incident points from filters (Severity level: level 2 or above; and Duration range: between 30min to 5 hours.)
2	Candidate station location	MA maintenance depot locations
3	Radius of each UAS station r	$r = 5$ miles; $r = 10$ miles
4	Expected coverage of incidents	90%; 95%

An example of the optimal UAS network is demonstrated in with a 10 mile radius and 95% coverage. Note that the incident frequency in each station is different. We define “key stations” as stations covering more than o incident per month during the observation period (between April 2013 and October 2017). The key stations are shown in red circles and the regular stations are in green circles. A total of 26 station locations are needed to cover 95% of the incidents, among which 13 are key stations that cover 81% of the incidents. It is also worth noting that the developed approach outputs show stable results despite selecting random starting points. The robustness is mainly in thanks to the two-stage method described in Figure 3.15 above (in the first stage, the raw candidates are generated; in the second stage, they are ranked and selected based on their importance). Another observation is that there are multiple incidents that occurred in very close time intervals (e.g. five minutes) at some key stations. Though such a situation does not happen frequently, it suggests the potential need for multiple UAS at some busy stations.

Clearly, if we reduce the expected coverage, the network parameters will change. Figure 3.17 shows the network with a 10 mile radius but 90% coverage. In this case, only 19 stations in total are needed, but there are still 13 key stations.

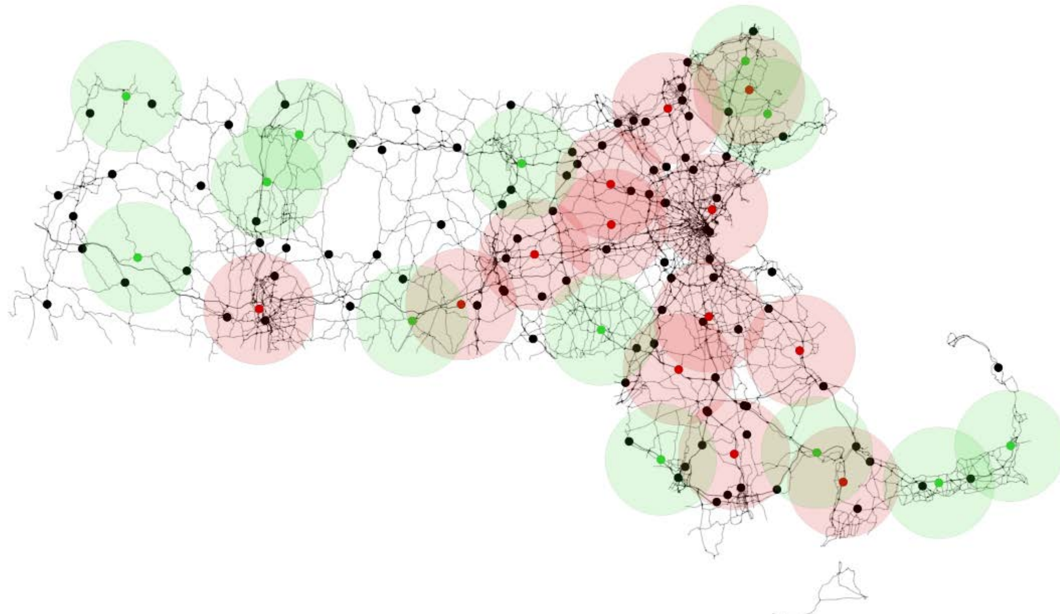
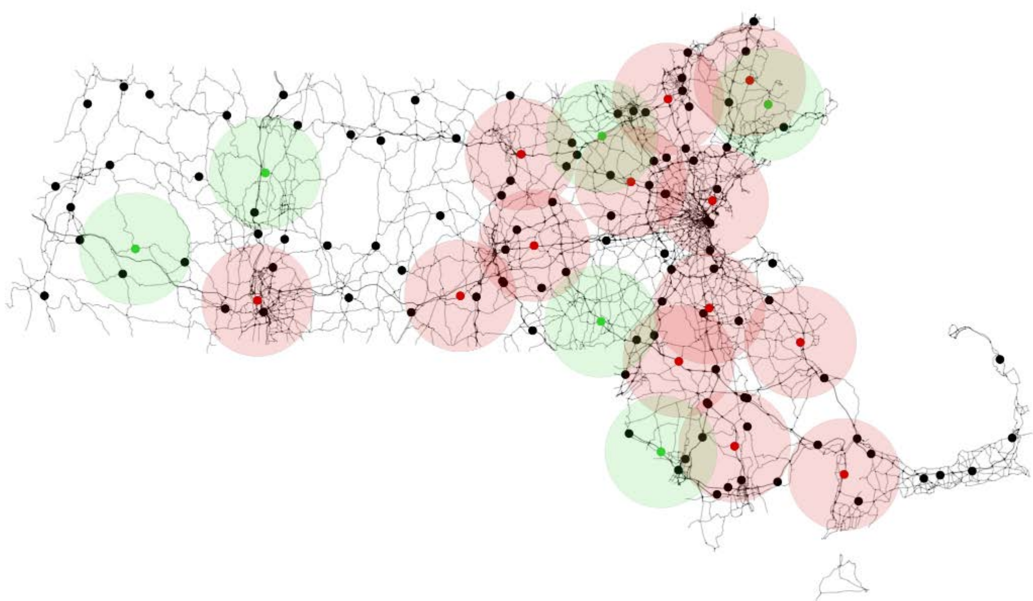


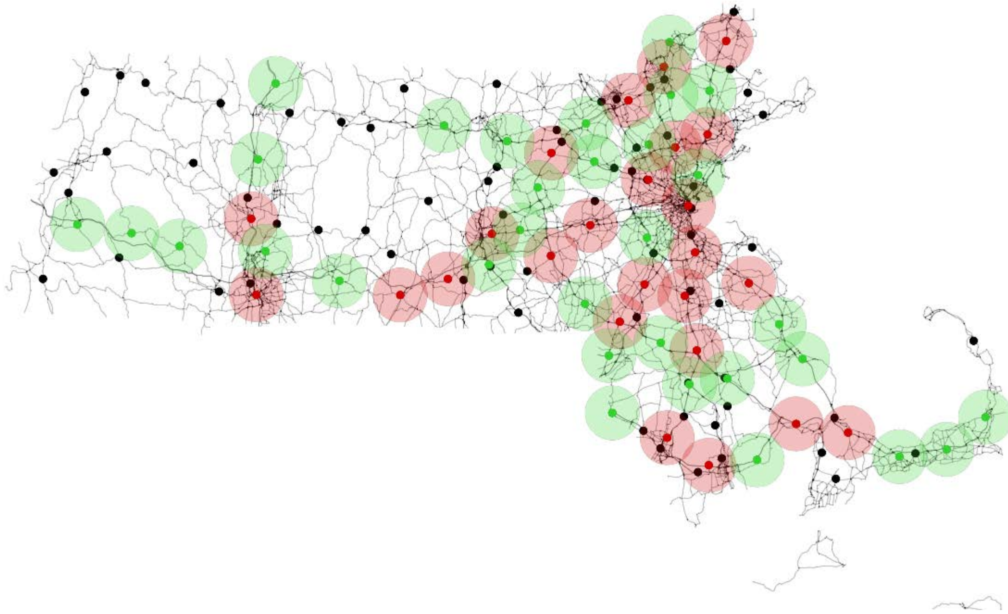
Figure 3.16: Optimal layout of UAS stations (radius = 10 miles, expected coverage = 95%)



Notes: Red circles for key stations and green circles for regular stations.

Figure 3.17: Optimal layout of UAS station (radius = 10 miles, expected coverage = 90%)

Apparently, the station radius is another important parameter that affects the optimal UAS station layout. Figure 3.18 shows the station layout and coverage when the station emergency response radius is reduced from 10 miles to five miles. With a smaller radius, the number of total stations required for coverage increase to 98, with 25 designated as key stations. The key stations now only cover 70% of the incidents.



Notes: Red circles for key stations and green circles for regular stations

Figure 3.18: Optimal layout of UAS stations (station radius = 5 miles)

We further conducted a sensitivity analysis regarding a different radius and expected coverage when keeping the other parameter unchanged. Figure 3.19 shows that the marginal cost (the number of stations per coverage) increases as the expected coverage approaches 100% when the radius is kept the same. This suggests that the cost-effectiveness decreases when the expected coverage increases. Additionally, the marginal benefit of the radius decreases as the radius increases, as shown in Figure 3.20. This result suggests that increasing the radius will help to reduce the number of stations needed, but the the benefits decrease after a certain extent. The sensitivity analysis will help us decide what type of drones to use when given limited resources.

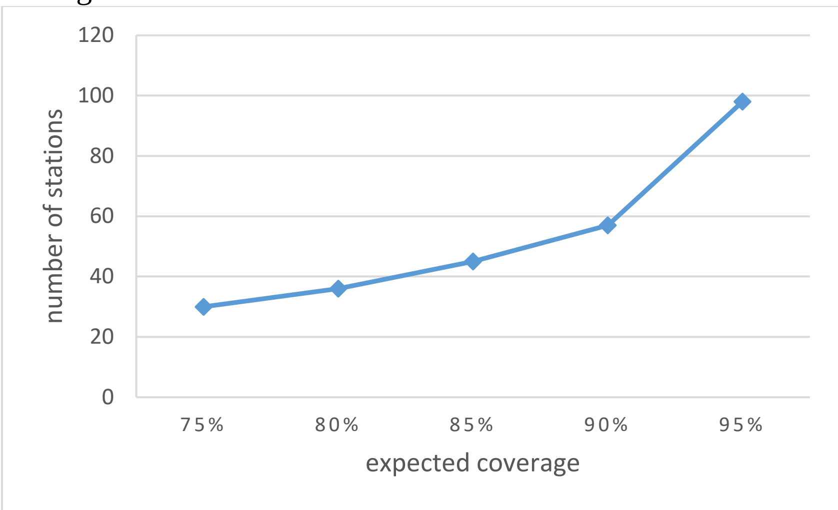


Figure 3.19: Number of stations in varied expected coverage (radius = 5 miles)

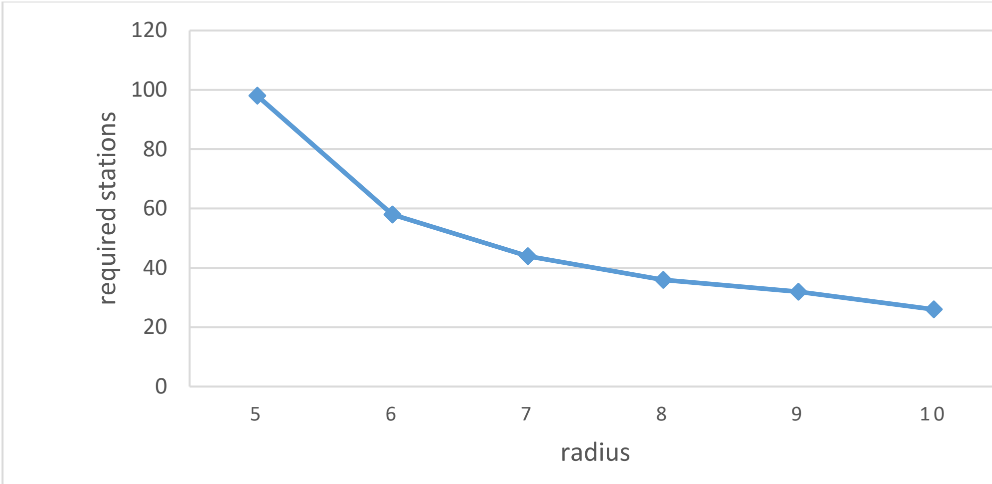


Figure 3.20: Number of stations in varied radius (expected coverage=95%)

3.3.2 UAS station coverage on other disaster events

In this section, we show that the UAS networks based on traffic incidents can be used for emergency responses to major weather-related events. These events are important as they can cause incidents such as downed trees or power lines, or major floods that might result in transportation infrastructure blockage. Specifically, two key major weather events in Massachusetts that causes these kinds of problems are hurricanes and other moisture-carrying events that cause major and rapid flooding to occur.

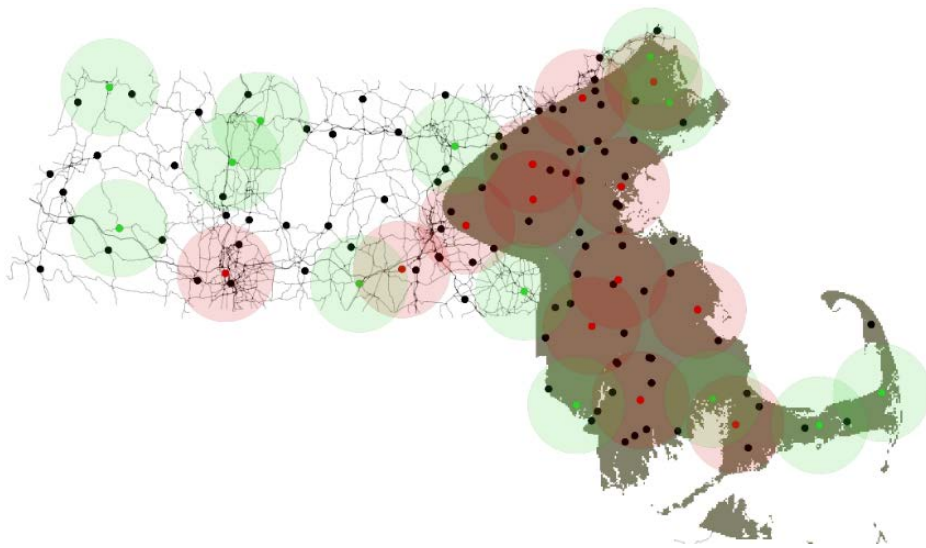
3.3.2.1 Hurricanes

Hurricanes have the obvious ability to cause extensive damage across Massachusetts. While we fully recognize historical data related to hurricanes are likely not a great predictor of future hurricane geographic footprints, it is a worthwhile exercise to examine the history of Massachusetts' hurricane events to see how those footprints might influence UAS station placement. Considering the excellent reaction time and mobility capability of UAS, placement of UAS emergency response stations with some consideration of where hurricanes have hit before could enhance our ability to respond and could provide a first-hand understanding about areas where infrastructures was previously affected by damage (e.g. tree, power line falls or flooding) due to hurricanes.

We considered two Massachusetts historical hurricanes – Bob (1991) and Floyd (1999) – as both had winds measured at 50 knots (about 57 mph). Next, we used the UAS network with a 10-mile radius and 95% incident coverage developed based on traffic incidents to see how much the influenced areas of the hurricanes fall within the coverage of this UAS network. The visualized results are shown in Figure 3.21 and Figure 3.22 for Floyd 1999 and Bob 1991 respectively, in which the dark shaded regions indicate the influenced area. Table 4-3 shows the coverage result.

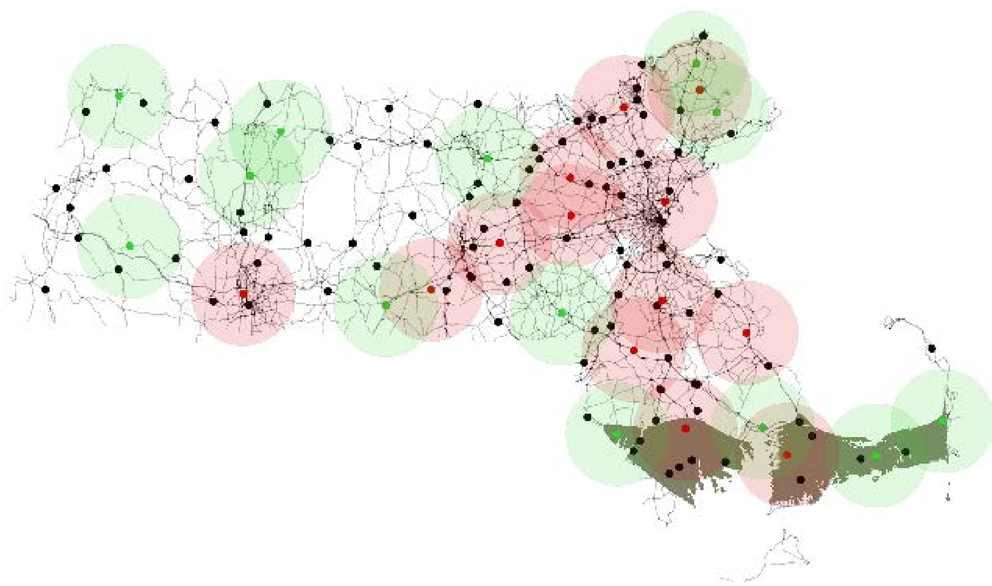
Table 3.3: Disaster coverage (radius=10, expected incident coverage =95%)

Disaster	Coverage	Key station coverage
Bob 1991	86%	71%
Floyd 1999	94%	62%



Notes: Dark shaded region indicates influenced area of hurricane, red circles for key stations and green circles for regular stations.

Figure 3.21: Station coverage on Floyd 1999 hurricane



Notes: Dark shaded region indicates influenced area of hurricane, red circles for key stations and green circles for regular stations.

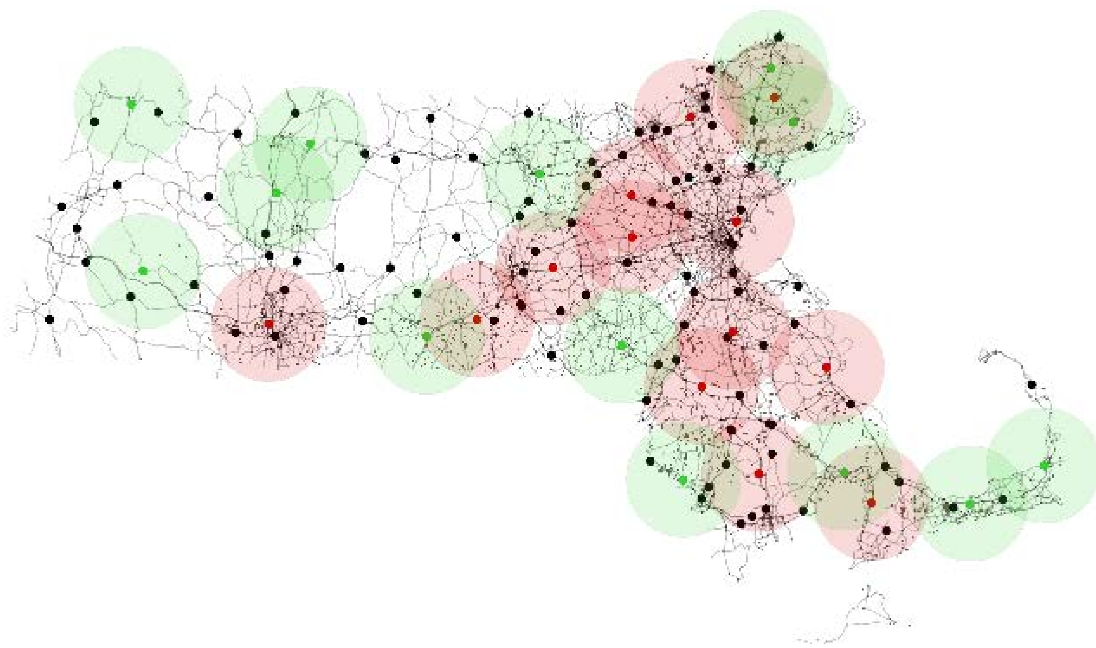
Figure 3.22: Station coverage on Bob 1991 hurricane

Our historical analysis of hurricanes (50 knots or greater peak wind) reveals that the UAS stations have acceptable performances on assessing the disaster scenarios. The coverages on the investigated historical datasets all reach 80%+, even though they are not as thoroughly covered as what was discovered for roadway incidents. The likely reason for this is that hurricane high wind areas are found more closely to coastal areas, while many of the UAS stations are mostly arranged inland.

3.3.2.2 Flooding

Flooding events are another highly critical disaster type that could require UAS-based emergency response. To examine UAS emergency response station placement, we utilized NOAA 2% flood risk maps for the Commonwealth available at MassGIS.

Figure 3.23 shows the UAS station coverage on NOAA 2% flood risk areas. The UAS stations provide an 88% total coverage with a 66% key station coverage. Note that the risk areas are shown in dots with their size representing the size of the area. However, since the areas are very small compared to the whole commonwealth, they appear like points in the figure.



Notes: Dots indicate risk area, red circles for key stations and green circles for regular stations.

Figure 3.23: Station coverage on NOAA 2% flood risk area

Overall, the results in this section suggest that a UAS network developed based on traffic incidents provide a very good coverage of the natural disasters. Of course, it is also possible to develop a UAS network based on the temporal and spatial distributions of the natural disasters. This can be easily done using the same procedure.

3.4 Summary

In this chapter, the procedure to develop a UAS network for emergency responses was proposed, based on the analyses of multiple historical datasets. A framework was developed for designing an optimal UAS network, specifically to answer two major questions:

1. 1) when – in what situations – can drones be used? and
2. 2) where should UAS fleets be located?

To answer the first question, the statistics of the Massachusetts incident dataset are analyzed. A simple and effective procedure is used to identify incidents for UAS application. Critical incidents are identified by two filters: a higher severity level (Level 2+), and appropriate duration (30-300 minutes). A greedy algorithm is developed to solve the second question, which automatically calculates the optimal parameter for the UAS network (i.e. the number and locations of the stations). The network parameters are discussed considering different station radius and expected coverage. Specifically, the number of stations needed increases with the expected coverage but decreases with the station radius. The further sensitivity analysis suggests the marginal benefits vary with the input range changes, which potentially impacts the cost-effectiveness. Furthermore, the UAS application on natural disaster scenarios is discussed with hurricane and flood information. The coverages on the disaster influenced areas are found to be satisfactory, even though they are not as thoroughly covered as what was discovered for roadway incidents.

4.0 Conclusions

In this report, the applications of UAS for emergency response are examined through a thorough literature review. Moreover, we developed a flexible procedure to design a UAS network in Massachusetts and recommended the network design based on the traffic incident analysis.

The literature review provides a comprehensive understanding on the public policy and administration aspects of UAS applications in the United States, particularly in Massachusetts. The findings also provide information on recent historical applications of UAS both nationally and internationally for emergency and incident response, as well as issues around the planning and design of UAS networks in advance of future emergencies or disasters. The practice and needs of UAS for emergency and incident response at MassDOT and MEMA were assessed.

The framework of designing a UAS network for emergency response is proposed based on the analysis of multiple empirical geospatial datasets, including traffic incident data, natural disaster data, and maintenance depot locations. The features of the traffic incidents in a five-year period were investigated. A two-step method was developed to select the applicable incidents for UAS applications and optimally determine the UAS network parameters. The first step identifies the applicable incidents by the severity as well as duration filters. In the second step, a greedy algorithm was used to automatically determine the number of stations needed and the locations of the stations, based on the given radius of UAS stations and the expected coverage. The results from the developed algorithm indicate that the UAS network parameters vary with the UAS station radius and the expected coverage. Specifically, the marginal cost (the number of stations per coverage) increases as the expected coverage approaches 100% (radius is kept the same), suggesting that the cost-effectiveness decreases when the expected coverage increases. Additionally, the marginal benefit of the radius decreases as the radius increases, suggesting that increasing the radius will help to reduce the number of stations needed, but the the benefits decrease after a certain extent. Furthermore, the UAS network developed for the traffic incidents was able to provide a satisfying coverage on the influence area of several natural disasters.

The results of the proposed framework can be used for decision-making, including UAS network parameters, drone types, fleet size, and applicable event type. It is worth noting that this effort could be conducted by considering that the constraint due to cost-related factors, e.g., budgets, cost-effectiveness, since the algorithm outputs (i.e. the number of locations of the stations) is closely related to the potential cost.

Future work is desired to improve the network design. An obvious gap, and one intentionally descoped from this research, was the lack of any practical or operational considerations in the utility of drones for the incident types discussed. The next step is to think about the practical implications and implementation considerations of drones at these “key stations” and factor in important considerations such as drone flight times, sensor capabilities, and airspace and property flyover restrictions. For this purpose, a pilot study is desired to calibrate the operational parameters of drones and identify potential issues that may arise in practice. Another future direction is further optimize the UAS network by considering more aspects of cost, such as the cost of the drones (capture purchase), drone maintenance, facility operation (such as the trucks needed to carry the drones), etc.

5.0 Appendices

Appendix A: Existing Applications of UAS in Emergency Responses

This part presents the detailed review of the existing applications of UAS in emergency responses. It focuses on how UAS can be used after an emergency has occurred.

Fire

Compared with manned aircraft, UAS have proven to be a cost-effective solution in response to small-to-medium scale wildfires (*40*). Helicopters cost roughly $2,500 per hour to fly, while UAV cost a fraction of that amount (*41*). In terms of efficiency, multiple UAV can be configured to perform rescue tasks simultaneously when a building is on fire (*42*).
Fire management is probably the most popular application area of UAS compared to other disasters. Between 2006 and 2010, the U.S. Forest Service and the National Aeronautics and Space Administration (NASA) flew 14 missions with NASA's Ikhana drone over 57 fires in the U.S., using a multispectral sensor to provide intelligence to firefighting teams (*43*). The Fire and Rescue Department of Montgomery County in Maryland purchased three drone systems in 2014 to provide real-time imagery during high-rise blazes to show fire strength and to assess building structural integrity (*43*).

UAS can be very useful during building fire rescue. A British start-up, Unmanned Life, developed a software package to simultaneously operate multiple autonomous drones to assist with a fire rescue mission (*42*). UAS can also be used for pre-disaster warning. Seo et al. (*44*) proposed a monitoring and emergency response method utilizing UAS for fires in buildings. This system can detect building fires using indoor and outdoor UAS and help to safely evacuate buildings.

Earthquake

Given damaged surface transportation infrastructure after an earthquake, UAS can be very useful in mapping the affected area to assess damage or share rescue sources (*40*). UAV can provide unique viewing angles at low altitudes, which is not possible from manned aircraft (*43*).

UAS are frequently used to perform mapping and rescue missions after an earthquake. In 2013, as part of the reconstruction efforts following the 2010 earthquake in Haiti, the inter-governmental International Organization for Migration teamed up with the Swiss nonprofit Drone Adventures to assess destroyed houses, take a census of public buildings and hospitals, and monitor camps for internally displaced persons (*45*).

Flooding

UAS have proven to be very effective in conducting pre-disaster and post-disaster mapping and assessment. UAV can be deployed to monitor the conditions of dams and river banks. In case of a broken dam or in situations where citizens are trapped in flooded areas, UAS can support search and rescue activities (*40*). In 2013, a mapping drone called eBees was deployed to identify potential flood-prone zones in Haiti, and helped collect information for constructing protective infrastructure to avoid future catastrophes (*45*).

Hurricane

After a hurricane, UAS can be deployed to affected locations which are often inaccessible due to fallen trees or utility poles, flooding, road damage, etc. (*46*), allowing responders to gain a clear picture of the overall damage distribution and to then prioritize rescue tasks (*43*).

UAS were used in Hawaii in 2014 following Tropical Storm Iselle (*46*). They were integrated into the Mobile Emergency Response and Command Interface (MERCI), a system for collecting damage assessment data. Drones were equipped with cameras and sensors to collect data to provide situational awareness and for identifying and quantifying damages. The data collected by drones was then integrated with other data sources (such as crowd-sourcing data), which were found invaluable for rescue, response, and recovery. A main challenge lies in how to rapidly process the various data sources and extract useful information. The "Flying COW"—a drone used in AT&T's Network Disaster Recovery system—was used to provide emergency 4G coverage in Puerto Rico during the aftermath of Hurricane Maria. Each Flying COW was able to cover about 22 square miles (*42, 47*).

Outside of the U.S., Drone Adventures used eBees to assist the Philippines with a post-disaster needs assessment following the 2013 Typhoon Haiyan. The gathered data provided local leaders and humanitarian organizations with detailed maps and damage information to plan and coordinate relief efforts (*45*). Drones were also used for post-disaster assessment after tropical Cyclone Pam in 2015 in Vanuatu (*48*). Ezequiel et al. (*49*) described an example of using ArduPilot MegaMission Planner to process UAS flight data on a coastal section of the City of Tacloban in the Philippines.

Volcanos

Amici et al. (*50*) developed a UAS-based real-time data acquisition system and tested it at the Le Salinelle mud volcano located at the southwest boundary of the Mt. Etna volcano, by integrating a low-weight thermal camera into a hexacopter. In their test, the UAS was able to record and transmit real-time videos to the remote ground station under an extreme environment.

Landslides

Huang et al. (*51*) developed a highway landslide warning and emergency response system based on UAS. This system consists of two main components: a landslide warning sub-system and a UAS emergency response sub-system.

Search and Rescue

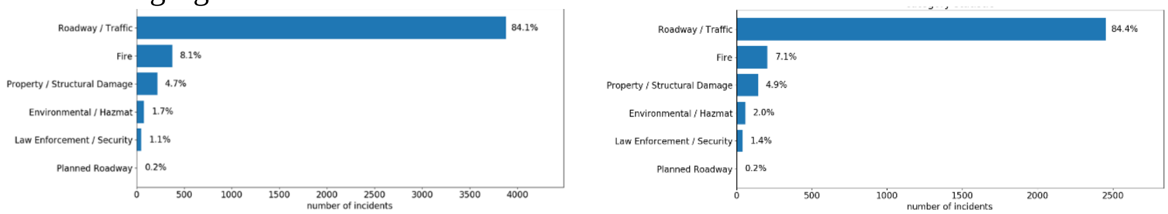
The first 72 hours after a disaster are the most precious for search and rescue operations (*52*). However, search and rescue operations in this period can be better suited for UAS than manned aircrafts (*43*). Different types of UAV can be applied in a variety of scenarios. A simple application is to use UAV to provide live video feeds that will assist in searching for missing persons.

In 2012, the Texas search and rescue group EquuSearch was able to use a drone to locate a missing boy in a pond after a failed ground search. The ground search was challenged by the presence of alligators, wild hogs, and poisonous snakes (*43*). In 2014, amateur drone operator David Lesh located an 82-year-old man alive in a bean field using an octocopter. Prior to this, hundreds of volunteers and a helicopter team had spent several days trying to find him (*43*).

While small drones excel at locating people such as in the two cases above, heavy-lift drones are often equipped with the additional capability to transport personnel and rescue survivors from a disaster site (*43*).

Appendix B: Incident Statistics with Different Thresholds

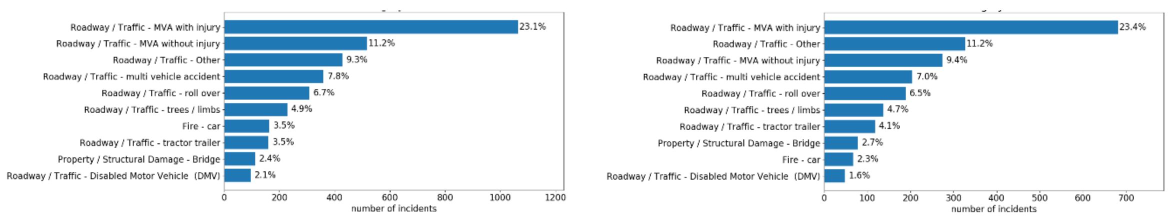
The following figures show the incident data statistics with different duration thresholds.



a) Severity > Level 2; 60min < Duration < 1000min

b) Severity > Level 2; 120min < Duration < 1000min

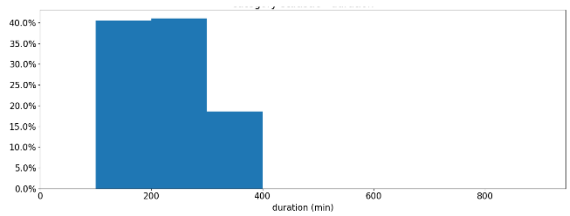
Figure 5.1: Frequency of each category under different thresholds



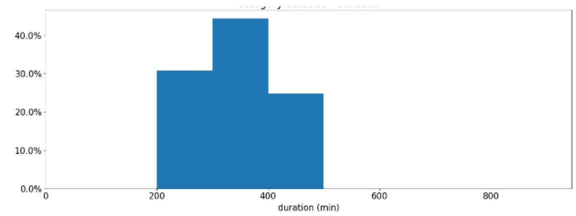
a) Severity > Level 2; 60min < Duration < 1000min

b) Severity > Level 2; 120min < Duration < 1000min

Figure 5.2: Frequency of top 10 subcategory under different thresholds



a) Severity > Level 2; 60min < Duration < 1000min



b) Severity > Level 2; 120min < Duration < 1000min

Figure 5.3: Duration distribution under different thresholds

Appendix C: Pseudo Code of the Greedy Algorithm

The pseudo codes of the greedy algorithm are shown in Table 5.1.

Table 5.1: The greedy algorithm pseudo codes

Step #	**Description**
Input	Incident set $\boldsymbol{I} = \{I_1, I_2, \ldots, I_n\}$, Station candidate position set $\boldsymbol{C} = \{C_1, C_2, \ldots, C_m\}$, Station radius r, the expected coverage E
Step 1.	Cover incidents by an appropriate amount of second-round candidates Covered incident set $\boldsymbol{CI} = \emptyset$ Second-round candidates set $\boldsymbol{SC} = \emptyset$ Pick a random start point C^* in $\boldsymbol{C}$ **While** $size(\boldsymbol{CI}) < n$ and $size(\boldsymbol{SC}) < m$: I^* =Find the incidents in $\boldsymbol{I}$ that are covered by C^* with radius r $\boldsymbol{CI}$.append(I^*) $\boldsymbol{I}$.remove(I^*) $\boldsymbol{SC}$.append(C^*) C^* = find the furthest candidate position from C^* in $\boldsymbol{C}$
Step 2	Select final stations from the second-round candidates set by the number of incidents they cover $\boldsymbol{SC}$.rank(by the number of incidents in $\boldsymbol{II}$ that are covered by SC_i with radius r) Optimal station set $\boldsymbol{S} = \emptyset$ **For** $potential\ stations\ SC_i$ in $\boldsymbol{SC}$**:** II^* =the number of incidents in $\boldsymbol{II}$ that are covered by SC_i **If** coverage > E: Break $\boldsymbol{S}$.append(SC_i) $\boldsymbol{II}$.remove(II^*)
Output	Optimal station set $\boldsymbol{S}$

In the greedy algorithm described above in Table 5.1, Step 1 is designed to avoid over-computation regarding the incident and candidate source (redundant candidates are dropped as soon as all incidents are covered, and vice versa). Step 2 is employed to guarantee the robustness by ranking the initial set by importance. The final station set is then selected from the more relevant ones to less relevant ones until meeting the expected coverage.This page left blank intentionally.

6.0 References

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