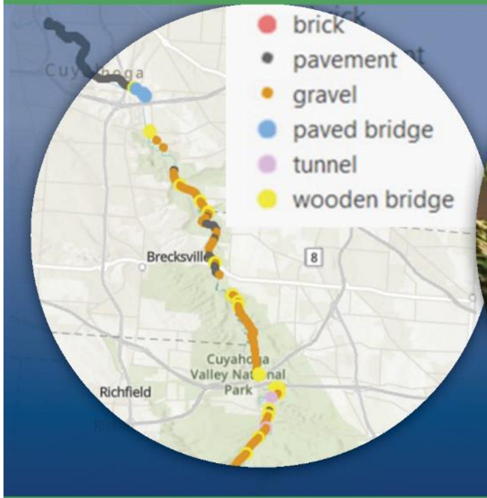
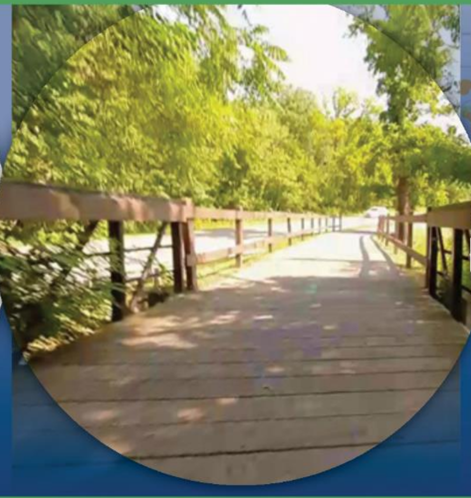
TRAILBLAZER:
A Data-Driven Trail Condition Assessment Methodology





a report by the
Western Transportation Institute
Montana State University

prepared for the
National Park Service
Transportation Branch
1849 C Street Washington, DC

February, 2023

NATIONAL PARK SERVICE

U.S. Department of Transportation
Federal Highway Administration

PUBLIC LANDS TRANSPORTATION FELLOWS PROGRAM

MONTANA STATE UNIVERSITY
Western Transportation Institute

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March 15, 2023

DISCLAIMER

ACKNOWLEDGEMENTS

The authors would like to thank the following individuals and organizations for their contributions to and support of this research.

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Summit County Metroparks
Ohio and Erie Canalways

Federal Highway Administration Innovation and Research Council (FHWA IRC)
Smart Delta
ElectriCity Bikes of Washington, DC

Abbreviations and Acronyms

ATP	Alternative Transportation Program
CHOH	Chesapeake and Ohio Canal National Historical Park
CUVA	Cuyahoga Valley National Park
DCV	Data Collection Vehicle
FHWA	Federal Highway Administration
FLMAs	Federal Land Management Agencies
GWMP	George Washington Memorial Parkway
IRC	Federal Highway Administration Innovation and Research Council
MRR	Manually Rated Route
MSU	Montana State University
NPS	National Park Service
PLTF	Public Lands Transportation Fellowship
RIP	Road Inventory Program
WASO	National Park Service Washington Area Support Office
WTI	Western Transportation Institute

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EXECUTIVE SUMMARY

The Trailblazer Research Project piloted an innovative, data-driven trail condition assessment methodology for the National Park Service (NPS), that uses electric bikes (ebikes) equipped with a camera and sensor system to efficiently collect photographic, accelerometer and annotative data on multi-use trails. Figure A shows the Trailblazer ebikes with critical project materials.

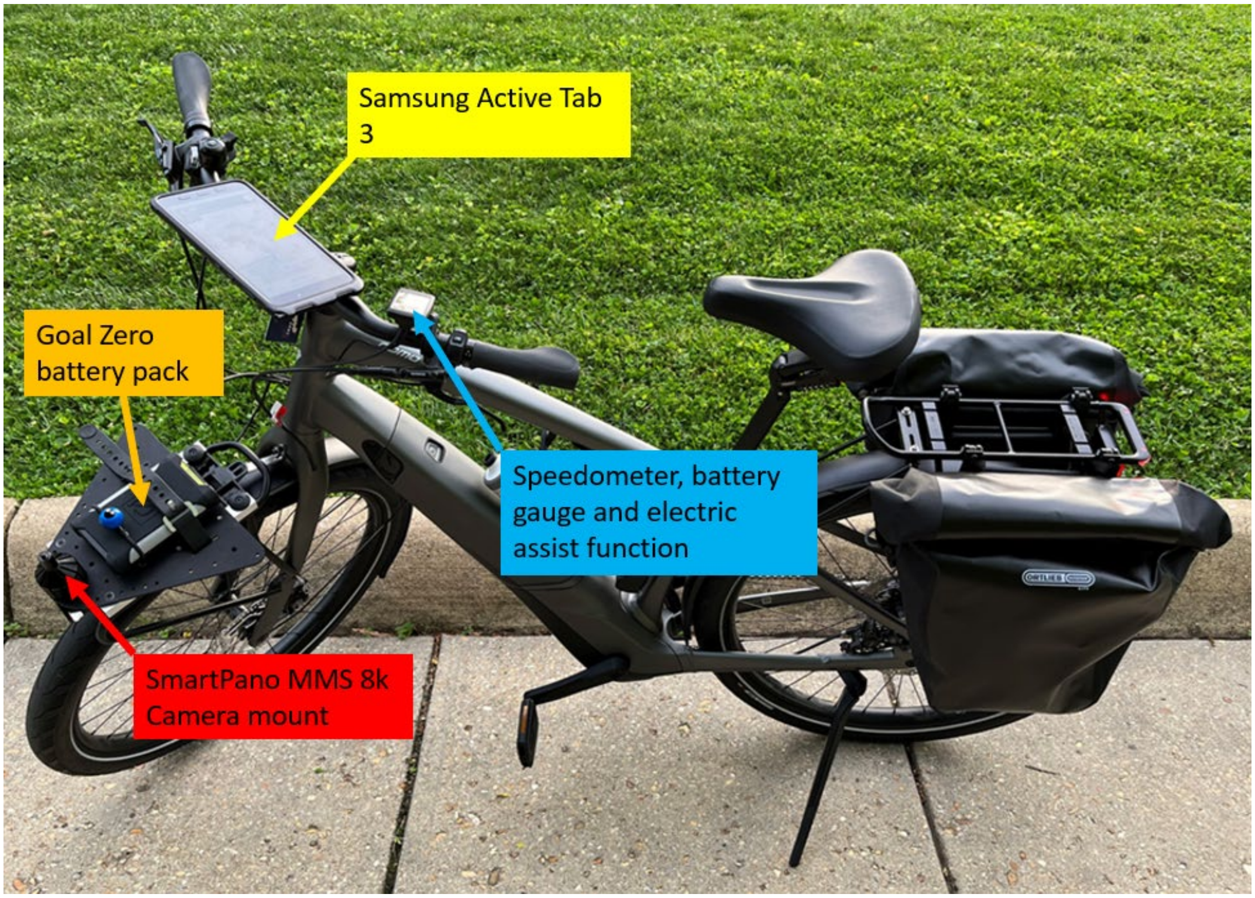


Figure A: Trailblazer ebike with critical project materials.

The Trailblazer Project Team collected data on a total of 234 miles of NPS transportation trails and partner-administered trails across 3 National Park areas: Chesapeake and Ohio Canal National Historical Park (CHOH), Cuyahoga Valley National Park (CUVA), and George Washington Memorial Parkways (GWMP).

Figure B: Example of photos taken of trails during data collection.

These data were used to create geodatabases in geographic information systems (GIS) that can be interpreted by NPS staff and administration to inform trail management priorities and decisions. Figures C and D display examples of the maps produced by the project team.

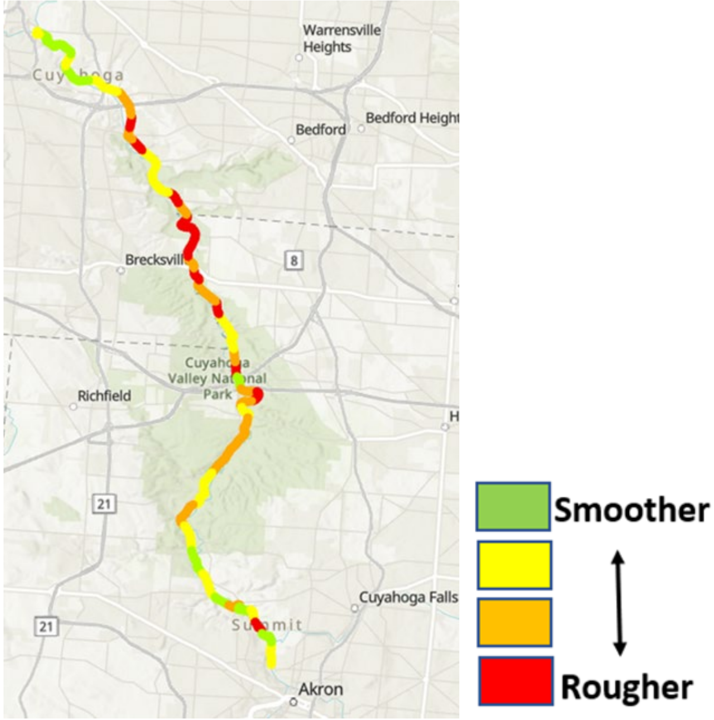


Figure C: Example of trail 'roughness' data averaged by half mile at CUVA.

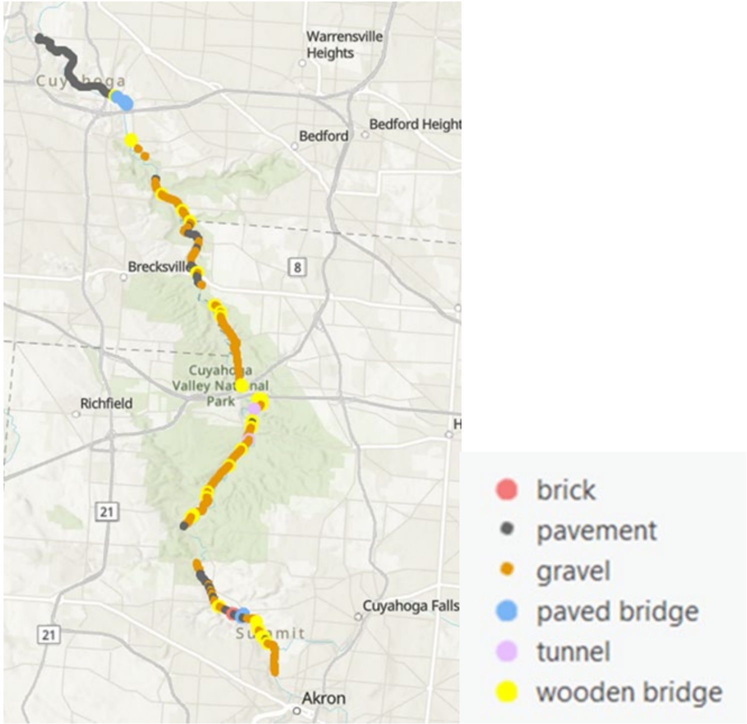


Figure D: Example of trail surface material mapped at CUVA.

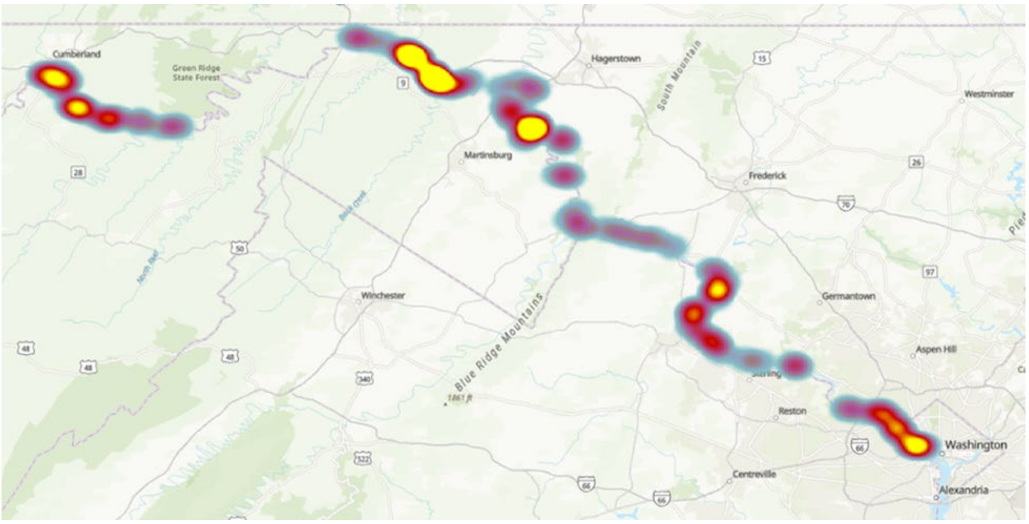


Figure E: Example of vegetation overgrowth heatmap at CHOH.

At a high level, trailblazer roughness data identifies the roughest and smoothest sections of trail, which can inform trail maintenance and rehabilitation priority areas. This information may also be used as a condition baseline, which can then be compared to subsequent Trailblazer assessments to track changes in trail condition over time. Mapping the surface material of the trail is also extremely useful when scoping trail maintenance or rehabilitation projects.

At a more granular level, trailblazer data can pinpoint specific damage such as potholes, cracks, rutting, etc. in a trail using photographic and annotative data. Furthermore, annotative and photographic data may be used to inventory specific trail features such as bridges, street crossings, mileposts and vegetation overgrowth, which was demonstrated by the project team over the pilot research period. This same custom annotation feature could be used in the future to inventory other trail features such as signage, access points, water resources and bathrooms, benches, etc.

The Trailblazer system could be scaled up to assess trail networks at a national level, as well as serve an array of other future uses. Ebikes outfitted with sensors and cameras may be able to collect data on user patterns and trends that inform planning decisions regarding connectivity and community development (Rico, A., Sakai, Y., & Larson, K., 2020), as well as to produce ‘virtual experiences’ of trails, roads, etc. The Trailblazer methodology could also be used to assess infrastructure damage after natural disasters and stream real-time 360-degree photographic or video data to multiple remote locations, such as emergency response units. Additionally, future Trailblazer projects could employ LiDAR sensors to improve data granularity and facilitate “virtual site visits” by project engineers. LiDAR use could also be expanded to create 3D maps of trail environments, which could be further fleshed out using photogrammetry. Finally, future advances in Artificial Intelligence algorithms may be able to examine large data files and identify useful patterns. This would allow analysts to label patterns, such as bridge locations, without the need for in-person annotations, and isolate them during analysis.

1. INTRODUCTION

The National Park Service (NPS) recognizes the critical importance transportation trails play in the NPS transportation network and in connecting with trails outside NPS boundaries. Transportation trails provide park access alternatives to driving, facilitate connectivity between parks and surrounding communities, and in some cases provide critical commuter services. The NPS's definition of a transportation trail is as follows:

Accommodates pedestrians and/or bicycles and connects to a larger transportation system including land and water-based transit and/or regional trail systems or direct connections to a community. A transportation trail provides functional access to a destination via non-motorized modes, AND provides an alternative to motorized transportation, enabling people to switch from motorized to non-motorized modes. (Volpe Center, 2022)

As such, trails that meet the definition of a transportation trail need to be managed at a higher performance and maintenance standard than other recreational trails.

1.1. Project Purpose

The NPS Trailblazer Research Project piloted the use of electric bikes (ebikes) equipped with a camera and accelerometer, and an annotative platform to collect data on transportation trails. Key questions this research sought to understand were:

1. Can ebikes be used to efficiently and cost-effectively collect trail condition data that NPS and other entities may use for analysis?
2. Can a detailed and replicable trail condition assessment methodology for multi-use (transportation) trails be produced using trailblazer data?
3. Can data collected using ebikes be used to inform NPS asset-specific management decisions?

1.2. Project Background

A total of 1,065 miles of NPS transportation trails have been inventoried as of August 2022 (Volpe Center, 2022). Figure 1 shows the transportation trail mileage by NPS region. The National Capital region contains 290 miles of NPS transportation trails, followed by the Southeast Region with 253 and the Northeast region with 161 miles.

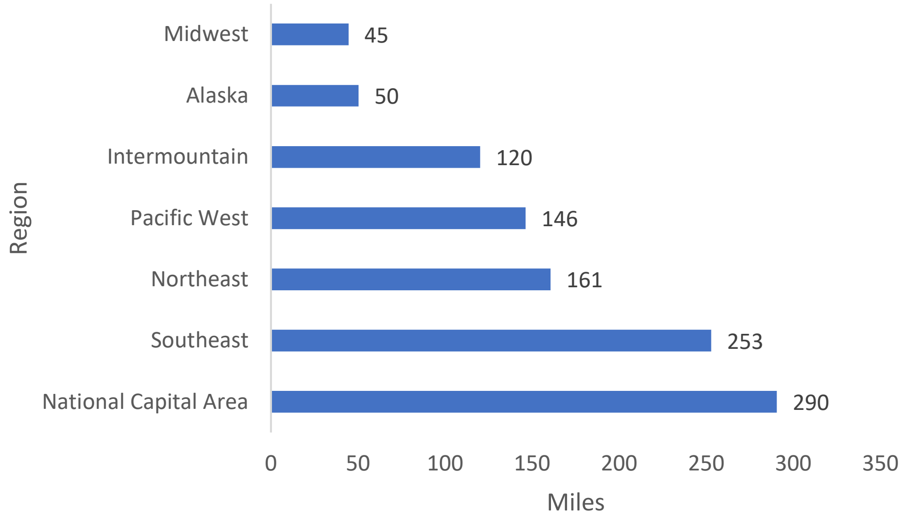
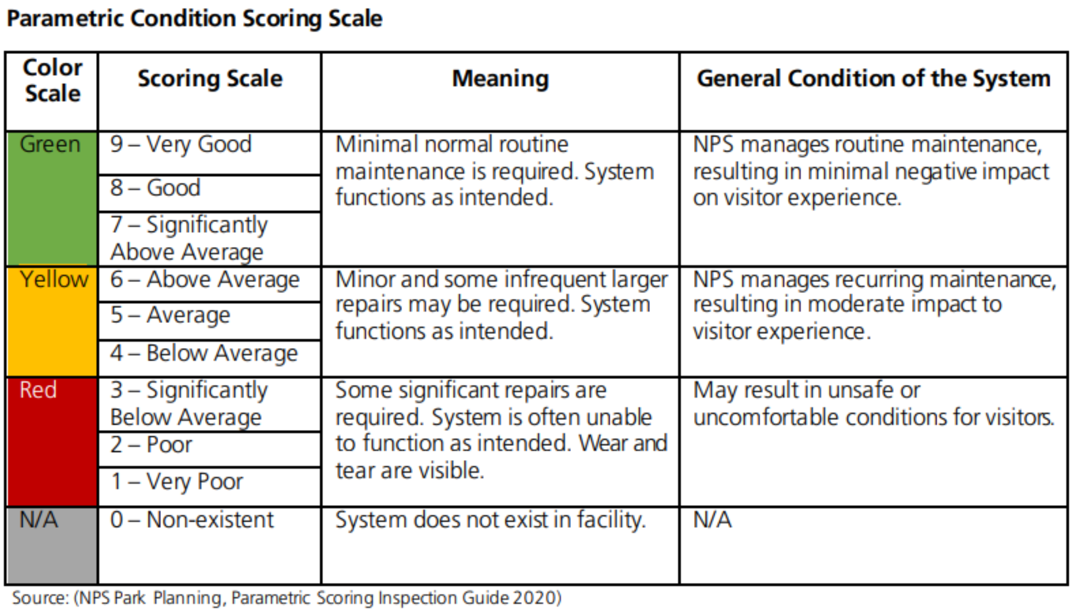


Figure 1: NPS transportation trail miles by NPS region (Volpe Center, 2022)

The NPS currently uses a parametric assessment to evaluate the condition of its transportation trails. This assessment is a rapid visual survey for developing portfolio-level estimates of deferred maintenance costs. The premise of the parametric approach is that mathematical models can create cost estimates using a small number of simple inputs that are easy to obtain. These assessments are generally conducted by NPS facilities staff using the Parametric Scoring Tool, which asks the user to assign a score for each of the "constituent systems" within the overall asset. The NPS Parametric Condition Scoring Scale, shown in Figure 2, ranges from 1 to 9, where 1 indicates very poor condition (significant repairs required) to 9, meaning very good condition (minimum routine maintenance required) (Volpe Center, 2022). Constituent systems for trails include:

- Plants, Vegetation and Trees – any vegetation along a trail that must be cleared to maintain the trail corridor or construct the trail.
- Surface, Base and Subbase – native or imported material that makes up the trail tread and supporting structure. Includes native material, gravel, pavement, and boardwalks.
- Structures – all constructed features of the trail used to preserve the trail foundation or surface; associated facilities, including walls, water bars, steps, causeways, and other structures integral to the trail.
- Site Features – features that are not integral to the trail but support its appearance and use, including signs, railings, fences, benches, tables, and other similar structures.



Parametric Condition Scoring Scale

Color Scale	Scoring Scale	Meaning	General Condition of the System
🟩 Green	9 – Very Good	Minimal normal routine maintenance is required. System functions as intended.	NPS manages routine maintenance, resulting in minimal negative impact on visitor experience.
	8 – Good		
	7 – Significantly Above Average		
🟨 Yellow	6 – Above Average	Minor and some infrequent larger repairs may be required. System functions as intended.	NPS manages recurring maintenance, resulting in moderate impact to visitor experience.
	5 – Average		
	4 – Below Average		
🟥 Red	3 – Significantly Below Average	Some significant repairs are required. System is often unable to function as intended. Wear and tear are visible.	May result in unsafe or uncomfortable conditions for visitors.
	2 – Poor		
	1 – Very Poor		
N/A	0 – Non-existent	System does not exist in facility.	N/A

Source: (NPS Park Planning, Parametric Scoring Inspection Guide 2020)

Figure 2: NPS Parametric Condition Scoring Scale.

In 2020, the NPS adopted the parametric approach as the standard method for estimating maintenance needs for trails. As previously stated, the simplicity of the parametric system for the field user is key to its practicality. However, there is interest in a more detailed assessment for transportation trails in addition to the parametric approach (Volpe Center, 2022). A more detailed, data-driven assessment would help asset managers form a more complete understanding of the condition of their trails, better prioritize maintenance, and track trail condition improvement over time. Based on the need for a higher standard of transportation trail condition data, identified in the ￼Transportation Trails report￼, the NPS Alternative Transportation Program (ATP) submitted a proposal to the Federal Highway Administration's (FHWA) Innovation Research Council (IRC). ATP received funding to pilot this more detailed, data-driven transportation trail condition assessment methodology.

2. METHODOLOGY

After conducting a literature review of related research, outlined in the Literature Review section, the project team created an ebike-based system that collects accelerometer, photographic, and annotative data on multi-use trails. This report will refer to this system as the Trailblazer system or the Trailblazer methodology, which was piloted on 223 miles of NPS transportation trails and 11 miles of NPS partner-administered multi-use trails.

The data collected on each trail was used to produce a geodatabase in ArcGIS, which was shared with NPS staff for the purpose of informing trail management decisions. The Trailblazer methodology provides data for trail managers to utilize but does not make specific trail maintenance recommendations. For more detailed information on accelerometer, photographic and annotative data, as well as analysis of the NPS transportation trails assessed, please see the Analysis section of this report.

This section outlines the materials selected to outfit the Trailblazer ebikes for trail condition assessments, a list of annotations developed to document various trail features, such as trail surface changes and overgrown vegetation, and the project team's trail selection process. For a checklist of project materials, information on Trailblazer system assembly, and details on conducting data collections, please see Appendix A of this report.

2.1. Materials Selection

This section describes considerations for selecting and procuring ebikes, sensors, and other materials needed for this research.

2.1.1. Ebike Selection

Initially, the project team considered whether to use ebikes or manual bikes (here referred to as "bikes"). Bikes have some advantages over ebikes: they are cheaper, do not require electric charging, and are widely available. However, the team also recognized drawbacks to bikes, including the high physical requirements for riding them, the inconsistencies in speed and movement caused by terrain, weather, and exhaustion, and the impacts of heavy gear on their rideability. Each of these factors would have harmed the consistency of the data, defeating the purpose of the study.

The project team selected ebikes for this study due to their ability to move heavy loads, their leveling of physical differences between riders, and their consistent performance under a wide range of conditions. Ebikes made it possible for a variety of riders to assist with the study, even if they had little experience with long-distance trail riding. The "electric assist" feature reduced the strength and endurance needed to pedal heavy equipment over long distances. Additionally, the bikes were unaffected by obstacles like headwinds and hills that would have slowed conventional bikes down and caused inconsistencies in the distribution of data points along the route. Ebikes made data collection both more accessible and consistent than would have been possible with conventional bikes.

Before purchasing, the team performed market research to identify the best ebike for the job. There are a few key differences between ebikes that have a major impact on their performance. One is the battery, which determines an ebike's range, but also makes up a significant portion of its weight. Other factors included the type of bike, and its cargo-carrying accessories.

The size and capacity of an ebike battery determines ebike's range in miles. To conduct research efficiently, the project team selected an ebike with a large battery that could support between 30 and 60 miles of riding per charge. This range varied due to factors like the hilliness of the terrain, the weight of the ebikes' payloads, and the degree of electric assistance the riders used. Quick-change batteries, rather than built-in batteries, were also selected, so that spare batteries could be procured and swapped in during the field collection process, if necessary.

A consequence of using a larger battery is a heavier ebike. While the riding range of a longer lasting battery is desirable, the added weight makes the ebikes very heavy, which may challenge some riders. However, the additional weight of a longer-range model may also provide a smoother ride, resulting in less "noise" in the accelerometer data. This research required a balance of weight, range, power, and durability.

Another factor which varies between ebikes is the type and quality of the electric assist feature. Ebikes are broken down into three classes by their electric assist feature. On Class 1 ebikes, the rider must pedal to activate the motor, and the motor does not provide assistance at speeds greater than 20 mph. Class 2 ebikes have pedal-assisted motors but can also be powered using a throttle on the handlebars. They are also limited to 20 mph. Class 3 ebikes do not have throttles, but the electric motor can assist riders up to 28 miles per hour. Just as the speeds of the electric assists vary between bikes, they also vary in quality. Generally, higher-quality motors accelerate more smoothly, can maintain more consistent speeds, and are more responsive to varying power requirements due to terrain or wind. Higher-quality motors are also less impacted by heavy loads and regular usage than lower-quality models. It was therefore important to select bikes with a smooth, consistent ride quality. The project team selected a Class 3 ebike for this research.

Because the ride quality of a motor can't be determined just by reading online articles, the project team felt it was important to get a feel for the differences between ebikes. In addition to the electric assist, the team wanted to evaluate the durability and smoothness of the ride offered by various bikes before purchasing. Project team members tested bikes at ElectriCity Bikes, a Washington, D.C. staple bike shop with one of the biggest stocks of ebikes on the east coast. Purchasing from a nearby bike shop enabled the team to modify and service bikes conveniently throughout the project.

Ebikes have a wide range of pricing. They rarely cost less than $1,000 and some models cost over $10,000. The team researched and tested a variety of models, determining that none of the bikes that met the project team's requirements cost less than $3,000. Related research projects in Minnesota and Iowa used ebikes that cost $5,000 or more. More information on these related research projects can be found in the Literature Review section of this report. Based on the considerations discussed above, the Specialized Como 4.0 650b ebike was selected for this research. The Specialized Como 4.0 650b aluminum frame ebike (Figure 3) has 8 traditional gears, 3 levels of electrical assist, and in 2022 the listed base price was $3,750.

Figure 3: Specialized Como 4.0 650b ebike with accessories.

2.1.2. Camera and Sensor System Selection

The types of data needed to conduct the desired analysis on a transportation trail's condition, and the materials procured by the project team to collect this data were:

- GPS – captures location data, used for mapping other collected data.
- Accelerometer – records the acceleration of an object, used to assess the roughness or smoothness of the trail surface.
- Camera – provides photographs and/or video of the trail surface and corridor.
- Annotation capabilities – complements the accelerometer and photographic data by allowing the rider to document features of the trail for subsequent review and analysis.
- Data management software – synchronizes and interpolates various data streams.
- Visualization capabilities – ability to see the data coming in real time during the data collection process.

The project team considered hiring an intern to build an app that synchronizes all data streams for GIS use and visualization. Given the difficulty of finding qualified interns to do this work, the team decided to use a predesigned platform for data synchronization and management. However, many products that collect all the desired data types are designed to be mounted on vehicles and are too large for bikes. Other reasonably sized products that are designed for bikes collect some, but not all the desired data types (i.e., a camera with a GPS, but no accelerometer). Through their research, the team identified the Smart Delta SmartPano MMS 8k camera (Figure 4), which collects all desired data types, synchronizes them, and provides software for real-time streaming, visualization, and post-collection data management. This product also has a built-in Wi-Fi hotspot that allows it to transmit data to a tablet in real-time, which streamlines data management and allows for real-time data visualization.

Figure 4: Smart Delta SmartPano MMS 8k Camera.

2.2. Annotations for Various Trail Features

Researchers used the Smart Delta software to drop an annotated, virtual ‘pin’ at the appropriate location to make note of the following trail conditions or experiences:

- Material Change – surface material changes.
- Bridge – riding over a bridge.
- Vegetation – overgrowth in trail path.
- Congestion – busy area with lots of people on/around trail.

- Dangerous – hazardous or dangerous trail condition/structure.
- Crosswalk – trail crosses street.
- Slow/Stop – the rider deviated from target speed.
- Issue – the rider experienced a technical/operational issue at this location, for consideration when reviewing accelerometer data.
- Mile Post – mile posts' location along trail.

These annotations are customizable and can be adjusted to collect the specific informational requirements of each trail. More information on custom annotations can be found in the Analysis section of this report.

2.3. Trail Selection Process

The trail selection process was based on the following factors:

- Status as an NPS transportation trail.
- Whether the trail allows bicycles.
- Proximity to the Department of the Interior in Washington, D.C.
- Length of the trail (longer trails were preferred because they provided a better environment to test the ebike data collection system functionality with varying conditions).

Considering these criteria, the following 3 trails were selected for piloting this methodology:

- Mount Vernon Trail, George Washington Memorial Parkway (GWMP) – 18 miles.
- Chesapeake and Ohio Canal Towpath Trail, Chesapeake and Ohio Canal National Historical Park (CHOH) – 185 miles.
- Ohio and Erie Canal Towpath Trail, Cuyahoga Valley National Park (CUVA) – 20 miles.

Further details on each of these trails can be found in the Analysis section of this report. It is worth noting that two of the trails selected for this research are former canal towpaths, which run parallel to canals and were traditionally used by draft animals towing canalboats. After these historic canals were decommissioned, the two towpaths were converted into biking and walking trails for recreation. Just as the canals did historically, these towpath trails connect cities and towns across the Eastern United States, and as such, they meet the criteria for an NPS transportation trails.

For a checklist of project materials, information on Trailblazer system assembly and details on conducting data collections, please see Appendix A of this report.

3. LITERATURE REVIEW

This section provides an overview of trail condition assessment methodologies from various organizations.

3.1. Federal Highway Administration – NPS Road Inventory Program (RIP)

The FHWA, NPS Road Inventory Program (NPS RIP) collects condition data for paved surfaces (asphalt, concrete, brick, and cobblestone) on roads, parkways, and parking areas in national parks nationwide. The road surface condition data is collected using an automated Data Collection Vehicle (DCV) and, manually, with Manually Rated Route (MRR) procedures. Roads having brick or cobblestone surfacing are not normally surveyed with the DCV but are manually rated for condition.

The FHWA RIP is based on the premise that an accurate pavement surface condition assessment can be accomplished using automated crack detection technology as applied to digital images. With the use of quality digital photography and automated crack detection software, FHWA RIP is tasked with executing a pavement condition assessment on approximately 5,700 miles of National Park Service roads and parkways.

The FHWA developed a set of manual rating methods for pavement that are appropriate for Federal Roadways. Two different methods were developed for linear roads and a separate method was developed for parking areas and nonlinear roads. These methods employ a 0 to 100 rating scale and improve consistency and objectivity in the manual evaluation of surface distresses. They are compatible with ratings that are collected by the automated Data Collection Vehicle (DCV) (Federal Highway Administration, National Park Service Road Inventory Program Appendix).

3.2. Previous NPS Trail Condition Assessments

Mount Vernon Trail

In 2019 the NPS and the U.S. Department of Transportation Volpe Center performed a corridor study of the Mount Vernon Trail, an NPS paved trail within the George Washington Memorial Parkway (GWMP) unit. The study identified opportunities to improve the trail based on analysis of trail conditions, safety concerns, users' needs, and resource management considerations. The study manually assessed the following pavement quality issues for each 0.25-mile segment of the trail:

- Ruts
- Cracks
- Edge cracking
- Potholes
- Root heaves
- Uneven surface

The study then classified pavement condition for each 0.25-mile segment as “good” or “fair,” as follows:

- Good - nine or fewer pavement quality issues.
- Fair - more than nine pavement quality issues. The summary report also included qualitative descriptions of the above deficiencies in various zones.

The study separately assessed the following issues since they may affect safety and visitor experience:

- Encroachment of dirt, weeds, etc., which limits trail width or blocks sight lines.
- Overhang of branches, vegetation, etc.
- Tidal flooding.
- Damaged facilities (restrooms, benches, signs, water fountains).

The study did not rate the above issues for 0.25-mile segments, but instead marked specific instances of each on a map (Volpe Center, 2022).

Chesapeake and Ohio Canal Towpath Trail

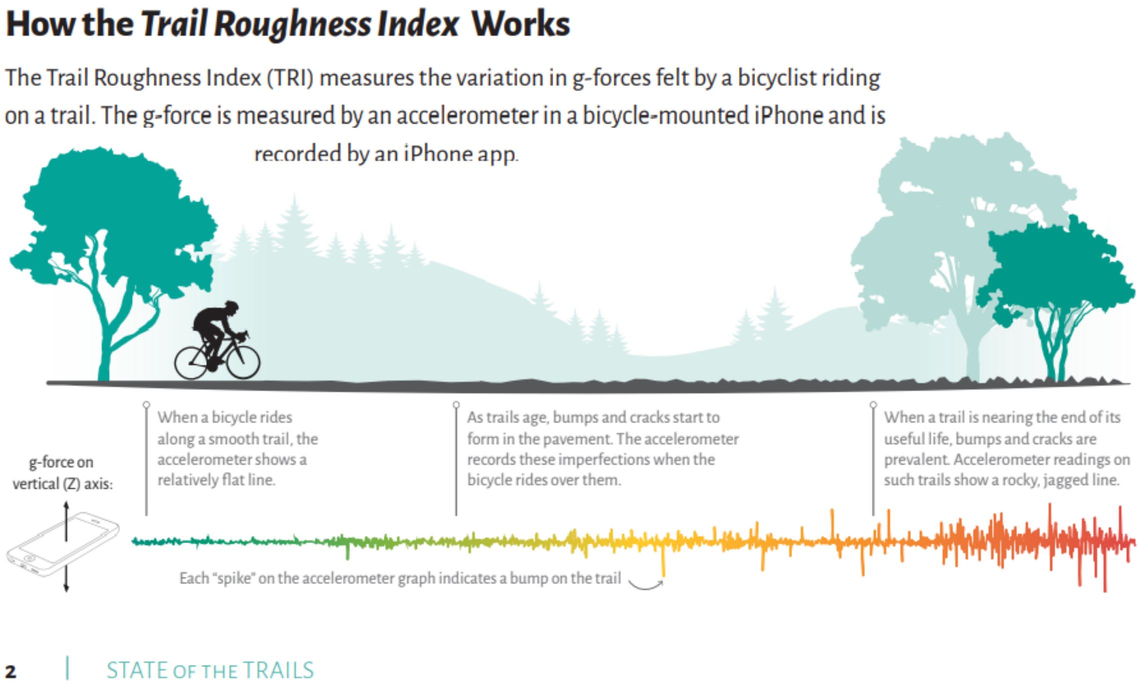
In 2016, the Allegheny Trail Alliance commissioned a safety assessment of the Chesapeake and Ohio Canal Towpath for NPS. Similar to the Mount Vernon Trail assessment, this study manually assessed the trail in 0.25-mile segments. However, given that the towpath is predominantly unpaved, the metrics differed. The study assigned an integer between zero (worst conditions) and three (best conditions) for each 0.25-mile segment in each of eight metrics (Volpe Center, 2022):

- Trail width
- Trail surface
- Mud
- Center grass strip
- Ruts/potholes
- Root encroachment
- Drainage to river side of trail
- Drainage to prism side of trail

3.3. Other Trail Condition Assessment Methodologies and Related Research

The NPS Transportation Trails: Inventory, Assessment Practices, and Program Recommendations Report reviewed a wide variety of trail condition assessment methodologies. One of these methodologies, detailed below, deployed an ebike to collect objective trail condition data.

In 2019, the Parks and Trails Council of Minnesota released its second edition of the State of the Trails Report. This report analyzed data from approximately 600 miles of paved State of Minnesota trails, and tracked changes in condition from a baseline assessment two years prior. The assessment was conducted using one ebike outfitted with multiple cameras and a smartphone that collected location, accelerometer, and photographic data as it moved throughout the trail network. The accelerometer data collected in the study was averaged by the mile, which provided an average condition rating per mile of trail. The camera also recorded a photograph of the trail every two seconds. This project was commended by local stakeholders and has provided a valuable methodology to track changes in system condition over time (Park and Trails Council of Minnesota, 2019). Figure 5, from the Parks and Trails Council of Minnesota's 2019 report on the State of the Trails, provides a visualization of how accelerometer data communicates trail roughness.



How the *Trail Roughness Index* Works

The Trail Roughness Index (TRI) measures the variation in g-forces felt by a bicyclist riding on a trail. The g-force is measured by an accelerometer in a bicycle-mounted iPhone and is recorded by an iPhone app.

When a bicycle rides along a smooth trail, the accelerometer shows a relatively flat line.

As trails age, bumps and cracks start to form in the pavement. The accelerometer records these imperfections when the bicycle rides over them.

When a trail is nearing the end of its useful life, bumps and cracks are prevalent. Accelerometer readings on such trails show a rocky, jagged line.

Each "spike" on the accelerometer graph indicates a bump on the trail

Figure 5: Trail Roughness Index (Parks and Trails Council of Minnesota, 2019).

Beyond the examples reviewed in the NPS Transportation Trails: Inventory, Assessment Practices, and Program Recommendations Report, there have been other successful projects that use ebikes or similar systems to collect trail condition data.

The Des Moines Area Metropolitan Planning Organization, in partnership with the Iowa Department of Public Health and the Iowa Natural Heritage Foundation, developed the Iowa Data Bike to collect trail condition data from roughly 600 miles of trails in the Des Moines Metropolitan Area and beyond. This project had a very similar structure to the Minnesota Parks and Trails project, utilizing an ebike outfitted with a 360-degree camera, a GoPro, and a smartphone logging accelerometer and location data. This project resulted in comprehensive baseline condition data for hundreds of miles of trail that can be replicated to track trail condition change over time and inform a long-term maintenance strategy (Des Moines Area MPO, Iowa Data Bike).

Based on the work conducted by the Des Moines Area MPO and the Parks and Trails Council of Minnesota, the Community Planning Association of Southwest Idaho (COMPASS) developed a Data Bike as well, used to map trail condition on a cyclical basis in the Boise area, and the 25-mile Boise Greenbelt Trail in particular. Like the Iowa Data Bike, COMPASS utilized market software that processed accelerometer data collected by the bike and was available for purchase (COMPASS, 2021).

The METRANS Transportation Center of the University of Southern California is currently leading a project funded by USDOT that uses ebikes to capture vibration and video data from bike trails and instantaneously upload these data to a cloud server for public trail users and administrative organizations to access and interpret. The goal is to provide current condition and hazard data to the cycling community and asset-managing organizations (METRANS, 2021).

Massachusetts Institute of Technology's City Lab led an effort titled JettSen, which utilized ebikes outfitted with sensors and cameras to not only collect information on infrastructure condition to inform maintenance, but also collect data on user patterns and trends that would better inform planning decisions regarding connectivity and community development. Unlike the Iowa and Minnesota examples, this project is set to be scaled up and deployed in a neighborhood in Japan, where it will collect large amounts of data over time rather than utilize only a single ebike on a set course (i.e., specific bike trial). This project demonstrates the opportunity for expanded collection and application of a variety of data types with a similar, ebike-based system (Rico, A., Sakai, Y., & Larson, K., 2020).

The High Efficiency Trail Assessment Process, or HETAP, is an inventory process that collects objective information about trail conditions. The information obtained through these assessments can be used by land managers to enhance the safety and enjoyment for all trail users by providing accurate, objective information about trail conditions. It also allows land managers to monitor and address environmental impacts on trails, identify potential access barriers (e.g., difficult terrain), map trail systems, and improve or create existing parks or management plans. This process uses a pushcart, rather than a bike, but it collects similarly objective trail condition data (Indiana Department of Natural Resources, High Efficiency Trail Assessment Process).

3.4. Comparing Related Research to Trailblazer Methodology

The literature review documents a number of similar data collection projects and types of condition analysis bicycle setups across the country. Most of these projects have been completed by localities or subregions on a small scale but eventual implementation of a similar methodology by the NPS could be on national scale, increasing the cost effectiveness and transferability to other national agencies. The Trailblazer project builds on related research, exploring the value of ebike-based trail condition assessment, and assessing the feasibility of implementing this strategy on a larger scale. Of the related research reviewed in this section, the Data Bike projects are the most similar to the Trailblazer system.

During the research period, the project team met with representatives from the Parks and Trails Council of Minnesota, the Des Moines Area MPO, and COMPASS to learn about their Data Bikes and the challenges experienced during their projects, and to discuss similarities and differences between their work and the Trailblazer methodology. These meetings provided valuable insight into how other organizations are using their Data Bikes, and potential uses and applications of these similar systems.

There are a few notable differences between the Trailblazer system and the other Data Bike systems reviewed in this section.

1. Other Data Bikes use a 360-degree camera mounted on a post behind the seat of the bicycle, as well as a GoPro camera mounted on the front or back rack, facing the trail surface. The Trailblazer system uses a single camera mounted on the front of the bike to capture 360-degree photos of the trail surface and surroundings.
2. Unlike the Trailblazer system, other Data Bikes do not process their own accelerometer data but use software to process the data and build maps. They also record their accelerometer data with a smartphone, while the Trailblazer system records accelerometer data with the SmartPano camera.
3. The Trailblazer System uses a handlebar-mounted tablet with an interface to record geolocated annotations of trail features, which the other DataBikes do not. In comparison, the annotation feature is a strength of the Trailblazer methodology.
4. Some of the other Data Bikes had longer lasting batteries or even two batteries per ebike, which allowed for more trail mileage to be assessed per charge compared to the Trailblazer system. This is a weakness of the Trailblazer system as the Trailblazers' maximum range was approximately 40 miles, depending on total weight. This could be solved by using an ebike with more battery capacity or bringing a spare battery.

4. ANALYSIS

The Trailblazer methodology collects trail roughness data, photos, and annotations of key conditions/features that are combined into a geodatabase that may be used as an analysis tool by trail managers, maintenance staff, and others to inform trail management decisions. This method does not make specific recommendations for trail maintenance or capital improvement projects. Sections 4.1 through 4.3 define the analysis methods for the accelerometer data, photographic data, and annotations. Sections 4.4 through 4.6 summarize data analyses for trails through Cuyahoga Valley National Park, Chesapeake and Ohio Canal National Historic Park, and the George Washington Memorial Parkway.

4.1. Accelerometer Data

The purpose of collecting geolocated accelerometer data is to assess a trail's 'roughness' or 'bumpiness'. An accelerometer records how quickly an object moves in three dimensions along x- (forward and back), y- (side-to-side), and z-axes (up and down) over very short periods of time. Because trail surface condition may be better understood by how 'bumpy' a trail is, this research project focused solely on the vertical accelerometer data (z-axis). Thus, when the ebike goes over a bump, there is a spike in the z-axis accelerometer value recorded at that location.

This system collects 200 accelerometer readings per second, providing significant detail into how rough or smooth the trail surface is. Given that the project team assessed over 200 miles of trail data, they decided to use the maximum vertical (z-axis) accelerometer value per meter as the baseline accelerometer data for analysis. This simplifies data processing while providing sufficient detail on trail roughness for further assessment.

Relative Roughness

An important consideration of the Trailblazer methodology is that, unlike many of the trail condition assessment methodologies documented in the Literature Review section of this report (see Literature Review), it does not establish fixed categories of 'good,' 'fair,' 'poor,' etc. for trail segments. Rather, the Trailblazer methodology visualizes the 'smoothness' and 'roughness' of trail segments relative to the distribution of baseline accelerometer values for the entire trail being assessed.

Figure 6 displays an example of baseline accelerometer data distribution from CUVA's Towpath Trail. A value of negative 9.8 m/s^2 is indicative of a smooth trail with no vertical deflection detected, as $-9.8\ m/s^2$ represents constant gravitational acceleration. Moving to the right along the x-axis of Figure 6 indicates an increasingly rough trail as the accelerometer values increase.

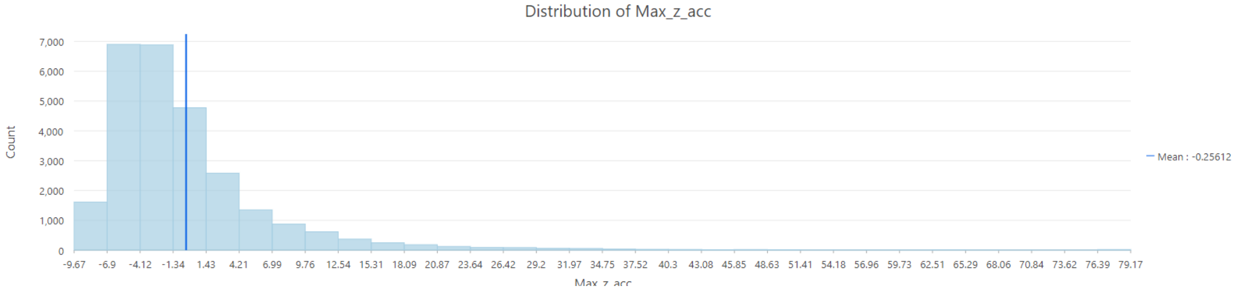


Figure 6: Example of baseline accelerometer data distribution (from CUVA).

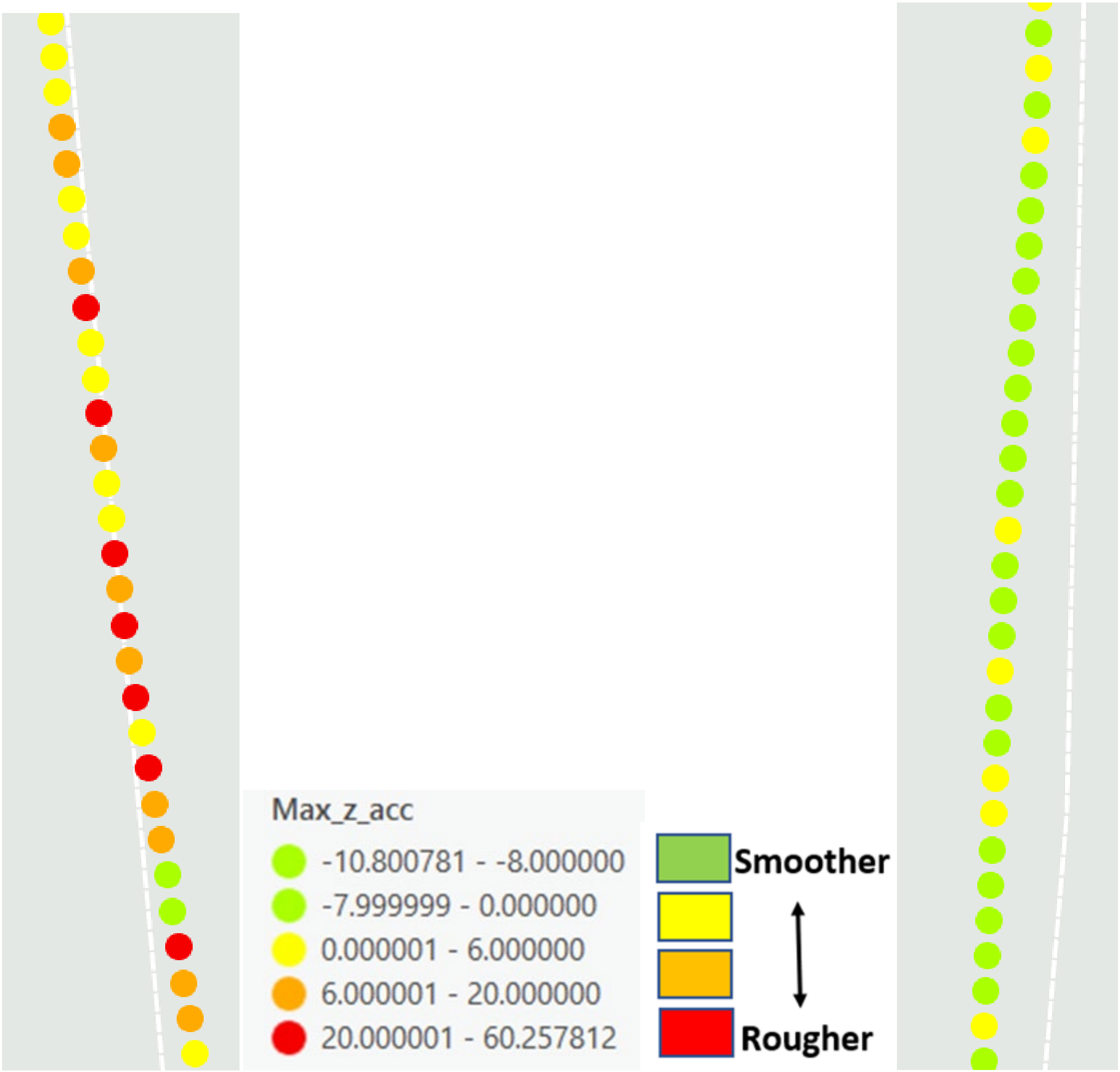


Figure 7: Baseline accelerometer data visualized in ArcGIS.

Figure 7 shows baseline accelerometer data (maximum z-axis accelerometer value per meter) on two portions of CUVA's Towpath Trail. The red and orange dots correspond to higher accelerometer readings, indicating a relatively rough section of trail (shown on left) and the green and yellow dots correspond to lower accelerometer readings, indicating a relatively smooth section of trail (shown on right).

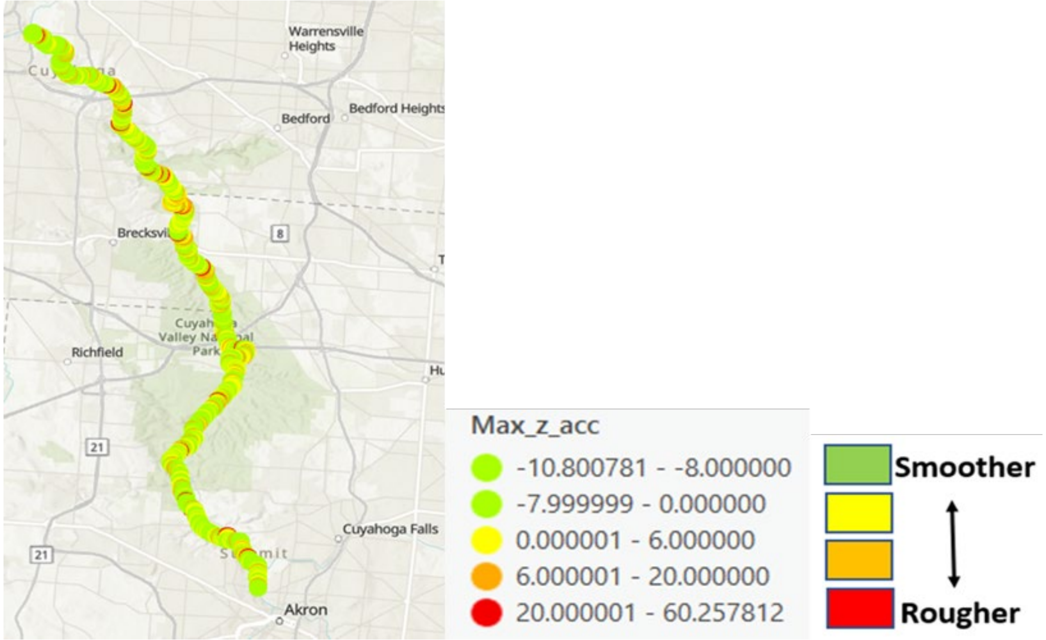


Figure 8: Baseline accelerometer data for CUVA.

Figure 8 zooms out further to show the maximum z-axis accelerometer value per meter over 31 miles of the Ohio and Erie Canal Towpath Trail at CUVA.

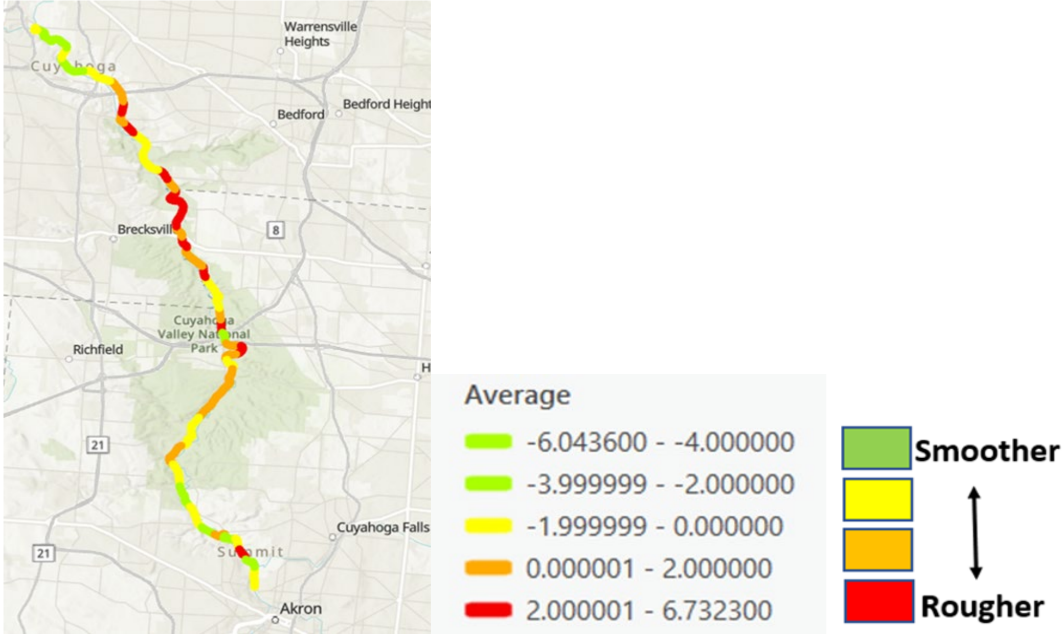


Figure 9: Baseline accelerometer data averaged by half mile increments at CUVA.

Figure 9 shows the baseline accelerometer data from Figure 8 averaged by half mile increments. This reveals a more general pattern of trail roughness and smoothness over the length of the trail.

4.2. Photographic Data

The purpose of collecting geolocated photographic data is to produce a visual, digital archive of a trail, and to provide a means to better understand the accelerometer patterns and annotative data documenting key conditions/features collected on that trail.

The SmartPano camera system used for the Trailblazers project is capable of collecting 360-degree video of the trail in 8k resolution. However, because the project team assessed over 200 miles of trail data, the project team decided to collect 360-degree images in 4k at one frame per second (fps) to reduce the demand for storage capacity while still recording images clear enough to view and assess trail conditions. Irregular light patterns, like that of sunlight shining through trees, can make close inspection of the trail surface difficult.

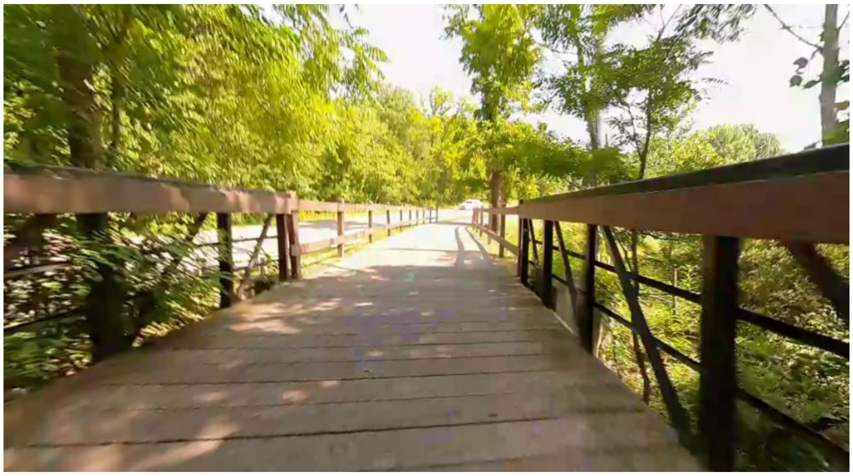


Figure 10: A wooden bridge trail surface, which consistently yields rough accelerometer data.

Figure 11: A crushed limestone trail surface.

Figure 12: A paved trail surface.

Figure 13: Heavy cracking on concrete trail surface.

Figure 10, Figure 11, Figure 12, and Figure 13 are screenshots from a 360-degree viewer, where the user can pan around the photograph horizontally and vertically.

4.3. Annotative Data to Identify Trail Features

The purpose of collecting geolocated annotative data is to locate specific features of a trail (such as a bridge or hazard) and to document issues or inconsistencies in the collection process (such as a technical or mechanical issue). Annotations are recorded by pressing a digital icon on the handlebar-mounted tablet. This allows the rider to make quick annotations while riding. The custom annotation interface displayed in Figure 14 was developed by Smart Delta, the company that produced the SmartPano cameras, for the purpose of this project.

Figure 14: Smart Delta user interface with map and annotations. The numbered icons are: 1) bridge, 2) congestion, 3) crosswalk, 4) hazard, 5) trail surface material change, 6) milepost, 7) slow/stop, and 8) vegetation.

This interface allows the project team to create custom annotation buttons that can be tailored to record the specific information desired by different trail managers. For example, the Chesapeake and Ohio Canal National Historical Park was interested in documenting the location of trail mileposts, so the project team added a 'milepost' annotation.

Interpreting Completed Maps

Figure 15 demonstrates how accelerometer, photographic, and annotation data complement each other to produce a more complete understanding of trail condition and features in ArcGIS. The accelerometer data indicates a relatively smooth section of trail (green and yellow) with a small rough portion (red and orange). From the 'bridge' annotation, it is apparent that there is a bridge at the "rough" location. The user may click on one of the imbedded photographs at the bridge location to open a 360-viewer within ArcGIS that shows the surface of the bridge, which, in this case, has a wooden deck.

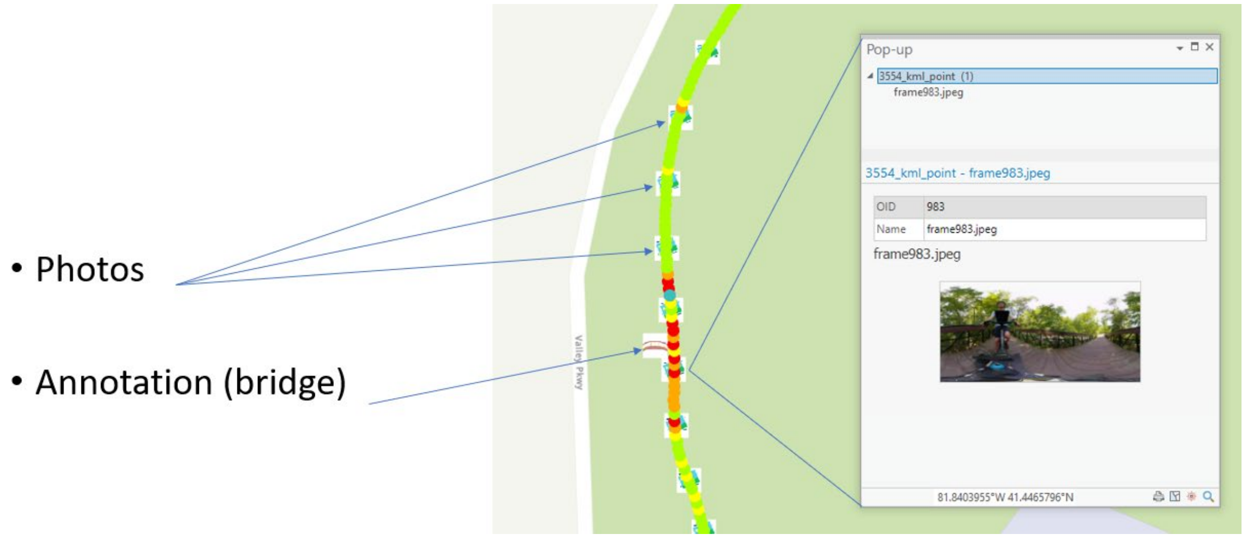


Figure 15: An example of accelerometer, photographic and annotative data mapped in ArcGIS.

4.4. Cuyahoga Valley National Park

Cuyahoga Valley National Park is a 33,000-acre park located in the Cleveland-Akron metropolitan area of Northeast Ohio. The park provides a wide variety of recreational opportunities and green spaces for the dense population centers that surround it, welcoming over two million visitors per year. Visitors can ride the Cuyahoga Valley Scenic Railroad, paddle on the Cuyahoga River, hike through forests and scenic rock features, ride horses on bridle trails, mountain bike, and enjoy an array of historical and cultural experiences (NPS.gov/CUVA).

Cuyahoga Valley National Park also contains 20 of the 98-mile Ohio and Erie Canal Towpath Trail, which connects Cleveland to Akron and beyond. This trail has been described as the 'spine' of the regional bike network and facilitates thousands of bike trips annually. The Towpath Trail is an excellent example of an NPS Transportation Trail (see Background Section) and stood out as an ideal candidate for piloting the Trailblazer condition assessment methodology.

Data Collection Details

Two project team members travelled to Cuyahoga Valley National Park to assess the towpath trail during the week of June 20th, 2022. In addition to assessing the 20 miles of the towpath trail within the National Park, the team collected data north and south of the park boundary, totaling 31 miles of the Towpath Trail between Cleveland and Akron.

On Tuesday, June 21st, the project team collected data from the Cleveland Metroparks' Ohio and Erie Canal Reservation on Harvard Avenue in Cleveland, Ohio, south to the National Park's Boston Visitor Center. There they turned around and rode back north to Harvard Avenue. On Thursday, June 22nd, the team began collecting data at the Boston Visitor Center and rode south to Summit County Metroparks' Memorial Parkway Trailhead, where they turned around and rode back north to the Boston Visitor's Center. This 'out and back' approach resulted in two sets of data for the total assessed mileage of the Towpath Trail, totaling 62 miles ridden on 31 miles of trail. To ensure consistency, the project team only used one of the rider's north-to-south accelerometer data for GIS roughness analysis but used photos and annotative data from both riders.

Data Visualizations

Figure 16 shows CUVA's baseline roughness data, and Figure 17 shows that data averaged by half mile.

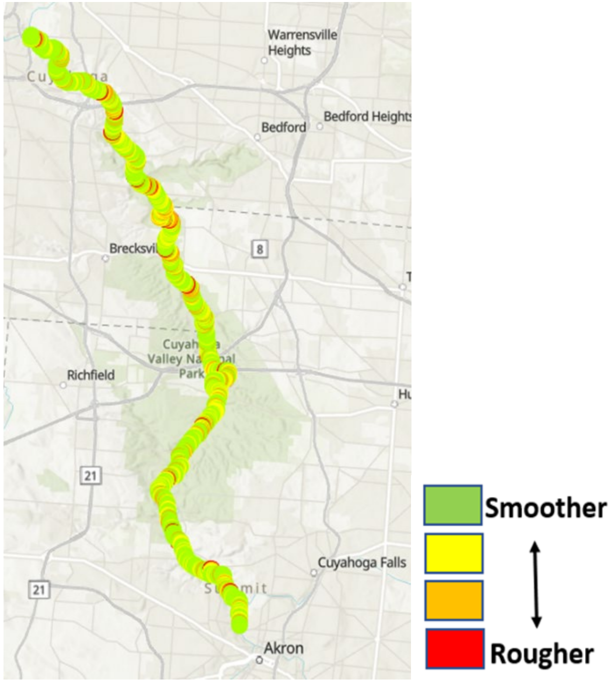


Figure 16: CUVA baseline roughness data.

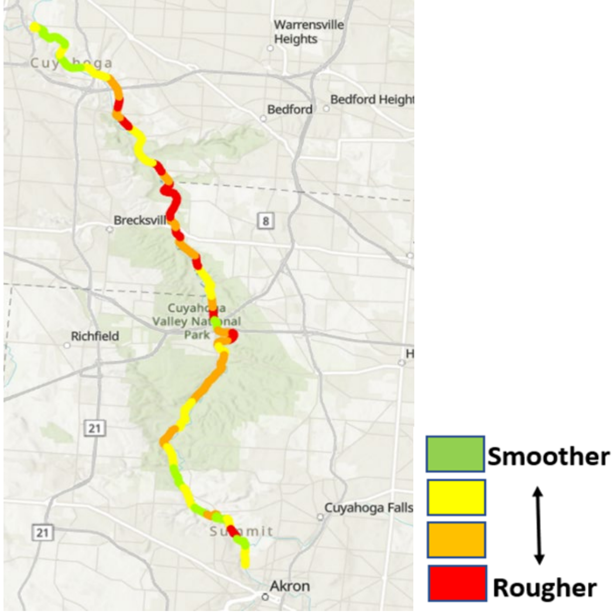


Figure 17: CUVA baseline roughness data averaged by half mile.

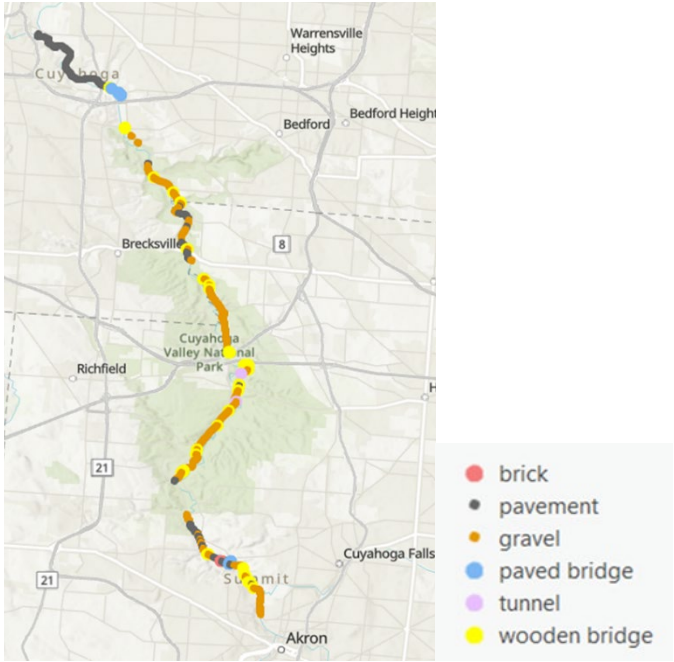


Figure 18: CUVA trail surface materials.

Figure 18 demonstrates the ability of the trailblazer methodology to produce a trail surface material map for trail managers. This map was produced by using the 'trail surface material change' annotation feature at every location where the trail material changed. These annotations allowed the project team to reference photographs of these locations after data collection was complete, and produce a map of the various surface materials along the trail.

Figure 19: CUVA annotations.

Figure 19 displays some of the annotations collected by the project team at CUVA. These icons include bridge, trail surface material change, and hazard. See Figure 14 for more information on annotations.

Figure 20 shows the accelerometer distributions (along the x-axis) for different trail materials (along the y-axis). As discussed previously, negative 9.8 m/s^2 indicates a smooth surface. This figure shows that pavement and paved bridges tend to be relatively smooth, with average accelerometer readings close to negative 9.8 m/s^2. Wooden bridges are rougher with average accelerometer readings of approximately 10 m/s^2, while gravel surfaces have accelerometer readings slightly less than 0 m/s2, indicating they tend to be rougher than pavement, but smoother than wooden bridges.

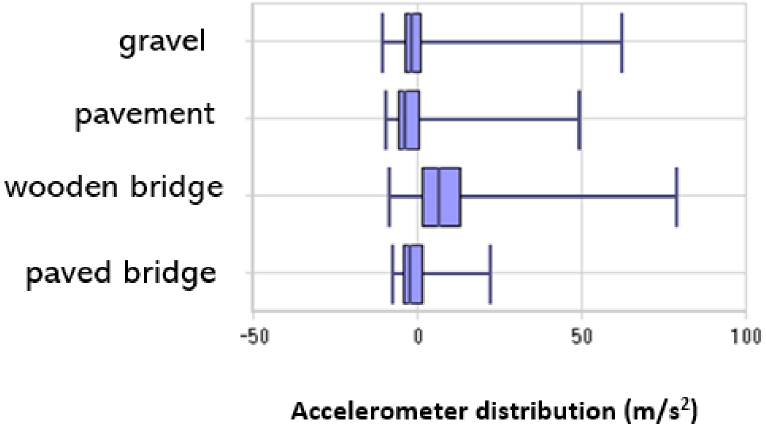


Figure 20: Distribution of baseline roughness data by trail material.

4.5. Chesapeake and Ohio Canal National Historical Park

Beginning in Washington, D.C.'s Georgetown neighborhood, the Chesapeake and Ohio Canal National Historical Park (CHOH) follows the C&O Canal's 185-mile historical corridor through the District of Columbia, West Virginia, and Maryland to Cumberland, Maryland. Though the canal has long been out of service, the corridor now hosts a multi-use trail, which is open to hikers and bikers. This trail ties into the Great Allegany Passage trail at Cumberland, MD, which allows bikers to ride between Pittsburgh and Washington, D.C. As such, the Chesapeake and Ohio Canal Towpath Trail stands out as the NPS' longest transportation trail (NPS.gov/CHOH).

On Sunday, August 14th, 2022, two project team members travelled by passenger train from Washington, D.C. to Cumberland, MD with the Trailblazer ebikes (Figure 21) and project equipment. Unlike Cuyahoga Valley's Towpath Trail, where data was collected in an 'out and back' fashion, the plan for the C&O Canal Towpath Trail was to ride from Cumberland, MD back to Washington, D.C. over the course of 3 days, riding roughly 60 miles each day. This approach required the project team to transport all personal belongings and project equipment on the bikes over the course of the trip. The most significant limitation of this approach is that the project team was forced to find suitable locations to charge the ebike batteries during the collection periods, as the battery would not last the entire 60-mile ride each day. Chesapeake and Ohio Canal NHP staff were extremely helpful in identifying locations to charge the batteries along the way.

Figure 21: The project team at Chesapeake and Ohio Canal Towpath Trail Trailhead in Cumberland, MD.

On Monday, August 15th, 2022, the project team rode approximately 60 miles from Cumberland, MD to Hancock, MD. The weather was rainy and there was significant water and mud on the trail. This portion of the trail is in poor condition overall, which, combined with the water and mud, created slippery and sometimes hazardous riding conditions, especially as the project team tried to maintain the official target speed of 15 mph.

The rough condition of the ride took its toll on the ebikes, as the front rack on one of the ebikes lost a screw near milepost 150, forcing the project team to disassemble the camera and sensor apparatus to avoid damaging the equipment and leaving only one ebike capable of data collection. Later that day, as the project team approached Hancock, MD, the other ebike's front wheel detached from the frame, forcing the project team to drag the fully laden bike for the last mile of the trail before Hancock.

On the morning of Tuesday, August 16th, 2022, the project team took the ebikes to C&O Bicycles in Hancock to repair the damage to both bikes. Once the bikes were fully operational, the project team set out towards Harper's Ferry, WV. The weather was clearer and sunnier than the previous day, and there were no significant setbacks on the ride. Similarly, the following day, Wednesday, August 17th, was clear and sunny and the project team was able to get back to Washington, D.C. on schedule.

This trip demonstrated that the Trailblazer methodology can collect data on over 60 miles of trail a day, though weather and poor trail condition can result in significant challenges.

Upon review of the data collected, it was discovered that one of the two cameras experienced technical issues and failed to collect data for the majority of the trip. This speaks to the value of conducting a Trailblazer assessment with multiple ebikes and completing equipment checks throughout the collection period, so that issues with one piece of equipment or the other do not result in a total loss of data for the trip. For statistical consistency, only the more complete dataset was used to analyze roughness, and there is a gap between Cumberland, MD and Hancock, MD where no data was collected due to the mechanical issues experienced on the first day. It is worth noting that despite the lack of accelerometer data for that section of trail, the project team confirmed that Paw Paw, WV to Hancock, MD was extremely rough and in poor condition compared to the rest of the trial.

Data Visualizations

Figure 22 shows the baseline roughness data collected at CHOH and Figure 23 shows the data averaged by mile.

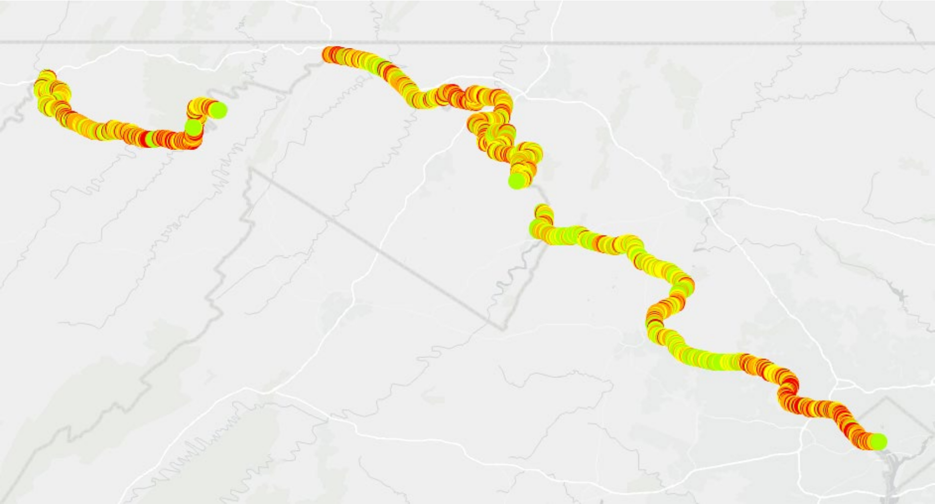


Figure 22: CHOH baseline roughness data.

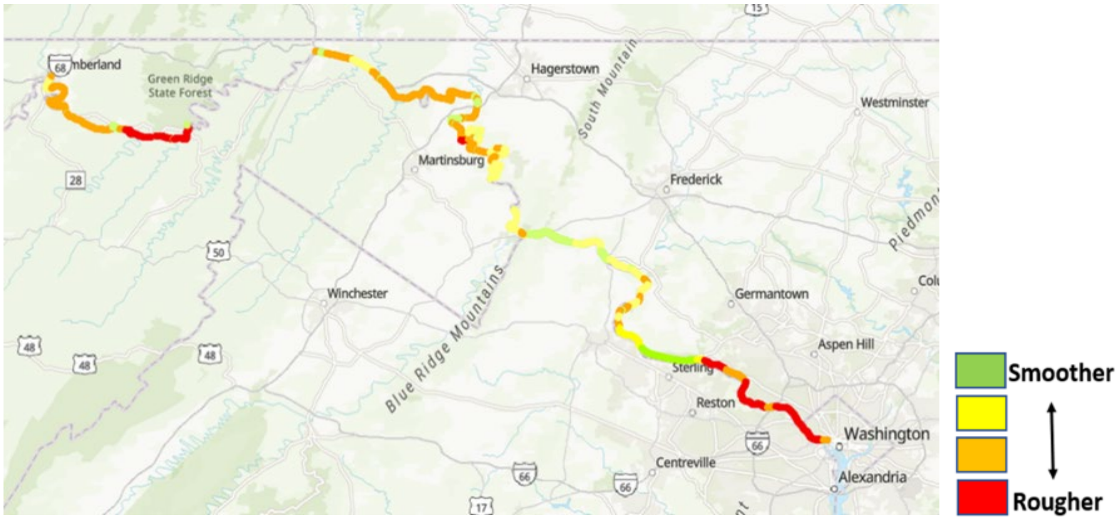


Figure 23: CHOH baseline roughness data averaged by mile.

Figure 24, Figure 25, and Figure 26 show the baseline accelerometer data distributions from three days of data collection at CHOH. These distributions are another way of looking at the data in Figure 23, and can be helpful for understanding the roughness of a given trail section. For example, Figure 24 has a mean accelerometer value of 19.03 m/s^2, compared to Figure 25 and Figure 26, which have mean values of 4.06 m/s^2 and 4.56 m/s^2, respectively. This suggests that the portion of trail between Cumberland, MD and Hancock, MD is significantly rougher than the sections of the trail between Hancock, MD and Washington, D.C.

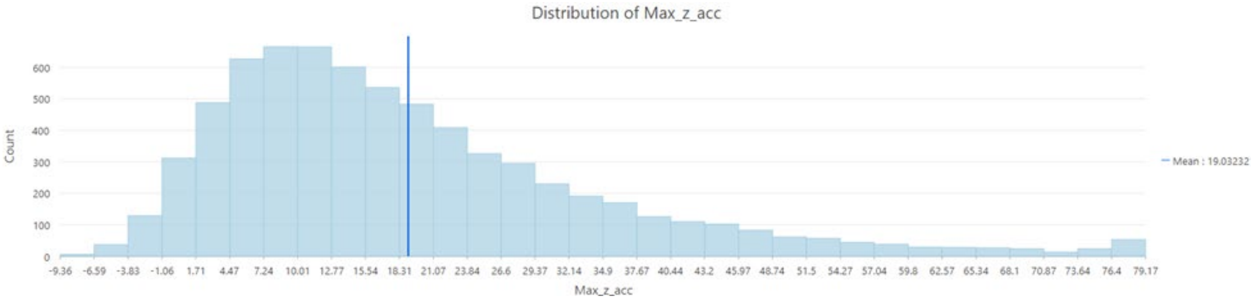


Figure 24: CHOH distribution of baseline roughness data between Cumberland, MD and Hancock, MD (Day 1).

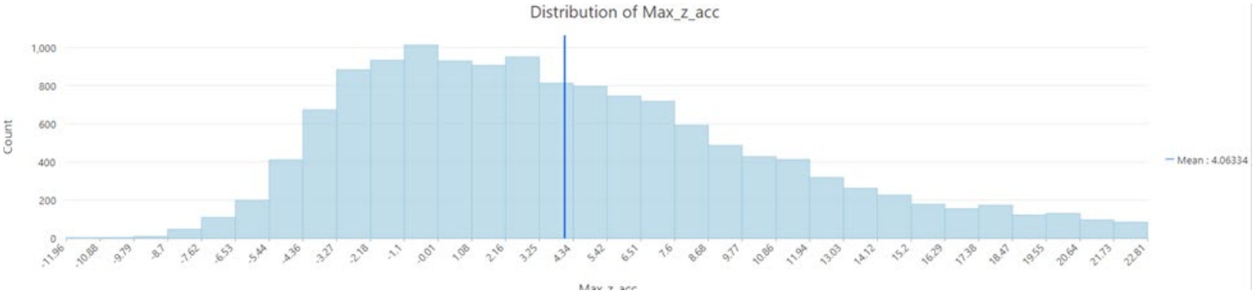


Figure 25: CHOH baseline roughness data distribution between Hancock, MD and Harper's Ferry, WV (Day 2).

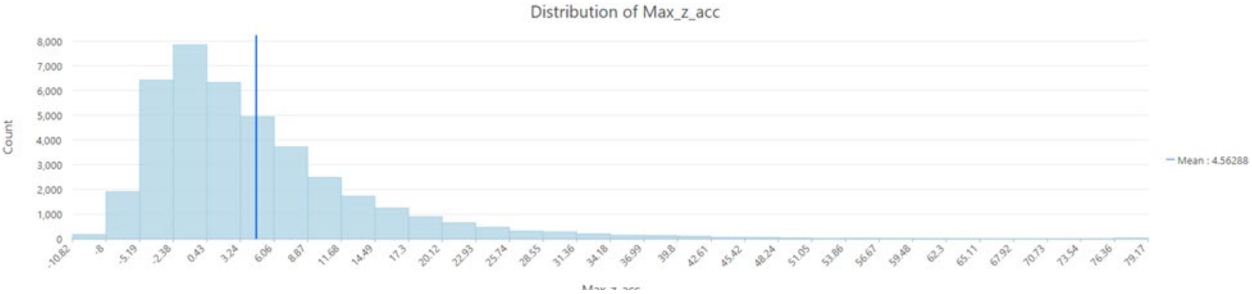


Figure 26: CHOH distribution of baseline roughness data between Harper's Ferry, WV and Washington, D.C. (Day 3).

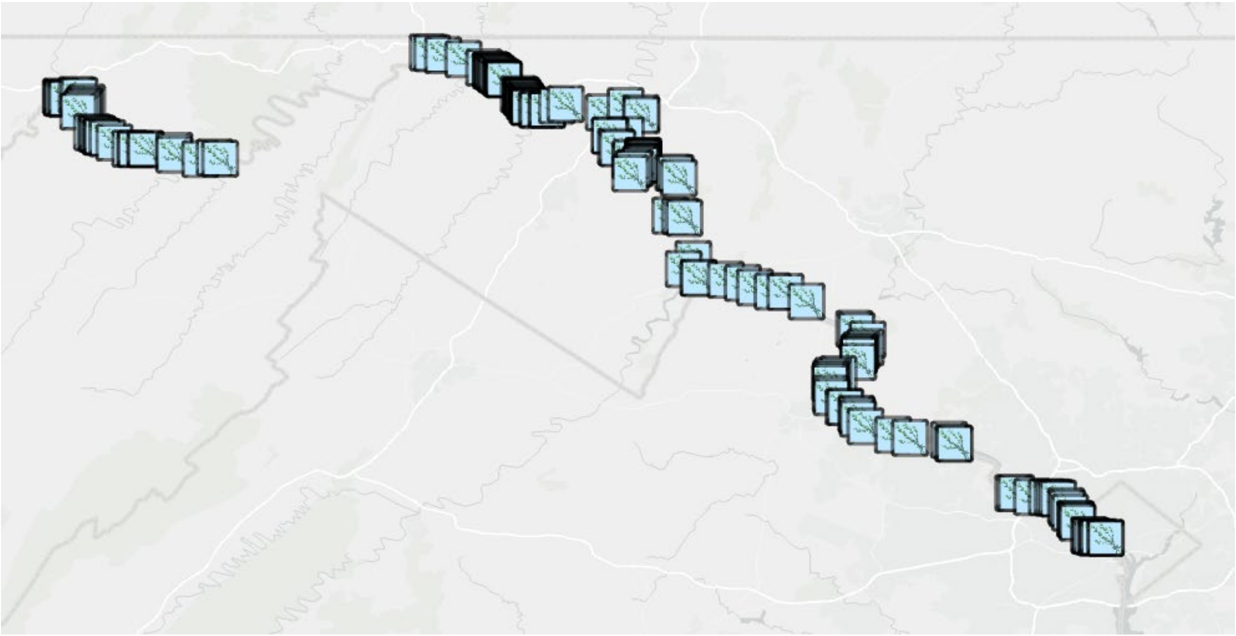


Figure 27: CHOH vegetation overgrowth annotations.

The vegetation overgrowth data from Figure 27 was used to complete a cluster analysis in ArcGIS, which produced the heatmap displayed in Figure 28. Figure 28 could help NPS staff identify priority areas for vegetation management.

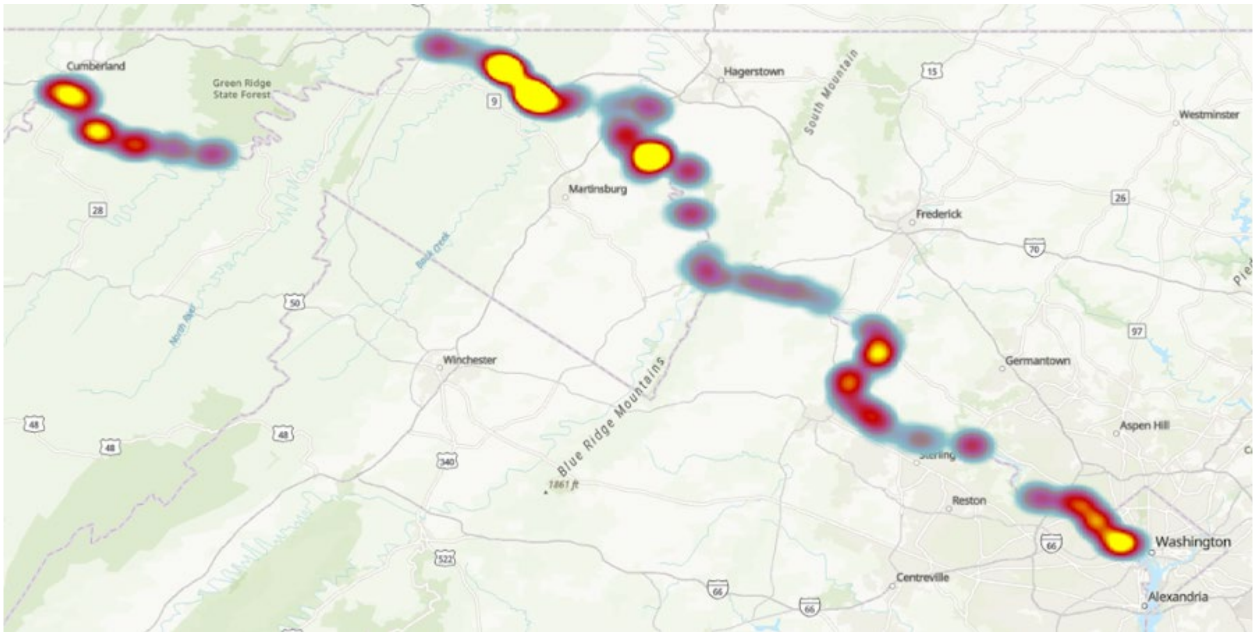


Figure 28: CHOH vegetation overgrowth heatmap.

Figure 29: CHOH baseline data averaged by mile with milepost annotations.

The NPS National Capital Region Transportation Program and the staff at CHOH were interested in the Trailblazer project team pinpointing the milepost locations along the 185-mile CHOH trail. Figure 29 demonstrates the customizable nature of the annotation function, showing the location of mileposts collected by the project team as well as the average baseline accelerometer data averaged by mile.

4.6. George Washington Memorial Parkway

George Washington Memorial Parkway's Mount Vernon Trail is an 18-mile paved multi-use trail that stretches from George Washington's Mount Vernon Estate in Northern Virginia to Theodore Roosevelt Island. It connects with regional trails, including the Potomac Heritage, Custis, Rock Creek, Four Mile Run, and the Woodrow Wilson Bridge Trails (NPS.gov/GWMP). Located in the dense Washington, D.C. metropolitan area and featuring so many connections to the regional trail network makes the Mount Vernon Trail a great example of an NPS Transportation Trail.

The project team made use of the Mount Vernon Trail's proximity to the Department of Interior's Main Interior Building, where the Trailblazer ebikes were stored, to conduct initial proof-of-concept data collections and test rides throughout the early stages of project development. Data used for analysis were collected at various times during the months of June and July, 2022, by the project team. For consistency in accelerometer data, one team member's data was used for the roughness analysis.

Data Visualizations

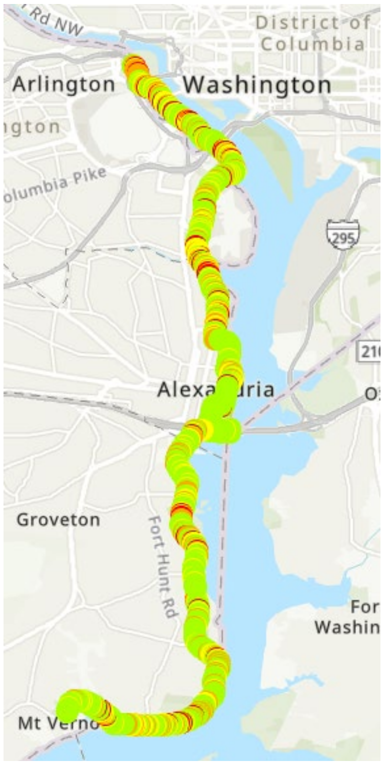


Figure 30: GWMP baseline roughness data.

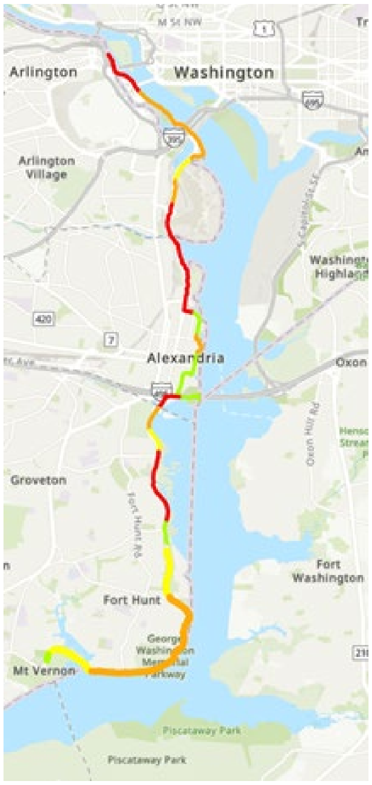


Figure 31: GWMP baseline roughness data averaged by half mile.

Figure 32: GWMP baseline roughness data averaged by mile.

Figure 30 shows the baseline roughness data from the Mount Vernon Trail, Figure 31 shows trail roughness averaged by half mile, and Figure 32 shows trail roughness averaged by mile. (NOTE: a small amount of data in the Alexandria area was collected on paved roads that serve as a bike route but are not on the Mount Vernon trail.)

Figure 33: A rough section of Mount Vernon Trail near the Arlington Memorial Bridge.

Figure 33 is an image taken from the ArcGIS 360-degree image viewer that shows a rough section of the Mount Vernon Trail.

Figure 34: example of bridge annotations and trail surface material layer.

Figure 34 provides an example of the utility of annotations, in this case ‘bridge’ annotations, in creating a trail surface material map. The annotations serve as a reference for the project team to examine these locations and codify segments of trail as either pavement or wooden bridge.

4.7. Variables and Considerations

4.7.1. Speed

Speed is an important variable to consider when conducting an assessment. The project team tested the impact of speed and weight on accelerometer data. The findings suggest that the faster the ebike is moving, the higher the accelerometer values are compared to accelerometer data collected on the same section of trail at a slower speed. The data displayed in Figure 35 was collected by the same rider going the same direction on the same wooden bridge, where the ‘fast’ speed was 15 mph and the ‘slow’ speed was 10 mph.

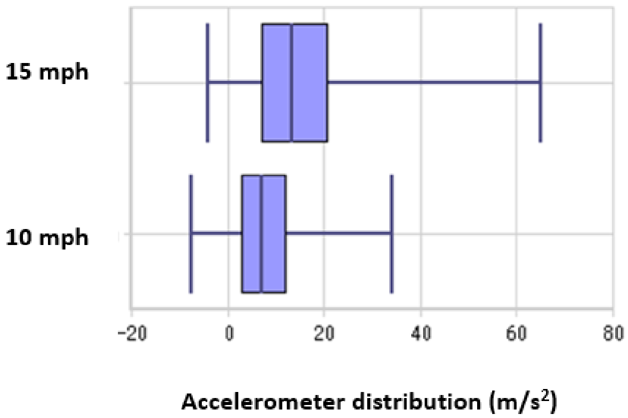


Figure 35: The effect of speed on baseline roughness data.

These findings suggest that maintaining a consistent speed is critical for the integrity of roughness data. Understanding this, the project team tried to maintain a constant speed of 15 mph for all data collection, with a margin of +/- 2 mph. The target speed can be adjusted for future use of the Trailblazer methodology, but maintaining a consistent speed is critical (the electrical assist function of the ebike is essential for this). Furthermore, the project team would mark the ‘slow/stop’ annotation in areas where the target speed was not met, such as a congested area, for review after data collection.

4.7.2. Weight

Weight, like speed, is also an important variable to consider when conducting a trail condition assessment. Weight also has a major effect on accelerometer data, and, like speed, it is important to keep the combined weight of the rider and ebike consistent for the duration of data collection on any given trail. The project team compared the effects of an approximately 50 lb. weight differential on accelerometer data between two riders travelling at the same speed on the same section of trail.

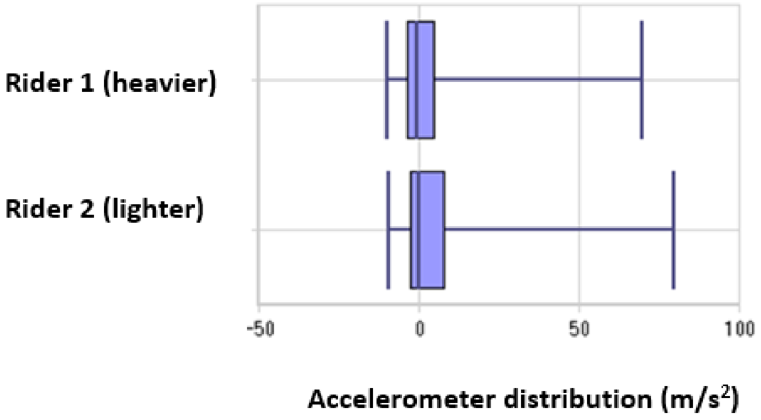


Figure 36: The effect of weight differential on baseline roughness data distribution

Figure 36 shows the distribution of baseline accelerometer data collected by a heavier rider (top) and a lighter rider (bottom). This data suggests that the less a rider weighs, the broader the total distribution of baseline roughness data will be, as bumps register higher accelerometer values. To address variability in weight, it is important to label datasets with rider information, and not to compare accelerometer data between two riders with significantly different weights. Keeping this in mind, the project team only used one project team member's accelerometer data for the roughness analysis on any given trail.

4.7.3. Trail Surface Material

Trail surface material has a significant effect on accelerometer data. The project team mapped trail surface material not only because the data are useful in their own right, but because they provide context for further analysis of trail roughness since some surface materials are 'rougher' than others.

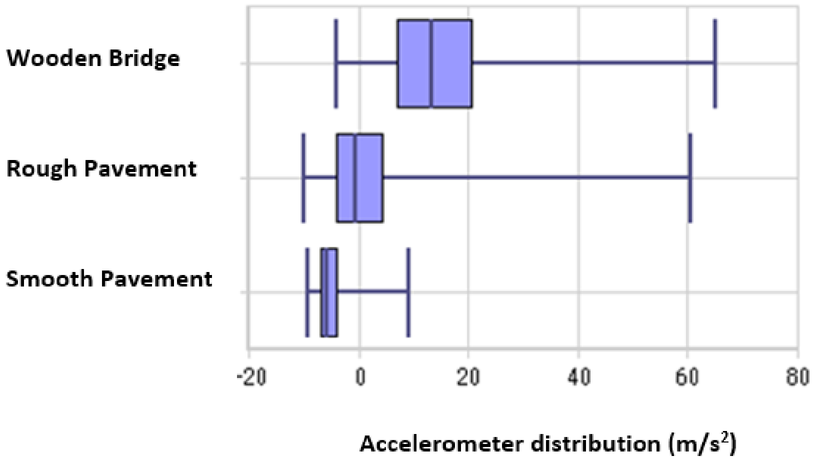


Figure 37: The effect of trail surface material on baseline roughness data distribution

Figure 37 demonstrates the difference in accelerometer data for a wooden bridge (top), rough pavement (middle) and smooth pavement (bottom) when collected by the same rider going a consistent speed.

4.7.4. Battery Life

The length of the ebike battery charge is an important consideration that limits the amount of data that can be collected on a single ride. To maximize riding distance, the project team used the minimal amount of electrical assist necessary to maintain the target speed in order to preserve battery life. The fully laden Trailblazer ebikes would usually cover roughly 40 miles of trail before the batteries were depleted. Weight also impacted ride distance, as the heavier riders' charge diminished more quickly than that of the lighter rider. The disparity might be addressed by carrying a spare battery for each rider. However, doing so would also add weight to the bike. Spare batteries could also be cached at locations along a trail for riders to swap.

For 'out and back' data collections, the project team needed to turn around before the ebike battery lost half of its charge in order to return to the starting location with some amount of charge remaining per rider. This usually meant turning around when one ebike's battery charge dropped to 60%, which limited the miles over which data could be collected in a single ride. On the CHOH Towpath Trail collection, the project team travelled one-way, rather than 'out and back,' for roughly 60 miles each day. Therefore, the project team needed to charge the batteries as soon as charging infrastructure was available after roughly 30 miles of data collection. The charging process usually took several hours to reach the point where the batteries would last until the final destination for the day, which limited the amount of data the project team was able to collect.

4.7.5. Data Storage

Data storage is a difficult variable to manage. Because the Trailblazer methodology collects so much data, it can be difficult to process, transfer, and store with a typical computer. For example, the full dataset from CHOH was over 200 GBs when fully processed and exported as a map package. The project team utilized external solid-state drives to manage the project data and required high-powered computers to process it. Most of the data was too large to transfer online and needed to be delivered to partners on an external storage device.

Photographic data constitutes the vast majority of data storage needs. Photographic data is also the most difficult data type to manage in ArcGIS. This challenge may be addressed with more powerful computers, lower resolution photographs, a less frequent photograph capture frame rate, or a combination of these options.

5. DISCUSSION

5.1. Research Questions and Results

The following is a list of research questions that were outlined and answered during the Trailblazer project:

1. Can ebikes efficiently and cost-effectively collect trail condition data that may then be analyzed by NPS and other entities?

This research confirms that ebikes can be used to efficiently collect trail condition data for analysis by NPS and other entities. The project team's assessment of CHOH demonstrates that trail condition data can be collected on more than 60 miles of trail in one day. While the methodologies that use cars for data collection can collect at a similar rate, the vehicles may be too large to drive along the trail corridor. Additionally, one fully equipped trailblazer bike cost around $10,000, which was less expensive than a typical motor vehicle, though more than a typical bicycle. Costs could be also reduced with a different selection of ebike and accessories. The project team felt that the ebikes provided a balance of speed and efficiency and were a manageable size for transport by car-mounted bike rack and passenger train. In summary, the trailblazer methodology provides an efficient and cost-effective means for the NPS and other entities to collect trail condition data for analysis.

2. Can a detailed and replicable trail condition assessment methodology be produced for multi-use (transportation) trails using Trailblazer data?

This methodology visualizes the 'smoothness' and 'roughness' of trail segments relative to the distribution of baseline accelerometer values for the entire trail being assessed. The 4k, 360-degree photographs taken once per second allow trail managers to look closely at distinct features and trail conditions. Furthermore, the annotations system allows data collectors to pinpoint specific trail features such as potholes, cracking, and rutting, which allows trail managers to understand trail condition in great detail. The ability to customize annotations allows trail managers to be flexible in the type of detailed assessment they use. The project team replicated the assessment methodology on three separate trails. The data collected on each trail were used to produce a geodatabase in ArcGIS, which was shared with NPS staff for the purpose of informing trail management decisions. This method provides data for trail managers to utilize but does not make specific trail maintenance recommendations.

Though the trailblazer methodology is detailed and replicable, the photographic, annotative and accelerometer detail collected is not a substitute for a detailed engineering analysis of trail prism integrity below the surface material, or trail features such as bridges and tunnels. These aspects of trail condition would require further engineering analysis.

3. Can data collected using ebikes be used to inform NPS asset-specific management decisions?

The photographic, annotative and accelerometer data collected by the trailblazers can be used to inform NPS asset-specific management decisions in many ways. At a high level, trailblazer roughness data identifies the roughest and smoothest sections of trail, which can inform trail maintenance and rehabilitation priority areas. The project team assessed average roughness in mile and half mile increments, but the baseline accelerometer data could be averaged across any unit of distance over one meter. This information can be used as a condition baseline, which can be compared to subsequent Trailblazer assessments to track changes in trail condition over time. Mapping the surface material of the trail is also extremely useful information when managing trail maintenance or rehabilitation projects.

At a more granular level, trailblazer data can pinpoint specific damages such as potholes, cracks, rutting, etc. in a trail with photographic and annotative data. Furthermore, annotative and photographic data can be used to inventory specific trail features such as bridges, street crossings, mileposts and vegetation overgrowth, all of which the project team demonstrated over the pilot research period. This same custom annotation feature could be used to inventory other trail features such as signage, access points, water resources and bathrooms, and benches.

5.2. Recommendations for National Park Service Use of the Trailblazer Methodology

As this pilot study was conducted to provide more information on the condition of NPS transportation trails, the Trailblazer methodology could be implemented across the NPS network on a standard, cyclic basis to track changes in trail condition over time and identify the trail segments most in need of maintenance and rehabilitation. Beyond necessitating a larger fleet of bikes, data collection equipment and program personnel, this would require the NPS to streamline data collection, processing and management, and would be most effective if Trailblazer data were integrated into existing online GIS platforms, such as the NPS Navigator. The project team recommends that the NPS ATP scope out and evaluate options for a service-wide cyclical transportation trail condition assessment program based on the Trailblazer methodology.

If the NPS wanted to pilot an expanded Trailblazer program on a subset of transportation trails, the NPS National Capital Area (NCA) stands out as an ideal region to implement and expand the Trailblazer program. The NCA is the smallest geographic region of the NPS, yet it contains more transportation trail miles (290) than any other NPS region. Furthermore, the Washington Area Support Office (WASO), where the Trailblazer pilot program was developed under the ATP and where the Trailblazer equipment is stored, is located within the NCA and only a mile from the NCA regional headquarters (HQ). The proximity of WASO and NCA HQ, as well as their proximity to all 290 miles of transportation trails within the NCA, would make Trailblazer management and logistics in the NCA much more cost-effective than any other NPS region. There are also partners in the Washington, D.C. area, such as DDOT, that could benefit from a partnership with this program.

An expanded regional program would require oversight from the NCA HQ Transportation Branch, support from NPS units within the NCA that manage transportation trails, and a working relationship with NCA/WASO GIS specialists. It would also require collaboration with WASO ATP in setting up and running the program, familiarizing staff with the project procedure and equipment, and reporting results.

Since the Washington, D.C. area is home to many universities and students, the NCA could hire summer interns to conduct data collections, process data, and work with the NCA GIS staff to produce NCA transportation trail network condition assessments on a cyclic basis. An ideal intern would have experience with GIS and data management, have an interest in supporting federal lands, have a basic knowledge of bicycle maintenance and enjoy bike riding. Utilizing interns would also significantly cut costs for the pilot program.

5.3. Potential Applications

Aside from a cyclical condition assessment program for NPS transportation trails, there are many ways the NPS and other agencies could utilize the Trailblazer system. One application is to efficiently inventory trail signage, access points, water resources, bathrooms, benches, parking, and other trail facilities.

The Trailblazer system could also be used to assess infrastructure damage after storms, flooding, fires, etc. Not only could the annotation function be used to mark the locations of downed trees, high water, erosion, or other infrastructure damage, but the SmartPano cameras are capable of streaming real-time 360-degree photographic or video data to multiple remote locations, such as emergency response units, ranger stations, and headquarters offices. Using the Trailblazer systems for destructive event reconnaissance could provide information faster than a person walking, but with more flexibility than a motor vehicle, as the ebikes can be carried over obstructions and navigate off-road.

The Trailblazer ebikes could also be used to produce a ‘virtual experience’ of trails, roads, etc. similar to Google Street View. Though the project team collected 4k photographs at one frame per second, the SmartPano cameras are capable of recording and streaming 8k photos or video. This photo/video data could be used to produce interpretive virtual and online tours of trails for people who are unable to travel to or access certain NPS locations.

Additionally, future Trailblazer projects could employ LiDAR sensors supported by the SmartPano system. Incorporating LiDAR into the methodology may improve the granularity of the data collected, facilitating “virtual site visits” by project engineers, and gathering detailed, comparable logs of site changes over time. LiDAR use could also be expanded to create 3D maps of trail environments, which could be further fleshed out using photogrammetry.

A coming advancement that will potentially transform the usefulness of the Trailblazer data is the increasing availability and sophistication of Artificial Intelligence (AI). AI algorithms could examine large data files, identifying useful patterns. For example, there is likely a specific accelerometer signature associated with wooden boardwalks. An AI could be trained to recognize that signature, and isolate every instance in which it occurs. This would allow an analyst to label those areas “boardwalks,” and then exclude them from an analysis of pavement condition, for example. AI could also eliminate the manual annotation of features like mileposts by being trained to recognize them in the photographic data. Over time, this would make documenting features safer for riders and more consistent for analysts.

In the next 20 years, if ebikes become cheaper, smart technologies become ubiquitous and inexpensive, and AI develops on its current trajectory, it is possible that collecting Trailblazer data could be inexpensively crowdsourced to the public. Already, the NPS has placed inexpensive tablets and portable GPS units in the hands of untrained visitors who then undertake large-scale surveys, like the 2019 Yellowstone Visitor Use Study. As the NPS moves to adopt micromobility technologies at parks, increasing numbers of visitors will have access to standardized, wireless-enabled bicycles. A fleet of connected, condition-sensing ebikes could produce high quality, current condition data throughout a park while being ridden many miles every day by members of the public.

5.4. Project Costs

The material costs of this project were approximately $21,000. Material costs were split into two categories, described below, and detailed in Appendix A.

1. Critical project materials consisted of ebikes, camera/sensor systems, tablets, batteries, bike storage, and data storage. These items totaled approximately $18,600 for two bikes, or approximately $9,300 per bike.
2. Standard biking materials consisted of items such as helmets, bike bells, lights, pump, tire patches, multi-tool, chain lube, bike locks and hitch/bike rack to transport bikes on a vehicle. These items totaled approximately $2,400, or about $1,200 per bike.

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7. APPENDIX A

<u>Materials Checklist</u>

This section documents the equipment that the project team used to conduct the Trailblazer pilot study. This is not an endorsement of any specific vendors or brands.

7.1. Critical Project Materials

1. ebike model:
    a. Specialized Como 4.0 650b
2. Camera/Sensor
    a. Smart Delta SmartPano MSS 8k camera
    b. Camera Mount
        i. Custom apparatus constructed by ElectriCity Bikes in Washington, DC on the front rack of the ebike
3. Tablet
    a. Samsung Active Tab 3
    b. Tablet Handlebar Mount
        i. Quad Lock's 'out front mount'
4. Battery
    a. Goal Zero's Venture 75 power bank
5. Storage
    a. ORTLIEB waterproof saddlebags for project and personal equipment
6. Data Storage
    a. Solid State Drives for storing substantial amounts of data

7.2. Standard Biking Materials

7. Safety
    a. Helmet
    b. Ebike includes bell for signaling
    c. Front and rear lights
8. Maintenance
    a. Tire pump
    b. Tire patches, multi-tool, chain lube, extra tire tubes

7.3. Project Equipment Costs

Category	Product	Quantity	Price	Total
Critical project materials				
Ebike	Specialized Como 4.0 650b	2	$4,398.99	$8,797.98
Camera/Sensor/ Software	Smart Delta "SmartPano" MSS 8k camera system (includes GPS, accelerometer, data management software, annotation, and visualization capabilities)	2	$3,572.00	$7,144.00
Front Rack with Camera and Tablet Mounts	Custom apparatus constructed by ElectriCity Bikes in Washington, DC on the front rack of the ebike with Quad Lock's 'out front mount'	2	$493.92	$987.84
Tablet	Samsung Galaxy Tab Active 3 Enterprise Edition 8" Rugged Multi-purpose Tablet (64G & Wi-Fi), Biometric Security (SM-T570NZKAN20)	2	$434.98	$869.96
Battery	Goal Zero Venture 75 Portable Charger Power Bank 19200mAH 60W USB-C Power Delivery Port, 2 USB Outputs	2	$119.95	$239.90
Storage on bike	ORTLIEB Back-Roller City Rear Pannier: 1 Pair	2	$179.99	$359.98
Data Storage	Samsung SSD T7 Portable External Solid-state Drive 1TB, up to 1050MB/s, USB 3.2 Gen 2	2	$109.99	$219.98
	Subtotal			*$18,619.64*
Support equipment (standard biking materials)				
Vehicle Bike Rack	Thule 903202 EasyFold XT 2" Hitch Rack: 2-Bike (65lbs per bike) - rack stowable reinforced ramp	1	$953.99	$953.99
Trailer Hitch	Class 3 trailer hitch with 2" receiver	1	$317.99	$317.99
Support equipment	Miscellaneous items include folding bike locks/frame mounts, bike repair kits, pump, rear bike racks, water bottle cages/bottles, high visibility vests, helmets, seatpost to accommodate shorter rider	2	$553.88	$1,107.76
	Subtotal			*$2,379.74*
	Total			**$20,999.38**

7.4. Trailblazer Assessment Preparation Guidelines

1. Transportation
    a. Option 1: Ride bikes to location for nearby sites
    b. Option 2: Bike rack on personal or government vehicle for longer distances
    c. Option 3: Ship bikes to location
2. Pre-Ride
    a. Charge ebike, tablet, SmartPano and battery pack
    b. Check tire pressure, pump to sufficient pressure if necessary
        i. Tire pressure should remain near target of 40 PSI for consistency
    c. Check battery levels
    d. Ensure breaks, gears, and electric assist are functioning
    e. In Saddlebag:
        i. SmartPano case
        ii. Tire pump
        iii. Tire patches
        iv. Back-up tubes
        v. Tube lever
        vi. Multi-tool
        vii. Chain lube
        viii. Bike charger
        ix. Battery pack charger
        x. Charging blocks for SmartPano and Tablet chargers
3. Assembly
    a. Battery
        i. Attach fully charged battery to mount on front rack, turn on
    b. SmartPano
        i. Attach fully charged SmartPano to mount on front rack, turn on
        ii. Plug into batter pack, ensure camera is charging
        iii. Turn on the camera’s Wi-Fi hotspot, QR code should display
    c. Tablet
        i. Scan the camera’s QR code to connect to the camera’s Wi-Fi hotspot
        ii. Once connected, scan the subsequent QR code displayed on the camera to access the camera’s web page

            1. Smart Delta’s internal offline webpage should load on tablet screen
            2. 

        iii. Above: screenshot of the tablet’s screen featuring an offline map and annotation buttons
        iv. Attach tablet to tablet mount on handlebars
        v. Plug into battery pack, ensure tablet is charging

    d. Saddlebags

        i. Attached full saddlebags to ebike

7.5. Trailblazer Assessment Riding and Data Collection Guidelines

4. Riding

        i. Alignment

            1. Remain as near to the center the appropriate trail lane as possible

        ii. Speed

            1. Respect trail speed limits
            2. Should aim for a consistent speed of 15mph for consistency in data
            3. Use higher electric assist and lower gears going up large hills to remain near target speed

        4. Reduce speed and electric assist at top of hills, do not heavily accelerate at top of hills so to not exceed target speed and not require heavy breaking
        5. Avoid hard breaking that abruptly changes speed- aim for smooth breaking and minimal changes in target speed
    iii. Passing
        1. Use the bell or say “passing” when passing, try to stay at the target speed in the center of trail lane
        2. Stay in correct trail lane unless necessary to pass in oncoming lane
    iv. Etiquette
        1. Let faster trail users pass
        2. Try not to exceed trail speed limit
    v. Turning
        1. Avoid abrupt turns, go through turns smooth while trying to remain at target speed
    vi. Gears
        1. Use gears to keep peddling rate smooth, lower gear for going up hills and higher gear when riding flat or going downhill
    vii. Electrical Assist
        1. Stay on level 1 unless going up a hill
    viii. Stopping
        1. When stopping, press the ‘slow/stop’ annotation on the tablet, and then pause the collection with the ‘pause’ button on the screen

Once desired section of trail is complete, or battery limit is reached, researchers end recording of SmartPano by pressing the ‘stop’ button on the tablet

a. Turn off SmartPano and Tablet
b. Once at transportation or destination:
    i. Detach SmartPano and put it in its case, store it
    ii. Detach Tablet and store it
    iii. Detach battery pack and store it
    iv. Turn off ebike
    v. Remove bike battery (?) and load bike into transportation or secure storage
c. After transportation, recharge:
    i. ebike battery
    ii. Battery pack

        iii. Camera
        iv. Tablet

    d. Data Processing
        i. Copy the entire MMS folder from the SmartPano Camera to an external solid-state drive for subsequent processing and analysis of data