Use of Unmanned Aircraft Systems (UAS) to Enhance the Design, Construction, Inspection, and Maintenance of Transportation Infrastructure

August 2023

FHWA Global Benchmarking Program Study Report

RPT NO FHWA-PL-23-007

U.S. Department of Transportation
Federal Highway Administration

FOREWORD

The use of Unmanned/uncrewed Aircraft Systems (UAS) in the United States (U.S.) has greatly increased in recent years. U.S. transportation agencies and partnering organizations have started to evaluate and use UAS as a toolset for new data collection and analysis methods to supplement or enhance experts' day-to-day work and to help focus their attention on high-risk or unusual issues. UAS applications benefiting transportation agencies include bridge inspection, corridor and site surveys, geotechnical investigations and damage assessment, road traffic monitoring, road assessments, vehicle accident investigations, and volumetric measurement, among others. Transportation agencies have begun to measure the condition of transportation assets more safely, objectively, and quickly using UAS compared to traditional methods.

The U.S. Federal Highway Administration (FHWA) conducts Global Benchmarking Program (GBP) studies to assess, evaluate, and implement global innovations to respond to 21st century challenges in U.S. highway transportation. FHWA initiated the GBP study on the "Use of Unmanned Aircraft Systems (UAS) to Enhance the Design, Construction, Inspection, and Maintenance of Transportation Infrastructure" in 2019. The purpose of the study was to learn about mature UAS applications in advanced digital project delivery and contactless practices conducted by international experts. The goal of the study was to identify opportunities to adopt UAS to enhance the design, construction, inspection, and maintenance of transportation infrastructure, thereby benefiting the U.S. highway transportation and digital construction sectors.

The U.S. study team included two FHWA representatives, representatives from the Departments of Transportation (DOT) of two states – California and North Carolina, and a report writer from the U.S. DOT Volpe Center. The study team conducted virtual and in-person meetings with subject matter experts in the United Kingdom (U.K.) and Germany. This final study report organizes study findings by i) UAS use cases and best practices benefiting the highway transportation and digital construction sectors, ii) digital models and data management supported by UAS, and iii) asset lifecycle management supported by UAS.

The "Use of Unmanned Aircraft Systems (UAS) to Enhance the Design, Construction, Inspection, and Maintenance of Transportation Infrastructure" study supports U.S. DOT and FHWA priorities of Safety, Economic Growth, and Transformation.

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14. ABSTRACT

The U.S. Federal Highway Administration (FHWA) conducts Global Benchmarking Program (GBP) studies to assess, evaluate, and implement global innovations in key technology areas to help the nation respond to 21st century highway transportation challenges. FHWA initiated the GBP study on the "Use of Unmanned Aircraft Systems (UAS) to Enhance the Design, Construction, Inspection, and Maintenance of Transportation Infrastructure" in 2019. The purpose of the study was to learn about mature UAS applications in advanced digital project delivery and contactless practices conducted by international experts. The goal of the study was to identify opportunities to adopt UAS to enhance the design, construction, inspection, and maintenance of transportation infrastructure, thereby benefiting the U.S. highway transportation and digital construction sectors. In this report, UAS refers to unmanned and remotely piloted aircraft systems weighing less than 55 lbs. in the U.S. or less than 25 kg in the United Kingdom (U.K.) and Germany.

The study team identified diverse uses of UAS as a supplemental or enhancing tool (rather than a replacement) for human workers performing critical structural inspections, conducting construction site surveys, working at high or difficult-to-reach locations, etc. Most importantly, the study team found that mature UAS use cases internationally have improved safety along with one or more of the following benefits: improved efficiency, improved data quality, greater data quantity, cost savings, and time savings compared to traditional methods.

This report summarizes findings from virtual meetings and in-person visits conducted with subject matter experts (SMEs) in the U.K. and Germany. The U.S. study team visited the U.K. in June 2022 and Germany in September 2022. The team and international SMEs agreed that, at a time when transportation infrastructure in each country is nearing the end of anticipated design life or approaching the need for major maintenance/rehabilitation, UAS serve as an important tool to supplement and enhance transportation agencies' and construction organizations' day-to-day operations. Advances in the processing and managing of UAS-collected data present opportunities to "digitize" common practices in the construction sector, saving time and money in the initial construction design phase and allowing SMEs to focus their attention on high-risk or unusual issues. Data collected using UAS and digital models created using that data can accelerate the construction design process, increase safety during construction, and increase efficiency in construction inspection and maintenance tasks. UAS also provide economic growth and workforce development opportunities.

This report organizes findings from the U.K. and Germany by i) UAS use cases and best practices benefiting the highway transportation and digital construction sectors; ii) digital models and data management supported by UAS, and iii) asset lifecycle management supported by UAS. The study supports the U.S. Department of Transportation and FHWA's Safety, Economic Growth, and Transformation priorities.

15. SUBJECT TERMS

Asset management; beyond visual line of sight; bridge inspection; construction; confined space inspection; data management; digital construction; digital models; digital twins; drones; FHWA; highway infrastructure; highway operations; highway transportation; maintenance, repair, and overhaul; Remotely Piloted Aircraft; state departments of transportation; structures; structural inspection; transportation infrastructure; Uncrewed Aircraft Systems; Unmanned Aircraft Systems; workforce development

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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)

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List of Abbreviations

Abbreviation	Term
3D	Three-dimensional
AFISO	Aerodrome Flight Information Service Officer
AI	Artificial Intelligence
ANPR	Automatic Number-Plate Recognition
ASCE	American Society of Civil Engineers
ATC	Air Traffic Control
AVIS	National Highways Asset Visualisation and Information System
BASt	German Federal Highway Research Institute
BMDV	German Federal Ministry for Digital and Transport
BUW	Bauhaus Universität Weimar
BVLOS	Beyond Visual Line of Sight
C2	Command and Control
CAA	U.K. Civil Aviation Authority
Caltrans	California State Department of Transportation
CNPC	Command and Non-payload Control
CONOPS	Concept of Operations
DfT	U.K. Department for Transport
Dipul	German Digital Platform for Unmanned Aviation
DLR	German Aerospace Center
DOT	This term refers to any Department of Transportation in the U.S. – federal, regional, state, local, tribal, etc.
DPC	National Highways Digital Product Catalogue
DZSF	German Center for Rail Transport Research
EASA	European Aviation Safety Agency
EBA	German Federal Railway Authority
EDC	FHWA Every Day Counts
EU	European Union
EVLOS	Extended Visual Line of Sight
FAA	U.S. Federal Aviation Administration
FCS	FAA Cloud Services
FedRAMP	U.S. Federal Risk and Authorization Management Program
FHWA	U.S. Federal Highway Administration
FMS	National Highways Flight Management System
FY	Fiscal Year
GBP	Global Benchmarking Program
GmbH	Gesellschaft mit beschränkter Haftung (Company with Limited Liability)
GNSS	Global Navigation Satellite System
GUI	Graphical User Interface
HHLA	Hamburger Hafen und Logistik AG (Port of Hamburg Logistics Company)
ICC	HHLA UAS Integrated Command Center
IEC	International Electrotechnical Commission
ISA	International Society of Automation
JARUS	Joint Authorities for Rulemaking of Unmanned Systems
LBA	German Civil Aviation Authority
LiDAR	Light Detection and Ranging
MEWP	Mobile Elevating Work Platform
MIDAS	National Highways Motorway Incident Detection and Automatic Signaling

Abbreviation	Term
ML	Machine Learning
mm	Millimeter
mm/pix	Millimeter per pixel
MRO	Maintenance, Repair, and Overhaul
MSL	Mean Sea Level
NCDOT	North Carolina State Department of Transportation
NH	National Highways
NRTS	U.K. National Roads Telecommunications Service
NRW	North Rhine-Westphalia
OIP	FHWA Office of International Programs
PIC	Pilot in Command
PML	Product Maturity Level
PPE	Personal Protective Equipment
PPP	Precise Point Positioning
PSE	Plans, Specifications, and (best) Estimates
REM	National Highways Rapid Engineering Model
RF	Radio Frequency
RIS	U.K. Road Investment Strategy
ROI	Return on Investment
RTK	Real Time Kinematics
RWTH	Rhine-Westphalia Technical (Universities)
SAIL	Specific Assurance and Integrity Level
SCRG	National Highways Safety Control Review Group
SLAM	Simultaneous Localization and Mapping
SMDC	Smart Motorways Development Centre
SME	Subject Matter Expert
SORA	Specific Operations Risk Assessment
SRN	U.K. Strategic Roadway Network
[State] DOT	Department of Transportation for a State in the U.S. e.g., NCDOT is North Carolina Department of Transportation, or Utah DOT is Utah Department of Transportation
TRL	Technology Readiness Level
U.K.	United Kingdom
U.S.	United States
U.S. DOT	United States Department of Transportation
UA	Unmanned Aircraft
UAS	Unmanned/uncrewed Aircraft Systems
UDVeo	Efficient Organization of Urban Drone Traffic
UTM	UAS Traffic Management
VLOS	Visual Line of Sight
VTOL	Vertical Takeoff and Landing

Executive Summary

Study Overview

The Federal Highway Administration (FHWA) Global Benchmarking Program (GBP) serves as a tool for accessing, evaluating, and implementing proven global innovations that have the potential to significantly improve highway transportation in the U.S. Instead of recreating advances already developed by other countries, the program focuses on acquiring and adopting technologies and best practices already available and used abroad.

The GBP study on the "Use of Unmanned Aircraft Systems (UAS) to Enhance the Design, Maintenance, Inspection, and Construction of Transportation Infrastructure" was conducted to learn about mature UAS applications in other countries with a focus on advanced digital project delivery and contactless practices. The goal of the study was to identify opportunities to adopt UAS to enhance the design, construction, inspection, and maintenance of transportation infrastructure, thereby benefiting the highway transportation and digital construction sectors.

The study was motivated by several factors, including:

- Increasing prevalence of UAS and broadening of UAS applications
- Increasing need to address aging transportation infrastructure coupled with increasing demand for the infrastructure
- Opportunities to supplement and enhance transportation agencies' day-to-day operations through UAS technological advances
- Opportunities to enhance data processing, data management, data analysis, and asset management
- Improved understanding of safety risks associated with UAS operations
- Opportunities for economic growth and workforce development resulting from the adoption of UAS

The U.S. study team included representatives from the FHWA Office of Infrastructure, FHWA Western Federal Lands Highway Division, California Department of Transportation, North Carolina Department of Transportation, and the U.S. DOT Volpe Center.

The study was conducted in two phases. The first phase of the study produced a domestic desk review that described the current UAS state of technology, state of practice, and regulations in the U.S., as well as use cases of potential benefit to the highway transportation and digital construction sectors. This was followed by an international desk review of several countries demonstrating organizational and technological innovations in the UAS sector. This initial research identified the U.K. and Germany as countries implementing advanced use cases with a wide range of reported benefits that could be replicated in the U.S.

During the study's second phase, the study team conducted virtual meetings with U.K. and German SMEs in June 2021. These virtual meetings provided a strong foundational understanding of the organizational and regulatory elements of UAS operations in each country. The study team visited the U.K. in June 2022 and Germany in September 2022 to conduct in-person meetings and technical site visits.

This report presents the study findings most relevant to the U.S. highway transportation and digital construction sectors. In addition, this report quantifies international advancements in terms of improved safety, improved efficiency, data quality, data quantity, cost savings, and/or time savings. The findings are organized into three categories:

I. **UAS use cases and best practices**
   - UAS enhancing infrastructure inspection and confined space inspection
   - UAS enhancing road construction mapping and visual survey
   - UAS enhancing pavement preservation
   - UAS supporting port operations
   - UAS operations management
   - Additional UAS use cases and best practices

II. **Digital models and data management supported by UAS**
   - Digital Product Catalogue (DPC) and data standardization
   - UAS supporting digital model creation
   - Machine Learning (ML)/Artificial Intelligence (AI) for structural defect detection

III. **Asset lifecycle management supported by UAS**
   - Scaling UAS operations for asset lifecycle, ML/AI for model-to-model change detection
   - UAS fleet Maintenance, Repair, and Overhaul (MRO)
   - Rapid Engineering Model (REM) for asset lifecycle management

Key Findings and Recommendations

The study team observed the following common themes and developed recommendations for advancing the state of practice of UAS in the transportation infrastructure and digital construction sectors:

- **Countries share similar challenges in the design, construction, inspection, and maintenance of transportation infrastructure**
  - Convening international meetings could support the establishment of data collection, data sharing, algorithm development, and other agreements among partnering countries
- **Countries aim to improve legacy processes in the highway transportation and digital construction sectors**
  - Convening workshops related to data standardization, data management, and the use of artificial intelligence/machine learning could help improve algorithm training and automated structural defect detection. Countries could consider adopting a lifecycle-oriented mode of thinking for data related to highway transportation infrastructure, construction projects, construction products, etc. Standardization and digitization of common construction elements would allow workers to focus their attention on high-risk and unusual issues

- **Use of UAS provides measurable benefits via a range of mature applications**
  - There may be a need to update, and potentially standardize, performance metric tracking associated with emerging and traditional methods of design, construction, inspection, and maintenance. The full set of metrics may include sub-metrics within the following:
    - Safety
    - Efficiency
    - Data quality
    - Data quantity
    - Cost
    - Time
- **Use of UAS can increase consistency and repeatability in producing standardized data to enhance digital construction**
  - It could be beneficial to adopt common data standards for construction design and construction elements and to improve the ability to access digitized design files (potentially via interoperable cloud-based data management systems). UAS use cases involving automated and repeated flights can collect data to support 3D model change detection, and advances in cloud-based data management can support the storage and sharing of data, as well as algorithm outputs
- **Standardization of the application of UAS-collected data to various digital construction uses is needed**
  - UAS can be considered a toolset to generate consistent, repeatable, standardized datasets yielding benefits throughout the construction lifecycle. UAS, depending on onboard sensors and other flight operation parameters, can collect data at various quality levels to support differing digital construction applications. U.S. DOT could contribute to the development of data quality, data quantity, and data management standards for bridge inspection and other infrastructure inspection and survey tasks
- **Minimum requirements are needed for Maintenance, Repair, and Overhaul (MRO) practices associated with UAS**
  - There is an opportunity for governments to collaborate with industry and standards-making agencies to develop minimum MRO requirements for UAS and UAS components. Minimum MRO requirements will support UAS use cases involving automated and repeated flights to collect the quantity of data necessary for machine learning-enhanced assessments of infrastructure
- **Countries aim to maintain economic growth and retain a talented workforce in the transportation infrastructure sector**
  - Additional work is needed to assess the benefits and shortfalls of training transportation workers in UAS (such as 14 CFR Part 107 Remote Pilot certification) versus contracting UAS services to the industry; both organizational models were observed in partnering countries

Introduction

Background

The use of Unmanned Aircraft Systems (UAS) in the United States has greatly increased in recent years as transportation agencies and their partners have started to evaluate and use these platforms for new data collection and analysis methods. Advancements in the use of UAS have been shown to improve safety and potentially improve efficiency, improve data quality, increase data quantity, deliver cost savings, or deliver time savings in day-to-day and safety-critical operations.

International public and private sector UAS growth has progressed rapidly, and many countries have successfully implemented UAS applications and innovations benefiting highway transportation. Learning from international experience allows the U.S. to deploy similar applications to enhance the design, maintenance, inspection, and construction of transportation infrastructure.

Despite these developments, the full potential of UAS technology has yet to be achieved due to rapidly changing technology, the time needed to develop national and local rules, and the need for more case studies for transportation agencies to assess and understand potential benefits. The U.S. House of Representatives Committee on Appropriations report for the FY2019 Transportation, Housing, and Urban Development appropriations bill (H. Rept. 115-750, 2018) identified a "*… growing need to accelerate the adoption of best practices, technologies, and materials that lead to faster construction and cost-effective rehabilitation of highway infrastructure*" and "*… [directed] the Secretary [of Transportation] to prioritize demonstrations and deployments of advanced digital construction management systems*." Addressing the nation's infrastructure needs using emerging tools such as UAS supports U.S. DOT's strategic goals (U.S. DOT, 2022) of safety,[1] economic growth and global competitiveness,[2] and transformation.[3]

Study Objectives

This study was undertaken by FHWA, an agency of the United States Department of Transportation (U.S. DOT). It was conducted under the FHWA's Global Benchmarking Program, which serves as a tool for accessing, evaluating, and implementing proven foreign innovations that can help improve highway transportation in the U.S. The purpose of the study was to learn about mature UAS applications in other

[1] U.S. DOT Strategic Goals, Safety: "Make our transportation system safer for all people. Advance a future without transportation related serious injuries and fatalities." March 28, 2022.
Retrieved from: https://www.transportation.gov/dot-strategic-plan
[2] U.S. DOT Strategic Goals, Economic Strength, and Global Competitiveness: "Grow an inclusive and sustainable economy. Invest in our transportation system to provide American workers and businesses reliable and efficient access to resources, markets, and good-paying jobs." March 28, 2022.
Retrieved from: https://www.transportation.gov/dot-strategic-plan
[3] U.S. DOT Strategic Goals, Transformation: "Design for the future. Invest in purpose-driven research and innovation to meet the challenges of the present and modernize a transportation system of the future that serves everyone today and, in the decades, to come." March 28, 2022.
Retrieved from: https://www.transportation.gov/dot-strategic-plan

countries with a focus on advanced digital project delivery and contactless practices. The goal of the study was to leverage the international experience and identify opportunities to adopt UAS to enhance the design, construction, inspection, and maintenance of transportation infrastructure, thereby benefiting the highway transportation and digital construction sectors. Additional objectives of the study included:

- Understanding the organizational management of UAS programs and operations in the highway transportation and digital construction sectors
- Learning about how data collected from UAS operations are managed and how these data improve engineering practices
- Communicating study findings, international innovations, and international best practices to U.S. transportation agencies
- Assisting transportation agencies in adopting UAS if the technology results in improved safety and one or more of the following: improved efficiency, improved data quality, increased data quantity, cost savings, or time savings

Study Team Members

The FHWA GBP study team included the following members:

- James Gray, P.E. (Team Lead) – FHWA Office of Infrastructure, FHWA UAS Program Manager
- Zekial Rios, P.E., P.L.S. – FHWA Western Federal Lands Highway Division, FHWA UAS Program Coordinator
- Aaron Chamberlin, C.E., UAS Pilot – California Department of Transportation (Caltrans), Division of Construction, Senior Innovation Engineer, and Construction UAS Coordinator
- Thomas Walls, sUAS thermographer, UAS Pilot – North Carolina Department of Transportation, Division of Aviation, UAS Operations Manager
- Jason Lu (Report Lead) – U.S. DOT Volpe Center

See **Appendix A: Biographies of U.S. Study Team Members** for short bios and more information on the study team members.

Study Methodology and Itinerary

The study was conducted in two phases. The first phase of the study resulted in a domestic desk review that described the current UAS state of technology, state of practice, and regulations in the U.S., as well as use cases of potential benefit to the highway transportation and digital construction sectors. This was followed by an international desk review of several countries demonstrating organizational and technological innovations in the UAS sector. This initial research identified the U.K. and Germany as countries implementing advanced use cases with a wide range of reported benefits that could be replicated in the U.S.

- Domestic desk review – This report was developed to document the state of the practice of UAS in the U.S. and to identify UAS use cases that could benefit the highway transportation and

digital construction sectors (FHWA Office of Infrastructure, 2020). Use cases were identified within the following broad categories:
  - Infrastructure inspection and monitoring
  - Transportation systems management and operations
  - Geological monitoring to inform the protection of transportation assets
  - Weather-related data collection to support traffic and incident monitoring
- International desk review – This report documented examples of international advances in UAS in the use cases most relevant to FHWA. The U.K. and Germany were identified as key countries of interest due to their advanced UAS applications in the highway transportation and digital construction sectors which demonstrated a wide range of reported benefits that could be replicated in the U.S.
- Desk review addendum – Follow-on research was conducted to document updates in the UAS sector between the publication of the domestic desk review and the subsequent in-person study visits. Key findings of the desk review addendum include:
  - State DOT UAS fleets have grown significantly in recent years
  - State DOTs are conducting an increasing number of advanced small UAS operations enabled through Federal Aviation Administration (FAA) Part 107 waivers
  - Both the FAA and State DOTs are advancing beyond visual line of sight (BVLOS) operations. Federal agencies (FAA, NASA, etc.) and State DOTs are building UAS Traffic Management (UTM) capabilities in support of unmanned operations in public airspace where traditional air traffic control (ATC) services are not provided (FAA, 2022)
  - State DOTs are partnering with industry technology developers in use case-specific advancements
  - Domestic programmatic advancements have allowed state, local, and other public and private entities to access FAA expertise and resources to advance use cases

After completion of the desk review addendum, the study team conducted virtual meetings with U.K. and German SMEs in June 2021. These virtual meetings provided a strong foundational understanding of the organizational and regulatory elements of UAS operations in each country.

The second phase of the study included in-person meetings and site visits in the U.K. (Moreton-in-Marsh and Birmingham) from June 6-8, 2022; and in Germany (Hamburg, Cochstedt-Magdeburg, Weimar, and Cologne) from September 12-15, 2022. In each country, the study team met with federal government officials; transportation, construction, and aerospace sector experts; regulatory experts; structural engineers; test engineers; software developers; academic experts; UAS service providers (piloting, operational management, data processing, etc.); and other stakeholders. The study team also participated in technical site visits to gain first-hand observations of UAS systems and operations.

This **final study report** summarizes the most relevant findings across all study activities and provides recommendations for future actions. The study team extends their gratitude to all organizations who participated in email correspondence, virtual exchanges, in-person meetings, and technical site visits. See **Appendix D: Study Itinerary**, **Appendix E: Meeting Participants**, and **Appendix F: Meeting Hosts Information** for more information on the virtual and in-person meetings conducted throughout this study.

Referencing U.S. and International UAS Regulations

The study team cites U.S. and international UAS regulations throughout this report to provide necessary context on the study's motivations, methodology, and findings. Commentary on the evaluation of U.S. or international UAS regulations is outside the scope of this study. All UAS operations and use cases described in this study report take place within the regulatory framework of their respective countries and regions.

All highway transportation agencies and partners are required to follow FAA and other federal, state, regional, local, tribal, and organizational UAS regulations where applicable, and encouraged to use relevant guidance. See **Appendix G: Relevant U.S. and International UAS Regulations, Guidance, and Commentary** for a non-exhaustive list of relevant domestic and international UAS regulations and their respective citations.

Need for Study

Increasing Prevalence of UAS and Broadening of UAS Applications

The U.S. and international public and private sectors have greatly increased the use of UAS for new methods of data collection. As of 2022, the FAA reported over 620,000 cumulative commercial small UAS registrations since April 1, 2016, with a current pace of approximately 8,000 new registrations per month (FAA, 2022). Organizations are evaluating the potential benefits of UAS and their ability to supplement or enhance (rather than replace) human workers performing day-to-day tasks (e.g., construction site monitoring) and safety-critical tasks (e.g., "arms-length" bridge inspection, safety inspection/survey in difficult-to-reach spaces, etc.).

Figure 1 shows a photo taken by a UAS of land erosion under a bridge. This type of photo provides workers an initial assessment of a difficult-to-reach location to understand safety hazards before entering the location themselves. Figure 2 shows bridge trusses where workers traditionally work at height and in the presence of various safety hazards to perform inspection and maintenance tasks.

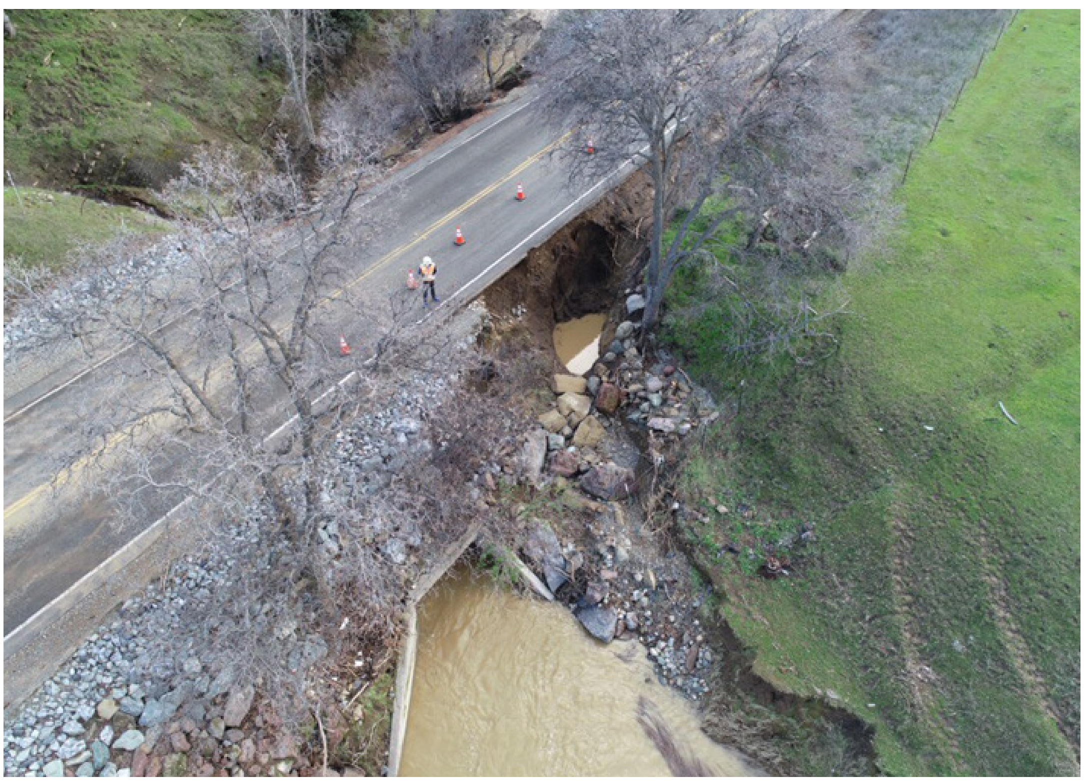

Figure 1. Example of UAS Photography of Land Erosion under a Bridge, Resulting in a Difficult-to-Reach Location for Human Workers (Image Courtesy: Caltrans)

Figure 2. Example of Bridge Trusses where Workers Traditionally Work at Height (Image Courtesy: FHWA Western Federal Lands Highway Division)

Increasing Need to Address Aging Transportation Infrastructure

The U.S., U.K., Germany, and other countries have seen an increasing need to address transportation infrastructure nearing or beyond the end of its anticipated design life or requiring major maintenance/rehabilitation. The American Society of Civil Engineers (ASCE) U.S. Infrastructure Report Card (ASCE, 2020) estimated a funding gap of over $2 trillion to address the nation's infrastructure needs. Aging infrastructure places increased burdens on workers (e.g., bridge inspectors) to focus their resources on the areas of most immediate need to prevent serious or catastrophic incidents. Countries have established efforts to fund infrastructure projects to meet this need. Recent U.S. legislation such as the Bipartisan Infrastructure Law (BIL) authorized funding for "*… the use of innovative aviation technology, such as [UAS], to support transportation safety and efficiencies, including traffic monitoring and infrastructure inspection*" (Public Law 117-58, § 25005, 2021). International efforts such as the U.K. *Road Investment Strategies* (RIS) (U.K. DfT, 2021)[4] and German BMDV's *2030 Federal Transport Infrastructure Plan* (German BMDV, 2016)[5] are concurrent examples.

[4] The U.K. RIS1 (covering 2015-20) invested £17 billion into road infrastructure. The RIS2 will invest £27 billion in RIS2 (2021-25). The RIS3 considers 32 significant projects for funding in 2025-30.

[5] The German BMDV's *2030 Federal Transport Infrastructure Plan* estimates €132.8 billion total investment in federal trunk roads, with €67 billion to structural maintenance and replacement, during the years 2016-30.

Opportunities to Supplement and Enhance Transportation Agencies' Operations

The design of UAS (which refers to the entire system including aircraft platform, navigation and control systems, communication links, sensors, etc.) has evolved rapidly in recent years, with significant advances in flight navigation in difficult-to-reach places. The FHWA Every Day Counts (EDC)-5 Initiative identified that UAS can "*…improve operations, constructions, construction, and safety by collecting data needed to design, build, and operate the highway system"* and provide benefits in terms of increased safety, accelerated construction, and asset maintenance.[6] Figure 3 shows an example of workers conducting bridge maintenance via traditional methods – in this case, using a "snooper" carriage. This method requires workers to work at height and over water and the closure of at least one road lane for several hours.

Figure 3. Example of Workers Conducting Bridge Maintenance from a Snooper Carriage (Reproduced from (Chen, 2014))[7]

Figure 4 shows workers deploying UAS to inspect a bridge deck interior. Using UAS can reduce the total number of workers on site, allows workers to remain close to exit hatches in case of an emergency, and can reduce the total time required to complete the task. The "caged" housing for the UAS allows for some collisions with walls and obstacles without damaging onboard sensors and power sources.

[6] FHWA, Center for Accelerating Innovation, Every Day Counts, EDC-5: Unmanned Aircraft Systems (UAS); March 4, 2022. Retrieved from: https://www.fhwa.dot.gov/innovation/everydaycounts/edc_5/uas.cfm
[7] Image reproduced under Creative Commons Attribution 3.0 Unported license.

Figure 4. Workers Deploying UAS in Bridge Deck Interior (Image Courtesy: NCDOT)

Opportunities to Enhance Data Processing, Data Management, Data Analysis, and Asset Management

The ability for organizations to store data collected by UAS and techniques to manage and process data collected by UAS have developed and advanced rapidly in recent years, providing opportunities to “digitize” highway transportation and digital construction sector practices. Improvements in the quantity of data collected can support routine, repeated surveys to acquire the data necessary to train Artificial Intelligence (AI) and Machine Learning (ML)-based change detection algorithms. These advancements in data management and storage can support data sharing with stakeholders.

Figure 5 shows an example of a three-dimensional (3D) model produced using photogrammetry techniques supported by UAS. One emerging use case for 3D models is to create a baseline model of a structure and then create subsequent models at regular time intervals to perform change detection analysis. This allows for the detection of new cracks, deformations, and other defects on the structure, which in turn helps infrastructure owners perform preventative maintenance on structures, stopping potentially catastrophic events years early and saving time and money on smaller-scale repairs.

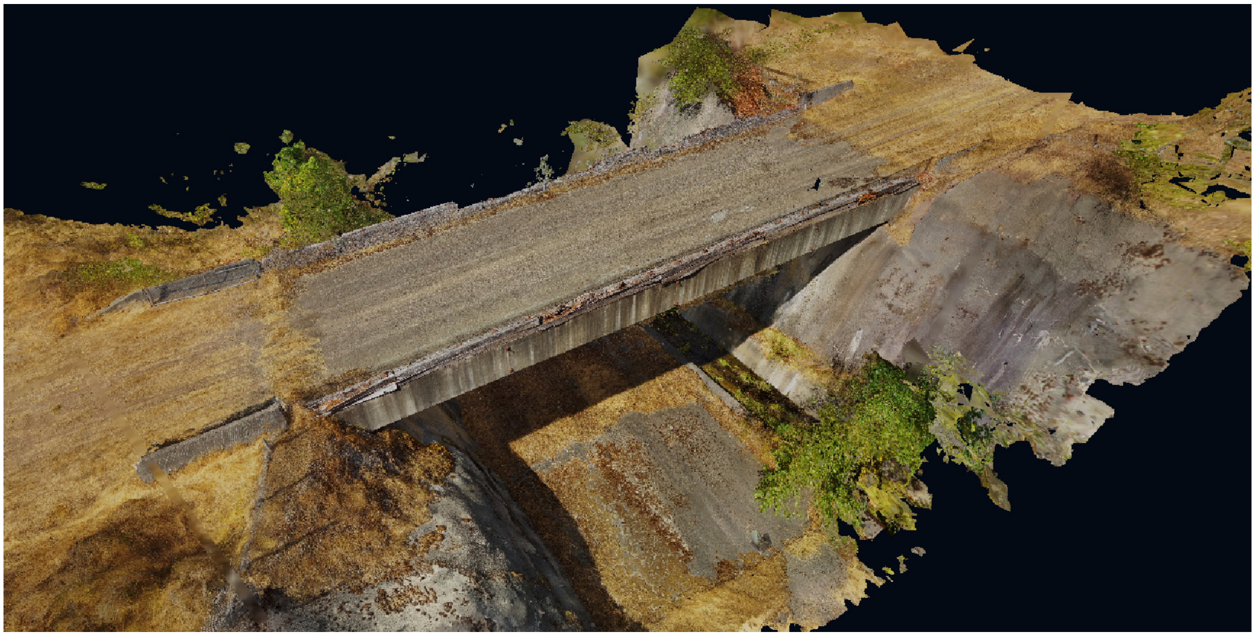

Figure 5. Example of a Bridge 3D Model Produced from Photogrammetry (Image Courtesy: FHWA Western Federal Lands Highway Division)

Improved Understanding of Safety Risk Associated with UAS Operations

U.S. and international UAS regulations have become more well-defined in recent years, with advanced operations (including BVLOS operations, operations over gatherings of people or over critical infrastructure, multiple-aircraft operations, etc.) becoming more routine for users and more accepted by authorities. Both authorities and end users are gaining a mutual understanding of the safety risks associated with these operations. Authorities such as FAA and the European Aviation Safety Agency (EASA) are disseminating resources and tools for users to quantify the safety risk associated with advanced operations.

Economic Growth and Workforce Development from Adoption of UAS

The UAS sector presents an opportunity for economic growth, workforce development, and education for states and localities to attract talented individuals into essential job positions such as bridge inspection. The EU projects the drone services market in Europe can reach "*€14.5 billion by 2030, with a compound annual growth rate of 12.3 percent, and create 145,000 jobs*" (European Commission, 2022). Private sector analyses estimate a growth in economic impact from $1.9 billion to $8.5 billion worldwide for drones in the construction sector (Levitate Capital, 2020). However, the full potential of UAS technology has not yet been achieved.

Study Findings

This section summarizes the information gathered from virtual exchanges and in-person meetings. The findings are organized into three broad categories:

UAS Use Cases and Best Practices

UAS Enhancing Infrastructure Inspection and Confined Space Inspection

National Highways (NH) is a government-owned company that operates, maintains, and improves the U.K.'s Strategic Roadway Network (SRN) which includes its M-designated motorways[8] and major A-roads.[9] Table 1 shows an example UAS infrastructure inspection and confined space inspection use case taking place in southwestern England, the outputs of the UAS operation, and the observed benefits. NH is evaluating a new practice using small UAS where only the remote pilot-in-command (PIC), visual observer, and support engineers (who do not need to be UAS remote pilots) are required to be on-site. The bridge inspector may evaluate photos and video on-site or remotely. This differs from the traditional practice, which includes a four-person confined space inspection team with personal protective equipment (PPE) entering the interior of a structure and a four-person rescue crew standing by in case of emergency situations.

[8] U.K. M-designated motorways are comparable to U.S. Interstate Highways e.g., I-95.
[9] U.K. Major A-roads are comparable to roadways in the U.S. National Highway System e.g., U.S. Route 1.

Table 1. Example UAS Infrastructure Inspection and Confined Space Inspection Use Case

UAS Use Case	Use Case Type	Baseline/non-UAS Work Tasks	UAS Operation Outputs	UAS Operation Benefits
A38 Mardle Viaduct (U.K.)	Confined space inspection	*A four-person confined spaces inspection team with associated breathing apparatus, winch, and access and monitoring equipment entering a steel box structure in the interior of a major A-road structure	*Video and imagery for input into NH's Structures Management System *Livestream footage to on-site NH engineer	*Reduced time from two days to one day (UAS can scan a segment of the bridge deck interior between adjacent access hatches in 10 minutes) *Gained access to the viaduct's interior, which has remained uninspected for long periods due to the safety risk of entering *Removed the need for human workers to enter the structure; only need one remote pilot, one visual observer, and one engineer on-site *Minimal monetary loss of less than £1,000 if UAS is lost within the bridge deck interior *Significant cost savings

The UAS is a caged platform with a diameter of less than 0.5 m that can navigate from one access hatch to another in as little as 10 minutes. The UAS provided its own lighting while collecting photo and video data identifying damp patches, water damage, corrosion, and other potential issues in the structure's interior. NH remarked that finding evidence of water damage can help identify issues for major maintenance up to four years earlier and support predictive maintenance and renewal operations.

This use of UAS reduces risk to bridge inspection workers and rescue crew and reduces the required time from a few days to hours. The UAS costs less than £1,000,[10] and in the event of contingencies, the UAS platform may be left inside the structure, and the operation can be aborted. Workers do not need to enter the structure to retrieve the UAS. When using the UAS described above, NH noted the limitation that the aircraft's propellers could spin up dust and debris in the confined space, potentially degrading the quality of photo and video data. NH is also evaluating the use of a smaller caged UAS platform with a diameter of less than 0.2 m.

Through discussions with NH SMEs, the study team made the following conclusions:

- The U.K. and U.S. are using similar caged UAS platforms
- UAS operations and data collected are supplementary and are not intended to replace the jobs of bridge inspectors
- UAS operations and data collected can support general inspections (and the U.S. equivalent), while bridge inspectors may continue to perform essential tasks in principal inspections
- Organizations do not necessarily need to train bridge inspectors in UAS piloting; both workforces can be developed to meet current and future transportation infrastructure needs
- With respect to data management, photos are currently more manageable for documentation; videos offer greater context during the operation, and photos can be extracted from videos
- Caged UAS appear to be more suitable than tethered UAS for confined space inspection

[10] £1,000 is approximately $1,260 (U.S. Dollars) using June 2023 exchange rates.

UAS Enhancing Road Construction Mapping and Visual Survey

NH developed the *Use of Drones for Mapping and Visual Surveys Exemplar* document (National Highways, 2021) as a detailed use case. The document describes the benefits of using UAS in the most recent 12 months of a roadway construction project in Hull, East Yorkshire, England. This project involves the installation of an underpass below an existing roundabout, the installation of a pedestrian footbridge, and the exhumation of a burial ground. All flights were conducted in visual line of sight (VLOS) within 500m of the remote pilot. A typical UAS flight on the Scheme[11] takes a half day to complete and a further 24 hours to process the data; NH had conducted 80 flights in the most recent 12 months at the time of writing. Using UAS resulted in the following benefits as compared to the following traditional methods:

- As compared to the survey on-foot:
  - Requires only one-third of the time
  - Provides a unique perspective and more comprehensive data from the air, enabling the creation of at least eight 3D models of buildings on or near the Scheme
  - Mitigates the safety risk of workers on an active road
  - Reduces the likelihood of driver distraction as UAS are less noticeable than workers taking photos and videos along the road
- As compared to the survey using vehicle dash cameras:
  - Provides greater quantity and more comprehensive data from the air
  - Mitigates the need to obtain concurrence to drive on private roads
  - Reduces risk to other traffic on the road, pedestrians, cyclists, and other roadway users
  - Reduces carbon emissions
- As compared to terrestrial light detection and ranging (LiDAR) scanners:
  - Provides greater quantity and more comprehensive data from the air, albeit at potentially a lower level of accuracy (a perimeter of terrestrial LiDAR scanners around the construction site can provide extremely accurate data)
  - Requires less equipment transport, setup, and tear-down time
  - Requires a few hours of data capture compared to several days
  - Requires up to one day of data processing compared to several days
  - Requires fewer workers

Additionally, UAS data processing provided a remote work option during the COVID-19 pandemic lockdowns in the U.K., saving time and money for workers commuting to and from the work site.

The use of UAS carried the following safety risks and risks to the project as compared to traditional methods:

- UAS flights at the work site are 20 miles from a Category D airspace flight restriction zone
- VLOS flights are conducted only during daytime hours and visual meteorological conditions
- Aircraft component failure may cause loss of control
- Bird strikes to aircraft are more likely in a coastal city than in other locations

[11] The term "Scheme" is used in the U.K. and generally refers to a construction project, construction site, and the environment therein. The term is used is used in sections of the report describing findings from U.K. SMEs.

- Inattention and fatigue of remote pilot and visual observers
- Potential of a negative public reception of UAS operations; however, NH found that sharing UAS footage with local stakeholders, local news agencies, and on social media can shift public perception in a positive manner

In summary, using UAS on the Hull construction project yielded improved safety, greater data quantity, cost savings, and time savings benefits, on the condition that the UAS operator/service provider has been properly trained and obtained the relevant Civil Aviation Authority (CAA) authorizations to conduct VLOS flights.

UAS Enhancing Pavement Preservation

During a tour of the Smart Motorways Development Centre (SMDC), NH showed an example of a pavement preservation operation using UAS. NH and Leeds University tested using UAS to detect and fill roadway pavement cracks in a "sandbox" environment. The ability to scale this platform and apply it to routine pavement preservation programs would represent a significant safety improvement over the traditional crack sealing practice. This use case can potentially reduce workers' exposure to hazards on the roadway, reduce impact on the public during crack sealing operations, reduce road closure timeframes, enable more timely pavement preservation treatments, and reduce costs for crack sealing operations. Figure 6 shows a photo taken by the study team of the pavement crack filling site. This and other activities at the SMDC represent the "innovation" portion of NH's "innovation-standardization-automation" practices.

Figure 6. National Highways Smart Motorways Development Centre – UAS Enhancing Pavement Preservation

UAS Supporting Port Operations

HHLA Sky is a company within the logistical and digital company at the Port of Hamburg (called "HHLA"). HHLA Sky develops industrial solutions supporting single or fleet UAS BVLOS operations including the UAS Integrated Command Center (ICC), which was demonstrated to the U.S. study team. HHLA Sky currently uses in-house aircraft for its operations to mitigate safety, cybersecurity, and data security risks. The in-house fleet of aircraft and systems includes:

- More than ten small rotorcraft
- One rotor/fixed-wing hybrid vertical takeoff and landing (VTOL) aircraft
- Drone-in-a-box system complete with shelter, box beacon, landing pad, and battery charging; the "home base" box can receive and transmit information with the ICC

The Port of Hamburg has traditionally performed human inspections of port infrastructure, with workers climbing onto shipping containers, cranes, and other structures. Recent inspections of shipping containers and cranes using UAS yielded 60 percent cost savings and 70 percent time savings while mitigating the safety risk of workers performing inspections at height.

Port perimeter and environmental surveillance using UAS have resulted in 60 percent cost savings and more than 50 percent time savings. In addition, last-mile delivery using UAS, connecting the Port of Hamburg with two major airports serving the city, generated 70 percent cost savings and 50 percent time savings.

HHLA Sky has earned a standing authorization from the German Civil Aviation Authority to fly UAS over the Port of Hamburg's waterways, given that operating requirements agreed upon with aviation authorities are satisfied. German UAS regulations currently restrict flights over public waterways.

HHLA Sky reported significant cost savings from using UAS to identify structural defects on port infrastructure such as shipping containers and cranes. The company is exploring the development of training datasets acquired during a wide range of weather conditions and covering a variety of defect types to support ML and neural networks. In addition, the company has collaborated with Deutsche Bahn to create Building Information Modeling (BIM) models.

During in-person meetings, HHLA Sky demonstrated a typical UAS operation at the Port of Hamburg, below 200 ft above ground level (AGL), BVLOS of PIC, and monitored by visual observers. The UAS operation was displayed in UAS ICC and in UDVeo; ICC served as the UTM service provider, and UDVeo served as the authorities' approving and monitoring platform in the concept of operations.

UAS Operations Management

NH Flight Management System (FMS) and FMS Providers

NH and other U.K. government-owned transportation companies, such as Network Rail, are working with DroneCloud™ to transition to digital management of UAS operations; integrate UAS operational details, airspace data, and geospatial data; and oversee third-party UAS operations on behalf of, near, or around company-managed infrastructure networks. DroneCloud™ is a U.K.-government-funded software platform that companies can use to centrally manage their UAS operations, with the vision to achieve routine, autonomous, large-scale operations across the country (comparable to UTM service providers' platforms in the U.S.) that can be deployed more quickly passing safety and compliance checks.

The DroneCloud™ platform guides users through all phases of a UAS operation. Initially, the user sees the local area with geospatial data layers, airspace hazards, and ground hazards (e.g., airfields, railroad tracks, residential areas). Next, the user specifies an operating area and timespan (which is extended into 12-hour blocks as a conservative depiction), and the platform checks these parameters against civil aviation spatial and temporal restrictions. Finally, the user specifies additional inputs, including the Activity Manager identity, Safety Risk Management (SRM) categorization, number of flights planned, and activity outcomes, and submits the information to infrastructure owners (e.g., NH, Network Rail) for review.

Another FMS provider, Sees.AI, obtained the most advanced BVLOS trial authorization from the U.K. CAA in April 2021 at three sites in the U.K., flying below 150 ft AGL.[12] The Sees.AI software platform is used to monitor and control UAS operations in industrial and construction sites and navigation in between power lines. The software platform also manages the real-time creation of 3D models of the operating environment. The aircraft carries LiDAR, camera, and inertial sensors and performs Simultaneous Localization and Mapping (SLAM) to navigate dense obstacle environments. Real-time creation of 3D models is performed onboard the aircraft and the data are streamed to the ground via cellular networks, albeit at relatively low resolution. The 3D model data are categorized as "survey grade", "general applications", or "[not for project use]" depending on the quality of the data. A human (e.g., the pilot in command (PIC)) may monitor the UAS operation and intervene to change the UAS operation when necessary, though the human is not required to intervene.

UAS Operations Management in Germany – Digital Platform for Unmanned Aviation (Dipul) for Public Users

The German Federal Ministry for Digital and Transport (BMDV) is the federal agency in Germany governing all transportation modes, road user safety, freight transport and logistics, information technology in transportation, and broadband, among other areas. In addition, Germany follows similar Unmanned Traffic Management (UTM, also known as "U-Space" in the EU) service models as in the U.S., where a single common information service provider makes data available to and interfaces with industry UTM service platforms, UAS operators access that information and execute operations through U-Space service platforms, and the UTM service platforms access federal, centralized sources of air

[12] Sees.ai, CAA Authorises Trial of a Concept for Routine BVLOS Operations; April 20, 2021. Retrieved from: https://www.sees.ai/2021/04/20/caa-authorises-trial-of-a-concept-for-routine-bvlos-operations/

traffic management data owned by aviation authorities.

The BMDV launched the Digital Platform for Unmanned Aviation (Dipul) in January 2022, which collects all information, rules, and procedures concerning the operation of drones in Germany on one central web-based tool. The Dipul's map tool displays geographical flight zones, airspaces, temporary airspace restrictions, and other relevant geospatial information. In addition, the Dipul allows the public to learn about UAS operations and serves as a "getting started" tool for prospective UAS operators to work with authorities. Once UAS operators have the basic information they need to plan their UAS operations, they may work with aviation authorities to obtain approval, execute their operation, and implement agreed-upon risk mitigations.

UAS Operations Management in Germany – Efficient Organization of Urban Drone Traffic (UDVeo) for Authorities

The Efficient Organization of Urban Drone Traffic (UDVeo) system serves as the authorities' approval and monitoring platform for UAS operations. UDVeo provides a "comprehensive legal-technical concept for the management of drone traffic." The German Civil Aviation Authority (Luftfahrt-Budesamt, LBA) uses UDVeo to review and approve ongoing and proposed UAS operations, including advanced operations such as BVLOS and multi-aircraft operations. UDVeo can display UAS operations and their associated planned flight volumes (nominal and contingency flight volumes) and geo-fences. In addition, the system can display GIS information (land features, waterways, manmade structures, etc.), weather information, aviation information (flight restrictions, airspace notifications, airport and aerodrome statuses, etc.), air traffic information, and other transportation mode information (such as maritime traffic operating in Hamburg's waterways and port). Authorities can examine ongoing and proposed UAS operations in the context of a comprehensive view of the operational environment.

HHLA Sky UAS Integrated Command Center (ICC)

HHLA Sky developed the UAS Integrated Command Center (ICC) to support planning, management, execution, auditing, and other functions associated with UAS operations at the Port of Hamburg. The UAS ICC serves as a U-Space service platform that can be used both by HHLA Sky and external organizations. HHLA Sky noted that the U-Space in and around the city-state of Hamburg is the most advanced in Germany.

The HHLA Sky team demonstrated an example UDVeo interface which was synchronized in time with the HHLA Sky ICC during HHLA Sky's BVLOS operation. During the demonstration, the UDVeo interface displayed a close-up view of the Port of Hamburg and showed the following information relevant to the operation at low altitude AGL:

- Manmade structures
- Waterways and maritime traffic
- Helicopter flight routes and helicopters (if in proximity)
- UAS operation geo-fence
- UAS flight trajectory
- UAS flight kinematics such as altitude AGL, speed, heading
- UAS system characteristics such as battery life

The UAS ICC has received the International Society of Automation (ISA) and International Electrotechnical Commission (IEC) ISA/IEC62443 Cybersecurity certification (ISA/IEC, 2019) and the IEC61508 Functional Safety certification (IEC, 2010) to enable secure management of UAS operations. As UAS operations become more routine and widespread, the cybersecurity and information systems security of UAS operations becomes increasingly important. The UAS ICC's front-end is a web browser graphical user interface (GUI) guiding users through all phases of a UAS operation. The system uses a cloud-based back-end. This practice is comparable to FAA Order 1370.121B (FAA, 2022) governing the transition of current information systems to cloud-based environments. The FAA Order states that, "*…for all FAA systems and applications that are considered cloud suitable or will be redesigned to be cloud suitable, the System Owner must fully utilize the FAA Cloud Service (FCS) environment*" and "*…have and maintain a Federal Risk and Authorization Management Program (FedRAMP) authorization throughout the cloud service lifecycle while in use.*"

The following sections summarize the steps an operational team (PIC, remote pilot(s), visual observer(s), and other support staff) follows within the UAS ICC to conduct and audit UAS operations and manage data collected from UAS operations.

ICC – Planning Operations

The user (who may be the UAS operation PIC, or another individual involved with the operation with appropriate permissions)[13] accesses the UAS ICC to complete common user authentication and authorization processes such as web login, two-factor authentication, etc. The user first sees their previous missions and details (interactive map, aircraft used, time span, flight distance, create and change logs). They may then import details from a previous mission or create a new mission in the GUI.

The user may create one of the following types of new missions, templates for which may differ in the UAS ICC:

- Waypoint mission – a mission defined by flight path waypoints vs. time; automated flight capabilities may be used in this mission type
- Area mission – a mission defined by a 3D polygon within a specified time interval; automated flight capabilities may be used in this mission type
- Recording mission – a mission of any of the above types where the flight trajectory and other details are recorded for replication and automated flight
  - HHLA Sky reported precise navigation among shipping containers and port infrastructure as a use case for recording missions
  - This mission type could support bridge inspection, safety inspection, and survey in difficult-to-reach spaces, as well as routine, repeated surveys to acquire the data necessary for change detection analysis of assets
- Ad-hoc mission (features are in development)

HHLA Sky demonstrated the creation of a waypoint mission during the study visit. The user enters the following inputs to define the flight trajectory and time span. In addition, the user must specify a geo-

[13] During HHLA Sky's demonstration of the UAS ICC, the user also served as the PIC. Our description of the UAS ICC continues under this assumption.

fence and safe landing location(s) to complete mission creation.

- Select aircraft
- Activate Precise Point Positioning (PPP) capabilities, if available
- Activate Real Time Kinematics (RTK) capabilities, if available
- Takeoff point
- Lateral position waypoints relative to takeoff point vs. time
- Altitude waypoints vs. time
    - The user may specify altitude above takeoff point or altitude above Global Navigation Satellite System (GNSS) reference elevation
- Speed vs. time
- Camera orientation vs. time
- Payload actions vs. time
- Geo-fence, i.e., flight boundaries that the UAS cannot exceed – required to complete planning
- Safe landing locations, i.e., locations where the UAS can automatically navigate in the event of a lost link and other in-flight contingency events – required to complete planning
- Optionally, the user may attach additional documentation to the UAS mission plan, including operation manuals, CONOPS, SRM analyses, European Specific Operations Risk Assessment (SORA) analyses, etc.

After the user completes all planning steps, they "release" the mission for review. Then, a second user from the same organization performs the "four-eyes" practice, reviewing all aspects of the mission before providing additional concurrence. Following this step, the mission may be released to approving authorities.

ICC – Obtaining Approval through UDVeo

HHLA Sky also demonstrated a mock-up of UDVeo being accessed by approving authorities. Once a mission passes the internal "four-eyes" practice and is released from the organization, authorities receive the mission and all associated information. The approver views the mission in the context of Geographical Information Systems (GIS) information, airspace information, ground hazards, and waterway hazards.

HHLA Sky practices the "four-eyes" rule when planning UAS operations and submitting them for authorities' approval. A mission creator (who may be the PIC) creates the mission plan using ICC and releases the plan to a mission auditor. The mission auditor reviews the plan and can approve or deny the plan. If the mission auditor denies the plan, they can give feedback to the mission creator.

One type of feedback that may be provided is "strategic deconfliction." This type of deconfliction uses information already known to authorities, such as helicopter flight schedules, commercial flights from Hamburg's airports, and shipping schedules at the port. Once the approver is satisfied with the initially submitted or revised mission, they give approval to the submitter. However, approval of a mission is not equivalent to activation of a mission, which is described in the next step.

ICC – Executing UAS Operations

Once the PIC has received approval for the mission from authorities, the PIC, remote pilot(s), visual observer(s), and support staff may proceed to pre-flight checks. In HHLA Sky's demonstration, the PIC was in the office while the remote pilot, visual observer, and support staff were on-site. Due to a limited supply of certified PICs in the U.S. and Germany, it is recommended that the PIC should be responsible for finalizing the planning phase and associated documentation, overseeing other members of the team before and during the mission, and performing auditing post-mission. In contrast, other team members perform the hands-on tasks of handling aircraft components, flying or observing the aircraft, etc.

The PIC communicates with on-site team members during pre-flight checks, and each side must acknowledge the other when each step is complete. Pre-flight checks may vary depending on the aircraft used. Critical aircraft components, such as batteries, are tracked with unique identifiers. Once all pre-flight checks are complete, the PIC sends a request to authorities to activate the mission. The approver receives the "request to activate" in UDVeo, performs another check of potential conflicts in the operational environment, and allows the mission to be activated.

The PIC receives the approval to activate the mission and communicates to the on-site team members that the mission may begin. As the remote pilot performs takeoff and flies the aircraft, the aircraft's location and altitude can be seen in UAS ICC and UDVeo. During the demonstration, UAS ICC simultaneously displayed the aircraft trajectory and status, the status of the operating environment, the video camera feed onboard aircraft, and the thermal camera feed onboard aircraft.

While the mission is in-flight, the approver may provide "tactical deconfliction" feedback to the user who submitted the mission. This type of deconfliction uses dynamic information in the airspace and operating environment not previously known to authorities, such as emergency response operations. The approver may also request the PIC to terminate the operation, which the PIC is required to follow. UDVeo can send a notification to ICC for the PIC's review in the event of any change in the operating environment, and the PIC may act on this information to either change or abort the operation.

During the demonstration, the PIC showed a lost link procedure. The PIC says "drone signal weak" to the remote pilot if such a status is displayed. The "weak signal" status changes to "potential lost link" if this status persists for 20 seconds and to "lost link" after 10 more seconds. In "lost link" status, the aircraft automatically navigates to a user-specified safe landing location, if possible; alternatively, the aircraft flies until 5 meters from the geo-fence boundary defined during mission planning and performs a safe landing at that location. Navigation and safe landing methods differ among aircraft models in the current market.

ICC – Post-flight, Auditing, and Program Management

In the mission's post-flight phase, on-site team members perform post-flight checks, which may include flying the aircraft for an additional number of minutes to drain the battery. The UAS ICC generates a report to be reviewed by the PIC, and the PIC may enter additional comments before the report is saved. If the mission was conducted on behalf of external stakeholders, UAS ICC generates an additional client-facing report to be sent to those external stakeholders. The PIC may view a dashboard of statistics associated with the mission, and the mission is recorded in the cache of previous missions to be viewed in future user sessions.

ICC performs "every-mouse-click" logging for all tasks performed on the platform. The activity logs are protected in accordance with ISA/IEC62443 and IEC61508. HHAL Sky staff with the appropriate access permissions may then review these activity logs during nominal operations, as well as during investigations of incidents.

During the in-person study, HHLA Sky discussed its UAS program management documentation, including the Aircraft Flight Manual, Standard UAS Concept of Operations (CONOPS), and Operations Manual. The documents comply with German and EU UAS regulations and safety practices specific to the Port of Hamburg and the shipping and logistics sectors. The documents include additional safety practices for on-site and remote UAS PIC, UAS remote pilots, and support staff. In addition, HHLA Sky discussed UAS ICC training courses offered to UAS operators performing operations for the company. The courses are one to two weeks long and allow up to 10 individuals per course. All of these are UAS program management practices relevant to this study.

Additional UAS Use Cases and Best Practices

NH UAS Use Cases and Benefits

At the time of the meeting, NH and its contractors had performed over 680 UAS operations across 33 highway Schemes. These operations include media imagery capture, construction monitoring, topographic survey, pre-Scheme surveys, bridge deck surveys, geotechnical inspections, and internal structural inspections.

Table 2 shows examples of UAS operations highlighted by NH SMEs that support their goal of maintaining the SRN. NH has used UAS to perform geotechnical inspections, confined space inspections, corrosion prevention coating inspections, and traffic surveys, among other use cases. NH reported surveying as one of its most common operations and confined space navigation as one of the biggest recent successes.

Table 2. Examples of Recent National Highways UAS Operations

UAS Use Case	Use Case Type	Baseline/non-UAS Work Tasks	UAS Operation – Outputs	UAS Operation – Benefits
M5 Wynhol Cutting	Geotechnical inspection	*A 2 to 5-person roped access team inspects and assesses a 2.4km length of rock slopes adjacent to the M-designated Motorway *Typically requires 8 weeks to complete an inspection	*Video and imagery data *3D model	*Reduced time from eight weeks to two days *Reduced the number of human workers on-site and the need for human workers to work at height. *Enabled targeted deployment of workers to areas of concern *Significant cost savings

UAS Use Case	Use Case Type	Baseline/non-UAS Work Tasks	UAS Operation – Outputs	UAS Operation – Benefits
M1 Tinsley Viaduct	Corrosion prevention coating inspection	*A large inspection team inspecting corrosion prevention coating on a two-level steel structure carrying the Motorway *Involves the use of scaffolding and Mobile Elevating Work Platforms (MEWPs) *Involves use of a pontoon for inspecting a section of the structure spanning a river	*Video and imagery for input into NH's Structures Management System *Livestream footage to on-site NH engineer	*Reduced the length of the program from eight months to two weeks *Reduced the need for human workers to work at height *Reduced the need for human workers to work adjacent to water *Gained ability to determine specific areas of concern where human workers can perform additional hands-on inspection *Removed the need for train and rail possessions/power isolations
M5 Junction 19	Traffic survey	*A combination of street mounted Automatic Number-Plate Recognition (ANPR) cameras, and worker-driven surveys to capture footage at the junction	*Traffic count and footage of vehicles using junction	*Removed the need for vehicles and workers to access the active junction *Obtained accurate traffic count categorized into vehicle types *Provided a unique perspective of the junction not attainable using traditional traffic survey methods; flew at 90 m above ground level (AGL), 100 m horizontal distance from the junction

NH Drone Governance Team

The NH Drone Governance Team is responsible for developing and maintaining UAS operational procedures and requirements which comply with U.K. CAA regulations, with additional safety mitigations applicable to operations on and around the SRN. The Drone Governance Team has developed, among other documents, the following:

- CHE 471/20 – Interim drone operating standard complying with U.K. CAA CAP 722 Edition 8
- GG104 – Safety Risk Management (SRM) process for all NH operations used by NH, third parties working on behalf of NH, and third parties operating on and around the SRN
- GG954 – Upcoming requirements for the safe operation of drones whilst working for or on behalf of NH within proximity to the SRN or when using NH equipment

Operations conducted by or on behalf of NH must meet the following criteria:

- Fly at or below 120m AGL
- Fly at least 50m from the SRN
    - May fly closer than 50m from the SRN with authorization from U.K. CAA and an acceptable risk assessment according to GG104
- Take off and land at least 30m from the SRN
- Activity Manager and remote pilots must mitigate all safety risks associated with operating at a reduced distance from roadway users and company property, including risks associated with roadway user distraction

- May operate below roadway users' field of view (e.g., below a highway bridge deck), given all other safety requirements are met

The Drone Governance Team has developed the Drone Governance Hub (DGH) web portal to support third party UAS operations on and around the SRN. NH requests third parties to submit operational details into the DGH when undertaking operations. NH may review the submitted information and give feedback. Once a new operation has been accepted within the DGH, the Activity Manager must inform the DGH of all individually planned flights and is responsible for updating any SRM documentation throughout the duration of the operation. If any incident or near miss (of the unmanned aircraft to manned aircraft, infrastructure, roadway users, persons on the ground, etc.) occurs, then the operation must cease immediately, and the Activity Manager must inform NH via the DGH. The operation may not resume until the incident has been reviewed in the DGH.

Finally, NH implements the "no lone working" best practice which mitigates UAS operational safety risks, human factors risk for workers, and other risks associated with one worker undertaking tasks on or near construction sites or the SRN. FHWA follows a similar practice.

NH Collaborations with UAS Stakeholders

NH is a sponsor of the COMIT2drones industry working group,[14] which brings together UAS technology developers, UAS service providers, construction companies, infrastructure managers, U.K. federal government agencies, and other U.K. construction and infrastructure stakeholders. COMIT2drones conducted a study at the SMDC evaluating the accuracy of data collected versus the combined cost of aircraft platform and sensor(s). The study consisted of nine aircraft-plus-sensor systems flown in the same area within the SMDC, capturing color orthographic imagery. The results showed no necessary correlation between accuracy of data versus cost of system and that a medium-cost system provided the most suitable or appropriate level of performance among the systems evaluated. The study team agreed with U.K. SMEs in terms of observing appropriate level of data accuracy from medium-cost systems in U.S. State DOT survey projects.

NH and National Rail, through consulting services, have used UAS to collect surveying data. The data are post-processed with photogrammetric methods already in use by FHWA. These methods have an accuracy of 3-5 millimeters (mm) across entire models and are more accurate than 3mm in some instances. The use of UAS resulted in surveying accuracy comparable to traditional methods while not requiring surveyors to work on the tracks, resulting in safety, time, and cost improvements. For instance, one NH UAS service provider reported time savings of one year to eight weeks to survey a three-way rail junction with seven tracks and 38 rail switches. In addition, this type of surveying can yield significant benefits in highly sensitive situations, such as designing pre-cast concrete bridge elements.

German Aerospace Center (DLR) UAS Operations

The study team met with the German Aerospace Center (DLR) Institute of Flight Systems; Institute of Flight Guidance; Institute of Maintenance, Repair, and Overhaul; and Institute of Transportation

[14] COMIT2Drones – The construction industry drone community; Retrieved from: https://comit2drones.com/

Systems at the DLR National Experimental Test Centre for UAS.[15]

The National Test Centre is located at the Magdeburg-Cochstedt Airport in central Germany. The surrounding area is primarily agricultural land with relatively low population density. The Magdeburg-Cochstedt airport provides an airfield, air traffic tower staffed by aerodrome flight information service officers (AFISO), runways and taxiways, hangars, office buildings to serve as operational centers and other facilities for stakeholders' use. The National Test Centre operates a special testing area for UAS consisting of a 22-by-10 km polygon extending from the surface to 3,000 ft Mean Sea Level (MSL). The Centre obtains concurrence from local landowners before conducting UAS operations. Operational scenario-based tests performed by the Centre include:

- Individual UAS
- Multiple UAS
- BVLOS
- Manned aviation in proximity of UAS operations
- Counter-UAS operations
- Pilot psychological/human factors testing
- Freight and air mobility
- Occasional flights over rural highways

The DLR Institute of Flight Systems has operated the following fleet of in-house aircraft for testing purposes at both the Cochstedt and Braunschweig facilities:

- Small multi-rotor aircraft (weighing 1-10 kg)
- Unmanned helicopter midiARTIS (14 kg), superARTIS (90kg)
- Fixed-wing aircraft (35 kg)
- ALAADy autogyro freight aircraft (450 kg)[16]

The National Test Centre and other DLR facilities serve as national hubs for government, industry, and academia (domestic and international) to synchronize technological and regulatory development and test novel advancements in UAS. The Centre primarily conducts tests related to civilian UAS applications. Recently, the Centre hosted a large-scale demonstration (unrelated to this study) of UTM capabilities and UAS emergency response and cargo delivery attended by the German government, U.K. government, and industry stakeholders.[17] The Centre has also hosted public days to engage the local and national community and maintains a good relationship with local news media. The DLR, in general, establishes UAS-related networks on national and international levels.

The Institute of Flight Guidance conducted a bridge inspection over the Elbe River in 2019. This

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[15] Abbreviated as "the National Test Centre" or "the centre" in this section. The phrase "the centre" is not used in any other context in this report.
[16] German Aerospace Center, Vision of a Drone – Automated Low Altitude Air Delivery (ALAADy); May 2, 2018. Retrieved from: https://www.dlr.de/content/en/videos/2019/vision-einer-transportdrohne_automated-low-altitude-air-delivery-ALAADy.html
[17] German Aerospace Center, Deconfliction of Uncrewed and Crewed Aircraft Tested at Magdeburg-Cochstedt Airport; November 30, 2022. Retrieved from: https://www.dlr.de/content/en/articles/news/2022/04/20221130_deconfliction-of-uncrewed-and-crewed-aircraft-at-cochstedt-airport.html

inspection used AI algorithms to combine photo data and detected a crack of 1.5 mm on the structure. DLR reported that the UAS operation and data produced were received positively by the local bridge inspector. The study team has also observed positive feedback from bridge inspectors with respect to the benefits gained from using UAS; however, bridge inspection standards would need to be updated to preclude the current "arms-length" inspection requirement.

The Institute of Flight Guidance's Department of Pilot Assistance conducts research related to human behavior and stressors when working in air traffic management and ATC and as fixed-wing aircraft, helicopter, and UAS remote pilots. The department conducted a human-in-the-loop simulator-based study and reported that UAS supervisor (for example, the PIC may be supervising UAS operations conducted by on-site staff) attentiveness significantly decreases when attempting to supervise five or more aircraft at the same time.

The Institute of Transportation Systems develops solutions for the digitization and automation of transportation on the road, on rail, and at intermodal hubs. Related to the digitization of the transportation system, the Institute has conducted the following activities to support digital construction (not all items below are within the scope of this study):

- Structural defect detection on railroads and rail switches (in collaboration with academia)
- Creation of digital twins of airports, modeling, and simulation of airport operations
- Creation of a digital twin of the city of Braunschweig to support multi-modal research
- Creation of naturalistic datasets of road vehicles, cyclists, pedestrians, and other roadway users

Digital Models and Data Management Supported by UAS

Digital Product Catalogue (DPC) and Data Standardization

NH's DPC is a web-based interface used to facilitate the faster design of products through a modular approach, standardize data sharing practices, and increase data transparency among all links of the supply chain. DPC represents the "standardization" portion of NH's "innovation-standardization-automation" practices. The system is hosted on the NH cloud environment and can only be accessed within the NH internal network. The system is used to store, manage, and share digital models ranging from small individual construction products up to large structures. Following the in-person meetings in June 2022, the study team conducted additional meetings with NH regarding DPC software functional requirements and capabilities (National Highways, 2021). DPC assigns users to specific access groups along the supply chain, along with specific permissions:

- Designers (project managers, Scheme users, etc.) – can read data, download data, and can create an instance of a product for use in a project; can submit data into DPC for review
- Suppliers (i.e., product vendors) – can only view their own products and associated data; can submit data into DPC for review
- Moderators (i.e., product evaluators) – can evaluate data submitted to the system and accept or reject submissions

- Administrators – provide access to DPC and assign permissions to users
- Auditors – review change logs for products, perform version control on digital models

Users from each link of the supply chain can access digital models of assets and structures. Users can create highly consistent design files that are software-defined from the start. The DPC presents data according to Building Information Modeling (BIM) standards for asset properties BS EN ISO 23386:2020 (ISO, 2020), and BS EN ISO 23387:2020 (ISO, 2020). Figure 7 shows an example of product attributes in DPC.

Parameter	Value
Wall Height	1.80 m
Concrete Grade	C40/50
Easting	317234.983
Northing	194693.839
Rebar Spacing	200 mm c/c
Rebar Diameter	16 mm
Material Cost	£16765.56
Date of Arrival to Site	20th April 2020
Construction Date	15th May 2020
Test Result	63.2 N/mm^2
Last Inspection Date	6th December 2022
List of Defects	Spalled concrete

Figure 7. National Highways Digital Product Catalogue – Example of Product Attributes (Reproduced from NH Presentation Materials)

In terms of user groups and permissions, designers and suppliers can download blank data templates from DPC, fill the template with attributes of the item being delivered, and submit the completed template back into DPC. Suppliers cannot upload data directly into the system. Moderators receive the submissions of new or updated data sheets, review the data, and upload the data into DPC. NH performs additional analysis on the data stored in DPC by regularly extracting product data and activity logs to determine trends among products submitted to and work performed in the system. This process results in designs that can be incorporated into Plans, Specifications, and (best) Estimates (PSE) packages without the need for bespoke element design.

UAS can be used to collect high-accuracy attribute data for existing products to be stored within digital platforms such as DPC, allow for rapid identification and resolution of differing site conditions, and increase the efficiency of construction inspection. These benefits are present in inspection and maintenance throughout the lifecycle of a roadway. For instance, NH used UAS to map all 120 miles of M25,[18] the roadway profile, construction products along the road, and other attributes and stored the data in the DPC. NH cites the following as key benefits of digital design tools such as DPC:

- Design with the safety of workers and customers in mind
- Get designs right the first time, reducing the need to make changes at later stages
- Modular and offsite fabrication reduces carbon emissions, reduces waste, and reduces overhead which is a large part of project costs[19]

Finally, NH reports several hundred current DPC users and expects the number of users to increase rapidly in the coming years as construction practices become increasingly digitized (and automated where possible) in the U.K.

UAS Supporting Digital Model Creation

BUW Digital Model Creation Using UAS

The study team met with the BUW Institute of Structural Engineering and Institute of Computer Vision in Engineering. These organizations have used UAS to collect data at both newly constructed and aged structures, created 3D models at various resolution levels (levels commonly given in millimeters per pixel (mm/pix)) for differing applications, and developed analysis techniques to process data collected by UAS to support a wide range of infrastructure maintenance, inspection, and construction practices.

Table 3 shows examples of UAS operations conducted by BUW to support the operations of local infrastructure stakeholders and to develop, train, and refine datasets and data analysis techniques supporting infrastructure maintenance, inspection, and construction. The table shows UAS data outputs at various quality levels; BUW presented these quality levels in terms of a "good-better-best" framework and matched these levels to appropriate applications (for instance, from large-scale assessments such as structural deformation, down to micro-scale assessments such as crack detection).

Table 3. Examples of Recent Bauhaus Universität Weimar UAS Operations

UAS Use Case	Use Case Type	UAS Operation – Outputs	UAS Operation – Benefits
Highway retaining walls, Thuringia	Structure condition assessment of a 600m wall section	*280 images (four lines across the wall, 70 images each) *3D point cloud of 1.9 billion points	*Acquired imagery data in 20 minutes *Produced 3D point cloud with 6mm resolution *Provided a baseline for change detection analysis (collect the same images at a future time, produce point cloud, and compare to baseline) *Reduced highway traffic closures or disruptions

[18] The M25 is a U.K. Major motorway traveling around greater London, equivalent to Beltways seen around the U.S.
[19] In informal discussions, NH remarked that typically 60 percent of project costs go to overhead, and 40 percent go to on-site work. Most on-site work costs are spent on earthworks and few resources go to construction or the use of technology. Through standardization of individual elements, suppliers save time and cost when fabricating in bulk quantities.

UAS Use Case	Use Case Type	UAS Operation – Outputs	UAS Operation – Benefits
Anna-Ebert-brücke, Magdeburg	Digital modeling of bridge stone masonry	*3D model of stone masonry reliefs for restoration work *3D model of bridge	*Acquired imagery data in three days *Each data collection flight required bridge closure of less than one hour *Produced 3D model of stone masonry reliefs at 0.2 mm/pix; produced overall resolution of <1 mm/pix
Kersten-Miles-brücke, Hamburg	Bridge condition assessment after fire	*3D model of bridge arches	*Produced 3D model resolution of 0.2 mm/pix
Maintalbrücke rail bridge, Würzburg	Bridge pillar digital model, damage detection	*3D models of two data quality levels	*Produced 3D model resolution of 0.67 mm/pix for V-shaped pillars *Produced 3D model resolution of 0.1mm/pix for specific locations on the structure
Hochmosel-brücke, Rhineland-Palatinate	Bridge digital model basis for future inspection	*Imagery of all concrete surfaces	*Provided a baseline for a newly constructed viaduct to support future inspections and to support change detection analysis
Scherkonde-talbrücke, Thuringia	Viaduct structural deformation monitoring	*Imagery data *Automated, repeated flight path planning for precise scans	*Repeatable flight pattern supports precise scanning and future scanning for change detection *Improved navigation around 90-degree corners of structures *Produced a "good resolution" complete bridge model; "better resolution" partial bridge model; and "best resolution" pillar model
Brünn-talbrücke, Thuringia	Viaduct crack monitoring	*Imagery data *3D model	*Created a repository of structural deformation data depicting an aged viaduct, which may be used to train future structural deformation datasets *Enabled a professional bridge inspector to perform validation of imagery data rather than working at height
Ahr Valley, Rhineland-Palatinate	Post flood condition assessment	*Aerial photos *3D models created two months apart	*Ability to notify public about the conditions of the disaster *Ability to assess the condition of the environment for repair and rebuilding of infrastructure

SpectAir Digital Model Creation Using UAS

The study team met with SpectAir GmbH, which is a small business based in Cologne, Germany, providing UAS piloting, inspection, survey, data collection, and other services in Germany and other EU countries. The German BASt, the independent engineering company TÜV Rhineland,[20] and SpectAir published *Support of Building Inspection Through Innovative Digital Image Analysis – Pilot Study* in November 2017 (German BASt, 2017). SpectAir operated its HT-8 C180 UAS[21] at three major structures in Germany, the Schildescher Viaduct in Bielefeld, the Talbrücke Nuttlar, and the Europabrücke in Koblenz. The use of UAS allowed for the identification of structural defects that "*confirmed or even*

[20] TÜV Rheinland Group; Retrieved from: https://www.tuv.com/germany/de/rechtliche-hinweise/impressum/
[21] SpectAir HT-8 C180. Largest dimension = 100 cm, max takeoff weight = 5kg, max flight time = 20 minutes.

exceeded" bridge inspectors' assessments, and the "*…targeted use of UAS* [can] *result in reduced service failures and an increase in the quality of results*." The report concluded that UAS can be used as an auxiliary tool in bridge inspections.

During in-person meetings, SpectAir presented on a wide range of UAS inspection and survey work, including:

- Outdoor video camera-based inspection work, including telecommunications towers, industrial smokestacks, industrial piping and plumbing, sports stadiums, and offshore infrastructure
- Thermal sensor inspection of industrial piping and plumbing with navigation in confined spaces
- Structure interior inspection, such as in grain silos, enabled by onboard SLAM
- Creation of digital twins of industrial smokestacks at different inspection times to support change detection analysis
- Data collection for STRUCINSPECT, a digital structural inspection software company based in Vienna, Austria[22]
    - Data capture of the Talbrücke Eisern in west-central Germany to support the creation of a 3D model of the bridge
- Assistance with bridge inspection in Sweden and Switzerland

SpectAir and the study team discussed the ability of UAS to collect greater quantities of data and to provide improved data quality, as well as the applicability of that data to advanced data processing methods. SpectAir has flown UAS at a 3-5 m distance from structures to produce digital twins with 0.5-1.5 mm/pix resolution. The company found 1.5 mm/pix data suitable for photogrammetry and 0.5 mm/pix data suitable for change detection analysis using AI. SpectAir reported feedback from some bridge inspectors that, in their opinion, as a conservative estimate, 0.15 mm/pix resolution would be equivalent to an "arms-length" inspection.

SpectAir produced a digital twin of the Martin-Luther-Kirche in Gütersloh at 0.5 mm/pix; this work was performed by three pilots collecting over 11,000 images over half a day. The company performed data capture of the 220-m long Schleuse Sülfeld floodgate in north-central Germany, supporting the creation of a digital twin with a resolution of 0.2 mm/pix. At times, the UAS was flown in winds of up to 50 km per hour and in the rain. SpectAir noted that rain covering a surface affects lighting, contrast, and other photogrammetry analysis parameters. The data collection campaign was completed in two days, which saved significant time compared to traditional methods.

Finally, SpectAir and the study team discussed workforce development and retention. SpectAir remarked that public infrastructure owners lack funding to train their own pilots, thus turning to a limited set of private UAS service providers. The communication and coordination between the government, infrastructure owners, bridge inspectors, UAS service providers, and other stakeholders require time, effort, and resources. The study team agreed that the U.S. shares similar challenges and countries can collaborate in this area.

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[22] STRUCINSPECT; Retrieved from: https://strucinspect.com/

Machine Learning (ML)/Artificial Intelligence (AI) for Structural Defect Detection

The BUW Institute of Computer Vision in Engineering presented on automated image analysis to support structural defect detection, automated defect detection using ML, and visualization and optimization of UAS flight trajectories to collect data at an appropriate level of quality to support the data processing techniques.

Optimization of UAS flight trajectories involves balancing UAS capabilities, environmental constraints, data quantity (coverage of structure and/or amount of data at specific locations on the structure), data quality (resolution appropriate to the use case), and end-user needs, among other design factors. The Institute of Computer Vision in Engineering has developed algorithms to visualize proposed trajectories that can be imported onto UAS platforms. During in-person meetings, the group showed a visualization of a simplistic "slices" trajectory to collect imagery data of a structure. The aircraft orbits a part of the structure (such as a bridge pillar), attempting to keep a constant distance from the structure and constant height along the structure, and then transitions to the next highest or lowest orbit along the structure. The group showed the application of the "slices" trajectory to a structure with 90-degree corners, such as a vertical pillar below a bridge deck, and showed a real-world use case navigating V-shaped pillars under the Maintalbrücke rail bridge near Würzburg, Germany. At the Maintalbrücke rail bridge, the UAS was flown at 1.5 m from the structure, and the data collected was used to produce a "good" quality 3D model (0.67 mm/pix) for the entire structure and "best" quality 3D model (0.1 mm/pix) for specific locations on the structure where structural defects were suspected. The Maintalbrücke rail bridge pillars use case showed good performance that can be improved upon and demonstrated a UAS platform-agnostic means to plan UAS trajectories for structural inspection, enabling the use of UAS as an enhancing or supplemental tool to the work of bridge inspectors. After reviewing the "good" and "best" 3D models of the structure, bridge inspectors can perform an "arms-length" inspection while focusing their attention on potential problem areas identified in the 3D models.

The Institute of Computer Vision in Engineering has created a Structural Defects Dataset (S2DS) (Benz, 2022) consisting of over 700 annotated images showing structural defects in the classes of cracks, spalling, corrosion, efflorescence, and vegetation growth. The set of annotated images is a subset of over 8,000 images submitted by BUW collaborators that passed data quality filters (resolution, lighting, contrast, etc.). The set of annotated images was manually processed by 2-3 graduate students working for 2-3 months and can serve as a training dataset for subsequent computer vision algorithms. The group cited the following challenges in the initial analysis and subsequent development/refinement of computer vision algorithms:

- Crack-like artifacts resulting in "false positives"
- Variance among the size and orientation of structural defects
- Variance among the coloring and lighting of potential structural defects in the imagery
- Multiple defects at the same location
- Large amounts of data at the appropriate level of quality necessary to train algorithms

The group applied the "hierarchical multi-scale attention" methodology, also used in highly automated vehicle scene perception, to the assessment of structural defects (Benz & Rodehorst, Image-Based Detection of Structural Defects Using Hierarchical Multi-scale Attention, 2022). The group discussed the next steps for improving the algorithm, including revisiting the initial analysis as human subjective assessments change as they work through more images, adding more images and greater diversity of images to the annotated set, translating the method from 2D into 3D, and scaling data storage on the cloud (international and domestic providers).

Finally, the Institute of Computer Vision in Engineering and the study team discussed scaling of the methods in this section to, for instance, construction asset management in a state. The group noted the German Daimler AG CityScapes (Cordts et al., 2016) data challenge to collect and standardize highly automated vehicle scene perception data and how this practice can be replicated for structural inspection data. The Institute of Computer Vision in Engineering and the Institute of Structural Engineering collaborated on a "simple universal format" for construction asset data and structural inspection data. The study team, in agreement, cited the initial efforts necessary and subsequent benefits of data standardization in NH's DPC and REM systems. To potentially address this shared challenge, the study team commented on the benefit of ISO standard(s) describing data quality that can support structural inspection.

Asset Lifecycle Management Supported by UAS

Scaling UAS Operations for Asset Lifecycle, ML/AI for Model-to-Model Change Detection

The BUW Institute of Structural Engineering presented on the potential benefits of UAS for modeling and simulation of structures and predictive intervention of structural failure events. The Institute of Structural Engineering is also collaborating with the German BASt on a "crack detection state-of-practice" and developing strategies and software to independently assess private industry software packages in the market.

Like the U.S. and U.K., Germany has been examining ways to modernize infrastructure inspection and maintenance practices. Current structural inspection documentation can be supplemented by photos with an upper limit on file size, but the assessment of structural condition and automation thereof are lacking. The Institute of Structural Engineering is working towards the following goals to support the modernization of infrastructure inspection and maintenance practices:

- Develop workflows for efficient data generation and analysis
    - Digitization of structural condition assessment documents allows for analysis of the structure at differing time epochs and enabling change detection analysis (for instance, collecting a set of images to create a baseline digital model, collecting images in the same way at a future time epoch, and producing a new digital model and comparing to the baseline model)
    - Change detection of digital models of structures can be automated and integrated into centralized data management platforms that are accessible and editable by the appropriate users. The publication (Taraben & Morgenthal, 2020) provides "*…voxel-*

based methods for the automated assignment of geometrical representations of data to elements of [digital models]*, as well as to past damage scans, which describe the same damage entity*"

- Understanding the quantity, quality, and density/distribution of visual imagery data to meet the needs of structural inspectors
  - Structural deformation only requires a "good" data quality level, whereas crack detection might require a "best" data quality level, which drives the planning of UAS flight trajectories
- Efficiently building digital models for structures as large as dams and defects as small as cracks
- Extracting quantitative data from visual imagery data

The Institute of Structural Engineering has developed a framework for systematic data generation and processing (Morgenthal et al., 2019). The framework includes the visualization and optimization of UAS flight trajectories and computer vision-based analysis techniques discussed in the previous section, with additional steps to form a full repeatable workflow to collect, process, store, and manage UAS-collected structural inspection data. BUW and the study team agreed and reiterated that such a framework is not intended to replace the work of structural engineers and bridge inspectors but rather to reduce their workload and focus their attention on the areas of greatest need.

The group also developed INFRA\\TWIN platform,[23] which serves as the user-facing side of the framework. INFRA\\TWIN is a web browser tool that can accept digital models of structures from internal and external sources. Like advancements in the U.K., this platform uses a cloud-based back end and provides a remote work option to save time and money for users, as well as a low-barrier-to-entry viewing tool for stakeholder engagement. The platform implements differing levels of user rights for viewing, annotating, auditing, and other tasks and records all activity logs.

During the in-person meetings, BUW demonstrated the digital model of a dam which combined over 24,000 photos (collected by UAS over 1 ½ days) as an example of the scale of data being managed. A digital model of a bridge was also shown, including the capability for a user to toggle on/off the structure itself to only show manually annotated defects. The INFRA\\TWIN tool is used not only by BUW but also by a small base of infrastructure owners and UAS service providers who provide feedback for continued improvement to the platform. The next steps for the tool include integrating structural defect algorithms such as those for crack detection, among others.

UAS Fleet Maintenance, Repair, and Overhaul (MRO)

The DLR Institute of Maintenance, Repair, and Overhaul (MRO) conducts MRO testing and evaluation of UAS at the National Test Centre. The Institute contains the Departments of Product Lifecycle Management, Process Optimisation and Digitalisation, and Maintenance and Repair Technologies. The institute performs inspection and condition monitoring on UAS and individual components, with the goal of developing a dedicated maintenance framework to support future automated and repeated UAS

[23] INFRA\\TWIN: Digitale Bauwerkserhaltung; Retrieved from: https://infratwin.com/

operations.[24] Figure 8 shows an MRO test setup which includes DLR's Smart Vertiport and sensor suite.

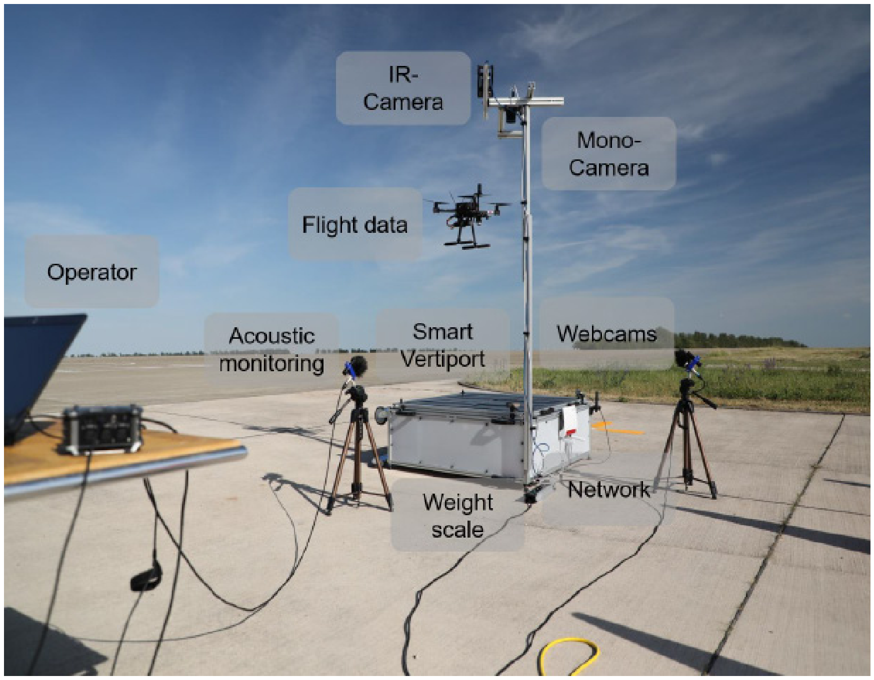

Figure 8. German DLR Institute of Maintenance, Repair, and Overhaul (MRO) – UAS MRO Test Setup with Smart Vertiport

The UAS hovers over the vertiport to allow acoustic, infrared, and video cameras to capture its condition. The UAS may fly away from the setup (e.g., fly outward and back) where onboard sensor and health data are recorded. The propulsion and energy storage subsystems on the UAS generally experience the most degradation from repeated use and can be most easily damaged in day-to-day operations. Acoustic measurements may reveal an unhealthy propeller before the issue is observed during human pre-flight checks. The institute has created digital twins of UAS and individual components to model repeated-use loads, providing a picture of the component's lifecycle and allowing end users to plan for the MRO and eventual disposal of tools such as UAS.

The Institute of MRO and the study team discussed the potential benefits of MRO practices for organizations using UAS or contracting UAS services. MRO practices go beyond pre-flight and post-flight checks of individual UAS flights. Emerging "drone-in-a-box" technologies can potentially incorporate the capability to remotely detect damage and degradation to the aircraft and critical components. MRO data can potentially be included in organizations' UAS operating manuals or in independent engineering standards.

Finally, the institute envisions extending MRO practices performed on small vehicles, such as UAS, to emerging "*technologies like electric propulsion and new vehicle concepts*" such as air mobility, further preparing for a more connected and automated transportation system.

[24] DLR Institute of MRO, Flight Testing at DLR's National Experimental Test Centre for UAS in Cochstedt; August 24, 2022. Retrieved from: https://www.youtube.com/watch?app=desktop&v=afxgys_b5k8

Rapid Engineering Model (REM) for Asset Lifecycle Management

NH and the supply chain use REM to automate the design and construction of products. This represents the "automation" portion of NH's "innovation-standardization-automation" practices. REM is an automated design workflow platform or "golden thread of design," enabling data standardization and data sharing for products throughout the lifecycle. Designers and suppliers can create a product, deploy it many times (first virtually among other existing digital roads models, then in the field), and add or revise attributes over time. REM accelerates routine design, which allows SMEs to focus their expertise on high-risk and unusual design issues.

Figure 9 shows NH's "golden thread of design" for asset lifecycle management. Suppliers can fill out digital product attribute templates and submit them into DPC. Reviewers approve the digital products for inclusion in DPC, and then designers can import digital products into REM into a comprehensive digital model of a construction project. Elements of the model follow the figure. The benefits of DPC and REM are primarily realized in the individual component design and project-level preliminary design phases, which typically carry the highest cost and time commitments.

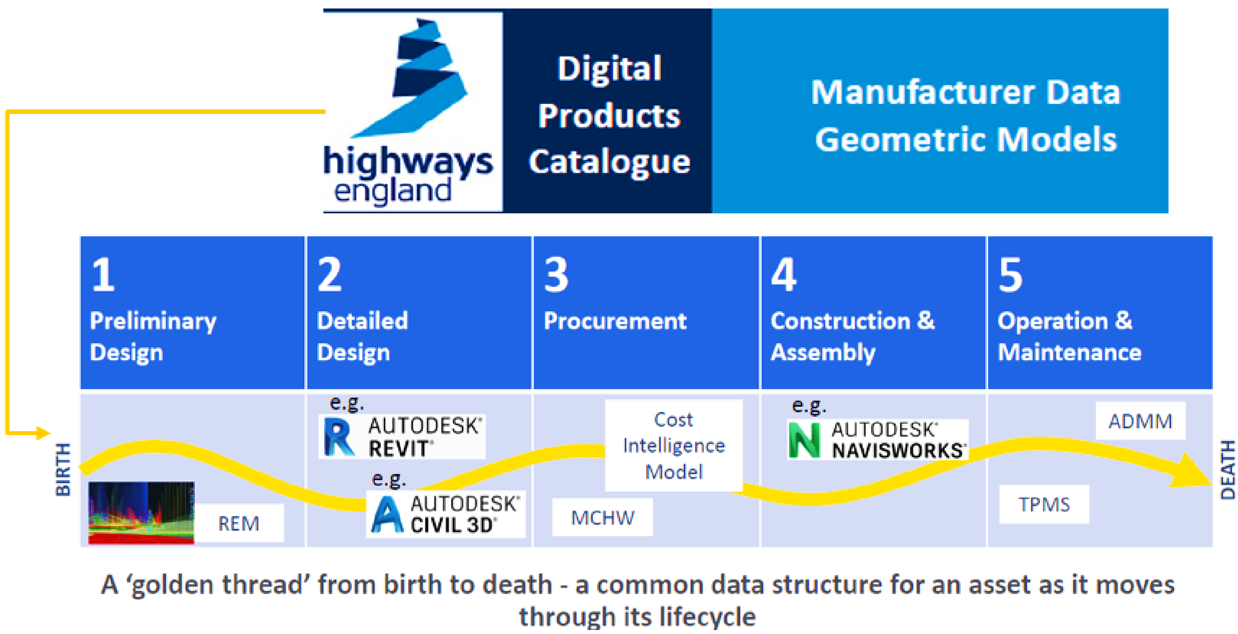

Figure 9. NH Digital Products Catalogue, Rapid Engineering Model, and "Golden Thread of Design" (Reproduced from NH Presentation Materials)

REM integrates engineering standards (from digitizing the current literature), topographic and environmental data (from inspection and survey tools such as UAS), and product data from the supply chain (collected in DPC). The REM v1.0 release is a free-to-use tool for NH and NH's Tier 1 contractors. REM v1.0 offers two main toolsets to the user: the Analysis Tool and the Roles-based Engine. The Analysis Tool is used to evaluate digitally captured topographic and environmental data to understand the suitability of the environment for new construction Schemes and products or construction modifications. Topographic and environmental data elements in the Analysis Tool include:

- Digital survey data
    - Digital terrain model
    - Roadway attributes – curves, internal road edge, road markings, hard strip, and barriers
    - Bridge locations and models
- Environmental data
    - Flood zones
    - National parks
    - Areas of outstanding natural beauty
    - Local parks and gardens
    - Heritage assets
    - European assets
    - European water sites
    - Sites of specific scientific interest
    - Ancient woodlands
    - Housing receptors
    - Conservation areas
    - Wildlife areas
- Existing assets
    - Technology Performance Management System (TPMS)[25]
    - Motorway Incident Detection and Automatic Signalling (MIDAS)[26]
    - National Roads Telecommunications Service (NRTS)[27] Service Delivery Points
    - Cantilever structures
    - Road surveillance (video cameras, speed cameras, etc.)
    - Emergency areas

The Roles-based Engine applies engineering standards (which have been coded into REM as data-driven rule sets) to the integration of the product or Scheme and the environment model. This integration results in a nearly automated design file that can be exported into common file formats and shared with the supply chain. The engineering standards coded into rule sets are non-proprietary, allowing use with multiple civil engineering software platforms. Users can also input project requirements into the product/Scheme/environment model to examine design tradeoffs during initial design. The Roles-based Engine results in significant time savings in the initial design and provides a jumping-off point for experienced designers to tune projects and visualize those adjustments.

NH's use of REM v1.0 has reduced average design costs from approximately £1 million to less than £150 thousand per project. Average design times for products have also decreased from approximately one year to as little as a few weeks, which is the timeframe to run the product/Scheme/environment model. The automation of routine design, which is estimated to be 80 percent of overall design, allows engineers to focus their expertise on high-risk and unusual design issues. The final deliverables are also more consistent and allow for full 3D models without a designer needing to repeat their work creating

[25] TPMS transmits the status of IP based devices to a central system, notifying the Regional Control Centre if a device is failing.
[26] MIDAS is a network of radar sensors scanning traffic counts and speeds, transmitting the information to Regional Control Centres.
[27] NRTS SDPs are roadside cabinets connecting all roadside technology back to Regional Control Centres.

each digital asset.

The use of REM has resulted in highly consistent design files that are software-defined from the start of the lifecycle. As with DPC, UAS flown in precise, repeated trajectories can supply valuable topographic and environment data into REM. This combination of REM and UAS can allow for the rapid identification and resolution of differing site conditions and yield improved data quality, greater data quantity, cost savings, and time savings for construction projects. As in other use cases, UAS can offer improved safety and an option for remote analysis work to further benefit construction projects. NH published a recent case study that lists the following benefits of REM v1.0 (National Highways):

- Minimized changes in the construction and maintenance phases
- Reduced development time for initial designs by 50 percent, and reduced re-work required after project completion
- Achieved improved safety through “safe by design” Schemes that enable the use of off-site manufacturing and modular construction techniques

During in-person meetings, NH demonstrated a “fly-through” of a 40km segment of the M3 motorway in southern England in 10m elements. The digital road model contains environmental constraints; physical attributes of assets; relevant engineering requirements; and potential safety hazards such as areas needing a retaining wall, high gradient segments, and segments subject to visibility hazards, among other information. The digital road model can display color-coding for infrastructure elements to show whether the element meets design standards or whether the use of automated design can help meet design standards. The model also visualizes proposed/planned modifications to the transportation infrastructure, in this case, the widening of a motorway junction.

Looking forward, REM v2.0 release is currently under development with the vision to extend digital survey, environment, and asset data on expressways; connectivity to the U.K. Smart Motorways and NH systems; and ability to interact with Digital Built Britain[28] and NH’s digital twins. NH aims to continue improving REM’s ease-of-use and intuitiveness, reducing user interactions from 160 down to 20 screens or clicks. REM performs “every-mouse-click” logging for all tasks performed on the platform.

[28] University of Cambridge, Centre for Digital Built Britain; September 2022.
Retrieved from: https://www.cdbb.cam.ac.uk/

Key Findings and Recommendations

This section summarizes the most significant study findings and includes recommendations for FHWA, U.S. highway transportation agencies, and other relevant stakeholders.

Countries Share Similar Challenges in the Design, Construction, Inspection, and Maintenance of Transportation Infrastructure

Countries are working under similar transportation infrastructure regulations and guidance. Countries also experience similar challenges in the sector, including and not limited to the following:

- Transportation infrastructure nearing the end of anticipated design life, beyond the end of anticipated design life, or approaching the need for major maintenance or rehabilitation
- Increasing demand on, and use of, transportation infrastructure
- Aging and attrition within the transportation workforce
- Safety risks to human workers when conducting safety inspection and survey operations
- Limitations on the use of emerging tools such as UAS (albeit with recent regulatory advances)
- Hesitancy to adopt emerging tools such as UAS

There is a common desire to convene working groups within the highway transportation and digital construction sectors to collaborate on the challenges listed above.

Recommendations: Key stakeholders could convene international meetings to establish data collection, data sharing, algorithm development, and algorithm sharing agreements among partnering countries. Countries have different funding priorities within the highway transportation and digital construction sectors, which presents opportunities for collaboration. Countries aim to inspect transportation infrastructure in similar ways (e.g., comparable bridge inspection standards); updates to infrastructure inspection standards to account for the use of UAS could be made based on the concurrence of partnering countries.

Countries Aim to Improve Legacy Processes in the Highway Transportation and Digital Construction Sector

Countries share similar legacy processes in the design, construction, inspection, and maintenance of transportation infrastructure, which may be costly or lengthy. Advances in UAS design, UAS navigation, data collection, data analysis, and data management present opportunities to modernize, digitize, and accelerate legacy processes.

Both the U.K. and Germany are implementing systems with web browser front-ends and organization-internal cloud back-ends to manage digital construction data and supporting data, including but not limited to:

- Design parameters of structures
- Catalogs of structures at a location/in a region
- Defects found on structures
- LiDAR point clouds of structures
- Initial 3D models as baselines for change detection and subsequent 3D models supporting change detection analyses
- UAS flight plans (if integrating UAS into operations)
- UAS flight operation logs (if integrating UAS into operations)

Recommendations: Relevant stakeholders could convene workshops related to data standardization, data management, use of ML/AI for algorithm training, and automated structural defect detection. Countries could consider adopting a lifecycle-oriented or "golden thread of design" mode of thinking for data related to highway transportation infrastructure, construction projects, construction products, etc., with the expectation that the full suite of benefits will not be realized right away but rather over time. Standardization and digitization of common construction elements yield significant cost and time savings in initial design, allowing SMEs to focus their attention on high-risk and unusual issues.

Use of UAS Provides Measurable Benefits via a Range of Mature Applications

International SMEs presented a multitude of use cases where the use of UAS improved safety as well as one or more of the following: improved efficiency, improved data quality, greater data quantity, cost savings, and time savings in day-to-day operations. These use cases include bridge and crane inspection (over land and over water), highway retaining wall inspection, structure interior inspection, and creation of digital models, among others. All use cases exhibited safety improvements when UAS were used to supplement or enhance human workers' tasks. All use cases also exhibited time savings compared to traditional methods in terms of worker-hours, time to complete the task, and overall construction lifecycle times. Most use cases exhibited comparable data quality relative to traditional methods.

Recommendations: Relevant stakeholders may consider updating and standardizing performance metric tracking associated with emerging and traditional methods of design, construction, inspection, and maintenance. The full set of metrics may include sub-metrics within the categories of safety, efficiency, data quality, data quantity, cost, and time. A survey of State DOT usage of the metrics above may be beneficial.

Use of UAS Can Increase Consistency and Repeatability in Producing Standardized Data to Enhance Digital Construction

Advances in UAS flight guidance, navigation, and control allow for accurate and precise flight paths to be repeatedly flown to support infrastructure inspections. Data collected at the same location and orientation at multiple time intervals allows for human and ML-augmented change detection analyses. International SMEs reported the ability to plan such flight paths in a technology provider-agnostic manner.

Simultaneously, advances in data management allow for large amounts of data to be stored, processed, and monitored for early threat intervention. In the U.K., NH has developed REM and DPC with web browser front-ends and organization-internal cloud back-ends to manage digital construction data. Cataloguing common construction structure elements mitigates the risk of bespoke designs (i.e., a new design for each customer) to save time and money on projects. In addition, NH has expressed the goal of creating digital models of entire major roadways enabled by cloud-based storage with cybersecurity certification.

Data management systems accessible by public authorities, developers (AI/ML specialists, computer scientists, software engineers), and end users (bridge inspectors, civil engineers, and the local community) help these stakeholders speak a common language during the construction lifecycle, which will yield cost and savings and will indirectly facilitate public acceptance by providing safety benefits. U.S. government agencies are moving towards cloud-based data management to help authorities and end users “speak the same language” in all phases of an operation or project’s lifecycle.

Recommendations: Relevant stakeholders could adopt common data standards for construction design and construction elements to mitigate the need for bespoke design and improve the ability of the supply chain to access standardized, digitized design files. UAS use cases involving automated and repeated flights can collect data to support 3D model change detection, and advances in cloud-based data management can support the storage and sharing of data and algorithm outputs. State DOTs could collaborate on single or multi-state cloud-based data management systems that are interoperable with other such systems.

Standardization of the Application of UAS-collected Data to Various Digital Construction Uses

U.K. and German SMEs reported that data of differing quality levels (in terms of mm/pix, position accuracy, or other metrics) can be managed and used for varying digital construction applications. Table 4 shows a conceptual “good-better-best” data quality framework corresponding to resolution and accuracy requirements. Highly precise data might be too costly and time-consuming to acquire, and the same construction tasks can be done with good-quality data. Collecting data at the appropriate level of quality will also yield cost savings and time savings.

Table 4. Summary of Data Quality Corresponding to Construction Use Cases from U.K. and German SMEs

Data Quality Level (Conceptual)	Data Quality Requirement	Construction Use Cases	UAS Operational Requirements
"Good"	<1 mm/pix	*3D models and digital twins for stakeholder engagement *Structural deformation assessment	*Manual flight by on-site remote pilot is sufficient
"Better"	<0.5 mm/pix	*3D models and digital twins for planning and analysis *Defect detection: corrosion, efflorescence, spall, vegetation growth	*Combination of manual flight and highly automated and repeatable flight
"Best"	<0.2 mm/pix	*3D models and digital twins as baselines for change detection *Defect detection: crack *Generation of data for change detection *Masonry restoration	*Highly automated and repeatable pre-planned flight patterns

Recommendations: UAS can be thought of as a toolset to generate consistent, repeatable, standardized datasets yielding benefits throughout the construction lifecycle. UAS, depending on onboard sensors and other flight operation parameters, can collect data at various quality levels to support various digital construction applications. Relevant stakeholders may work with end users of data (e.g., bridge inspectors and UAS service providers) to obtain concurrence on data quality-to-use case standardization. State DOTs could evaluate enhancements gained from highly automated and repeatable UAS flight paths for data collection. U.S. DOT could contribute to the development of data quantity, data quality, and data management standards for bridge inspection and other infrastructure inspection and survey tasks.

Minimum Requirements are Needed for Maintenance, Repair, and Overhaul (MRO) Practices Associated with UAS

As the use of UAS becomes increasingly routine, transportation agencies may benefit from working with UAS technology developers to understand the repeated use of UAS in both normal and challenging conditions allowable within current regulations. Transportation agencies may need to periodically refresh their fleets in their future practices. Transportation agencies may benefit from understanding safety risks to human workers (e.g., attention, focus, fatigue) when monitoring, piloting, and maintaining UAS in a routine manner.

Commonly shared MRO practices can help organizations prepare to scale UAS operations into routine, widespread, and potentially automated operations in states, in localities, and in or near large construction sites. This will help ensure organizations' tools are as healthy as possible to achieve the safety, efficiency, data quantity and quality, cost savings, and time savings offered by those tools.

Recommendations: U.S. DOT could collaborate with industry and standards-making agencies to develop minimum MRO requirements for UAS and UAS components. Minimum MRO requirements will support UAS use cases involving automated and repeated flights to collect the quantity of data necessary for machine learning-enhanced assessments of infrastructure. Relevant stakeholders may work with UAS service providers and UAS technology providers to obtain concurrence on UAS repeated use standards and MRO standards in normal and challenging conditions e.g., Minnesota DOT's use of UAS for bridge inspections (MNDOT, 2021).[29] UAS technology providers could be encouraged to share additional data related to the MRO of various UAS models.

Countries Aim to Maintain Economic Growth and Retain a Talented Workforce in the Transportation Infrastructure Workforce

The study team and international SMEs all observed a need to attract and retain highly skilled workers, such as bridge inspectors, land surveyors, etc., within the transportation infrastructure workforce. An additional need exists in the U.S., U.K., and Germany to develop trust and concurrence that data collected by UAS are intended to support or enhance structural inspections rather than replace human workers. At the same time, a gap exists between the data quality generated by UAS and post-processing and the level of data quality SMEs are comfortable using.

Recommendations: To attract entry-level and early career talent, the U.S. educational curricula supporting civil engineering and the infrastructure sector could be updated, as what is necessary to perform jobs in transportation has drastically changed. FHWA has funded a curriculum refresh program that high schools and universities can freely use to update civil engineering, surveying, and inspection coursework. Caltrans, NCDOT, and other state DOTs have established STEM programs to expose students to UAS and digital construction technologies.

To attract and retain mid-career workers, FHWA and State DOTs could support workers in UAS training. The FAA Part 107 certification is a relatively low bar for entry and can yield significant benefits. Additional research may be conducted to understand the benefits and shortfalls of current workers obtaining UAS training versus employing UAS service providers. Both models were observed in the U.K. and Germany.

[29] Crossroads, Minnesota's Transportation Research Blog. Bridges and Structures, Drone Technology Enhances Bridge Inspections; March 15, 2022; Retrieved from: https://mntransportationresearch.org/2022/03/15/drone-technology-enhances-bridge-inspections/

References

ASCE. (2020, December). *A Comprehensive Assessment of America's Infrastructure, 2021 Report Card for America's Infrastructure*. Retrieved from https://infrastructurereportcard.org/wp-content/uploads/2020/12/National_IRC_2021-report.pdf

Benz. (2022). *Structural Defects Dataset (S2DS)*. Retrieved from https://github.com/ben-z-original/s2ds

Benz, & Rodehorst. (2022, September 20). Image-Based Detection of Structural Defects Using Hierarchical Multi-scale Attention. *German Conference on Pattern Recognition (GCPR) and the International Symposium on Vision, Modeling, and Visualization (VMV)* (pp. 337-53). Konstanz, Germany: Springer. Retrieved from https://link.springer.com/chapter/10.1007/978-3-031-16788-1_21

Chen. (2014). Mobile Imaging and Computing for Intelligent Structural Damage Inspection. *Advances in Civil Engineering*. Retrieved from https://www.researchgate.net/publication/274895120_Mobile_Imaging_and_Computing_for_Intelligent_Structural_Damage_Inspection/download

Cordts et al. (2016). *Daimler AG Cityscapes Dataset*. Retrieved from https://www.cityscapes-dataset.com

Deutsches Institut für Normung. (1999, November). *DIN1076 Engineering Structures in Connection with Roads - Inspection and Test*. Retrieved from ANSI Web Store: https://webstore.ansi.org/standards/din/din10761999de

EASA. (2019, November 6). *EASA Commission Implementing Reguation 2019/947 on the Rules and Procedures for the Operation of Unmanned Aircraft*. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019R0947&from=EN

EASA. (2020, September 8). *EASA Commission Delegated Regulation 2019/945 on Unmanned Aircraft Systems and on Third-Country Operators of Unmanned Aircraft Systems (Updated)*. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02019R0945-20200809&from=EN

EASA. (2020, March 13). *EASA Opinion No. 01/2020 High-level Regulatory Framework for the U-Space*. Retrieved from https://www.easa.europa.eu/en/downloads/111303/en

EASA. (2021, April 22). *EASA Commission Implementing Regulation (EU) 2021/664 on a Regulatory Framwork for the U-Space*. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021R0664&from=EN

EASA. (2021, March 31). *EASA Guidelines on Design Verification of UAS Operated in the 'Specific' Category and Classified in SAIL III and IV*. Retrieved from https://www.easa.europa.eu/en/downloads/126318/en

EASA. (2022, September). *Easy Access Rules for Unmanned Aircraft Systems*. Retrieved from https://www.easa.europa.eu/en/downloads/110913/en

Eißfeldt et al. (2020, March 25). *The Acceptance of Civil Drones in Germany*. Retrieved from https://elib.dlr.de/134782/3/Ei%C3%9Ffeldt%20et%20al%20%282020%29%20The%20acceptance%20of%20civil%20drones%20in%20Germany.pdf

European Commission. (2022, November 29). *Communication from the*

Commission to the European Parliament, the Council, the European Economic and Social Committee, and the Committee of the Regions: A Drone Strategy 2.0 for a Smart and Sustainable Unmanned Aircraft Eco-system in Europe. Retrieved from https://transport.ec.europa.eu/system/files/2022-11/COM_2022_652_drone_strategy_2.0.pdf
FAA. (n.d.). *14 CFR Part 135 Air Carrier and Operator Certification*. Retrieved from https://www.ecfr.gov/current/title-14/chapter-I/subchapter-G/part-135?toc=1
FAA. (n.d.). *14 CFR Part 137 Agricultural Aircraft Operations*. Retrieved from https://www.ecfr.gov/current/title-14/chapter-I/subchapter-G/part-137
FAA. (n.d.). *14 CFR Part 91 General Operating and Flight Rules*. Retrieved from https://www.govinfo.gov/content/pkg/CFR-2011-title14-vol2/pdf/CFR-2011-title14-vol2-part91.pdf
FAA. (2016, June 21). *FAA News, Summary of Small Unmanned Aircraft Rule (Part 107)*. Retrieved from https://www.faa.gov/uas/media/part_107_summary.pdf
FAA. (2021, March 10). *14 CFR Parts 1, 11, 47, 48, 89, 91, and 107 RIN 2120-AL31 Remote Identification of Unmanned Aircraft (Final Rule; delay of effective and compliance date; correction.)*. Retrieved from https://www.govinfo.gov/content/pkg/FR-2021-03-10/pdf/2021-04882.pdf
FAA. (2021, January 15). *14 CFR Parts 11, 21, 43, and 107 RIN 2120-AK85 Operation of Small Unmanned Aircraft Systems Over People (Final Rule)*. Retrieved from https://www.govinfo.gov/content/pkg/FR-2021-01-15/pdf/2020-28947.pdf
FAA. (2022, June). *FAA Aerospace Forecast Fiscal years 2022-42, Unmanned Aircraft Systems*. Retrieved from https://www.faa.gov/sites/faa.gov/files/2022-06/Unmanned_Aircraft_Systems.pdf
FAA. (2022, April 25). *FAA Order 1370.121B - FAA Information Security and Privacy: Policy*. Retrieved from https://www.faa.gov/regulations_policies/orders_notices/index.cfm/go/document.information/documentID/1040976
FAA. (2022, August 16). *Unmanned Traffic Management (UTM) Concept of Operations (CONOPS) Version 2.0*. Retrieved from https://www.faa.gov/sites/faa.gov/files/2022-08/UTM_ConOps_v2.pdf
FAA. (n.d.). *Part 107 Operational Waiver Application Instructions*. Retrieved from https://www.faa.gov/sites/faa.gov/files/uas/commercial_operators/part_107_waivers/waiver_application_instructions.pdf
FAA. (n.d.). *Part 107 Waiver Section Specific Evaluation Information*. Retrieved from https://www.faa.gov/sites/faa.gov/files/uas/commercial_operators/part_107_waivers/Part-107-Waiver-Section-Specific-Evaluation-Information.pdf
FHWA. (2022, May 6). *23 CFR Part 650 National Bridge Inspection Standards (Final Rule)*. Retrieved from https://www.govinfo.gov/content/pkg/FR-2022-05-06/pdf/2022-09512.pdf
FHWA Office of Infrastructure. (2020, August). *FHWA-HIF-20-091 Global Benchmarking Study on Unmanned Aerial Systems for Surface Transportation: Domestic Desk Review*. Retrieved from https://www.fhwa.dot.gov/uas/hif20091.pdf
German Aerospace Center. (2021, March). *DLR at a Glance*. Retrieved September 2022, from

https://www.dlr.de/content/en/downloads/publications/brochures/2019/dlr-at-a-glance-2019.pdf?__blob=publicationFile&v=5
German Aerospace Center. (2021, March). *The National Experimental Test Center for Unmanned Aircraft Systems and UAS Research at DLR*. Retrieved September 2022, from https://www.dlr.de/content/en/downloads/publications/brochures/2021/brochure-unmanned-aircraft-systems-cochstedt.pdf?__blob=publicationFile&v=5
German BASt. (2017, November). *BASt Report B 139 Support of Building Inspection Through Innovative Digital Image Analysis – Pilot Study*. Retrieved from https://bast.opus.hbz-nrw.de/opus45-bast/frontdoor/deliver/index/docId/1840/file/B139_barrierfreies_Internet_PDF.pdf
German BASt. (2022, July). *BAST Annual Report 2021: Reports of the (German) Federal Highway Research Institute*. Retrieved September 2022, from https://bast.opus.hbz-nrw.de/opus45-bast/frontdoor/deliver/index/docId/2701/file/A_47_Annual_Report_2021.pdf
German BMDV. (2015, December). *Road Map for Digital Design and Construction: Introduction of Modern, IT-based Processes and Technologies for the Design, Construction, and Operation of Assets in the Built Environment*. Retrieved September 2022, from https://www.bmvi.de/SharedDocs/EN/publications/road-map-for-digital-design-and-construction.pdf?__blob=publicationFile
German BMDV. (2016, August). *The 2030 Federal Transport Infrastructure Plan*. Retrieved from https://www.bmdv.bund.de/SharedDocs/EN/publications/2030-federal-transport-infrastructure-plan.pdf?__blob=publicationFile
German BMDV. (2020, May). *Unmanned Aircraft Systems and Innovative Aviation Strategies: The Federal Government's Action Plan*. Retrieved September 2022, from https://www.bmvi.de/SharedDocs/DE/Anlage/DG/aktionsplan-drohnen-englisch.pdf?__blob=publicationFile
H. Rept. 115-750. (2018, June 12). *H. Rept. 115-750 Departments of Transportation, and Housing and Urban Development, and Related Agencies Appropriations Bill, 2019. 115th Congress, Second Session (2018-19)*. Retrieved from https://www.congress.gov/115/crpt/hrpt750/CRPT-115hrpt750.pdf
H.R. 5315 Drone Infrastructure Inspection Grant Act. (2021, September 21). *H.R. 5315 - Drone Infrastructure Inspection Grant Act, 117th Congress (2021-2022)*. Retrieved from https://www.congress.gov/bill/117th-congress/house-bill/5315
Hamdan et al. (2021, May 10). A Semantic Modeling Approach for the Automated Detection and Interpretation of Structural Damage. *Automation in Construction (128)*, 103739. Retrieved from https://www.sciencedirect.com/science/article/abs/pii/S0926580521001904
IEC. (2010, April 30). *IEC 61508 Functional Safety of Electrical/Electronic/Programmable Electronic Safety-Related Systems*. Retrieved from https://webstore.iec.ch/publication/5515&preview=1
ISA/IEC. (2019, February 27). *ISA/IEC 62443 Industrial Communication Networks - Network and System Security Standard Series*. Retrieved from https://webstore.iec.ch/publication/34421&preview

ISO. (2020, March 25). *BS EN ISO 23386:2020 Building Information Modelling and Other Digital Processes Used in Construction - Methodology to Describe, Author, and Maintain Properties in Interconnected Data Dictionaries*. Retrieved from https://www.en-standard.eu/bs-en-iso-23386-2020-building-information-modelling-and-other-digital-processes-used-in-construction-methodology-to-describe-author-and-maintain-properties-in-interconnected-data-dictionaries/

ISO. (2020, July 22). *BS EN ISO 23387:2020 Building Information Modelling. Data Templates for Construction Objects Used in the Life Cycle of Built Assets. Concepts and Principles*. Retrieved from https://www.en-standard.eu/bs-en-iso-23387-2020-building-information-modelling-bim-data-templates-for-construction-objects-used-in-the-life-cycle-of-built-assets-concepts-and-principles/

JARUS. (2019, November 11). *JARUS Guidelines on SORA, JARUS-STS-01 Standard Scenario for Aerial Work Operations, Edition 1.1*. Retrieved from http://jarus-rpas.org/sites/jarus-rpas.org/files/jar_doc_6_sora_sts_01_edition1.1.pdf

JARUS. (2019, September 25). *JARUS Guidelines on SORA, JARUS-STS-02 Standard Scenario for Aerial Work Operations, Edition 1.0*. Retrieved from http://jarus-rpas.org/sites/jarus-rpas.org/files/jar_doc_6_sora_sts_02_edition1.0.pdf

JARUS. (2019, January 30). *JARUS Guidelines on Specific Operations Risk Assessment (SORA) Edition 2.0*. Retrieved from http://jarus-rpas.org/sites/jarus-rpas.org/files/jar_doc_06_jarus_sora_v2.0.pdf

Levitate Capital. (2020, December). *The Future of the Drone Economy, A Comprehensive Analysis of the Economic Potential, Market Opportunities, and Strategic Considerations in the Drone Economy*. Retrieved from https://levitatecap.com/levitate/wp-content/uploads/2020/12/White-Paper-v4.pdf

MNDOT. (2021, May). *Minnesota State DOT (MNDOT). Unmanned Aircraft Systems (UAS) - Metro District Bridge Inspection Implementation*. Retrieved from https://www.dot.state.mn.us/research/reports/2021/202113.pdf

Morgenthal et al. (2019, January). Framework for Automated UAS-based Structural Condition Assessment of Bridges. *Automation in Construction (97)*, 77-95. Retrieved from https://www.sciencedirect.com/science/article/abs/pii/S0926580518305156

National Highways. (2021). *Digital Product Catalogue (DPC) Functional Requirements v1.0 [Presentation Slides]*. Birmingham, United Kingdom.

National Highways. (2021, August). *Introducing Digital Roads. Safer Construction and Operations - Faster Delivery - Better Customer Experience*. Retrieved from https://nationalhighways.co.uk/media/2chotw13/introducing-digital-roads.pdf

National Highways. (2021). *Use of Drones (UAVs) for Mapping and Visual Surveys Exemplar [Redacted]*. Birmingham, United Kingdom.

National Highways. (2022, July). *National Highways' Performance, Report to Parliament 2021/22*. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1091008/national-highways-performance-report-to-parliament-2021-to-2022-print-version.pdf

National Highways. (n.d.). *Rapid Engineering Model (REM) - Case Study*. Retrieved

from https://s3.eu-west-2.amazonaws.com/assets.highwaysengland.co.uk/digital+roads/Case+Studies_REM_FINAL.pdf
Public Law 117-58, § 25005. (2021, November 15). *Public Law 117-58 Infrastructure Investment and Jobs Act.* Retrieved from https://www.congress.gov/117/plaws/publ58/PLAW-117publ58.pdf
Taraben, & Morgenthal. (2020, November 14). Methods for the Automated Assignment and Comparison of Building Damage Geometries. *Advanced Engineering Informatics (47),* 101186. Retrieved from https://www.sciencedirect.com/science/article/abs/pii/S1474034620301579
U.K. CAA. (2020, November 5). *CAP 722 Unmanned Aircraft System Operations in UK Airspace - Guidance, Eighth Edition.* Retrieved from http://publicapps.caa.co.uk/docs/33/CAP722%20Edition8(p).pdf
U.K. DfT. (2021, December). *Planning Ahead for the Strategic Road Network, Developing the Third Road Investment Strategy*. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1045938/planning-ahead-for-the-strategic-road-network-developing-the-third-road-investment-strategy.pdf
U.K. House of Commons. (2019, October 8). Retrieved from https://publications.parliament.uk/pa/cm201719/cmselect/cmsctech/2021/2021.pdf
U.K. Office of Rail and Road. (2022, May). *Road Investment Strategy 3 (RIS3), Our Role and Approach.* Retrieved from https://www.orr.gov.uk/sites/default/files/2022-05/Road-Investment-Strategy-3-our-role-and-approach-2022-05-04.pdf
U.S. Congress. (2019, December 20). *Public Law 116-94 Further Consolidated Appropriations Act, 2020. 116th Congress (2019-2020).* Retrieved from https://www.congress.gov/116/plaws/publ94/PLAW-116publ94.pdf
U.S. DOT. (2017, May 17). *Statement of the Honorable Elaine L. Chao, Secretary of Transportation, Before the Committee on Environment and Public Works, U.S. Senate.* Retrieved from https://www.transportation.gov/testimony/improving-america%E2%80%99s-transportation-infrastructure-road-forward
U.S. DOT. (2022, April). *U.S. Department of Transportation Strategic Plan FY 2022-2026.* Retrieved from https://www.transportation.gov/sites/dot.gov/files/2022-04/US_DOT_FY2022-26_Strategic_Plan.pdf

Appendix A: U.S. Study Team Members

James Gray (Study Team Lead)
UAS Program Manager
Federal Highway Administration
james.gray@dot.gov

Zekial Rios (Study Team Member)
UAS Program Coordinator
Federal Highway Administration
zekial.rios@dot.gov

Aaron Chamberlin (Study Team Member)
Senior Innovation Engineer and Construction UAS Coordinator
California Department of Transportation (Caltrans), Division of Construction (DOC)
aaron.chamberlin@dot.ca.gov

Thomas Walls (Study Team Member)
UAS Operations Manager
North Carolina Department of Transportation
tmwalls@ncdot.gov

Jason Lu (Report Lead)
General Engineer
U.S. Department of Transportation, Volpe Center
jason.lu@dot.gov

Basil Yap (former study team member)
UAS BEYOND Program Manager
North Carolina Department of Transportation, Division of Aviation

Tarek Tabshouri (former study team member)
Senior Transportation Engineer and UAS Program Manager
Caltrans

Paul Wheeler (former study team member)
UAS and Advanced Air Mobility Program Manager
Utah Department of Transportation, Division of Aeronautics

Appendix B: Study Focus Questions

This appendix contains Focus Questions developed by the study team. Focus Questions are intended to expound the study team's interests and guide information collection.

Focus Area: Organizational Management of UAS Programs and Operations

- What are examples of UAS program organizational structures in your country?
  - Number of personnel
  - Number of UAS in your fleet
  - Location of personnel and UAS (e.g., centralized or localized in multiple field offices)
  - Responsibility for conducting UAS operations (e.g., internal staff or external contractors)
    - If contractors or contracts are used, what is being acquired (e.g., skill, software, hardware, data and data processing, end-to-end operation)?
  - Data collection and processing
  - Project delivery
  - Digital and contactless practices
- What is your UAS program's budget and how are you funded?
- How are roles and responsibilities between the European Union Aviation Safety Agency (EASA); federal governments; and regional, provincial, and local governments communicated and coordinated?
- What frameworks are used to facilitate information exchange among stakeholders?
- How does your agency interact with the public in terms of:
  - Making data collected from UAS operations available to the public
  - Gaining public acceptance of new UAS operations
  - Assuring the public that their privacy will be maintained
- Can you discuss examples of collaboration with academia, industry, and other partner organizations?

Focus Area: Programs and Partnerships to Advance UAS Operations

- **UAS and Innovative Strategies Action Plan**
  The study team is interested in programs and use cases that have been implemented after the Federal Ministry for Digital and Transport's Action Plan document was published, specifically related to:
  - Digital construction
  - Contactless practices
  - Digital infrastructure, including but not limited to data sharing between Germany and European Union partners
- **National Experimental Test Centres and Research Aerodromes**
  The study team is interested in use cases and operational concepts being advanced at the German Aerospace Center's test sites, specifically related to:
  - Digital construction
  - Contactless practices
  - Digital infrastructure

Focus Area: Status of Specific UAS Programs and Applications

- The study team is interested in learning more about the status and maturity of the following applications identified in the United Kingdom during the Desk Review Phase, as well as any other similar applications
  - Construction Monitoring/Contactless Practices
  - Bridge Inspection support or enhancement
  - Digital Construction
  - Tunnel Construction
- The study team is interested in learning more about the status and maturity of the following applications identified in Germany during the Desk Review Phase, as well as any other similar applications.
  - Digital Construction e.g., use of UAS for construction site surveys and collection of telemetry data and construction surveying in support of highway construction projects
  - Highway Asset Management e.g., traffic dynamical datasets captured by UAS

Focus Area: UAS Implementation – Best Practices and Lessons Learned

UAS Use Case Studies and Best Practices

- What are some best practices and lessons learned you have observed when working with/from your country's UAS certification and standards processes?
  - Scale of operations: local, regional, national
  - Operational concepts: BVLOS, operations over people, operations at night, etc.
  - Data collection methods: advanced sensors used and data storage
  - Training best practices: pilots-in-command, visual observers, safety staff, etc.
  - Pre-flight best practices: safety risk management processes, UAS construction, airworthiness, maintenance practices
  - In-flight best practices: contingency and emergency procedures
  - Post-flight best practices: documentation, data pre-processing

UAS Applications and Concepts of Operation

- What types of mature UAS applications have been implemented in your country?
- How are new UAS applications identified and what rationale is used?
- How long does the process take from identifying an application to implementing it?
- What operations within the construction sector pertaining to i) design, ii) construction, iii) structural inspection, and iv) asset management are being supported by UAS?
  - Are these UAS operations conducted by public or private operators?
  - Have UAS operations provided comparable or greater benefits than traditional non-UAS practices?
  - Are data integrated and automated among discrete operations?
- Have you performed UAS operations: i) over critical infrastructure, ii) over people, and iii) beyond visual line of sight? If so:
  - Have you encountered difficulty obtaining public acceptance of these operations?
  - How have you mitigated air risk and ground risk associated with these operations?
- Have you performed UAS operations in operating environments that are hazardous to personnel or unmanned aircraft (e.g., forest fires)? If so, how have you mitigated the associated risks?

    - What mitigations are used when environmental conditions approach operational limits? (e.g., high temperature, high wind)
- Have you deployed UAS for recurring or automated operations, such as continual/periodic monitoring or inspection of a critical asset?
- Have you deployed UAS operations remotely? Have the aircraft operated autonomously?

UAS Technologies

- How are new technologies and new systems tested prior to implementation?
- How is the use of the radiofrequency (RF) spectrum by UAS regulated or managed?
- How are command and control (C2) or command and non-payload control (CNPC) architectures regulated or managed?
- What unmanned aircraft platforms are being used in mature applications?
- What sensors are being used in mature applications, and why were they chosen? Examples include:
    - LiDAR
    - Radar
    - Video, thermal, or infrared cameras
    - Additional sensors not listed
- What unmanned aircraft platforms and sensors are being considered for use soon?
- What hardware and software are being used to support in-flight operation? Examples include:
    - Terrain following technologies
    - Waypoint tracking technologies
    - Change detection
    - Additional technologies not listed
- What methods are being used for power source and battery life management?
- What tools are being used to track fleets of unmanned aircraft?
- What technologies are being used in operating environments that are challenging to navigation via Global Navigation Satellite System (GNSS), such as tunnels and bridge underpasses?
- What, if any, technologies are being used to protect critical infrastructure from unknown UAS users?

Data Collection and Management

- How are various types of data (e.g., numeric, photo, video) stored and secured after collection, and do you have concerns about data security?
- What are your best practices related to data?
    - Data governance roles and responsibilities
    - Data storage
    - Data quality assurance
- What hardware and software are being used to support in-flight or post-flight data processing? Examples may include:
    - Machine learning
    - Convolutional neural networks
    - Other methods not listed
- What tools are being used to integrate data collected by a fleet of unmanned aircraft, potentially consisting of different unmanned aircraft platforms?

Outcomes and Lessons Learned

- What is the return on investment (ROI) regarding UAS integration?
    - Programmatic ROI
    - Application-based ROI
    - Other ROI types

- What quality improvements or efficiency gained have you observed?
- How much change in safety-related metrics have you observed?
- What operational benefit (and in contrast, risk, or detriment) of UAS has surprised you the most?
- What aspect of UAS program management has surprised you the most?
- What is your biggest challenge or roadblock in deploying or integrating UAS operations?
- What impacts from public outreach, and what changes in public perception and acceptance have you observed, as more UAS operations are flown?
- What are the key lessons learned from your experience?
- What should managers be aware of when developing a UAS program?

Additional Questions

- Are there any additional relevant observations from UAS operations with respect to cost savings, efficiency gains, quality improvements, safety improvements, or other metrics?
- Is there any additional information that you can share that would interest us?

Focus Area: UAS Implementation – Mature Applications Related to "Advanced Digital Construction" or "Contactless Practices"

The study team is interested in the organizational management and project delivery for mature UAS applications. The study team is also interested to learn how national, regional, local, and other government jurisdictions communicate and work together in the implementation of these applications. If possible, the team would like to organize site visits to view these applications in person.

- Scale of operations: local, regional, national
- Operational concepts: BVLOS, operations over people, operations at night, etc.
- Data collection methods: advanced sensors used and data storage
- Training best practices: pilots-in-command, visual observers, supporting staff, etc.
- Pre-flight best practices: safety risk management processes, UAS construction, airworthiness, maintenance practices
- In-flight best practices: contingency and emergency procedures
- Post-flight best practices: documentation, data pre-processing

Appendix C: National Highways Responses to Focus Questions (August 2021)

This appendix includes NH's written responses to the Focus Questions, which were submitted to the study team in August 2021 following the U.S.-U.K. virtual exchanges. The study team thanks NH for the detail and technical depth of the responses, which are indicated by *blue italic* text.

Note that these responses represent the status of UAS operations, organizational management, and data management as of August 2021, and NH UAS operations and practices may have changed since this time. Portions of these responses have been edited for clarity.

- What are some best practices and lessons learned you have observed when working with/from your country's UAS certification and standards processes?
    - Scale of operations: local, regional, national
      At present UAS deployment across Highways England infrastructure has been dealt with at a regional level tactically, with national oversite of risk assessments to ensure best practice and consistency of approach, review, comment, and approval via the Safety Control Review Group (SCRG), these sessions are held every 2 weeks where the UAS team undertaking the activity present the risk assessment for review and ultimate approval by the SCRG. This can be for a single activity or for a programme of activities or a period, the main criteria being that under either scenario, the location of deployment and the predetermined geographic limits of use remain constant
    - Operational concepts: BVLOS, operations over people, operations at night, etc.
      Operations to date have been VLOS, EVLOS within relevant CAA envelopes of operational constraints. BVLOS is a study being undertaken by [U.K.] DfT called 'Pathfinder' which is being closely developed under trials conditions. No nighttime UAS activity has been endorsed across the SRN at this time
    - Data collection methods: advanced sensors used and data storage
      Dominant sensor technologies have been LiDAR and Photogrammetry with emerging technologies in Hyper-spectral devices for vegetation assessments and other environmental considerations. Data storage is within a central system known as Asset Visualisation and Information System (AVIS). This provides a 'near current' dataset of the road asset across England. The best way to describe this is a Google Earth data set for Highways England with accuracies of certain assets down to the +/- 30mm scale
    - Training best practices: pilots-in-command, visual observers, safety staff, etc.
      All pilots and observers (as a minimum) are to be suitably qualified and trained via recognized certified organizations for national UAS activity
    - Pre-flight best practices: safety risk management processes, UAS construction, airworthiness, maintenance practices
      As mentioned above [regarding] the SCRG, this review ensures that all the requirements such as airworthiness, suitability of technologies etc. are taken into consideration
    - In-flight best practices: contingency and emergency procedures
      Examples of in-flight best practice can be found in the [Use of Drones UAVs) for Mapping and Visual Surveys Exemplar]. It is noteworthy that we do have other risk assessment examples that vary [depending] on the UAS being used e.g., [SenseFly] EBee vs. [DJI] Mavic
    - Post-flight best practices: documentation, data pre-processing
      Examples of post-flight best practice can be found in the [Use of Drones UAVs) for Mapping and Visual Surveys Exemplar]. In terms of data processing, [NH] have survey

data standards to which all asset data are to be processed to meet. This is to ensure interoperability of data from various supplier sources nationwide

- What types of mature UAS applications have been implemented in your country?
  Currently the main UAS applications in England are asset data capture for the following purposes: i) construction activity progress reporting (e.g., earthworks progress cut/fill); ii) bridge condition inspections; iii) data capture for design input (digital terrain data); iv) environmental impact assessment (e.g., water course monitoring)

- How are new UAS applications identified and what rationale is used?
  Problem statement and use cases are developed from a need presented by the business e.g., incident response requirements. The business has three key imperatives against which a new UAS must demonstrate alignment and enhancement and is assessed against these as follows: Safety, Customer, Delivery

- How long does the process take from identifying an application to implementing it?
  We adopt a process called 'the 4Ds': discover, develop, demonstrate, deliver. Timelines for each phase are typically discover (12 weeks), develop (16 weeks), demonstrate (6 months), delivery is variable dependent on complexity. The overall average [for this process] has been circa 18 months to complete all four stages.

- What operations within the construction sector pertaining to i) design, ii) construction, iii) structural inspection, and iv) asset management are being supported by UAS?
  Design, construction, and structural inspection are established as business as usual activities supported by UAS. Asset management is being [supported by UAS] in very small scale at this time
    - Are these UAS operations conducted by public or private operators?
      All [UAS operations are conducted by] private operators at this time, public operators including NH will commence shortly with the media team having their own pilots trained for media activities across the network
    - Have UAS operations provided comparable or greater benefits than traditional non-UAS practices?
      Significant safety benefits have been realized using UAS solutions, reducing roadworker exposure to roadside risk has been the dominant benefit. This coupled with the secondary benefit of reducing disruption to the road user (customer) through reduction in traffic management measures. Costs have been comparable to traditional approaches due to requirements such as no lone working requirements and VLOS constraints
    - Are data integrated and automated among discrete operations?
      Asset data survey information is integrated at a data storage level. We are currently working towards automating the integration as part of the next generation AVIS development taking place now

- Have you performed UAS operations: i) over critical infrastructure, ii) over people, and iii) beyond visual line of sight? If so:
    - Have you encountered difficulty obtaining public acceptance of these operations?
    - How have you mitigated air risk and ground risk associated with these operations?
      No activity of this nature has been undertaken by NH. As mentioned previously [these operations are being progressed] by U.K. DfT

- Have you performed UAS operations in operating environments that are hazardous to personnel or unmanned aircraft (e.g., forest fires)? If so, how have you mitigated the associated risks?
    - What mitigations are used when environmental conditions approach operational limits? (e.g., high temperature, high wind)
      We have not undertaken this yet but are actively exploring a piece of development work to use UAS solutions for incident response purposes

- Have you deployed UAS for recurring or automated operations, such as continual/periodic monitoring or inspection of a critical asset?
  Pre-programmed activities with set flight plans for periodic progress reporting of construction activities have been used in off [SRN] environment to very significant and positive effect, reducing the need for quantity surveyors to be deployed and therefore enhancing safety, and reducing costs

- Have you deployed UAS operations remotely? Have the aircraft operated autonomously?
  Not in an active [SRN] environment, this has been undertaken in controlled conditions at the [SMDC]

- How are new technologies and new systems tested prior to implementation?
  As mentioned before [NH utilizes] 'the 4Ds' alongside which we use Product Maturity Levels (PMLs) (derived from Technology Readiness Levels (TRLs)) to stage-gate the development and testing for use on the SRN. This stage-gate approach ensures cost and time are monitored; and that technical compliance, in a consistent and efficient way across various solutions, are being delivered

- How is the use of the RF spectrum by UAS regulated or managed?
  U.K. DfT is in better position to answer this question

- How are C2 or command and CNPC architectures regulated or managed?
  This is currently being developed as part of the [FMS] deployment and further details will be available later

- What UAS platforms are being used in mature applications?
  Most platforms used to date have been DJI, these are the primary system for VLOS flights. [Platforms include DJI] Phantom 4, Mavic, S1000, and Matrice M300

- What sensors are being used in mature applications, and why were they chosen? Examples include:
  - LiDAR – *Mature usage*
  - Radar – *Emerging usage*
  - Video – *Used in photogrammetry*
  - Thermal – *Emerging usage*
  - Infrared cameras – *Emerging usage*
  - Additional sensors not listed – *As part of our innovation work, we have been discussing the use of ultrasonic sensors for crack and deterioration detection; [as well as] 3D printing units*

- What UAS platforms and sensors are being considered for use soon?
  Continue to use standard off the shelf systems where possible. Sensor range may increase. Additionally, maintaining a 'watching brief' on technologies being developed and deployed in the military environment that may produce spin-off applications and solutions. Namely the likes of 'x-ray style' technologies for structures penetration purposes. Audio frequency systems for incident response and multi-sensor platforms

- What hardware and software are being used to support in-flight operation? Examples include:
  - Terrain following technologies
  - Waypoint tracking technologies
  - Change detection
  - Additional technologies not listed
    This is a [significant] subject area that would warrant a more expansive response as this is [highly dependent] on platform, operator, application, and environment. Various software systems are being used for drone flight management. This depends on which operator is used. Generally, [operators] use systems such as Pix4D

- What methods are being used for power source and battery life management?
  Only pre-charged batteries have been used to date. Battery management being done using [UAS platforms'] own operating software

- What tools are being used to track fleets of unmanned aircraft?
  This is managed by our operators; each have their own way of doing this

- What technologies are being used in operating environments that are challenging to navigation via GNSS, such as tunnels and bridge underpasses?
  This is often done visually, there have been some discussions around creating a temporary Mobile Network Operator (MNO) network within those types of environments, [currently the signal used] would be 4G, however, we are discussing the use of 5G. For closed construction sites, solutions [from] the mining industry are currently being considered to create a micro-network for greater accuracy of coordinated control

- What, if any, technologies are being used to protect critical infrastructure from unknown UAS users?
  The government are looking at this using companies such as Nexus9 to detect UA, and [are using] other companies to capture or bring down rogue UA. However, NH is not looking at these technologies now, as mentioned above

- How are various types of data (e.g., numeric, photo, video) stored and secured after collection, and do you have concerns about data security?
  LiDAR and photogrammetry data are stored in a secure PostgreSQL database (the DPC), hosted centrally and in-line with all central government cybersecurity requirements

- What is the ROI regarding UAS integration?
  - Programmatic ROI
  - Application-based ROI
  - Other ROI types
    ROI has been broken down slightly differently to the above. Namely project level [ROI] initially to understand both qualitative and quantitative benefits. Qualitative [benefits have] been measured against the three key NH imperatives (safety, customer, delivery). Against these the use of UAS must demonstrate value added and safety either maintained or enhanced as a minimum. Quantitative benefits have been dominated by cost evaluation but broken down into specific task and/or project time [and] cost benefits. In most [EVLOS operations] there are marginal cost benefits at task level due to the increased number of resources required to be deployed, including the requirement for 'no lone working' [which doubles] the resource requirements. VLOS has better performance [with respect to less] human resources needed. Obviously, the bigger savings have been [observed in terms of] project time and associated cost. As the need for added traffic management and planning requirements is removed, and the opportunity to be agile when deploying UAS vs. 'boots on the ground' provides both time reduction and schedule surety (i.e., mitigation of [schedule] slippage)

- What quality improvements or efficiency gained have you observed?
  In terms of the survey activities undertaken on the [SRN], the quality has started from a basis of parity with existing practices (e.g., data accuracy +/- 30mm requirements). We anticipate with the advancements in sensing, platform stability, processing speeds, and reduced dependency on Ground Position Markers that levels of quality will continue to increase. This is driving us to revisit and refine existing standards to keep pace with the changing landscape of performance

- What operational benefit (and in contrast, risk, or detriment) of UAS has surprised you the most?
  Benefits – Large reduction in risk to [workers], increase in speed of data capture, increase in quality and currency of data captured

Disbenefits – Lack of discipline consistently being shown across the supply chain. Delivery partners have wildly different views of the levels of safety and control needed when employing the use of drones. Supply chains [have shown] varied lack of appreciation of potential third-party impacts when using drones, [such as impacts on] road users, local communities, etc.

- What aspect of UAS program management has surprised you the most?
  Speed of adoption by delivery partners to utilize UAS solutions has perhaps been the biggest surprise. Acceptance by local communities to the use of drones in the surrounding area as the benefits to understanding impacts, has been the driving force behind reduced resistance. The concerns about gathering of personal and property data have been significantly offset against the opportunity to understand (through digital public consultation and visualization) what the impact of future construction works will look like from an adjacent property owner's point of view. This has helped with the reduction in time to gain feedback and refine designs

- What is your biggest challenge or roadblock in deploying or integrating UAS operations?
  Biggest challenge is ensuring consistency of deployment across the U.K. with close collaborations across DfT, Network Rail, and other infrastructure owners. [As well as] understanding and accepting the change in risk from standard practices

- What impacts from public outreach, and what changes in public perception and acceptance have you observed, as more UAS operations are flown?
  As mentioned in other sections, there is a general acceptance of the use of UAS across the [SRN]. We have a significant number of instances now flow with little or no interest from the public. [Data show] that instances of driver distraction are near zero with no detrimental impacts on daily life. In specific cases we have had to ensure that UAS operations are suitably supported, particularly with Schemes that are of a sensitive nature (e.g., [when] local acceptance of the Scheme has been less positive), but in these cases [the less positive acceptance] isn't specifically [related] to UAS activity, rather more related to the wider ramifications of the Scheme being constructed

- What are the key lessons learned from your experience?
  Lack of sufficient risk management controls being used by the supply chain, that has been picked up by infrastructure owners to ensure that sufficient levels of safe best practice are adopted in-line with corporate and CAA requirements. As part of the construction design development process, the time taken to gather site data has been a significant factor when launching design commencement. Traditional methods have historically taken months in planning for traffic management, safe systems of work at specific sites, etc. Now with the use of UAS, the ability to gather data quickly and introduce this to the designers with a high degree of accuracy and veracity has significantly reduced the time take to commence design. Couple this with our REM (automated design workflow), we have now managed to reduce design development from years to weeks!

- What should managers be aware of when developing a UAS program?
  The one key message to managers would be to take the time to ensure a clear policy, set of standards, and safety requirements before approaching the supply chain. Undertake a series of industry engagements throughout the development of those policies, standards, and requirements to gain feedback and SME insights prior to launching [the program]. Take incremental steps when looking to deploy any [FMS], ensure it is scalable, interoperable, and open. We have spent a lot of time well-spent navigating the 'minefield' of proprietary systems that are closed and have no open links to third-party systems

Appendix D: Study Itinerary

The study team conducted virtual exchanges and in-person meetings with U.K. and German SMEs in 2021 and 2022. The study itinerary is as follows:

- Virtual exchange with U.K. SMEs; June 11, 2021
- Virtual exchange with German SMEs: June 14-15, 2021
- U.K. in-person visit
  - NH Smart Motorways Development Centre, Moreton-in-Marsh; June 6, 2022
  - NH Structures Group, Birmingham; June 7, 2022
- Germany in-person visit
  - HHLA Sky, Port of Hamburg; September 12, 2022
  - German Aerospace Center (DLR), Cochstedt National Experimental Test Centre for UAS; September 13, 2022
  - Bauhaus Universität Weimar; September 14, 2022
  - SpectAir GmbH, Cologne; September 15, 2022

Appendix E: Meeting Participants

The study team conducted virtual exchanges and in-person meetings with U.K. and German SMEs in 2021 and 2022. This appendix shows all virtual or in-person meeting participants. Table E-1 shows all U.S. meeting participants, note that only the current study team attended in-person meetings in the U.K. and Germany.

Table E-1. U.S. Meeting Participants

Organization	Name	Title
FHWA Office of Infrastructure	James Gray	UAS Program Manager *(Study team lead)*
FHWA Western Federal Lands Highway Division	Zekial Rios	UAS Program Coordinator *(Study team member)*
Caltrans	Aaron Chamberlin	Senior Innovation Engineer and Construction UAS Coordinator *(Study team member)*
	Tarek Tabshouri	Chief, Office of Technical Services and Programs *(Former study team member)*
NCDOT	Thomas Walls	UAS Operations Manager *(Study team member)*
	Basil Yap	UAS BEYOND Program Manager *(Former study team member)*
U.S. DOT Volpe Center	Jason Lu	General Engineer *(Report lead)*
Federal Aviation Administration	Paul Albuquerque	UAS Integration Office, Flight Technologies and Procedures
	Christopher Swider	UAS Integration Office, Senior Technical Adviser
	William C. (Christopher) Brown	UAS International Division, Europe co-lead
	Elisabeth Walker	UAS International Division, Europe co-lead
FHWA Office of Bridges and Structures	Joe Krolak	Team Leader, Hydraulics and Geotechnical Engineering Team
	Samantha Lubkin	Team Leader, Safety Inspection Team
	Derek Soden	Team Leader, Structural Engineering Team

Table E-2 and Table E-3 show U.K. virtual and in-person meeting attendees, respectively.

Table E-2. U.K. Virtual Meeting Participants (June 2021)

Organization	Name	Title
National Highways Major Projects	Steve Ellis	Head of Digital Design Tools Deployment and Development
	Lorraine Butler	Major Projects Delivery Director
	Lila Tachtsi	Asset Management Director
	Christopher Batey	Senior Project Manager
	Inga Broomhall	Senior Administrator
U.K. Department for Transport	Fozia Chughtai	Team Leader, Unmanned Aircraft and Air Mobility
	Stephanie Gooby	Policy Team Lead, Unmanned Aircraft and Air Mobility
	Teena Patel	Policy Team, Unmanned Aircraft and Air Mobility
U.K. Civil Aviation Authority	Frederic Laugere	Innovation Services Lead

Table E-3. U.K. In-Person Meeting Participants (June 2022)

Organization	Name	Title
National Highways Major Projects	Steve Ellis	Head of Digital Design Tools Deployment and Development
	Lorraine Butler	Major Projects Delivery Director
	Lila Tachtsi	Asset Management Director
	Ian Bilington	Major Projects Production & Product Delivery
	Inga Broomhall	Senior Administrator
	Callum Brown	Airspace Standards – Assistant Advisor, Safety, Engineering & Standards
	Jason Glasson	Asset Capability Team Leader
National Highways Structures	Peter Hill	Head of Structures
	Colin George	Deputy Head of Structures
	Malcolm Dangerfield	Assets Needs Manager, Midlands
	Stephen Dennis	Principal Structures Advisor
	Kieran Dodds	Head of Operational Engineering
	Neil Loudon	Structures Group Manager
	Mark Maynard	Principal Structures Advisor, Southwest
	Francis McKeown	Senior Structures Advisor
	Terry Robinson	Structures Engineering Manager, Southwest
	Dennis Safukiwa	Head of Specialism, Midlands
	Antonis Tsampos	Senior Structural Advisor, Midlands
	Pierfrancisco (Pierre) Valerio	Principal Structures Advisor, Southeast
DroneCloud	Andrew Blogg	Co-founder Provider for NH Flight Management System
Frazer Nash	Stuart Keenan	Head of Uncrewed Air Systems Centre of Excellence & Group Leader Program Manager for NH Flight Management System
	Matt Hopkins	Consultant, Uncrewed Air Systems
	David Stone	Senior Engineer

Organization	Name	Title
Jacobs Engineering Group	Faris Mahder	Digital Delivery Lead Product Owner of NH Rapid Engineering Model
IBI Group	Daniel Austin	Consultant
Plowman Craven	Thomas Wren	Head of Client Solutions, Rail, and Infrastructure
ProDroneWorx	Ian Tansey	Managing Director
Sees.ai	John McKenna	Co-founder & Chief Executive Officer

Table E-4 and Table E-5 show German virtual and in-person meeting participants, respectively.

Table E-4. Germany Virtual Meeting Participants (June 2021)

Organization	Name	Title
German Federal Ministry for Digital and Transport	Dr. Jan Dirks	Director, UAS
	Peter Schmitz	Advisor, UAS
	Christian Trempler	Lead, UAS Coordination Unit
German Federal Highway Research Institute	Ralph Holst	Head, Maintenance of Engineering Structures
	Sonja Neumann	
German Federal Railway Authority/Center for Rail Transport Research	Dr. Ascelina Hasberg	Faculty, University of Cologne, Institute of Geology and Minerology
	Dr. Rustam Tagiew	Faculty, University of Bielefeld
German Civil Aviation Authority	Christopher Klann	Team Leader UAS Operations
German Landesbetrieb Straßenbau North-Rhine Westphalia	Sebastian Riedel	Head, Department of Surveying
Bauhaus Universität Weimar	Prof. Dr. Guido Morgenthal	Chair, Modelling and Simulation of Structures Institute of Structural Engineering
RWTH Aachen University	Dr. Lutz Eckstein	Director and Chair Institute for Automotive Engineering
Helmut-Schmidt-Universität, UDVeo	Sebastian Törsleff	Research Group Leader, Project Developer HHLA Sky
	Karlotta Victor	Air Traffic Department

Table E-5. Germany In-Person Meeting Participants (September 2022)

Organization	Name	Title
German Federal Ministry for Digital and Transport	Dr. Jan Dirks	Director, UAS
HHLA Sky (Port of Hamburg)	Dr. Matthias Gronstedt	Managing Director
	Dr. Lothar Müller	Managing Director
	Jan Henniges	U-Space, CONOPS, SORA & Business Solutions
	Juan Martin	Project Development Manager
	Martin Rothermund	Operations Manager
	Sebastian Törsleff	Research Group Leader Helmut-Schmidt-Universität, Project Developer HHLA Sky
	Nico Wenz	Drone Pilot
	Michael Witting Schipper	Operations Manager
	Dr. Jörg Fochtmann	Coordinator Scientific Infrastructure

Organization	Name	Title
German Aerospace Center: Cochstedt National Experimental Test Centre for UAS	Nadine Dörge	Coordinator UAS Campaigns
German Aerospace Center: Institute of Maintenance, Repair, and Overhaul	Dr. Florian Raddatz	Head of Department
	Philipp Conen	Research Scientist
	Alexander Kamtsiuris	Research Scientist
German Aerospace Center: Institute of Transportation Systems	Dr. Andreas Leich	Research Scientist
German Aerospace Center: Institute of Flight Systems	Dr. Gordon Strickert	Research Scientist
German Aerospace Center: Institute of Flight Guidance	Andreas Volkert	Research Scientist
Bauhaus Universität Weimar	Prof. Dr. Guido Morgenthal	Chair, Modelling and Simulation of Structures Institute of Structural Engineering
	Prof. Dr. Volker Rodehorst	Professor Institute of Computer Vision in Engineering
	Christian Benz	Research Associate Institute of Computer Vision in Engineering
	Paul Debus	Research Associate Institute of Computer Vision in Engineering
	Norman Hallermann	Research Associate Institute of Structural Engineering
	Dr. Charles (CJ) Riley	Associate Professor of Civil Engineering (Oregon Institute of Technology), Professional Engineer
SpectAir GmBH	Salih Gülhan	Head of Engineering
	Roman Preylowski	Professional Drone Pilot

Appendix F: Meeting Hosts Information

United Kingdom Meeting Hosts Information

National Highways (formerly Highways England)

National Highways (NH) is a U.K. government-owned company that operates, maintains, and improves M-designated motorways and major A-roads in the country of England – also referred to as the Strategic Road Network (SRN) (National Highways, 2022). The U.S. study team learned about NH's drone governance and best practices, Digital Product Catalogue, and Rapid Engineering Model that supports a comprehensive approach to digitize and streamline lifecycle operations in the highway transportation and digital construction sectors. Today, NH continues working to deliver the goals stated in U.K. *Road Investment Strategy 3*. Learn more about NH at https://nationalhighways.co.uk/.

NH published *Introduction to Digital Roads* in August 2021 (National Highways, 2021), which describes the organization's 2025 vision to "*harness data, technology, and connectivity to improve the way the Strategic Road Network (SRN) is designed, built, operated, and used*." The 2025 vision consists of three core themes implemented to digitize the design, construction, maintenance, and disposal of transportation infrastructure:

- Digital design and construction – "*increasing automated, modular, and off-site activities resulting in safer production, reduced network disruption, increased productivity, and smoother journeys for customers*"
- Digital operations – "*leverage data to drive increasingly pre-emptive interventions resulting in improved asset resilience, increased asset life, and a safer, smoother running network*"
- Digital for customers – "*customers will be better informed and have trust in the journey information they access, ensuring that they feel safe and in control of their journeys*"

The study team visited the NH SMDC in Moreton-in-Marsh. The SMDC is located on the site of the former Royal Air Force Moreton-in-Marsh airfield while also sharing the property with the Fire Service College. NH conducts a wide range of activities at the SMDC benefiting the highway section, including fire protection on roadway surfaces, testing of sustainable roadway surfaces, skid testing, use of solar power to operate motorway equipment, UAS pavement crack filling, and others.

NH has tested and improved novel developments in the highway sector (such as new roadway surfaces for motorway emergency pull-offs) at the SMDC, which has resulted in the significantly accelerated deployment of these advances. With the introduction of its digital construction tools, NH practices the process of "innovation-standardization-automation" as it relates to the design and deployment of roadway assets/products. The SMDC serves as the "innovation" ground where new concepts for products are discovered and quickly assembled; the Digital Product Catalog (DPC) "standardizes" and digitizes the design of common transportation- or transportation facility-related structures (sign masts, roadside barriers, etc.) to mitigate the need for bespoke designs and construction elements. The Rapid Engineering Model (REM) "automates" the design and construction of products. Unrelated to UAS though related to faster construction practices, NH showed the study team a new roadway surface made of recycled materials developed in two years, compared to legacy roadway surface development and implementation processes, which may require up to 10 years. Learn more about the SMDC at https://vimeo.com/474868205.

The study team met with the NH Structures Group. During in-person meetings, the NH Structures Group reported that 57 percent of the over 23,000 structures managed by the organization will be over 45 years old by 2025-2030. U.K. bridge inspections, like those in the U.S., include a general inspection every two years and a principal "arms-length" inspection every six years. NH Structures stated goals of conducting 6,500 bridge inspections each year, no inspections overdue by more than 180 days, and gaining the ability to perform predictive renewal on structures. Significant challenges to these objectives include a traditional three-month period required to write bridge inspection reports and difficulty in hiring and developing bridge inspectors. Learn more about the work of NH Structures Group and NH's roadways projects at https://nationalhighways.co.uk/our-roads/.

U.K. Department for Transport

The U.K. Department for Transport (DfT) provides policy, guidance, and funding to local authorities to help them run and maintain their road networks; invests in, maintains, and operates the motorway and trunk road network in England through the services of NH; along with a range of responsibilities in the rail industry, bus transportation, maritime sector, aviation sector, and promoting cycling and walking. Learn more about U.K. DfT at https://www.gov.uk/government/organisations/department-for-transport.

Germany Meeting Hosts Information

German Federal Ministry for Digital and Transport

The German Federal Ministry for Digital and Transport (BMDV) is the federal agency governing all transportation modes, road user safety, freight transport and logistics, information technology in transportation, and broadband, among other areas in the Federal Republic of Germany. The German BMDV maintains "bilateral and multilateral" relations with the EU on matters of transportation and beyond. The German BMDV works to implement the latest EU UAS regulations within the country. Learn more about the BMDV at https://bmdv.bund.de/.

The BMDV published its Unmanned Aircraft Systems Government Action Plan in May 2020 (German BMDV, 2020). The Action Plan lists "*construction and property industries (especially through photogrammetry)*" and "*surveying (including of construction sites…)*" as key applications to be advanced in the coming years. The Action Plan states that "*structures that are part of the railway and road infrastructure… [must] be regularly subjected to a visual inspection, which is labour-intensive, time-consuming, and costly. UAS can be used here to provide support*." German SMEs and the study team agreed that UAS represents a valuable set of *support tools*, rather than serving as a replacement for human workers conducting critical safety inspection and survey tasks. The document also emphasizes the ability of UAS to capture data in difficult-to-reach locations, at height, and in challenging environmental conditions, saving time and money across a range of use cases. The document cites analyses that estimate a rapid increase in the proportion of commercially used UAS from 2 percent to approximately 17 percent by 2030. The Action Plan stated a goal for the BMDV to "*establish a central digital platform for UAS used for civilian purposes (unmanned aviation digital platform) and consolidate in it all information relevant to the control of UAS*" which was achieved through the Dipul platform described below.

The BMDV published its Road Map for Digital Design and Construction in December 2015 (German BMDV, 2015). The Road Map document lays out a vision to apply BIM widely across the country and describes minimum requirements for the collection of data – to support BIM and achieve the full benefits thereof, including increased design accuracy, increased cost certainty; transparent, robust, and comprehensive data; optimization of life cycle costs; availability of information among stakeholders, and others. The minimum data collection requirements may include "*…the geometry but also further attributes of the asset and/or its components with relevance for the client, such as the construction materials along with their properties (e.g., thermal transmittance, sound insulation properties or ecological footprint). The client can, moreover, specify that a digital description of the construction* *process and a detailed break-down of the costs (5D model).*" As the study team has reported in the U.K. findings and will report in the German findings, UAS flown repeatedly with accurate and precise trajectories capturing structure and asset data, along with advancements in the processing and management of this data, can satisfy these and perhaps more stringent requirements, greatly benefiting the digital construction sector. And, same as in the U.S. and U.K., the German federal bridge inspection standard DIN 1076 requires the equivalent of an "arms-length" bridge inspection every six years (Deutsches Institut für Normung, 1999).

The BMDV launched the Digital Platform for Unmanned Aviation (Dipul) in January 2022, which pools all information, rules, and procedures concerning the operation of drones in Germany on one central web-based tool. The Dipul's map tool displays geographical flight zones, airspaces, temporary airspace restrictions, and other relevant geospatial information. Learn more about the BMDV Dipul at https://www.dipul.de/homepage/de/.

The BMDV published its U-Space strategy in December 2022. The U-Space strategy "*helps define responsibilities, necessary structures, and the procedure for the designation of U-spaces in accordance with Implementing Regulation (EU) 2021/664.*" The document is currently available in German and will be made available in English soon.

UDVeo is a "comprehensive legal-technical concept for the management of drone traffic" funded by the German BMDV and developed and used at HHLA Sky. UDVeo was demonstrated to the U.S. study team along with the Integrated Command Center. Learn more about UDVeo at https://www.bmdv.bund.de/SharedDocs/DE/Artikel/DG/UAV-Projekte/udveo.html.

HHLA Sky GmbH at the Port of Hamburg

HHLA Sky is a company within the logistical and digital company at the Port of Hamburg (HHLA). The company is 68 percent owned by the city-state of Hamburg and 32 percent privately owned. HHLA Sky develops industrial solutions supporting "single UAV or in fleet operation beyond visual line of sight" mission planning, execution, and auditing. HHLA demonstrated its UAS ICC solution to the U.S. study team. Learn more about HHLA Sky at https://hhla-sky.de/en/.

German Aerospace Center

The German Aerospace Center (DLR) is the Federal Republic of Germany's research center for aeronautics and space. The DLR employs 10,000 staff performing research in Aeronautics, Space, Energy, Transport, Security, and Digitalisation. The DLR published its latest summary document in March 2021 (German Aerospace Center, 2021). Learn more about the DLR at https://www.dlr.de/EN/Home/home_node.html.

The DLR facilities in Cochstedt-Magdeburg are home to the National Experimental Test Centre for Unmanned Aircraft Systems, which combines skills and expertise for the development of unmanned aircraft systems and facilitates the networking of scientific research and industry for the ongoing development of unmanned aircraft systems technologies. The centre provides a test environment that can be used by any UAS manufacturer, user, or regulatory authority where UAS technologies and missions can be comprehensively tested and qualified under realistic conditions within a controlled environment. The test centre published its summary of facilities and research in March 2021 (German Aerospace Center, 2021). Learn more about the Cochstedt National Experimental Test Centre for Unmanned Aircraft Systems at https://www.dlr.de/ux/en/desktopdefault.aspx/tabid-13303/23288_read-67121/.

Bauhaus Universität Weimar

Bauhaus Universität Weimar (BUW) was founded in 1919 in the unique, cultural city of Weimar. The U.S. study team met with the faculty and staff of the Institute of Structural Engineering and the Institute of Computer Vision in Engineering. The Institute of Structural Engineering's interests includes "bridge construction and bridge dynamics, as well as inspection and monitoring to extreme impacts and progressive structural collapse." The U.S. team learned about the institute's UAS operations, and UAS flight planning methods as described in the main body of this report. Learn more about the institute at https://www.uni-weimar.de/en/civil-engineering/chairs/modelling-and-simulation-of-structures/research/.

The Institute of Computer Vision in Engineering "focuses on the automated analysis of image-based information… [and] develop[s] sensor platforms and innovative computer algorithms to derive spatial information of objects from digital images." The U.S. study team learned about the institute's UAS data processing techniques, as described in the main body of this report. Learn more about the institute at https://www.uni-weimar.de/en/media/chairs/computer-science-department/computer-vision/.

SpectAir GmbH

SpectAir GmbH is a small business based in Cologne with five total employees. The U.S. study team learned about SpectAir's UAS services to federal and regional government agencies and various businesses in Germany and elsewhere in Europe. Learn more about SpectAir GmBH at https://www.spectair.com/

German Federal Highway Research Institute

The German Federal Highway Research Institute (Bundesanstalt für Straßenwesen, BASt) was founded in 1951. BASt began its work with research in the field of highway construction (German BASt, 2022). "Today BASt is a practice-oriented, technical, and academic research institute of the Federal Government with a focus on the road sector. It covers diverse research subjects resulting from the relationship between road, people, and the environment. Its function consists of improving the safety, environmental compatibility, economic viability, and efficiency of roads. BASt provides scientifically based decision support to the BMDV in technical and transport policy issues." Learn more about BASt at https://www.bast.de/EN/Home/home_node.html.

Appendix G: Relevant U.S. and International UAS Regulations, Guidance, and Commentary

The study team cites U.S. and international UAS regulations throughout this report to provide necessary context on the study's motivations, methodology, and findings. Commentary on the evaluation of U.S. or international UAS regulations is outside the scope of this study. All UAS operations and use cases described in this study report take place within the regulatory framework of their respective countries and regions.

All highway transportation agencies and partners are required to comply with FAA and other federal, state, regional, local, tribal, and organizational UAS regulations, and encouraged to use applicable guidance. Relevant U.S. UAS regulations and guidance reviewed during this study include:

- 14 CFR Part 89 "Remote Identification of Unmanned Aircraft" (FAA, 2021) – Remote Identification equipment is required for some BVLOS UAS operations
- 14 CFR Part 91 "General Operating and Flight Rules" (FAA) – some UAS operations with operational parameters outside of the bounds set by Part 107 (e.g., weight of aircraft) may fall under this rule
- 14 CFR Part 107 "Small Unmanned Aircraft Systems" (FAA, 2016) – many small UAS operations in the UAS fall under this category, and many UAS operations benefiting the highway transportation and digital construction sectors may be conducted under this rule
    - 14 CFR Part 107 has been updated to include Operation of Small UAS over People and at Night (FAA, 2021)
- FAA Part 107 Waiver Resources – explains various Subparts of Part 107 that can be waived (FAA), and provide instructions to apply for Part 107 waivers (FAA)
    - Through correspondence with applicants, FAA may also provide CONOPS templates, and SRM analysis templates, among other documents
- 14 CFR Part 135 "Air Carrier and Operator Certification" (FAA) – UAS operators may obtain certification under Part 135 to conduct some advanced operations
- 14 CFR Part 137 "Agricultural Aircraft Operations" (FAA) – some UAS operations may involve dispensing substances from the aircraft onto surfaces

Relevant international UAS regulations, guidance, and commentary reviewed during this study include:

- EASA Easy Access Rules for Unmanned Aircraft Systems (EASA, 2022)
- EASA Commission Delegated Regulation (EU) 2019/945 "on Unmanned Aircraft Systems and on Third-Country Operators of Unmanned Aircraft Systems" (EASA, 2020)
- EASA Commission Implementing Regulation (EU) 2019/947 "on the Rules and Procedures for the Operation of Unmanned Aircraft" (EASA, 2019)
- EASA Commission Implementing Regulation (EU) 2021/664 "on a Regulatory Framework for the U-Space" (EASA, 2021)
- EASA Guidelines on Design Verification of UAS Operated in the "Specific" Category and Classified in Specific Assurance and Integrity Level (SAIL) III and IV (EASA, 2021)
- German Federal Ministry for Digital and Transport "Unmanned Aircraft Systems Government Action Plan" (German BMDV, 2020)
- Joint Authorities for Rulemaking of Unmanned Systems (JARUS) "Guidelines on Specific Operations Risk Assessment (SORA), Edition 2.0" (JARUS, 2019)
- JARUS "Guidelines on SORA, JARUS-STS-01 Standard Scenario for Aerial Work Operations,

Edition 1.1" (JARUS, 2019)

- JARUS "Guidelines on SORA, JARUS-STS-02 Standard Scenario for Aerial Work Operations, Edition 1.0" (JARUS, 2019)
- The Acceptance of Civil Drones in Germany (Eißfeldt et al., 2020)
- U.K. Civil Aviation Authority CAP 722 "Unmanned Aircraft System Operations in UK Airspace – Guidance" (U.K. CAA, 2020)
- U.K. House of Commons Science and Technology Committee "Commercial and Recreational Drone Use in the UK" (U.K. House of Commons, 2019)

U.S. Department of Transportation
Federal Highway Administration