MEASURING, MANAGING, AND REDUCING PAVEMENT MACROTEXTURE AND ROUGHNESS TO IMPROVE CYCLISTS' SAFETY AND RIDE QUALITY

FINAL PROJECT REPORT

by

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16. Abstract

The surface texture and roughness of bikeways directly affect bicyclists' ride quality. Texture and/or roughness requirements for bike paths and shoulders need to be established to improve cyclists' comfort. Aggregate embedment depth and macrotexture for chip seals need to be controlled during construction to achieve smoother pavement surfaces that are more suitable for bicycles. Effective post-construction treatments to improve ride quality should also be determined. Improved bikeway surfaces and ride quality can potentially increase bicycle use for commuting and recreational purposes in the Pacific Northwest. Reduced texture and roughness on bikeways can also reduce bicycle damage and increase cyclists' safety.

This study developed a pavement data collection system (with GPS and camera components) that can be installed on bicycles to evaluate the impacts of bikeway surface texture, roughness, and distresses on cyclists' comfort. On the basis of correlations between collected pavement data and cyclists' perceptions of ride quality (determined from surveys that were conducted with the cyclists), the study determined the effectiveness of the developed automated bikeway condition measurement system at identifying user comfort and safety. The study also developed suggestions for pavement design and construction stages to reduce rolling resistance on shoulders and bikeways. Reduced rolling resistance is expected to improve cyclists' safety and comfort and to encourage the use of bicycles for recreational purposes and as a mode of transportation in the Pacific Northwest.

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List of Abbreviations

COV	Coefficient of variation
DAQ:	Data acquisition system
DOT:	Department of transportation
FHWA:	Federal Highway Administration
G	Gravitational force
GFP	Good-Fair-Poor
ODOT:	Oregon Department of Transportation
GPS	Global Positioning System
MATLAB	Matrix Laboratory
PacTrans:	Pacific Northwest Transportation Consortium
UTC:	Universal Time Coordinated

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Executive Summary

This study developed a pavement data collection system (with Global Positioning System and camera components) that can be installed on bicycles to collect bikeway surface texture, roughness, and distress data. On the basis of correlations between collected pavement data and cyclists' perceptions of ride quality (determined from the surveys that were conducted with the cyclists), the researchers determined the effectiveness of the developed automated bikeway condition measurement system at identifying user comfort. The report also provides suggestions for pavement design and construction stages to reduce rolling resistance on shoulders and bikeways. Reduced rolling resistance is expected to improve cyclists' safety and comfort and to encourage the use of bicycles for recreational purposes and as a mode of transportation in the Pacific Northwest.

This study determined the effects of pavement-related factors on cyclists' comfort. It also determined texture and roughness thresholds (in terms of acceleration and vibration parameters) for chip seal and other pavement surfaces to achieve acceptable and high cyclist comfort levels. Design and construction guidelines and procedures to reduce texture and roughness on shoulders and bike paths were developed. In addition, the possibility of installing three-axis accelerometer systems on bicycles for quantification of cyclists' user comfort was determined.

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1 INTRODUCTION

According to recent research studies (Circella et al., 2016), the travel behavior of young adults has started to significantly change within the last decade, and non-motorized means of transportation have started to be used more often. To promote bicycle use, the City of Portland pursued a "build it, and they will come" strategy by constructing more bikeways and improving the conditions of existing ones (Birk and Geller, 2006). This strategy paid off well, and bicycle commute trips in Portland doubled from 1990 to 2000. This outcome clearly shows that increasing the size of the bikeway network, improving the condition of bikeways, and increasing ride quality and safety can significantly increase the use of bicycles for commuting and recreational purposes. An improved bikeway network is also expected to promote bicycle tourism in urban and rural areas (Ritchie et al., 2010).

The surface texture and roughness of bikeways directly affect bicyclists' ride quality (Li et al., 2013). Texture and roughness requirements for bike paths and shoulders need to be established to improve cyclists' comfort. Aggregate embedment depth and macrotexture for chip seals need to be controlled during construction to achieve smoother pavement surfaces that are more suitable for bicycles. Effective post-construction treatments to improve ride quality should also be determined. Improved bikeway surfaces and ride quality can increase bicycle use in the Pacific Northwest for commuting and recreational purposes. Reduced texture and roughness on bikeways can also reduce bicycle damage and increase cyclists' safety.

This research study determined the effects of pavement-related factors on cyclists' comfort. It also determined texture and roughness thresholds (in terms of acceleration and vibration parameters) for chip seal and other pavement surfaces to achieve acceptable and high cyclist comfort levels. Design and construction guidelines and procedures to reduce texture and roughness on shoulders and bike paths were developed. The possibility of installing three-axis accelerometer systems on bicycles for quantification of cyclists' user comfort was also determined.

1.1 Key Objectives and Tasks of This Study

This research had four objectives:

- Develop a system to measure and evaluate cyclists' ride quality.
- Determine the impacts of pavement-related factors on cyclists' ride quality.
- Identify some routes with lower ride quality by using the developed system.
- Provide suggestions and guidelines to improve user comfort.

The research tasks were as follows:

1) Identification of routes with high and low ride quality: Bike trips with cyclists were organized in Benton County, Oregon. To determine routes with high and low ride quality, a short survey was conducted with the cyclists.
2) Identification of factors affecting bicycle ride quality: Macrotexture and bicycle vibration data (collected with a three-axis accelerometer installed on different types of bicycles) for the sections identified in Task 1 were collected.
3) Surveys of bicycle ride quality: Bicycle rides on the selected routes were scheduled with several cyclists in the region. After the bicycle rides, the researchers surveyed the cyclists to determine their perceptions of ride quality.
4) Data analysis: By conducting statistical analysis of the data collected in tasks 2 and 3, the researchers determined correlations between macrotexture, roughness, and vibrations and cyclists' perceptions of ride quality. On the basis of the results of statistical analysis, they also determined texture and roughness thresholds (based on

acceleration and vibration measurements) to achieve acceptable and high cyclist comfort levels.

5) To increase user comfort, suggestions were also provided to improve mix design procedures (aggregate size and gradation requirements), construction methods (to reduce roughness and additional rolling on shoulders to reduce chip seal texture), and materials used (e.g., chip seal, slurry seals, microsurfacing, etc.) for shoulders and bicycle paths.

1.2 Organization of the Report

This introduction section is followed by a discussion of "Research Methodology and System Development" in Chapter 2. The details of the bike system development and the data collection components are described in this chapter. Chapter 3 shows the "Data Analysis and Final Results." Details of the collected data types and the data processing methods are discussed in this chapter. "Conclusions and Suggested Bike Path Pavement Improvement Strategies" are presented in Chapter 4. Details of the results are summarized in this section. In addition, general suggestions to improve bike path performance and ride quality are provided.

2 RESEARCH METHODOLOGY AND SYSTEM DEVELOPMENT

The existing pavement condition assessment frameworks for determining pavement surface quality have a limited scale, with only five performance levels (very poor, poor, fair, good, very good). This makes it difficult to assess the actual pavement condition objectively, and individual evaluations are prone to variation. The surface texture and roughness of bikeways directly affect bicyclists' safety and ride quality. This study aimed to develop texture and roughness requirements (based on collected acceleration and vibration data) for bike paths and shoulders that could be used to ensure cyclist comfort. The requirements could be used to determine whether the existing bike paths require resurfacing and whether new bike paths have an acceptable level of smoothness. To establish requirements for bike path surface texture and ride quality, bicyclists' perceptions of ride quality needed to be correlated with an empirical measurement of surface texture. For the purpose of this study, the surface texture and roughness of bike paths were indirectly quantified by using an accelerometer system mounted on a trailer at the back of a bike. By correlating these two data points, acceleration and surface properties, it was possible to characterize the impact of the surface texture of bike paths on cyclists' comfort, as well as to create a threshold for maximum allowable texture and roughness-related surface accelerations before the ride quality could be defined as poor.

2.1 System Development

The bike data collection system was developed as an easily deployable and user-friendly system for characterizing the impact of the surface texture and roughness of bike paths and other paved surfaces on cyclists' comfort. The system was predicated on the assumption that a paved surface's texture and roughness can be correlated with the vertical acceleration of a vehicle traveling over the surface as measured by an accelerometer.

Figure 2-1 shows the components of the developed system, and Figure 2-2 shows the developed bike system with all components. An ADXL 335 accelerometer was secured directly to the axle of a bike trailer so that the movement of the wheels would directly translate to the accelerometer. The trailer had the necessary capacity to carry the electronics and data acquisition system (DAQ) as the bike was ridden. The accelerometer produced an analog voltage output that was converted to a digital signal by the DAQ and then saved to a laptop in the electronics package. All of the accelerometer data for each section of pavement was saved to a single data file. In order to analyze this file, the accelerometer data corresponding to a specific bike rider had to be isolated. The system was designed to be versatile by utilizing three independent records that could be correlated to accelerometer data.

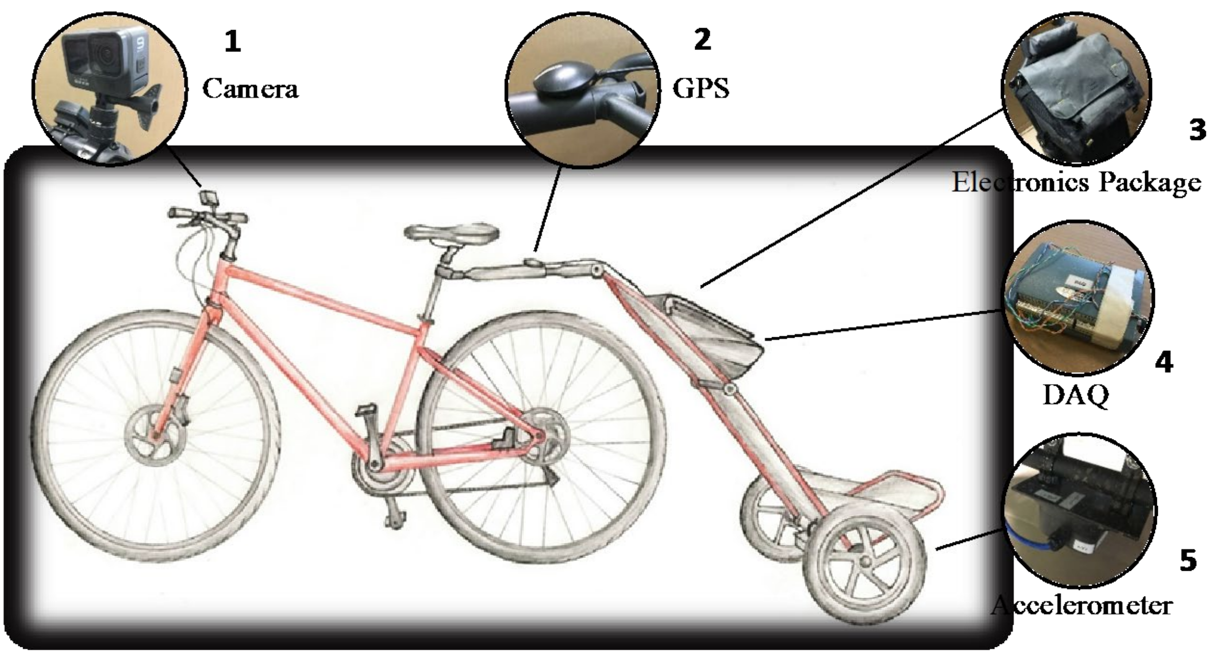


Figure 2-1. The bike path data collection system.

Figure 2-2. Developed bike system with all components with a high and low texture comparison.

The first installed component was a video camera that recorded the pavement surface during the entire ride. This video could be reviewed to compare visible surface defects and distresses with accelerometer data. The bike rider could also issue voice commands to the camera, which could be used to automatically highlight and isolate segments of the accelerometer data. The camera recordings were synchronized with the collected accelerometer data.

The second component of the system was a Global Position System (GPS) device that recorded the bike position, synchronized with collected accelerometer data. This system could be overlayed by a satellite image to identify a specific section of a bike path and the corresponding accelerometer data.

The third component of the system was the electronics package that included the laptop used for data collection and the developed software and connection cables. The Coordinated Universal Time (UTC) time stamps were synchronously recorded with the accelerometer data using the software installed on the laptop. This system proved an expedient means of ordering sequential sets of data.

A special algorithm was developed in MATLAB to synchronize all components of the developed system. A link to the accelerometer data sheet is provided in the References (Accelerometer Data Sheet, 2023).

2.2 Test Sections and Data Collection Procedure

The objective of the developed system was to correlate pavement surface roughness and texture, as indirectly recorded by an accelerometer, with perceptions of ride quality as evaluated by bike riders. Six (A to F) pavement sections were analyzed in this study, each 25 feet long and of uniform surface roughness. During all tests, the bike and trailer tire pressures were kept at 40 psi (276 kPa) to ensure a consistent dynamic reaction resulting from pavement surface texture and roughness. Each participant rode the bike at a constant velocity of 10 mph ± 1 mph, which was measured with a simple speedometer.

Six different participants rode each section (replicate evaluations) and evaluated them on a five-point scale, 1 being the highest surface roughness and 5 being the smoothest. This scale was intended to correspond to the Oregon Department of Transportation's (ODOT) standard pavement condition ratings (ODOT, 2010) of "very poor, poor, fair, good, and very good," respectively. This standard is also commonly called the Good-Fair-Poor (GFP) rating, and several other state DOTs follow similar standards. The six sections were selected to provide a wide range of surface textures at both extremes of the ODOT's GFP scale. When participants started riding on a test section of pavement, they issued a voice command. These voice commands were recorded by the camera system and were used to isolate segments of accelerometer data corresponding to each participant and section.

The photos of the six test sections with different surface textures are shown in Figure 2-3. The two photos show the extent and texture of each section from different height levels. The third photo (on the far right) shows an orthogonal view of a 6-in. roller to illustrate the relative scale of the surface texture.

Section A

Section A was a concrete sidewalk with a smooth surface texture and no distress patterns outside of the expansion joints every 4-ft. Rating: Good

Section B

Section B was a highly compacted gravel parking lot with a relatively high (rough) surface texture . Rating: Poor

Section C

Section C was a smooth asphalt bike path with some bumps cased by adjacent tree roots but no visible distress patterns. Rating: Good

Section D

Section D was an asphalt bike path with a rough surface texture and occasional distress patterns. Rating: Fair

Section E

Section E was an asphalt bike path with a rough surface texture, and moderate bumps caused by adjacent tree roots. Rating: Fair

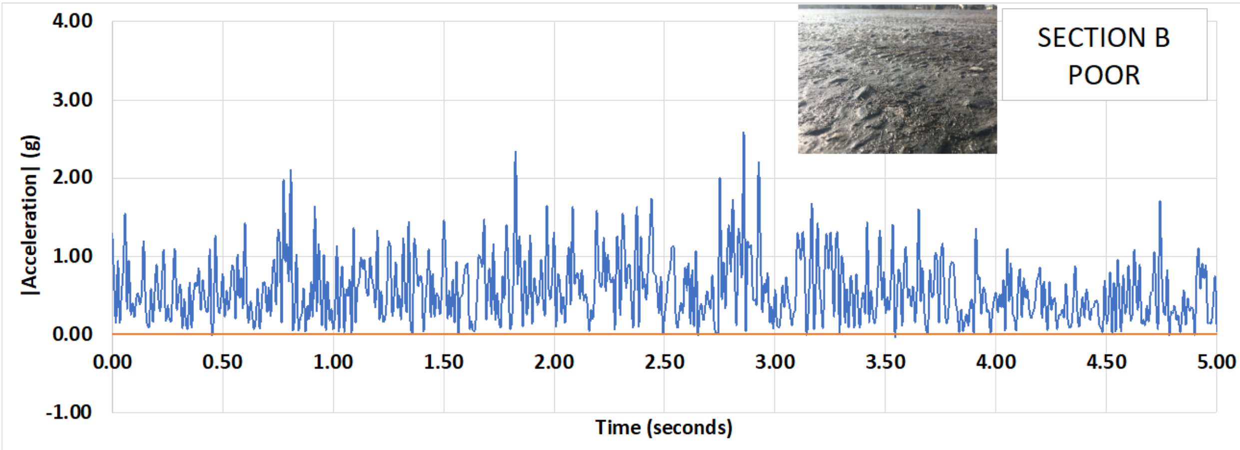
Section F
Section F was a smooth asphalt bike path with no bumps or distress patterns. Rating: Very Good

Figure 2-3. Evaluated test sections with different surface textures and rating levels.

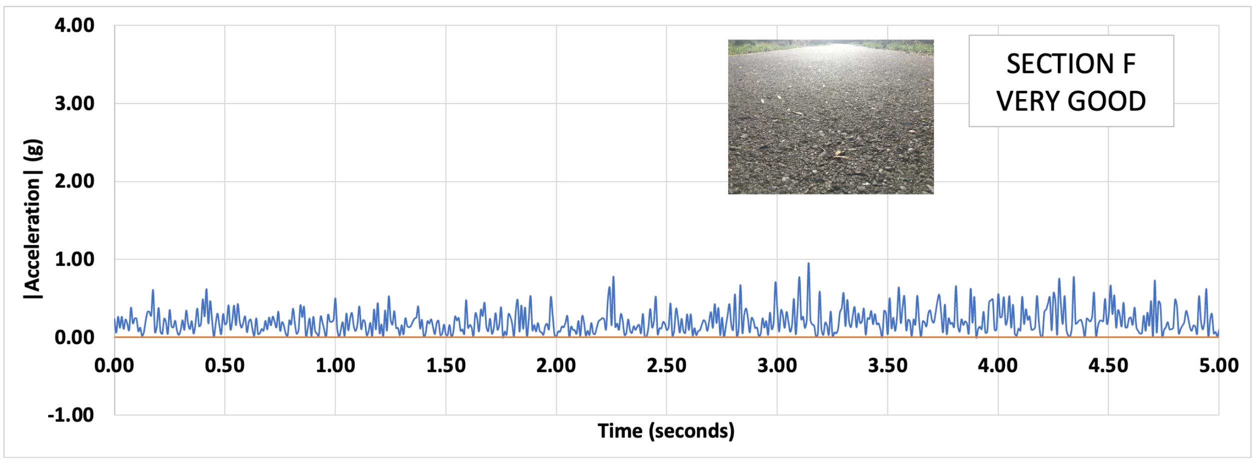
3 DATA ANALYSIS AND FINAL RESULTS

After the data se had been recorded, the accelerometer data corresponding to each of the six participants were isolated for further analysis. This isolation was performed by cross-referencing video footage with accelerometer data using the relative times that the recordings were initiated. Future iterations of the system might include a button the bike rider could press at the beginning of each section. This system would require less extensive post-processing and would be less susceptible to background noise triggering false voice commands. A 5-second interval of acceleration data was used for each bike path section. Each participant took no less than 5 seconds to ride over the 25-ft. length of pavement, so this time interval ensured a consistent base of comparison between different sections.

Once the raw data from the DAQ had been converted to units of gravitational force (Gs), they could be analyzed and correlated to the perceptions of ride quality. The first analysis method assessed the maximum value of vertical acceleration recorded over each section. This value was extracted from the data by subtracting the mean acceleration and taking the absolute value. This defined all acceleration values as positive acceleration starting from zero. Figure 3-1 shows the calculated acceleration parameter for the first rider for the roughest (Section B) and smoothest (Section F) test sections. The figure shows that there were significant differences in measured acceleration and its variation across the two test sections. The sections with the highest surface textures had the greatest normalized acceleration starting from zero acceleration. The accelerometer data were also assessed by using the standard deviation and coefficient of variation. The means of these values were assessed across all six participants for each section.



(a)



(b)

Figure 3-1. Example acceleration data from two sections with best and worst surface textures – Absolute value of normalized acceleration.

The three parameters described in the previous paragraph could be correlated with the mean perception of ride quality. Perceptions of ride quality data were collected by conucting surveys with the six bike riders using the GFP ratings (1 to 5) (ODOT, 2010). The three scatter plots (figures 3-2, 3-3, and 3-4) illustrate a clear negative correlation between the perception of ride quality and the vertical acceleration of the bike, which proves the effectiveness of the developed system at quantifying the quality of pavement surface and rider experience.

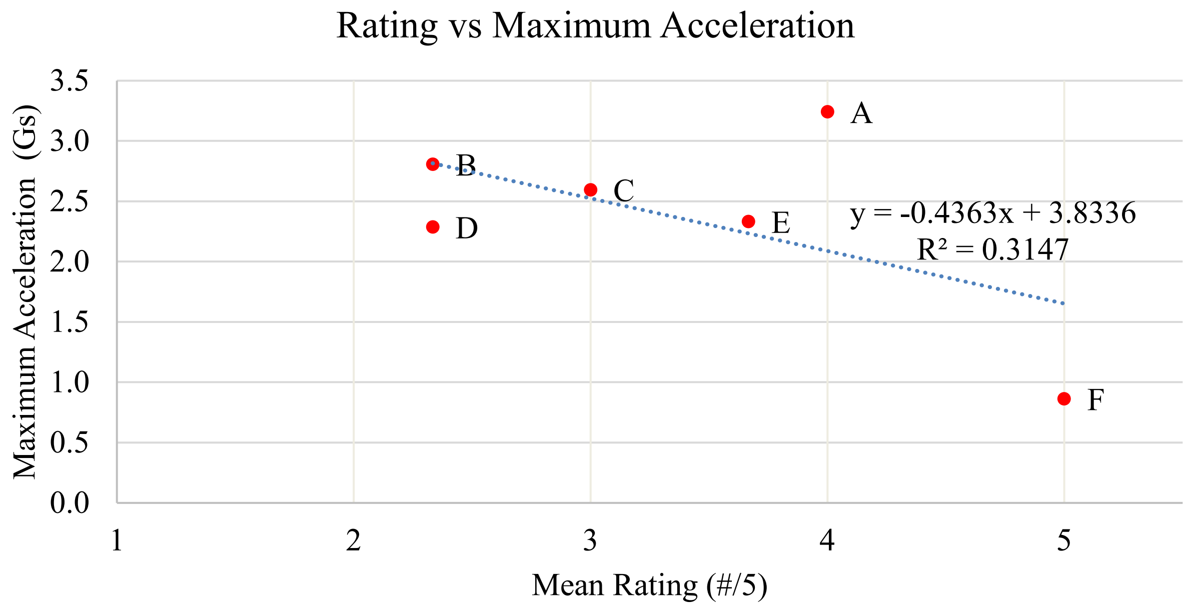


Figure 3-2. Maximum vertical acceleration of the bike correlated with the mean value of the participants' perceptions of ride quality.

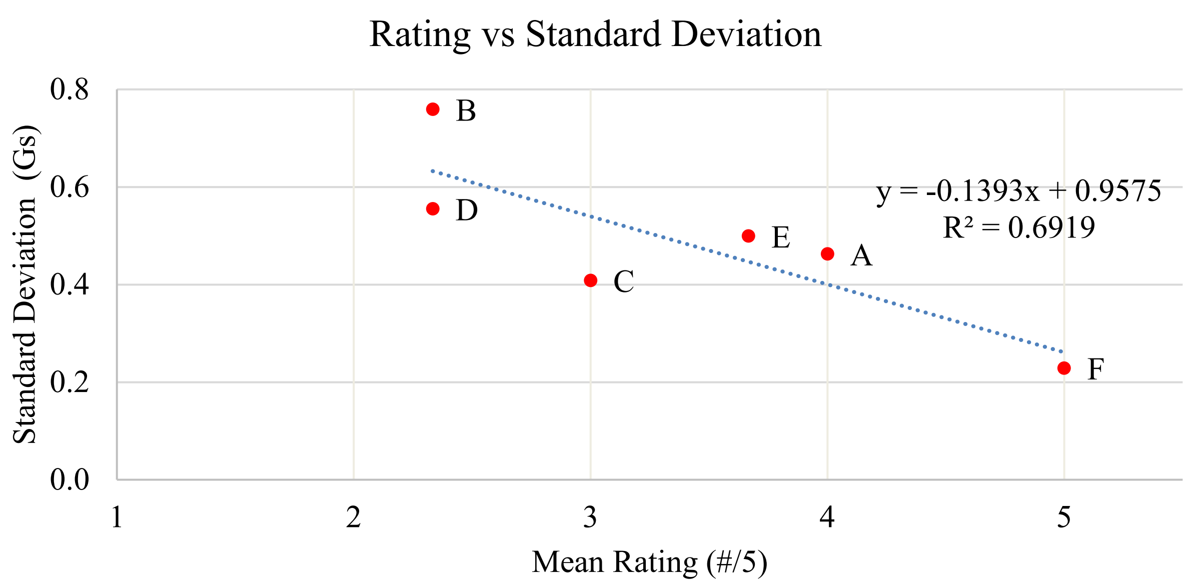


Figure 3-3. Standard deviation of acceleration correlated with the mean value of the participants' perceptions of ride quality.

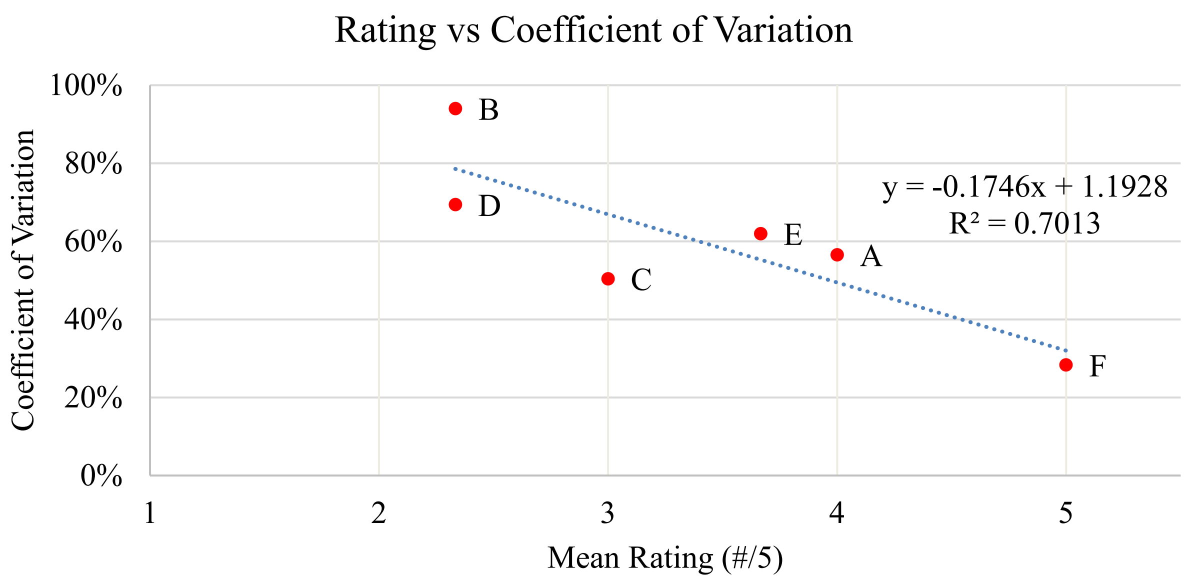


Figure 3-4. Coefficient of variation of acceleration correlated with the mean value of the participants' perceptions of ride quality.

Table 3-1. Mean perceptions of ride quality, standard deviation, coefficient of variation, maximum acceleration, and mean |acceleration| of pavement sections from A to F.

Mean	**Section**					
	A	**B**	**C**	**D**	**E**	**F**
Rating (#/5)	4.00	2.33	3.00	2.33	3.67	5.00
Standard deviation	0.46	0.76	0.41	0.55	0.50	0.23
Coefficient of variation	56.5%	94.0%	50.4%	69.4%	61.9%	28.3%
Max acceleration (Gs)	3.24	2.81	2.60	2.29	2.33	0.86
Mean |acceleration| (Gs)	0.30	0.61	0.28	0.43	0.38	0.18

Figure 3-2 shows that for the average results for Section A, the strength of the linear correlation between the system output and the mean perception of ride quality obtained from the rider survey was reduced. This was a result of the periodic spikes in the data for Section A, which resulted from the joints in the concrete sidewalk. The raw normalized absolute value of the acceleration data for Section A is given in Figure 3-5. Those jumps on the joints did not appear to negatively affect the perceptions of ride quality for the riders, whereas their quality perceptions were highly affected by surface texture and roughness. For this reason, maximum acceleration is not recommended as an effective parameter for evaluating ride quality and surface properties.

These results suggested that the standard deviation and coefficient of variation of acceleration provide a more holistic assessment of ride quality. Figures 3-3 and 3-4 show that those two parameters were linearly correlated with the average perception of ride quality values. The coefficient of determination value for the coefficient of variation parameter (Figure 3-4) was higher than the coefficient of determination value for the standard deviation parameter (Figure 3-3). For this reason, this study recommends use of the coefficient of variation parameter for surface and ride quality evaluations. Note that it was not possible to achieve a very high coefficient of variation value (around 90 percent) because there was also some level of variability between the responses of the riders. Some gave a rating of 2 for one section, whereas others gave a rating of 4 for the same section. This may have been a result of deviance in the exact ride line on the pavement section. The high variability among the riders of each test section suggests that some of the riders may have hit rougher spots, which may have resulted in lower ratings. The variation may also have been a result of differences in perceptions among different riders.

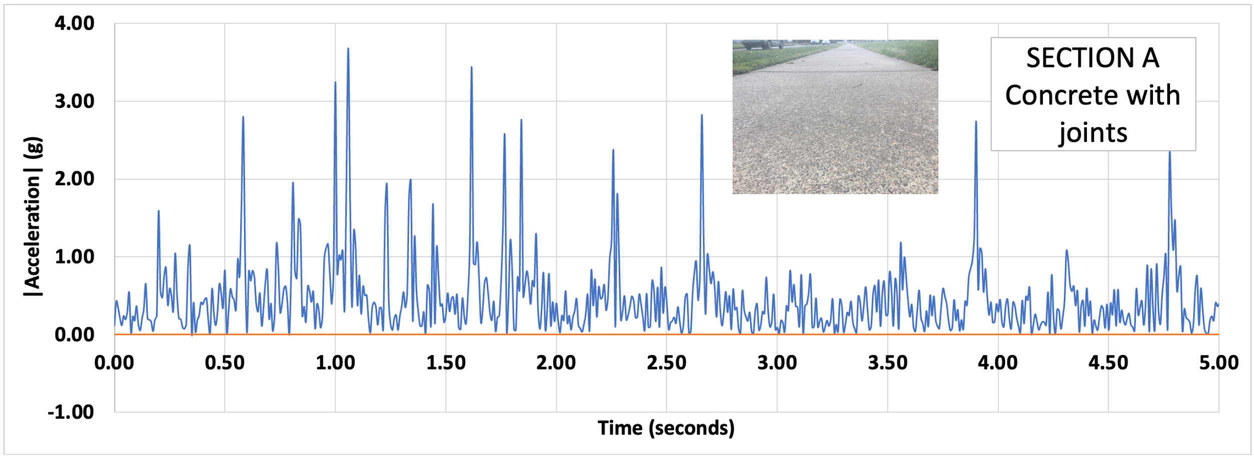


Figure 3-5. Acceleration data from Section A (concrete sidewalk with joints) – Absolute value of normalized acceleration.

State DOTs generally evaluate network-level pavement performance based on “fair or better” percentages. The “fair or better” rating includes roads judged to be in fair, good, and very good conditions. For this reason, in this study, the bike path failure threshold was determined to achieve “fair or better” ride quality. This corresponded to ratings at level 3 and higher. Using the linear function provided in Figure 3-4, the coefficient of variation threshold was calculated as follows:

COV parameter = -0.1746*Rating + 1.1928 Eq 1

For Rating=3, COV parameter threshold = -0.1746*3+1.1928 = 0.67 (67%)

On the basis of this calculation, after 5-second data collection and data processing, if the coefficient of variation (COV) parameter from the system is higher than 67 percent (a worse than fair rating), then the surface of the bike path needs to be improved by maintenance. This number can be called a “maintenance trigger” parameter for bike path condition assessment and management.

4 SUMMARY, CONCLUSIONS AND SUGGESTED BIKE PATH PAVEMENT IMPROVEMENT STRATEGIES

This study developed a pavement data collection system (with GPS and camera components) that can be installed on bicycles to collect bikeway surface texture, roughness, and distress data. On the basis of correlations between collected pavement data and cyclists' perceptions of ride quality (determined from surveys that were conducted with the cyclists), the effectiveness of the developed automated bikeway condition measurement system at identifying user comfort was determined. Suggestions for pavement design and construction stages were also developed to reduce rolling resistance on shoulders and bikeways. Decreased rolling resistance is expected to improve cyclists' safety and comfort and to encourage the use of bicycles for recreational purposes and as a mode of transportation in the Pacific Northwest.

In this study, the effects of pavement-related factors on cyclists' comfort were determined. The researchers determined texture and roughness thresholds (in terms of acceleration and vibration parameters) for chip seal and other pavement surfaces to achieve acceptable and high cyclist comfort levels. They also developed guidelines and procedures (for design and construction) to reduce texture and roughness on shoulders and bike paths were developed. The possibility for implementing three-axis accelerometer systems installed on bicycles for quantification of cyclists' user comfort was also determined.

4.1 Potential Methods (for Design and Construction) to Reduce Texture and Roughness on Bike Paths and Potential Future Research

Depending on funding availability, a bike path can be maintained either by replacing the entire asphalt/concrete material (a thick pave or rebuild) or by laying a thin preservation surface on the pavement (a thin pave, chip seal, crack seal, fog seal). Those options vary in cost and should be selected carefully to maintain the path with minimum cost to achieve longer pavement life (see Figure 4-1).

Preservation surfaces are generally more cost effective, but some might result in lower ride quality for users. Chip seals are a commonly used, lower-cost preservation strategy to improve the condition of the pavement and ride quality. They require the application of an asphaltic emulsion on the surface, one layer of the aggregate application, compaction with a roller compactor, and a second emulsion application on top. However, if larger aggregate sizes (called coarse gradation) are used in the chip seal design or if the embedment of the aggregate after compaction is low (resulting in a higher surface texture), then rougher rides and reduced ride quality might result. Aggregate embedment depth and the macrotexture for chip seals need to be controlled during construction to achieve smoother pavement surfaces that are more suitable for bicycles. For these reasons, the impacts of chip seal gradation, other mixture properties, and construction methods on ride quality should be evaluated in a future study by using the developed bike system and the recommended 67 percent COV threshold.

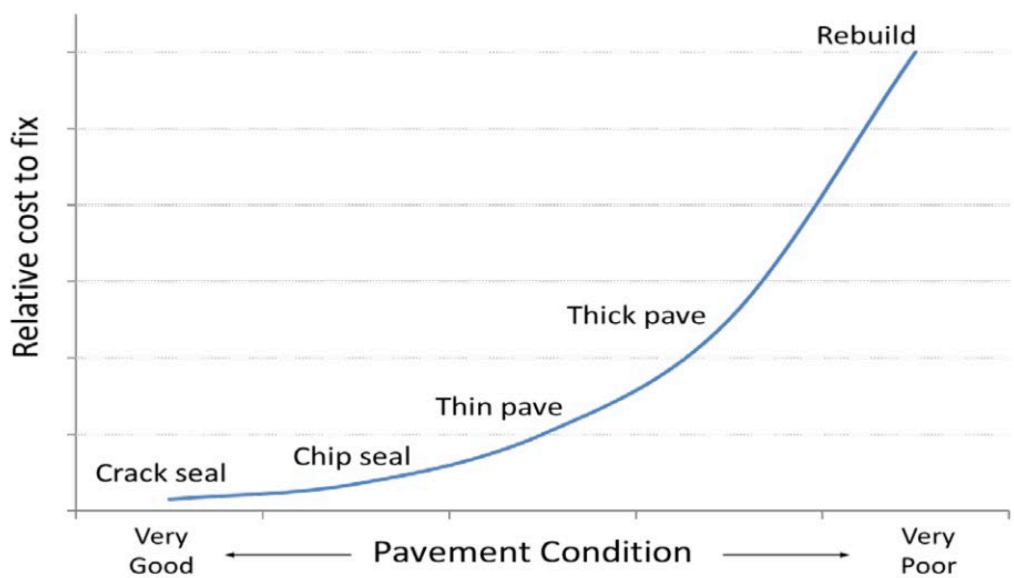


Figure 4-1. Pavement condition versus required maintenance and rehabilitation strategies with cost (Coplantz, 2022)

Another lower-cost option that can be used to preserve the quality of the ride is fog sealing. If the condition of the bike path is deteriorating at a rapid pace (meaning the COV value measured with the bike system is increasing very fast), then the entire surface can be fog sealed to improve the ride quality. For this reason, it is important to periodically collect pavement ride quality data with the system developed in this study (maybe every six months) to determine decreases in the COV value over time. Pavement conditions generally decease in a highly nonlinear trend when the pavement starts failing from thermal effects. When severe cracks are observed on the pavement surface, it is generally too late for maintenance/preservation. For this reason, the developed bike path performance monitoring system should be used periodically to collect COV data to identify a rapid reduction in ride quality and thus be able to make better decisions for maintenance timing.

Thin or thick asphalt concrete surfaces for bike paths will almost always provide higher-quality rides for users. However, they can be more costly than lower-cost maintenance strategies (e.g., chip seal, fog seal, crack sealing, etc.). For this reason, bike path data must be periodically collected to identify the timing of required maintenance (a COV of 67 percent recommended in this study). If the time to reach a 67 percent COV can be determined for various bike path sections, then this information can be used to rank the effectiveness of all those aforementioned strategies. Life cycle cost analysis (LCCA) can also be conducted with this service life information to select among the most effective bike path maintenance, rehabilitation, and reconstruction options. Additional research studies should be conducted to develop a process for periodic bike path data collection. A bike path pavement management system should also be developed to store the collected data, process all the results, conduct the life cycle cost analyses, and make informed decisions for pavement surface improvements using the processed data.

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