Testing Survey Methods for Detecting Bats Roosting in Bridges

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PREPARED BY:

Piper L. Roby, Ph.D.

Crystal Birdsall

Timothy Divoll

Copperhead Environmental Consulting, Inc.

PREPARED FOR:

Missouri Department of Transportation

Construction and Materials Division, Research Section

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16. Abstract
Bats are a critical component of our natural world, and many species are at risk. Protecting roosting habitat is one way we can help conserve a variety of species. Although many bats use natural roosts, a growing number are adapting to anthropogenic structures due to habitat encroachment. In this study, we tested methods for detecting bats using bridges as roosts. We visited 20 bridges four times each to test six daytime methods (human visual and hearing, use of an acoustic detector, use of an agitator to induce bat vocalization, visual search with a spotlight, use of a thermal camera, and a borescope) and three evening emergence methods (human visual, thermal camera, and acoustic detector). Occupancy modeling revealed that the most effective way to document bat use at bridges is with an acoustic detector during evening emergence. This was followed by the use of thermal cameras during evening emergence, and the third best model was use of thermal cameras during the day. Surveying longer did not increase detectability in any of the top models. Based on our findings and suggestions in guidance documents for detecting bats in bridges, the first step is to survey a bridge with a spotlight, listening for bat vocalizations, and noting smell. If bats are not detected during the day, using acoustic detectors and thermal cameras during emergence will determine if bats are using bridges and can provide additional data if they are documented using them during the day.

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By
Piper Roby, PhD
Crystal Birdsall
Timothy Divoll, PhD
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List of Abbreviations and Acronyms

DOT .... department of transportation

ESS............................effective sample size

ft...............................feet

GLMM.........................general linear mixed models

IUCN...........................International Union for Conservation of Nature

MCMC.........................Markov Chain Monte Carlo

Pd...............................*Pseudogymnoascus destructans*

$\hat{R}$ ....R hat

WAIC...........................Widely Applicable Information Criterion

WNS............................White nose syndrome

U.S..............................United States

Δ.................................delta (change)

Executive Summary

Bats fill a wide variety of ecological niches and are found on every continent except Antarctica. Feeding on everything from insects to pollen to blood, bats are essential pest control agents and act as pollinators. However, many bat species are at risk from roosting and foraging habitat loss and modification. Disease, human-caused direct mortality, and the development of wind energy pose immediate risks to the survival of individuals and populations. Conservation measures to protect many species are in place, but further reduction of impacts to bats is important for their survival.

Bats use a wide variety of roosts, both natural and artificial. As humans encroach on their natural habitat, bats have adapted to using anthropogenic structures such as culverts and bridges. As transportation structures age and fall into disrepair, bats may take advantage of cracks and crevices. This can be problematic when the structures need maintenance or deconstruction. In this study, methods for detecting bats roosting in bridges were tested to determine the most effective way to document bat use. A power analysis was conducted to determine the effective number of sites and repeated visits to result in a robust statistical results. Bridges with prior bat use were selected with help from state and federal agencies in several states, with emphasis on threatened and endangered bat use. Nine methods of bat detection were tested. During the day, six methods were tested: 1) unaided human vision and hearing, 2) human vision aided with spotlights, 3) human hearing aided with acoustic detectors, 4) human vision aided with a borescope; 5) human vision aided with thermal cameras, and 6) an ultrasonic agitator to induce bat vocalization detectable with unaided human hearing. In the evening, three methods of detecting emerging bats were tested: 7) unaided human vision, 8) video recording with a thermal camera, and 9) bat vocalization recording with acoustic detectors. Because not all bridges had roosting bats during every visit, occupancy modeling was conducted to analyze the data. Covariates used were numeric variables of bridge area and height, day and night ambient temperature and relative humidity, survey duration, and bat height in roost. Categorical variables were summarized as descriptive factors and not used in statistical analysis.

Nineteen bridges were visited four times each, and one bridge was visited three times because it was destroyed by Hurricane Helene before a fourth visit could be conducted. The data collected fit the model well and was sufficient for a robust analysis using Bayesian statistical methods. The model with the greatest detection probability and the lowest Widely Applicable Information Criterion (WAIC) value, and therefore the most effective method for detecting bats at bridges, was using an acoustic detector at emergence. Although there was not enough statistical support to make comparisons (i.e., ΔWAIC > 2), the second-best model was using a thermal camera to detect bats emerging from bridges. The third-best method was observing bats during the day using a thermal camera. All three had high probability of positive detections. The covariate with an effect was the “duration of method,” which had a negative effect on detectability: the length of the survey did not increase detectability.

The easiest and suggested first way to survey bridges for bats is visually (preferably with a spotlight), audibly, or sometimes by smell. Even if bats are detected, recording emergence with an acoustic detector and thermal camera can provide information on the number of bats using the bridge and timing of use. Using an acoustic detector during the day was ineffective at detecting roosting bats. Using a thermal camera during the day was an option, but results were not definitive due to other “hot spots” in cracks in bridges. The borescope was useful only for detecting low-roosting bats but could potentially help in identifying species and counting individuals. The agitator was almost completely ineffective. Human observation of emergence was moderately effective, but human sight was impeded by darkness quickly.

Chapter 1. Introduction

There are more than 1,450 species of bats in the world (Simmons and Cirranello 2025), comprising about 20 percent of all mammal species. The International Union for Conservation of Nature (IUCN) tracks the population size, range, habitats, and ecology of 1,396 bat species (). Bats, an important indicator of ecosystem health, provide many ecological services, including insect control, seed dispersal, and pollination (Ducummon 2000, Jones et al. 2009). Insectivorous bats in farmland ecosystems have a direct economic value to agriculture, saving an estimated $22.9 billion per year by reducing the use of pesticide applications on crops (Boyles et al. 2011, Ancillotto et al. 2024, Tuneu-Corral et al. 2024). Bat numbers are declining worldwide due to human development, habitat destruction/modification, pesticides/pollution, wind energy, climate change, and disease. Currently, 24% of the world's bats are listed by the IUCN as critically endangered (n = 33), endangered (n = 91), vulnerable (n = 122), or near threatened (n = 98). In the United States (U.S.), there are 49 species of bats, 10 of which are listed by IUCN as endangered (n = 3 species), vulnerable (n = 3 species), or near threatened (n = 4 species). Several of the species in the U.S. are in decline due to habitat loss, impacts from wind energy facilities, climate change, and more recently, white nose syndrome (WNS), a high-mortality disease caused by the cold-loving fungus *Pseudogymnoascus destructans* (Pd) that was accidentally introduced from Europe in 2006 (Cohn 2008). Such stressors have caused many bats to either adapt or perish.

Bats exhibit a variety of roosting behaviors based on their environment and reproductive needs. Natural roosts include the use of exfoliating bark on trees, cavities, and dead leaf clusters, all common for insectivorous bats in the eastern U.S. (Gardner et al. 1991, Agosta 2002, Krynak 2010). With the loss of natural habitats, bats have adapted roosting behaviors to include the use of anthropogenic structures such as houses, bridges, and culverts. Bats are routinely found roosting in transportation structures around the world, particularly in the continental western U.S. where this phenomenon has been studied longer and for more bat species (see H. T. Harvey & Associates and HDR Inc. 2021). Interest in studying eastern U.S. occurrences of roosting in transportation structures has increased only in the past several years. As more bridges and culverts are surveyed for bats, it is becoming evident that these structures are used extensively year-round in some cases and seasonally in others (Wetzel and Roby 2023). In addition, federally threatened or endangered species, as well as those proposed or under review for listing, have been documented as using these anthropogenic roosts. To compound this issue, there are more than 40,000 structurally deficient bridges in need of repair in the U.S. Although departments of transportation (DOTs) generally avoid impacts to bats during repairs or replacement of bridges and culverts, the use of these structures by federally listed species poses the need for additional understanding and protection.

A recent report compiling known information about the use of transportation structures by bats outlined five projects that could increase our understanding of bats' use of bridges in the eastern U.S. (Wetzel and Roby 2023). Working together, Copperhead Consulting and the Missouri Highways and Transportation Commission decided that testing methods for detecting bats in bridges should be prioritized. This project was created to determine the detection probabilities of various methods used at bridges that were documented to house bats. Results were intended to provide the best method for positively documenting bats roosting in bridges.

Chapter 2. Methods

Project Setup

Method Selection

A review of bat occupancy studies in transportation structures throughout the U.S. was conducted in a previous study (Wetzel and Roby 2023). However, a crucial gap was that the specific detection methods employed in each study remain undocumented. This lack of detail presented a significant challenge to meeting current research objectives.

To bridge this gap, a structured questionnaire was disseminated among various agencies, inquiring about their standard practices in surveying bats in structures. The responses, as summarized in Table 6 of the same report (Wetzel and Roby 2023), indicated a predominance of visual inspection techniques, encompassing the use of light sources, binoculars, borescope cameras, and thermal cameras. Additionally, it was noted that overnight emergence surveys were occasionally conducted on an ad-hoc basis, particularly in scenarios where bat presence was suspected, but not confirmed, through initial surveys.

Power Analysis

While answers from the questionnaire provided valuable insights into common survey practices, the information fell short of delivering the empirical data needed for robust power analysis. Specifically, the general detection probabilities associated with each of these survey methods were still unknown, i.e., assuming bats are roosting in a structure, how good are any of the survey methods in detecting them? This constituted a critical limitation, as accurate estimation of detection probabilities is fundamental to the design and execution of a scientifically sound power analysis and the resultant sample size. Without an initial estimate of detection probabilities, it was challenging to gauge how large a sample was needed. While estimating detection probabilities is not ideal due to the inherent uncertainty, such estimation is often a necessary step in the early stages of study design, particularly when no direct data are available. A combination of expert opinion, analogous studies, and literature review served as a foundation for these initial estimates, which were essential for an informed power analysis and effective study design.

When conducting the power analysis to determine the number of samples needed, a simple setup was assumed, with only the detection methods in a model considered. A test that approximates the comparison of two proportions was selected, and G*Power Version 3.1.9.6 (Faul et al. 2007) was used to estimate sample sizes. G*Power does not directly handle complex models like general linear mixed models (GLMMs) or occupancy models, but a test for comparing two independent proportions was used as a proxy to get an initial estimate. G*Power provided the total sample size required to achieve the specified power, that is the number of independent observations (or independent comparisons in the case of detection probabilities) needed per group. Even with the results of a power analysis, the feasibility of field work was considered when selecting the level of effort.

Because these estimates were not calculated from data collected for this project (e.g., in a pilot study), the predicted detection probabilities are provided (Table 1). The lowest detection probability (20.7% chance of detecting bats if they were there) of the selected methods was from a single, unaided human doing a daytime, roost inspection. This detection probability of 0.207 equates to needing seven repeat site visits to be 80% confident that bats do or do not occupy a given bridge, and 10 site visits to be 90% confident bats do or do not occupy a given bridge (roost_human; Table 1). The greatest detection probability of the selected methods was the emergence count using two thermal cameras (one on either end of the bridge), with a 70.5% chance of detecting bats if they were there (emergence_humanThermal; Table 1). This estimated (low-balled) detection probability of 0.705 equates to being more than 90% confident that bats do or do not occupy a given bridge after only two visits (Table 1).

Selecting 20 bridges to visit four times each, for a total of 80 samples, equated to a detectable difference between proportions (methods) of ~30% (biased high), assuming a Power of 0.8 (i.e., 80% likely to find bats that are there) and an alpha of 0.05 (i.e., 5% chance of concluding bats were present when they were not). This approach assumed that each detection event was independent, which does not hold in actual occupancy or detection probability studies where repeated measures on the same site are involved. This analysis provided a ballpark figure for sample sizes, guiding early planning stages.

Table 1. Detection probabilities of methods tested to detect bats roosting in bridges prior to data collection.

Detection Name	Detection Description	Predicted Detection Probability
roost_human	Unaided human eyes and ears	0.207
roost_humanLight	Aided human vision with a spotlight	0.457
roost_humanDetector	Aided human hearing with an acoustic detector (not recorded)	0.354
roost_humanThermal	Aided vision with a thermal camera (not recorded)	0.457
roost_humanBorescope	Aided vision with a borescope camera (not recorded)	0.457
roost_humanAgitator	Aided hearing with an agitator to induce bat vocalization	0.207
emergence_human	Unaided human vision observing bats emerging	0.371
emergence_humanThermal	Aided vision observing bats emerging with a thermal camera (recorded)	0.705
emergence_detector	Aided recording of bat vocalization during emergence	0.594

Field Work

Biologists at the U.S. Fish and Wildlife Service (USFWS), state agencies, and state departments of transportation (DOTs) in Indiana, Ohio, Kentucky, and Tennessee were contacted to get information about bridges housing bats, and in particular, federally listed bats. There were 27 bridges identified in four states initially that had prior bat detections. The Indiana DOT required permits that could not be executed, so those three bridges were excluded from the project. There were 14 bridges in Kentucky, but four did not house bats upon initial visitation. All bridges visited in Ohio housed bats, as did those in Tennessee. A total of 20 bridges were scheduled to be surveyed each four times from April through October 2024. Ten bridges were surveyed in Kentucky, seven in Tennessee, and three in Ohio (Figure 1). Nine survey methods were used: six during the day to detect roosting bats and three in the evening to detect bats emerging (Table 1). All data were collected in ArcGIS Survey123 (ESRI, Redlands, CA) forms created by Copperhead Consulting (Appendix A) prior to field deployment (henceforth referred to as Survey123).

Daytime survey methods included:

1. unaided human visual search of the bridge
2. aided audible search using acoustic detectors (Anabat SD2, Titley Scientific, Brendale QLD, Australia)
3. aided visual search using thermal cameras (FLIR Scion OTM260 Thermal Handheld Camera Model # 19761295, Teladyne, Thousand Oaks, CA)
4. aided visual search using spotlights (10 Watt LED Rechargeable Spotlight, Model #LEDLIB, Black and Decker, New Britain, CT; Yeirblue Rechargeable Spotlight Floodlight Combo, UPC #768447605225 Shenzhen Yizhiyuan Technology Co., LTD, Shenzhen, China; EverStart Maxx, Rechargeable Li-Ion Spotlight, Model #SL10LEDE, distributed by Walmart, Bentonville, AR)
5. aided visual search using a borescope (2.0 Megapixels Wireless Endoscope, Model #WF010, Depstech, Shenzhen, China)
6. an ultrasonic agitator (Dog Dazer II Ultrasonic Dog Deterrent, Dazzer, Amazon) to initiate bat vocalization audible by unaided human hearing

The unaided human visual-only search was always the first method tested as the least invasive method, and the agitator was always the last survey method tested due to possible disturbance to the bats. The acoustic detectors, thermal cameras, spotlight, and borescope were always tested in a randomly generated order to eliminate bias in the data. Cloud cover and weather conditions along with temperature and humidity (Kestrel 3500 Weather Meter, Model #0835, Kestrel, Boothwyn, PA) were all collected at the bridge prior to the start of the evaluation timer (i.e., daytime ambient weather conditions).

The daytime survey began when all the personnel and equipment were under the bridge, and the evaluation timer commenced at the start of the first method. If a bat was detected within the 45-minute unaided human visual search, the time it took to detect a bat was recorded, and all other techniques were tested at the location of the detection for 5 minutes or until a method detected a bat. If a method worked during the 5-minute search period, it was recorded and was no longer tested during that survey. All other survey techniques that did not detect bats during that 5-minute period were tested for another 40 minutes or until another survey technique method detected bat presence. This resulted in all methods being tested until they detected a bat or for a total of 45 minutes, whichever came first.

An evening emergence survey commenced 30 minutes before sunset each night and lasted for 60 minutes after sunset for a total of 90 survey minutes. Two personnel used two thermal cameras on tripods and two acoustic detectors (Anabat Swift, Titley Scientific, Brendale QLD, Australia) elevated approximately 3 feet (ft) off the ground, but higher if vegetation impeded line-of-site. One of each method was set up on opposite sides of the bridge and diagonal to each other so that activity could be detected on both sides of the bridge and not duplicated. Acoustic detectors, thermal cameras, and personnel were set up on the outside of the bridge, when possible, with equipment pointed parallel with the bridge. If vegetation obstructed the span of the bridge, or if it was raining, equipment and personnel were set up just beneath the bridge on their respective sides with equipment still pointed parallel with the bridge. Cloud cover and weather conditions, along with temperature and humidity (using a Kestrel Weather Meter 3500), were all collected at the bridge 30 minutes before sunset (i.e., nighttime ambient weather conditions).

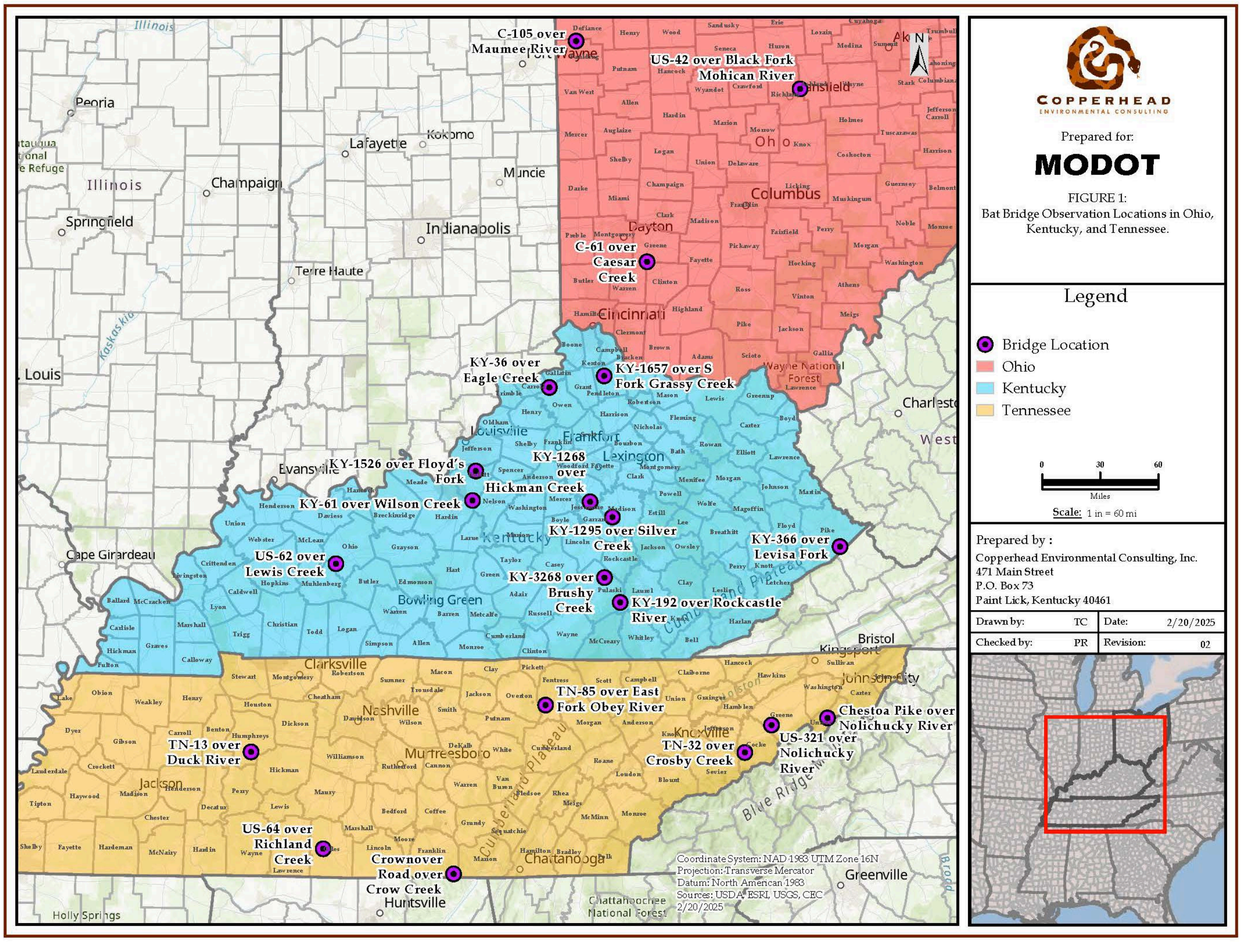

Figure 1. Bat bridge observation locations in Ohio, Kentucky, and Tennessee.

Statistical Analysis

Although bridges with known prior bat roosting were targeted, encountering bats during each visit was not guaranteed. Therefore, detection probabilities from occupancy models were used. Program R version 4.3.2 (R Core Team 2024) was used, and a Quarto workbook was created in RStudio to work through the processing and investigate output results. Data were extracted from Survey123 in two tables: one for the site assessments and one for survey results. Downloaded Comma-Separated Values (.csv files) were read into the workflow, and data columns were renamed so variables were associated with one of the following categories: project, personnel, site, bridge, method, and weather. The site assessment dataframe was then expanded (79 visits) to create an entry for each possible method across all visits (693 possible scenarios). The same procedure was followed for the method results dataframe (531 detection method attempts) was conducted to create an expansion for each possible method (1,165 possible scenarios). The expanded site and detection data were joined and flattened into one dataframe (711 possible scenarios).

Tests were conducted for errors in data entry related to the method order and the duration of survey. Field crews helped to correct data from original sources and updated Survey123 entries to ensure that 'roost_human' was always the first method employed and that there was a similar level of effort at each site visit. Missing data were imputed using the mean for numeric columns and removing any surveys in which the entire detection history was "NA."

Data were prepared for modeling by creating lists for the survey data, site-level occupancy covariates, detection covariates at the site- and observation-level, the sites, and the spatial coordinates. The data list was fed into a presence-only model (Spatial Integrated Occupancy Model with Polya-Gamma latent variable with 20 sites, 4 visits per site; Doser et al. 2022), first testing occupancy among the nine method orders without covariates to identify the method with the best detection. After identifying the best methods, covariates for detection were added and the model was re-run to assess which covariates might have an effect on each of the top three detection methods. The covariates used were numeric variables of bridge area and height, day and night ambient temperature and relative humidity, survey duration, and bat height in roost. Categorical variables were summarized as descriptive factors and not used in statistical analysis.

Daytime ambient temperature and relative humidity data were used as covariates for testing methods used during the day to detect bats (n = 6 methods) whereas nighttime ambient temperature and relative humidity data were used as covariates for testing methods used in the evening to detect bats (n = 3 methods). Model fit was assessed using R hat ($\hat{R}$) where a value of <1.1 is considered a good fit, and effective sample size (ESS) metrics where 100 is considered a large sample size, as well as visual inspection of Markov Chain Monte Carlo (MCMC) trace plots to ensure model convergence. The best model was assessed using Widely Applicable Information Criterion (WAIC), where the lowest WAIC values with greatest probability of positive effect on detection indicated the best method. WAIC scores typically use a delta of 2 (Δ = 2), so models with a score less than 2 points away from the top model would be equally plausible. Conversely, models with a score of more than 2 points away do not contain enough statistical support from which to draw conclusions, compared to the statistical support of top-ranked models. Covariate parameter estimates were then plotted to find those without posterior samples crossing zero. For any that did not cross zero (i.e., method duration), data were plotted for those covariates against probability of detection.

Chapter 3. Results

Location and Physical Descriptions of Bridges

All 20 bridges in three states (Table 2) were visited four times each, except for Site 13, which was visited three times because it was destroyed by Hurricane Helene on 27 September 2024. Bridges were 32.0 ± 3.2 ft wide on average (range: 14.6 – 79.7 ft wide) and 389.4 ± 93.2 ft long on average (range: 128.5 – 2,038.7 ft long). However, removing the outlier bridge that was 2,038.7 ft long, the average was reduced to 302.6 ± 35.7 ft long (range: 128.5 – 677.4 ft long). Most of the bridge construction was cast-in-place (n = 9 bridges), but five pre-stressed girder bridges and three flat slab-box bridges were also used; one each of parallel box beam, steel continuous, and steel I-beam bridges were visited (Table 3, Appendix B).

Table 2. Name and location of each bridge visited for testing methods to detect bat use.

Site ID	DOT Structure No.	State	County	Bridge Road	Crossing	Latitude	Longitude
1	090B00062N	KY	Nelson	KY-61	Wilson Creek	37.81439	-85.69428
2	7003072	OH	Richland	US-42	Black Fork Mohican River	40.81362	-82.41179
3	6330800	OH	Paulding	C-105	Maumee River	41.23822	-84.60191
4	2930331	OH	Greene	C-61	Caesar Creek	39.57069	-83.97387
5	094B00032N	KY	Owen	KY-36	Eagle Creek	38.65036	-84.94600
6	076B00061	KY	Madison	KY-1295	Silver Creek	37.66804	-84.37888
7	25SR0850003	TN	Fentress	TN-85	East Fork Obey River	36.27235	-85.04477
8	43SR0130013	TN	Humphreys	TN-13	Duck River	35.93475	-87.76599
9	28SR0150011	TN	Giles	US-64	Richland Creek	35.21077	-87.10019
10	260A5910001	TN	Franklin	Crownover Road	Crow Creek	35.01764	-85.91286
11	15SR0320013	TN	Cocke	TN-32	Crosby Creek	35.87343	-83.22147
12	30SR0350001	TN	Greene	US-321	Nolichucky River	36.07053	-82.96637
13	860A0680001	TN	Unicoi	Chestoa Pike	Nolichucky River	36.10545	-82.44778

Site ID	DOT Structure No.	State	County	Bridge Road	Crossing	Latitude	Longitude
14	057B00035N	KY	Jessamine	KY-1268	Hickman Creek	37.78710	-84.58606
15	096B00030N	KY	Pendleton	KY-1657	S Fork Grassy Creek	38.72653	-84.41966
16	015B00057N	KY	Bullitt	KY-1526	Floyd’s Fork	38.03454	-85.65956
17	098B00186N	KY	Pike	KY-366	Levisa Fork	37.38070	-82.25458
18	092B00052N	KY	Ohio	US-62	Lewis Creek	37.34763	-86.98383
19	100B00097N	KY	Pulaski	KY-3268	Brushy Creek	37.21685	-84.46896
20	100B00087N	KY	Pulaski	KY-192	Rockcastle River	37.02772	-84.32882

Table 3. Descriptions of each bridge visited for testing methods to detect bat use.

Site ID	Bridge Type	Underdeck Material	End/ Back Wall Type	Roosting Crevices	Road Type	Deck Width (ft)	Deck Length (ft)	Bridge Alignment
1	cast in place	concrete	concrete	no	state rd	33.0	200.0	NW_SE
2	flat slab-box	concrete	concrete	yes	us hwy	45.3	205.5	NE_SW
3	flat slab-box	concrete	concrete	yes	country rd	33.0	402.0	N_S
4	flat slab-box	concrete	concrete	yes	country rd	28.2	335.7	E_W
5	pre-stressed girder	concrete	concrete	yes	state rd	26.0	432.7	NW_SE
6	cast in place	concrete	concrete	yes	state rd	22.5	173.2	NE_SW
7	pre-stressed girder	steel	concrete	no	state rd	28.5	380	E_W
8	cast in place	concrete	concrete	yes	state rd	41.6	2,038.7	NE_SW
9	pre-stressed girder	corrugated steel	concrete	no	us hwy	79.7	492.9	E_W
10	pre-stressed girder	concrete	concrete	yes	county rd	22.6	130.0	NE_SW
11	cast in place	concrete	concrete	yes	state rd	48.4	386.0	N_S
12	steel continuous	concrete	concrete	yes	us hwy	34.5	677.4	NE_SW
13	cast in place	concrete	concrete	no	county rd	31.9	424.9	E_W
14	parallel box beam	concrete	concrete	yes	state rd	28.5	135.5	N_S
15	cast in place	concrete	concrete	yes	state rd	28.1	128.5	NW_SE
16	cast in place	concrete	concrete	no	state rd	14.6	282.2	E_W
17	cast in place	concrete	concrete	yes	county rd	15.5	215.6	E_W
18	pre-stressed girder	concrete	concrete	no	us hwy	28.2	168.1	N_S

Site ID	Bridge Type	Underdeck Material	End/ Back Wall Type	Roosting Crevices	Road Type	Deck Width (ft)	Deck Length (ft)	Bridge Alignment
19	cast in place	concrete	concrete	yes	state rd	20.1	128.9	NW_SE
20	steel I-beam	concrete	concrete	yes	state rd	30.0	451.0	NW_SE

Results of Occupancy Modeling

Model Fit

Of the 80 bridge visits intended, 79 bridge visits were conducted due to the loss of Site 13 before the final visit. The presence-only model (Spatial Integrated Occupancy Model with Polya-Gamma latent variable with 20 sites) was run with all the data and converged well with $\hat{R}$ values < 1.1 and large ESS. The base model was run comparing the nine different detection methods, and the spatial parameters looked good as well. In Table 4, sigma.sq is the spatial variance in occurrence, while phi is the spatial correlation. The output suggests that there is low correlation between sites (phi) and high variability of occurrence across sites (Table 4). The model trace plots show good model convergence (Figure 2). The different colors are the different chains of MCMC that overlap (agreement between chains) and do not show any clear bias pattern (3,900 posterior estimates; Figure 2). In short, the data collected fit the occupancy model well, and enough data were collected to create a robust model.

Table 4. Results of model testing and data fitting.

Spatial parameter	Mean	Standard deviation	2.5%	50%	97.5%	$\hat{R}$	ESS
Sigma.sq	0.6776	0.6632	0.1748	0.5033	2.1249	1.0541	2,128
phi	0.0001	0.0000	0.0000	0.0001	0.0001	1.0158	1,385

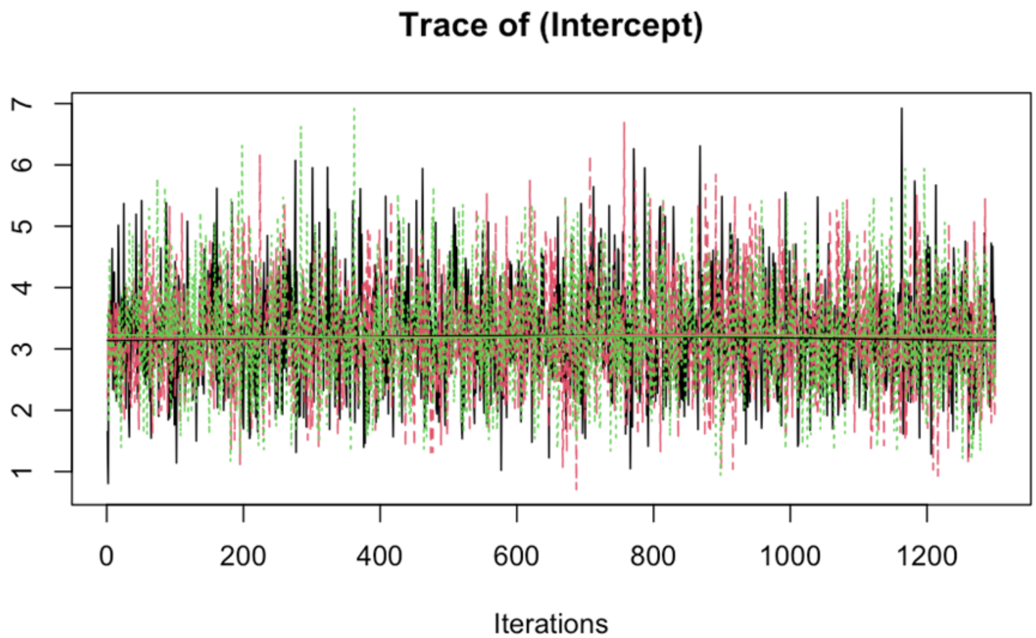

Figure 2. Model trace plots of the occupancy model for model convergence. Convergence of MCMC chains is evident by the "caterpillar" shape of the plot, with traces from each chain (red, black, green) overlapping through all iterations, 1,300 per chain.

Probabilities were the mean of all 3,900 posterior estimates, and WAIC scores were calculated from occupancy model outputs. The lower WAIC values indicated the best-fitting models, whereas the probabilities indicated whether there is a positive effect on detection, and both are considered to rank the "best" models. For example, as seen in Table 5, the roost_human_agitator model fit moderately well (fourth-best fit) but had a negative effect on detection (probability of effect = 0). The plot in Figure 3 shows the relative strength of positive and negative effects based on the parameter estimates. However, for the methods crossing zero (i.e., roost_human_borescope), it is not appropriate to say whether they have a positive or negative effect on detection.

Table 5. Results of occupancy modeling to determine the most effective method for detecting bats roosting in bridges.

Data source	Detection probability prior to data collection	WAIC score	Probability of positive effect on detection
emergence_acoustic	0.594	41.79	0.9999
emergence_human_thermal	0.705	66.88	0.9999
roost_human_thermal	0.457	78.95	0.9999
roost_human_agitator	0.207	82.25	0
roost_human_light	0.457	85.39	0.9999
roost_human	0.207	97.61	0.9989
emergence_human	0.371	98.56	0.9999
roost_human_acoustic	0.354	107.4	0.0271
roost_human_borescope	0.457	109.51	0.4682

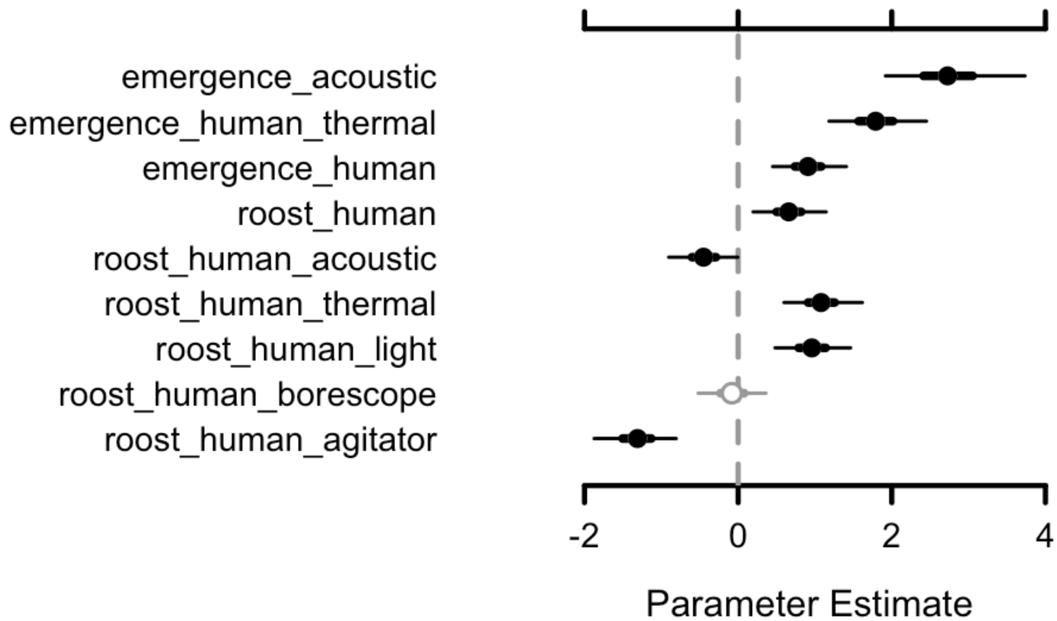

Figure 3. Relative strength of positive and negative effects of each method based on the parameter estimates. All of the models with parameter estimates to the right of zero had a high probability of positive detection, despite emergence_acoustic carrying the statistical support for the best method.

Best Models

The model with the lowest WAIC value, and therefore most likely to be the most effective method for detecting bats at bridges, is using an acoustic detector at emergence (emergence_acoustic, WAIC = 41.79; Table 5). In this analysis, no additional models were within Δ2 from the top model, thus there is not enough statistical support to make comparisons about the rest of the methods. For example, observing roosts with unaided human sight and hearing is not necessarily better than observing emergence with unaided sight, despite them having similar WAIC scores (roost_human v. emergence_human; Table 5). The second and third best methods were observing bats using a thermal camera at emergence (2nd) and during the day (3rd). These methods were also predicted to be the most effective methods prior to data collection (Table 1). This information is included in order to discuss the effects of covariates, as they still had a high probability of positive detection.

Effects of Covariates

Of the covariates tested to determine whether they had an effect on the top three detection models, the duration of the method tested had a statistically negative effect for all three top models. For all models, duration of the method did not increase the effectiveness of the method, i.e., if bats were detectable by a method, that detection occurred quickly.

Effect of Method Duration

Detection decreased as duration increased past 49 of 90 minutes for the top model of acoustic detection at emergence (Figure 4). The emergence survey began 30 minutes before sunset, and even though there were a few detections within the initial 30 minutes, the majority were detected 11 – 19 minutes after sunset.

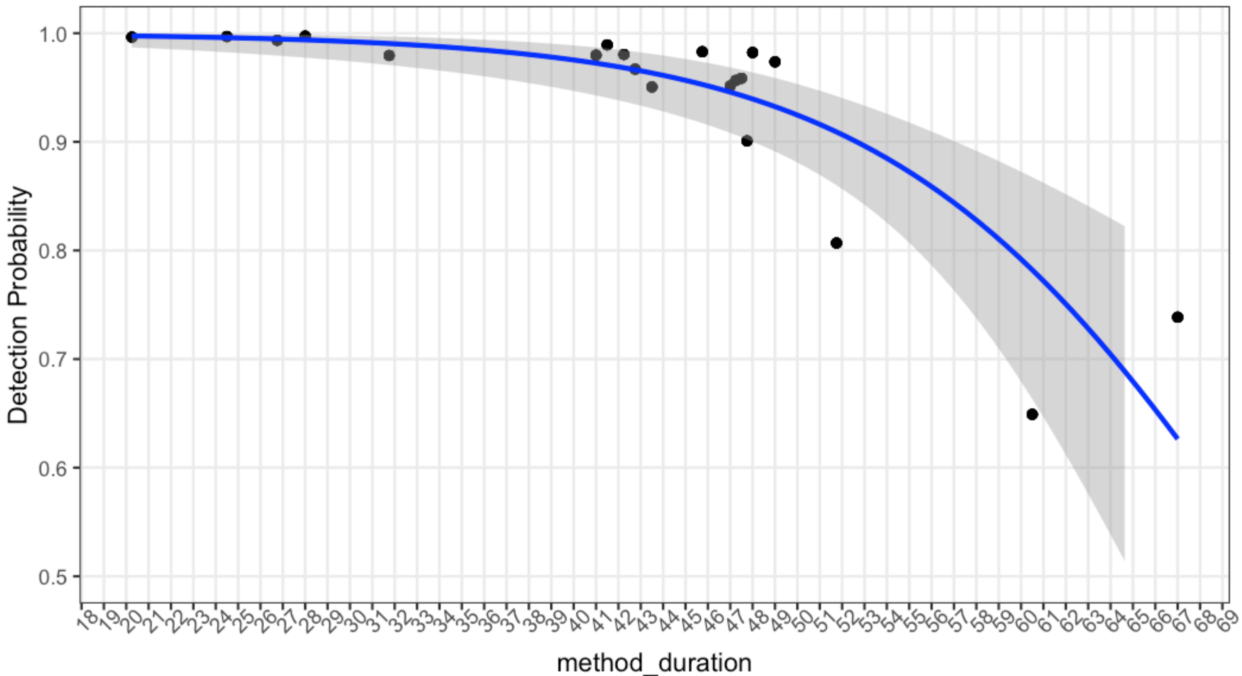

Figure 4. Detection probability versus the covariate of duration for detecting bats using acoustic recorders at emergence.

The slope of the decrease in detection for thermal camera detection at emergence (second model) was not as steep as the slope of decrease in the top model, but detection probability was less than 0.9 at 51 of 90 minutes (Figure 5). There were no detections of bats on camera within the first 30 minutes of the survey, so all detections occurred at or after sunset, with the majority of detections (i.e., > 0.9 detection probability) occurring within 21 minutes after sunset. Using a thermal camera during the day, detection of bats roosting in the bridge occurred very quickly, with the majority of detections occurring within 25 minutes of the start of the survey (Figure 6). As with the other methods, increasing the survey time did not increase the detection probability.

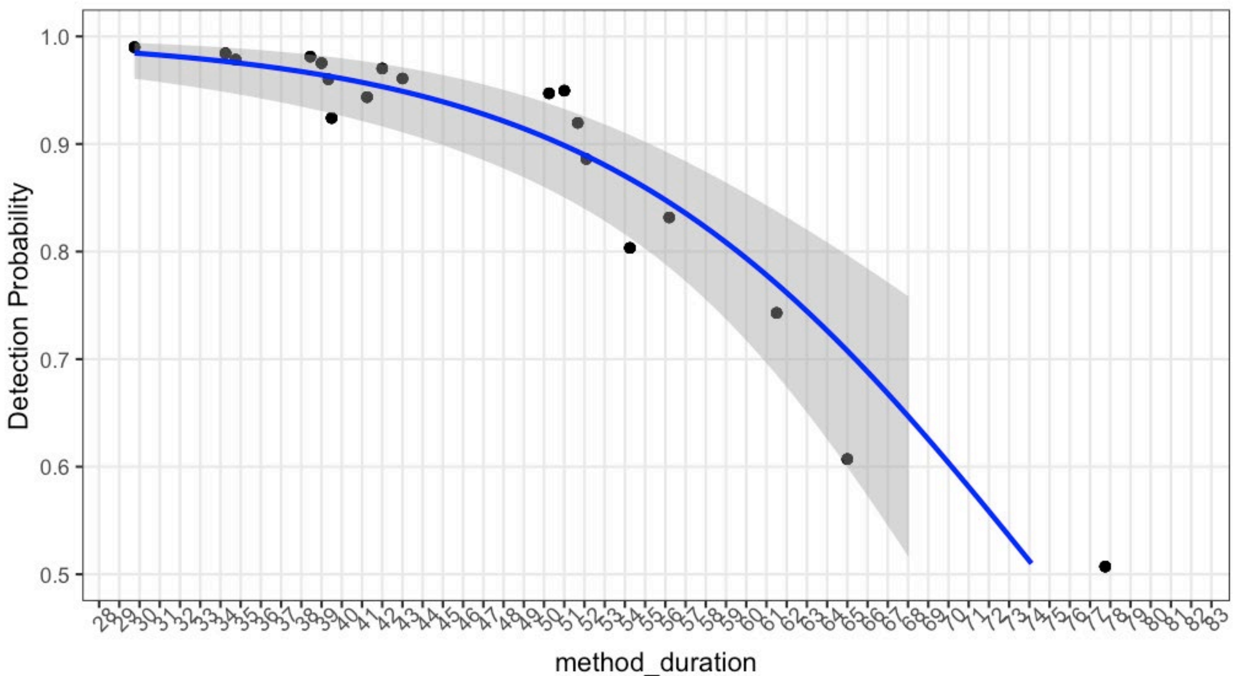

Figure 5. Detection probability versus the covariate of duration for detecting bats using thermal cameras at emergence.

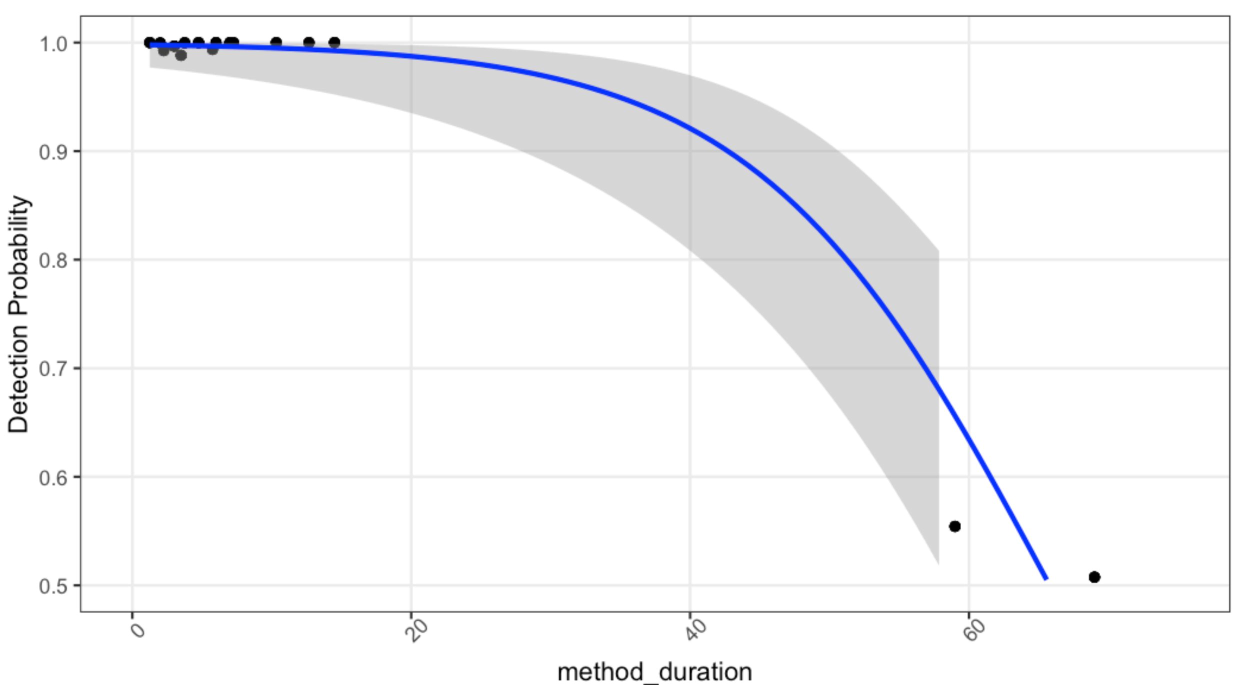

Figure 6. Detection probability versus the covariate of duration for detecting bats roosting in bridges using thermal cameras during the day.

Chapter 4. Discussion

Best Model

Results indicate that using an acoustic detector at emergence is the most effective way to detect bats roosting in bridges, which was also found by Civjan et al. (2017). Although the ΔWAIC score for the next-best model (using a thermal camera to detect emergence) did not support the feasibility of this method, Civjan et al. (2017) also found that the use of aided visual detection (in their case, infrared photos and video) was an effective method of observing bat movements, making the claim that "visual observation alone would not be sufficient to identify these bats or emergence locations." The caveat to the results of the top two models in the current study (i.e., acoustic emergence and thermal camera emergence) is that it is possible and likely that larger-bodied bats roosting in nearby trees (such as *Lasiurus* species) that emerge earlier in the evening (Thomas and Jacobs 2013) could be detected as they passed under the bridge, so these calls would not represent bats roosting in the bridge. It was beyond the scope of this project to determine species' use of bridges, so it is unknown whether calls were created by bridge-roosting bats such as *Myotis* species, or by tree-roosting species such as *Lasiurus* species. In addition, collecting acoustic recordings at bridges may produce suspect results due to call structure of emerging bats versus the recordings of free-flying bats used in call libraries.

Viele et al. (2002) found that Indiana bats (*Myotis sodalis*) began emerging from tree roosts 18 – 19 minutes after sunset. In our results, most emergence data were collected from 10 to 18 minutes after sunset, and although bat species was not documented as part of the data, anecdotal notations indicate that a combination of Indiana bats, little brown bats (*M. lucifugus*), gray bats (*M. grisescens*), and big brown bats (*Eptesicus fuscus*) were using bridge roosts, with a few small-footed bats (*M. leibii*), and at least one bridge had several Mexican free-tailed bats (*Tadarida brasiliensis*). The calls collected from 10 to 18 minutes after sunset could have been made by the larger-bodied gray bats or big brown bats, with the smaller Indiana bats and little brown bats emerging later. However, there is a law of diminishing returns in which surveying longer did not produce more detectability. In fact, bats documented later in the survey were more likely not to be roosting in the bridge and more likely to be passing through. Information about emergence timing of bats from natural versus artificial structures was not found, but emergence timing appears to be associated with predator avoidance (Thomas and Jacobs 2013, Arndt et al. 2018). It is unclear whether bats in bridges emerge earlier to avoid crepuscular mammals such as racoons or emerge later to avoid diurnal raptors. Weather did not appear to influence emergence times in our study, which was supported by Viele et al. (2002).

Visual inspection during the day should be the first method used to detect obvious bat use, but if bats are not visible or audible (or smelled) during the day, observing bats emerging in the evening is a more definitive method. Even though the use of thermal cameras did not appear to be as effective as acoustics in the modeling, the combination of using acoustics along with thermal camera recordings is the method most likely to definitively determine whether bats are using the bridges on the days they are roosting there. As with all electronics, the thermal cameras failed to record on occasion, so the use of at least one camera on each side is essential, and having unaided human sight as a backup for detecting use is critical.

Other Models, Anecdotal Info

Although none of the other models appeared to be beneficial for detecting bats, anecdotal observations were made about each since they have been used by other researchers.

Unaided Human Observation

Looking and listening for bats under a bridge is the easiest way to survey, but it may result in a false-negative. If bats are observed and no other information is needed, the survey can be complete. However, if species or numbers of bats are of interest, continue with the following methods.

Visual Observation with Light and/or Thermal Camera During the Day

Visual observation with a spotlight is probably the more common way to survey bridges for bats. This practice is effective if bats are positioned for detection, and it is a good way to initiate a bridge survey. If bats are low enough, less than 20 ft from the ground, a spotlight is likely sufficient to see bats (see photos of bats roosting in bridges in Appendix C). If a light cannot reach the roost, a thermal camera may be employed (third-best model); however, detecting bats with the thermal camera from a great distance (i.e., more than 20 ft away) can be tricky. There can be several objects in bridge cracks that are warm and appear to be bat-sized. It is generally important to view the “hot spot” for several minutes before determining whether bats are present, such as from bat movement. Observation on colder days may be easier. If only a few bats are observed or they are only heard, a follow-up emergence survey could help inform the extent of use in terms of numbers of bats and timing of emergence.

Visual Observation of Emergence in the Evening

Although setting acoustic detectors and thermal cameras to record bat emergence is the most definitive way to document bat use of bridges, human observation of events that may happen off camera (e.g., other animal or human activity) can provide additional information.

Use of Borescope, Acoustic Detectors, and Agitators

The use of a borescope is not likely the first usable detection method, but it could help with identifying species and possibly with getting a more accurate count of roosting bats. The length of the borescope and ability to gain access to high-roosting bats can create limitations.

Acoustic detectors worked infrequently at detecting bats, as bats are not typically echolocating during the day while roosting. In addition, if bats were heard on the acoustic detector, they were also audibly detected by unaided human hearing. Even when bats were heard by unaided human ears, they were not always picked up on the acoustic detector.

Agitators worked only if bats were already vocalizing. Although not recorded as a behavior, bats were observed to “cower” when the agitator was directed at them. They did not like the sound, but they did not necessarily vocalize in response.

Other Options/Future Work/Things Not Tested Here

It was not the original intention to document the presence of guano at bridge roosts, but guano ended up being a good indicator of bat presence. Small pellets on walls may indicate night roosting or infrequent daytime use, but larger piles of guano on the ground were good indicators of current and past bat roosting. If guano is present but bats are not, repeated visits may be needed to determine extent and timing of bat use.

The sizes of expansion joints or other cracks that could be used by bats were not measured. Keeley and Tuttle (1999) found that crevices 0.5 – 1.25 inches wide were used by roosting bats. Smaller cracks in our study tended to be free of bats, but there is probably a minimum crack size per bat species needed for roosting.

Surveys were conducted during the day on parts of the bridge that were accessible by humans without boats, rappelling gear, or construction equipment such as cherry pickers or snooper trucks. Therefore, for most bridges, only part of the total area available for roosting bats was surveyed. Keeley and Tuttle (1999) found that most species of bats roosted 10 ft or more off the ground and not over busy roadways. In addition, research indicates that bats often select roosting sites near the ends of bridges, particularly close to abutments. This behavior has been documented in studies such as those of Ferrara and Leberg (2005) and Geluso and Mink (2009), which found that bats tend to roost near the ends of bridges longitudinally, near the abutments. Therefore, surveying the end areas of the bridge is likely to be sufficient for detecting the majority of bats. Detecting bats during evening emergence, however, does effectively “survey” the whole bridge.

Although not definitive, watching bat behavior on the thermal camera is more likely to provide more information about whether the bat was emerging from the bridge (i.e., seeing a bat drop down out of the bridge) rather than flying straight through. There were thermal cameras set on either side of the bridges to record simultaneously, but it was outside the scope of this project to document which camera recorded first and whether the second camera picked up the same bat. However, future work with thermal cameras could help determine whether a bat was passing through, i.e., a bat was detected on one camera and then the other, or whether a bat was dropping out of the bridge and exiting one side. In bridges with hundreds of bats, this detection method may be more complicated, but in that case, it would be obvious that bats were using the bridge without the aid of thermal cameras.

The bridges surveyed during this study were relatively small and could be surveyed by two people. There are much longer bridges that could not be completely surveyed by a two-person team on either end of the bridge, even with thermal cameras. In this case, it could be possible to record bat emergence from a drone housing a thermal camera. This method has been tested on smaller bridges and works well to survey bats emerging from both sides of the bridge (pers. obs. with E. Black, Canebrake Consulting). The drone is not loud enough to interfere with bat activity, and it covers large expanses of the bridge. In addition to documenting bat use of bridges, recordings can be viewed later to determine whether bats are emerging from the bridge or if they are passing by it, similar to viewing thermal camera footage taken from the ground.

Benefits of Bridges

Bridges provide a unique opportunity for roosting bats in that bridges absorb and retain significant amounts of heat (see thermal image of bridge in Appendix C). Because bats are heterothermic, this external heat source allows bats to reduce their metabolic rate by passively warming while in the roost. This could be particularly useful for bats migrating in the spring and fall when the air temperature is cooler but solar radiation warms the bridge. In addition to the thermal properties, bridges are also not ephemeral like tree roosts. A disadvantage of bridges may be human impact, either from traffic or human activity under the bridge, especially since bats tend to roost on the ends of bridges where they could be more susceptible to predation and human conflict.

Bats roosting in bridges can be considered problematic for bridge maintenance, but overall, having bats in bridges can be beneficial to humans. The Congress Avenue bridge in Austin famously houses 1.5 million Mexican free-tailed bats, and the city has adopted them as a major tourist attraction. Another benefit of having bats roost in bridges, particularly insectivorous bats, is encouraging bat populations to inhabit an area for pest control (Keeley and Tuttle 1999, Boyles et al. 2011).

Notes on Other Guidance Documents

These five documents provide guidance on how to survey for bats in transportation structures:

- Keeley and Tuttle (1999) – Bats in American Bridges
- H. T. Harvey & Associates and HDR Inc. (2021) – Caltrans Bat Mitigation: A guide to developing feasible and effective solutions
- North Carolina Department of Transportation (2024) – Standard Operating Procedures (SOP), NCDOT Preliminary Bat Habitat Assessments (Structures, Caves & Mines)
- Schuhmann et al. (2024) – Assessing bridges, culverts, and tunnels for bat presence and use
- USFWS (2024) – Appendix K: Assessing & Surveying Bridges & Culverts for Bat Use *in* Range-wide Indiana bat & northern long-eared bat survey guidelines

The first step in all of the documents was a visual review of the bridge that included looking for roosting bats, staining, and guano. Steps 2 – 4 varied by document; however, all of them included some version of using acoustic detectors or conducting emergence counts. All of the documents that suggested using acoustic detectors provided the caveat that it should be done with caution and by experts with the understanding that detecting bats acoustically does not guarantee those bats were roosting in that bridge. In the Caltrans document, it was suggested that bridges be visited multiple times to fully describe site use by bats.

In Appendix K of the USFWS guidance, it would be helpful to add a thermal camera to the list of beneficial equipment for detecting bats in bridges. Although an expensive piece of equipment, it can be invaluable, especially during emergence counts. Another suggested change to Appendix K is in reference to when emergence surveys should be conducted. Currently the document reads: "Emergence surveys may be used as a supplementary tool to determine use of a structure and *can only be used once [Indiana bat] and/or [northern long-eared bat] colony presence has been confirmed*" (emphasis added). The top model in this analysis was emergence surveys with acoustic detectors, and in some cases, emergence surveys were the only method of determining whether or not bats were roosting in bridges. This method cannot provide information about the species composition of the bats in the bridge, but it will undoubtedly determine whether bats are roosting in the bridge, especially if recorded with at least one thermal camera.

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Appendix A: Survey123 Forms Used to Collect Data

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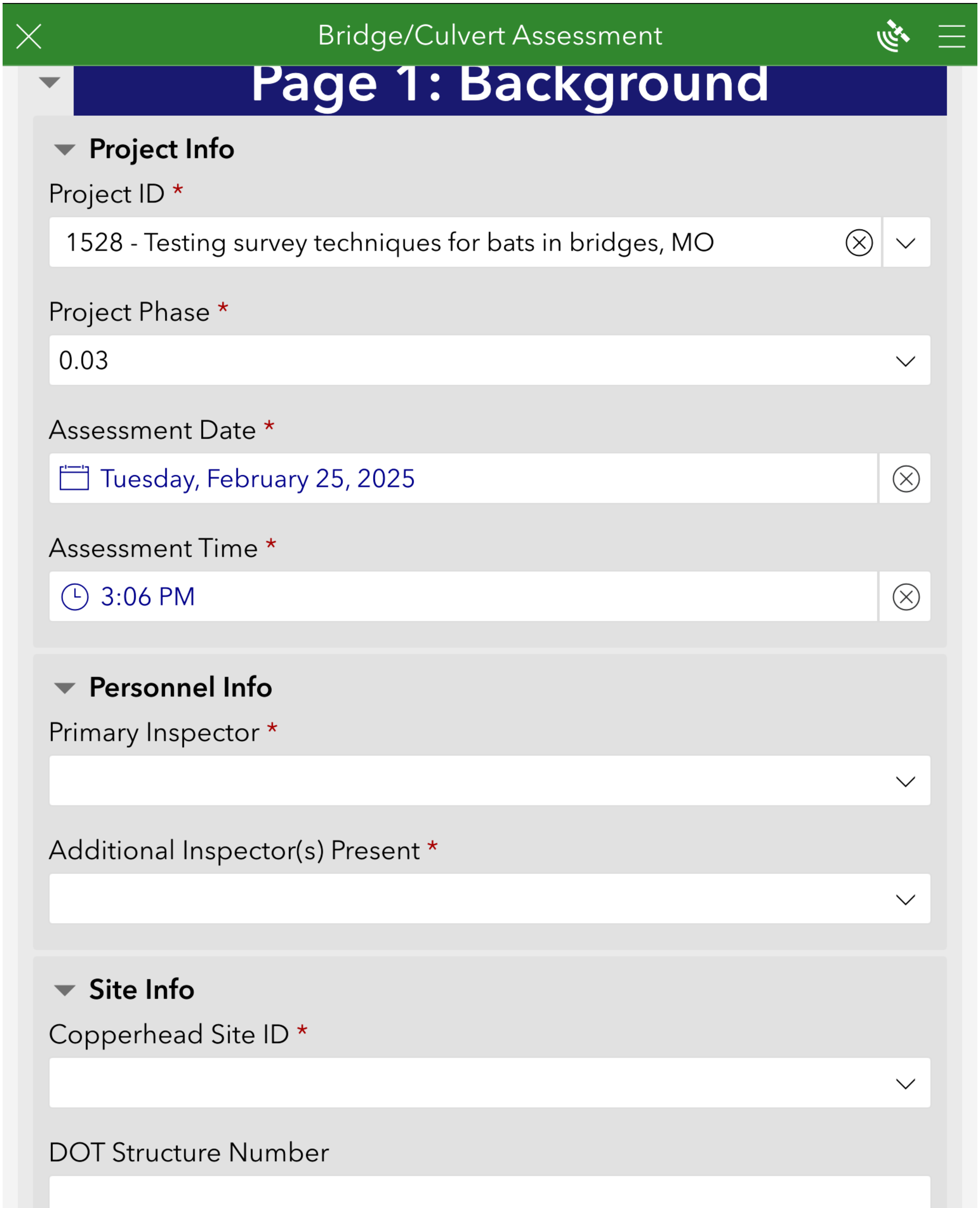


Bridge/Culvert Assessment

Page 1: Background

Project Info

Project ID *

1528 - Testing survey techniques for bats in bridges, MO

Project Phase *

0.03

Assessment Date *

Tuesday, February 25, 2025

Assessment Time *

3:06 PM

Personnel Info

Primary Inspector *

Additional Inspector(s) Present *

Site Info

Copperhead Site ID *

DOT Structure Number

Bridge/Culvert Assessment

State *

County *

Read-only until State is selected

Bridge Road *

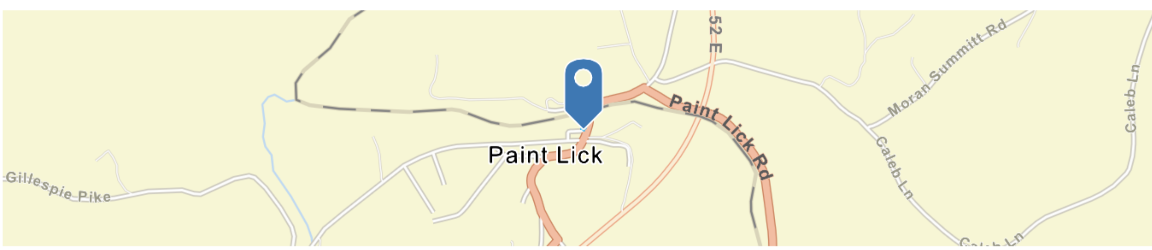
(Name of Road/Facility carried)

Crossing *

(Name of Feature/Stream intersected)

Location *

37.617°N 84.408°W ± 12.3 m, 250.2 ± 19.1 m



Site X Coordinate (read only)

To manually enter or correct GPS, use the geopoint ribbon above

-84.408249

Site Y Coordinate (read only)

To manually enter or correct GPS, use the geopoint ribbon above

37.617436

Bridge/Culvert Assessment

Page 2: Structure Information

Bridge Type *

- Parallel Box Beam
- Pre-stressed Girder
- Cast in Place
- Steel I-beam
- Flat Slab/Box
- Trapezoidal Box
- Culvert - Box
- Culvert - Pipe/Round
- Timber
- Other

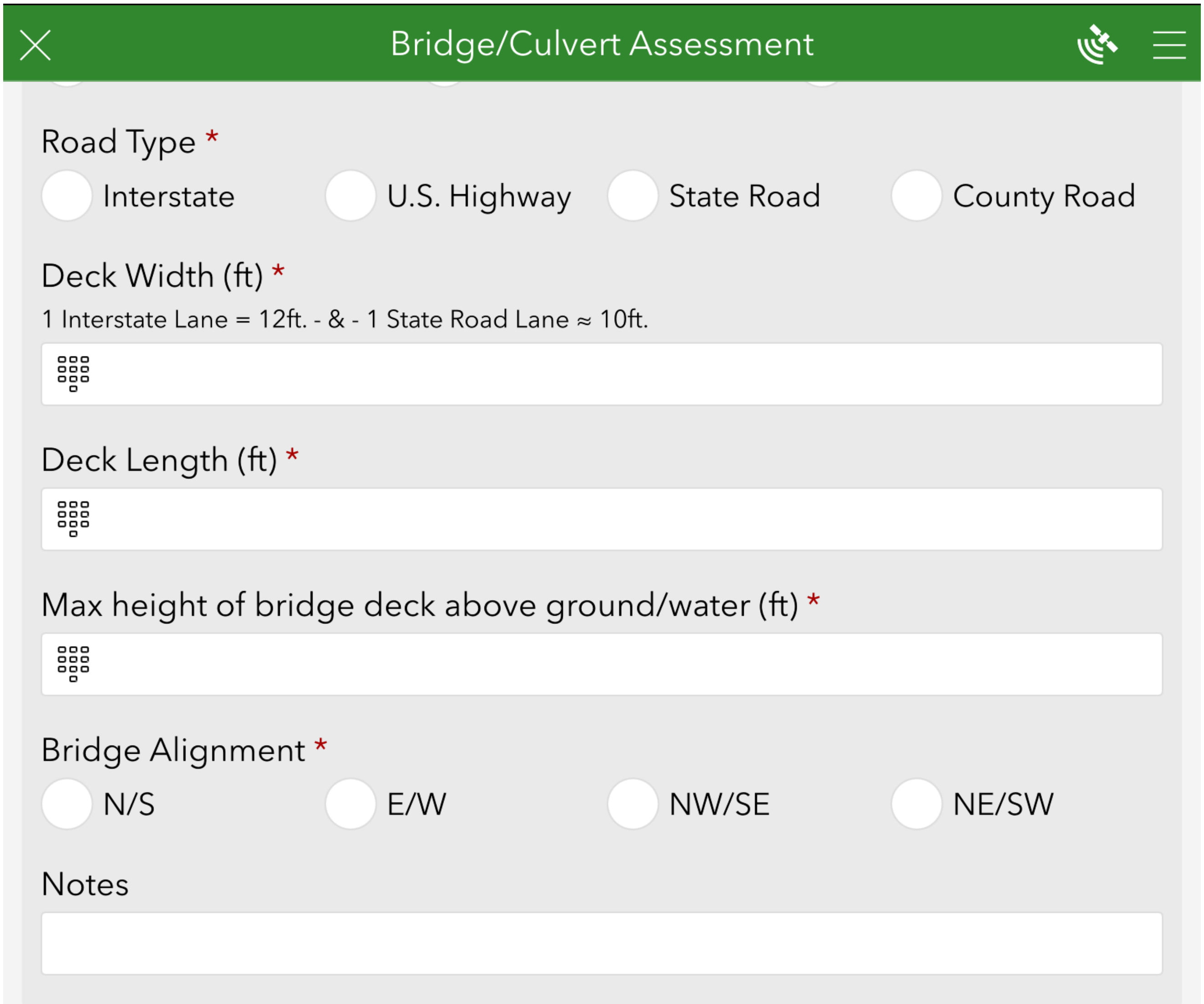
Underdeck Material *

End/Back Wall Type *

Sustainable Roosting Crevices *

(0.5" to 1.25" wide)

Yes No Unknown


Bridge/Culvert Assessment

Road Type *

Interstate
U.S. Highway
State Road
County Road

Deck Width (ft) *

1 Interstate Lane = 12ft. - & - 1 State Road Lane ≈ 10ft.

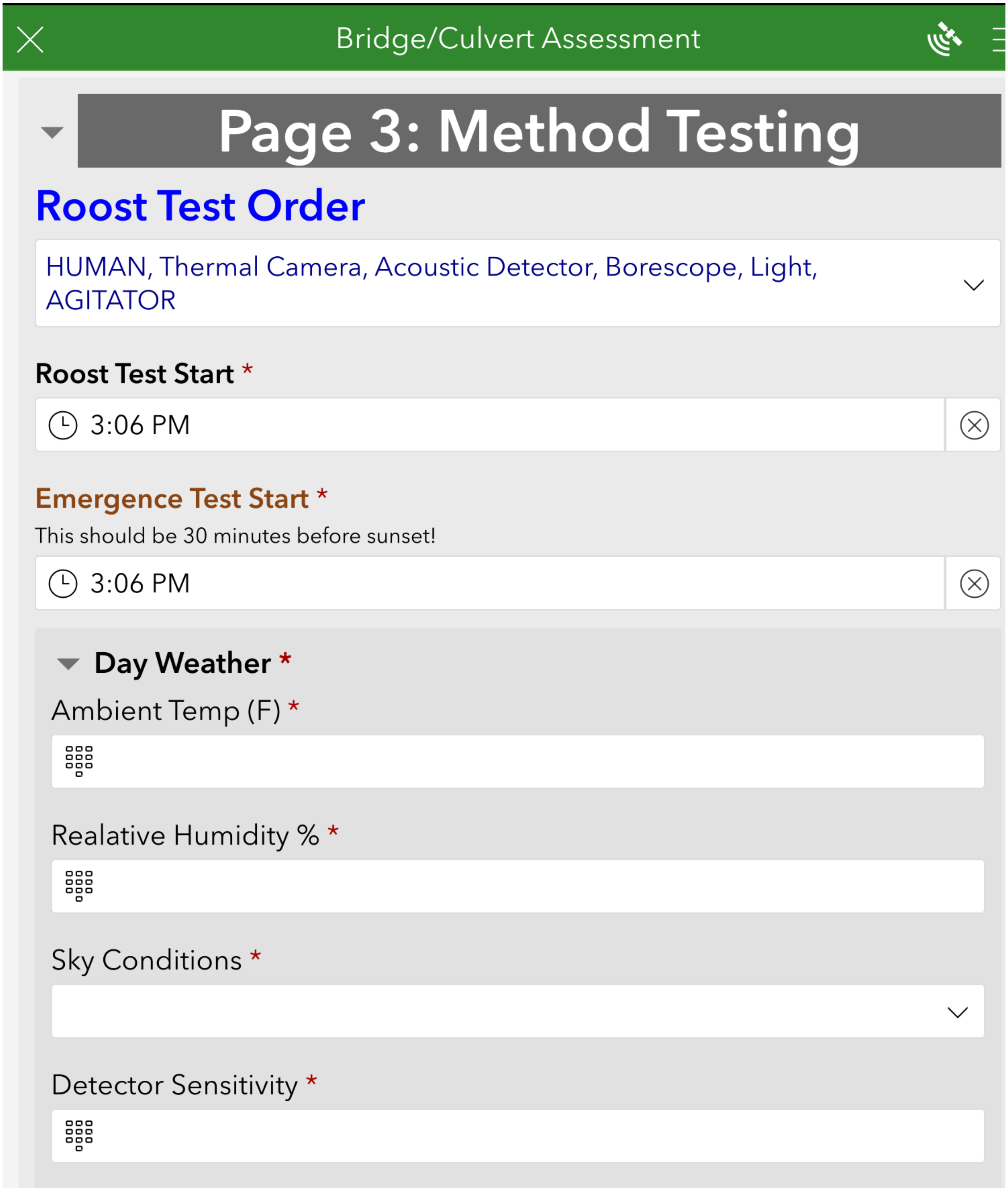
Deck Length (ft) *

Max height of bridge deck above ground/water (ft) *

Bridge Alignment *

N/S
E/W
NW/SE
NE/SW

Notes


Bridge/Culvert Assessment

Page 3: Method Testing

Roost Test Order

HUMAN, Thermal Camera, Acoustic Detector, Borescope, Light, AGITATOR

Roost Test Start *

3:06 PM

Emergence Test Start *

This should be 30 minutes before sunset!

3:06 PM

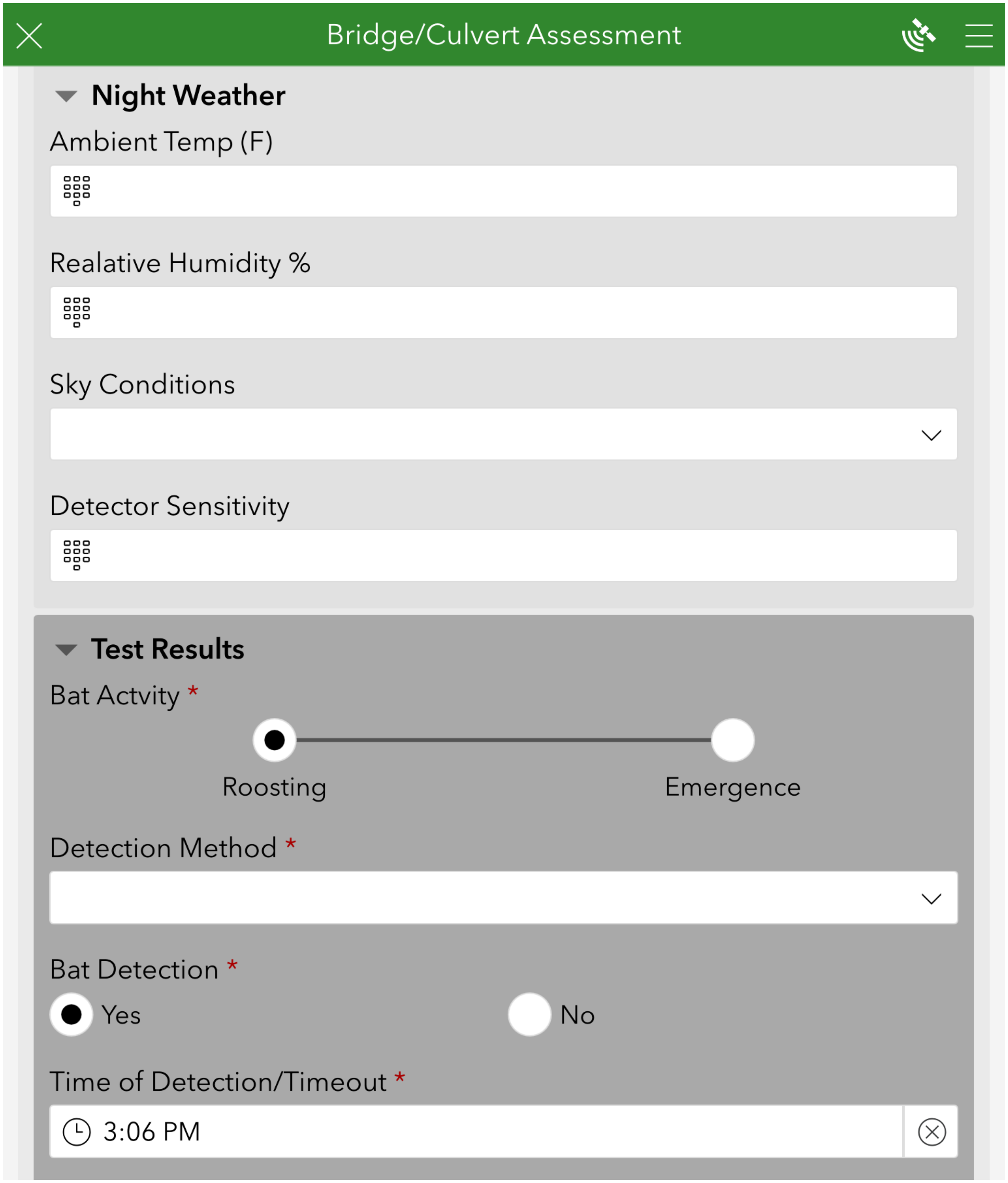
Day Weather *

Ambient Temp (F) *

Realative Humidity % *

Sky Conditions *

Detector Sensitivity *


Bridge/Culvert Assessment

Night Weather

Ambient Temp (F)

Realative Humidity %

Sky Conditions

Detector Sensitivity

Test Results

Bat Actvity *

Roosting

Emergence

Detection Method *

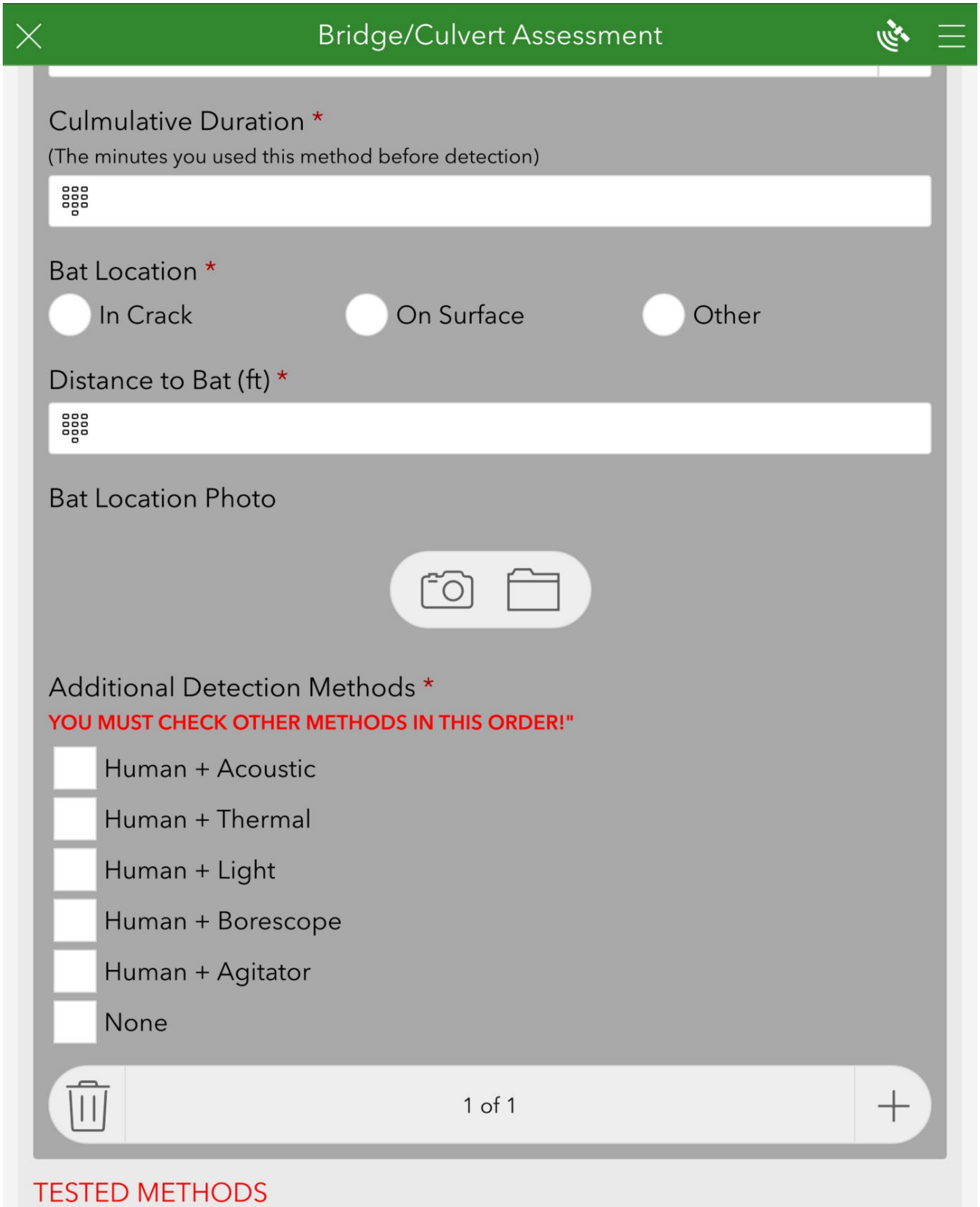
Bat Detection *

Yes

No

Time of Detection/Timeout *

3:06 PM


Bridge/Culvert Assessment

Culmulative Duration *
(The minutes you used this method before detection)

Bat Location *
In Crack
On Surface
Other

Distance to Bat (ft) *

Bat Location Photo

Additional Detection Methods *
YOU MUST CHECK OTHER METHODS IN THIS ORDER!"

- Human + Acoustic
- Human + Thermal
- Human + Light
- Human + Borescope
- Human + Agitator
- None

1 of 1

TESTED METHODS

Appendix B: Photo Log of Bridges

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View from top of bridge

View from under bridge

View from top of bridge

View from under bridge

View of height of bridge from water

View from top of bridge

View from under bridge

View of height of bridge from water

View from top of bridge

View from under bridge

View of height of bridge from water

	Testing Survey Methods for Detecting Bats Roosting in Bridges	
Site Number (County, State): **5 (Owen, Kentucky)**	**MoDOT project Number:** **TR202420**	**Photograph Log Page Number:** **40**

View from top of bridge

View from under bridge – dirt and open

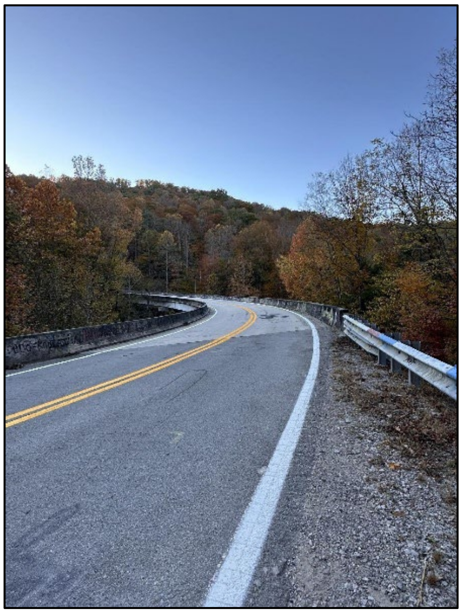
View from under bridge – rocks and vegetation

COPPERHEAD ENVIRONMENTAL CONSULTING	**Testing Survey Methods for Detecting Bats Roosting in Bridges**	
Site Number (County, State): 6 (Madison, Kentucky)	**MoDOT project Number: TR202420**	**Photograph Log Page Number: 41**

View from top of bridge

View from under bridge

COPPERHEAD ENVIRONMENTAL CONSULTING	**Testing Survey Methods for Detecting Bats Roosting in Bridges**	
Site Number (County, State): 7 (Fentress, Tennessee)	**MoDOT project Number: TR202420**	**Photograph Log Page Number: 42**



View from top of bridge

View from under bridge

COPPERHEAD ENVIRONMENTAL CONSULTING	**Testing Survey Methods for Detecting Bats Roosting in Bridges**

Site Number (County, State): 8 (Humphreys, Tennessee)	**MoDOT project Number: TR202420**	**Photograph Log Page Number: 43**

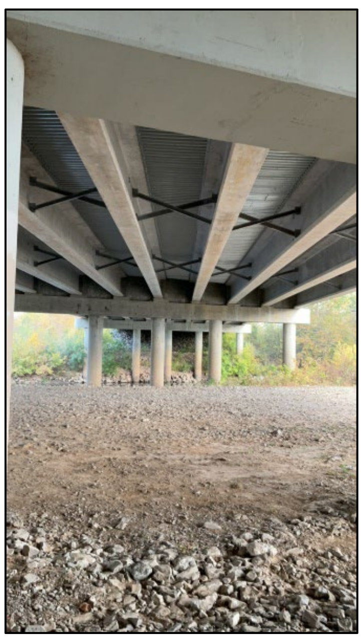
View from top of bridge

View from under bridge

COPPERHEAD ENVIRONMENTAL CONSULTING	**Testing Survey Methods for Detecting Bats Roosting in Bridges**	
Site Number (County, State): 9 (Giles, Tennessee)	**MoDOT project Number: TR202420**	**Photograph Log Page Number: 44**

View from top of bridge

Guano pile



View from under bridge

COPPERHEAD ENVIRONMENTAL CONSULTING	**Testing Survey Methods for Detecting Bats Roosting in Bridges**	
Site Number (County, State): 10 (Franklin, Tennessee)	**MoDOT project Number: TR202420**	**Photograph Log Page Number: 10**

View from top of bridge


Metal beam supporting bridge


View from under bridge

COPPERHEAD ENVIRONMENTAL CONSULTING	**Testing Survey Methods for Detecting Bats Roosting in Bridges**	
Site Number (County, State): 11 (Cocke, Tennessee)	**MoDOT project Number: TR202420**	**Photograph Log Page Number: 11**

View from top of bridge

View from under bridge

COPPERHEAD ENVIRONMENTAL CONSULTING	Testing Survey Methods for Detecting Bats Roosting in Bridges	
Site Number (County, State): 12 (Greene, Tennessee)	**MoDOT project Number: TR202420**	**Photograph Log Page Number: 12**

View from top of bridge

View from under bridge

View of height of bridge from water

Guano Pile

COPPERHEAD ENVIRONMENTAL CONSULTING	Testing Survey Methods for Detecting Bats Roosting in Bridges	
Site Number (County, State): **13 (Unicoi, Tennessee)**	**MoDOT project Number:** **TR202420**	**Photograph Log Page Number:** **13**

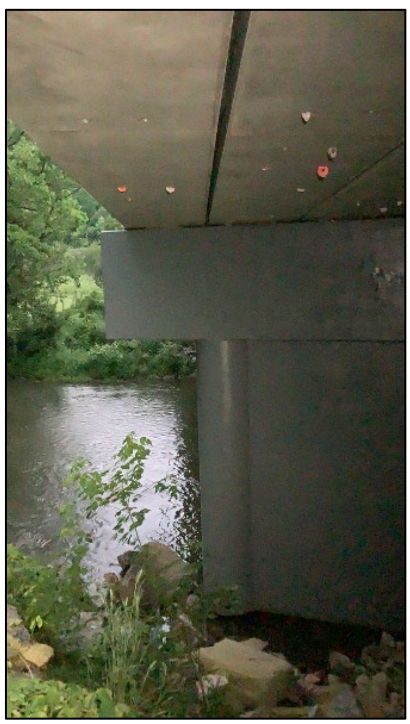
View from top of bridge

View from under bridge

COPPERHEAD ENVIRONMENTAL CONSULTING	**Testing Survey Methods for Detecting Bats Roosting in Bridges**	
Site Number (County, State): 14 (Jessamine, Kentucky)	**MoDOT project Number: TR202420**	**Photograph Log Page Number: 14**

View from top of bridge

View of height of bridge from water



View from under bridge

COPPERHEAD ENVIRONMENTAL CONSULTING	Testing Survey Methods for Detecting Bats Roosting in Bridges	
Site Number (County, State): 15 (Pendleton, Kentucky)	MoDOT project Number: TR202420	Photograph Log Page Number: 15

View from top of bridge

View from under bridge

View from under bridge – person for scale

View from top of bridge

View from under bridge

View from top of bridge

View from under bridge

COPPERHEAD ENVIRONMENTAL CONSULTING	**Testing Survey Methods for Detecting Bats Roosting in Bridges**	
Site Number (County, State): 18 (Ohio, Kentucky)	**MoDOT project Number: TR202420**	**Photograph Log Page Number: 18**

View from top of bridge

View from under bridge

COPPERHEAD ENVIRONMENTAL CONSULTING	**Testing Survey Methods for Detecting Bats Roosting in Bridges**	
Site Number (County, State): 19 (Pulaski, Kentucky)	**MoDOT project Number: TR202420**	**Photograph Log Page Number: 154**

View from top of bridge

View from under bridge

View of height of bridge from water

Guano pile

COPPERHEAD ENVIRONMENTAL CONSULTING	**Testing Survey Methods for Detecting Bats Roosting in Bridges**	
Site Number (County, State): 20 (Pulaski, Kentucky)	**MoDOT project Number: TR202420**	**Photograph Log Page Number: 20**


View from top of bridge


View of height of bridge from water


View from under bridge

Appendix C: Photo Log of Miscellaneous Observations

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Under decking crevice with a big brown bat at Site 2.

Under decking crevice with little brown bats at Site 2.

Thermal camera view at Site 3.
White = hot, black = cold

Guano piles under bridge at Site 8.

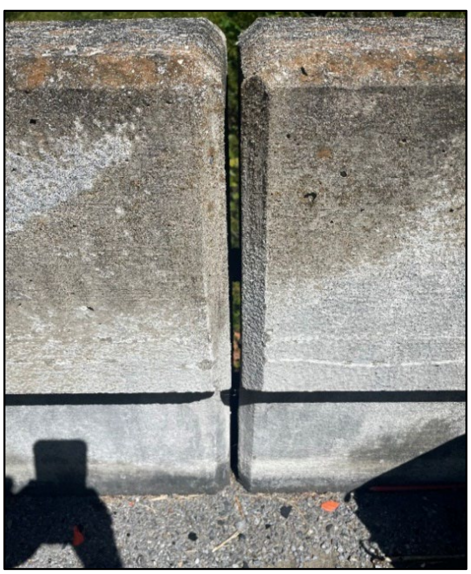
Unknown bat species in crevice at Site 8.

Mexican free-tailed bats and big brown bats in a crevice at Site 10.

Guano piles under bridge at Site 11.

Banded little brown bats in crevice at Site 11.

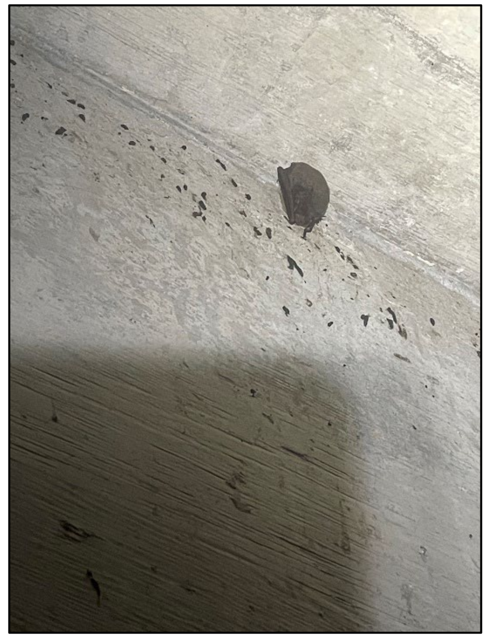
Guano piles under bridge at Site 12.



Big brown bat in upper decking of bridge at site 13.

Small-footed bat in upper decking of bridge at site 13.

Flood line under Site 20 bridge on 10/1/2024.



Gray bat under bridge decking at Site 20.