Development of Instrumented Bikes: Toward Smart Cycling Infrastructure and Maintenance

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A Research Report from the Pacific Southwest Region University Transportation Center

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16. Abstract
This project is to develop an instrumented bike with a sensor logger, a video device (e.g., GoPro), a mobile app, and a cloud server/website to detect real-time quality of cycling infrastructure systems (bike trails, sidewalks, pedestrian pathways, etc), and immediately share the information with cyclists (road users) and governments/authorities (road managers) such that (1) cyclists (road users) will be aware of upcoming potential hazards prior to cycling and be able to adjust their cycling route accordingly, and (2) governments (road managers) will be able to effectively prioritize their maintenance needs. A computing algorithm using the sliding window method was developed in support of the development of instrumented bike. Based on field cycling test, the sliding window computing algorithm is capable of analyzing vibration patterns and identifying potential hazards (potholes, bumps, uneven surface, cracks, etc.) through multiple cyclists. The purpose of the project is to introduce an instrumented bike to the cycling community and agencies with a goal to provide "smart wheels" for day-to-day cycling operations, improve bike efficiency, safety, and mobility, promote cycling activities, and reduce emissions.

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Table of CONTENTS

About the Pacific Southwest Region University Transportation Center

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The Pacific Southwest Region UTC conducts an integrated, multidisciplinary program of research, education and technology transfer aimed at improving the mobility of people and goods throughout the region. Our program is organized around four themes: 1) technology to address transportation problems and improve mobility; 2) improving mobility for vulnerable populations; 3) Improving resilience and protecting the environment; and 4) managing mobility in high growth areas.

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Disclosure

Principal Investigator, Co-Principal Investigators, others, conducted this research titled, "Development of Instrumented Bikes: Toward Smart Cycling Infrastructure and Maintenance" in the Department of Civil Engineering, Construction Management, and Environmental Engineering, and the Department of Geography, Planning, & Recreation at the Northern Arizona University. The research took place from 08/15/2021 to 08/14/2022 and was funded by a grant from the US Department of Transportation in the amount of $99,996. The research was conducted as part of the Pacific Southwest Region University Transportation Center research program.

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Abstract

This project is to develop an instrumented bike with a sensor logger, a video device (e.g., GoPro), a mobile app, and a cloud server/website to detect real-time quality of cycling infrastructure systems (bike trails, sidewalks, pedestrian pathways, etc), and immediately share the information with cyclists (road users) and governments/authorities (road managers) such that (1) cyclists (road users) will be aware of upcoming potential hazards prior to cycling and be able to adjust their cycling route accordingly, and (2) governments (road managers) will be able to effectively prioritize their maintenance needs. A computing algorithm using the sliding window method was developed in support of the development of instrumented bike. Based on field cycling test, the sliding window computing algorithm is capable of analyzing vibration patterns and identifying potential hazards (potholes, bumps, uneven surface, cracks, etc.) through multiple cyclists. The purpose of the project is to introduce an instrumented bike to the cycling community and agencies with a goal to provide “smart wheels” for day-to-day cycling operations, improve bike efficiency, safety, and mobility, promote cycling activities, and reduce emissions.

Development of Instrumented Bikes: Toward Smart Cycling Infrastructure and Maintenance

Executive Summary

The market of connected vehicles has been growing dramatically in recent years; with the global market expected to reach $225.16 billion by 2027. However, as a part of intelligent transportation systems, the use of geospatial and remote sensing in cycling mobility has yet to receive significant attention, likely due to limited efforts in manufacturing instrumented bikes or smart bikes to actually promote cycling mobility and reduce greenhouse gas emissions. Particularly, during the current COVID-19 pandemic, the encouraging of cycling can decrease exposure to others on public transport, reduce air pollution, and promote improved health and well-being. This project is to develop an instrumented bike with a sensor logger, a video device (e.g., GoPro), a mobile app, and a cloud server/website to detect real-time quality of cycling infrastructure systems (bike trails, sidewalks, pedestrian pathways, etc), and immediately share the information with cyclists (road users) and governments/authorities (road managers) such that (1) cyclists (road users) will be aware of upcoming potential hazards prior to cycling and be able to adjust their cycling route accordingly, and (2) governments (road managers) will be able to effectively prioritize their maintenance needs. The purpose of the project is to introduce an instrumented bike to the cycling community and agencies with a goal to provide "smart wheels" for day-to-day cycling operations, improve bike efficiency, safety, and mobility, promote cycling activities, and reduce emissions.

The project began with the design of sensor logger consisting of a microprocessor with a Wi-Fi module, accelerometers, Global Positioning System (GPS) unit, and a battery system followed by a few field tests performed by four different cyclists including male and female and varying bikes. The report started with introduction of the project and the background of instrumented bike (Chapter 1). Based on our previous research work, a threshold method to identify severity level of cycling facilities is not considered as an effective approach. Thus a generic deep learning based computing algorithm using the sliding window method was developed in support of the development of instrumented bike (Chapter 2). We conducted two different field tests on paved and unpaved cycling facilities/trails on the Northern Arizona University campus and the City of Flagstaff bike trails with goals to evaluate the effectiveness of sliding window computing algorithm in identification of potential hazards (bumps, potholes, uneven surface, cracks, etc) known as point of interest (POI). A list of the severity level of cycling facility ratings was conducted on the two paved cycling trails (Chapter 2). In addition, the existing conditions of the bike facilities (both paved and unpaved) were compared against the guidelines set forth in the American Association of State Highway and Transportation Officials (AASHTO) Guide for the

Development of Bike Facilities and the Manual on Uniform Traffic Control Devices (MUTCD, 2012) (Chapter 3). The conclusions and recommendation were provided in Chapter 4.

Based on the results, the project concluded that the sliding window computing algorithm is capable of analyzing vibration patterns and identifying potential hazards (PIOs) through multiple cyclists; it has achieved the state-of-the-art performance in classifying and localizing cracks/potholes without any human-controlled supervision (e.g., annotated dataset used to train the classifier; threshold adjustments for distress classifications) while achieving human-level perception. The development of instrumented bike provides a promising methodology to (1) help local government or agency in reviewing existing cycling trail conditions based on real time cycling information such that a list of repair priorities can be provided for decision making for maintenance and (2) share the results with cyclists so allowing them to adjust cycling routes prior to cycling.

Introduction

The market of connected vehicles has been growing dramatically in recent years; with the global market expected to reach $225.16 billion by 2027 (1). However, as a part of intelligent transportation systems, the use of geospatial and remote sensing in cycling mobility has yet to receive significant attention, likely due to limited efforts in manufacturing instrumented bikes or smart bikes to actually promote cycling mobility and reduce greenhouse gas emissions. Particularly, during the current COVID-19 pandemic, the encouraging of cycling can decrease exposure to others on public transport, reduce air pollution, and promote improved health and well-being. While cycling on bike facilities, the roadway surface structure plays an important role in bike ride quality. With the continued growth in cycling activity and infrastructure throughout the country, the question of how to obtain real time information on cycling facilities that would help better maintain the quality of these facilities and provide safe environment for cyclists has become a concern among city, county, and state engineers. The use of sensors/accelerometers attached on bikes have been investigated by numerous researchers to study cyclist behavior, monitor cycling motion, and measure the force of pedaling (2)-(9), however this technology presents an untapped potential to assess bike facility surface conditions. There is an urgent need to meet increasing demands for cyclist safety to motivate increased activity, thus the research team believes that the interactive behavior of cyclists plays an important role in bringing together improved bike mobility and community engagement. More importantly, how to encourage cycling activities through a well-designed program, and enable riders to stay connected has been a challenge nationally.

This project is to develop an instrumented bike with a sensor logger, a video device (e.g., GoPro), a mobile app, and a cloud server/website to detect real-time quality of cycling infrastructure systems (bike trails, sidewalks, pedestrian pathways, etc), and immediately share the information with cyclists (road users) and governments/authorities (road managers) such that (1) cyclists (road users) will be aware of upcoming potential hazards prior to cycling and be able to adjust their cycling route accordingly, and (2) governments (road managers) will be able to effectively prioritize their maintenance needs. The purpose of the project is to introduce an instrumented bike to the cycling community and agencies with a goal to provide “smart wheels” for day-to-day cycling operations, improve bike efficiency, safety, and mobility, promote cycling activities, and reduce emissions.

Chapter 1 Background of Instrumented Bike

Introduction to instrumented bike

The instrumented bike can be seen as a smart bike with the ability to sense the roads and cycling trails during riding, report anomalies, and share the information with cyclists. Its functions are sensing, transmitting, and storing cycling information and data collected from the cycling trails. The instrumented bike is equipped with a sensor logger consisting of a microprocessor with a Wi-Fi module, accelerometers, Global Positioning System (GPS) unit, and a battery system (Figure 1-1). A sensor logger is connected and paired with a mobile phone installed with the application that the team developed (Figure 1-2). During traveling, all vibration data will be stored in a smart phone through a newly developed mobile application named “Motion Tracking” (Fig. 1-3). As shown in Fig. 1-3, the fundamental functions of this app is capable of data collection and restoration from accelerometers and the GPS chip, data visualization of the value of accelerometers, and a location of instrumented cycling motion in a real time Google map. The mobile app is designed to receive the raw signals, georeferenced their locations, and store the data. After vibration data was collected using an instrumented bike along cycling trails, all data were retrieved from the mobile apps for signal processing and analysis using the computing algorithms developed by the team. Based on the results, the severe locations (potholes, uneven surfaces, bumps, etc.) known as points of interest (POI) were selected, georeferenced, displayed in maps, and shared with end users (i.e., cyclists, government employees, etc.). The information shared with the end users can be used to help cyclists avoid hazards and inform road managers to do the maintenance. In order to identify the crucial points in a vast amount of data, the research team uses a machine learning (ML) computing algorithm to locate these points thus making sure the analysis results are reliable and accurate for the end users.

Figure 1-1: Instrumented bike with a sensor logger attached on the rear rack

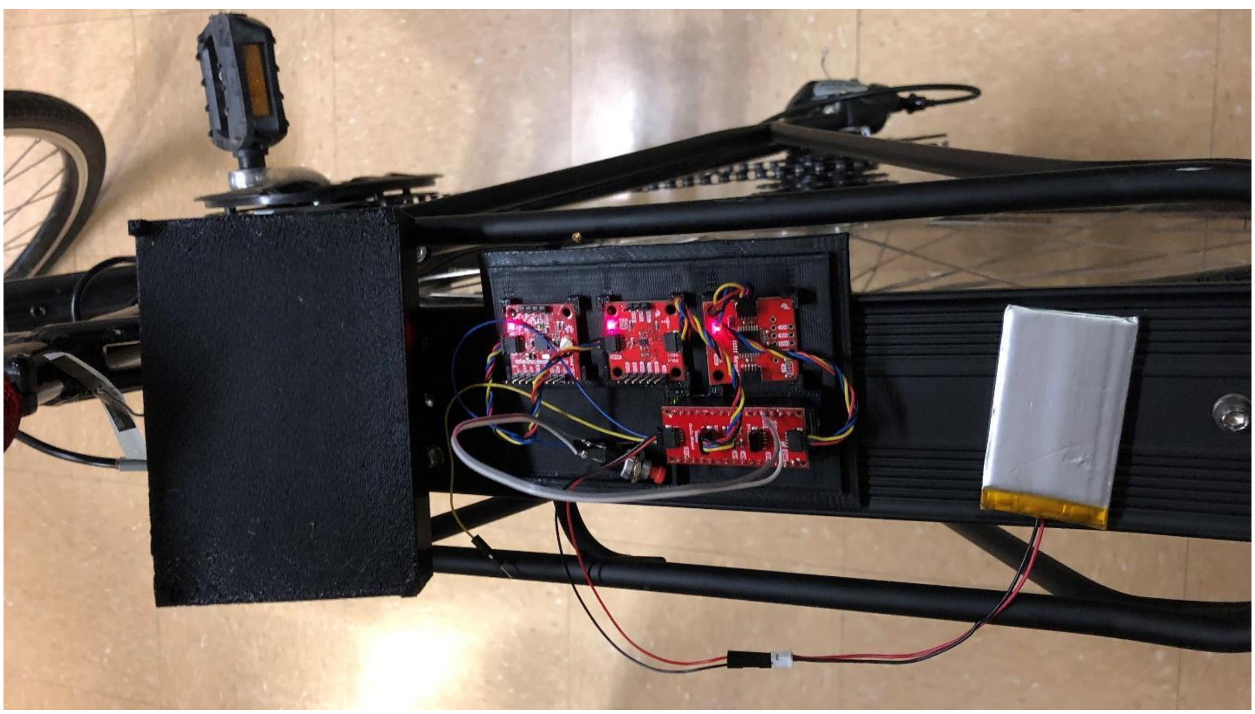


Figure 1-2: Layout of a sensor logger

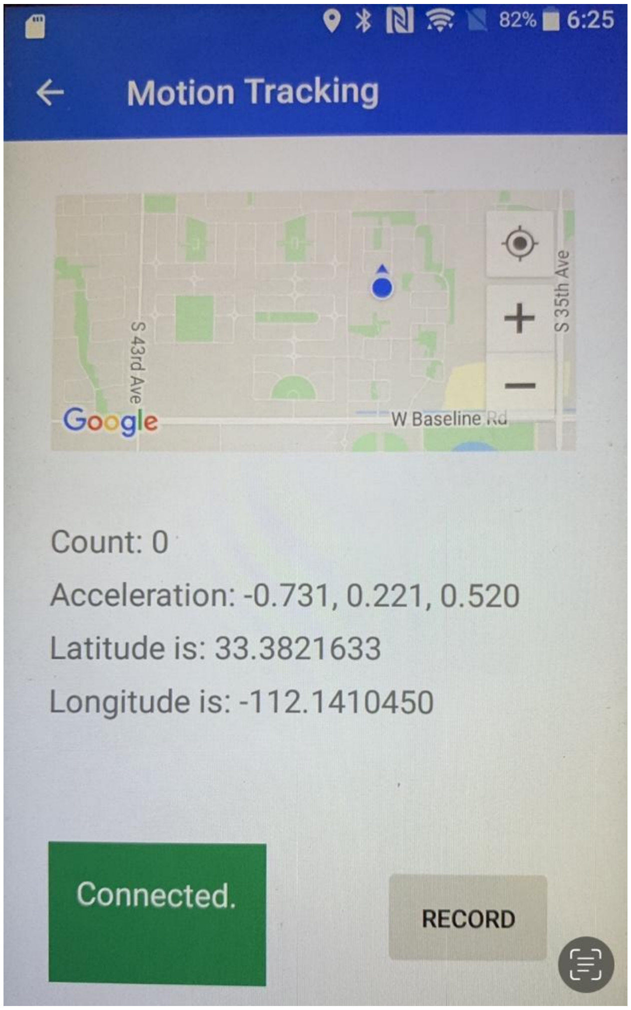


Figure 1-3: Mobile apps with motion tracking

Background of Computing Algorithms of Instrumented Bike

An instrumented bike was first developed at Northern Arizona University (NAU) in 2018 [7][8]. The prototype of the instrumented bike already had the competence to collect, analyze and share data. The instrumented bike is equipped with a sensor logger, a mobile application, and a cloud-based platform to provide the cycling community with a tool that can be taken into account to assess road/cycling trail conditions and share the real-time information obtained from the cyclists traveling on trails. However, the limitations of the original device are apparent. First, the hardware promotion is necessary since the sensor logger contains many components without integration, and the bike needs a specific platform to hold the entire device. Second, the original computing algorithm can recognize the cracks/potholes in a specific condition, using a 0.95g as a threshold. In the original computing algorithm, the research team only used Fast Fourier Transformation (FFT) to transfer raw signal in the Fourier domain into a true signal domain which eliminates the signal noise. Even though the transformed signal is reliable to some extent, complex environmental conditions are difficult to control by people. There are several concerns if the team just used FFT to accomplish road monitoring. The biggest concern is that the key parameters of FFT must be hand-crafted, while the result highly depends on those parameters. This may lead to complex thresholding in different scenarios, destabilizing the whole system. The second concern is that FFT is time-and-memory-consuming while dealing with long sequence data, considering this is only a preprocessing of data. The third concern is that the weights of each rider and bike vary which would have a significant impact on the determination of threshold used to identify POIs. Besides, weather and climate conditions would influence the road conditions leading to a difficult situation for the determination of thresholds. If the variables keep changing while riding, it will hardly define which threshold should be used. As a result, this is not convenient and accurate for the identification of POIs since the threshold is just based on statistical analysis data distributions and does not take other computing algorithms into calculations for the POI classification.

To advance these defaults, the research team developed a new computing algorithm using a generic deep learning approach with an objective to provide a systematic computing process and improve the computing capability currently used in the instrumented bike. This new algorithm framework is reliable for identifying the cracks/potholes and locating them which will be discussed in Chapter 2.

Chapter 2 Development of Computing Algorithms

The focus of this chapter is on how a generic machine learning based algorithm was developed to identify patterns that would represent severe or hazardous road conditions.

Literature Review

The developed Instrumented bike [7][8][9] provides a reliable framework to sense, transmit and store acceleration information on various biking trails. The variation of acceleration in 3-axes can physically encode the intrinsic features of cracks and potholes: the acceleration will change dramatically in either axis when cracks/potholes are encountered. Taking advantage of those collected acceleration data to detect and localize cracks/potholes, however, becomes inherently intractable. Previously, the window-interpolation method proposed by Qiu et al. [10], can detect cracks/potholes by dividing the data into many non-overlapping chunks and then determining the difference between maximum and minimum accelerations within one window. However, as previously mentioned, the handcrafted threshold varies dramatically in different scenarios. Even though different thresholds can be tested out in different scenarios, it is practically infeasible to handcraft threshold in every single event. This method even fails in some cases where 1) two adjacent cracks/potholes are very close; 2) the cracks/potholes are very small; 3) the speed is so fast that beyond the sampling frequency. In addition, this method only works for limited sampling frequency (around 50Hz), while the accelerometer is capable of higher sampling frequency (around 200Hz), resulting in the sparsity of samples within a given time slot.

Recently, the advances in many machine learning techniques enable the team to take advantage of the huge amount of data to uncover the hidden pattern within a sequence of acceleration data. The majority of them [11]-[14], however, need annotated data to train a classifier in a supervised setting to identify whether a subsequence of the acceleration data contains cracks/potholes. In practice, it is laborious to manually label the crack/pothole pattern within a sequence of acceleration data. In addition, human bias may also be introduced during labeling, as manual annotation is equivalent to perceptually identifying the cracks/potholes. Furthermore, many classical powerful machine learning methods (e.g., Support Vector Machine, Random Forest) still need to handcraft features a-priori and generally fail to capture the long-range time dependencies between data points. Cracks/potholes are jointly encoded by a small sub-sequence of acceleration in a specific order within a certain time slot. For example, the acceleration in the Z-axis first goes up and then goes down for cracks (Potholes work in the opposite way).

Accordingly, a generic method is desired to detect and localize cracks/potholes accurately and robustly while minimizing the impact of variations of physical conditions such as speed, sampling frequency, weather, different bikes, etc. Recently, recurrent neural networks (RNNs) based methods are widely used to process acceleration data in human activity recognition task [11]-[14]. The RNNs has the capability of capturing the dependencies of data with respect to time, which represents the acceleration data in a probabilistic way over time. However, the RNN-based methods are trained in a supervised way which inputs an acceleration sequence and outputs a label indicating the classification category (e.g., cracks or non-cracks). However, the process of annotating acceleration data is laborious and expansive. To tackle the lack of annotated data, the team built on the concept of another family of machine learning techniques-unsupervised Representation Learning [15]. The principal idea is that instead of learning the direct mapping from acceleration sequence to crack/pothole label, the algorithm learns the representation of normal biking trails on crack/pothole-free areas. During inference, the anomaly crack/pothole can be detected as their patterns are different from those from crack/pothole-free regions. The whole idea was implemented as an RNN-based autoencoder neural network [14][15]. Finally, the team takes advantage of sliding window technique to localize cracks/potholes to map them to corresponding location coordinates. The paper also provides an efficient solution to do inference with sliding window technique and the proposed neural network. In this paper, the team presents an automated and systematic approach to detect and localize cracks/potholes getting rid of any human-supervision. The whole framework is illustrated in Figure 2-1.

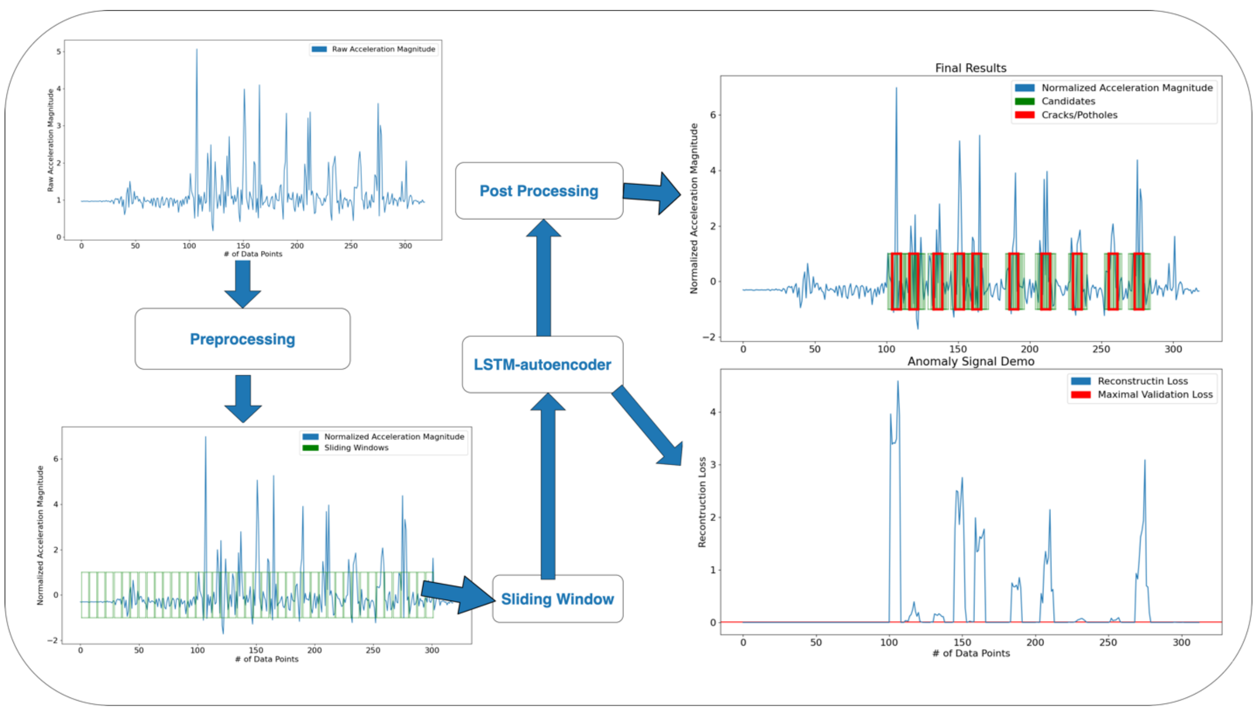


Figure 2-1: The whole framework including preprocessing, Sliding Window, LSTM-autoencoder Neural Network, Post processing

Classification with LSTM-Autoencoder

Cracks/potholes detection from acceleration data is a challenging task for machines, even though the variation of accelerations in 3 axes can physically encode the pattern of cracks/potholes. While the pattern of cracks/potholes can be distinguished effortlessly by human-beings out of a sequence of acceleration. The human-beings recognize cracks/potholes by their visualization and riding experience based on the dramatic changes of acceleration within a certain sub-sequence. Accordingly, the intrinsic representation of cracks/potholes encoded by acceleration are physically and perceptually sufficient for human-beings to identify them. Autoencoders which mimic the human-beings to learn the representation of cracks/potholes without annotated data are desired for this task.

An autoencoder is made up of the encoder and the decoder. The encoder projects the input data space χ into the latent space Γ, which is also known as the latent representation, via a function $\varphi: \chi \rightarrow \Gamma$. While the decoder, which generally has mirror architecture to the encoder, reconstructs the input data from the latent representation via a function : $\Gamma \rightarrow \chi$. Mathematically, an autoencoder is defined as

$$\varphi, \Phi = arg\, min_{\varphi, \Phi} ||\chi - (\varphi \circ \Phi)\chi||^2,$$

which minimizes the distance between the input data and the output reconstruction from the network. The formulation of the autoencoder suggests that the training of an autoencoder is fully unsupervised, or technically self-supervised, which is another motivation of using the autoencoder architecture. However, cracks/potholes are not commonplace during normal biking, since extracting them from the original signal is equivalent to detecting them. Alternatively, the representation of crack/pothole-free biking sequence (smoothing sequence), as they are more easily obtained, can be used to help recognize cracks/potholes as anomalies. Once the reconstruction loss in the inference is greater than the maximal validation reconstruction loss during training, the sequence is identified as cracks/potholes.

Another insight to perceptually human-level cracks/potholes recognition is that the order of the data points supports human-beings to identify them. For example, the acceleration in the Z-direction firstly goes up then goes down or vice versa. Thus, the dependencies between the data points are another key factor to identify cracks/potholes, leading to the Recurrent Neural networks. The RNN captures the temporal dependencies (or orders) of sequence input by propagating the information from the current state to the next state. The vanilla RNNs, in practice, lose long-term dependencies [16]. Therefore, the vanilla RNN was replaced by Long short-term Memory (LSTM) architecture which inherently captures the long-term dependencies. The problem of long-term dependency is quite tricky during the data processing because the dependency relies on the size of cracks/potholes. In the cases where the sizes of cracks/potholes are large, the long-term dependency is likely to be supportive to detect them. Whereas, for small cracks/potholes, the long-term dependency barely has an apparent impact on the result. In the meanwhile, the vanilla RNNs generally encounter exploding or vanishing gradients during training [16], because the weights will either decay or grow exponentially if they are not equal to identity, while the LSTM mitigates this issue [17]. As a result, the LSTM unit is incorporated into the autoencoder architecture so that the network can learn the sequence representation in a self-supervised way. The proposed network is implemented as a LSTM-autoencoder as shown in Figure 2-2.

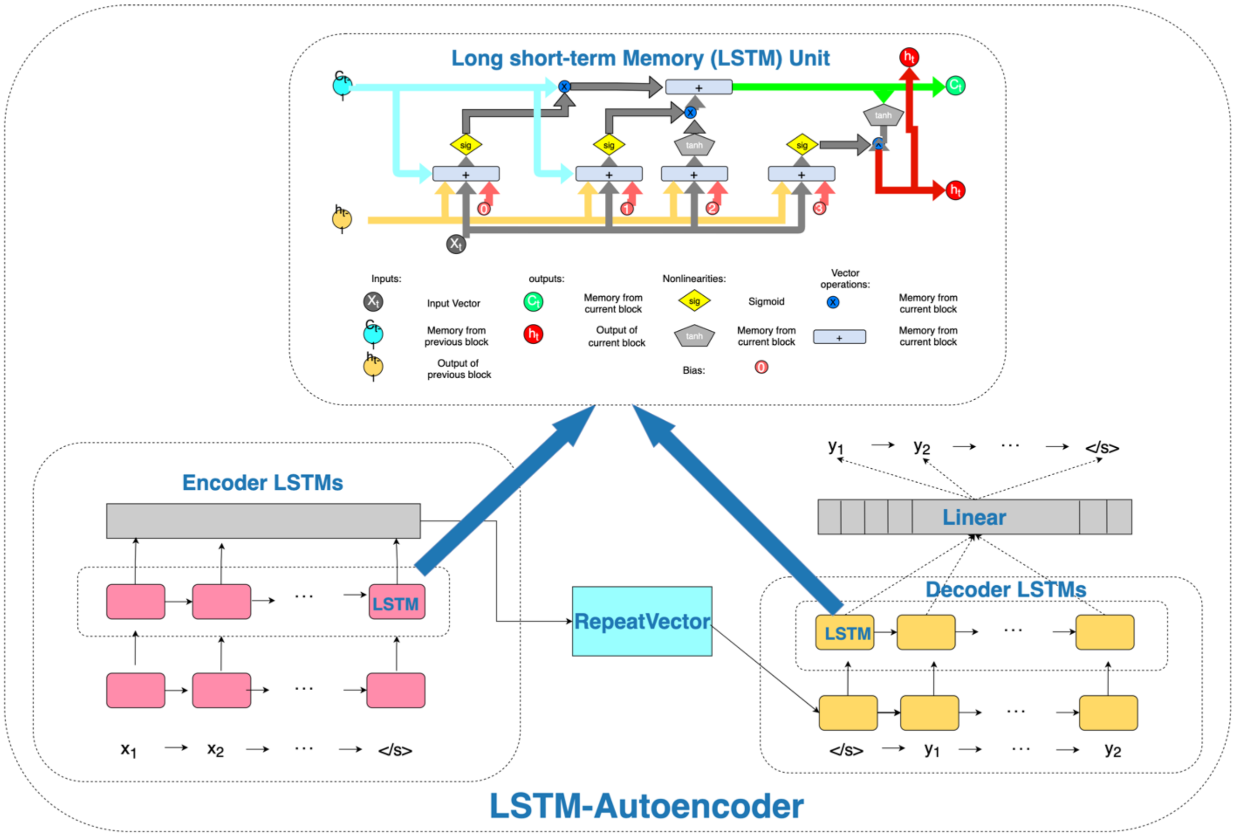


Figure 2-2: The architecture of proposed LSTM-Autoencoder.

Even though, for the purpose of demonstrating the effectiveness of our methodology, a simple architecture including 2 LSTM units with 2 layers was used for both the encoder and the decoder, and the performance is extraordinary (the stationary training loss and validation loss is close to 0 as is shown in Figure 2-3. The paper's intent is to leave the possibility to build more complex architecture in the future.

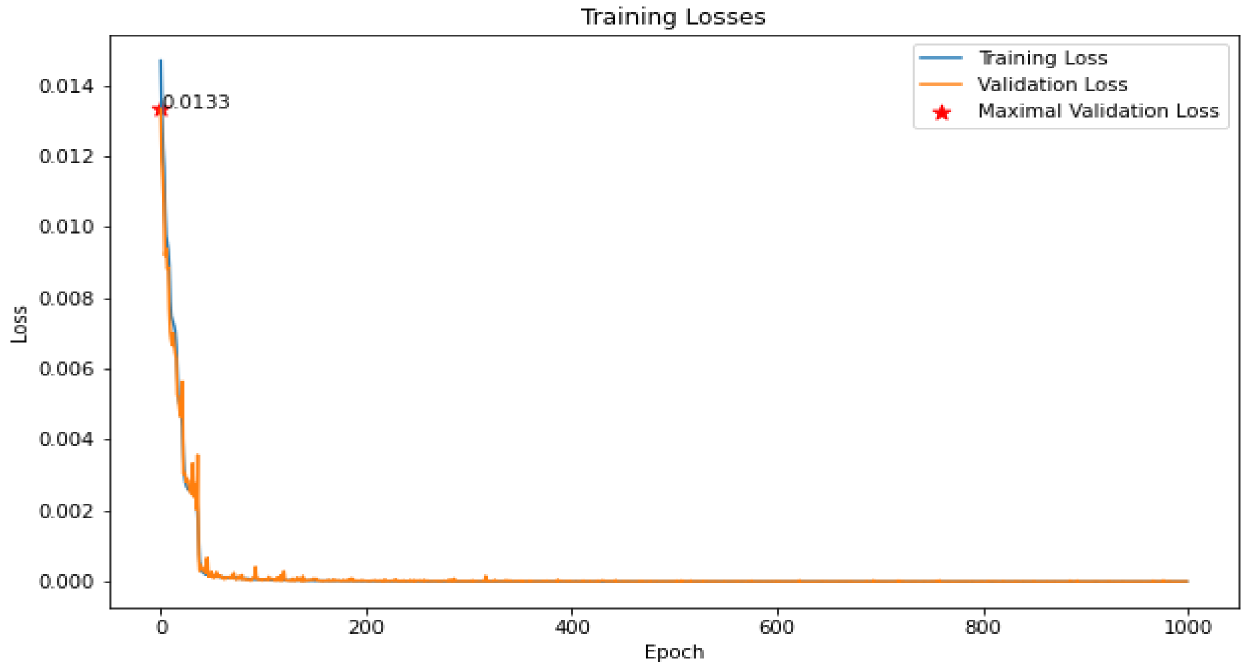


Figure 2-3: Training and Validation losses after each training epoch during neural network training process.

Preliminary Test

The preliminary test was conducted by biking across ten PVC pipes on a flat pavement to validate the effectiveness of the proposed method. As is shown in Figure 2-4, the performance of the proposed method is impressive. The reconstruction loss for the smoothing pattern is close to zero as illustrated by the training process, the reconstruction loss above the maximal validation loss (as is shown by the horizontal red line in Figure 2-4) should be identified as anomalies. The anomaly patterns classified by the LSTM-Autoencoder have a one-to-one match to the crack/pothole patterns in the raw signal as promised. Subsequently, the sliding window technique accurately localized the candidates of cracks/potholes as illustrated by green bounding boxed in Figure 5. The final aggregated bounding boxes of cracks/potholes were achieved through the post-processing as illustrated by red bounding boxes (where the preinstalled 10 PVC pipes were located) in Figure 2-4. The preliminary testing sufficiently proves this fully automated method achieves human-level perception in identifying “bumps” (caused by the 10 artificial PVC pipes) out of a sequence of acceleration values without any supervision (annotated dataset). This preliminary test highlights the advantage of using the proposed sliding window method to effectively detect cracks/potholes without a threshold setting in the computing algorithm so that a human-being bias would be avoided.

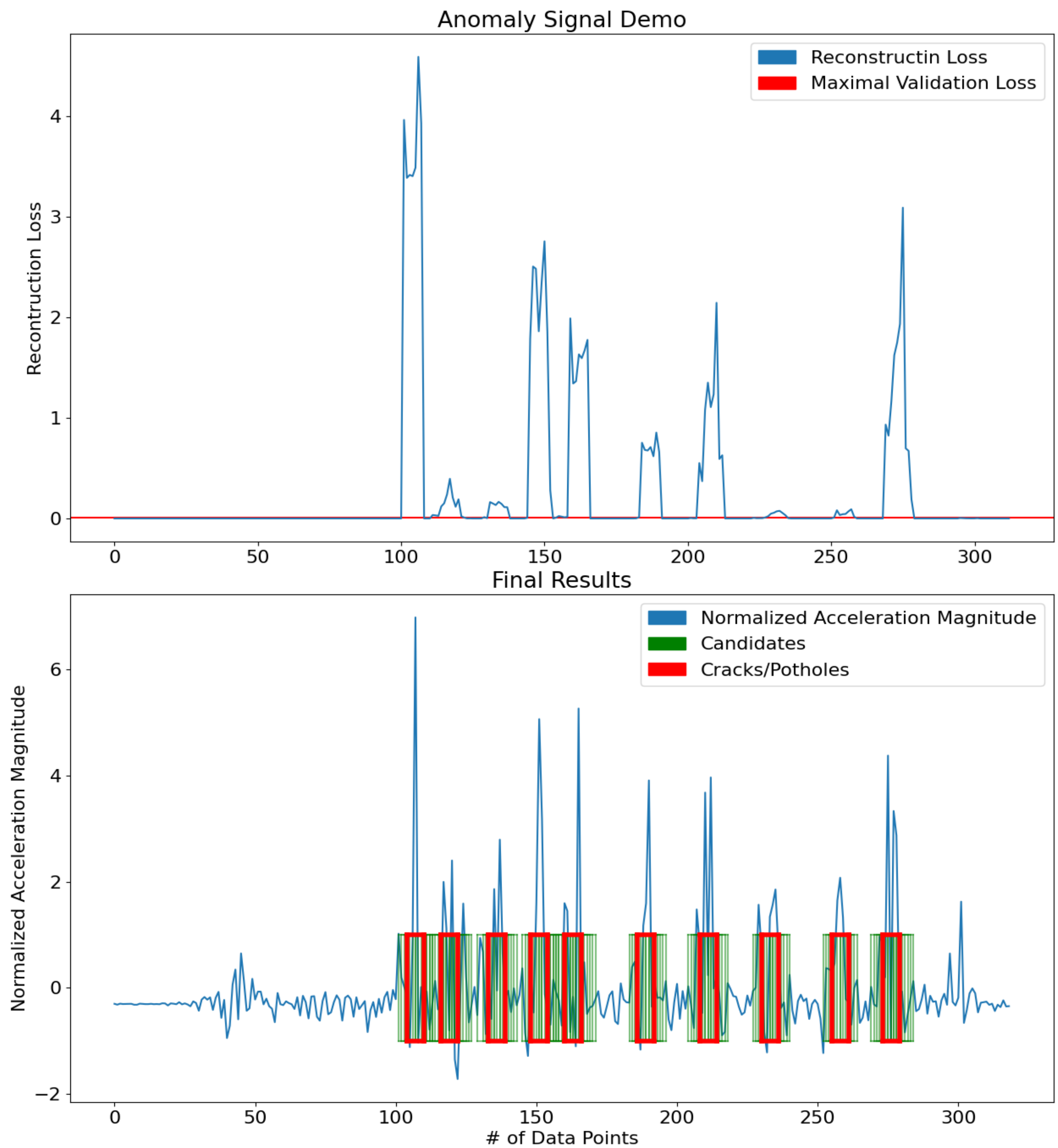


Figure 2-4. Preliminary test results on 10 PVC pipes using proposed method.

Note: From top to bottom: 1) anomalies detected by the LSTM-Autoencoder; 2) the localized crack/pothole candidates by sliding window technique and aggregated cracks/potholes by post-processing.

Field validation (Single Cyclist)

After preliminary test was successfully done to detect bumps (e.g., artificial PVC pipes) known as POIs, a bike trail on the Northern Arizona University campus was selected for a field validation of the instrumented bike in detecting and localizing cracks/potholes, using the computing algorithms developed in the paper. The bike trail selected for the field validation exhibits varying pavement roughness conditions (good, fair, and poor) which is suitable for the purpose of the data collection and processing. During instrumented cycling along the bike trail, all vibration data were recorded and wirelessly transferred to a cloud server. All data stored in the cloud server were retrieved and then analyzed using the sliding window method associated with LSTM-based autoencoder neural network to aggregate candidates and detect cracks/potholes as illustrated in Figure 2-5. A total of 2474 vibration points were sensed, collected, and analyzed for field validation, and a total of 62 cracks/potholes known as POI were recorded and localized with coordinates. Notice that the data used for field validation is different from those used for training (they came from two different paths). As shown in Figure 6, the anomalies (potential cracks/potholes) detected by the proposed neural network matches perfectly to the patterns of cracks/potholes in the raw accelerometer data. The final aggregated boxes from the detected cracks/potholes candidates bound the crack/pothole pattern in the original signal. The selected 62 POIs were retrieved from the original dataset and imported and graphed in a map using ArcGIS for review (Figure 2-6). To further validate the accuracy of the POI detection, a physical visit was scheduled to visualize the degree of POI and evaluate if the proposed computing algorithms are effective in detecting pavement distressed points along the bike trail. Four POIs are preselected and labelled as S1 through S4 on a map prior to a site visit. Based on the field observations, the four POI locations accurately reflect the detection of POIs with significant cracks/potholes being shown on the trail surface (Figure 2-6).

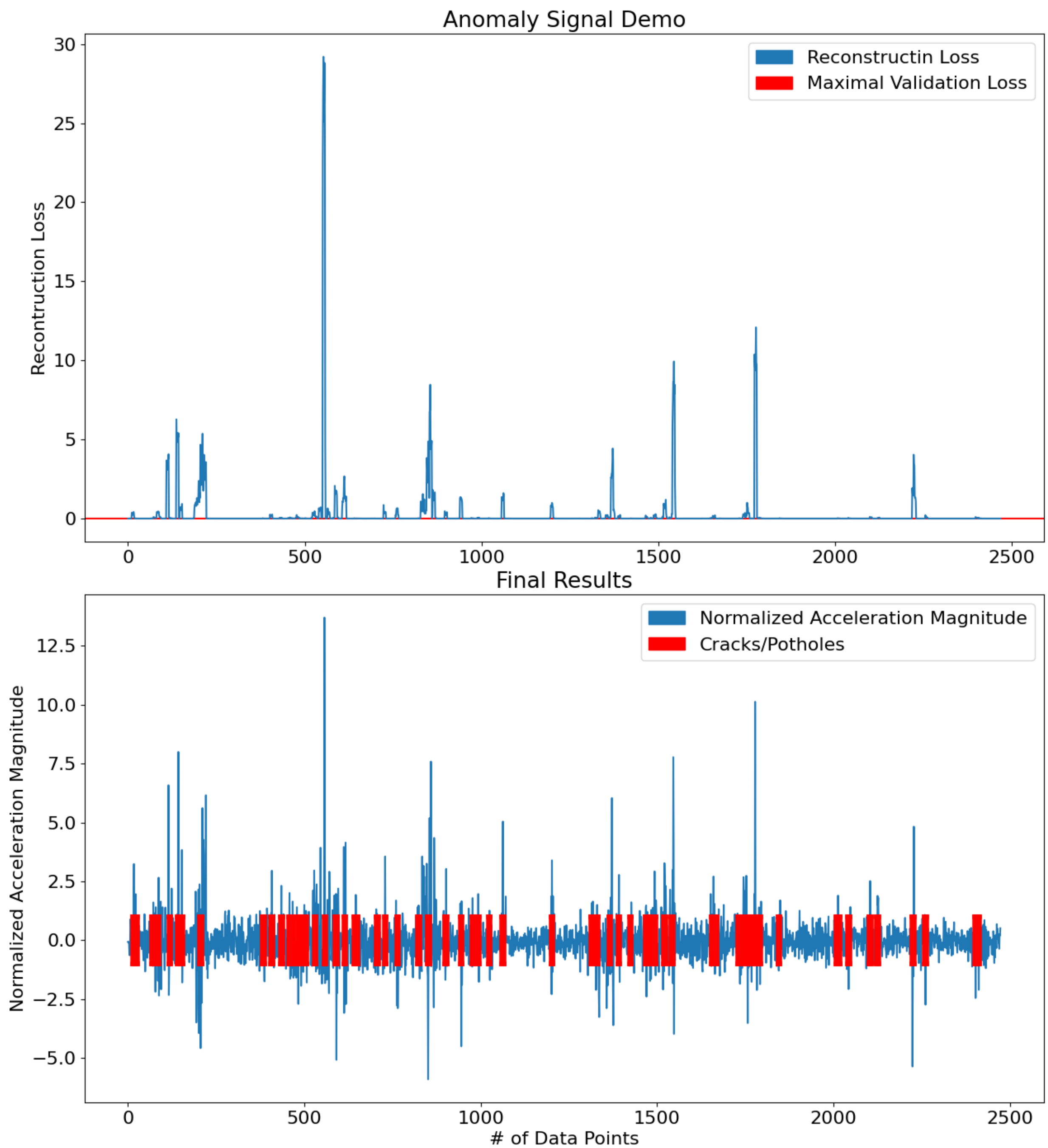


Figure 2-5: The localization of field validation at Northern Arizona University campus with proposed method.

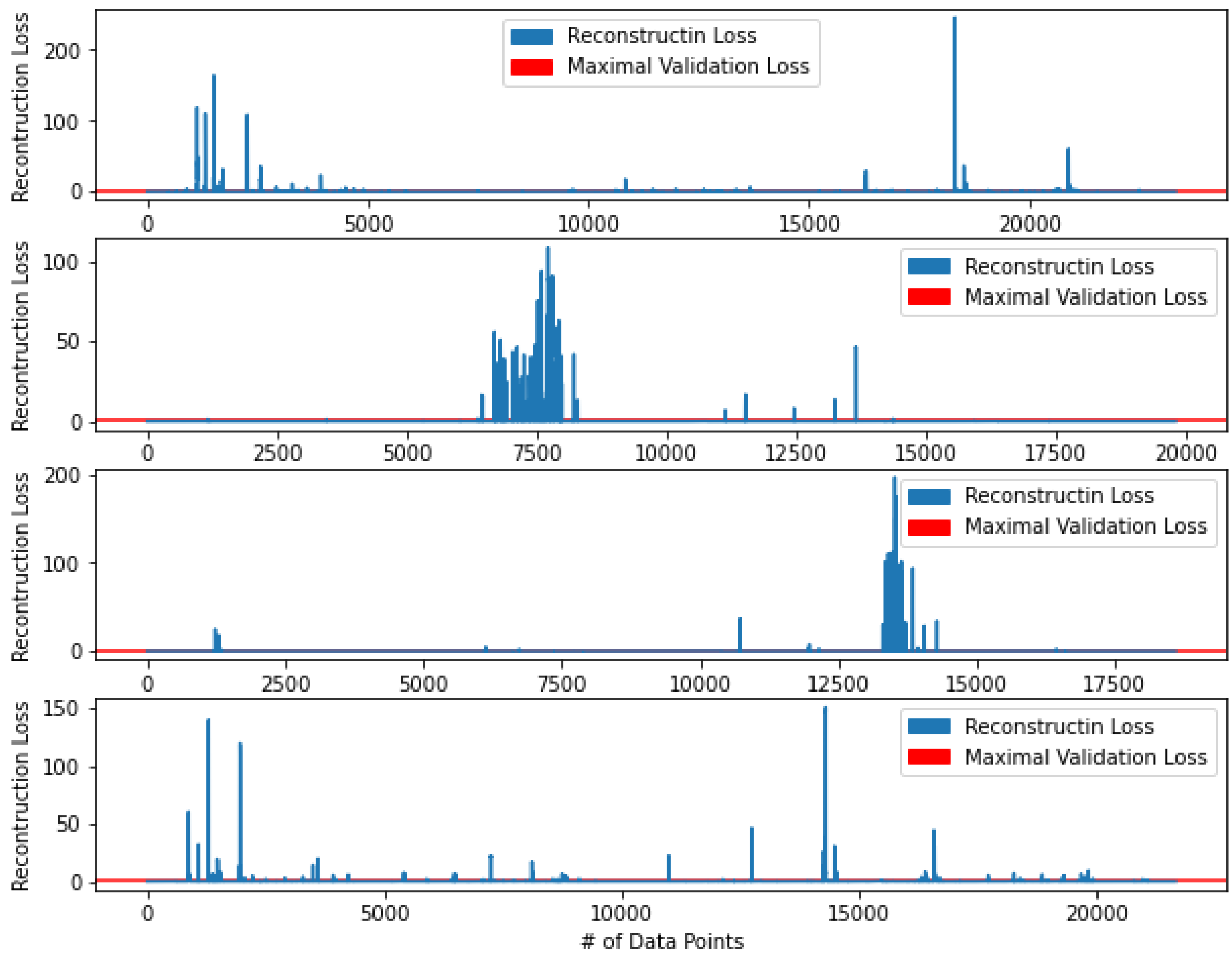
Note: From top to bottom: 1) anomalies detected by the LSTM-Autoencoder; 2) the localized crack/pothole candidates by sliding window technique and aggregated cracks/potholes by post-processing.

Figure 2-6: cracks/potholes detection and localization in a map.

Field Validation (Multiple Cyclists)

During the implementation of instrumented bike prototyping, some questions raised. For example, the weight of different cyclists, cycling speeds, tire pressure of bikes, etc. are considered as factors that would have an impact on the accuracy of identification of distresses on cycling facilities. Based on the previous research by Ho et al. (9), one of concerns in instrumented cycling is how to determine a "threshold" of vibration data based on each of factors to identify POIs. In the past, we have noticed the fact that cyclists come from a variety of body and device weights, and it is not practical to define a single threshold to determine POIs. To address the issues, one of solutions is to use "pattern recognition" instead of thresholds to analyze vibration signals and select patterns that would represent actual POIs. As a part of crowd sourcing data collection process, the team recruited four cyclists and has each one of them travel on the selected bicycle route using their individual instrumented bike. Each trip generated a variety of "vibration patterns" based on the surface conditions and individual cyclist. All patterns generated by instrumented cycling was normalized and analyzed using the sliding window computing algorithm to screen all normalized patterns and select candidates of POIs. The computing principle is that even though different cyclists and bikes would result in varying magnitudes of vibration patterns, however, the normalized patterns of severe cracks, bumps, potholes, uneven areas collected from multiple cyclists will be screened, detected, and identified as POIs. Instead of learning the direct mapping from acceleration sequence to crack/pothole label, the algorithm learns the representation of normal traveling by instrumented bike on crack/pothole-free areas.

After each one of four cyclists completed individual cycling on the selected bicycle route, all data was stored in the mobile apps and then transferred to the computer for analysis. Using the same sliding window computing algorithms, the patterns of potential hazards (i.e., POI) of each cyclist were screened and identified by the sliding window analysis (Figure 2-7 and Figure 2-8) and their georeferenced locations were displayed in maps (Figure 2-9 and Figure 2-10). As can be seen in Figure 2-7 and Figure 2-8, the magnitude of normalized vibration patterns against the number of data points fluctuates depending on individual cycling. Based on the data, the sliding window computing algorithms have been able to screen all normalized vibration patterns and identify POIs (squared in red colors). However, based on Figures 2-7 and 2-8, it is still somewhat vague to be able to evaluate if all cyclists or some of cyclists have had identified similar POIs along the two selected bike routes. To obtain better understanding of the effectiveness of sliding window computing algorithm, the selected and georeferenced POIs from the two bicycle routes were imported in a geographic information system (GIS) map as shown in Figure 2-9 and Figure 2-10.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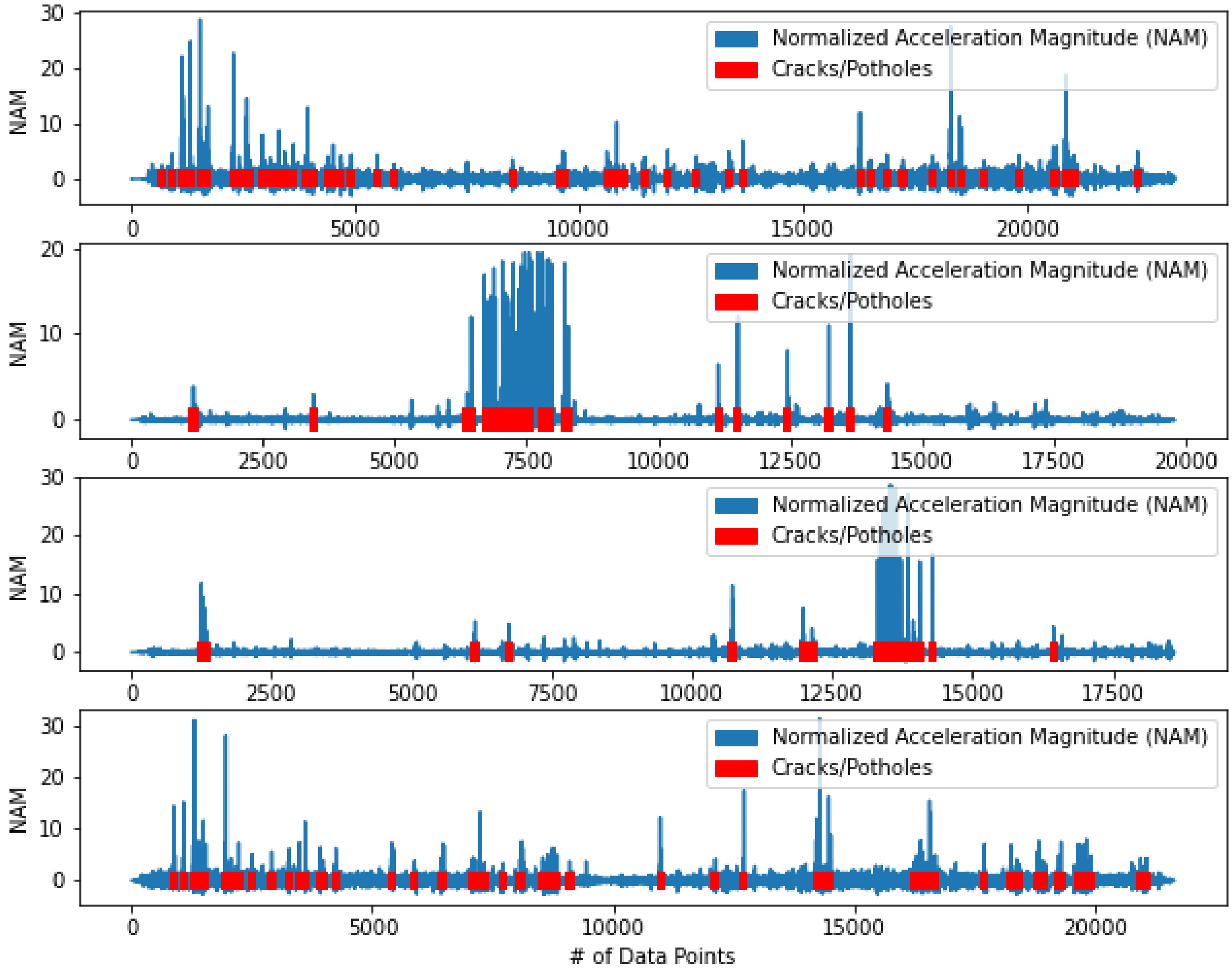
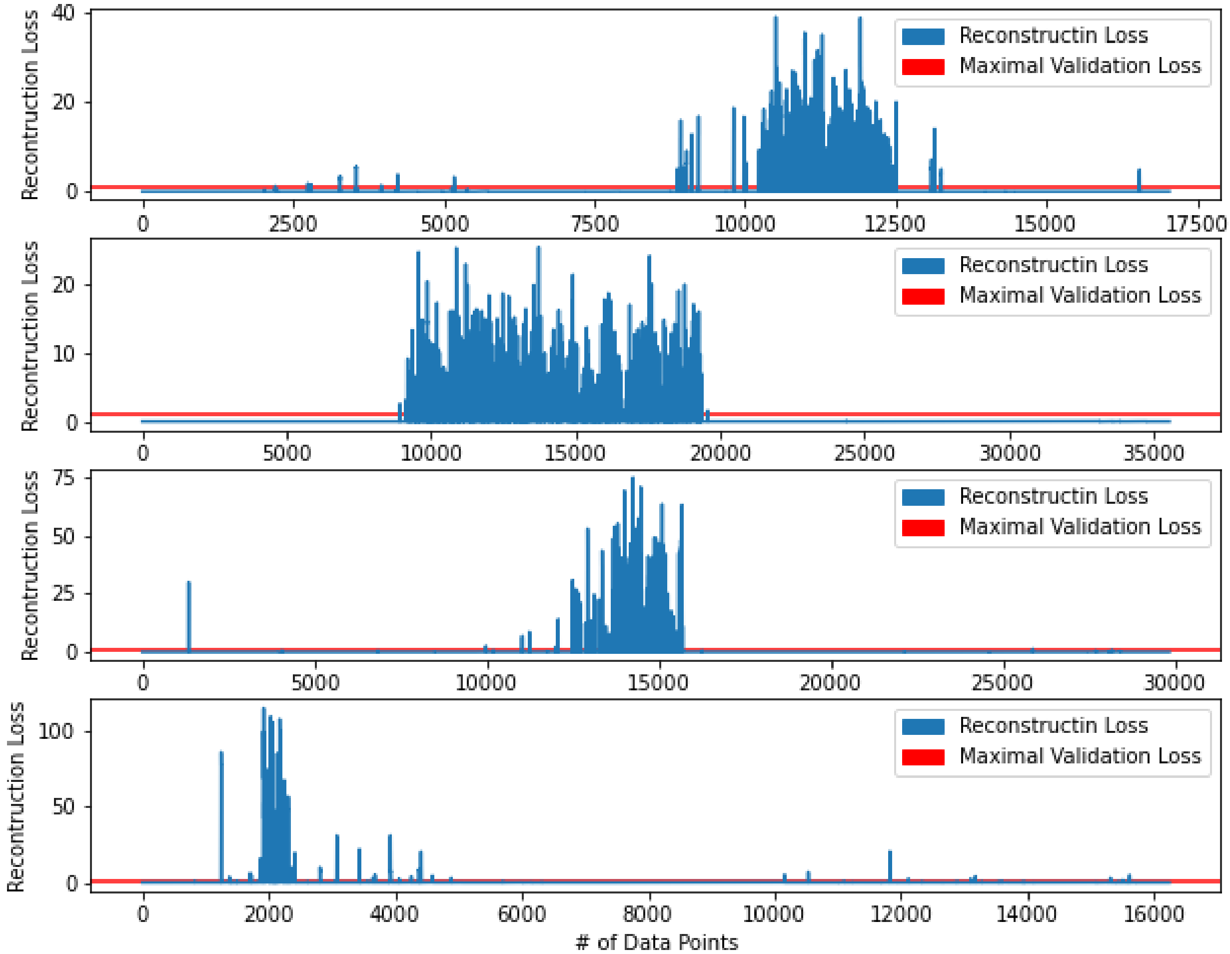


Figure 2-7: The localization of identified POIs on bicycle route 1 (from top to bottom, cyclist 1 through cyclist 4)


Reconstruction Loss
Reconstructin Loss
Maximal Validation Loss
0
20
40
0
2500
5000
7500
10000
12500
15000
17500
0
10
20
0
5000
10000
15000
20000
25000
30000
35000
0
25
50
75
0
5000
10000
15000
20000
25000
30000
0
50
100
0
2000
4000
6000
8000
10000
12000
14000
16000
# of Data Points

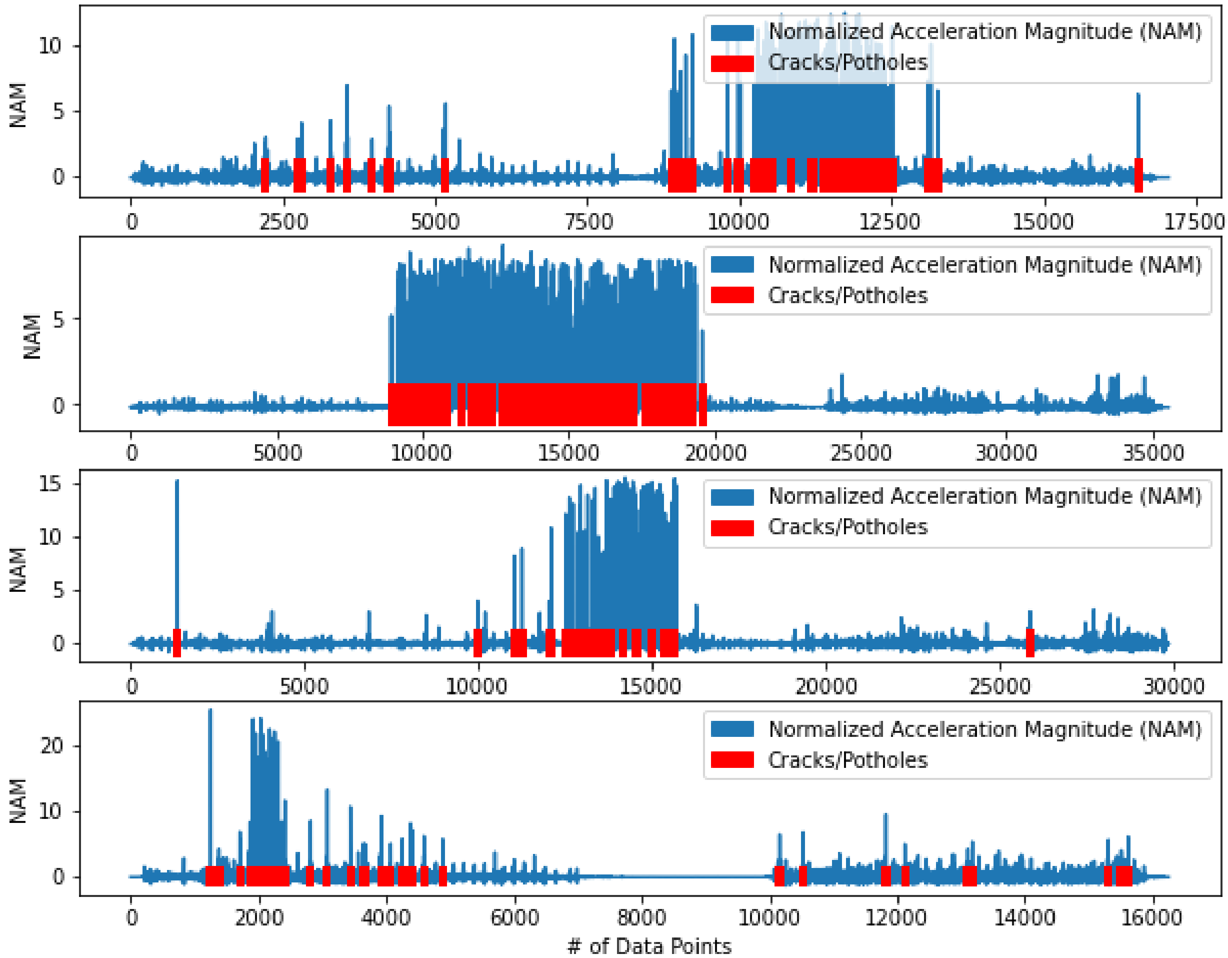
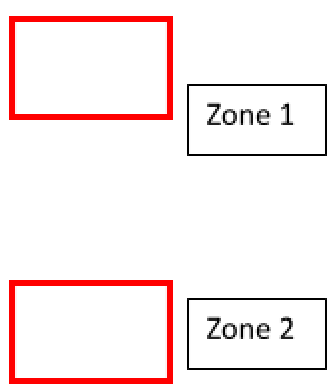


Figure 2-8: The localization of identified POIs on bicycle route 2 (from top to bottom, cyclist 1 through cyclist 4)



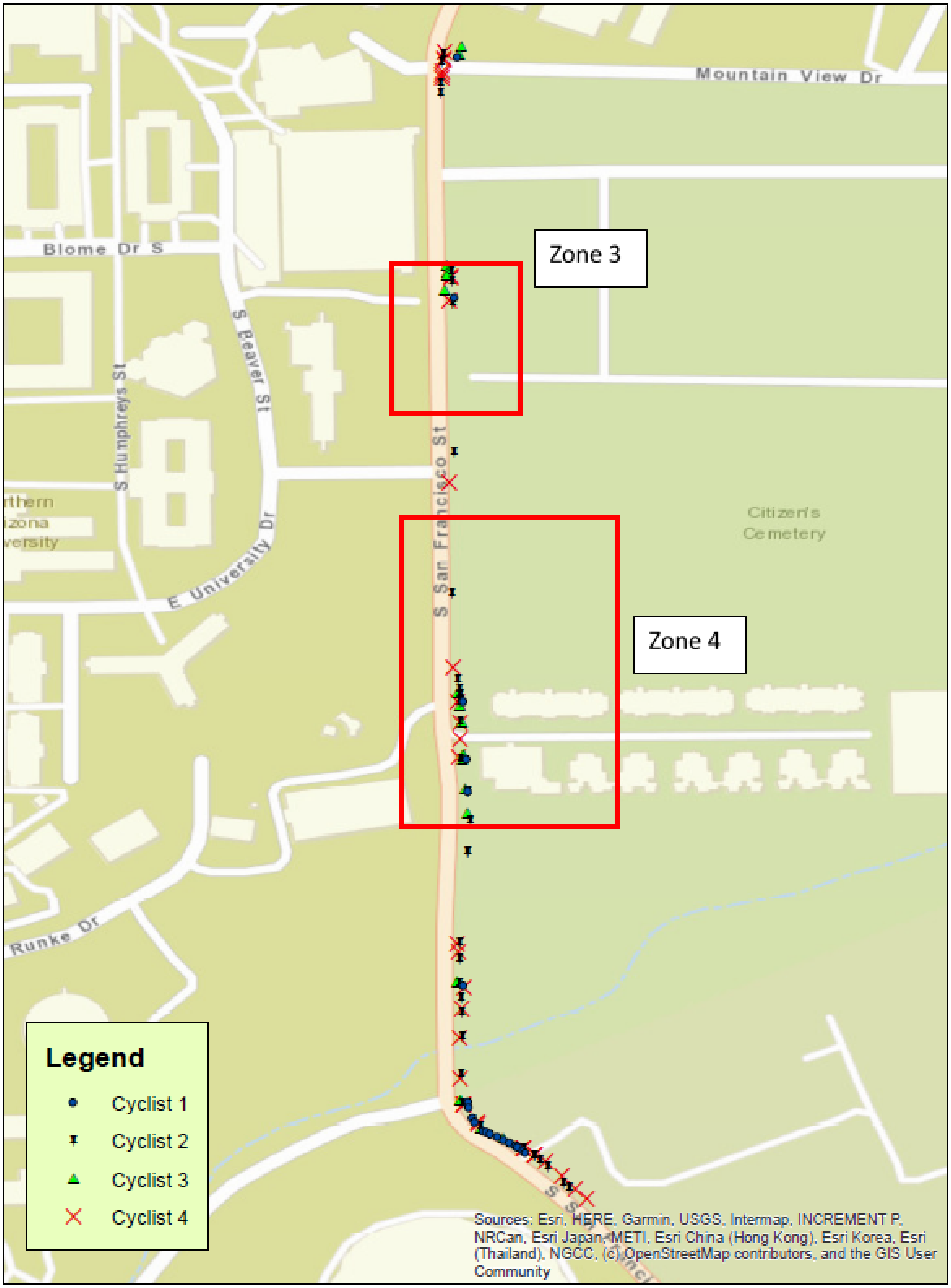


Figure 2-9: Locations of identified POIs on bicycle route 1

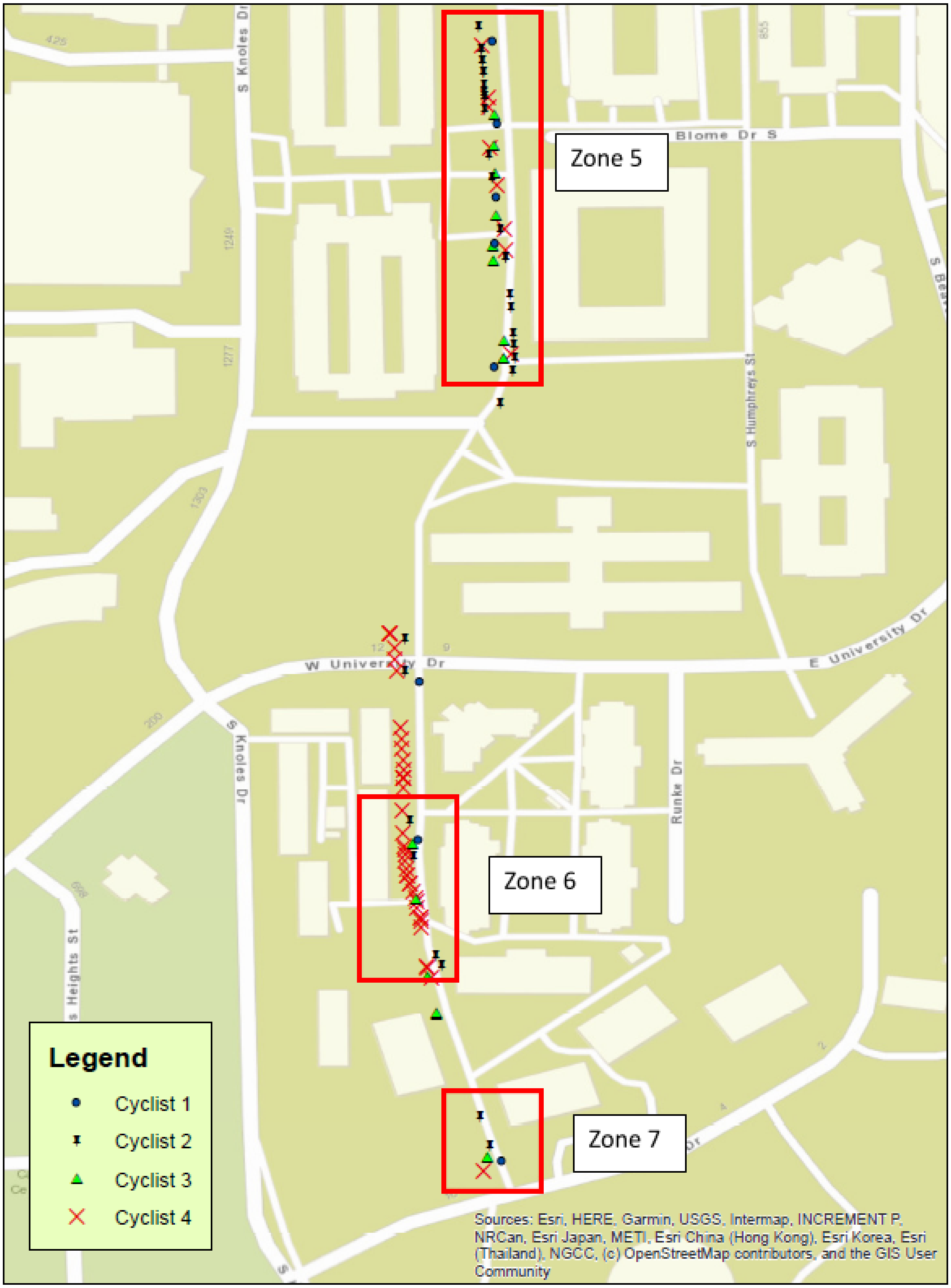


Figure 2-10: Locations of identified POIs on bicycle route 2

In Figure 2-9, there are four zones (Zones 1-4; highlighted in red lines) where all of four instrumented cycling have identified POIs while three zones in Figure 2-10 (Zones 5-7; highlighted in red lines) in which all instrumented cycling have shown POIS. There are a few POIs that were generated by only one or two instrumented cycling. This is due to the fact that the degree of deteriorated pavement surface is not significant such that the magnitude of vibration patterns fell through the initial screening and selection process.

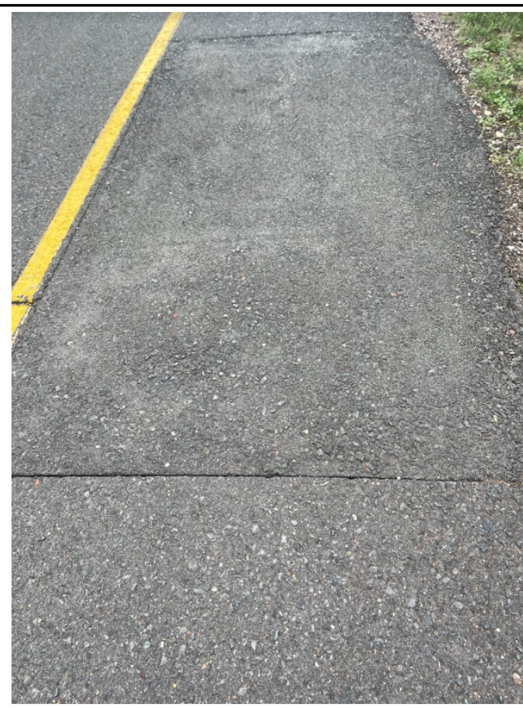
The team went on to the two bicycle routes and observe the deteriorated pavement surfaces in the total of seven zones. The purpose of the field observation is to determine what types of pavement distress or failures have caused the bicycle routes to deteriorate and how these deteriorated pavement conditions are in relation to the selection process of sliding window computing algorithm. As mentioned previously, factors such as weight of cyclists, speeds, and tire pressures are seen as variables that would have influenced on the accuracy of instrumented cycling, particularly when a “threshold” was used in identification of pavement distress. Thus, a field observation is a vital task to facilitate the evaluation of effectiveness of sliding window computing algorithm in the identification of POIs during multiple cycling activities.

In order to systematically record the level of pavement distress and failure on the two bicycle routes and relate the pavement distress to the accuracy of the sliding window computing algorithm, a rating handbook, “Distress Identification Manual”, published by Federal Highway Administration (19) was used as rating guidance when recording a level of pavement distress on identified POIs. The Distress Identification Manual provides a very detailed definition and explanation on each type of pavement distress as to how to identify distress types and record a level of corresponding pavement distress. An example of pavement distress identification and rating on the seven zones within two bicycle routes is shown in Table 1. When developing the sliding window computing algorithm, it is of interest to know how sensitive and significant the magnitude of vibration patterns will be generated based on the level of pavement distress conditions. Also another question the team intends to address is: would a different bike (street bike or mountain bike) and cyclists (male or female with different weights) be able to generate significant patterns that could be sufficiently recognizable by the computing algorithm such that these recognized patterns will be properly screened and identified as POI.

Based on the rating results, it is obvious that any pavement distress labeled as “high” or in some cases “moderate” in the severity level would lead to the generation of significant patterns among all cyclists. Another situation observed in the field is that some pavement distress areas labeled as moderate or low were not fully recognized by all instrumented cycling activities; vibration signals were only registered and identified as POIs by part of cyclists. This is due to the path of cycling and less significant vibration responses that were not selected by the sliding window computing algorithm. From the maintenance standpoint, the ignorance of low or moderate pavement distress areas is acceptable as these mild pavement distress surfaces would not create cycling discomfort and raise a flag for maintenance. Instead, all pavement distress areas labeled as high in the rating book (Table 1) and Figures 2-9 and 2-10 obviously exhibit adverse cycling conditions that would jeopardize the cycling safety and mobility, and more importantly provide useful information for local authorities to prioritize repairs, and for cyclists to plan for their trip and route prior to cycling.

Table 1: Examples of identification of pavement distress on selected zones 1-7 within bicycle routes 1 and 2

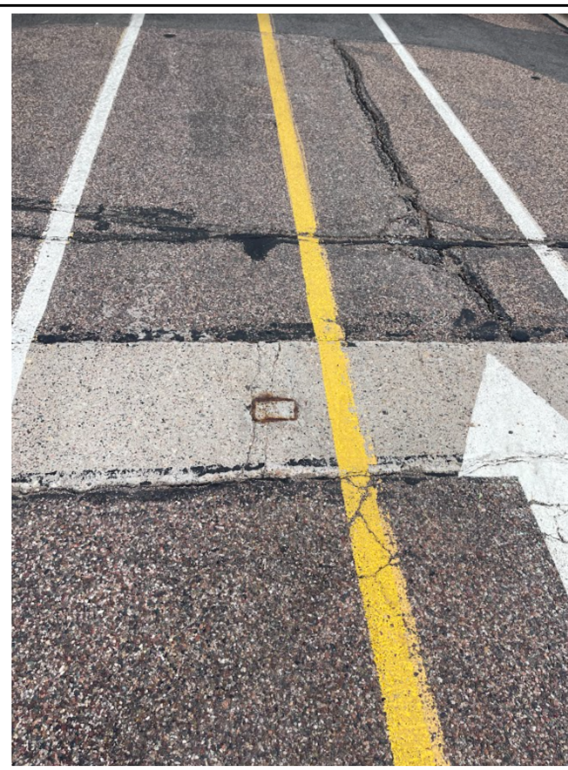
Zone	Pavement distress	Severity level	Figures
Zone 1	Ramp/uneven surface	N/A	

Zone 2	**Transverse cracking**	**high**	
Zone 2	**Patching**	**Moderat e**	

Zone 3	**Ramp/uneven surface** **Polished aggregate/raveling**	**N/A** **N/A**	
Zone 3	**Transverse cracking**	**High**	

Zone 3	**Marking bumps**	**N/A**	
Zone 4	**Transverse cracking** **Patching**	**High** **Moderat e**	

Zone 4	**Patching** **Uneven surface**	**High** **N/A**	
Zone 5	**Manhole** **Patching** **Longitudinal cracking** **Block cracking**	**N/A** **High** **High** **High**	
Zone 5	**Patching** **Polished aggregate/raveling**	**High** **N/A**	

Zone 6	**Patching** **Corner cracking** **Uneven surface**	**High** **High** **N/A**	
Zone 6	**Patching** **Transverse cracking** **Longitudinal cracking** **Alligator cracking** **Uneven surface** **Polished aggregate/raveling**	**High** **High** **High** **High** **N/A** **N/A**	

Zone 7	**Patching** **Transverse cracking** **Longitudinal cracking** **Polished aggregate/raveling**	**High** **High** **High** **N/A**	

Given the results presented in Figures 2-7 to 2-10 along with the pavement rating record in Table 1, it is clear that the sliding window computing algorithm used by multiple instrumented cyclists is capable of screening and analyzing vibration patterns, selecting POIs that represent pavement distress areas on bicycle routes, and displaying POIs in a map. Interested users such as local authorities, transportation planners, cyclists, etc. would have access to the information provided by instrumented cycling, share with other users, and prioritize the repair needs or navigate properly their individual cycling trip prior to traveling. If the quality of cycling facilities can be better improved and shared with cyclists, people would most likely be interested in considering using cycling as their daily transportation mode. The results presented in the report will be helpful in support of development of instrumented bikes, improving cycling safety, as well as promoting cycling mobility.

Chapter 3 Identification of Potential Bicyclist Safety Issues Using Field-Collected Video

Introduction

This chapter focuses on a field test of the Instrumented Bike and LSTM-Autoencoder where a volunteer bicyclist rode on different bike routes to gain an understanding of how the LSTM-Autoencoder detects points of interest along real bicycle facilities.

For this experiment, a volunteer bicyclist was sent to ride six different bicycle routes around Northern Arizona University's campus in Flagstaff, Arizona. A GoPro recording collected from the volunteer's test rides was used to examine the geometric conditions of the bike facilities where they have traveled to identify any safety deficiencies. The existing conditions of the bike facilities were compared against the guidelines set forth in the American Association of State Highway and Transportation Officials (AASHTO) Guide for the Development of Bike Facilities [20] which provides nationwide guidance on the geometric design of bike facilities. Instances where a violation of these guidelines were identified and flagged as a potential safety deficiency. The locations of these potential safety deficiencies were identified using GPS. In addition, the LSTM-Autoencoder was installed on a cell phone that was attached to the bicycle to detect points of interest (POIs) along each route. The likely geometric conditions that have caused each POI were determined using the GoPro recordings. Ultimately, this process would be useful to agencies in proactively identifying potential safety issues on bike facilities and addressing them as quickly as possible. The cell phone and GoPro were attached to the handlebars of the bicycle, and Figure 3-1 shows an image of the configuration.

Figure 3-1. The experiment device set up

Each of the six routes with their names are listed below in Table 3-1 as well as their directionality, surface material, and approximate length. Maps for each route can be found in Appendices A1-A6.

Table 3-1. The experiment device set up

Route No.	Route Name	Primary Surface Type	Directionality	Approximate Length (miles)
1.	Skydome	Paved	North – south	0.7
2.	Arizona Trail	Unpaved	East – west	0.7
3.	Skyview	Paved	North – south	0.9
4.	Library	Paved	North – south	0.8
5.	Beulah	Paved/Unpave d	North – south	0.4
6.	McConnell	Unpaved	East – west	0.3

AASHTO and MUTCD Guidance

Using AASHTO's Guide for the Development of Bicycle Facilities [20], a comprehensive list of all potential requirements and guidelines relevant for the types of bicycle facilities ridden on was created. This included side-paths, multiuse paths, unpaved recreational paths but not shared lanes or bike lanes. This list is available in Appendix – A-7. The table lists the primary section within the AASHTO guide that each guideline was discussed in, a description of the guideline, the detectability of each guideline, and whether the guideline is recommended or mandatory for bicycle infrastructure.

The detectability of each guideline is a subjective ranking of how difficult each guideline would be to identify exclusively from the GoPro recordings from the road tests. Detectability was ranked as easy, medium, or hard. Easily detectable guidelines were those that are always immediately visible to viewers such as a cracked pavement or the absence of required signage. Detectability was determined to be medium when a geometric condition could sometimes be immediately visible from a video recording but not in every instance, such as the requirement for objects to have a two-foot lateral clearance from the pathway. In that instance, it is immediately visible that a violation is occurring when an object is on the path or flush to the path but when the object has an offset from the pathway, it is impossible to accurately measure the distance the object is away from the pathway using just a video recording. Hard to detect guidelines were those that are nearly impossible to identify from a video such as having the ideal super elevation of a curve.

Points of Interest Analysis

The intent of this POI analysis is to identify the pathway anomaly that resulted in the LSTM-Autoencoder to record each POI. This was done using the list of POIs obtained for each route in conjunction with the GoPro recordings from each route. The coordinate points of each

POI was obtained using the phone's GPS. Each POI's coordinates were inserted into ArcGIS Pro to spatially visualize their locations along the route. Then, a satellite overlay was used on the map to identify permanent physical landmarks near the POIs. The potential pathway anomalies that caused each POI to be recorded were identified by using the video recordings of each route and locating the rider's approximate location relative to the POIs by using landmarks identified from the ArcGIS Pro satellite view map.

The results from the analysis are available below in Figures 3-2 to 3-11. Each table lists the POIs in the order they were recorded. For each POI, its coordinates are given as well as the time stamp in its respective video where each POI occurs, the likely cause of each violation, and the AASHTO guidelines associated with each likely cause.

For this analysis, the list of AASHTO guidelines in Appendix A-7 was reduced to only include guidelines that a bicycle facility in violation of would likely cause a POI to be recorded. In addition, non-guideline choices were included for common causes of POIs that were not mentioned in the AASHTO guideline. This list of guidelines used for this analysis is available in Table 3-12. For each of the guidelines that were present in the routes, there is a screenshot image example in Table 3-13.

For this analysis, instrumental error caused the POI data for the north to south Skyview and Skydome routes to be unreliable and were not analyzed for pathway anomalies. Additionally, often recurring pathway anomalies such as a pathway with loose gravel or the volunteer bicyclists' behavior resulted in either multiple POIs being recorded for the same pathway anomaly or for continuous POIs to be recorded simultaneously. This is seen in Table 3-2 below where an ongoing patch of loose gravel created 20 POIs in eight seconds. Because in these instances it is challenging to determine the exact time each POI occurred, only the beginning and ending POI caused by the same patch were recorded. For some instances, two or more POIs were recorded for the same incident.

Table 3-2. detected potential pathway anomalies for the Arizona Trail east to west ride

Number	Latitude	Longitude	Time Stamp	Likely Cause	Primary Associated Guideline	Secondary Associated Guideline
1	35.18364167	-111.6484133	0:00	Loose gravel	17	7
2	35.18364167	-111.6484133		Loose gravel	17	7
3	35.18364167	-111.6484133		Loose gravel	17	7
4	35.18364167	-111.6484133		Loose gravel	17	7
5	35.18364167	-111.6484133		Loose gravel	17	7
6	35.18365416	-111.6484117		Loose gravel	17	7
7	35.18365833	-111.6484133		Loose gravel	17	7
8	35.18366211	-111.6484133		Loose gravel	17	7
9	35.18367	-111.6484133		Loose gravel	17	7

10	35.18369923	-111.6484318		Loose gravel	17	7
11	35.18370167	-111.6484333		Loose gravel	17	7
12	35.18372548	-111.6484536		Loose gravel	17	7
13	35.183735	-111.6484617		Loose gravel	17	7
14	35.183735	-111.6484617		Loose gravel	17	7
15	35.18375787	-111.6484845		Loose gravel	17	7
16	35.18376667	-111.6484933		Loose gravel	17	7
17	35.18376667	-111.6484933		Loose gravel	17	7
18	35.18378333	-111.6485517		Loose gravel	17	7
19	35.18378233	-111.6485847		Loose gravel	17	7
20	35.18378167	-111.6486067	0:08	Loose gravel	17	7
21	35.18377	-111.6486417	0:08	Rider induced - rider crashed	98	17
22	35.18377	-111.6486417		Rider induced - rider crashed	98	17
23	35.18377	-111.6486417		Rider induced - rider crashed	98	17
24	35.18377028	-111.6486511		Rider induced - rider crashed	98	17
25	35.18378	-111.6486567		Rider induced - rider crashed	98	17
26	35.18378	-111.6486567		Rider induced - rider crashed	98	17
27	35.18379167	-111.64867		Rider induced - rider crashed	98	17
28	35.18379287	-111.6486709	1:00	Rider induced - rider recovering from crash	98	17
29	35.18379833	-111.648675	1:00	Rider induced - rider recovering from crash	98	17
30	35.18379833	-111.648675	1:00	Rider induced - rider recovering from crash	98	
31	35.18379833	-111.648675	1:00	Rider induced - rider recovering from crash	98	
32	35.18379833	-111.648675	1:00	Rider induced - rider recovering from crash	98	
33	35.18379833	-111.648675	1:00	Rider induced - rider recovering from crash	98	

34	35.18379833	-111.648675	1:00	Rider induced - rider recovering from crash	98	
35	35.18379833	-111.648675	1:00	Rider induced - rider recovering from crash	98	
36	35.18379833	-111.648675	1:00	Rider induced - rider recovering from crash	98	
37	35.18379833	-111.648675	1:00	Rider induced - rider recovering from crash	98	
38	35.18379833	-111.648675	1:00	Rider induced - rider recovering from crash	98	
39	35.18379833	-111.648675	1:00	Rider induced - rider recovering from crash	98	
40	35.18379833	-111.648675	1:00	Rider induced - rider recovering from crash	98	
41	35.18379833	-111.648675	1:00	Rider induced - rider recovering from crash	98	
42	35.18379833	-111.648675	1:00	Rider induced - rider recovering from crash	98	
43	35.18379833	-111.648675	1:00	Rider induced - rider recovering from crash	98	
44	35.18379833	-111.648675	1:00	Rider induced - rider recovering from crash	98	
45	35.18379833	-111.648675	1:00	Rider induced - rider recovering from crash	98	
46	35.18376167	-111.6487733	1:11	Loose gravel	6	
47	35.18367	-111.648865	1:11	Loose gravel	6	
48	35.18262167	-111.6518617	2:37	Significant water erosion	7	17
49	35.18262167	-111.6518617	2:37	Significant water erosion	7	17
50	35.18264987	-111.6518745	2:37	Significant water erosion	7	17

51	35.18265833	-111.6518783	2:37	Significant water erosion	7	17
52	35.18296	-111.6523233	3:10	Rider induced - rider avoiding rock	98	6
53	35.18258833	-111.6529033	3:47	Surface transition	1	6
54	35.18258833	-111.6529033	3:47	Surface transition	1	6
55	35.18241	-111.6533417	3:58	Unknown	99	
56	35.180895	-111.6551367	5:09	Rough surface	6	
57	35.180815	-111.6553083	5:13	Loose gravel	17	7
58	35.18080333	-111.6553517		Loose gravel	17	7
59	35.18078806	-111.6553919		Loose gravel	17	7
60	35.180765	-111.6554483		Loose gravel	17	7
61	35.180745	-111.6554917	5:17	Loose gravel	17	7

Table 3-3. detected potential pathway anomalies for the Arizona Trail west to east ride

Number	Latitude	Longitude	Time Stamp	Likely Cause	Primary Associated Guideline	Secondary Associated Guideline
1*	35.180317	-111.656315	N/A	N/A		
2*	35.180317	-111.656315	N/A	N/A		
3*	35.180327	-111.656315	N/A	N/A		
4	35.181827	-111.654753	1:15	Minor water erosion	7	15
5	35.181827	-111.654753	1:15	Minor water erosion	7	15
6	35.181850	-111.654730	1:17	Minor water erosion	7	15
7	35.182592	-111.653023	2:08	Rider induced - Gear shift	98	
8	35.182852	-111.652471	2:43	Rider induced - rider tilted bike	98	
9	35.182657	-111.651992	2:58	Minor water erosion	7	15
10	35.183523	-111.648945	4:12	Loose gravel	17	7
11	35.183544	-111.648914		Loose gravel	17	7
12	35.183545	-111.648912		Loose gravel	17	7
13	35.183570	-111.648877		Loose gravel	17	7
14	35.183593	-111.648850		Loose gravel	17	7
15	35.183598	-111.648843		Loose gravel	17	7
16	35.183598	-111.648843		Loose gravel	17	7
17	35.183627	-111.648813		Loose gravel	17	7
18	35.183658	-111.648785		Loose gravel	17	7
19	35.183670	-111.648770		Loose gravel	17	7
20	35.183690	-111.648746		Loose gravel	17	7
21	35.183707	-111.648730		Loose gravel	17	7
22	35.183728	-111.648708		Loose gravel	17	7
23	35.183758	-111.648679		Loose gravel	17	7
24	35.183758	-111.648678		Loose gravel	17	7
25	35.183758	-111.648678		Loose gravel	17	7
26	35.183775	-111.648653		Loose gravel	17	7
27	35.183775	-111.648653		Loose gravel	17	7
28	35.183803	-111.648623		Loose gravel	17	7
29	35.183803	-111.648623		Loose gravel	17	7
30	35.183815	-111.648608		Loose gravel	17	7
31	35.183827	-111.648593		Loose gravel	17	7

32	35.183835	-111.648567		Loose gravel	17	7
33	35.183835	-111.648567		Loose gravel	17	7
34	35.183840	-111.648541		Loose gravel	17	7
35	35.183840	-111.648538		Loose gravel	17	7
36	35.183840	-111.648538		Loose gravel	17	7
37	35.183840	-111.648538		Loose gravel	17	7
38	35.183830	-111.648517		Loose gravel	17	7
39	35.183830	-111.648517		Loose gravel	17	7
40	35.183825	-111.648492		Loose gravel	17	7
41	35.183825	-111.648492		Loose gravel	17	7
42	35.183817	-111.648472		Loose gravel	17	7
43	35.183810	-111.648469		Loose gravel	17	7
44	35.183800	-111.648463		Loose gravel	17	7
45	35.183796	-111.648461		Loose gravel	17	7
46	35.183785	-111.648453		Loose gravel	17	7
47	35.183767	-111.648444		Loose gravel	17	7
48	35.183748	-111.648442		Loose gravel	17	7
49	35.183748	-111.648442		Loose gravel	17	7
50	35.183732	-111.648447		Loose gravel	17	7
51	35.183722	-111.648446		Loose gravel	17	7
52	35.183707	-111.648442		Loose gravel	17	7
53	35.183707	-111.648442		Loose gravel	17	7
54	35.183696	-111.648438		Loose gravel	17	7
55	35.183673	-111.648432		Loose gravel	17	7
56	35.183667	-111.648432		Loose gravel	17	7
57	35.183666	-111.648432		Loose gravel	17	7
58	35.183653	-111.648430		Loose gravel	17	7
59	35.183653	-111.648430		Loose gravel	17	7
60	35.183641	-111.648429		Loose gravel	17	7
61	35.183640	-111.648428		Loose gravel	17	7
62	35.183630	-111.648420		Loose gravel	17	7
63	35.183630	-111.648420		Loose gravel	17	7
64	35.183627	-111.648418		Loose gravel	17	7
65	35.183618	-111.648413		Loose gravel	17	7
66	35.183610	-111.648409		Loose gravel	17	7
67	35.183607	-111.648407		Loose gravel	17	7
68	35.183597	-111.648403	4:50	Loose gravel	17	7

*The first three points of interest in this data set were collected before the GoPro was recording, therefore the pathway anomalies that triggered the points cannot be determined.

Table 3-4. detected potential pathway anomalies for the Skyview south to north

Number	Latitude	Longitude	Time Stamp	Likely Cause	Primary Associated Guideline	Secondary Associated Guideline
1	35.18085667	-111.6567567	0:30	Cracked surface	1	
2	35.18297333	-111.65606	2:02	Fill segment not flush	25	1
3	35.18297333	-111.65606	2:02	Cracked surface	1	
4	35.18352333	-111.6562333	2:11	Cracked surface	1	
5	35.1835818	-111.6562764	2:12	Fill segment not flush	25	
6	35.18358667	-111.65628	2:13	Cracked surface	1	
7	35.18374333	-111.6563167	2:14	Cracked surface	1	
8	35.18407333	-111.656365	2:20	Cracked surface	1	
9	35.18431333	-111.6563783	2:21	Cracked surface	1	
10	35.18447333	-111.6563733	2:22	Cracked surface	1	
11	35.18470833	-111.6563617	2:27	Cracked surface	1	
12	35.18500833	-111.656365	2:33	Road crossing ramp	97	1
13	35.18512833	-111.65638	2:37	Detectable warning	0	
14	35.18627333	-111.6560367	2:56	Surface transition	1	
15	35.18638667	-111.6559917	3:00	Cracked surface	1	
16	35.18638667	-111.6559917	3:00	Cracked surface	1	
17	35.18646077	-111.6559892	3:01	Eroded surface	1	
18	35.18680667	-111.656035	3:04	Fill segment not flush	25	
19	35.18686833	-111.6560367	3:07	Cracked surface	1	
20	35.186995	-111.6560233	3:07	Cracked surface	1	
21	35.18704879	-111.6560256	3:08	Fill segment not flush	25	
22	35.18717667	-111.6560283	3:11	Fill segment not flush	25	
23	35.18729667	-111.6560333	3:13	Fill segment not flush	25	
24	35.18743	-111.6560317	3:14	Cracked surface	1	
25	35.187745	-111.6560633	3:16	Fill segment not flush	25	1
26	35.18791771	-111.656075	3:24	Cracked surface	1	
27	35.18833	-111.6560833	3:32	Eroded surface	1	
28	35.18838167	-111.656015	3:34	Eroded surface	1	

29	35.18842833	-111.6550867	3:50	Surface transition	21	
30	35.18905	-111.6548467	4:08	Fill segment not flush	25	
31	35.19299833	-111.6537017	5:17	Rider induced - rider braking	98	
32	35.193025	-111.6536913		Rider induced - rider braking	98	
33	35.19305833	-111.6536783		Rider induced - rider braking	98	
34	35.19305833	-111.6536783		Rider induced - rider braking	98	
35	35.19305833	-111.6536783		Rider induced - rider braking	98	
36	35.19311972	-111.6536532		Rider induced - rider braking	98	
37	35.19312333	-111.6536517		Rider induced - rider braking	98	
38	35.19318021	-111.6536298		Rider induced - rider braking	98	
39	35.19318833	-111.6536267		Rider induced - rider braking	98	
40	35.19318833	-111.6536267		Rider induced - rider braking	98	
41	35.1932391	-111.6536083		Rider induced - rider braking	98	
42	35.19324833	-111.653605		Rider induced - rider braking	98	
43	35.19324833	-111.653605		Rider induced - rider braking	98	
44	35.19328338	-111.6535912		Rider induced - rider braking	98	
45	35.19330333	-111.6535833		Rider induced - rider braking	98	
46	35.19334667	-111.65357		Rider induced - rider braking	98	
47	35.19335366	-111.653568		Rider induced - rider braking	98	
48	35.19338667	-111.6535583		Rider induced - rider braking	98	
49	35.19338667	-111.6535583		Rider induced - rider braking	98	
50	35.19339398	-111.6535553		Rider induced - rider braking	98	

51	35.19341833	-111.653545	5:35	Rider induced - rider braking	98	

Table 3-5. detected potential pathway anomalies for the McConnell west to east ride

Number	Latitude	Longitude	Time Stamp	Likely Cause	Primary Associated Guideline	Secondary Associated Guideline
1	35.17752167	-111.661875	0:21	Roots uplifting pathway	22	23
2	35.17752167	-111.661875	0:21	Roots uplifting pathway	22	23
3	35.17807167	-111.660975	0:39	Surface transition	21	1
4	35.17807167	-111.660975	0:40	Loose gravel	1	
5	35.17807167	-111.660975		Loose gravel	1	
6	35.17807167	-111.660975		Loose gravel	1	
7	35.17819333	-111.6607267		Loose gravel	1	
8	35.17821833	-111.6606617		Loose gravel	1	
9	35.17825	-111.660595		Loose gravel	1	
10	35.17825	-111.660595		Loose gravel	1	
11	35.17827333	-111.6605283		Loose gravel	1	
12	35.17827333	-111.6605283		Loose gravel	1	
13	35.17832833	-111.66034		Loose gravel	1	
14	35.17834	-111.6602767	0:53	Loose gravel	1	
15	35.17849167	-111.65955	1:04	Loose gravel	1	7
16	35.17856	-111.6595133	1:08	Loose gravel	1	7
17	35.17869	-111.6593567	1:12	Loose gravel	1	
18	35.178725	-111.659085	1:15	Loose gravel	1	

Table 3-6. detected potential pathway anomalies for the McConnell east to west ride

Number	Latitude	Longitude	Time Stamp	Likely Cause	Primary Associated Guideline	Secondary Associated Guideline
1	35.179095	-111.6581183	0:06	Unknown	99	
2	35.17878359	-111.6592401	0:28	Unknown	99	
3	35.178675	-111.6594717	0:31	Loose gravel	1	7
4	35.17863167	-111.65949	0:34	Loose gravel	1	7
5	35.17848167	-111.65968	0:41	Loose gravel	1	
6	35.17847475	-111.6597023		Loose gravel	1	
7	35.17845667	-111.6597767		Loose gravel	1	
8	35.17844833	-111.6598233		Loose gravel	1	
9	35.17843833	-111.65988		Loose gravel	1	
10	35.17841	-111.66004	0:51	Loose gravel	1	
11	35.17830667	-111.6604683	0:56	Loose gravel	1	
12	35.17825833	-111.6606733	0:59	Loose gravel	1	
13	35.17825833	-111.6606733	0:59	Loose gravel	1	
14	35.17810167	-111.66091	1:04	Loose gravel	1	
15	35.178085	-111.66094	1:07	Loose gravel	1	
16	35.178085	-111.66094	1:08	Surface transition	21	1
17	35.17763667	-111.661725	1:35	Roots uplifting pathway	22	23
18	35.17753	-111.6619167	1:44	Utility cover on path	10	9

Table 3-7. detected potential pathway anomalies for the Beulah north to south ride

Number	Latitude	Longitude	Time Stamp	Likely Cause	Primary Associated Guideline	Secondary Associated Guideline
	35.17611064	-111.6635197	0:30	Loose gravel	1	
2	35.17575333	-111.6639083	0:37	Minor water erosion	15	7
3	35.17573013	-111.6639665	0:38	Loose gravel	1	
4	35.17570833	-111.6640283	0:42	Rough surface	1	6
5	35.17569667	-111.6640533		Rough surface	1	6
6	35.175685	-111.6640817		Rough surface	1	6
7	35.17567581	-111.6641035		Rough surface	1	6
8	35.17567167	-111.6641133		Rough surface	1	6
9	35.17566911	-111.6641185		Rough surface	1	6
10	35.175655	-111.6641467		Rough surface	1	6
11	35.17565187	-111.6641523		Rough surface	1	6
12	35.17563833	-111.6641767	0:45	Rough surface	1	6
13	35.17563833	-111.6641767	0:45	Loose gravel	1	
14	35.17562	-111.664205		Loose gravel	1	
15	35.17562	-111.664205		Loose gravel	1	
16	35.17562	-111.664205		Loose gravel	1	
17	35.17562	-111.664205		Loose gravel	1	
18	35.17561577	-111.6642112		Loose gravel	1	
19	35.17560167	-111.6642317		Loose gravel	1	
20	35.1755998	-111.664235		Loose gravel	1	
21	35.17558667	-111.6642583		Loose gravel	1	
22	35.17558371	-111.6642632		Loose gravel	1	
23	35.17556833	-111.6642883		Loose gravel	1	
24	35.17555	-111.6643167		Loose gravel	1	
25	35.17555	-111.6643167		Loose gravel	1	
26	35.17555	-111.6643167		Loose gravel	1	
27	35.17552833	-111.6643433		Loose gravel	1	
28	35.17552833	-111.6643433		Loose gravel	1	
29	35.17551	-111.66437		Loose gravel	1	
30	35.17549167	-111.6643967		Loose gravel	1	
31	35.17547667	-111.6644233		Loose gravel	1	
32	35.17547667	-111.6644233		Loose gravel	1	
33	35.17547667	-111.6644233		Loose gravel	1	
34	35.17545918	-111.6644419		Loose gravel	1	
35	35.17545	-111.6644517		Loose gravel	1	

36	35.17542167	-111.6644783		Loose gravel	1	
37	35.17542167	-111.6644783		Loose gravel	1	
38	35.17542167	-111.6644783		Loose gravel	1	
39	35.17538667	-111.6645033		Loose gravel	1	
40	35.17535167	-111.66453		Loose gravel	1	
41	35.17535167	-111.66453		Loose gravel	1	
42	35.175315	-111.6645533		Loose gravel	1	
43	35.175315	-111.6645533		Loose gravel	1	
44	35.17528333	-111.6645783		Loose gravel	1	
45	35.17528333	-111.6645783		Loose gravel	1	
46	35.17528333	-111.6645783		Loose gravel	1	
47	35.17522551	-111.6646178		Loose gravel	1	
48	35.175215	-111.664625		Loose gravel	1	
49	35.1752126	-111.6646261		Loose gravel	1	
50	35.17517667	-111.6646433		Loose gravel	1	
51	35.17517667	-111.6646433		Loose gravel	1	
52	35.17517667	-111.6646433		Loose gravel	1	
53	35.17514167	-111.6646667		Loose gravel	1	
54	35.17514167	-111.6646667		Loose gravel	1	
55	35.17509833	-111.6646833		Loose gravel	1	
56	35.17509833	-111.6646833		Loose gravel	1	
57	35.17506333	-111.6647017		Loose gravel	1	
58	35.17506333	-111.6647017		Loose gravel	1	
59	35.17506333	-111.6647017		Loose gravel	1	
60	35.175025	-111.6647233		Loose gravel	1	
61	35.17502179	-111.6647247		Loose gravel	1	
62	35.17492629	-111.6647746		Loose gravel	1	
63	35.174905	-111.6647867		Loose gravel	1	
64	35.17486833	-111.6648067		Loose gravel	1	
65	35.17483167	-111.6648283		Loose gravel	1	
66	35.17483167	-111.6648283		Loose gravel	1	
67	35.17479833	-111.6648517		Loose gravel	1	
68	35.17479833	-111.6648517		Loose gravel	1	
69	35.174765	-111.66487		Loose gravel	1	
70	35.174735	-111.6648883	1:15	Loose gravel	1	
71	35.174695	-111.6649133	1:16	Surface transition	21	
72	35.174695	-111.6649133	1:16	Rider induced - rider stops	98	
73	35.17469389	-111.6649133		Rider induced - rider stops	98	

74	35.17467833	-111.6649133		Rider induced - rider stops	98	
75	35.17467488	-111.6649133		Rider induced - rider stops	98	
76	35.17467	-111.6649133		Rider induced - rider stops	98	
77	35.1746684	-111.6649149	1:19	Rider induced - rider stops	98	
78	35.17466333	-111.66492	1:21	Detectable warning	0	
79	35.17466333	-111.66492	1:21	Detectable warning	0	
80	35.17463436	-111.6649515	1:22	Eroded surface	1	
81	35.17455667	-111.6650233	1:24	Surface transition	21	
82	35.1745	-111.665075	1:26	Detectable warning	0	
83	35.17438	-111.6651567	1:28	Surface transition	21	
84	35.174345	-111.6651717	1:30	Loose gravel	1	
85	35.174345	-111.6651717	1:30	Loose gravel	1	

Table 3-8. detected potential pathway anomalies for the Beulah south to north ride

Number	Latitude	Longitude	Time Stamp	Likely Cause	Primary Associated Guideline	Secondary Associated Guideline
1	35.17201333	-111.6659767	0:31	Loose gravel	1	
2	35.17336	-111.66519	0:58	Bridge transition	13	
3	35.173545	-111.665235	1:03	Bridge transition	13	
4	35.173545	-111.665235	1:03	Bridge transition	13	
5	35.173545	-111.665235	1:03	Bridge transition	13	
6	35.17439833	-111.665095	1:24	Surface transition	21	
7	35.17463	-111.66495	1:34	Detectable warning	0	
8	35.17469833	-111.6648933	1:36	Surface transition	21	
9	35.17477333	-111.6648517	1:38	Loose gravel	1	
10	35.1749685	-111.664736	1:44	Loose gravel	1	
11	35.17535584	-111.6644742	1:55	Loose gravel	1	
12	35.17562333	-111.6641824	2:05	Road crossing ramp	97	
13	35.17571667	-111.6639267	2:11	Minor water erosion	7	

Table 3-9. detected potential pathway anomalies for the Library south to north ride

Number	Latitude	Longitude	Time Stamp	Likely Cause	Primary Associated Guideline	Secondary Associated Guideline
1	35.17909167	-111.6578533	0:05	Rider induced - standing on pedals	98	
2	35.17909167	-111.6578533		Rider induced - standing on pedals	98	
3	35.17909167	-111.6578533		Rider induced - standing on pedals	98	
4	35.17909167	-111.6578533		Rider induced - standing on pedals	98	
5	35.17909167	-111.6578533		Rider induced - standing on pedals	98	
6	35.17909167	-111.6578533		Rider induced - standing on pedals	98	
7	35.17909167	-111.6578533		Rider induced - standing on pedals	98	
8	35.17909167	-111.6578533		Rider induced - standing on pedals	98	
9	35.17909167	-111.6578533		Rider induced - standing on pedals	98	
10	35.17909167	-111.6578533		Rider induced - standing on pedals	98	
11	35.17909167	-111.6578533		Rider induced - standing on pedals	98	
12	35.17909167	-111.6578533		Rider induced - standing on pedals	98	
13	35.17909167	-111.6578533		Rider induced - standing on pedals	98	

14	35.17909167	-111.6578533		Rider induced - standing on pedals	98	
15	35.17909911	-111.6578595		Rider induced - standing on pedals	98	
16	35.17914115	-111.6578955		Rider induced - standing on pedals	98	
17	35.179155	-111.6579217		Rider induced - standing on pedals	98	
18	35.179155	-111.6579217		Rider induced - standing on pedals	98	
19	35.17918167	-111.657965		Rider induced - standing on pedals	98	
20	35.17918167	-111.657965		Rider induced - standing on pedals	98	
21	35.17921167	-111.6580083		Rider induced - standing on pedals	98	
22	35.17923064	-111.6580336		Rider induced - standing on pedals	98	
23	35.17923667	-111.6580417		Rider induced - standing on pedals	98	
24	35.17923667	-111.6580417		Rider induced - standing on pedals	98	
25	35.17925782	-111.6580671		Rider induced - standing on pedals	98	
26	35.17926167	-111.6580717		Rider induced - standing on pedals	98	
27	35.17926167	-111.6580717		Rider induced - standing on pedals	98	
28	35.17928333	-111.658105		Rider induced - standing on pedals	98	

29	35.17928793	-111.6581109		Rider induced - standing on pedals	98	
30	35.17930667	-111.658135		Rider induced - standing on pedals	98	
31	35.17930667	-111.658135		Rider induced - standing on pedals	98	
32	35.17936667	-111.6582167	0:13	Rider induced - standing on pedals	98	
33	35.17938167	-111.6582483	0:56	Rider induced - standing on pedals	98	
34	35.18036167	-111.6585267		Rider induced - standing on pedals	98	
35	35.180415	-111.6584933		Rider induced - standing on pedals	98	
36	35.180465	-111.6584533		Rider induced - standing on pedals	98	
37	35.180465	-111.6584533		Rider induced - standing on pedals	98	
38	35.18053167	-111.65838		Rider induced - standing on pedals	98	
39	35.18061564	-111.6582772		Rider induced - standing on pedals	98	
40	35.18061667	-111.658275		Rider induced - standing on pedals	98	
41	35.18062833	-111.6582467		Rider induced - standing on pedals	98	
42	35.18063038	-111.6582421		Rider induced - standing on pedals	98	
43	35.18064167	-111.6582167		Rider induced - standing on pedals	98	

44	35.18064167	-111.6582167		Rider induced - standing on pedals	98	
45	35.18064167	-111.6582167		Rider induced - standing on pedals	98	
46	35.18064167	-111.6582167		Rider induced - standing on pedals	98	
47	35.18064167	-111.6582167		Rider induced - standing on pedals	98	
48	35.18064667	-111.6582032		Rider induced - standing on pedals	98	
49	35.180675	-111.6581317		Rider induced - standing on pedals	98	
50	35.18068667	-111.6581067		Rider induced - standing on pedals	98	
51	35.18068667	-111.6581067		Rider induced - standing on pedals	98	
52	35.18068667	-111.6581067		Rider induced - standing on pedals	98	
53	35.18070167	-111.6580817		Rider induced - standing on pedals	98	
54	35.18070683	-111.6580707		Rider induced - standing on pedals	98	
55	35.18071851	-111.6580454		Rider induced - standing on pedals	98	
56	35.18072879	-111.6580222		Rider induced - standing on pedals	98	
57	35.18074167	-111.6579917		Rider induced - standing on pedals	98	
58	35.18074633	-111.657979		Rider induced - standing on pedals	98	

59	35.18075333	-111.65796		Rider induced - standing on pedals	98	
60	35.18075333	-111.65796		Rider induced - standing on pedals	98	
61	35.18077	-111.65793		Rider induced - standing on pedals	98	
62	35.180785	-111.6578967		Rider induced - standing on pedals	98	
63	35.180785	-111.6578967		Rider induced - standing on pedals	98	
64	35.18082667	-111.6578		Rider induced - standing on pedals	98	
65	35.18082667	-111.6578		Rider induced - standing on pedals	98	
66	35.18084667	-111.6577633		Rider induced - standing on pedals	98	
67	35.18084667	-111.6577633	1:24	Rider induced - standing on pedals	98	
68	35.18323167	-111.6571683	2:15	Fill segment not flush	25	
69	35.18384218	-111.657176	2:26	Road crossing ramp	97	
70	35.18405167	-111.65719	2:29	Cracked surface	17	
71	35.18425667	-111.657195	2:37	Tool cut transverse joint	5	
72	35.18582333	-111.6572433	3:17	Tool cut transverse joint	5	
73	35.18605833	-111.6571391	3:19	Eroded surface	17	
74	35.18613167	-111.6571333	3:21	Fill segment not flush	25	
75	35.18617833	-111.6571467	3:25	Tool cut transverse joint	5	
76	35.18648	-111.6572233	3:30	Road crossing ramp	97	

77	35.18653	-111.6572267	3:32	Road crossing ramp	97	
78	35.18653	-111.6572267	3:32	Road crossing ramp	97	
79	35.18674667	-111.6572283	3:37	Road crossing ramp	97	
80	35.18692	-111.6572367	3:43	Unknown	99	
81	35.18752667	-111.6572583	3:53	Road crossing ramp	97	
82	35.18903333	-111.6572417	4:17	Road crossing ramp	97	

Table 3-10. Detected potential pathway anomalies for the Library north to south ride

Number	Latitude	Longitude	Time Stamp	Likely Cause	Primary Associated Guideline	Secondary Associated Guideline
1	35.1900759	-111.6571756	0:00	Rider induced - rider starting	98	
2	35.18995333	-111.65719	0:08	Tool cut transverse joint	8	1
3	35.18951	-111.6571567	0:25	Utility cover on path	10	9
4	35.18908	-111.6572117	0:28	Cracked surface	1	
5	35.18908	-111.6572117	0:28	Cracked surface	1	
6	35.18903833	-111.6572083	0:29	Cracked surface	1	
7	35.18899333	-111.6572017	0:30	Cracked surface	1	
8	35.18812667	-111.65723	0:51	Utility cover on path	10	9
9	35.18803264	-111.65725	0:52	Eroded surface	1	
10	35.18797667	-111.6572433	0:54	Transverse joint tool cut rather than saw cut	10	1
11	35.18797667	-111.6572433		Eroded surface	1	
12	35.18789667	-111.6572367	0:55	Tool cut transverse joint	10	1
13	35.18786333	-111.6572417	0:57	Tool cut transverse joint	10	1
14	35.18779	-111.6572567	0:59	Road crossing ramp	97	
15	35.18779	-111.6572567	0:59	Road crossing ramp	97	
16	35.18770833	-111.657245	1:01	Eroded surface	1	
17	35.18763167	-111.6572417	1:03	Eroded surface	1	
18	35.18763167	-111.6572417	1:03	Eroded surface	1	
19	35.18700667	-111.657225	1:19	Tool cut transverse joint	8	1
20	35.18693	-111.6572317	1:22	Road crossing ramp	97	
21	35.18683166	-111.6572417	1:22	Road crossing ramp	97	
22	35.18661167	-111.6572567	1:27	Unknown	99	
23	35.186565	-111.6572467	1:29	Road crossing ramp	97	
24	35.18653375	-111.6572456	1:30	Rough surface	1	27

25	35.186515	-111.657245	1:30	Rough surface	1	27
26	35.18647	-111.6572417	1:31	Road crossing ramp	97	
27	35.18642333	-111.65724	1:32	Eroded surface	1	99
28	35.18642333	-111.65724	1:32	Eroded surface	1	99
29	35.18637833	-111.657245	1:32	Eroded surface	1	99
30	35.18629167	-111.65725	1:32	Eroded surface	1	99
31	35.18629167	-111.65725	1:32	Eroded surface	1	99
32	35.18625	-111.6572483	1:35	Tool cut transverse joint	8	1
33	35.18620667	-111.6572417	1:37	Tool cut transverse joint	8	1
34	35.18616	-111.657235	1:39	Tool cut transverse joint	8	25
35	35.18616	-111.657235	1:39	Tool cut transverse joint	8	25
36	35.18611667	-111.65722	1:39	Tool cut transverse joint	8	25
37	35.18609417	-111.6572192	1:41	Tool cut transverse joint	8	25
38	35.18607167	-111.6572183	1:42	Debris	17	
39	35.18607167	-111.6572183	1:42	Debris	17	
40	35.186035	-111.65723	1:42	Eroded surface	1	
41	35.186035	-111.65723	1:43	Cracked surface	1	
42	35.18595833	-111.6572683	1:43	Cracked surface	1	
43	35.18592333	-111.6572867	1:44	Road crossing ramp	97	
44	35.185725	-111.6573233	1:50	Eroded surface	1	
45	35.18567667	-111.6573267	1:51	Tool cut transverse joint	8	1
46	35.18528	-111.6573933	1:57	Eroded surface/Utility cover on path	1	10
47	35.185165	-111.6573617	2:02	Eroded surface/Fill segment not flush	25	1
48	35.18504167	-111.65732	2:05	Tool cut transverse joint	8	1
49	35.18500167	-111.6573	2:09	Detectable warning	0	
50	35.18497381	-111.6572893	2:09	Detectable warning	0	

51	35.18495833	-111.6572833	2:10	Road crossing ramp	97	1
52	35.18487667	-111.65724	2:12	Cracked surface	1	
53	35.18487667	-111.65724	2:12	Cracked surface	1	
54	35.18484667	-111.657215	2:14	Detectable warning	0	
55	35.184815	-111.6572017	2:14	Road crossing ramp	97	
56	35.184815	-111.6572017	2:14	Road crossing ramp	97	
57	35.18471261	-111.6571293	2:15	Tool cut transverse joint	1	
58	35.18469333	-111.6571217	2:18	Utility cover on path	10	9
59	35.18465833	-111.657125	2:18	Utility cover not flush	10	9
60	35.18462	-111.6571267	2:19	Tool cut transverse joint	8	
61	35.18454167	-111.6571283	2:20	Cracked surface/Surface transition	1	
62	35.18446	-111.65714	2:25	Cracked surface/Surface transition	1	
63	35.18421	-111.6571367	2:30	Unknown	99	
64	35.18406667	-111.6571433	2:34	Tool cut transverse joint	8	
65	35.18394	-111.65716	2:36	Surface transition	21	
66	35.18331167	-111.657155	2:52	Fill segment not flush	25	
67	35.18327167	-111.65716	2:53	Fill segment not flush	25	
68	35.18266667	-111.6571433	3:07	Surface transition	21	
69	35.18218667	-111.6568367	3:18	Surface transition	21	
70	35.18130167	-111.6569717	3:32	Utility cover on path	10	9
71	35.17999834	-111.6586369	4:07	Rider induced - rider leaning to turn curve	98	

72	35.17967667	-111.65874	4:12	Rider induced - rider leaning to turn curve	98	
73	35.179585	-111.6586817	4:14	Unknown	99	

Table 3-11. detected potential pathway anomalies for the Skydome south to north ride

Number	Latitude	Longitude	Time Stamp	Likely Cause	Primary Associated Guideline	Secondary Associated Guideline
1	35.18176333	-111.6526617	0:18	Fill segment not flush	25	1
2	35.18282333	-111.6528	0:35	Cracked surface	1	
3	35.18380167	-111.6526983	0:58	Raised pavement markings	16	
4	35.18380167	-111.6526983	0:58	Raised pavement markings	16	
5	35.18383	-111.6527067	1:04	Cracked surface	1	
6	35.18383	-111.6527067	1:04	Cracked surface	1	
7	35.18391889	-111.6527281	1:09	Fill segment not flush	25	
8	35.18393333	-111.6527317	1:09	Fill segment not flush	25	
9	35.18393333	-111.6527317	1:09	Fill segment not flush	25	
10	35.18396667	-111.6527433	1:14	Raised pavement markings	16	
11	35.18396667	-111.6527433	1:14	Raised pavement markings	16	
12	35.18400333	-111.65275	1:15	Raised pavement markings	16	
13	35.18403833	-111.6527567	1:15	Cracked surface	1	
14	35.18403833	-111.6527567	1:16	Surface transition	21	1
15	35.18403833	-111.6527567	1:16	Surface transition	21	1
16	35.18403833	-111.6527567	1:16	Surface transition	21	1
17	35.18403833	-111.6527567	1:16	Surface transition	21	1
18	35.18403833	-111.6527567	1:16	Surface transition	21	1
19	35.18411	-111.65276	1:16	Cracked surface	1	
20	35.18411	-111.65276	1:16	Cracked surface	1	

21	35.18414136	-111.6527586	1:17	Rider induced - rider swerving to avoid debris	1	17
22	35.18414833	-111.6527583	1:17	Rider induced - rider swerving to avoid debris	1	17
23	35.18418667	-111.6527667	1:17	Eroded surface	1	
24	35.18418667	-111.6527667	1:17	Eroded surface	1	
25	35.18420031	-111.6527696	1:18	Eroded surface	1	
26	35.184225	-111.652775	1:18	Detectable warning	0	1
27	35.184225	-111.652775	1:18	Detectable warning	0	1
28	35.18423846	-111.6527769	1:19	Eroded surface	1	
29	35.18426	-111.65278	1:20	Eroded surface	1	
30	35.18426	-111.65278	1:20	Eroded surface	1	
31	35.18428741	-111.6527857	1:20	Eroded surface	1	
32	35.18433833	-111.6527917	1:21	Detectable warning	0	1
33	35.18441667	-111.6527967	1:23	Eroded surface	1	
34	35.18445667	-111.6527983	1:24	Detectable warning	0	1
35	35.18446231	-111.6527988	1:25	Eroded surface	1	
36	35.18599	-111.652815	1:51	Utility cover on path	25	
37	35.18626167	-111.6528417	1:55	Utility cover on path	25	
38	35.18700756	-111.6528213	2:07	Utility cover on path	25	
39	35.18703833	-111.65282	2:08	Cracked surface	1	
40	35.18757167	-111.65285	2:09	Cracked surface	1	
41	35.18791	-111.652935	2:10	Cracked surface	1	
42	35.18850667	-111.6529333	2:27	Detectable warning	0	

Table 3-12. List of guidelines associated with potential pathway anomalies

Guideline Number	AASHTO Section	Requirement
0	5.3.2	Crossing ramps should have detectable warnings placed across the full width of a ramp. 分8
1	4.2	Bike corridors should avoid potholes, large cracks, and gravel surfaces.
2	4.3	Bike corridors should have bike compatible drainage grates, bridge expansion joints, and railroad crossings
3	4.5	Where practical, the paved section of the approach to a roadway should be sloped down to prevent loose material getting onto the shoulder
4	4.5	Raised pavement markers (pavement reflectors) should be avoided along bicycling routes.
5	4.12.8	Drainage grates should have openings small enough that bicycle wheels cannot fall into its slots. Its slots should be no more than an inch wide, and slots should be perpendicular to the direction of bike traffic.
6	5.2.9	Hard, all weather pavement surfaces are generally preferred over that of crushed aggregate, sand, clay, or stabilized earth
7	5.2.9	In areas that experience frequent or even occasional flooding or drainage problems, or in areas of moderate or steep terrain, unpaved surfaces will often erode and are not recommended.
8	5.2.9	Portland cement concrete pavements, transverse joints should be saw cut rather than tooled to provide a smoother ride.
9	5.2.9	Utility covers and drainage grates should be flush with the pavement surface on all sides.
10	5.2.9	If possible, utility covers and drainage grates should be on the side of paths
11	5.2.9	Railroad crossings should be smooth and be designed at an angle between 60 and 90 degrees to the direction of travel.
12	5.2.9	When shared use paths cross an unpaved road or driveway, the road should be paved a minimum of 20’ on each side of the crossing
13	5.2.10	At transitions and approaches from paths to bridge decks, the height of the path’s surface should match the height of the bridge deck surface.
14	5.2.10	Bridge deck lips should be avoided all together
15	5.2.11	Where necessary, drainage should flow under the path.

16	5.4.1	No pavement marking should rise above 0.16” (4 mm) above the pavement
17	7.2	Bikeways should be adequately maintained and regularly swept.
18	7.2	Gravel or sand used on roadways during wintery conditions shouldn’t accumulate on paths.
19	7.2.2	Edge of a surface repair shouldn’t run longitudinally through a bike lane or shoulder
20	7.2.2	Invasive tree roots shouldn’t be present on paths
21	7.2.3	Pavement overlays should not leave any ridges in areas where bicyclists are anticipated to ride.
22	7.2.4	Root barriers should be installed where appropriate
23	7.2.4	Vegetation should be cut to prevent encroachment
24	7.2.8	Chip seals should not be used on shared use paths
25	7.2.10	Cuts should be filled such that they are flush with the surface (no humps)
26	7.3.2	Effective and convenient passage is needed during construction for bicyclists.
27	7.2.3	Path project areas should be swept after overlay to prevent loose gravel from adhering to the freshly paved shoulder or bike lane
97		Other
98		Rider induced
99		Unknown cause

Table 3-13. Screenshot examples of each pathway anomaly

No.	Item	Description	Picture
1.	Rider induced	Any sort of movement induced by the rider that would trigger the accelerometer independently of what pathway conditions are present	
2.	Loose gravel	The presence of loose gravel on a path in a substantial quantity. On unpaved paths, loose gravel is distinct from compacted gravel that the path may be made out of.	
3.	Rough surface	The pathway surface texture is rough in nature, not due to erosion or an excessive presence of loose debris.	
4.	Minor water erosion	Water runoff from a small area has caused the path to begin to erode. Water channels are no more than about a foot wide or a foot deep.	

5.	Significant water erosion	Water from a larger watershed runs through the path. Water is likely to exceed 1’ in width when flowing.	
6.	Surface transition	Pathway surface material changes from gravel, concrete, or asphalt.	
7.	Detectable warning	Rough textured strip intentionally placed at crossings to assist blind pedestrians while crossing streets.	
8.	Eroded surface	The pathway surface is not cracking but has roughened significantly from its initial state.	

9.	Cracked surface	The pathway has formed a crack or cracks or distinct divots in the surface.	
10.	Road crossing ramp	Ramps at roadway crossings that allow for smooth transitions between the road and pathway.	
11.	Bridge transition	The pathway transitions from being on the surface to being on a bridge deck.	
12.	Fill segment not flush	A segment of the pathway has been cut and refilled, but the filled in segment is not flush with the existing pathway.	

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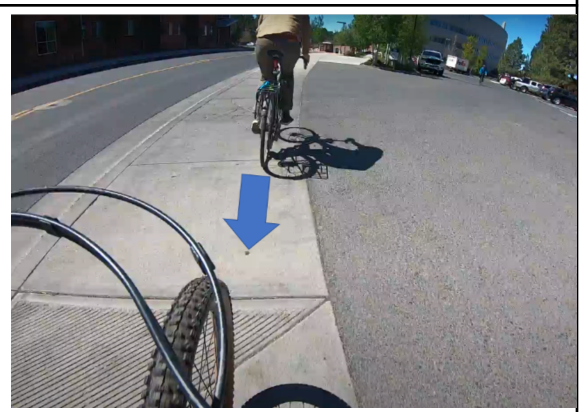
13.	Tool cut transverse joint	Transverse cuts on sidewalks were formed using tools while the concrete was drying rather than cut with a saw.	
14.	Utility cover on path	Utility cover on a pathway.	
15.	Debris	Small rocks, vegetation, or litter that the bicyclist ran over.	
16.	Roots uplifting pathway	Tree roots underneath the pathway are causing changes within the pathway.	

17.	Raised pavement markings		

Visually Detectable Analysis

A secondary analysis was performed to detect geometric conditions within the bicycle facilities that are in violation of AASHTO and the Manual on Uniform Traffic Control Devices [21] (MUTCD, 2012) guidelines using only the GoPro video recording data. This analysis used the comprehensive AASHTO guideline list in Appendix A-7 and eliminated all guidelines that would be impossible to accurately find from only a video recording. In addition, for this observation, guidelines from the MUTCD were included when detecting bicycle facility violations. Table 3-23 has the AASHTO and MUTCD violations that were being analyzed in this analysis. For all six routes, a list of violations was generated as well as a map of the approximate location of each violation. Below in Figures 3-2 to 3-7 are the maps of each violation detected. Tables 3-14 to 3-22 contain the specific violation type, and a screenshot of each violation. The violations were listed from south to north if the route's directionality was north to south and listed from west to east if the route's directionality was east to west.

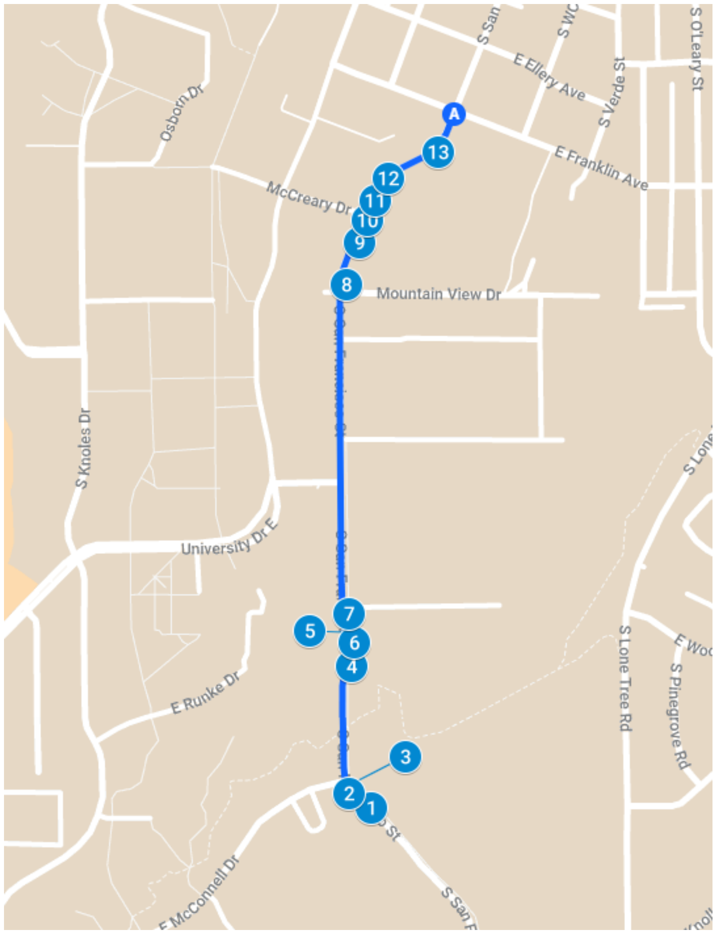


Figure 3-2. Skydome route map with violations

Table 3-14. Skydome violation list

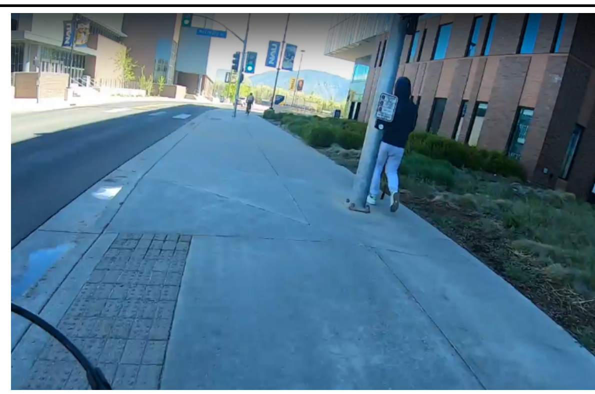
Map No.	Reason	Violation No.	Requirement	Video	Time
1.	Fence not flared	4	Recommended	skydomego	0:08
2.	Fence not flared	4	Recommended	skydomego	0:18
3.	Powerline flush to path	13	Recommended	skydomego	0:18
4.	Fence not flared	4	Recommended	skydomego	1:01
5.	Fence not flared	4	Recommended	skydomego	1:11

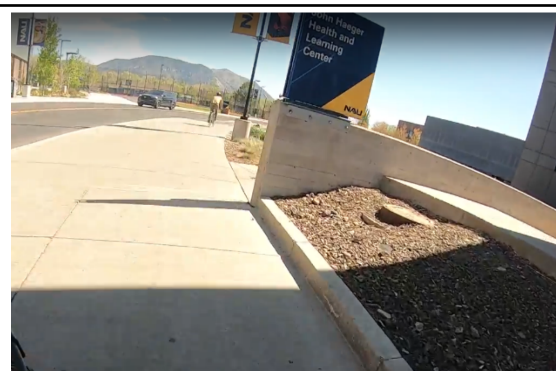
6.	Fence not flared	4	Recommended	skydomeback	3:08
7.	Designated bicycle path goes away	6	Recommended	skydomego	2:27
8.	Wheeled users not separated from pedestrians on a busy pathway	2	Recommended	skydomego	2:34
9.	Traffic light on pathway	13	Recommended	skydomego	2:43
10.	Traffic light on pathway	13	Recommended	skydomego	2:45
11.	Object flush to path	13	Recommended	skydomego	2:53
12.	Bollards on path	10	Recommended	skydomego	3:07

Table 3-14. Skydome violation screenshots

Map No.	Image
1. Fence not flared (violation #4 – recommended)	
2. Fence not flared (violation #4 – recommended)	

3. Powerline flush to path (violation #13 – recommended)	
4. Fence not flared (violation #4 – recommended)	
5. Fence not flared (violation #4 – recommended)	
6. Fence not flared (violation #4 – recommended)	

7. Designated bicycle path goes away (violation #6 – recommended)	
8. Wheeled users not separated from pedestrians on a busy pathway (violation #2 – recommended)	
9. Traffic light on pathway (violation #13 – recommended)	

10. Traffic light on pathway (violation #13 – recommended)	
11. Object flush to path (violation #13 – recommended)	
12. Bollards on path (violation #10 – recommended)	

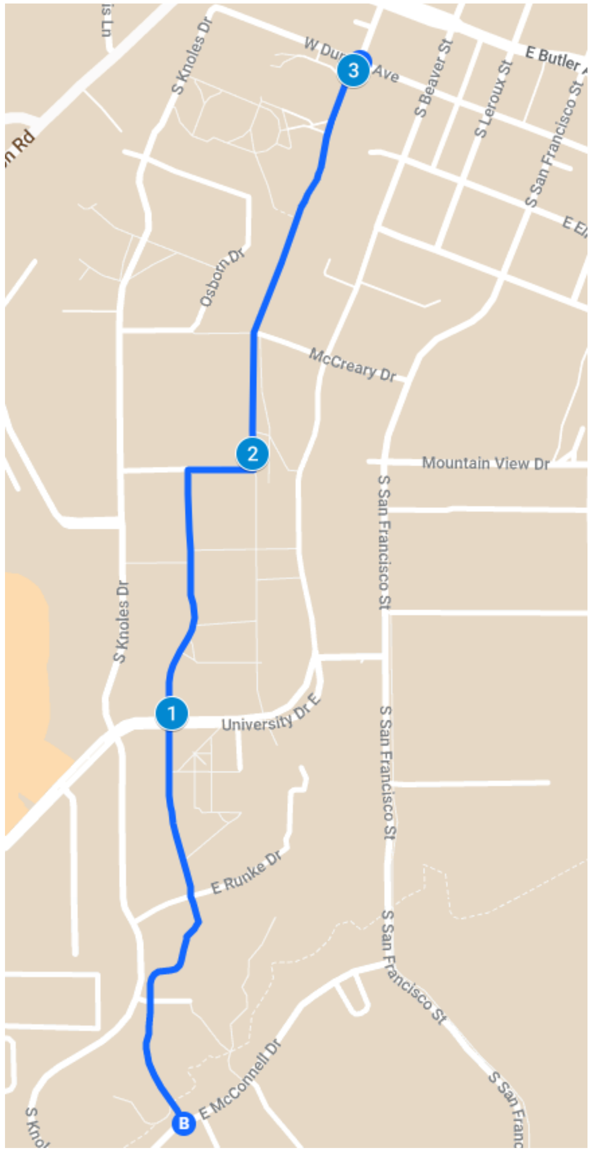
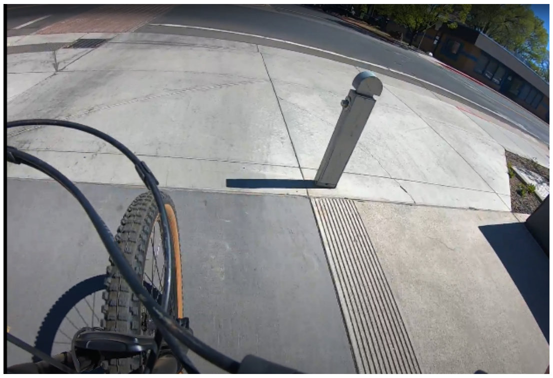


Figure 3-3. Skyview route map with violations

Table 3-16. Skyview violations list

Map No.	Reason	Violation No.	Requirement	Video	Time
1.	Bollard on path	10	Recommended	skyviewgo	2:36
2.	Wheeled users not separated from pedestrians on a busy pathway	2	Recommended	skyviewgo	3:55
2.	Bollard on path	10	Recommended	skyviewgo	5:32

Table 3-16. Skyview violations screenshots

Map No.	Image
1. Bollard on path (violation #10 – recommended)	
2. Wheeled users not separated from pedestrians on a busy pathway (violation #2 -recommended)	
3. Bollard on path (violation #10 – recommended)	

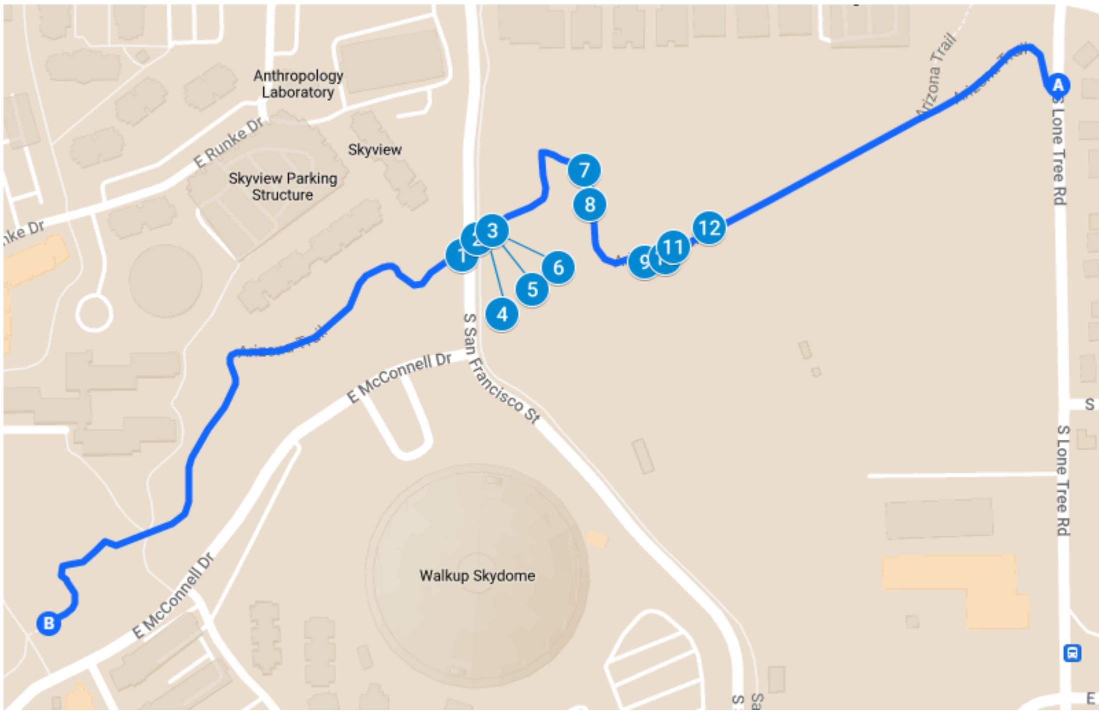


Figure 3-4. Arizona Trail route map with violations

Table 3-16. Arizona Trail violation list

Map No.	Reason	Violation No.	Requirement	Video	Time
1	Bollard on path	10	Recommended	AZtrailgo	2:08
2.	Unmarked midblock crossing	16,9	Recommended	Aztrailgo	2:12
3.	Bollard on path	10	Recommended	Aztrailgo	2:19
4.	Bollard on path	4	Recommended	Aztrailgo	2:19
5.	Fence not flared	4	Recommended	Aztrailgo	2:20
6.	Fence not flared	4	Recommended	Aztrailgo	2:20
7.	Fence not flared	4	Recommended	Aztrailgo	2:54
8.	Fence not flared	4	Recommended	Aztrailgo	2:58

9.	Fence not flared	4	Recommended	Aztrailgo	3:19
10.	Fence not flared	4	Recommended	Aztrailgo	3:19
11.	Fence not flared	4	Recommended	Aztrailgo	3:20
12.	Fence not flared	4	Recommended	Aztrailgo	3:20

Table 3-17. Arizona Trail violation screenshots

Map No.	Image
1. Bollard on path (violation #10 – recommended)	
2. Unmarked midblock crossing (violation #16,9 -recommended)	
3. Bollard on path (violation #10 – recommended)	

4. Fence not flared (violation #4 – recommended)	
5. Fence not flared (violation #4 – recommended)	
6. Fence not flared (violation #4 – recommended)	

7. Fence not flared (violation #4 – recommended)	
8. Fence not flared (violation #4 – recommended)	
9. Fence not flared (violation #4 – recommended)	

10. Fence not flared (violation #4 – recommended)	
11. Fence not flared (violation #4 – recommended)	
12. Fence not flared (violation #4 – recommended)	

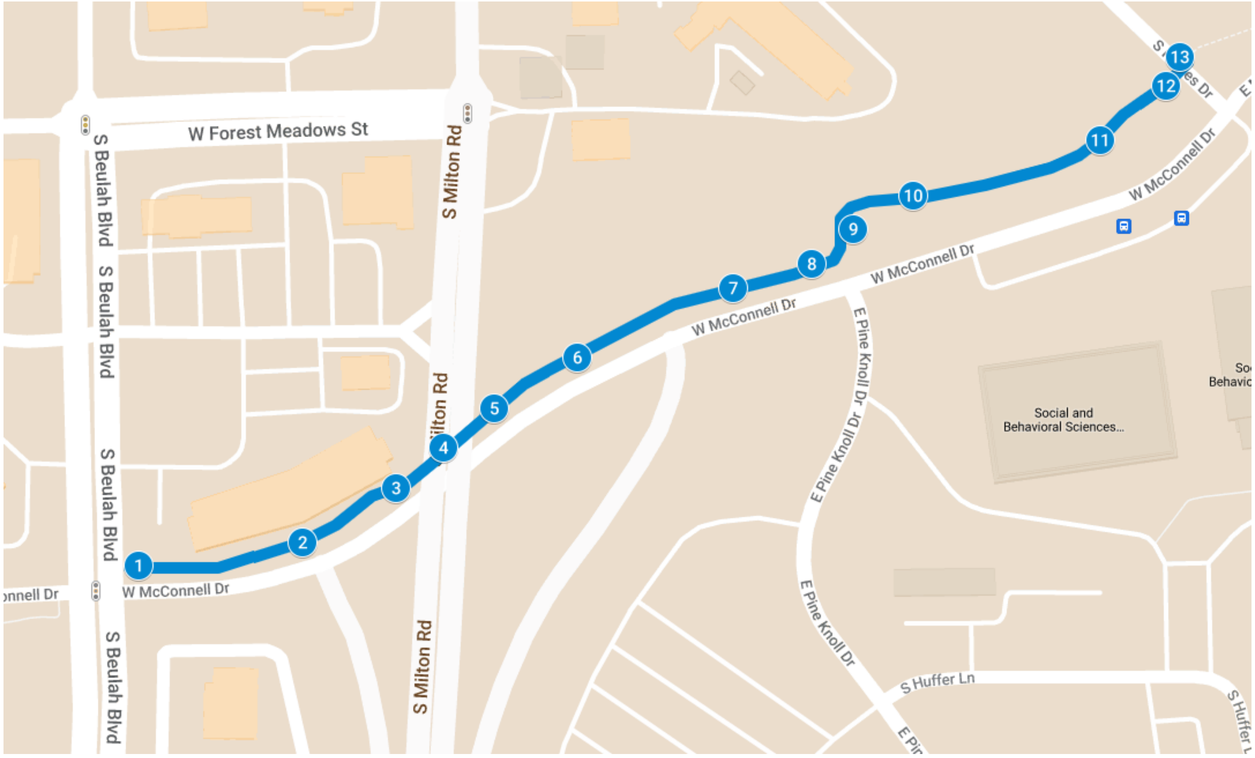


Figure 3-5. McConnell route map with violations

Table 3-18. Skydome violation list

Map No.	Reason	Violation No.	Requirement	Video	Time
1.	Fence not flared	4	Recommended	hamptongo	2:05
2.	Gravel from snow mitigation on pathway	12	Recommended	hamptonback	0:14
3.	Fencing not flared. *Side note: Damaged fencing poses significant impact risk to riders (not on list)	4	Recommended	hamptobback	0:24
4.	Side wall has no lateral clearance	5	Recommended	hamptonback	0:27
5.	Fencing not flared	4	Recommended	hamptongo	1:07
6.	Surface texture roughens significantly without a warning sign	17	Recommended	hamptonback	0:35
7.	Fencing not flared	4	Recommended	hamptonback	1:00

8.	Fencing not flared	4	Recommended	hamptonback	1:02
9.	Fencing not flared	4	Recommended	hamptonback	1:07
10.	Fencing not flared	4	Recommended	hamptonback	1:14
11.	Fencing not flared	4	Recommended	hamptonback	1:36
12.	Bollard	10	Recommended	hamptonback	1:37
13.	Crosswalk not clearly visible	9	Recommended	hamptonback	1:39

Table 3-19. McConnell violation list

Map No.	Image
1. Fence not flared (violation #4 – recommended)	
2. Gravel from snow mitigation on pathway (violation #12 – recommended)	

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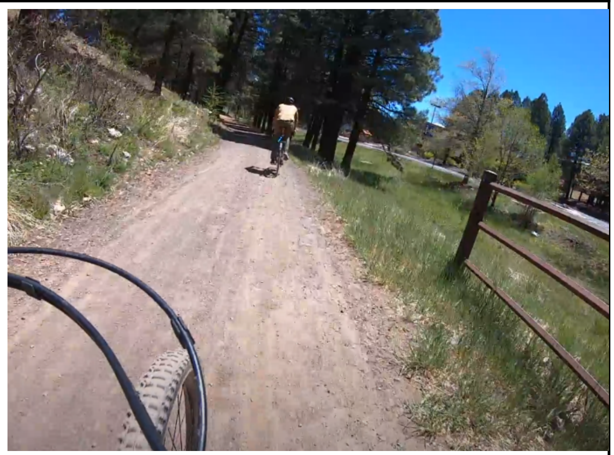
University Transportation Center

3. Fence not flared (violation #4 – recommended) *Damaged fencing poses an injury risk for riders.	
4. Side wall has no lateral clearance (violation #5 – recommended)	
5. Fence not flared (violation #4 – recommended)	

6. Surface texture roughens significantly without a warning sign (violation #17 – recommended)	
7. Fence not flared (violation #4 – recommended)	
8. Fence not flared (violation #4 – recommended)	

9. Fence not flared (violation #4 – recommended)	
10. Fence not flared (violation #4 – recommended)	
11. Fence not flared (violation #4 – recommended)	

12. Bollard on path (violation #10 – recommended)	
13. Unmarked midblock crossing (violation #9 – recommended)	

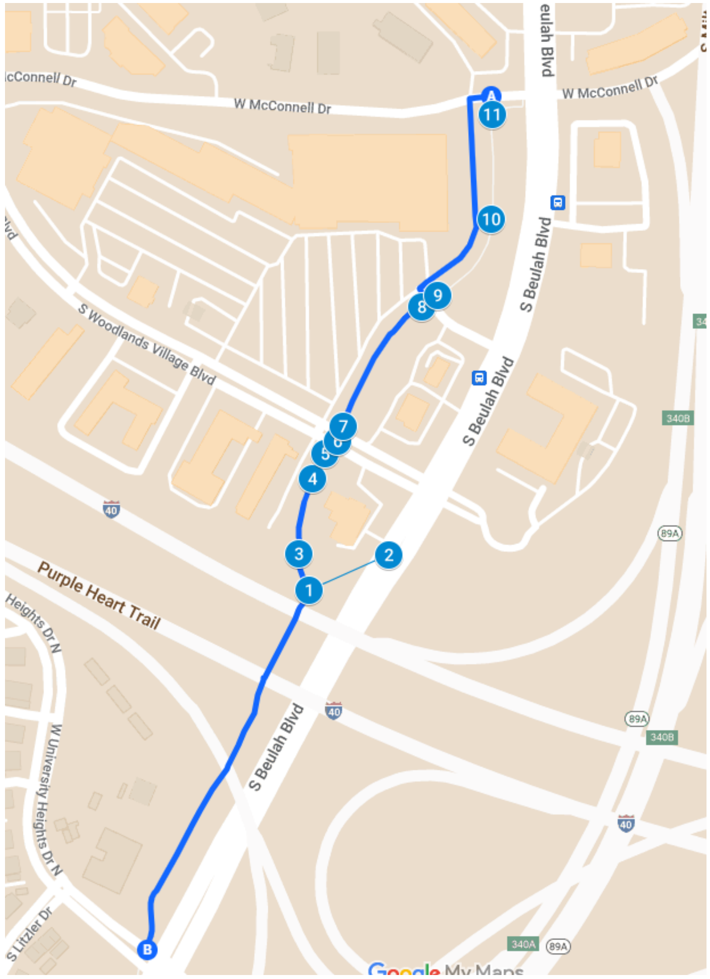


Figure 3-6. Beulah route map with violations

Table 3-20. Beulah violation list

Map No.	Reason	Violation No.	Requirement	Video	Time
1.	Fence not flared	4	Recommended	walmartback	0:55
2.	Object has no lateral clearance	13	Mandatory	walmartback	0:55
3.	Fence not flared	4	Recommended	walmartback	1:06
4.	Fence not flared	4	Recommended	walmartback	1:21

5.	Bollard on path	10	Recommended	walmartback	1:24
6.	Low visibility crosswalk	9, 16	Recommended	walmartback	1:27
7.	Bollard on path	10	Recommended	walmartback	1:35
8.	Bollard on path	10	Recommended	walmartback	2:03
9.	Bollard on path	10	Recommended	walmartback	2:07
10.	Wall adjacent to path	5	Recommended	walmargo	0:14
11.	Bollard on path	10	Recommended	walmartback	2:37

Table 3-21. Beulah violation list

Map No.	Image
1. Fence not flared (violation #4 – recommended)	
2. Object has no lateral clearance (violation #13–recommended)	

3. Fence not flared (violation #4 – recommended)	
4. Fence not flared (violation #4 – recommended)	
5. Bollard on path (violation #10 – recommended)	

6. Low visibility crosswalk (violation #9, #16 – recommended)	
7. Bollard on path (violation #10 – recommended)	
8. Bollard on path (violation #10 – recommended)	

9. Bollard on path (violation #10 – recommended)	
10. Wall adjacent to path (violation #5 – recommended)	
11. Bollard on path (violation #10 – recommended)	

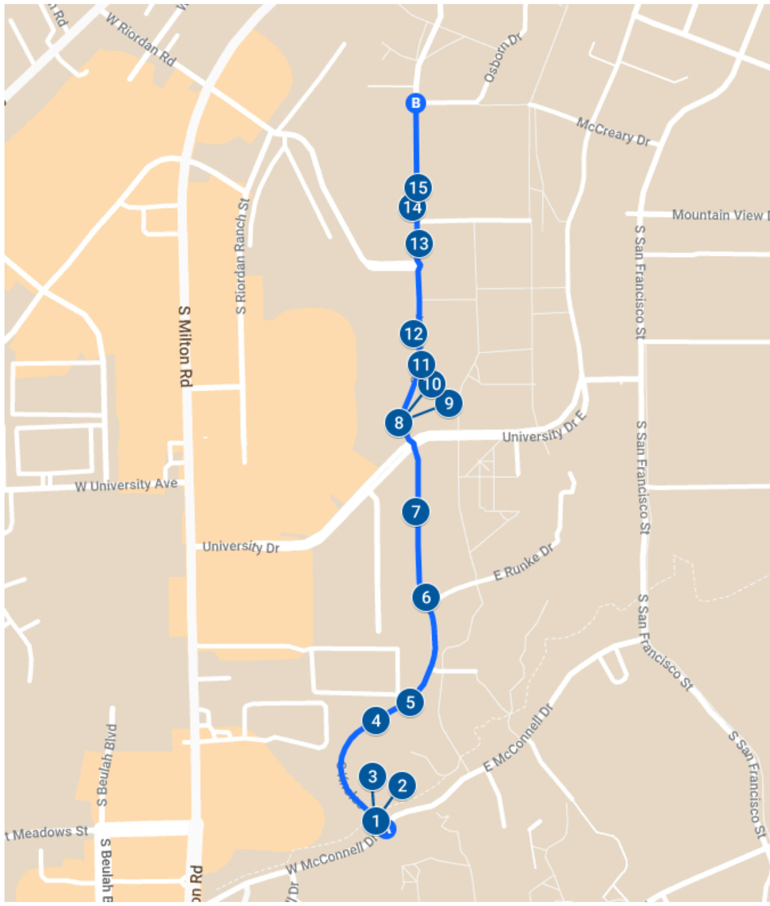


Figure 3-7. Library route map with violations

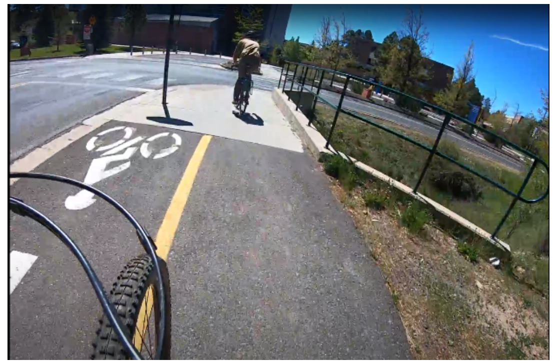
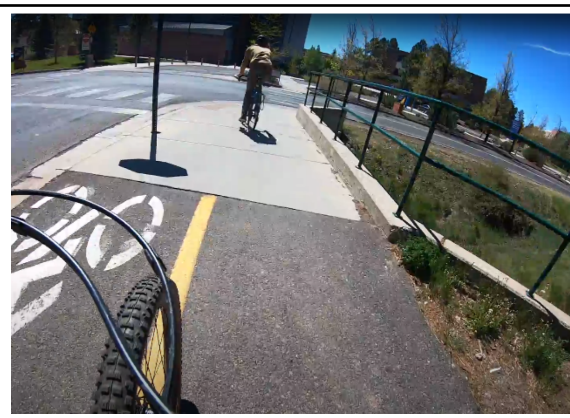
Table 3-22. Library route map violations

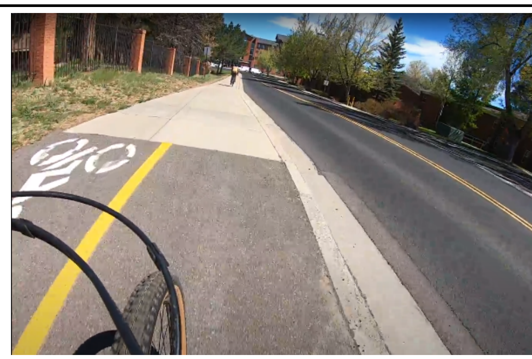
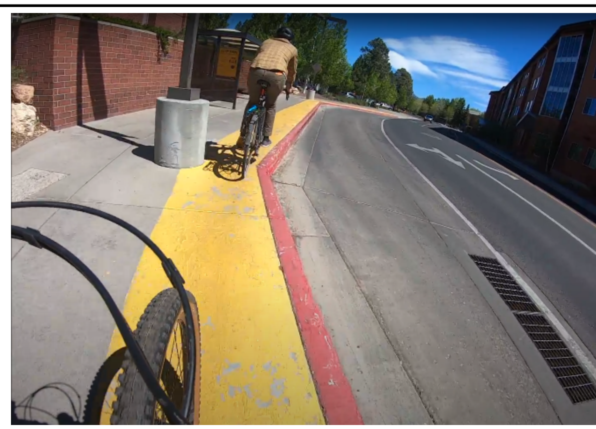
Map No.	Reason	Violation No.	Requirement	Video	Time
1	There is no lateral clearance from a stop sign.	13	Mandatory	Librarback	4:30
2	There is no warning of the steep incline for users traveling north.	7	Recommended	Librarygo	0:01
3.	The side-path abruptly transitions into a sidewalk without facilities for bicyclists traveling south.	6	Recommended	Libraryback	4:26
4.	There is no warning of the steep decline for users traveling south.	7	Recommended	Libraryback	3:51

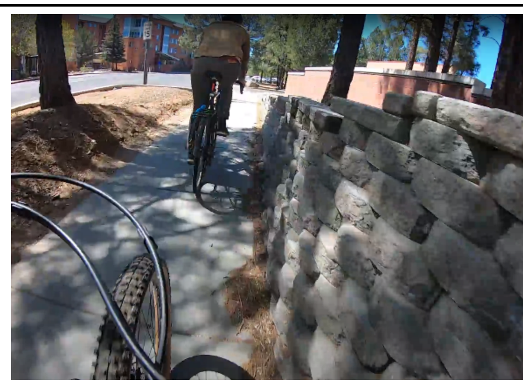
5.	Pedestrian warning signs not accompanied by diagonal arrows pointing to the crosswalk.	18	Mandatory	Librarygo	1:36
6.	Uncontrolled crossing has no warning signs for side-path users or motorists on the road.	16	Recommended	Librarygo	1:56
7.	Shared use side-path abruptly ends and becomes a narrower sidewalk, without providing adequate facilities for bicyclists.	6	Recommended	Librarygo	2:26
8.	A light pole is directly on the path.	5	Recommended	Librarygo	3:02
9.	There is no lateral clearance from a bus station shelter, retaining wall, and garbage collectors.	5	Recommended	Libraryback	1:99
10.	A light pole is directly on the path.	5	Recommended	Libraryback	1:56
11.	Uncontrolled crossing has no warning signs for side-path users or motorists on the road.	16	Recommended	Librarygo	3:20
12.	There is no lateral clearance from a retaining wall.	5	Recommended	Libraryback	1:26
13.	Uncontrolled crossing has no warning signs for side-path users or motorists on the road.	16	Recommended	Librarygo	4:00
14.	Trash cans are directly on the path	5	Recommended	Libraryback	0:32
15.	Uncontrolled crossing has no warning signs for side-path users or motorists on the road.	16	Recommended	Librarygo	4:16

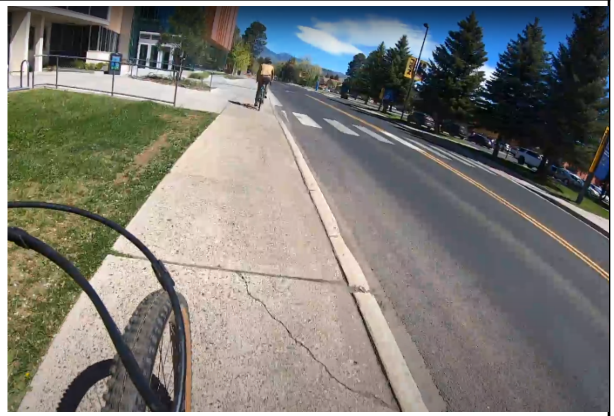
Table 3-22. Library route map violations screenshot

Map No.	Image

1. There is no lateral clearance from a stop sign (violation #13 – mandatory)	
2. There is no warning of the steep incline for users traveling north (violation #7 – recommended)	
3. Side-path transitions into sidewalk without separate facilities for wheeled users (violation #6 – recommended)	
4. There is no warning of the steep decline for users traveling south (violation #7 – recommended)	

5. Pedestrian warning signs not accompanied by diagonal arrows pointing to the crosswalk (violation #18 -mandatory)	
6. Uncontrolled crossing has no warning signs for side-path users or motorists on the road (violation #16 – recommended)	
7. Side-path transitions into sidewalk without separate facilities for wheeled users (violation #6 – recommended)	
8. Light pole on path (violation #5 – recommended)	

9. There is no lateral clearance from a bus station shelter, retaining wall, and garbage collectors (violation #5 – recommended)	
10. Light pole on path (violation #5 – recommended)	
11. Uncontrolled crossing has no warning signs for side-path users or motorists on the road (violation #16 – recommended)	
12. There is no lateral clearance from a retaining wall (violation #5 – recommended)	

13. Uncontrolled crossing has no warning signs for side-path users or motorists on the road (violation #16 – recommended)	
14. Trash can directly on path (violation #5 – recommended)	

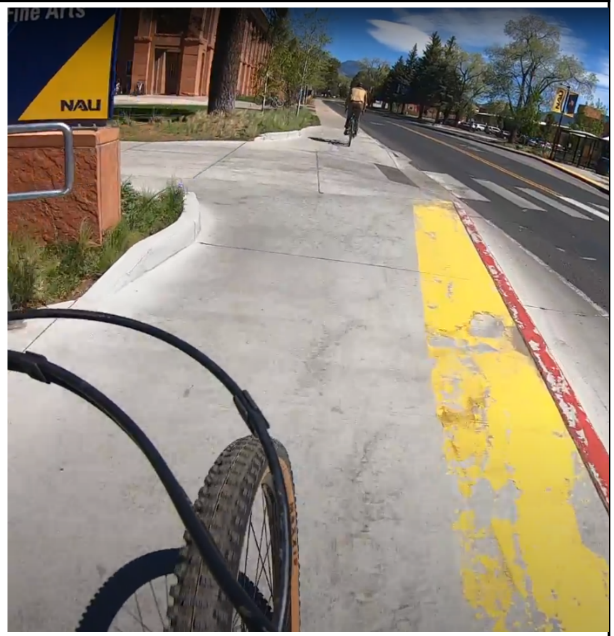
15. Uncontrolled crossing has no warning signs for side-path users or motorists on the road (violation #16 – recommended)	

Table 3-23. AASHTO and MUTCD guidelines

Number	Section	Requirement	Detectability	Requirement
AASHTO (2012)				
1	5.2.1	Pathways with heavy peak hour volumes should use a centerline stripe on a path to help clarify the direction of travel	Easy	Recommended
2	5.2.1	Areas with extremely heavy pathway volumes should segregate wheeled users from pedestrians. The minimum pathway width for this scenario is 15' where at least 10' is for two-way wheeled users and 5' is for pedestrians	Moderate	Recommended
3	5.2.1	Barrier/rails should extend prior to and beyond area of need, have a lateral offset of 1' from the edge of the path	Moderate	Recommended
4	5.2.1	Ends of barriers should be flared away from path edges. Barriers or rail ends that remain within 2' clear area should be marked with object markers	Moderate	Recommended

5	5.2.1	A minimum of 2' clearance should be provided for clearance from lateral objects (bushes, large rocks, poles)	Moderate	Mandatory
6	5.2.2	When terminated, sidepaths should accommodate bicyclists onto another path or a bicycle compatible facility. It should not leave bicyclists inclined to ride against traffic.	Moderate	Recommended
7	5.2.7	Where excessive grades are present, consider providing signage that alerts path users to the maximum percent of grade as shown in the MUTCD	Moderate	Recommended
8	5.3.2	Intersections should be as close to a right angle as practical	Easy	Recommended
9	5.3.2	High visibility marked crosswalks are recommended at uncontrolled path-roadway intersections	Easy	Recommended
10	5.3.5	Bollards shouldn't be used on shared use paths to restrict motor vehicle traffic unless there is a documented history of unauthorized intrusion by motor vehicles.	Moderate	Recommended
11	5.4.1	White edgeline striping should be considered for shared use paths where paths are used at night or if pathway design includes a separate area for pedestrian travel.	Easy	Recommended
12	7.2	Gravel or sand used on roadways during wintery conditions shouldn't accumulate on paths.	Moderate	Recommended
MUTCD (2012)				
13	9B.01	Where used on a shared-use path, no portion of a sign or its support shall be placed less than 2 feet laterally from the near edge of the path, or less than 8 feet vertically over the entire width of the shared-use path	Moderate	Mandatory
14	9B.03	YIELD (R1-2) signs (see Figure 9B-2) shall be installed on shared-use paths at points where bicyclists have an adequate view of conflicting traffic as they approach the sign, and where bicyclists are required to	Easy	Mandatory

		yield the right-of-way to that conflicting traffic.		
15	9B.12	Uncontrolled crossing has no warning signs for side-path users or motorists on the road (violation #16 – recommended) This sign may be used to supplement a solid white pavement marking line on facilities with bike and pedestrian infrastructure	Moderate	Recommended
16	9B.16	Intersection Warning (W2-1 through W2-5) signs (see Figure 9B-3) may be used on a roadway, street, or shared-use path in advance of an intersection to indicate the presence of an intersection and the possibility of turning or entering traffic.	Easy	Recommended
17	9B.17	The Bicycle Surface Condition Warning (W8-10) sign (see Figure 9B-3) may be installed where roadway or shared-use path conditions could cause a bicyclist to lose control of the bicycle. Can include need to warn for bumps, dips, or pavement ending.	Moderate	Recommended
18	9B.18	Bicycle warning and bike/ped signs at crossings shall be supplemented with a diagonal downward pointing arrow to show the location of the crossing	Easy	Mandatory
19	9C.03	Solid white lines may be used on shared use paths to separate different types of users.	Easy	Recommended

Planning Applications for an Instrumented Bike

Moving forward, the continued advancement of the instrument bike technologies described in this report has a prospect of contributing to national and local movements to further motivate bicycling as a low-cost, healthy, and sustainable mobility option. The identification of possible bicyclist safety issues via the LSTM-autoencoder and videorecording capabilities of this piloted instrumented bike has revealed the possibility for this active transportation innovation to help transportation departments and planning agencies ensure the maintenance of current off-street and on-street bike networks. Furthermore, a potential for this smart technology to collect crowdsourced information on bicycling activity and bike infrastructure conditions may provide planners and policymakers an empirically-driven decision-making tool capable of informing the prioritization of facility improvements and opportunities to expand bike networks.

In the local context of Flagstaff, the City's ongoing bicycle planning efforts could be bolstered by a larger-scale deployment of the instrumented bike described in this research. Of note, the city maintains and operates the Flagstaff Urban Trail System (FUTS), a network of nonmotorized, shared-use paths and trails that presently spans 56 miles [22] (Flagstaff, 2022). The pilot data analyzed for this report were collected on segments of the FUTS, which in its entirety is evenly distributed between on- and off-street facilities that are paved in concrete or asphalt and off-street facilities comprised of hard-packed, aggregate gravel. The deployment of an instrumented bike fleet delivering real-time feedback to both system users and city officials carries an opportunity to better inform near- and long-term decisions regarding travel routes and maintenance schedules.

For instance, the daily routing choice of a bicyclist could be modified if given the knowledge that a segment on their travel route was adversely impacted by inclement weather conditions or another circumstance that created a temporary travel impediment. Provided with this information from a system of instrumented bikes, a bicyclist could make routing adjustments that mitigate discomfort that they would otherwise encounter and ensure only modest changes to their travel time. In turn, giving this information to a city official will permit the quick identification of travel impediments that may include the mild erosion of an unpaved surface from a rainstorm or collection of loose materials (e.g., cinders) on an on-street facility from adjacent roadway treatments and a subsequent effort to remove the temporary obstruction by a city official in a timely manner. Beyond the identification of temporary hindrances along a travel route, the implementation of an instrumented bike could also permit the identification of longer-term infrastructure improvements that may be the result of weather-related damage or path anomalies created by utility work, local construction, or natural processes. In these circumstances, the technology of an instrumented bike can help to inform the prioritization of current network improvements based on objective data on the discomfort experienced by a bicyclist encountering a path anomaly. By inventorying long-term anomalies and the associated discomfort that they produce for bicyclists, city officials can best determine the sequencing of facility improvements to ensure they meet AASHTO and MUTCD guidelines.

However, the diagnosis of path anomalies that necessitate either short- and long-term solutions must be collected by a significant pool of bicyclists adopting instrumented bikes to prevent any potential reporting biases (due to an under-sampling lower-activity facilities) and validate the detection measures. One resource is the local population, which in Flagstaff is accustomed to bicycling as a mobility option, as shown with the city's 8% mode share (Flagstaff 2020). Through targeted marketing efforts, a possibility exists to successfully disseminate this app-based technology across the city's active transportation community, which constitutes a balanced mix of utilitarian bicyclists who primarily travel along on-street facilities and recreational bicyclists who may ride mountain bikes to access the city's network of off-street trails. The use of instrumented bikes by a subset of the latter population has the potential to help identify conditions of off-street facilities located outside of the city's core, which have lower bicyclist volumes and are more likely to incur frequent weather-related damage events (e.g., erosion). Crowdsourced instrumented bike data can also be provided by NAU students, who have a bike mode share of 15% [23] (Flagstaff 2020) and are likely to be more prone to technological adoption. As was illustrated in this report's data collection efforts, both temporary and more permanent path anomalies exist across the more-popular shared-use corridors on NAU's campus. While the adoption of instrumented bike technologies on privately-owned bicycles by NAU students can help direct the maintenance and safe operation of bicycles on the university's campus, this segment of the population is also likely to bicycle to off-campus residences and activity sites located in the city's core neighborhoods. By traversing high-activity bike facilities adjacent to the campus that are maintained by city officials, the instrumented bike data collected by NAU students can help to ensure that recent improvements to the bike network within the city's core such as the protected bike lanes on Butler Avenue and Beaver Street remain safe and clear of temporary obstructions or path anomalies.

A promising alternative to the adoption of app-based technologies that create a privately-owned 'smart bike' is the outfitting of public bicycles operated and maintained by a local bikeshare system. The Yellow Bike Program [24] (NAU 2022), which is a rental service on NAU's campus that provides students, staff, and faculty with free one-week access to a human-powered bicycle, represents an opportunity to partner with NAU on the introduction of an instrumented bike fleet in a living-laboratory setting. Beyond the NAU campus, there are currently no public bikeshare programs operating in the City of Flagstaff. However, the city previously partnered with the micromobility provider, Spin, in 2018 on a one-year pilot that brought human-powered dockless bikeshare services to the city's core and NAU's campus [25] (Arizona Daily Sun 2018). Before the onset of the Covid-19 pandemic, the Flagstaff City Council approved a six-month contract with Gotcha Mobility on the operation of a bikeshare system of 250 electric pedal-assist bikes that would have permitted its users to also ride on the city's off-street FUTS facilities [26] (KNAU 2019). While neither bikeshare system provider currently operates in Flagstaff, successes in the operation of the former system and the following commitment to launch a system of dockless e-bikes that would operate on varying surfaces hints at the potential for an innovative public-private partnership between policymakers and a future bikeshare provider to deliver a fleet of instrumented bikes capable of offering city residents and visitors a real-time glimpse at bike infrastructure conditions. An installment of the 'smart bike' technologies presented in this report that are capable of immediately identifying path anomalies coupled with the ability of a large-scale bikeshare system to ensure network coverage and detect high ridership corridors, may be used in tandem to offer decisionmakers with a robust planning tool that can objectively prioritize the short- and long-term maintenance of bike facilities and assurance of a safe and accessible network for bicyclists of all levels.

Chapter 4 Conclusion and Future Recommendation

Through instrumented cycling and sensing activities, the project has the following conclusions:

- The sliding window computing algorithm is capable of analyzing vibration patterns and identifying potential hazards (PIOs) through multiple cyclists; it has achieved the state-of-the-art performance in classifying and localizing cracks/potholes without any human-controlled supervision (e.g., annotated dataset used to train the classifier; threshold adjustments for distress classifications) while achieving human-level perception.
- The sliding window computing algorithm provides a generic computing process for anomaly classification and localization in analyzing time sequence data, which has the potentials to extract more sophisticated information along bike routes.
- The real-time inference of the sliding window computing algorithm facilitates the realization of potential hazards to be sensing, georeferenced, and visualized in a real-time manner.
- The field test validates the effectiveness of the sliding window computing algorithm in detecting potential hazards (PIOs), provided the fact that the pavement distress areas labeled as "high" or "moderate" are most likely screened as "recognizable" patterns and therefore identified as POIs. Interested users such as local authorities, cyclists, transportation planners, etc. would have access to the cycling information and share the real time results with other users.
- The sliding window computing algorithm can be a good technique in support of the development of instrumented bike and to promote the use of cycling as a daily transportation mode.
- The instrumented bike provides a promising methodology to help local government or agency in reviewing existing cycling trail conditions in compliance with AASHTO and MUTCD standards such that a list of repair priorities can be provided for decision making for maintenance.

Recommendation for future work

- An installment of the 'instrumented bike AKA "smart bike' technologies presented in this report will be recommended to expand its scope to a large-scale bikeshare system to ensure network coverage and detect high ridership corridors, such that it will offer decisionmakers with a robust planning tool that can objectively prioritize the short- and long-term maintenance of bike facilities and assurance of a safe and accessible network for bicyclists of all levels.

Bibliography

1. Allied Market Research (AMR), latest access in February 2021: https://www.alliedmarketresearch.com/connected-car-marketEuropean Cyclists' Federation (ECF). *Smart Cycling Series: you are what you share*. Latest Access June 2021, https://ecf.com/news-and-events/news/smarter-cycling-series-you-are-what-you-share
2. European Cyclists' Federation (ECF). Smart Cycling Series: *Big data and artificial intelligence are transforming bicycle navigation*. Latest Access June 2021, https://ecf.com/news-and-events/news/smarter-cycling-series-big-data-and-artificial-intelligence-are-transforming-1
3. Leitner, T., H. Kirchsteiger., H. Trogmann, and L. del Re. *Model based control of human heart rate on a bicycle ergometer*. European Control Conference (ECC), June 24-27, 2014. Strasbourg, France.
4. Liu, X., C. Xiang., B. Li, and A. Jiang, *Collaborative Bicycle Sensing for Air Pollution on Roadway*. 2015 IEEE 12th Intl Conf on Ubiquitous Intelligence and Computing, 10-14 August 2015, Beijing, China.
5. Pedotti, L.A.S., R.M. Zago., and F. Fruett, *Instrument based on MEMS accelerometer for vibration and unbalance analysis in rotating machines*. The 1st International Symposium on Instrumentation Systems, Circuits and Transducers (INSCIT), August 29-September 3, 2016. Belo Horizonte, Brazil.
6. Pigatto, A.V., K.O.A. Moura., G.W. Favieiro., and A. Balbinot, *A new Crank Arm Based Load Cell, with built-in conditioning circuit and strain gages, to measure the components of the force applied by a cyclist*. The 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), August 17-20, 2016, Orlando, Florida USA.
7. Ho, C.H., P. Qiu., S. Wen., X. Liu., M. Snyder., and K. Winfree, *Development of Instrumented Bicycle and Mobile Applications to Perform Cloud-Based Pavement Condition Management for Bike Roads*. Proceedings of 2019 Annual Conference of Transportation Research Board, Washington DC, January 13-17, 2019
8. Qiu, P., X. Liu., S. Wen.,Y. Zhang., K. Winfree, and C.H. Ho, *The Development of an IoT Instrumented Bike: for Assessment of Road and Bike Trail Conditions, 2018 International Symposium in Sensing and Instrumentation in IoT Era (ISSI)*, 2018, pp. 1-6, doi: 10.1109/ISSI.2018.8538268.
9. Ho, C. H., J. Gao,, M. Snyder., and P. Qiu, *Development and Application of Instrumented Bicycle and Its Sensing Technology in Condition Assessments for Bike Trails. Journal of Infrastructure Systems*, 27(3), 2021, 04021027.
10. Zhao, Yu, and R. Yang, Guillaume Chevalier, X. Xu, and Z. Zhang. *Deep residual bidir-LSTM for human activity recognition using wearable sensors*. Mathematical Problems in Engineering 2018 (2018).
11. Pienaar, S.W., and R. Malekian. *Human activity recognition using LSTM-RNN deep neural network architecture*. In 2019 IEEE 2nd wireless africa conference (WAC), pp. 1-5. IEEE, 2019.
12. Hammerla, N.Y., S. Halloran, and T. Plötz, Deep, convolutional, and recurrent models for human activity recognition using wearables. arXiv preprint arXiv:1604.08880 (2016).

13. Abbaspour, S., F. Fotouhi, A. Sedaghatbaf, H. Fotouhi, M. Vahabi, and M. Linden, *A comparative analysis of hybrid deep learning models for human activity recognition. Sensors*, *20*(19), 2020, 5707.
14. Bengio, Y., A. Courville, and P. Vincent. *Representation learning: A review and new perspectives. IEEE transactions on pattern analysis and machine intelligence* 35, no. 8 (2013): 1798-1828. Malhotra, P., A. Ramakrishnan, G. Anand, L. Vig, P. Agarwal, and G. Shroff, LSTM-based encoder-decoder for multi-sensor anomaly detection. arXiv preprint arXiv:1607.00148 (2016).
15. Srivastava, Nitish, E. Mansimov, and R. Salakhudinov, *Unsupervised learning of video representations using lstms. In International conference on machine learning*, pp. 843-852. PMLR, 2015. Bengio, Y., P. Simard, and P. Frasconi, *Learning long-term dependencies with gradient descent is difficult. IEEE transactions on neural networks*, *5*(2), 1994, 157-166.
16. Bayer, J.S. *Learning sequence representations. PhD diss*., Technische Universität München, 2015.
17. Dalal, N. and B. Triggs. *Histograms of oriented gradients for human detection. In 2005 IEEE computer society conference on computer vision and pattern recognition (CVPR'05)*, vol. 1, pp. 886-893. IEEE, 2005.
18. Sermanet, P., D. Eigen, X. Zhang, M. Mathieu, R. Fergus, and Y. *LeCun. Overfeat: Integrated recognition, localization and detection using convolutional networks*. arXiv preprint arXiv:1312.6229 (2013).
19. Federal Highway Administration (FHWA), Distress Identification Manuel, FHWA-HRT-13-092, 2014.
20. AASHTO (2012). Guide for the Development of Bicycle Facilities, 4th Edition. American Association of State Highway and Transportation Officials.
21. MUTCD (2012). Manual on Uniform Traffic Control Devices – 2009 Edition with 2012 Revisions. US Federal Highway Administration.
22. Flagstaff (2020). https://www.flagstaff.az.gov/DocumentCenter/View/46972/Active-Transportation-Master-Plan---Working-Paper-03---Mode-share-information-and-trends?bidId=
23. Flagstaff (2022). https://www.flagstaff.az.gov/1379/Flagstaff-Urban-Trails-System-FUTS
24. NAU (2022). https://in.nau.edu/green-nau/yellow-bike-program/
25. Arizona Daily Sun (2018). https://azdailysun.com/news/local/spin-bike-share-attracts-1-500-users-in-first-month-in-flagstaff/article_4548fd0a-12cc-5795-9af2-aaca92f01196.html
26. KNAU (2019). https://www.knau.org/knau-and-arizona-news/2019-09-06/flagstaff-approves-electric-bicycle-sharing-program

Data Management Plan

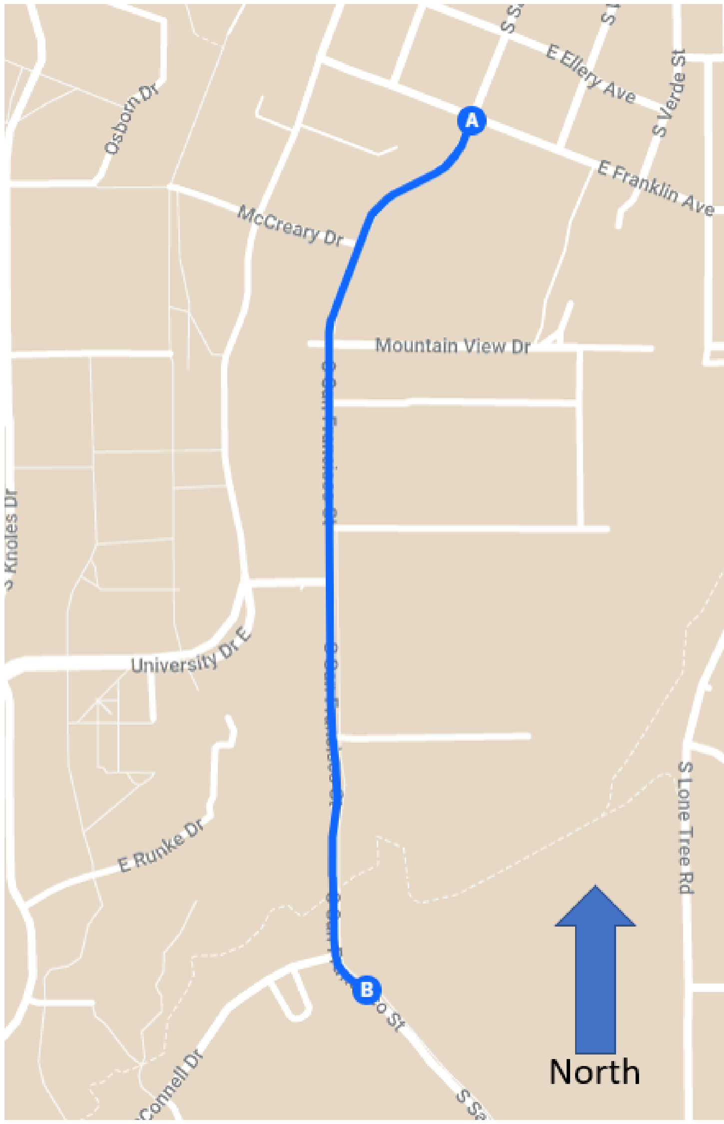
Products of Research
All field data collected for this research was vibration responses from sensors mounted on an instrumented bike that travelled on the cycling trails. All vibration data was used to analyze and detect anomalies along cycling trails using Python, Excel, and ArcGIS.

Data Format and Content
The format of all vibration data is in a csv file that was further converted to a .xls format. For computing purposes, all vibration data were analyzed against their accuracy for determination of pavement distress levels using python (in a .ipynb format). When severity levels of pavement distress were identified, maps were created using ArcGIS software and its format is in a .mxd format.

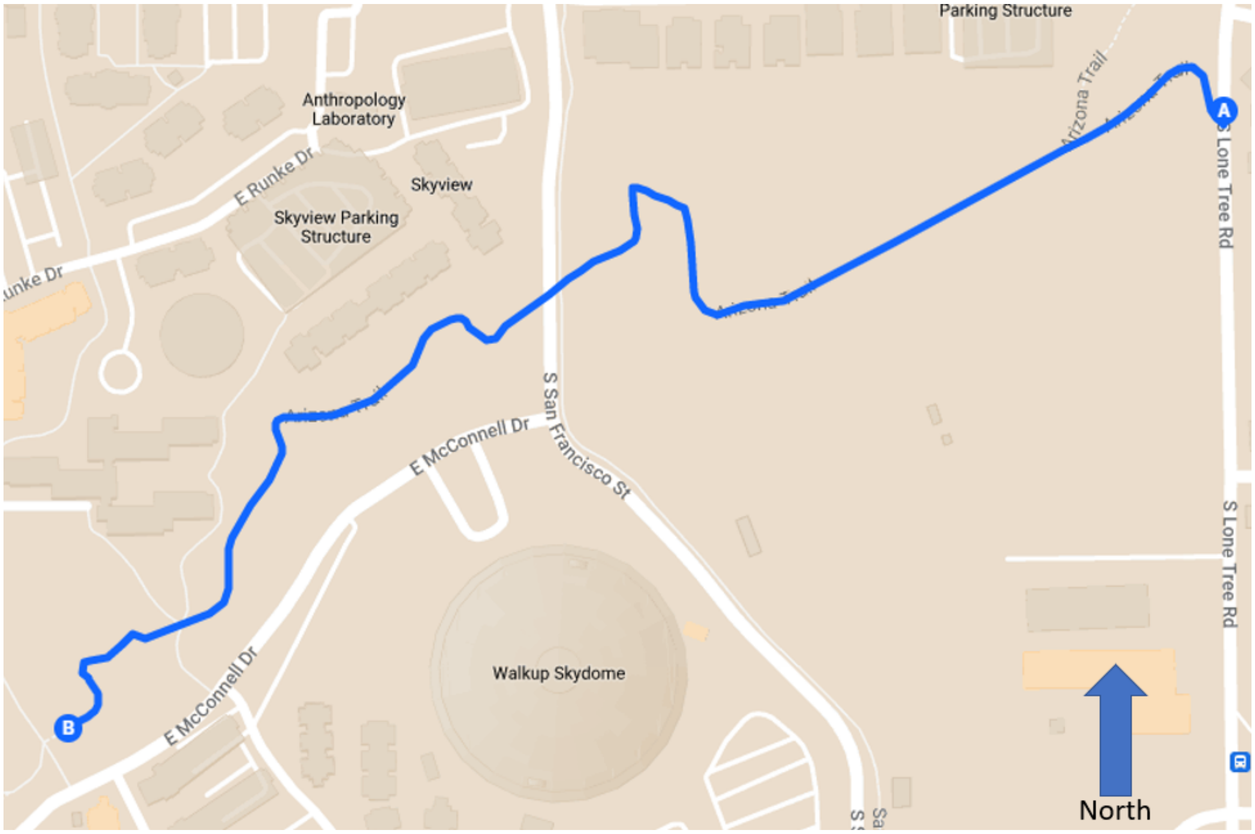
Data Access and Sharing
All vibration and analysis data are saved and stored at Northern Arizona University's secure drive. General public can make a request to the PI who will create a path directory using Google drive, Dropbox, or Onenote to allow general public access the requested data.

Reuse and Redistribution
Part of data requested by general public may be reused or redistributed for research purposes with permission of the PI.

Appendix A – Comprehensive List of AASHTO Bicycle Pathway Guidelines

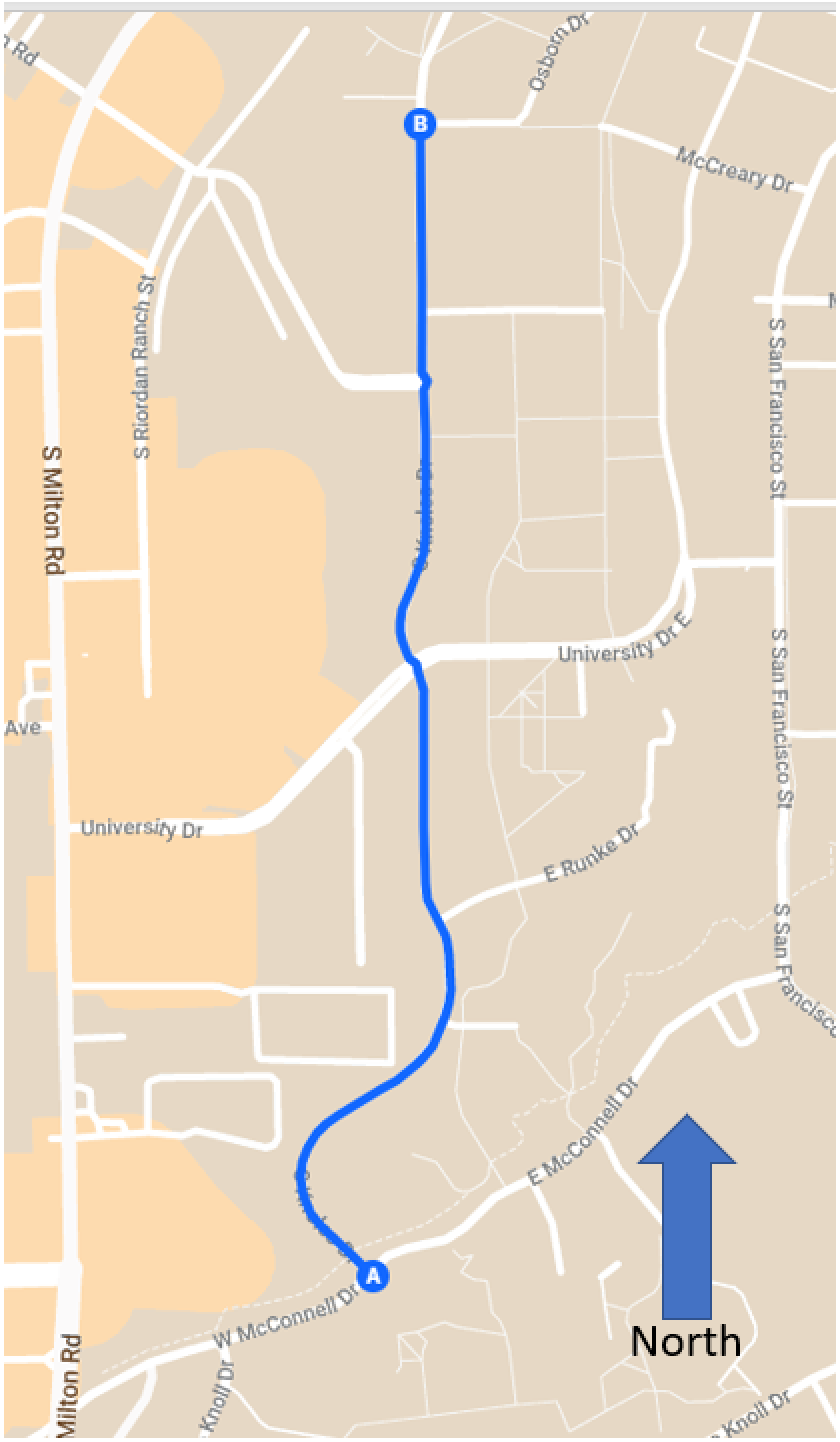


Appendix A-1. Skydome Route Map

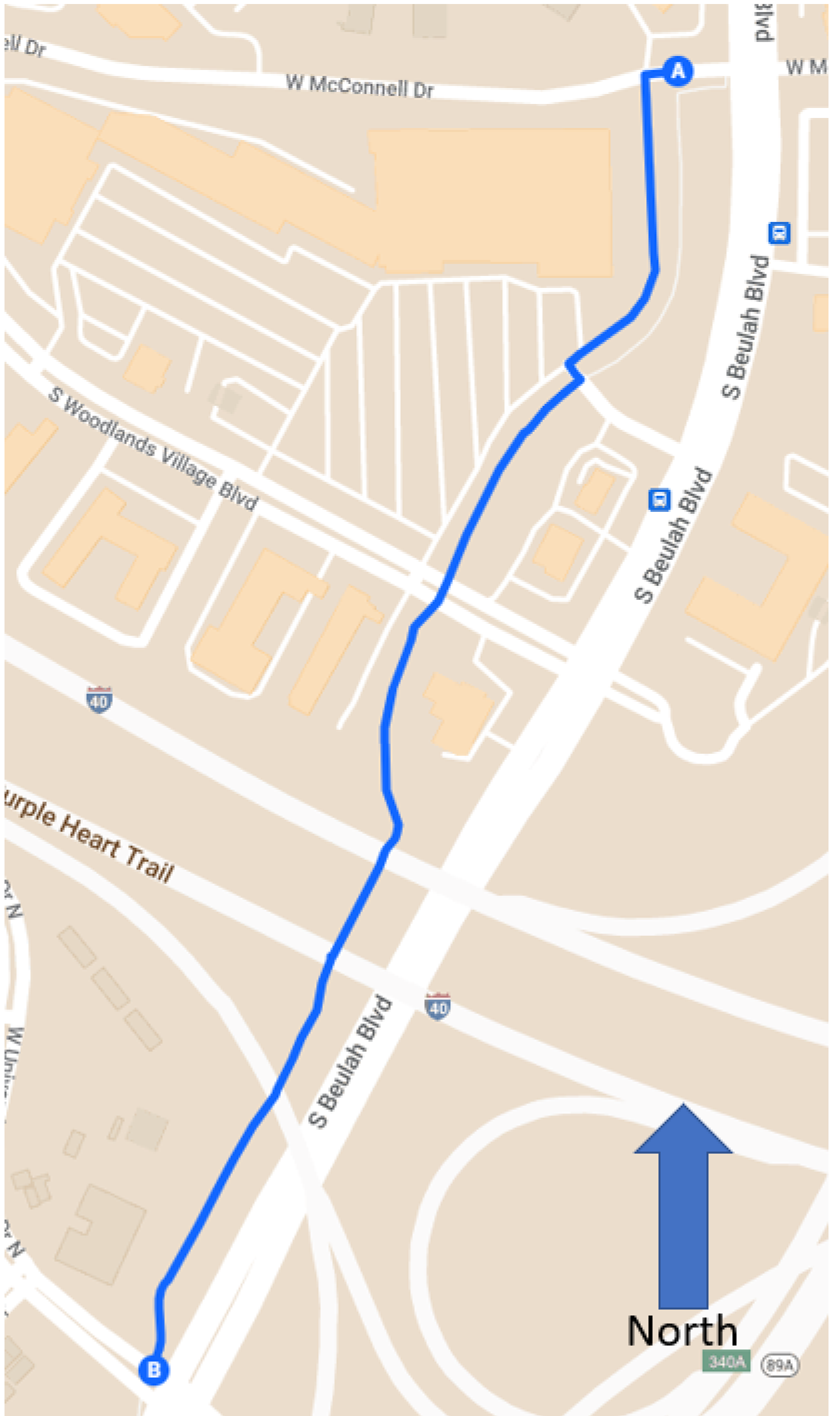


Appendix A-2. Arizona Trail Route Map

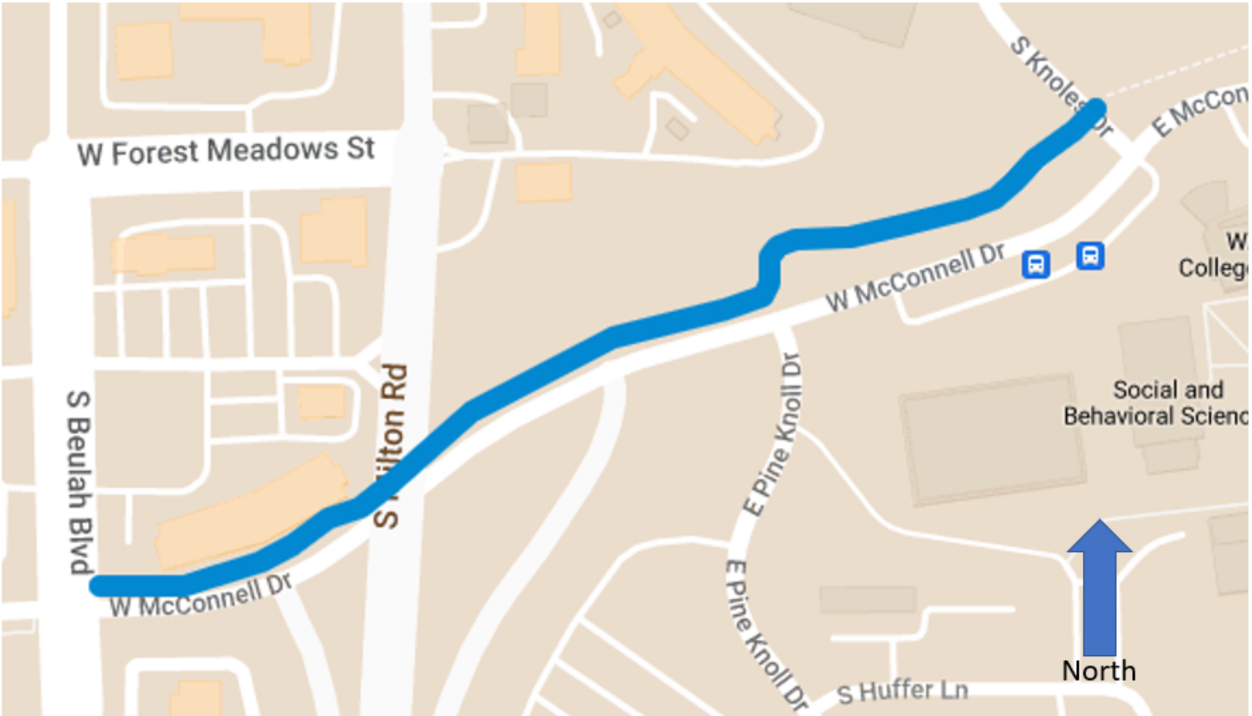
Appendix A-3. Skyview Route Map



Appendix A-4. Library Route Map



Appendix A-5. Beulah Route Map



Appendix A-6. McConnell Route Map

Appendix A-7. Comprehensive AASHTO Bike Guideline Table

Section	Requirement	Detectability	Mandatory or Recommended?
2.4.1	Master transportation plans need to include a bicycling component, as a stand alone section.	Hard	Recommended
2.7	Transit hubs (bus stations) should have bicycle storage.	Easy	Recommended
3.2	Minimum operating bike way widths should be no less than 4’ and are ideally 5’	Medium	Recommended
3.2	Generally design eye height with recumbent bicycles in mind (46”) and clearance for someone standing on pedals (100”)	Hard	Recommended
3.2	Bicycle medians should be long enough to hold a bicyclist with a child trailer (117” or 9.75’)	Medium	Recommended
3.2	It is generally undesirable for bikes to share a sidewalk with pedestrians, even if the sidewalk is wide.	Easy	Recommended
3.4.3	Wrong-way riding should be avoided on both bike lanes and sidewalks. Bike lanes in both directions of travel and signage can prevent this.	Easy	Recommended
3.4.3	Decision makers should minimize the amount of driveways on bicycling corridors and improve corner sight distance at driveways	Hard	Recommended
3.4.3	Bicycle lanes adjacent to parallel parking should have a double striped lane separating the two to prevent “dooring” if possible	Easy	Recommended
3.4.3	Bicycle corridors should minimize the amount of stop signs required for bicyclists to adhere to within a short distance.	Moderate	Recommended
3.4.3	Reduced curb radii at an intersection with lots of “right-hook” crashes into bicyclists can encourage slower turning speeds.	Hard	Recommended

3.4.3	Placing bike lanes to the left of right turning lanes can help to reduce "right-hook" crashes at intersections	Easy	Recommended
4.2	Chip-sealed surfaces should be avoided in bicycle corridors.	Easy	Recommended
4.2	Bike corridors should avoid potholes, large cracks, and gravel surfaces.	Easy	Recommended
4.3	Bike corridors should have bike compatible drainage grates, bridge expansion joints, and railroad crossings	Moderate	Recommended
4.3.1	(Roads) Lane widths of 16' or greater in congested areas are undesirable for bicyclists as it may encourage 2 vehicles to occupy the space within the single lane.	Hard	Recommended
4.3.2	"Share the Road" signs may be used only when a bike lane or shared use path ends and bicyclists must share a lane with other traffic. The sign may be used in work zones. It cannot be used to indicate a bike route .	Easy	Mandatory
4.3.2	"Bicycles May Use Full Lane" signs can be used on roadways without bike lanes or where travel lanes are too narrow for a bicyclist or motorist to operate side by side in the same lane (13ft or less)	Moderate	Recommended
4.3.2	"Wrong Way" bike signs should be placed where wrong-way riding bicyclists are frequently observed	Moderate	Recommended
4.4	The shared lane marking should be placed in locations where there is insufficient width to provide bike lanes. Can also be used to to reduce wrong-way bicycling. Applicable situations for this symbol are - Shared lane with adjacent on-street parallel parking. - Wide outside lanes to show bicyclists	Moderate	Recommended

	they have distance from both the curb and vehicular traffic. - A section of roadway with shared lanes that have a "gap" between bike lanes or shared use path.		
4.4	On steep downhills where the roadway only has enough room for one bike lane, the bike lane should be used for the uphill and the downhill bikes should have a shared lane marking.	Moderate	Recommended
4.4	Shared lane markings are more ideal than a bike lane for bikes going downhill along a steep hill with on street parallel parking	Moderate	Recommended
4.4	Shared-lane markings are not to be in paved shoulders, bike lanes, or roadways that have a speed limit above 35 miles per hour.	Easy	Mandatory
4.4	Shared-lane markings should be placed immediately after an intersection and spaced at intervals no greater than 250' after	Moderate	Mandatory
4.4	Shared-lane markings should be marked in a practical path of bicycle travel, even if that includes both sides of a lane	Hard	Recommended
4.4	Streets with on-street parallel parking, shared-lane markings should be placed at least 11' from the face of the curb or edge of traveled way	Moderate	Mandatory
4.4	Streets without on-street parallel parking, shared-lane markings should be placed within 4' of the curb or edge of traveled roadway	Moderate	Mandatory
4.4	Shared-lane markings can be placed farther in the lane than the minimum distance required such as in a narrow lane where side-by-side operation of a bicycle and motor vehicle isn't possible.	Moderate	Recommended
4.5	Bike lanes are travel lanes and cannot accommodate parking	Easy	Mandatory

4.5	At intersections, bicyclists should normally be to the left of right turning vehicles	Easy	Recommended
4.5	Shoulders meant for bicyclists should be at least 4' wide without vertical obstructions adjacent to the roadway, 5' if there are obstructions (ex. Guardrails, curbs. . .). Additional width should be granted if there are high motorist speeds (50mph+) or heavy bicyclist traffic.	Moderate	Recommended
4.5	Paved shoulders should be present on both sides of a road if possible	Easy	Recommended
4.5	If space is limited, one big paved shoulder is preferable to two small ones.	Moderate	Recommended
4.5	Where practical, the paved section of the approach to a roadway should be sloped down to prevent loose material getting onto the shoulder	Moderate	Recommended
4.5	Raised pavement markers (pavement reflectors) should be avoided along bicycling routes.	Easy	Recommended
4.12.8	Drainage grates should have openings small enough that bicycle wheels cannot fall into its slots. Its slots should be no more than an inch wide, and slots should be perpendicular to the direction of bike traffic.	Easy	Recommended
4.6	Bike lane widths should be a minimum of 5' wide	Moderate	Recommended
5.1.1	Paths in a public right-of-way that function as sidewalks should be designed in accordance with Public Rights-of-Way Accessibility Guidelines (PROWAG)	Moderate	Mandatory
5.1.1	PROWAG guidelines apply to all street crossings for all shared paths	Moderate	Mandatory
5.1.1	Shared paths in independent rights-of-way should meet the guidelines in the Advance Notice of Proposed Rulemaking (ANPRM) on Accessibility Guidelines for Shared Use Paths	Moderate	Mandatory

	(separates shared use paths from recreational trails)		
5.2.1	Minimum paved width for a two way shared use path is 10’	Moderate	Mandatory
5.2.1	The Shared Use Path Level of Service Calculator should be considered when determining the appropriate width of a pathway given high volumes and mixes of wheeled and non-wheeled users	Moderate	Recommended
5.2.1	11’ to 14’ pathways should be used in locations where pedestrians are 30% or more of total pathway volume and pathways that experience more than 300 users in the peak hour	Moderate	Recommended
5.2.1	Wider paths are recommended on steep grades	Moderate	Recommended
5.2.1	Wider paths are recommended on through curves	Moderate	Recommended
5.2.1	MUTCD guidelines can show ideal opportunities to provide passing guideline signs	Hard	Recommended
5.2.1	All markings on bikeways should be retroreflective	Easy (at night)	Mandatory
5.2.1	Pathways with heavy peak hour volumes should use a centerline stripe on a path to help clarify the direction of travel	Easy	Recommended
5.2.1	Solid yellow center lines should be used to indicate where passing is not permitted and a dashed line where passing is permitted	Easy	Recommended
5.2.1	Areas with extremely heavy pathway volumes should segregate wheeled users from pedestrians. The minimum pathway width for this scenario is 15’ where at least 10’ is for two-way wheeled users and 5’ is for pedestrians	Moderate	Recommended
5.2.1	Where wheeled users and pedestrians are segregated and there’s a view (lake, river) the pedestrian lane should be placed on the side of	Easy	Recommended

	the view.		
5.2.1	It is ideal to have a graded shoulder of at least 3 to 5 feet wide with a cross-slope no greater than 1:6	Moderate	Recommended
5.2.1	A minimum of 2’ clearance should be provided for clearance from lateral objects (bushes, large rocks, poles)	Moderate	Recommended
5.2.1	MUTCD requires 2’ clearance to post-mounted signs or traffic control devices	Moderate	Mandatory
5.2.1	If adequate clearance between a path and objects cannot be provided, consider using warning signs or other methods to protect riders	Hard	Recommended
5.2.1	Paths with a downward slope of 1:3 or greater, there should be wider separation between the path and lateral object. 5’ separation is recommended from the edge of the path pavement to the top of the slope.	Hard	Recommended
5.2.1	Engineering judgment is required for steep downhills to determine if it’s riskier for a bicyclists to hit a rail or fall off the path	Hard	Recommended
5.2.1	Physical barriers are generally recommended when recovery areas are less than 5’ and Slopes 1V:3H or steeper, with a drop of 6 ft (1.8 m) or greater;Slopes 1V:3H or steeper, adjacent to a parallel body of water or other substantial obstacle;Slopes 1V:2H or steeper, with a drop of 4 ft (1.2 m) or greater; and Slopes 1V:1H or steeper, with a drop of 1 ft (0.3 m) or greater.	Moderate	Recommended
5.2.1	Barrier/rails should extend prior to and beyond area of need, have a lateral offset of 1’ from the edge of the path	Moderate	Recommended
5.2.1	Ends of barriers should be flared away from path edges. Barriers or rail ends that remain within 2’ clear area should be marked with object markers	Moderate	Recommended

5.2.1	It is not desirable to place pathways in narrow corridors between two fences for long distances	Moderate	Recommended
5.2.1	Desirable vertical clearance to obstacles is 10’	Moderate	Recommended
5.2.1	The minimum vertical clearance in a tight area is 8’	Moderate	Recommended
5.2.2 Shared Use Paths Adjacent to Roadways (Sidepaths)			
5.2.2	It is undesirable to use a sidewalk as a shared use path.	Moderate	Recommended
5.2.2	Signage should not designate sidewalks as a shared use path when alternate facilities that can equally serve their needs exists	Moderate	Recommended
5.2.2	When terminated, sidepaths should accommodate bicyclists onto another path or a bicycle compatible facility. It should not leave bicyclists inclined to ride against traffic.	Moderate	Recommended
5.2.2	If both sides of a road have sidepaths, then bicycle traffic should flow in the same way as the road does and intersections should accommodate their needs	Moderate	Recommended
5.2.2	Where there is no curb, the minimum distance between a road and a sidepath should be 5’. When separation is less than 5’, physical barriers or railing should be used.	Moderate	Recommended
5.2.2	Railings/barriers along the edge of a sidepath should be a minimum of 42” high.	Moderate	Recommended
5.2.4	Max design speed should be 30mph (extreme downhills). 18mph is sufficient for a relatively flat path. (If you go faster than 30mph on a shared use path then you’re going faster than what any path is designed for)	Hard	Recommended
5.2.5	The lean angle method should be used to calculate minimum horizontal radius.	Hard	Recommended

U.S. Customary		
$R = \dfrac{0.067V^2}{\tan\theta}$		
where:		
R	=	minimum radius of curvature (ft)
V	=	design speed (mph)
θ	=	lean angle from the vertical (degrees)

Metric		
$R = \dfrac{0.0079V^2}{\tan\theta}$		
where:		
R	=	minimum radius of curvature (m)
V	=	design speed (km/h)
θ	=	lean angle from the vertical (degrees)

U.S. Customary		Metric	
Design Speed (mph)	Minimum Radius (ft)	Design Speed (km/h)	Minimum Radius (m)
12	27	19	8
14	36	23	11
16	47	26	15
18	60	29	18
20	74	32	22
25	115	40	35
30	166	48	50

5.2.5	Unpaved paths should consider calculating minimum radius based on superelevation using a lower friction factor due to the unpaved surface.	Moderate	Recommended
5.2.6	Cross slopes are recommended to be 1%	Moderate	Recommended
5.2.6	Cross slopes of shared use paths that function as sidewalks should not exceed 2%	Moderate	Recommended
5.2.6	If cross slopes are steeper than 2%, they should slope to the inside of the horizontal curve, regardless of drainage conditions	Moderate	Recommended
5.2.6	Cross slopes greater than 5% may occasionally be ideal for unpaved shared use paths to prevent puddling as well or for sharp turns.	Moderate	Recommended
5.2.7	The grade of a sidepath should match the grade of the road it is adjacent to	Moderate	Recommended
5.2.7	A shared use path should not exceed a 5% grade unless physical constraints or regulatory constraints exist (ex: terrain, endangered species)	Hard	Recommended
5.2.7	Where excessive grades are present, consider an additional 4 to 6 feet of width.	Moderate	Recommended
5.2.7	Where excessive grades are present, consider	Easy	Recommended

	providing signage that alerts path users to the maximum percent of grade as shown in the MUTCD		
5.2.7	Where excessive grades are not practical to maneuver, use short switchbacks with milder slopes instead of a direct path.	Moderate	Recommended
5.2.8	Stopping sight distances should be calculated using these equations. **U.S. Customary** $S = \frac{V^2}{30(f \pm G)} + 3.67V$ where: S = stopping sight distance (ft) V = velocity (mph) f = coefficient of friction (use 0.16 for a typical bike) G = grade (ft/ft) (rise/run) **Metric** $S = \frac{V^2}{254(f \pm G)} + \frac{V}{1.4}$ where: S = stopping sight distance (m) V = velocity (km/h) f = coefficient of friction (use 0.16 for a typical bike) G = grade (m/m) (rise/run)	Hard	Recommended
5.2.8	Paths with high volumes of users that have lower coefficient of frictions than bicyclists, such as inline skaters, should have increased stopping sight distances.	Hard	Recommended
5.2.8	For two-way shared use paths, the sight distance in the descending direction (users going downhill) must control the design.	Hard	Mandatory
5.2.8	Lateral clearances on horizontal curves should be calculated based on the sum of the stopping sight distances for path users traveling in the opposite direction around the curve.	Hard	Recommended
5.2.8	Where lateral clearances at horizontal curves cannot meet the minimum distance as calculated by the previous step, wider paths, yellow center line stripes, and curve warning signs should be considered.	Hard	Recommended
5.2.9	Hard, all weather pavement surfaces are generally preferred over that of crushed aggregate, sand, clay, or stabilized earth	Easy	Recommended
5.2.9	In areas that experience frequent or even occasional flooding or drainage problems, or in	Moderate	Recommended

	areas of moderate or steep terrain, unpaved surfaces will often erode and are not recommended.		
5.2.9	Unpaved paths are more appropriate where the primary use is recreation	Moderate	Recommended
5.2.9	Total pavement depth should typically be a minimum of 6 inches, including the surface and base course.	Hard	Recommended
5.2.9	Shared use paths should be designed to sustain wheel loads of occasional vehicles (ex; emergency or maintenance vehicles)	Hard	Recommended
5.2.9	If shared use paths are bound by raised curbs, the path should be an additional foot wide	Moderate	Recommended
5.2.9	Portland cement concrete pavements, transverse joints should be saw cut rather than tooled to provide a smoother ride.	Moderate	Recommended
5.2.9	Utility covers and drainage grates should be flush with the pavement surface on all sides.	Easy	Recommended
5.2.9	If possible, utility covers and drainage grates should be on the side of paths	Easy	Recommended
5.2.9	Railroad crossings should be smooth and be designed at an angle between 60 and 90 degrees to the direction of travel.	Moderate	Recommended
5.2.9	When shared use paths cross an unpaved road or driveway, the road should be paved a minimum of 20’ on each side of the crossing	Moderate	Recommended
5.2.9	Skid resistance qualities should not be sacrificed for the sake of smoothness. Broom finishes or burlap drag concrete are preferred	Hard	Recommended
5.2.10	The “receiving” clear width on the end of a bridge should allow 2’ of clearance on each side of the pathway.	Moderate	Recommended
5.2.10	10’ minimum vertical clearance is desirable for	Moderate	Recommended

	bridges and underpasses		
5.2.10	At transitions and approaches from paths to bridge decks, the height of the path's surface should match the height of the bridge deck surface.	Easy	Recommended
5.2.10	Bridge deck lips should be avoided all together	Easy	Recommended
5.2.10	Grade separation between paths and roadways or railroads should be determined by topography but if either are feasible, bridges are preferred.	Moderate	Recommended
5.2.10	A bridge or underpass built over a public right-of-way requires a connection between the path and roadway.	Easy	Recommended
5.2.10	Railing should be a minimum of 42" high. If the pathway leading into the bridge has a steep angle (25 degrees or more) then 48" is required	Moderate	Recommended
5.2.10	Openings between members of a railing should be small enough that a 6' sphere cannot pass between them in the lower 27" of the railing. Above the 27" line, design holes in rails such that a 8" sphere cannot fall through.	Moderate	Recommended
5.2.10	Where a bicyclist's handlebar may come into contact with railing or barriers, a smooth wide rub rail may be installed at a height of 36" to 44".	Moderate	Recommended
5.2.10	Decking materials should not be slippery when wet.	Moderate	Recommended
5.2.11	Unpaved shared use paths should have extra consideration for drainage to prevent erosion.	Hard	Recommended
5.2.11	Sloping in one direction is preferred over crowning	Moderate	Recommended
5.2.11	If significant runoff is arriving to the path from other locations, a ditch large enough to handle it should be placed on the uphill side of the path.	Moderate	Recommended

5.2.11	Where necessary, drainage should flow under the path	Moderate	Recommended
5.2.12	Where nighttime use is permitted, pathway lighting should be considered at crosswalks, especially if the crossing connects to existing sidewalks.	Moderate	Recommended
5.3 Shared Use Path-Roadway Intersection Design			
5.3.2	Intersection should be conspicuous to both road and path users	Easy	Recommended
5.3.2	Intersections and approaches should be on relatively flat grades	Moderate	Recommended
5.3.2	Intersections should be as close to a right angle as practical	Easy	Recommended
5.3.2	Mid-block path crossings should be as perpendicular to the road as possible. 90 degree angles are preferred but 60 degree angles are the minimum.	Easy	Recommended
5.3.2	High visibility marked crosswalks are recommended at uncontrolled path-roadway intersections	Easy	Recommended
5.3.2	The least restrictive crossing control that is necessary is ideal	Hard	Recommended
5.3.2	Detectable warnings should be placed across the full width of a ramp	Easy	Recommended
5.3.5	The opening of a shared use path at a roadway should be at least as wide as the shared use path.	Easy	Recommended
5.3.5	Unpaved shared use paths should be provided with paved aprons extending a minimum of 20' from a paved road's surface.	Moderate	Recommended
5.3.5	At intersections where crowding occurs at a roadway's edge, consider widening the path.	Moderate	Recommended
5.3.5	Bollards shouldn't be used on shared use paths	Moderate	Recommended

	to restrict motor vehicle traffic unless there is a documented history of unauthorized intrusion by motor vehicles.		
5.4.1	No pavement marking should rise above 0.16” (4 mm) above the pavement	Hard	Recommended
5.4.1	At mid-block locations, a crosswalk must be marked to be legally recognized.	Easy	Mandatory
5.4.1	Centerlines should be 4 to 6” wide	Moderate	Recommended
5.4.1	Centerlines should be solid where passing is not recommended	Hard	Recommended
5.4.1	White edgeline striping should be considered for shared use paths where paths are used at night or if pathway design includes a separate area for pedestrian travel.	Easy	Recommended
5.4.2	All signs must satisfy the MUTCD guidelines	Moderate	Mandatory
5.4.3	For crossings actuated manually, bicyclists should not have to dismount to activate the signal.	Easy	Recommended
7.2	Bikeways should be adequately maintained and regularly sweeped.	Moderate	Recommended
7.2	Gravel or sand used on roadways during wintery conditions shouldn’t accumulate on paths.	Moderate	Recommended
7.2.2	Edge of a surface repair shouldn’t run longitudinally through a bike lane or shoulder	Easy	Recommended
7.2.2	Invasive tree roots shouldn’t be present on paths	Easy	Recommended
7.2.3	Pavement overlays should not leave any ridges in areas where bicyclists are anticipated to ride.	Easy	Recommended
7.2.3	Path project areas should be swept after overlay to prevent loose gravel from adhering to the freshly paved shoulder or bike lane	Moderate	Recommended
7.2.4	Root barriers should be installed where	Moderate	Recommended

	appropriate		
7.2.4	Vegetation should be cut to prevent encroachment	Easy	Recommended
7.2.8	Chip seals should not be used on shared use paths	Easy	Recommended
7.2.10	Utility cuts should be finished as smooth as new pavement	Easy	Recommended
7.2.10	Cuts should be filled such that they are flush with the surface (no humps)	Easy	Recommended
7.2.11	Snow should be removed from streets with bike lanes and paved shoulders that are used by bicyclists	Hard	Recommended
7.2.11	Snow should not be stored on sidewalks	Hard	Recommended
7.2.11	Snow should be removed from shared use paths used by commuters	Hard	Recommended
7.3.2	Effective and convenient passage is needed during construction for bicyclists.	Easy	Recommended
7.3.2	Bike lanes should not be used for storage of work zone signs or materials	Easy	Recommended