drones

MDPI

Article

Unmanned Aircraft Systems (UAS) for Bridge Inspection Safety

Bryan Hubbard [1,*] and Sarah Hubbard [2]

1 Associate Professor, Purdue University School of Construction Management Technology, West Lafayette, IN 47907, USA
2 Associate Professor, Purdue University School of Aviation and Transportation Technology, West Lafayette, IN 47907, USA; sarahh@purdue.edu
* Correspondence: bhubbard@purdue.edu

Received: 30 June 2020; Accepted: 29 July 2020; Published: 4 August 2020

check for updates

Abstract: Unmanned aircraft systems (UAS) are an excellent tool to remove bridge inspection workers from potential harm. Previous research has documented that UAS for bridge inspection is a strategic priority of a state's Department of Transportation (DOT), and this paper presents how they can increase safety and presents one methodology to quantify the economic benefit. Although previous studies have documented the potential benefits of using UAS for bridge inspection, these studies have primarily focused on efficiency and capabilities. This paper investigates in greater detail the potential to use UAS to increase the safety of bridge inspection, and includes the results of a survey of bridge inspectors, as well as a benefit cost methodology that utilizes worker compensation rates to quantify the safety benefits of UAS; the methodology is demonstrated using a case study for a DOT. The results of this research present evidence that UAS can increase the safety of bridge inspection, and the benefit–cost methodology and analysis suggest that using UAS to increase safety will provide benefits that are greater than agency costs.

Keywords: unmanned aircraft systems; UAS; drone; safety; bridge inspection; benefit cost; innovation; DOT; worker compensation rates

1. Introduction

The objective of this paper is to document and quantify the safety benefits for UAS for bridge inspection safety, which is relevant for a state's Department of Transportation (DOT) and local transportation agencies. Transportation agencies can use unmanned aircraft systems (UAS) as a tool to support bridge inspection safety, and UAS can potentially increase safety for bridge inspection personnel, as well as for the motoring public. This paper includes a literature review and interviews with professionals in bridge maintenance and inspection, the results of a survey of bridge inspectors, and a methodology to quantify the economic benefits of increased safety using a benefit–cost ratio. The economic analysis is very conservative since it quantifies the safety benefits to bridge inspectors only, per the preference of the sponsor agency. There are additional benefits with respect to efficiency and capabilities, however, these benefits are deliberately excluded from this analysis, since the focus is on safety benefits to the bridge inspectors. The benefit cost ratio is calculated for a state DOT as a case study to illustrate the proposed methodology.

This research included three phases. The first phase was information gathering including both a literature review of UAS for bridge inspection and a series of interviews with personnel from DOTs and consultants from private industry that have expertise in bridge maintenance and inspection. The findings were used to better understand work that has been conducted to date and obtain an in-depth perspective from bridge inspection professionals. Based on these results, deployment of

UAS for bridge inspection safety was determined to be a strategic priority as previously documented. The second phase was a survey of bridge inspectors from the DOT and from private industry. The third phase was development of a methodology to determine the benefit–cost ratio (B/C) associated with the use of UAS for bridge inspection safety, and illustration of the B/C framework with a case study.

Based on the literature review and interviews with bridge maintenance and inspection professionals, there were a number of ways that UAS can be used to enhance safety during bridge inspection. Table 1 shows example activities that can be supported by UAS, based on the four phases of bridge inspection: (1) pre-inspection, which occurs before the actual inspection and ensures that inspection activities can be done safely and efficiently; (2) during the bridge inspection; (3) post-inspection, which includes processing of information collected during the inspection; and (4) damage assessment of bridge conditions which may be necessary after an accident or bridge hit (e.g., by a large truck) or after a storm or natural disaster.

Table 1. Unmanned aircraft systems (UAS) enhance safety during all phases of bridge inspections.

Phase	Activity
Pre-Inspection Activities	Provide an overview of bridge condition and areas of concern. Identify climb points and support safe access to bridge. Identify cracks and bridge components that need extra attention. Identify areas that need cleaning prior to inspection. Identify nests that cannot be disturbed and other environmental considerations. Identify potential wildlife hazards Identify structural elements with difficult accessibility (e.g., girders)
During Bridge Inspection	Pre-inspection UAS information reduces time required for actual inspection. Reduced inspection times reduces duration of lane closures and time required for snooper (also known as an under bridge inspection unit or UBIU) which increases safety for motoring public and bridge inspectors.
Post-Inspection Activities	Images collected by UAS can be used for inspection report. Data collected by UAS provides a robust record of bridge condition. Video, images and data collected with UAS can be reviewed to support the bridge inspection report.
Damage Assessment	Video and images collected by UAS may provide a unique perspective that cannot be obtained by the bridge climb team or from a bucket truck. The video and images collected by UAS may support legal activities and may be useful to the Indiana Department of Transportation (INDOT) for litigation since it effectively documents bridge damages, such as damage due to a bridge hit.

2. Results

UAS for bridge inspectors is evaluated based on the four phases outlined in Table 1: pre-inspection activities, during bridge inspection, post inspection, and damage assessment. In addition to analyzing these phases of bridge inspection, a survey of bridge inspectors was completed to better understand UAS implementation from their perspective. Results from a benefit–cost analysis for the Indiana State DOT are included to support the procurement processes for UAS. The UAS for this research were based on commercial, off the shelf UAS equipment with imagery capabilities. More advanced technologies incorporated with UAS for bridge inspection, such as light detection and ranging (LiDAR), thermal imaging, night vision and infrared, were not considered because the focus was on imagery to support bridge inspector safety; this was consistent with the preference of the DOT personnel involved in the study.

2.1. Pre-Inspection Activities

UAS can be an excellent tool to support pre-inspection activities. The railroads have been early adopters of UAS for pre-inspection [1]. Interview findings indicate that some rail companies have a UAS team that collects video on all railroad tracks and bridges prior to field inspection. This video is provided to the inspection team to allow a preview of the facilities that will be inspected. The preview can be used to ensure that cleaning and other required maintenance is accomplished prior to the team's field inspection and ensures the bridge inspection team can make the best use of their field time. This pre-inspection video can also be used to identify cracks or areas of concern that may need additional attention during the inspection.

Even basic cameras such as a GoPro camera, which is widely available but not the best tool for bridge inspection, can show cracks in concrete [2] and other bridge defects. Although inexpensive cameras have been replaced by better tools due to rapidly advancing technologies in both imaging and UAS, research has confirmed the benefits of even basic, inexpensive equipment that is widely available. The use of higher resolution cameras can improve the capability to identify cracks and other defects, and one study found that UAS can detect cracks less than a millimeter wide [3]. Use of a UAS for crack detection is ideal for areas over water and situations that currently require an under bridge inspection unit (UBIU), also known as a snooper truck. High-definition cameras can be used to identify small cracks in both concrete and steel bridges, and even deformation of cables [4]. Pre-inspection flights can also identify environmental conditions that warrant attention, such as nests that cannot be disturbed, dangerous wildlife, or other conditions that may present a hazard to the inspection team. UAS allow identification of potential hazards and conditions without the risks associated from physical contact. UAS have been used to identify vegetation characteristics [5], which may be helpful since vegetation may present risks (e.g., poison ivy, poison oak, and nettles). Examples of hazards that may be encountered during bridge inspection include [6,7]:

- Traffic and work zone safety
- Working at height
- Working in isolated environments
- Adverse weather
- Working in the dark and poorly lit areas
- Unsecured hazards in the work area
- Contact with electrical lines and other utilities
- Silica, nuisance, dust, dried lead or silt
- Improper ladder or scaffold use
- Work on, over or near water
- Diving operations
- Vessel operations
- Power and hand tool use
- Noise
- Exposure to contaminated water
- Confined spaces
- Discovery of unknown chemicals
- Vegetation: poison ivy, poison oak, thorns
- Insects and animals: snakes, ticks, dogs, falcons, and raccoons

Interview findings suggest that pre-inspection video can also be used to increase safety by identifying climb points and tie-off points, clearances, and potential risks, such as sharp edges on bridge components. A pre-flight of the bridge can provide important information about current conditions that change quickly, including soil erosion near the bridge that may limit access or increase the risk of a slip or fall.

Interview findings also suggest that information gained during a UAS pre-inspection flight may help the bridge team prioritize the elements of each bridge inspection and plan the optimal inspection route, which may reduce the number of times the team needs to cross travel lanes of traffic and reduce redundancy or inspection inefficiency. Increased efficiency and safety go hand in hand since reduced inspection time in the field correlates with reduced lane closure time for the bridge and approach, reduced climb time, and reduced exposure to the elements.

UAS are also able to access hard to reach places and document conditions with pictures. Although these conditions need to be confirmed with the hands-on inspection, the images collected by UAS may relieve the inspector of having to take photos during the inspection, which reduces the need to multi-task and reduces the required inspection time. High-resolution video collected by UAS can support visual inspection requirements, but do not replace the need for hands-on inspection of fracture critical components, connections, cracks, and other deficiencies.

Fracture critical members must be inspected within arm's reach per the Federal Highway Administration (FWHA) Bridge Inspector's Reference Manual which states, "A fracture critical member (FCM) inspection is performed within arm's length of steel members in tension, or with a tension element, whose failure would probably cause a portion of or the entire bridge to collapse." [8].

2.2. During Bridge Inspection

The use of a UAS for pre-inspection activities reduces the time required for the actual inspection and reduces the amount of time that equipment such as an under bridge inspection unit (UBIU) is needed. This reduces the amount of time that traffic lanes are closed and increases safety for both inspectors and the motoring public.

Since bridge inspectors have pre-viewed the bridge, they can confirm preliminary findings and then focus their field time on components that are distressed or need extra attention, as mentioned previously. UAS may also reduce the need for bridge inspection team members to cross traffic lanes multiple times, climb under the bridge, and around the bridge. The UAS capability of flying under, over, and around bridges without hindering the flow of traffic allows inspectors to gain useful information from a safe location. The safety of the bridge inspection team is also increased if tie-off points have been pre-planned using video and images collected during the pre-inspection phase.

During bridge inspections, UAS can provide real-time traffic monitoring when lane closures are required. Bridge inspectors close lanes to ensure their own safety and to inspect certain parts of the bridge [9]. Although lane closures are necessary, they increase risk to the traveling public since work zone accident rates are about 25% higher than comparable non-work zone areas [10].

UAS aerial views are ideal for traffic monitoring since they can capture the surrounding area [11]. UAS can be used to document traffic control (e.g., lane closure and work zone features required for bridge inspection) as well as traffic characteristics such as queue length. Although Part 107 restricts UAS from flying above people or cars, in some circumstances a UAS could fly next to the road without being directly above the traffic and people on the road. Flight near the roadway must be conducted with caution; if the UAS loses power and falls into traffic due to a gust of wind, Federal Aviation Administration (FAA) may interpret it as flight over traffic [12].

A list of hazards associated with bridge inspection are shown in Table 2. Some of these will be reduced by integrating information collected by the UAS. For example, if drones reduce the amount of time an inspector is working at height, and if they reduce the amount of time working in a work zone with a lane closure, overall safety will be increased.

Table 2. Examples of hazards associated with bridge inspections.

Environmental Hazards	Task Related Hazards
Adverse weather	Working at height
Silica, nuisance, dust, dried lead or silt	Working in isolated environments
Improper ladder or scaffold use	Working in the dark and poorly lit areas
Work on, over or near water	Unsecured hazards in the work area
Noise	Contact with electrical lines
Exposure to contaminated water	Diving operations
Confined spaces	Vessel operations
Discovery of unknown chemicals	Power and hand tool use
Vegetation: poison ivy, poison oak, thorns	Inspecting tight areas and confined spaces
Insects and animals: snakes, ticks, dogs, falcons and raccoons	

2.3. Post Inspection

Information collected by UAS provides a robust record of bridge conditions, and inspectors can review all information and select the information most appropriate for inclusion in the bridge inspection report. Since there are strict requirements regarding the maintenance of contents in the official inspection report, it is good practice to carefully consider the UAS products that should be included in the official report. Regardless of where the information is stored, historic video, images, and other bridge data collected by UAS can be used to assess changes in bridge condition. Since UAS can be programmed to collect images and video when following a specific and set path, it is very useful for comparison of data collected over time.

UAS images can also be used to create accurate photogrammetric models of the bridge, which can be used to identify and document small changes in crack propagation or member deflection. Photogrammetry models require high-resolution images with overlap between images.

2.4. Damage Assessment

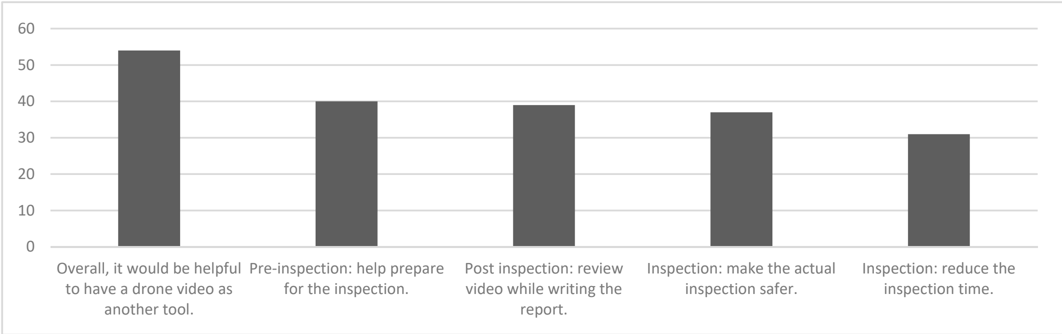
UAS may be especially helpful for damage assessment since it allows responders to safely obtain information about bridge components without risking personnel or using expensive equipment such as a manlift or snooper truck. Information collected by UAS may allow personnel to quickly assess the condition, provide information to experts located remotely, and facilitate the determination of whether a more detailed hands-on inspection is needed.

2.5. Results of a Survey of Bridge Inspectors

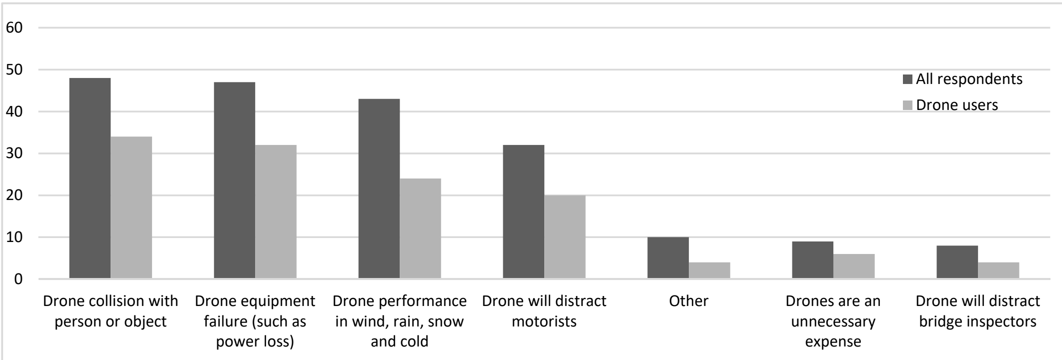
An online survey of bridge inspectors was conducted to learn more about their perspective. All responses were anonymous. The survey was distributed using the Indiana Department of Transportation (INDOT) bridge inspection listserv, which includes bridge inspectors who work for INDOT, as well as consultants who do bridge inspections under contract with INDOT and Indiana counties. Bridge inspections for all bridges on the Indiana state highway system are managed by INDOT, and all local bridges serving county, city, and towns roads are managed by the county, and are typically contracted to private consulting agencies that conduct the inspections. The private consulting agencies surveyed work at both the state and national level so data encompasses a national perspective.

Additional results from the survey are shown in Figure 1. Responses indicate that 83% of those surveyed (54 of 65 responses) believe overall it would be helpful to have UAS video as another tool. The majority indicate UAS video would be useful for pre-inspection (most often cited answer with 62%), post-inspection (60%), and during the actual inspection (57%).

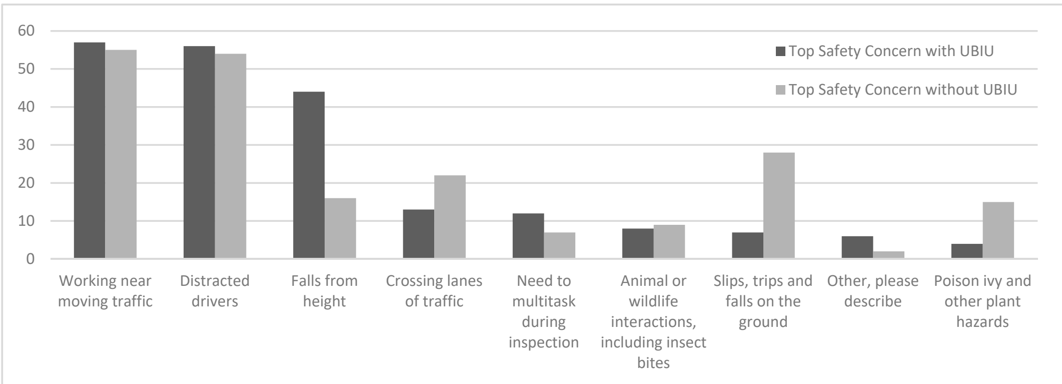
The greatest concerns for bridge inspectors are working near moving traffic and distracted drivers. When working with a snooper truck, the third cited concern was falls from height. When not using a snooper truck the third cited concern was slips, trips, and falls. All of these concerns are validated by national statistics regarding worker injuries and accidents in a highway work zone.



(a) Responses to question "What would drone video be useful for?"



(b) Responses to question "What are the top three concerns regarding drone use?"



Other description: 1) Homeless/people living under the bridges, 2) safety hazards to public from bridge

(c) Response to question "What are the top safety concerns with and without an UBIU?"

Figure 1. Results of survey of bridge inspectors.

Top concerns regarding UAS for bridge inspection include a collision with a person or object, a UAS equipment failure, or the capability of the UAS to perform in harsh conditions, such as wind, rain, and cold (Figure 1b). UAS battery life is compromised by cold, and there are limits regarding the capability to safely navigate drones in windy conditions.

It is notable that the concerns regarding UAS use are significantly lower for respondents who have experience using drones, than for all respondents. Respondents with UAS experience provided the following comments regarding concerns with UAS use:

- No concerns! Totally worth it.
- Useful for general inspection only, have strong reservations regarding fracture critical inspections/complex inspections.

- Not being able to adequately see and feel the area being inspected. In person is always better than a photograph.
- They should be used for safety and cost savings.

The concerns center less on the risks associated with UAS, and more on concerns that UAS would replace hands-on inspection. The proposed use of UAS in some applications could not replace hands-on inspection because of Federal Highway Administration (FHWA) arm's length inspection requirements [13] but would enable the use of UAS as another tool in the inspector toolbox.

2.6. Case Study: B/C Analysis for Bridge Inspection Safety

An overview of expected benefits and costs for UAS implementation for a state DOT is summarized in Table 3. Additional information for expected benefits and costs is discussed in greater detail below, with the caveat that actual costs and benefits may vary depending on a variety of factors.

Table 3. Summary of expected benefits and costs for INDOT.

Application	Benefits	Cost Considerations
Bridge Safety	Increase safety: • Identify potentially hazardous conditions on bridge or in bridge environment • Identify climb points • Identify inspection procedures • Ensure tools needed for safe inspection are readily available • Reduce lane closure time, increasing safety of team and public • Reduce road crossings by bridge inspection team • Overall: reduce risk exposure for bridge team by substituting UAS time with time on bridge (when appropriate) • Reduce risk to traveling public due to reduced inspection time on bridge in field	Costs vary significantly depending on capabilities (e.g., collision avoidance, quality of images). Entry level UAS with image capability only will provide significant benefits at a low cost and more advanced sensors can be integrated in the longer term.
Construction	• Reduce inspection time for construction progress and milestones • Increase public information during construction • Document work zone traffic control for quality control and in the event of a crash • Document pay items (e.g., excavation) • Document compliance with environmental controls (regular and special inspections) • Improve quality control (e.g., temperature of pavements using infrared on UAS) • Reduce surveying time	Costs vary; costs will be known prior to deployment if contracted as a separate line item.
Emergency Management	• Increase safety for responding team • Allow safe estimate of damage • Document damage for federal reimbursement	UAS cost may be as low as $1000 for a portable unit; battery can be charged by plugging into car with an inverter [14].

Changes in equipment prices and availability due to DOT and/or FAA flying restrictions or safety measures (e.g., no flying drones over traffic) are not considered but would potentially affect the benefit, cost, and benefit–cost ratio. Benefit–cost information for UAS reported by other transportation agencies varies significantly, reflecting different applications and the fact that not all benefits and costs are realized, measured, and assessed. Some of the benefits reported in Table 4 may imply changes to federal rules regarding arms' length inspection requirements. Although the information in Table 4 reflects a variety of assumptions, it provides an appreciation for the range that could be expected for different applications.

Table 4. Reported benefit and cost information. B/C = benefit–cost ratio.

Estimated B/C or Benefit	Application	Comments	Agency or Source
B/C ≈ 9.3	Bridge inspection	UAS would only be appropriate for approximately 56% of bridges	Oregon DOT [11]
B/C > 1	High mast pole and Bridge inspection	No specific B/C ratio provided but conclusion of proof of concept is that UAS are cost effective	[15]
B/C > 1 Benefit: Additional information	Routine bridge inspections	"Cost effective way to obtain information that may not normally obtained during routine inspections"	[16]
Benefits: Additional information	Bridge inspection planning for large bridges	"Can provide important pre-inspection information for planning large scale inspections"	[16]
B/C > 1	Bridge Inspection	UAS can allow for tracking of delamination "UAVs could provide reliable, rapid and cost effective Bridge Deck evaluation compared with conventional methods"	[17]
B/C > 1	Bridge and construction inspection	Cost and time requirements are about the same, but the benefits are greater since more information is provided	[18]
Benefit: 66% cost savings (resulting B/C would more than double)	Steel through Arch bridge with Multi-Girder Approach Spans	Hands-on inspection may still be required	MnDOT [19]
Benefit: Save time and money	Bridge inspection	Identify problem areas faster	MnDOT [19]
Benefit: Help locate the safest way to approach the bridge	Bridge inspection	Increase safety for bridge inspection team (reduce falls and environmental hazards)	MnDOT [19]
Benefit: Reduce duration of lane closures	Bridge inspection	Increase safety for bridge inspection team and motoring public	MnDOT [19]
Benefit: Increase safety due to faster data collection (reduced risk for workers and motoring public)	Bridge inspection	Traditional bridge inspection requires temporary work zones, traffic detours, and heavy equipment.	[20]
Benefit: 40% savings (resulting B/C would increase by 1.5 times)	Bridge inspection		MnDOT as reported by Federal Highway Administration (FHWA) [21]

Table 5 provides an overview of the potential costs for the DOT to incorporate UAS for bridge inspection and emergency response. A four-year evaluation period is considered, reflecting a reasonable lifecycle for a drone. Although UAS technology advances quickly, it is likely that a DOT would utilize a UAS for as long as it is able to serve as a useful tool, even if there are more advanced models available. This framework assumes that each district would have a drone, and existing district personnel would be trained to use the drone. A significant consideration is the specific UAS selected. The cost in this analysis reflects a quadcopter appropriate for visual inspection of the bridge (pre-inspection and during the bridge inspection). There are numerous new technologies being employed and developed for more sophisticated kinds of inspection, including LiDAR and FLIR (e.g., thermal, night vision and infrared) technology. Tens of thousands of dollars can be spent on UAS and sensors. These technologies provide even more detail of the structure, and may be able to identify cracks, deformations, and delamination in structures [22].

Table 5. Estimated cost for UAS for bridge inspection safety and emergency response.

Year	Description	Qty	Cost	Total
1	UAS DJI Mavic 2 Enterprise $2200	10 (1 per district with bridge team plus 3 extra)	$2200 per UAS	$22,000
	Parts and Repair (per year)	1	10% of capital	$2200
	Training for New Remote Pilot	10 (1 person per district plus 3 extra)	$1000	$10,000
	Time to Train New Remote Pilot *	5 days (40 h) for each of 10 people 3 day course 1.5 day operator training 0.5 day exam and paperwork	Average $32/h (salary plus benefits)	$12,800 *
	Exam	10	$150	$1500
	Total Cost Year 1			$35,700
2	UAS Parts and Repair			$2200
	Total Cost Year 2			$2200
3	UAS Parts and Repair			$2200
	Training for Recertification	10 remote pilots	$500	$5000
	Time for Recertification Training *	10 remote pilots 2 day (16 h) for each remote pilot 1.5 day training 0.5 day exam and paperwork	Average $32/h (salary plus benefits)	$5120
	Exam	10	$150	$1500
	Total Cost Year 3			$9700
4	UAS Parts and Repair			$2200
	Total Cost Year 4			$2200
	Total Cost Years 1 to 4			$49,800

* Training time is recognized but not included in the B/C since it does not require separate funds to be allocated.

While these technologies are starting to be used on infrastructure, the major focus of this analysis is to identify how UAS images and videos captured can be utilized by DOT bridge inspectors. There are also less expensive UAS that can be used. For example, North Carolina DOT has reported success with $1000 UAS, which is less than half the price of the $2200 UAS specified in this analysis. The inexpensive UAS used by North Carolina DOT were useful for emergency response since they fold for convenient storage and can be charged using a vehicle adapter [14]. North Carolina DOT used the $1000 UAS for 72 of the 112 missions flown after Hurricane Katrina [14].

The country in which a UAS was manufactured is becoming of increasing interest to organizations, including government agencies. This analysis does not consider the potential changes in price or availability due to restrictions based on the country in which the UAS or UAS parts originate.

Training requirements may vary, and different agencies have different perspectives and requirements on this topic. Table 5 includes a cost associated with training to recognize the opportunity cost of this time, however, per the preference of the agency, the value of time is not included in the calculation of the benefit–cost ratio since the DOT has already budgeted for this personnel expense, and no additional budget funds are required. Table 5 illustrates a cost for 5 days of training and practice for basic competency, including 3 days of study, 1.5 days of operator training, and 0.5 day for the exam and paperwork. No training time is included for the visual observer, since this role does not require FAA certification. Similarly, other bridge team members can serve as the operator under the supervision of the remote pilot. No FAA certification is required for the role of operator. In order to pass the FAA exam, the remote pilot must pass a two hour, 60 question multiple-choice exam (three candidate responses per question) with a minimum score of 70%. The test has a 92% pass rate, and must be renewed every two years [23]. This cost estimate reflects coverage of information for the Part 107 exam. Some DOTs have developed additional training requirements, which are not included in this estimate. The cost for training time is based on an average bridge inspector salary of $20.35 per hour [24]; it is assumed that the cost per hour for salary plus benefits is $32.00.

There may be other additional costs associated with UAS for bridge inspections if the work is performed by a consultant; these costs may include liability insurance. In this case, there would be no additional cost for the purpose of this benefit–cost ratio calculation, since these costs are covered under the agency's existing liability insurance and since liability is limited due to sovereign immunity (which varies by state).

In terms of benefits, UAS may reduce risks to bridge inspectors and motorists. Bridge inspectors face multiple risks during field inspections. One risk for bridge inspectors is the risk of injury. Injury may be due to the bridge inspection activities or may be due to the hazards of working near moving traffic. Previous research suggests that for highway work zones, 22% of worker injuries and 43% of fatal injuries are due to motor vehicle crashes [25]. Worker injury risks are reflected in the worker compensation rate, which is calculated for each state each year, based on the class code of the activity. Although premiums vary, an estimate of the relative risk of different activities is reflected by comparing the rate for different class codes. The rate is expressed in dollars and cents per $100 of payroll for the class code.

Table 6 provides rate information for Indiana for 2019. The top three class codes in Table 6 (5037, 5040, and 5506) reflect field activities related to roads and bridges. The average workers comp rate for these three activities is $4.90. This rate is an order of magnitude higher than the workers comp rate for field UAS (code 8720) and the associated data processing (code 8810), which have an average value of $0.48. Even if utilization of UAS does not reduce the overall time for the bridge inspection, if it shifts activities to lower risk categories, then the overall safety for bridge inspection is increased. For example, if utilization of UAS allows inspectors to spend less time on the bridge or near moving traffic, then overall safety is increased. The utilization of standard worker compensation rate data to quantify the benefits of using UAS has not be seen in the literature but provides an objective method based on reported data that is regularly updated. In the future, it may be appropriate to use this method for other applications.

Table 6. Indiana worker compensation rate data.

Class Code	Description	Indiana Rate [1]	Average Rate
Field activities in the road and bridge environment			
5037	Painting metal structures over 2 stories in height (including bridges)	6.33	
5040	Iron or steel erection frame structures (including metal bridges)	4.35	4.90
5506	Street or road construction: paving or repaving	4.03	
Activities related to UAS inspection			
8720	UAS operations, one component of Inspection of risks for insurance or valuation (not otherwise classified, includes safety engineers)	0.83	0.48
8810	Clerical office employees in computer or office work, includes wages paid to construction employees if work is exclusively office work	0.12	

[1] Indiana Rate as of 1 January 2019 as published by National Council on Compensation Insurance [26].

For example, analysis can quantify the financial and safety impact of shifting work from another class code that will be replaced by UAS to class code 8720 (for UAS field work) and class code 8810 (for office work related to UAS).

Based on reports of UAS by other agencies, it is assumed that utilization of a UAS will increase safety by reducing the exposure to hazards by 50%, since the hazardous duties in the field can be shifted to less hazardous UAS field time and time reviewing UAS video in the office. This is reasonable and may be a conservative assumption. Kansas DOT studies even suggest the possibility of complete bridge inspections performed by UAS in as little time as an hour [27], although this would not be consistent with current FHWA rules for arm's length bridge inspection.

Although most researchers do not suggest such dramatic reductions in inspection time in the near term, other UAS researchers do confirm the capability of UAS to reduce the duration of field activities for bridge inspection, especially since the cost to inspect a bridge may add up quickly when the cost of road closures and traffic re-routing are considered. Minnesota DOT researchers found that although a hands-on inspection may still be required, pre-planning with a UAV can save both time and money by identifying problem areas and helping to locate the safest way to approach the bridge. With a course of action readily identified, the traffic closures are for much shorter periods of time and cost much less [19].

In addition to the safety risk for the bridge inspection team, the motoring public realizes costs associated with bridge inspection activities. These costs include increased delay and an increased crash risk due to the temporary work zone required for inspection activities. The work zone may include traffic control, a reduced shoulder width and/or a reduction in the number of traffic lanes. Benefits to the motoring public are not quantified in this analysis, as a result the analysis is conservative and understates the total benefits.

In terms of delay, historically, work zones account for approximately 10% of all congestion [28] and approximately 24% of non-recurring freeway delay [29]. Bridge inspection work zones are a relatively small portion of all work zones, and the contribution of bridge inspection work zones to overall motorist delay has not been quantified.

In terms of increased crash risks, the crash risk associated with work zones is significant. One study found that crash rates in freeway work zones were 21.5% higher than during the pre-work zone period, with non-injury crashes increasing 23.8% and injury crashes increasing 17.3% [30]. Other research found that state highways and rural interstates are more vulnerable to work zone crashes [10,31,32].

Since crash costs are significant, reducing the duration of the work zone is significant. The estimated cost of a work zone crash varies. At the low end, Sorock et al. reported an average cost of $3687 for a work zone crash in 1996 [33]; this is equivalent to approximately $6000 in 2019 (cost in 2019 is estimated using the Bureau of Labor Statistics (BLS) Consumer Price Index (CPI) Inflation Calculator to adjust the value from January 1996 dollars to January 2019 dollars). Other research identified much higher costs for work zone crashes: $7673 for a property damage only (PDO) and $116,375 for an injury crash, as reported in 1996 dollars by Mohan and Gautam [34]. Converting these costs to current dollar values, the equivalent costs for 2019 would be approximately $12,750 for a PDO crash, and $193,000 for an injury crash. These values reflect direct costs, and do not consider the indirect costs, which may be 4 to 17 times the direct costs [34]. Other research confirms the high cost of work zone crashes, with the following estimates of the comprehensive cost in 2010 dollars: $542,533 for incapacitating crashes, $147,536 for non-incapacitating crashes, $86,900 for possible injury crashes, and $10,956 for PDO crashes [35]. These costs were significantly higher than the inflation-adjusted FHWA default values. The cost of incapacitating injury crashes was 105% higher than FHWA values, non-incapacitating injury crashes were 35% higher, and possible injury crashes were 50% higher than the inflation adjusted FHWA default values [35]. The values increase to $630,227 (incapacitating injury), $171,383 (non-incapacitating crashes), $100,946 (possible injury), and $12,727 (PDO) in 2019 dollars.

To provide another context for work zone crash risks, consider the prevalence of injuries and fatalities for construction workers relative to injuries and fatalities for motorists traveling through the highway work zone. According to research by Mohan and Gautam, 30% of the injuries involve workers, and 70% of the injuries involve motorists traveling in the work zone [34]. More recently, the Centers for Disease Control and Prevention (CDC) reported that each year there are 121 worker fatalities (14%) and 750 motorist fatalities (86%) due to work zone crashes. Additionally, 14% of the fatally injured workers were government workers, equally divided among state and local governments [36].

Additional information about risks to the bridge inspection team is provided in Table 7. Bridge inspectors are vulnerable to the two most frequent causes of occupational death: transportation incidents (2077 fatalities representing 40% of all fatalities) and fatal falls (887 fatalities representing 17% of all fatalities) [37]. The most common are workplace injuries and illness, which may be due to falls from height, sprains, and strains due to slips, trips, and overexertion, and illness and injuries due to a wide variety of environmental hazards that include insects and wildlife, as well as poison ivy.

One risk to bridge inspectors due to insects is Lyme disease, which is caused by deer ticks and mosquitos. This is an increasing risk in Indiana, and 440,000 people are diagnosed with Lyme disease each year [38]. Recent reports found that the number of cases of infectious disease from ticks, fleas, and mosquitoes in Indiana have tripled since 2004, and in 2016 there were 127 cases of Lyme disease [39].

In Indiana, the rate of nonfatal injury and illness per 100 workers was 2.4 for state workers, 2.8 for construction, 4.7 for transportation and warehousing, and 5.2 for local government [40]. It is difficult to estimate the injury and accident rate for bridge inspectors, due to the relatively low number of inspectors, and the work group does not have a separate designation for North American Industry Classification System (NAICS), which is used to identify the industries and sub-industries for workplace injury and illness data.

The estimated cost of a worker injury or illness in 2017 was $39,000 when a medical consultation was needed, and the cost per fatality that results from a workplace injury is $1,150,000 [41]. These costs include medical expenses (21% of the total cost), wages lost and lost productivity (31% of the total cost), employer costs (15% of the total cost), and administrative costs (32% of the total cost). These costs imposed a burden of $1100 per worker in 2017, which reflects the overall burden to the workforce, but not the average cost of a work-related injury.

Injuries due to roadway incidents is the leading cause of work-related fatality and the seventh leading cause of injury with days lost from work [42]. Transportation workers are especially vulnerable to these injuries, but their vulnerability may be reduced by reducing their field time by using UAS. UAS may be especially useful during emergency response, when conditions may be uncertain. UAS may also make workers less vulnerable to injuries and accidents that are related to fatigue; fatigue is a contributing factor for both occupational injuries and death [43].

Table 7. Sample risks to bridge inspectors working in the field.

Risk		Implications
Traffic accidents	 Photo: FHWA [44].	5.5% of disabling workplace injuries and 121 work zone fatalities in 2018 were due to traffic accidents [43].

Table 7. *Cont.*

Risk		Implications
Falls	 Photo: FHWA [13].	Falls are the leading cause of worker fatalities and account for almost 30% of the total workplace injury burden. Workplace falls cost $17.1 billion in direct costs in 2018 [43,45].
Sprains, strains and overexertion and slip or trip without fall	 Photo: FHWA [46].	27.3% of disabling workplace injuries cost $16 billion in 2018. Unstable banks, gravel on the roadway and other environmental hazards may increase the risks of sprains, strains and overexertion [43].
Environmental hazards due to insects, wildlife and vegetation (e.g., Lyme disease)	 Photo: The Centers for Disease Control and Prevention (CDC) [47].	Environmental hazards include insects, wildlife and vegetation. One example is Lyme disease, which cost an average of $16,000 annually per person (approximately half of this is due to lost productivity) [48,49].

Table 8 provides a summary of the estimated benefits related to safety that would be realized if INDOT implements UAS for regular bridge inspections. These estimated benefits reflect use of UAS for the inspections on half of INDOT's bridges (presumably only the larger ones) and reflect the fact that INDOT correlated with a reduction in hazard exposure for both the INDOT bridge inspection team and motorists.

Table 8. Estimated benefit for UAS for bridge inspection safety.

	Expected Impact (Per Year)
Bridges	Number of INDOT Bridges: 5766 • Bridges that would not utilize a drone: 5662 ▪ Average field inspection time without UAV: 2 man-hours • Bridges that would utilize UAS for inspection: 1162 ▪ 104 inspected every 12 months • Average field inspection time: 2 man-hours ▪ No change in inspection time • 50% reduction in bridge team hazard exposure due to UAS use ▪ 1058 inspected every 24 months (529 of these inspected every 12 months) ▪ Total 633 bridges inspected with UAV every 12 months • Average field inspection time with UAV: 4 h (2 h for 2-person team) • UAV for special bridges (include special detail inspection, bridges with more than two lanes in each direction, scour critical bridges, and those with routine frequency of less than 24 months)

Table 8. *Cont.*

	Expected Impact (Per Year)
Decrease exposure to injures for bridge team by reducing hazard exposure by 50%	2 man-hours * 633 bridges = 1266 man-hours reflects the reduction in hazardous field time by 50% (reflecting half of the 2 h inspection time for a 2-person team) • Value of reduced exposure to worker injury based on worker's compensation rates in Table 6: (1266 h * \$32/h)/\$100 * (\$4.9 – \$0.48) = \$1791 • This represents 15% of work zone injuries according to previous research by CDC [40].
Decrease motorist exposure to work zone crashes	Value of reduced injuries to bridge inspection workers is \$1133 per year. • If this reflects 15% of the work zone injuries, then motorists will realize a reduction in injury risk of \$10,147 (reflecting 85% of the work zone injuries). This estimated is based on exposure to fatality events per CDC [40]. • This generally correlates to the elimination of one possible injury accident every ten years based on the cost of crashers per Coburn et al (2013). • This correlates to a reduction in property damage for work zone crashes of \$2131 (for every \$1 of injury, there is a motorist cost of \$0.21 for property damage only (PDO) crashes). • Total value of reduced exposure to motorist injury and PDO crashes is \$12,278 per year. • Do not consider reduction in fatal crashes since it is a rare event.
Decrease motorist delay	Financial value of reduced motorist delay not included in analysis.
Total	Value of reduced exposure to worker injuries and motorist traffic injuries and PDO crashes is estimated to be \$14,068 per year.

The estimated values seem very reasonable and very conservative when considered in the context of the cost of worker injuries discussed above. Similarly, the use of six UAS for the inspection of 633 bridges is reasonable, with each UAS serving about 100 bridges, and being used for one hour on each bridge. This correlates to 400 hours of use over the proposed four-year lifespan and analysis period. This is consistent with life expectancy reports of 800 hours for a Phantom [50].

Table 9 provides an estimated benefit–cost ratio (B/C) for using UAS for bridge inspection. The benefits quantified reflect only the benefits related to safety, specifically the reduced exposure to inspection team workers to field hazards and the reduced exposure of motorists to injury and PDO crashes. There may be additional benefits related to reduced delay and increased capabilities that are not quantified; these additional benefits would increase the B/C. All values reflect 2019 dollars (considering the net present value, this B/C shown reflects an inflation rate that is the same as the real interest rate for the four-year analysis period). The benefit–cost analysis indicates that the proposed use of UAS for bridge inspection safety would provide a benefit–cost ratio greater than one and would therefore be an appropriate investment.

Table 9. Estimated benefit–cost for UAS for bridge inspection safety (four-year period).

Year	Expected Benefit	Expected Cost	Estimated B/C
1	\$14,068	\$33,950	
2	\$14,068	\$1540	
3	\$14,068	\$10,942	
4	\$14,068	\$1540	
Total	\$56,272	\$49,800	1.1

3. Discussion

UAS have been successfully deployed for a number of tasks and much of the research supporting deployment has focused on efficiency and capabilities. This paper presents concise information on the safety benefits of deploying UAS for bridge inspection, as well as a quantitative methodology to assess the safety benefits using a B/C methodology that leverages standard worker compensation data rates for different tasks, which reflect the relative safety of activities. This methodology can be used for a variety of other UAS applications using standard worker compensation tables that are published and widely available for a number of tasks. The capability to quantify the safety benefits may provide a useful tool to communicate the benefits of UAS and justify UAS deployment for new applications.

State transportation agencies are responsible for the maintenance and inspection of thousands of bridges. The case study presented here reflects data for a DOT that is directly responsible for the regular inspection of over 5766 bridges. The analysis conservatively estimates the benefits that would accrue if UAS are used for 633 of these bridges, which is approximately 10%. This is a conservative assumption, since other DOTs have suggested that UAS may be useful and provided benefits for approximately half of bridges. For example, Oregon DOT estimates that UAS would be useful for 56% of bridges [15]. The percent of bridges would depend on the bridge characteristics, which would vary depending on the road network and geography. Bridge inspection requirements vary depending on bridge size, condition, and structure type; UAS may not provide as much safety benefit for smaller bridges.

4. Conclusions

UAS are being widely implemented to support the construction, maintenance, and ongoing inspection of our nation's infrastructure, including bridges. While other research has focused on the capabilities and efficiency of UAS, this research documents the safety benefits of UAS and presents a methodology that can be applied for a variety of other tasks in both the private sector and public sector. The methodology presented in this research can be used to assess the B/C ratio related to safety for numerous other state DOT applications, such as high mast pole inspections, culvert inspections, and mechanically stabilized earth (MSE) wall inspections that are often inspected by the same inspection team and/or fall under the same inspection department. This methodology provides a basic framework that would need to be tailored to the specific applications and may require different UAS equipment and sensors. Safety for workers and the public is an important consideration and this research provides another tool to document the contribution of UAS to worker safety.

Author Contributions: Conceptualization, methodology, interviews, and investigation, S.H. and B.H.; survey lead, B.H.; B/C analysis lead, S.H.; writing—original draft preparation, review and editing, S.H. and B.H.; project administration and funding acquisition, S.H. and B.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Joint Transportation Research Program, a partnership of the Indiana Department of Transportation and Purdue University.

Acknowledgments: The authors would like to acknowledge Andrew Fitzgerald, Tim Wells, Barry Partridge, and the numerous professionals who provided input during the interviews for this project.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Canis, B. Unmanned aircraft systems (UAS): Commercial outlook for a new industry. In *Congressional Research Service*; Report #R44192; United States Library of Congress: Washington, DC, USA, 2015.
2. Dorafshan, S.; Maguire, M.; Hoffer, N.V.; Coopmans, C. Challenges in bridge inspection using small unmanned aerial systems: Results and lessons learned. In Proceedings of the 2017 International Conference on Unmanned Aircraft Systems (ICUAS), Miami, FL, USA, 13–16 June 2017; IEEE: Piscataway, NJ, USA, 2017; pp. 1722–1730.

3. Hallermann, N.; Morgenthal, G.; Rodehorst, V. Unmanned aerial systems (UAS)—Case studies of vision based monitoring of ageing structures. In Proceedings of the 2015 International Symposium Non-Destructive Testing in Civil Engineering, Berlin, Germany, 15–17 September 2015.
4. Intel Newsroom. Intel Commercial Drones Speed Up US Bridge Inspections [Video File]. 5 December 2018. Available online: https://www.youtube.com/watch?v=IqwXI67PSIE&t=88s (accessed on 5 June 2020).
5. Barfuss, S.; Jensen, A.; Clemens, S. *Evaluation and Development of Unmanned Aircraft (UAV) for UDOT Needs*; No. UT-12.08; Utah Department of Transportation Research Division: Salt Lake City, UT, USA, 2012.
6. OSHA. Infrastructure Repair and Restoration, Roadway and Bridge Inspection and Repair. Hurricane eMatrix. Available online: https://www.osha.gov/SLTC/etools/hurricane/roadway-bridge.html (accessed on 21 July 2020).
7. Ohio Department of Transportation (Ohio DOT). Bridge Inspection Manual, Chapter 6: Safety and Equipment. 2010. Available online: http://www.dot.state.oh.us/Divisions/Engineering/Structures/bridge%20operations%20and%20maintenance/Manual%20of%20Bridge%20Inspection%202014%20v8/Chapter%206_Safety%20and%20Equipment.pdf (accessed on 21 July 2020).
8. Federal Highway Administration (FHWA). *Bridge Inspector's Reference Manual*; FHWA NHI 12-049; FHWA: Washington, DC, USA, 2012.
9. Kamga, C.; Sapphire, J.; Cui, Y.; Moghimidarzi, B.; Khryashchev, D. *Exploring Applications for Unmanned Aerial Systems (UAS) and Unmanned Ground Systems (UGS) in Enhanced Incident Management, Bridge Inspection, and Other Transportation Related Operations*; University Transportation Research Center, City University of New York: New York, NY, USA, 2017.
10. Yang, H.; Ozbay, K.; Ozturk, O.; Xie, K. Work zone safety analysis and modeling: A state-of-the-art review. *Traffic Inj. Prev.* **2015**, *16*, 387–396. [CrossRef] [PubMed]
11. Gillins, D.T.; Parrish, C.; Gillins, M.N.; Simpson, C. *Eyes in the Sky: Bridge Inspections with Unmanned Aerial Vehicles*; No. FHWA-OR-RD-18-11; Federal Highway Administration: Washington, DC, USA, 2018.
12. Grey, J. (FHWA, Washington, DC, USA). Personal communication. 2019.
13. FHWA. Focus—Updated Course Offers Comprehensive Training on Bridge Safety Inspections—FHWA-HRT-12-011—March 2012: Federal Highway Administration. March 2012. Available online: https://www.fhwa.dot.gov/publications/focus/12mar/12mar02.cfm (accessed on 5 June 2020).
14. FHWA. Use of Small Unmanned Aerial Systems for Emergency Management of Flooding. FHWA-HIF-19-019; May 2019. Available online: https://www.fhwa.dot.gov/uas/resources/hif19019.pdf (accessed on 5 June 2020).
15. Otero, L.D. *Proof of Concept for Using Unmanned Aerial Vehicles for High Mast Pole and Bridge Inspections (No. BDV28-977-02)*; Florida Department of Transportation Research Center: Tallahassee, FL, USA, 2015. Available online: https://rosap.ntl.bts.gov/view/dot/29176 (accessed on 31 July 2020).
16. Zink, J.; Lovelace, B. *Unmanned Aerial Vehicle Bridge Inspection Demonstration Project*; No. MN/RC 2015-40; Minnesota Department of Transportation: St. Paul, MN, USA, 2015.
17. Omar, T.; Nehdi, M.L. Remote sensing of concrete bridge decks using unmanned aerial vehicle infrared thermography. *Autom. Constr.* **2017**, *83*, 360–371. [CrossRef]
18. Shaffer, P. (Butler, Fairman & Seufert, Indianapolis, Indiana). Personal communication. 27 July 2019.
19. Wells, J.; Lovelace, B. *Improving the Quality of Bridge Inspections Using Unmanned Aircraft Systems (UAS)*; Minnesota Department of Transportation: St. Paul, MN, USA, 2018.
20. FHWA. Unmanned Aerial Systems (UAS). 26 June 2019. Available online: https://www.fhwa.dot.gov/innovation/everydaycounts/edc_5/uas.cfm (accessed on 5 June 2020).
21. FHWA. [USDOTFHWA]. Unmanned Aerial Systems (UAS) [Video File]. 8 August 2019. Available online: https://www.youtube.com/watch?v=nN4zyuhlNHU&amp=&feature=youtu.be (accessed on 5 June 2020).
22. Seo, J.; Duque, L.; Wacker, J. Drone-enabled bridge inspection methodology and application. *Autom. Constr.* **2018**, *94*, 112–126. [CrossRef]
23. FAA. FAA Hits 100K Remote Pilot Certificates Issued. 26 July 2020. Available online: https://www.faa.gov/news/updates/?newsId=91086&omniRss=news_updatesAoc&cid=101_N_U. (accessed on 3 August 2020).
24. Salaries. Available online: https://www.payscale.com/ (accessed on 21 October 2019).
25. Bryden, J.; Andrew, L. Serious and Fatal Injuries to Workers on Highway Construction Projects. In Proceedings of the 78th Annual Meeting of the Transportation Research Board 1999, Washington, DC, USA, 10–14 January 1999.

26. National Council on Compensation Insurance (NCCI). Indiana Advisory Loss Costs, Advisory Rates, and Assigned Risk Rates Filing. 1 January 2019. Available online: http://icrb.net/rate_pages/1_1_2019rates.pdf (accessed on 5 June 2020).
27. McGuire, M.; Rys, M.J.; Rys, A. *A Study of How Unmanned Aircraft Systems Can Support the Kansas Department of Transportation's Efforts to Improve Efficiency, Safety, and Cost Reduction*; No. K-TRAN: KSU-15-3; Kansas Department of Transportation Bureau of Research: Topeka, KS, USA, 2016.
28. Cambridge Systematics and Texas Transportation Institute (TTI). *Traffic Congestion and Reliability: Trends and Advanced Strategies for Congestion Mitigation (No. FHWA-HOP-05-064)*; United States Federal Highway Administration: Washington, DC, USA, 2005. Available online: https://ops.fhwa.dot.gov/congestion_report_04/congestion_report.pdf (accessed on 5 June 2020).
29. Chin, S.M.; Franzese, O.; Greene, D.L.; Hwang, H.L.; Gibson, R.C. *Temporary Losses of Highway Capacity and Impacts on Performance: Phase 2*; Oak Ridge National Laboratory: Oak Ridge, TN, USA, 2004. Available online: https://info.ornl.gov/sites/publications/Files/Pub57300.pdf (accessed on 5 June 2020).
30. Khattak, A.J.; Khattak, A.J.; Council, F.M. Effects of work zone presence on injury and non-injury crashes. *Accid. Anal. Prev.* **2002**, *34*, 19–29. [CrossRef]
31. Chambless, J.; Ghadiali, A.M.; Lindly, J.K.; McFadden, J. Multistate work-zone crash characteristics. Institute of Transportation Engineers. *ITE J.* **2002**, *72*, 46.
32. Pigman, J.G.; Agent, K.R. Highway accidents in construction and maintenance work zones. *Transp. Res. Rec.* **1990**, *1270*, 12–21.
33. Sorock, G.S.; Ranney, T.A.; Lehto, M.R. Motor vehicle crashes in roadway construction work zones: An analysis using narrative text from insurance claims. *Accid. Anal. Prev.* **1996**, *28*, 131–138. [CrossRef]
34. Mohan, S.B.; Gautam, P. Cost of Highway Work Zone Injuries. *Pract. Period. Struct. Des. Constr.* **2002**, *7*. [CrossRef]
35. Coburn, J.S.; Bill, A.R.; Chitturi, M.V.; Noyce, D.A. Injury Outcomes and Costs for Work Zone Crashes. *Transp. Res. Rec.* **2013**, *2337*, 35–41. [CrossRef]
36. Center for Disease Control (CDC). Highway Work Zone Safety. 19 June 2017. Available online: https://www.cdc.gov/niosh/topics/highwayworkzones/ (accessed on 5 June 2020).
37. Bureau of Labor Statistics (BLS). Census of Fatal Occupational Injuries Summary. 2017 Released. 18 December 2018. Available online: https://www.bls.gov/news.release/cfoi.nr0.htm (accessed on 5 June 2020).
38. Cameron, D. How Big Is the Risk of Lyme Disease to Your Job? Available online: http://danielcameronmd.com/big-risk-lyme-disease-job/ (accessed on 5 June 2020).
39. Rudavsky, S. IU study: We have more ticks here that carry Lyme disease than thought. In *Indianapolis Star*; 24 May 2018. Available online: https://www.indystar.com/story/news/2018/05/24/iu-study-finds-lyme-ticks-areas-state-never-had-them-before/640126002/ (accessed on 5 June 2020).
40. Indiana Department of Labor. Indiana Nonfatal Injuries & Illnesses. 2016. Available online: https://www.in.gov/dol/files/DOL_SOII_Analysis_2016.pdf (accessed on 5 June 2020).
41. National Safety Council. Work Injury Costs. Available online: https://injuryfacts.nsc.org/work/costs/work-injury-costs/ (accessed on 5 June 2020).
42. U.S. Department of Labor. Spotlight on Statistics, Fatal Occupancy Injuries by Event or Exposure, 2011–2016 (Page 11). Available online: https://www.bls.gov/spotlight/2019/25-years-of-worker-injury-illness-and-fatality-case-data/home.htm (accessed on 5 June 2020).
43. National Safety Council Injury Facts, Work Related Fatigue. Available online: https://injuryfacts.nsc.org/work/safety-topics/work-related-fatigue/ (accessed on 5 June 2020).
44. Opiela, K.; Sant, B.; Childers, J. Turning Young Drivers into Survivors. September 2006. Available online: https://www.fhwa.dot.gov/publications/publicroads/06sep/03.cfm (accessed on 5 June 2020).
45. Liberty Mutual. Liberty Mutual Workplace Safety Index. 2018. Available online: https://business.libertymutualgroup.com/business-insurance/Documents/Services/Workplace%20Safety%20Index.pdf (accessed on 5 June 2020).
46. OSHA. Commonly Used Statistics. Available online: https://www.osha.gov/oshstats/commonstats.html (accessed on 5 June 2020).
47. FHWA. Assessing Stream Channel Stability at Bridges in Physiographic Regions. July 2006. Available online: https://www.fhwa.dot.gov/publications/research/infrastructure/hydraulics/05072/03.cfm (accessed on 31 July 2020).

48. Center for Disease Control (CDC). Lyme Disease Rashes and Look-Alikes. (Photograph); 21 December 2018. Available online: https://www.cdc.gov/lyme/signs_symptoms/rashes.html (accessed on 5 June 2020).
49. Zhang, X.; Meltzer, M.I.; Pena, C.A.; Hopkins, A.B.; Wroth, L.; Fix, A.D. Economic impact of Lyme disease. *Emerg. Infect. Dis.* **2006**, *12*, 653–660. [CrossRef] [PubMed]
50. Drone U. What Is My Drone Life Expectancy? Available online: https://www.thedroneu.com/adu-0704-life-expectancy-drone/ (accessed on 5 June 2020).