Global Benchmarking Program Study on Unmanned Aerial Systems (UAS) for Surface Transportation

Domestic Desk Review

U.S. Department of Transportation
Federal Highway Administration

Office of Infrastructure
FHWA-HIF-20-091

August 2020

FOREWORD

This report presents the results of research conducted for the Federal Highway Administration (FHWA) on the state of the practice for the use of unmanned aerial systems (UAS) for surface transportation operations in the United States. The information presented may be of interest to State and local transportation operators or policymakers who are considering incorporating UAS into the operational frameworks.

Brian J. Fouch, PE
Director, Office of Preconstruction,
Construction, and Pavements

Notice

This document is disseminated under the sponsorship of the U.S. Department of Transportation (USDOT) in the interest of information exchange. The U.S. Government assumes no liability for the use of the information contained in this document.

The U.S. Government does not endorse products or manufacturers. Trademarks or manufacturers' names appear in this report only because they are considered essential to the objective of the document. They are included for informational purposes only and are not intended to reflect a preference, approval, or endorsement of any one product or entity.

Non-Binding Contents

The contents of this document do not have the force and effect of law and are not meant to bind the public in any way. This document is intended only to provide clarity to the public regarding existing requirements under the law or agency policies.

Quality Assurance Statement

The Federal Highway Administration (FHWA) provides high-quality information to serve Government, industry, and the public in a manner that promotes public understanding. Standards and policies are used to ensure and maximize the quality, objectivity, utility, and integrity of its information. FHWA periodically reviews quality issues and adjusts its programs and processes to ensure continuous quality improvement.

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA-HIF-20-091	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Global Benchmarking Study on Unmanned Aerial Systems for Surface Transportation: Domestic Desk Review		5. Report Date August 2020 6. Performing Organization Code:
7. Author(s) Fischer, Stephanie; Lawless, Emily; Lu, Jason; Van Fossen, Kirsten		8. Performing Organization Report No. DOT-VNTSC-FHWA-20-15
9. Performing Organization Name and Address U.S. Department of Transportation John A. Volpe National Transportation Systems Center 55 Broadway Cambridge, MA 02142- 1093		10. Work Unit No. 11. Contract or Grant No. Intra-Agency Agreement 693JJ318N300013, HW05A1
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Highway Administration 1200 New Jersey Avenue, SE Washington, DC 20590		13. Type of Report and Period 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

This desk review presents a high-level summary of the current state of the practice of unmanned aerial systems (UAS) in the United States. The use of UAS by State Departments of Transportation (DOTs) for surface transportation use cases is steadily increasing, but States continue to report challenges in developing and implementing fully-functioning UAS programs. This report includes a summary of commonly used use cases, current and planned research, operational considerations, data management and analysis strategies, and opportunities for future research.

17. Key Words UAS, surface transportation, operations	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161. http://www.ntis.gov

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized.

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

Contents

1. Introduction 1

Overview 1

Methodology 1

2. UAS Use Cases 3

Infrastructure Inspection and Monitoring..3

Transportation Systems Management and Operations 5

Geological Monitoring and Research to Inform the Protection of Transportation Assets.......6

Weather-Related Data Collection to Support Traffic and Incident Monitoring.......................7

Future Use Cases 8

Maturity Level of Use Cases 10

3. UAS Flight Operations..16

4. UAS Data Collection and Processing Methods 18

5. Challenges and Opportunities for Future Research 21

Organizational 21

Cross-Organizational..21

Technological 21

Operational 22

References..23

List of Figures

Figure 1. Illustration. Data collection and processing - structure-from-motion (SfM) technique (Source: Ohio DOT). 18

Figure 2. Illustration. Data collection and processing - thermal imaging of concrete bridge sections (Source: Minnesota DOT). 19

Figure 3. Illustration. “Schematic view of MAV inspection operation with laser and altitude sensors for SLAM purposes” (Source: Tripicchio, Paolo et al. in *Confined Spaces Industrial Inspection with Micro Aerial Vehicles and Laser Range Finder Localization* (May, 2018), licensed under CC BY 4.0) 19

List of Tables

Table 1. Technology Readiness Level Scale 11

Table 2. Maturity Level of Identified Use Cases 13

List of Abbreviations

Abbreviation	Term
AASHTO	American Association of State Highway and Transportation Officials
BIM	Building Information Modeling
BVLOS	Beyond Visual Line of Sight
DOT	Department of Transportation
EIM	Enterprise Information Management
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
GPS	Global Positioning System
LAANC	Low Altitude Authorization and Notification Capability
LiDAR	Light Detection and Ranging
NASA	National Aeronautics and Space Administration
NCHRP	National Cooperative Highway Research Program
NCSL	National Council of State Legislatures
NOTAM	Notices to Airmen
RPAS	Remotely Piloted Aircraft Systems
RVAS	Remotely Piloted Aerial Vehicles
SfM	Structure-from-Motion
SLAM	Simultaneous Localization and Mapping
STLS	Stationary Terrestrial Laser Scanning
TFR	Temporary Flight Restrictions
TIM	Traffic Incident Management
TRL	Technology Readiness Level
TLS	Terrestrial Laser Scanning
UAS	Unmanned Aerial Systems
UAV	Unmanned Aerial Vehicle
USS	UAS Service Suppliers
UTM	UAS Traffic Management
VDC	Virtual Design and Construction

1. Introduction

Overview

This report presents a high-level summary of the current state of the practice of unmanned aerial systems (UAS) in the United States. Section 2 provides an overview of the landscape of current and planned UAS use cases by State Departments of Transportation (DOTs) and other public agencies. This overview is not meant to be exhaustive, but rather to highlight use cases that may be of particular interest to Federal Highway Administration (FHWA) stakeholders and the general public. Non-highway use cases are also noted, as these activities may feature transferable technology capabilities or processes that could be adapted to highway needs.

Section 3 notes the current policy and regulatory processes governing UAS flight operations at both the State and Federal level. This section identifies areas where States have developed additional rules or processes to address local needs or concerns.

Section 4 discusses processes for collecting, managing, and analyzing data generated from UAS operations and identifies challenges faced by transportation agencies in adapting to new sources and quantities of data.

Finally, section 5 identifies areas that early UAS deployers have identified as priorities for future UAS research and development and notes policy operational or policy gaps where lessons learned from international UAS deployments could provide valuable insights.

Throughout this document, the term UAS is used broadly to refer to unmanned aerial vehicles (UAVs) incorporating varying levels of automation technologies. For clarity, UAS is used as a general term to discuss systems that may be referred to by practitioners or researchers as drones, remotely piloted aircraft systems (RPAS), UAVs remotely piloted aerial vehicles (RVAS), or other similar terms.

The technical and operational capabilities of UAS are rapidly evolving. As a result, new use cases or operational techniques may be developed and adopted following the publication of this report.

Methodology

A significant portion of the information presented in this document was collected as part of the National Cooperative Highway Research Program (NCHRP) 17-01 Domestic Scan.[1] The study team assessed both the final desk scan report as well as unpublished notes and presentations to develop an inventory of use cases, flight operations procedures, and data management practices. Additional Internet searches were conducted to understand the current state of Federal- and

State-level legislation, regulations, policies, guidance, and research relating to the use of UAS in the United States.

2. UAS Use Cases

A recent survey conducted by the University of Massachusetts Transportation Center found that the following categories encompass the majority of current and planned UAS activities: asset management, construction, disaster management, environmental monitoring, infrastructure inspection, surveillance, and traffic operations.[2] A similar 2018 American Association of State Highway and Transportation Officials (AASHTO) survey provided additional detail, noting that "all of the 20 State DOTs operating drones on a daily basis are deploying them to gather photos and videos of highway construction projects. In addition to photography, 14 States also reported using [UAS] for surveying, 12 for public education and outreach, 10 for bridge inspections, 8 for emergency response, 6 for pavement inspections, 5 for scientific research, 2 for daily traffic control and monitoring, and 1…to conduct high-mast light pole inspections."[3]

According to this survey, an additional 15 States were actively researching opportunities to use UAS technology. A follow-up survey conducted by AASHTO in 2019 illustrated the increasing use of this technology, with the number of State DOTs' funding centers or programs for UAS operations growing to 36.[4] These results reflect the steadily growing interest in and adoption of UAS by the highway community. A comprehensive summary of State surveys and domestic scans is maintained by the National Transportation Library's National Transportation Knowledge Network.[5]

This section summarizes current exploratory and operationalized UAS use cases at State DOTs and other public agencies across the United States. Many, but not all, of these use cases relate either directly or indirectly to highway- or infrastructure-related activities. Building from the terminology of the Technology Readiness Level (TRL) scale, Research (TRL 1-5), Development (TRL 6-8), and Implementation (TRL 9) are used to categorize the following use cases according to maturity level at the conclusion of this section.

Infrastructure Inspection and Monitoring

Bridge Inspection

UAS are capable of collecting data on a bridge's physical and functional condition. Traditionally, bridge inspections have been a time- and labor-intensive process, typically completed by crews accessing various areas of the bridge using a combination of equipment (e.g., ladders, ropes, under-bridge vehicles, aerial work platforms, etc.).

Specific bridge inspection use cases include automated spall detection, delamination detection, asset management and condition assessment, underside inspection, and crack comparison. Geospatial outputs for UAS bridge deck sensing include orthoimages, digital elevation models, hillshade, thermal imagery, and point clouds. UAS are also used by some States to develop infrared and 3D models of bridge structures to monitor and measure cracking and condition information and to easily document and share inspection notes. Optical, thermal, and light detection and ranging (LiDAR) imagery from UAS support condition state monitoring and inform deterioration models.

Identification, Assessment, and Inventorying of Roadway Assets

Condition assessment imagery generated by UAS is used for asset management purposes. In addition to monitoring the condition of infrastructure (e.g., pavement cracking), algorithms and classifiers can be trained to detect and track assets such as signs, guard rails, and lamps.[6]

To support corridor mapping efforts, additional work is underway to use UAS and photogrammetry to develop 3D models to provide site and elevation information and to conduct surface surveys. This technique "provides real-world models for conceptual design, construction, and operational decisions, using simple photography rather than expensive LiDAR. 3D models created using [UAS] photogrammetry can be assessed and shared in CAD or GIS."[7] UAS surveying is also being considered as a method to support road design efforts.[8]

Virtual Design and Construction

Some State DOTs are using UAS in conjunction with stationary terrestrial laser scanning (STLS) and conventional surveying to support virtual design and construction (VDC).[9] UAS are used to help develop 3D parametric models in the initial phase of project development. These models are compatible with building information modeling (BIM) and virtual design software and can help significantly reduce the amount of time needed for the surveying process. UAS data also can function in BIM software to improve project design, monitoring, and tracking.[10]

Confined Space Inspection

UAS are being tested as a mechanism for conducting inspections of confined spaces (e.g., wells, culverts, tunnels, pump stations) that may be difficult or impossible for humans to access. This methodology has proven successful for inspections in or between steel and concrete box beams and pier towers.[11]

Volumetric Analysis

Using photogrammetric techniques, UAS provide accurate volume estimates much more quickly than traditional methods using tape measurements or survey-grade Global Positioning System (GPS) or LiDAR equipment. Additionally, UAS provide 3D digital data, which can be used for analysis and record-keeping.[12] This technique is useful for applications such as estimating the volume of fill needed for damaged roadway repairs,[13] or to compute volumes of aggregate mounds via digital elevation models.[14] Other uses include enabling landfill volume calculations or estimating the amount of water that would result in a body of water flooding and potentially endangering travelers on a nearby roadway.[15]

Construction Monitoring and Inspection

UAS collect data to inform the progress or quality of a construction project. Specifically, UAS are used for project documentation (via photos or video) and project management, inspection, and monitoring (e.g., control measures, bridge pours, or traffic control).[16]

Railroad Inspection

UAS are being tested for their effectiveness in inspecting railway conditions, including expansion, contraction, and cracking, via a thermal camera. Additional applications include inspecting track elements along the railway right-of-way, inspecting railway crossings, and supporting security efforts. UAS-based methods are expected to yield significant time and cost savings as compared to traditional manual inspections conducted by foot or with the use of a specially equipped truck.[17] Lessons learned regarding UAS inspection capabilities could inform the use of these technologies for highway infrastructure defect detection, asset monitoring, or structural assessments.

High Mast Light Pole Inspection

UAS collect data to inform the proper functioning of a high mast light pole, which can reduce or eliminate the need to remove guard rails, restrict travel, and perform manual inspections.[18] Such an inspection might identify the need to replace a fixture (e.g., light) or service a component (e.g., clean the luminary). In addition to providing safety benefits, UAS offer closer views and higher definition photos, which have been used by agencies to develop photo logs for identifying and tracking potential issues.[19]

Traffic Signal Inspection

UAS are anticipated to be used to collect data to inform the proper functioning of traffic signals.[20]

Transportation Systems Management and Operations

Traffic Incident Management

As of 2017, 11 State DOTs had or planned to research UAS applications for traffic incident management (TIM). Applications being tested include real-time traffic surveillance, simulation models calibration, vehicle and traffic conditions quantification, and semi-automated video and image annotation.[21] A demonstration of UAS for TIM determined that UAS are able to provide "real-time enhanced video and photography, non-video sensor data, payload mobility…communication of data to a traffic incident command center, guided mobile data collection, safe flight operation near or over live traffic, real-time confirmation and monitoring of a traffic incident, as well as monitoring of alternate routes, incident queuing, and secondary crashes…[However], researchers noted shortcomings and concerns with UAS-TIM capabilities for crash scene mapping," including the permissions associated with operating over public roadways and whether UAS images are sufficiently detailed for use in legal proceedings.[22]

Traffic information collected from UAS data can be used to calculate vehicle speed, cumulative number of vehicles entering/exiting a road, traffic in-flow and out-flow rates, traffic density, and space mean speed. Future applications could include using UAS in more complex traffic or weather conditions, advancing to a fully automatic vehicle detection tool, or demonstrating deployment in a traffic operations center.[23] UAS also collect data that researchers have used to map out traffic incidents that cause delays, such as a scene of a car crash. Researchers report that UAS can map a car crash scene in 5-8 minutes, whereas conventional practices can take 2-3 hours for a severe crash.[24] Operating UAS from the right-of-way has the potential to mitigate or eliminate procedural concerns regarding operations over live traffic.[25]

Collision Scene Reconstruction and Investigation

In combination with advanced imaging software, UAS have the potential to investigate and document collision scenes much more efficiently and allow roadways to be reopened more quickly than traditional methods, such as total station surveying and laser scanning. There may be some limitations to using UAS for this purpose in inclement weather or at night.[26]

Parking Lot Utilization Monitoring

UAS images and videos are used to assess parking lot capacity and the number of available and occupied spots. This information can help support commuter and event management, as well as parking forecasting efforts.[27] This approach also has the potential to be leveraged to support both real-time traffic monitoring and dynamic traffic demand forecasting.

Geological Monitoring and Research to Inform the Protection of Transportation Assets

The use cases noted below represent areas where UAS data have supplemented traditional monitoring and research techniques to more quickly and accurately inform efforts to protect transportation assets from geologic hazards.

Landslide and Rockslide Prediction and Monitoring

UAS capture visual data of rock-covered slopes at risk for rockslides. UAS data are capable of identifying changes over time that forewarn the occurrence of a rockslide. Using photogrammetry techniques, UAS imagery informs the development of "digital surface models used to evaluate rock-slope stability and landslide risk along transportation corridors…a safer alternative to the deployment and operation of [terrestrial laser scanning (TLS)] operating on a road shoulder because UAS can be launched and recovered from a remote location and capable of imaging without flying directly over the road. However, both the UAS and TLS approaches still involve traditional survey control and photo targets to accurately geo-reference their respective digital surface models."[28]

Erosion Research

UAS capture images to investigate areas of land that are deteriorating (or at risk of deteriorating) from natural causes such as wind and water. As part of bridge inspection efforts, UAS have been used "as an effective method to determine stream or river bank conditions upstream or downstream of the bridge as well as capture large overall aerial maps of dynamic bank erosion and lateral scour conditions."[29] This technique has also been used to aid post-disaster road reconstruction efforts.[30]

Geohazard Modeling and Monitoring

High-quality images and LiDAR data generated by UAS are useful for monitoring and assessing geohazards that could potentially impact roadways, such as rockslides, landslides, debris flows, embankment failures, sinkholes, and avalanches. UAS data also are useful for geohazard modeling (e.g., change detection, asset placement, project engineering, site monitoring). The use of UAS has been proven safer and more cost-effective than traditional means of geohazard monitoring, such as using helicopters.[31]

Geologic Mapping

UAS are capable of quantitative and qualitative hazard analysis via the following activities: "gaining an elevation advantage during reconnaissance; locating outcrops; producing scaled orthophoto mosaics for base maps; creating contoured topographic maps; and generating 3D computer models for manipulation, analysis, and 3D printing." These outputs can then be used to conduct damage assessments.[32]

Weather-Related Data Collection to Support Traffic and Incident Monitoring

The applications listed below support weather-responsive traffic management operations by enabling proactive planning via improved forecasting techniques and by facilitating response and recovery efforts. Understanding the intensity, duration, and path of weather events can inform decisions about infrastructure management, such as establishing detour routes or determining whether roadways should remain open.

Storm Damage Assessment

UAS are used to capture aerial imagery of the damage incurred from a storm. Assessing the damage from this perspective can provide immediate actionable information about the condition of transportation assets. UAS also support a variety of storm response activities including firefighting, search and rescue, law enforcement, utility or other critical infrastructure restoration, incident awareness and analysis, damage assessment supporting disaster recovery related insurance claims, and media coverage for providing crucial information to the public.[33]

Forecasting

Small UAS are being researched for their ability to collect atmospheric data to improve weather forecasts. Traditional atmospheric data collection technologies include ground-based instruments and weather balloons. Small UAS are expected to overcome the limitations of weather balloons (e.g., the frequency with which they can be launched).[34]

Snow Mapping

There is interest in using UAS for snow mapping operations.[35] Research has been conducted to compare the efficacy of snow-depth measurements from UAS photogrammetry with traditional manual probing techniques, which may enable improved snow removal efforts on critical roadways.[36]

Future Use Cases

Key areas of current and planned research include the following activities, with many smaller-scale efforts also underway across the Nation.

- **Federal Aviation Administration**:
  UAS operational capabilities and restrictions, including airspace integration, low-altitude traffic management, detect and avoid, communication, human factors, system safety, and certification. Information about Federal Aviation Administration's (FAA) research activities can be found at https://www.faa.gov/uas/research_development/.
- **Federal Highway Administration**:
  The Every Day Counts initiative includes a focus area on highway transportation use cases. For additional information, please visit https://www.fhwa.dot.gov/innovation/everydaycounts/edc_5/uas.cfm.
- **National Aeronautics and Space Administration**:
  Details about the UAS Traffic Management (UTM) research and development can be found at https://utm.arc.nasa.gov/index.shtml.
- **National Science Foundation**:
  The National Science Foundation has awarded over 40 UAS-related research grants since 2017.[37] Additional information about these research grants is available at https://www.nsf.gov/funding/.
- **Center for Unmanned Aircraft Systems:**
  Information about this cooperative research center involving Brigham Young University, the University of Colorado at Boulder, Virginia Tech, the University of Michigan, and Texas

A&M University can be found at https://c-uas.org/about.

- **Other Surface Transportation Initiatives:**
    - UMassAIR Research Projects: https://www.umasstransportationcenter.org/umtc/UMassAir_Research_Projects.asp
        - Application of Unmanned Aerial Systems in Surface Transportation Projects:[38]
            - Assessing roadway pavement condition with UASs
            - Evaluating speed sensing using UAS
            - Investigating the development of an emergency service UAS network to support surface transportation
            - Assessing situational awareness technology to support surface transportation
            - Evaluation of cybersecurity threats and countermeasures to surface transportation
            - Implementation, outreach, and technology transfer coordination and management
        - Unmanned Aircraft Vehicles for Mobile Sensing in Full Scale Structural Testing
        - Understanding Traffic Behavior
    - National Transportation Library Database - Unmanned Aerial Vehicles and Systems: Research Feed: https://transportation.libguides.com/uav/RSS
        - Relevant projects include:[39]
            - Delivering Maintenance and Repair Actions via Automated/Robotic Systems, Caching Unmanned Aerial Vehicle-Enabled Small-Cell Networks
            - Robotic System for Inspection by Contact of Bridge Beams Using UAVs
            - Testing Unmanned Aircraft for Roadside Snow Avalanche Monitoring
            - UAV Bridge Inspection through Evaluated 3D Reconstructions Applications of UAVs in Civil Infrastructure

Additionally, the FAA's Integration Pilot Program supports research into emerging use cases at nine pilot sites across the United States. Insights gained from these proof of concept operations could lead to new operations for State DOTs and other FHWA stakeholders.[40]

- **Choctaw Nation of Oklahoma, Durant, OK:** Agricultural, public safety, and infrastructure inspections; Beyond Visual Line of Sight (BVLOS) operations over people, nighttime operations.
- **City of San Diego, CA:** Border protection, package delivery of food, international commerce, Smart City/autonomous vehicle interoperability, surveillance.

- **Innovation and Entrepreneurship Investment Authority, Herndon, VA:** Package delivery in rural and urban settings; use of enabling technologies such as detect and avoid, identification and tracking, radar systems, and mapping tools.
- **Kansas Department of Transportation, Topeka, KS:** BVLOS operations in rural communities, precision agriculture operations using a statewide unmanned traffic management system.
- **Memphis-Shelby County Airport Authority, Memphis, TN:** Inspection of FedEx aircraft, autonomous operations to support airport operations (e.g., perimeter security surveillance; package delivery; working with a UTM concept that would also work with manned air traffic).
- **North Carolina Department of Transportation, Raleigh, NC:** Localized package delivery within a defined airspace.
- **North Dakota Department of Transportation, Bismarck, ND:** Diverse operations to expand UAS operations at night and BVLOS, leading to scalable operations for industries such as linear infrastructure operations, crop health monitoring, media reporting, and emergency response.
- **City of Reno, NV:** Time-sensitive delivery of life-saving medical equipment, such as medical defibrillators in emergency situations in urban and rural environments.
- **University of Alaska-Fairbanks, Fairbanks, AK:** Pipeline inspection and surveying in remote areas and harsh climate conditions; operations in both rural and urban areas, including public safety operations and UAS detection.

Maturity Level of Use Cases

One way to assess and communicate the maturity level of the various use cases presented above is to use the Technology Readiness Level Scale (Table 1).[41] A technology readiness level (TRL) is a number that is assigned to a technology based on how far along that technology is in the process of research, development, and implementation. Considering and answering the questions in the Requirements column of the Technology Readiness Level Scale table helps to determine the TRL of the technology undergoing analysis. For the purposes of this report, two research categories—Basic Research and Applied Research—are grouped into one Research category. Use cases that fall into TRLs 1-5 are categorized as Research, TRLs 6-8 as Development, and TRL 9 as Implementation.

Table 1. Technology Readiness Level Scale

TRL	Category	Description	Requirements
1	Basic Research	Basic principles and research	• Do basic scientific principles support the concept? • Has the technology development methodology or approach been developed?
2		Application formulated	• Are potential system applications identified? • Are system components and the user interface at least partly described? • Do preliminary analyses or experiments confirm that the application might meet the user need?
3		Proof of concept	• Are system performance metrics established? • Is system feasibility fully established? • Do experiments or modeling and simulation validate performance predictions of system capability? • Does the technology address a need or introduce an innovation in the field of transportation?
4	Applied Research	Components validated in laboratory environment	• Are end-user requirements documented? • Does a plausible draft integration plan exist, and is component compatibility demonstrated? • Were individual components successfully tested in a laboratory environment (a fully controlled test environment where a limited number of critical functions are tested)?
5		Integrated components demonstrated in laboratory environment	• Are external and internal system interfaces documented? • Are target and minimum operational requirements developed? • Is component integration demonstrated in a laboratory environment (fully controlled setting)?

TRL	**Category**	**Description**	**Requirements**
6	Development	Prototype demonstrated in relevant environment	• Is the operational environment (that is, user community, physical environment, and input data characteristics, as appropriate) fully known? • Was the prototype tested in a realistic and relevant environment outside the laboratory? • Does the prototype satisfy all operational requirements when confronted with realistic problems?
7		Prototype demonstrated in operational environment	• Are available components representative of production components? • Is the fully integrated prototype demonstrated in an operational environment (real-world conditions, including the user community)? • Are all interfaces tested individually under stressed and anomalous conditions?
8		Technology proven in operational environment	• Are all system components form-, fit-, and function-compatible with each other and with the operational environment? • Is the technology proven in an operational environment (meet target performance measures)? • Was a rigorous test and evaluation process completed successfully? • Does the technology meet its stated purpose and functionality as designed?
9	Implementation	Technology refined and adopted	• Is the technology deployed in its intended operational environment? • Is information about the technology disseminated to the user community? • Is the technology adopted by the user community?

Table 2. Maturity Level of Identified Use Cases

Use case	Maturity level	Justification for Maturity Level Categorization
Infrastructure Inspection and Monitoring		
Bridge Inspection	Development/ Implementation	Several State DOTs, including Alabama, California, Connecticut, Florida, Idaho, Kentucky, Michigan, and Minnesota, have tested UAS assistance for bridge data collection.[42,43,44] A 2018 AASHTO survey found that at least 10 State DOTs were operating UAS for bridge inspection purposes.[45] However, there is a range of research and development activity in bridge inspection use cases among State DOTs, and specific bridge inspection use cases may fall into lower maturity levels.
Identification, Assessment, and Inventorying of Roadway Assets	Development	Six State DOTs, including Ohio and Vermont, report using UAS for pavement inspections, but these activities appear to primarily be in the testing phase.[46]
Virtual Design and Construction (VDC)	Development	While VDC is used regularly by general contractors in the private sector,[47] there is limited documentation of use of UAS-supported VDC by public agencies. However, some States have incorporated UAS into their surveying operations to inform design projects.[48]
Confined Space Inspection	Development	Minnesota DOT has demonstrated the use of UAS for confined space inspections[49] and has shared videos and other data collected during such inspections.[50,51]
Volumetric Analysis	Implementation	There are several examples of academic research projects exploring volumetric analysis,[52] and multiple State DOTs actively use UAS for this purpose, including Colorado's work estimating pond capacity,[53] Michigan's work estimating aggregate mound volume,[54] and Vermont's volume estimation for damaged roadways.[55]
Construction Monitoring and Inspection	Development/ Implementation	Several States, including North Carolina and Montana, use UAS-based imagery to improve construction monitoring and inspection, and additional research is underway to incorporate UAS into "smart construction" processes.[56,57]

Use case	Maturity level	Justification for Maturity Level Categorization
Railroad Inspection	Development	While many potential uses for railway inspections have been identified, most States are in the early stages of incorporating these activities into their standard operations. State agencies in Vermont and North Carolina have explored the use of UAS for projects involving rail.[58] Additionally, the FAA Focus Area Pathfinder Program is using UAS to conduct supplemental track and structure inspection and track integrity flights for BNSF, which may provide information that could be applied to similar inspections of highway transportation assets.[59]
Parking Lot Utilization Monitoring	Development	UAS have been successfully tested as a tool for monitoring parking lots, but there is limited evidence of this use case currently in practice at State DOTs. Media reports indicate that Arizona, Colorado, and Delaware officials have used UAS to monitor parking lot utilization.[60] This information can be used to inform real-time traffic monitoring efforts.
High Mast Light Pole Inspection	Implementation	New Jersey has demonstrated a high number of successful flight operations. In January 2018, NJDOT reported 241 of their 250 high mast light pole inspections were successfully completed with UAS.[61]
Traffic Signal Inspection	Research	Traffic signal inspection has been identified as a potential future use case, but there is little evidence to support current use at State DOTs.
Transportation Systems Management and Operations		
Traffic Incident Management (TIM)	Development/ Implementation	Significant research and testing has been completed, notably in the State of Michigan, and some States have begun to operationalize UAS into specific aspects of TIM. However, several gaps have been identified where further research and development is needed to better supplement or replace traditional methods.[62] Surveys conducted by AASHTO indicate that numerous States are interested in or have begun testing this use case.
Collision Scene Reconstruction and Investigation	Development	While North Carolina DOT has demonstrated that using UAS-based imaging software for collision scene reconstruction has potential time and cost benefits,[63] additional work is needed to fully integrate UAS in more challenging situations, such as inclement weather or at night. Tippecanoe County Sheriff's Office in Indiana tested the technology at crash sites 20 times in 2018.[64]

Use case	Maturity level	Justification for Maturity Level Categorization
Geological Monitoring and Research to Inform the Protection of Transportation Assets		
Landslide and Rockslide Prediction and Monitoring	Implementation	In 2016, the Pacific Northwest Transportation Consortium researched UAS for landslide assessment.[65] Multiple State DOTs, such as Colorado, California, and Vermont, now use UAS to capture landslide-related imagery.[66] However, in many cases this is expected to enhance, rather than replace, traditional survey methods.
Erosion Research	Implementation	State DOTs, such as Minnesota and California, have integrated UAS into erosion-related bridge inspection, bank erosion mapping, and post-disaster road reconstruction efforts.[67,68] North Carolina DOT, Georgia-based Atlantic Coast Conservancy, and University of Delaware have also used UAS for erosion-related research.[69]
Geohazard Modeling and Monitoring	Implementation	Colorado DOT has integrated UAS into their Geohazards Program and has developed a comprehensive set of policies, procedures, and lessons learned related to site documentation and geohazard modeling.[70]
Geologic Mapping	Development	Testing and pilot demonstrations have been successful, and researchers are beginning to translate this technology into practical use.
Weather-Related Data Collection to Support Traffic and Incident Monitoring		
Storm Damage Assessment	Implementation	UAS were widely used during recent natural disasters, including use by North Carolina DOT following Hurricane Florence and Texas DOT following Hurricane Harvey; FAA has developed processes to facilitate these activities in the future.[71,72]
Forecasting	Development	A four-year, $6 million research effort is underway to assess opportunities for UAS to gather lower atmosphere weather data, with one pilot demonstration including 12 UAS completing 250 flights during a three-day period.[73]
Snow Mapping	Research	Snow mapping has been identified as a potential use case, but research appears to be in the early stages.

3. UAS Flight Operations

The National Council of State Legislatures (NCSL) tracks UAS legislation and regulations at both the State and Federal level. According to NCSL, as of April 2020, at least 44 States had passed legislation regarding UAS operations, with an additional three States adopting resolutions.[74] In general, State-level legislation focuses on definitional issues and the use of UAS by law enforcement, State agencies, and the public. AASHTO notes that 36 of the 49 States identified as deploying or researching UAS through its 2019 survey "have hired hundreds of staff, including highly-skilled personnel to manage drone operations. Those state DOTs…also reported having 279 FAA-certified drone pilots on staff or approximately eight pilots per state."[75]

Many States with active UAS programs have developed comprehensive guides to provide operators with information regarding relevant Federal regulations and exemptions, as well as State-specific guidelines and policies. Caltrans is an example of a State with well-defined UAS operational procedures. The department developed a UAS handbook that includes details on State-level processes for:

- Defining UAS remote pilot and crew roles and responsibilities.
- Reporting on UAS operations.
- Managing safety/traffic closure/right of way.
- Establishing procedures (operational, reporting, and insurance processes) for construction contractors and encroachment permittees.

States have also developed best practices for technical considerations that are not governed by Federal requirements. For example, the "Implementation of Unmanned Aerial Vehicles (UAVs) for Assessment of Transportation Infrastructure—Phase II Final Report" developed by Michigan Tech Research Institute and Michigan DOT provides detailed manuals for the use of UAS and sensors, as well as for several algorithms developed for infrastructure and traffic monitoring. Other examples of State-level policies and guidelines can be found in the use case examples documented in section 2.

UAS operators in both the public and private sectors must also adhere to statutory and regulatory requirements. Public aircraft operations (including UAS operations) are governed under the statutory requirements for public aircraft established in 49 USC 40102 and 40125. Additionally, both public and civil UAS operators may operate under the regulations promulgated by the FAA. The provisions of 14 CFR part 107 apply to most operations of UAS weighing less than 55 lbs. Operators of UAS weighing greater than 55 lbs. may request exemptions to the airworthiness requirements of 14 CFR part 91 pursuant to 49 USC 44807. UAS operators should also be aware of the requirements of the airspace in which they wish to fly. The FAA provides extensive resources and information to help guide UAS operators in determining which laws, rules, and regulations apply to a particular UAS operation. For more information, please see https://www.faa.gov/uas/.

4. UAS Data Collection and Processing Methods

The NCHRP 17-01 Domestic Scan contains several case studies of States implementing advanced data collection and processing methods. The Structure-from-Motion (SfM) technique is most widely used in geological surveying in order to capture complex rock formations, but has now been used by the Alaska Center of UAS integration to create a three-dimensional reconstruction of the 280-ft-long Placer River Bridge near Anchorage, AK (NCHRP, 2018, p. 84 of 254). SfM has also been used to survey land near the Moki Dugway in Bluff, UT (NCHRP, 2018, p. 92 of 254); any changes in land or infrastructure captured by UAS-enabled SfM would provide an early warning.

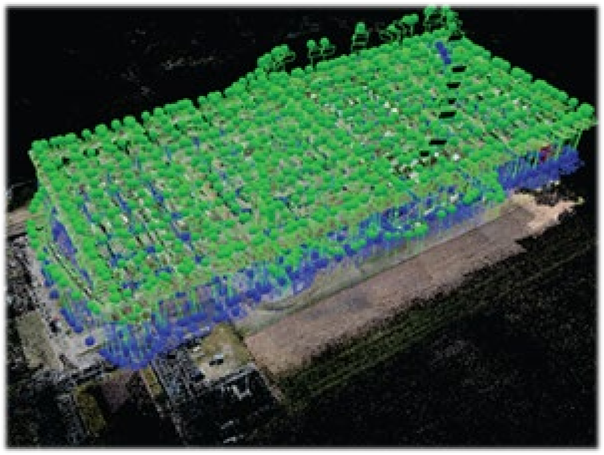

Figure 1. Illustration. Data collection and processing - structure-from-motion (SfM) technique (Source: Ohio DOT).

Thermal imaging is another advanced data collection and processing technique. In a series of lab and field tests led by Michigan Technical University, UAS flew over sections of concrete and industry thermal imaging sensors were used to capture delaminations (i.e., unwanted holes and voids below the surface).[76] Thermal imaging was used along a section of US Route 31 north of Muskegon, MI, and found "*that 13.6% of [a bridge over the White River] had delaminations*" and the bridge was given a "poor" rating (NCHRP, 2018, p. 86 of 254). A combined approach where in-situ methods are only applied after UAS-based thermal imaging identifies high-priority areas could prove very cost-effective.

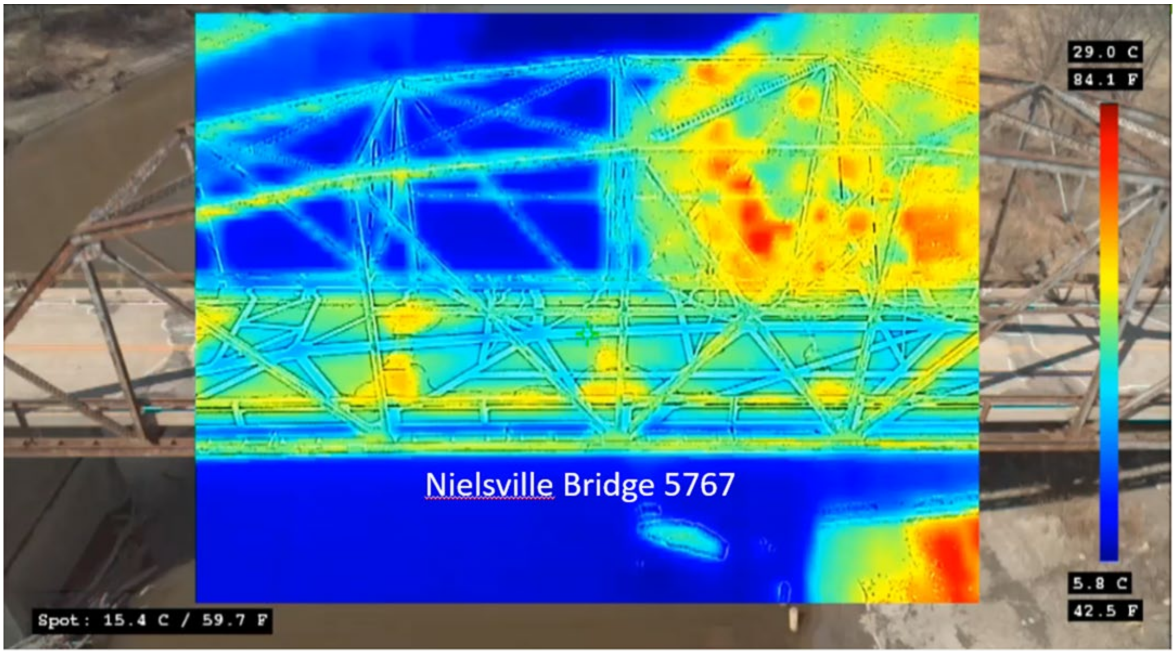

Figure 2. Illustration. Data collection and processing - thermal imaging of concrete bridge sections (Source: Minnesota DOT).

Simultaneous localization and mapping (SLAM) is the technique in which a remotely controlled vehicle (which can be a UAS), placed at an unknown location in an unknown environment, incrementally builds a picture of its own location as well as the environment.[77] One way to implement SLAM is by using laser range finders[78] and processing the range data with least-squares or sequential Kalman filtering techniques. In a Minnesota DOT bridge inspection operation, a UAS navigated very confined spaces to examine the health of structural elements from the inside while determining its position with SLAM (NCHRP, 2018, p. 89 of 254).

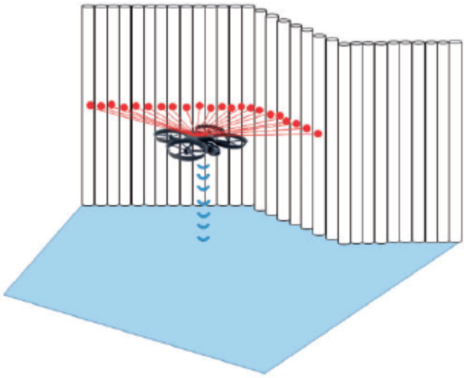

Figure 3. Illustration. "Schematic view of MAV inspection operation with laser and altitude sensors for SLAM purposes" (Source: Tripicchio, Paolo et al. in *Confined Spaces Industrial Inspection with Micro Aerial Vehicles and Laser Range Finder Localization* (May, 2018), licensed under CC BY 4.0)

Aside from NCHRP use cases, Minnesota State DOT has examined a wide range of image processing techniques and deliverables with respect to UAS photographic bridge inspection.[79] MNDOT's study tested five commercial software packages for image processing (MN State DOT, 2018, p. 38 of 345), and a variety of deliverables such as orthomosaic maps and digital surface models, which can satisfy a wide range of missions. MNDOT provides several examples of image processing outputs (MN State DOT, 2018, p. 42 of 345). Vermont State DOT used UAS to find debris blockages (mainly from felled trees and wooden light poles) of rural State highways,[80] and developed a threat and risk evaluation scheme to identify priority areas for authorities' attention (VT State DOT, 2016, p. 62 of 122). Such a method has the potential to help State DOTs effectively allocate limited resources.

Challenges of infrastructure inspection with UAS are just as important to note as the potential benefits. GPS coverage or lack thereof (in confined spaces or areas shadowed by infrastructure) can limit UAS navigation capabilities. Certain commercial UAS models are best suited for individual use cases while others may not meet minimum performance specifications with respect to data quality (e.g., a particular model may not be capable of identifying and documenting cracks in a low-lighting environment).[81] UAS battery life is sensitive to air temperature (hotter, less endurance) and to wind conditions (drains very quickly in 15 mph or higher).

5. Challenges and Opportunities for Future Research

This report identified a number of challenges for UAS operations. The following section presents a series of subsections that span the range of challenges, each offering examples within. These challenges represent areas where international advances could provide valuable lessons learned to advance the state of the practice in the United States.

Organizational

- **Obtaining executive support:** The business case for a UAS project is not always straightforward, although results from completed and ongoing research have demonstrated opportunities for cost savings over time.
- **Appetite for change within organizations:** Some organizational cultures might be too risk-averse to deploy emerging technologies, and some organizations may lack the internal capacity to effectively implement a UAS program.

Cross-Organizational

- **Lack of standardized training and operations:** Collaboration across organizations can be challenging due to inconsistent processes and procedures.
- **Lack of data management protocols and tools:** Data storage between agency and contractors can be a challenge. File sizes are very large and may take significant time to download, especially when passing through agency firewalls, and there is a large time investment associated with data organization and processing. Many agencies cited the need for improved storage solutions.

Technological

- **Battery storage limitation:** Each type of battery has a specified range; battery range might be reduced in certain conditions (e.g., extreme cold).
- **Rapid pace of technological development:** UAS technology is advancing at a rapid pace, and some potential operators may debate delaying their programs until more advanced technology can be acquired at a lower cost.
- **Radio frequency interference:** Some UAS rely on the 2.4 GHz radio frequency, which is the same radio frequency on which wireless computer networks rely.
- **"Off-the-shelf" limitations:** Additional research could inform a better understanding the limitations of different UAS models.
- **Cost of technology:** Purchasing a product or service in the UAS industry can become expensive, especially for more advanced systems capable of supporting complex use cases.
- **Firewalls:** Firewalls can slow the upload, download, or transfer of UAS data.

Operational

- **Difficult weather conditions:** Weather conditions, such as extreme cold, high winds, heavy rain, are a challenge for both the UAS and its human operator.
- **Poor GPS or satellite connectivity:** GPS is necessary for flying UAS in autopilot mode, which enables more advanced missions and functionality. Skilled pilots are needed to operate UAS in GPS-deprived environments.
- **Dense vegetation:** It can be difficult to navigate densely vegetated areas.

References

---

1 “Successful Approaches for the Use of Unmanned Aerial System by Surface Transportation Agencies," NCHRP, July 18, 2017, http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP20-68A_17-01.pdf.

2 Michael Plotnikov, Daiheng Ni, and John Collura, “The State of the Practice of Unmanned Aircraft Systems in State Departments of Transportation,” 2018, https://trid.trb.org/view/1495913.

3 “35 State DOTs are Deploying Drones to Save Lives, Time and Money,” accessed May 14, 2019, https://news.transportation.org:443/Pages/NewsReleaseDetail.aspx?NewsReleaseID=1504.

4 MissionControl, accessed May 22, 2019, https://www.transportation.org/wp-content/uploads/2019/05/MissionControl_Drones3.pdf.

5 Bobbi deMontigny, “LibGuides: Unmanned Aerial Vehicles and Systems: State Surveys and Domestic Scans,” accessed February 15, 2019, //transportation.libguides.com/uav/surveys.

6 “Michigan Bridge Conference Workshop: Applications of UAVs for transportation infrastructure assessment,” http://www.ctt.mtu.edu/sites/ctt/files/resources/bridge2016/workshop/10brooks-uav-assessment.pdf.

7 “Drone Program Takes off in Bureau of Aeronautics,” NJDOT Technology Transfer (blog), January 24, 2018, https://www.njdottechtransfer.net/2018/01/24/drone-program-takes-off-bureau-aeronautics/.

8 “Kansas Testing Drones for Designing Roads,” US News & World Report, accessed August 2, 2019, https://www.usnews.com/news/best-states/kansas/articles/2018-05-27/kansas-testing-drones-for-designing-roads.

9 “Virtual Design Construction,” n.d., http://proceedings.esri.com/library/userconf/proc17/papers/511_693.pdf.

10 “[CASE STUDY] DroneDeploy Drones Improve Contractor’s Site Planning, Design, Safety,” For Construction Pros, accessed August 2, 2019, https://www.forconstructionpros.com/construction-technology/article/20865700/case-study-dronedeploy-drones-improve-contractors-site-planning-design-safety.

11 Barritt Lovelace, “Improving the Quality of Bridge Inspections Using Unmanned Aircraft Systems (UAS),”July 2018, https://www.dot.state.mn.us/research/reports/2018/201826.pdf.

12 Richard Kramer Rhodes, “UAS as an Inventory Tool: A Photogrammetric Approach to Volume Estimation,” August 2017, https://scholarworks.uark.edu/cgi/viewcontent.cgi?article=3963&context=etd.

13 “Case Studies : UVM UAS Team : University of Vermont,” accessed August 2, 2019, http://www.uvm.edu/~uas/?Page=CaseStudies.php.

14 Brooks et al., “Implementation of Unmanned Aerial Vehicles for Assessment of Transportation Infrastructure – Phase II,” 2018, https://www.michigan.gov/documents/mdot/SPR-1674_FinalReport_revised_631648_7.pdf.

15 “Water Pond Surveying for Colorado DOT,” Datumate (blog), February 19, 2017, https://www.datumate.com/case-studies/colorado-dot/.

---

16 2018 DCE Meeting Aviation, accessed August 2, 2019, https://connect.ncdot.gov/projects/construction/Structural%20Design%20AGCDOT%20Joint%20Bridge%20Design%20Commi/2018%20DCE%20Meeting%20Aviation%20-%20Yap.pdf.

17 Javier Irizary et al., “Potential Unmanned Aircraft Systems Based Operations within a Department of Transportation: Findings from a Focus Group Study,” 2017.

18 “Flying the High Masts,” May 2, 2018, https://www.aopa.org/news-and-media/all-news/2018/february/05/flying-the-high-masts.

19 Drone Program Takes off in Bureau of Aeronautics,” NJDOT Technology Transfer (blog), January 24, 2018, https://www.njdottechtransfer.net/2018/01/24/drone-program-takes-off-bureau-aeronautics

20 “Traffic Management: Georgia DOT Contemplating Drones for Traffic Control | Roads & Bridges,” accessed August 2, 2019, https://www.roadsbridges.com/traffic-management-georgia-dot-contemplating-drones-traffic-control.

21 Charles R. Stevens, "Concept of Operations and Policy Implications for Unmanned Aircraft Systems Use for Traffic Incident Management (UAS-TIM)," March 2017, https://static.tti.tamu.edu/tti.tamu.edu/documents/PRC-15-69F.pdf.

22 Charles R. Stevens, "Concept of Operations and Policy Implications for Unmanned Aircraft Systems Use for Traffic Incident Management (UAS-TIM)," March 2017, https://static.tti.tamu.edu/tti.tamu.edu/documents/PRC-15-69F.pdf.

23 Brooks et al., “Implementation of Unmanned Aerial Vehicles for Assessment of Transportation Infrastructure – Phase II,” 2018, https://www.michigan.gov/documents/mdot/SPR-1674_FinalReport_revised_631648_7.pdf.

24 Purdue News Service, “Drones Shown to Make Traffic Crash Site Assessments Safer, Faster and More Accurate,” accessed August 2, 2019, https://www.purdue.edu/newsroom/releases/2019/Q1/drones-shown-to-make-traffic-crash-site-assessments-safer,-faster-and-more-accurate.html.

25 Charles R. Stevens, "Concept of Operations and Policy Implications for Unmanned Aircraft Systems Use for Traffic Incident Management (UAS-TIM)," March 2017, https://static.tti.tamu.edu/tti.tamu.edu/documents/PRC-15-69F.pdf.

26 NCDOT NCSHP Collision Study, accessed August 4, 2019, https://connect.ncdot.gov/resources/Aviation%20Resources%20Documents/NCDOT_NCSHP_Collision_Study.pdf.

27 Benjamin Coifman et al., “Roadway Traffic Monitoring from an Unmanned Aerial Vehicle,” 2006, https://doi.org/10.1049/ip-its:20055014.

28 Keith Cunningham, Joseph Wartman, and Claire Rault, “Unmanned Aircraft System Assessments of Landslide Safety for Transportation Corridors: Final Project Report,” December 2016, https://snap.uaf.edu/sites/default/files/UAS%20Assessments%20of%20Landslide%20Safety%20for%20Transporation%20Cooridors%20%281%29.pdf.

29 Barritt Lovelace, “Improving the Quality of Bridge Inspections Using Unmanned Aircraft Systems (UAS),”July 2018, https://www.dot.state.mn.us/research/reports/2018/201826.pdf.

30 “Time-Lapse View of California Highway 1 Reconstruction after 2017 Landslide,” accessed February 27, 2019, https://www.usgs.gov/center-news/time-lapse-view-california-highway-1-reconstruction-after-2017-landslide?qt-news_science_products=1#qt-news_science_products.

31 Beau Taylor, “Presentation: Geohazards Program UAS Operations and Other CDOT Use,” 2018.

---

32 Skip Watts, "An Introduction to the Use of Unmanned Vehicle Systems for Mapping Geohazards: Background, Capabilities and Regulations", August 3, 2016, https://www.marshall.edu/cegas/geohazards/2016pdf/S1/1_2016%20UAS%20GeoHaz%20Knoxville%20watts.pdf.

33 “FAA Supports Drone Operations for Florence Response,” U.S. Federal Aviation Administration, accessed August 3, 2019, https://content.govdelivery.com/accounts/USAFAA/bulletins/20eb8db.

34 “OSU Selected by NSF for UAS Weather Project,” Unmanned Aircraft Systems, accessed August 3, 2019, https://unmanned.okstate.edu/node/77.

35 Craig Gustafson, “Drones in Minnesota,” July 18, 2018, http://onlinepubs.trb.org/onlinepubs/conferences/2018/law/CRAIG_GUSTAFSON.pdf

36 Francesco Avanzi et al., “Centimetric Accuracy in Snow Depth Using Unmanned Aerial System Photogrammetry and a MultiStation,” Remote Sensing 10, no. 5 (May 2018): 765, https://doi.org/10.3390/rs10050765.

37 “NSF Award Search: Advanced Search Results,” accessed August 3, 2019, https://www.nsf.gov/awardsearch/advancedSearchResult?PIId=&PIFirstName=&PILastName=&PIOrganization=&PIState=&PIZip=&PICountry=&ProgOrganization=&ProgEleCode=&BooleanElement=All&ProgRefCode=&BooleanRef=All&Program=&ProgOfficer=&Keyword=UAS&AwardNumberOperator=&AwardAmount=&AwardInstrument=&ActiveAwards=true&OriginalAwardDateOperator=Range&OriginalAwardDateFrom=01%2F01%2F2017&OriginalAwardDateTo=02%2F27%2F2019&StartDateOperator=&ExpDateOperator.

38 “UMassAir Research Projects,” UMTC, accessed August 3, 2019, https://www.umasstransportationcenter.org/umtc/UMassAir_Research_Projects.asp.

39 Bobbi deMontigny, “LibGuides: Unmanned Aerial Vehicles and Systems: Research Feed,” accessed August 3, 2019, http://transportation.libguides.com/uav/RSS.

40 “Integration Pilot Program Lead Participants,” template, accessed August 3, 2019, https://www.faa.gov/uas/programs_partnerships/integration_pilot_program/lead_participants/.

41 “Technology Readiness Level Guidebook," Federal Highway Administration, September 2017, https://www.fhwa.dot.gov/publications/research/ear/17047/001.cfm.

42 S. Dorafshan et al., “Challenges in Bridge Inspection Using Small Unmanned Aerial Systems: Results and Lessons Learned,” in *2017 International Conference on Unmanned Aircraft Systems (ICUAS)*, 2017, 1722–30, https://doi.org/10.1109/ICUAS.2017.7991459.

43 Successful Approaches for the Use of Unmanned Aerial System by Surface Transportation Agencies," July 18, 2017, http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP20-68A_17-01.pdf

44 “Summary of Results from State DOT Drone Usage Surveys,” 2018, https://transportation.libguides.com/ld.php?content_id=41981307.

45 35 State DOTs are Deploying Drones to Save Lives, Time and Money,” accessed May 14, 2019, https://news.transportation.org:443/Pages/NewsReleaseDetail.aspx?NewsReleaseID=150

46 “Summary of Results from State DOT Drone Usage Surveys,” 2018, https://transportation.libguides.com/ld.php?content_id=41981307.

47 “[CASE STUDY] DroneDeploy Drones Improve Contractor’s Site Planning, Design, Safety,” For Construction Pros, accessed August 2, 2019, https://www.forconstructionpros.com/construction-technology/article/20865700/case-study-dronedeploy-drones-improve-contractors-site-planning-design-safety.

---

48 Trboyevich, Chris, “Life-Cycle Integrated Management (CIM) Advancements in Preliminary Design BIM for Infrastructure,” August 2019, http://dot.state.mn.us/research/reports/2019/201936.pdf.

49 Barritt Lovelace, “Improving the Quality of Bridge Inspections Using Unmanned Aircraft Systems (UAS),”July 2018, https://www.dot.state.mn.us/research/reports/2018/201826.pdf.

50 “Flyability Drone Inpsection Demonstration of Smith Avenue High Bridge Over Mississippi River - YouTube,” accessed August 3, 2019, https://www.youtube.com/watch?v=hEZqHTcqbNc&feature=youtu.be.

51 “Flyability Drone Inspection Demonstration, Hiawatha over Lake Street - YouTube,” accessed August 3, 2019, https://www.youtube.com/watch?v=7B04QVsA0lU&feature=youtu.be.

52 Richard Kramer Rhodes, “UAS as an Inventory Tool: A Photogrammetric Approach to Volume Estimation,”August 2017, https://scholarworks.uark.edu/cgi/viewcontent.cgi?article=3963&context=etd.

53 “Water Pond Surveying for Colorado DOT,” Datumate (blog), February 19, 2017, https://www.datumate.com/case-studies/colorado-dot/.

54 Brooks et al., “Implementation of Unmanned Aerial Vehicles for Assessment of Transportation Infrastructure – Phase II,” 2018, https://www.michigan.gov/documents/mdot/SPR-1674_FinalReport_revised_631648_7.pdf

55 “ University of Vermont UVM UAS Team: Case Studies,” Accessed August 27, 2020, http://www.uvm.edu/~uas/?Page=CaseStudies.php

56 Naveed Anwar, Fawad Najam, and Muhammad Amir Izhar, “Construction Monitoring and Reporting Using Drones and Unmanned Aerial Vehicles (UAVs),” 2018.

57 “UAV Usage Across Agencies,” 2018, https://transportation.libguides.com/ld.php?content_id=41792616.

58 Successful Approaches for the Use of Unmanned Aerial System by Surface Transportation Agencies," July 18, 2017, http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP20-68A_17-01.pdf

59 Second Edition Integration of Civil UAS NAS Roadmap, accessed May 3, 2019, https://www.faa.gov/uas/resources/policy_library/media/Second_Edition_Integration_of_Civil_UAS_NAS_Roadmap_July%202018.pdf.

60 “States Explore Drone Technologies to Improve Data, Save Time,” Transport Topics, April 2, 2018, https://www.ttnews.com/articles/states-explore-drone-technologies-improve-data-save-time.

61 Drone Program Takes off in Bureau of Aeronautics,” NJDOT Technology Transfer (blog), January 24, 2018, https://www.njdottechtransfer.net/2018/01/24/drone-program-takes-off-bureau-aeronautics

62 Charles R. Stevens, "Concept of Operations and Policy Implications for Unmanned Aircraft Systems Use for Traffic Incident Management (UAS-TIM)," March 2017, https://static.tti.tamu.edu/tti.tamu.edu/documents/PRC-15-69F.pdf.

63 “State DOTs’ Use of Drone Technologies Will Transform Transportation in New Ways," LinkedIn, accessed August 3, 2019, https://www.linkedin.com/pulse/state-dots-use-drone-technologies-transform-new-ways-jim-tymon/.

64 Drones Shown to Make Traffic Crash Site Assessments Safer, Faster and More Accurate” Purdue University Research Foundation News, January 16, 2019,

---

https://www.purdue.edu/newsroom/releases/2019/Q1/drones-shown-to-make-traffic-crash-site-assessments-safer,-faster-and-more-accurate.html

65 Keith Cunningham, Joseph Wartman, and Claire Rault, “Unmanned Aircraft System Assessments of Landslide Safety for Transportation Corridors: Final Project Report,” December 2016, https://snap.uaf.edu/sites/default/files/UAS%20Assessments%20of%20Landslide%20Safety%20for%20Transporation%20Cooridors%20%281%29.pdf.

66 “Summary of Results from State DOT Drone Usage Surveys,” https://transportation.libguides.com/ld.php?content_id=41981307.

67 Barritt Lovelace, “Improving the Quality of Bridge Inspections Using Unmanned Aircraft Systems (UAS),”July 2018, https://www.dot.state.mn.us/research/reports/2018/201826.pdf.

68 “Time-Lapse View of California Highway 1 Reconstruction after 2017 Landslide,” USGS, July 18, 2018, https://www.usgs.gov/center-news/time-lapse-view-california-highway-1-reconstruction-after-2017-landslide?qt-news_science_products=1#qt-news_science_products.

69 Successful Approaches for the Use of Unmanned Aerial System by Surface Transportation Agencies," July 18, 2017, http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP20-68A_17-01.pdf

70 Beau Taylor, “Presentation: Geohazards Program UAS Operations and Other CDOT Use,” 2018.

71 “FAA Supports Drone Operations for Florence Response,” U.S. Federal Aviation Administration, accessed August 3, 2019, https://content.govdelivery.com/accounts/USAFAA/bulletins/20eb8db.

72 “State DOTs’ Use of Drone Technologies Will Transform Transportation in New Ways," LinkedIn, accessed August 3, 2019, https://www.linkedin.com/pulse/state-dots-use-drone-technologies-transform-new-ways-jim-tymon/.

73 “Turn Your Eyes to the Skies for the Latest Explorers,” accessed August 3, 2019, https://www.nsf.gov/discoveries/disc_summ.jsp?cntn_id=189521.

74 “Current Unmanned Aircraft State Law Landscape,” accessed August 3, 2019, http://www.ncsl.org/research/transportation/current-unmanned-aircraft-state-law-landscape.aspx.

75 “"Evolution of Drones Part Three: State DOTs Hiring Next-Gen Workforce to Fly Drones Saving Lives, Time, and Money," accessed April 10, 2020, https://www.transportation.org/the-evolution-of-drones-part-3/.

76 Rüdiger Escobar-Wolf et al., “Unmanned Aerial Vehicle (UAV)-Based Assessment of Concrete Bridge Deck Delamination Using Thermal and Visible Camera Sensors: A Preliminary Analysis,” Research in Nondestructive Evaluation 29, no. 4 (October 2, 2018): 183–98, https://doi.org/10.1080/09349847.2017.1304597.

77 H. Durrant-Whyte and T. Bailey, “Simultaneous Localization and Mapping: Part I,” IEEE Robotics & Automation Magazine 13, no. 2 (June 2006): 99–110, https://doi.org/10.1109/MRA.2006.1638022.

78 Paolo Tripicchio et al., “Confined Spaces Industrial Inspection with Micro Aerial Vehicles and Laser Range Finder Localization,” International Journal of Micro Air Vehicles 10, no. 2 (June 2018): 207–24, https://doi.org/10.1177/1756829318757471.

79 Barritt Lovelace, “Improving the Quality of Bridge Inspections Using Unmanned Aircraft Systems (UAS),”July 2018, https://www.dot.state.mn.us/research/reports/2018/201826.pdf.

---

80 O’Neill-Dunne et al., Using Remote Data Collection to Identify Bridges and Culverts Susceptible to Blockage During Flooding Events, Final Report, University of Vermont Transportation Research Center, accessed August 4, 2019, http://www.uvm.edu/~transctr/research/trc_reports/UVM-TRC-16-003.pdf.

81 S. Dorafshan et al., “Challenges in Bridge Inspection Using Small Unmanned Aerial Systems: Results and Lessons Learned,” in 2017 International Conference on Unmanned Aircraft Systems (ICUAS), 2017, 1722–30, https://doi.org/10.1109/ICUAS.2017.7991459.