EVALUATION OF CURB RAMP COMPLIANCE: REVIEW OF TOOLS, METHODS, AND TIME TO DEVELOP ERROR TOLERANCES

Final Report

SPR 844

Oregon Department of Transportation

EVALUATION OF CURB RAMP COMPLIANCE: REVIEW OF TOOLS, METHODS, AND TIME TO DEVELOP ERROR TOLERANCES

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16. Abstract: Americans with Disabilities Act (ADA) compliance is critical to ODOT's mission to provide a safe and reliable multimodal transportation system by allowing equal access to infrastructure. Several challenges have resulted in difficulty in assessing compliance including inherent device errors, differences in measurement methods by inspectors, lack of consideration of flatness, settlement of ramps, lack of tolerances for construction processes and post-construction field settlement. In the absence of accepted construction tolerances, public agencies reject curb ramps when any measurement reading is greater than the allowed maximum slopes or where the slope readings themselves are inconsistent without acknowledging the inherent lack of precision with tools, variability of constructed surfaces, or understanding the error ranges of the measurement device. This research systematically evaluates the methods and tools used in the inspection process to achieve successful ADA compliance. To this end, the research investigates alternative technologies, determining the precision and repeatability of tools, identifying combinations of tools and methods, developing a flatness index, and providing an industry tolerance that considers these the cumulative potential effects on slope measurement.

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APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH					**LENGTH**		
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
		AREA					**AREA**		
in^2	square inches	645.2	millimeters squared	mm^2	mm^2	millimeters squared	0.0016	square inches	in^2
ft^2	square feet	0.093	meters squared	m^2	m^2	meters squared	10.764	square feet	ft^2
yd^2	square yards	0.836	meters squared	m^2	m^2	meters squared	1.196	square yards	yd^2
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi^2	square miles	2.59	kilometers squared	km^2	km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME					**VOLUME**		
fl oz	fluid ounces	29.57	milliliters	ml	ml	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
ft^3	cubic feet	0.028	meters cubed	m^3	m^3	meters cubed	35.315	cubic feet	ft^3
yd^3	cubic yards	0.765	meters cubed	m^3	m^3	meters cubed	1.308	cubic yards	yd^3
~NOTE: Volumes greater than 1000 L shall be shown in m^3.									
		MASS					**MASS**		
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.205	pounds	lb
T	short tons (2000 lb)	0.907	megagrams	Mg	Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)					**TEMPERATURE (exact)**		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C	°C	Celsius	1.8C+32	Fahrenheit	°F

*SI is the symbol for the International System of Measurement

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Drs. Olsen and Che have financial interests in EZDataMD LLC, a company which commercializes point cloud analysis technology related to this research. The conduct, outcomes, or reporting of this research could benefit EZDataMD LLC and could potentially benefit Drs. Olsen and Che.

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1.0 INTRODUCTION

Americans with Disabilities Act (ADA) compliance is critical to ODOT's mission to provide a safe and reliable multimodal transportation system by allowing equal access to infrastructure, particularly for those with disabilities. One challenge ODOT faces is the degree of scrutiny of how work is measured and inspected. An unscientific synthesis of nationwide practice by anecdotal observation is that the national ADA requirements are not consistently and systemically met. Due to variations, lack of precision, and confronted with a 'compliant' and 'non-compliant' measurement, sometimes a compromise is reached declaring the facilities to be 'compliant' when it closely conforms to ADA requirements rather than performing the extensive work needed to achieve full conformance. However, when these situations are under the scrutiny of third-party inspection, they may not pass strict compliance with national ADA requirements, resulting in significant costs to ODOT to remediate. Given these challenges and the legal ramifications of non-compliance, this research comprehensively evaluates the compliance assessment process for curb ramps to generate best practices for success in increased precision and compliance.

1.1 PROBLEM STATEMENT

ODOT agreed to a settlement (ODOT, 2016) in late 2016 to inventory and remediate all curb ramps identified in the 2017 inventory, which consists of approximately 25,000 ramps. Although ODOT has made progress toward their goals, ODOT has had to re-construct several curb ramps for non-compliance after initial construction. ODOT has made efforts to improve workmanship but still acknowledges other factors that can contribute to non-compliance. Compliance evaluation consists of very precise slope and size measurements without an "industry standard" of tolerances associated with those measurements.

Six key challenges exist:

1. Digital "smart" levels are commonly used for the assessment, which have inherent device measurement errors and inconsistencies, particularly when they are not properly calibrated or utilized by inspectors who have limited training,

2. Measurements are not reliably repeated if different inspectors measure the same surface (i.e., different methods to measure, quantities of measurement, locations of measurement, etc.), which often results in inconsistent estimates of the curb ramp slope,

3. A flatness index (similar to roadway smoothness) to account for surface variability is not considered or defined for evaluations,

4. Field effects over time, such as soil settlement, are not considered for compliance,

5. Section 104 of the ADA standards provide a clause to allow for recognized industry construction and manufacturing tolerances (U.S. DOJ, 2010) to be considered in specified values "except where the requirement is stated as a range with specific minimum and maximum end points". The running and cross slopes do not provide a range and are specified to not be steeper than 1:12 and 1:48 slopes and thus should allow for tolerance. However, there is currently not a recognized tolerance for curb ramp slopes, so many designers specify much shallower (e.g., 1% less) running slope and cross slopes as a buffer to account for construction tolerances, and

6. Due to the precision of measurements required, it is uncertain how much the concrete planar surface (i.e., flatness including dips and crowns) changes during hardening and curing processes. As a result, there is much difficulty in obtaining reproducible QA/QC measurements in the exact same place, orientation, etc. over time.

The ADA guidelines also require that slopes not vary along a ramp run or turning space. In the absence of accepted construction or measurement tolerances, public agencies are forced to reject curb ramps when any measurement reading is greater than the allowed maximum slopes or where the slope readings themselves are inconsistent without acknowledging the inherent lack of precision with tools, variability of constructed surfaces, or understanding the error ranges of the measurement device. ODOT needs an improved understanding of the magnitude of local variations in flatness on sloped, planar concrete surfaces in standard industry construction practices to designate and apply an achievable tolerance to measurements of constructed curb ramps. These aspects were detailed as further research in US Access Board's publication (Ballast, 2011).

While ramp flatness (sometimes referred to as smoothness or roughness) is visually assessed, there is no formal, consistent, quantified method of measure employed for curb ramps. Standardized approaches exist for floor slabs in buildings but are not relevant to curb ramps given the difference in scale. This research will provide recommendations on an appropriate flatness measure.

1.2 OBJECTIVES

This research enables ODOT to reliably and systematically evaluate the methods and tools used in the inspection process to achieve successful ADA compliance by:

1. Investigating alternative technologies used for ADA compliance assessments such as laser scanning,

2. Developing a research database of existing and newly constructed curb ramps, acquiring measurements over time using several tools and methods to determine their precision and repeatability,

3. Identifying the optimal combination(s) of tools and methods to achieve higher precision and reproducibility but still maintain efficiency and cost-effectiveness,

4. Identifying an appropriate overall flatness index measure to assist with the compliance determination when localized outlier variations indicate non-compliance (i.e., outside of existing specified slope limits) or the actual maximum slope of the ramp may be missed due to differences in sampling technique, and

5. Establishing the expected variance for (1) instruments used to measure the ramps, (2) flatness of the concrete material itself, and (3) movement or settlement of a ramp to determine an industry tolerance for concrete sloped planar surfaces considering the cumulative potential effects from the aforementioned sources.

This research will not focus on assessing the accuracy of existing measures; rather it will comprehensively evaluate the compliance assessment process for curb ramps to generate best practices for success in increased precision, reproducibility, and compliance.

1.3 BENEFITS

The final report will help ODOT make informed decisions to utilize the most optimal tool(s) and method in the compliance process. One of ODOT's values is Integrity, especially with the resources entrusted to the agency. Curb ramp cost is largely driven by the risk of rejection, which has led to a significant rise in curb ramp costs due to strict acceptance criteria. Applying strict adherence to curb ramp grades has resulted in efforts to identify errors and improve the measuring process, which has the potential to minimize and detect early stages of non-compliance. Rejection of a curb ramp results in contractors having to reconstruct them with significantly increased costs. In some cases, a curb ramp measurement at construction indicated compliance, but at a later time (possibly a year later or more) a third-party measurement indicated non-compliance. This research will enable ODOT to have a consistent measurement process for all so this situation is less likely to occur. In situations where measurements still conflict but are reasonably close to the threshold, ODOT could discuss options to avoid reconstruction in accordance with the Safe Harbor clause of the ADA regulations, which permits curb ramps to remain if they met the standard at the time of construction. Project costs are expected to continue to rise if ODOT is unable to reduce measurement errors in the assessment process and curb ramps continue to need reconstruction.

1.4 IMPLEMENTATION

The results of this research provide guidance to better the process and reduce error (increase precision and reproducibility). The research identifies an appropriate flatness index and compares this index against existing measurements. As this research is being conducted during the construction timeframe, it is not intended to compare accuracy against the standard set forth in the settlement. After the curb ramp inventory identified in the settlement has been constructed, the research database developed in this project could be incorporated into ODOT’s data per each site examined during the research project. These additional scans, measurements, and information may provide added value to ODOT in future years.

1.5 ORGANIZATION OF REPORT

The remainder of this report is organized as follows:

- Section 2 provides background information and a review of relevant literature on tools and methods for evaluating curb ramp slope compliance. It also describes flatness calculation methods.

- Section 3 presents a rigorous error analysis determining errors in slope measurement resulting from smart level placement based on a combination of simple tests and theoretical modeling.

- Section 4 describes calibration testing to evaluate the measurement accuracy of several measurement devices including terrestrial laser scanners and smart levels.

- Section 5 explores the variation in slope measurements obtained by different inspectors completing the evaluation to evaluate the consistency of field methods.

- Section 6 describes a laboratory experiment to evaluate changes in curb ramp slope with time on ramps constructed at different slopes to evaluate construction influences.

- Section 7 documents work completed to capture scans at a variety of curb ramps throughout the state and establish an in-situ curb ramp research database.

- Section 8 describes additional testing completed to evaluate the precision of the smart levels based on the in-situ curb ramp database (ISCRampeD).

- Section 9 presents the proposed slope measurement process that incorporates roughness.

- Section 10 presents an example hierarchical assessment procedure to optimize use of different technologies in the assessment process to more rigorously determine whether ramps are in compliance.

- Section 11 presents the conclusions to this work and outlines several recommendations of methods and metrics for ODOT to consider implementing.

Additionally, the following appendices are included with this report:

- Appendix A, containing the current ODOT evaluation form and procedures.

- Appendix B, containing data supporting the calibration testing.

1.6 MAPPING OF CHALLENGES, OBJECTIVES, AND REPORT SECTIONS

For the convenience of the reader, this section maps the six challenges presented in the problem statement (Section 1.1), the objectives (Section 1.2), and the specific sections of the report related to those challenges and objectives.

Table 1.1: Mapping Of Challenges And Objectives To The Report Sections.

Challenges (Section 1.1)	Objectives (Section 1.2)	Report Sections
1. Smart level calibration	• Objective 3 (Identify tools for high precision and reproducibility) • Objective 5 (Establish expected variance for (1) instruments in the field, (2) flatness of concrete material itself, (3) movement or settlement of a ramp.)	• Section 2.3.3 Digital inclinometers (smart level) • Section 3.0 Error Analyses • Section 8.0 In-Situ Data Analysis and Monitoring (Section 8.2, direct and reverse reading comparison)
2. Measurement variability from different inspectors	• Objective 5 (Establish expected variance for (1) instruments in the field, (2) flatness of concrete material itself, (3) movement or settlement of a ramp.)	• Section 2.2 Curb Ramp Design and Construction Practices • Section 5.0 Operator Variability Testing
3. Flatness index for surface variability	• Objective 4 (Identify flatness index) • Objective 5 (Establish expected variance for (1) instruments in the field, (2) flatness of concrete material itself, (3) movement or settlement of a ramp.)	• Section 2.4 Flatness evaluation • Section 4.0 Calibration Testing
4. Field effects over time such as soil settlement	• Objective 2 (Remeasurement of curb ramps over time) • Objective 5 (Establish expected variance for (1) instruments in the field, (2) flatness of concrete material itself, (3) movement or settlement of a ramp.)	• Section 2.2 Curb Ramp Design and Construction Practices • Section 7.0 In-Situ Curb Ramp Database • Section 8.0 In-Situ Data Analysis and Monitoring
5. An industry tolerance is not specified for ADA standards.	• Objective 1 (investigate alternative technologies) • Objective 5 (Establish expected variance for (1) instruments in the field, (2) flatness of concrete material itself, (3) movement or settlement of a ramp.)	• Tolerances are determined in Sections 2.0, 3.0, 4.0, and 5.0 for the operation of smart levels. Section 6.0 provides tolerances from concrete curing and construction, and Section 7.0 and 8.0 provide tolerances for time effects. Sections 9.0 and 10.0 provide a new methodology to incorporate these tolerances.
6. Movement of the concrete planar surface changes during hardening/curing processes.	• Objective 5 (Establish expected variance for (1) instruments in the field, (2) flatness of concrete material itself, (3) movement or settlement of a ramp.)	• Section 2.2 Curb Ramp Design and Construction Practices • Section 6.0 Concrete Testing

2.0 BACKGROUND AND LITERATURE REVIEW

This section contains a literature review and background for the project. The section first reviews ADA regulations and policies. Next, it discusses curb ramp design and construction practices. The next subsection describes the tools and methods that are or could be used to assess compliance of curb ramps in detail. Lastly a review of flatness evaluation metrics is provided.

2.1 ADA REGULATIONS AND POLICIES

ADA was signed into law on July 26, 1990, to prohibit discrimination and guarantees that people with disabilities have the equal opportunity to enjoy employment opportunities, to purchase goods and services, and to participate in state and local government programs and services (U.S. Access Board, n.d.). On July 26, 1991, the Department of Justice (DOJ) published the ADA Title II (state and local government services) and Title III (public accommodations and commercial facilities) regulations including the 1991 ADA Accessibility Guidelines (ADAAG) issued by the Access Board, which are to be applied during the design, construction, and alteration of public and commercial buildings and facilities. The 1991 ADAAG was later revised and restructured into the 2004 ADAAG. In 2006, the Department of Transportation (DOT) ADA Standards for Transportation Facilities adopted ADAAG 2004 including additional requirements in locations of accessible routes, detectable warnings on curb ramps, bus boarding and alighting areas, and rail station platforms. The revised ADA regulations were published on September 15, 2010, and include ADA Title II and Title III, the updated ADA Standards for Accessible Design (2010 Standards), and the 2004 ADAAG. Compliance with the 2010 Standards was mostly required on March 15, 2012. In 2016, the ADA Title II and III regulations were revised, and the final rule was published on December 2, 2016, and took effect on January 17, 2017. Title II of the ADA requires that public agencies maintain an ADA self-evaluation and transition plan. For new construction of sidewalks and streets, crosswalks, curb ramps, pedestrian signals, on-street parking, and other components of public rights-of-way, the proposed Public Rights-of-Way Accessibility Guidelines (PROWAG) released in 2011 under the ADA and Architectural Barriers Act (ABA) has been followed by ODOT and many other agencies. The U.S. Access Board is currently in the process of finalizing these guidelines.

2.2 CURB RAMP DESIGN AND CONSTRUCTION PRACTICES

ADA requires the installation of ramps along accessible routes to span changes in surface height greater than ½ in. There are several forms of ramps. Curb ramps, which are the focus of this research project consist of two types:

- *Perpendicular* - ramps that cut through curbs, are built up to curbs at right angles, or meet the gutter break at right angles for curved curbs.

- *Parallel* – ramps with the running slope in line with the sidewalk direction of travel. The ramp lowers the sidewalk to a level turning space to allow access to the pedestrian street crossing.

Blended transitions are similar to curb ramps for pedestrian access and consist of raised street crossings, depressed corners, or other connections between the street crossings and sidewalks. Geometric requirements for both perpendicular and parallel curb ramps, as well as blended transitions are outlined in Section R304 in PROWAG. Section R305 covers detectable warning surfaces for curb ramps.

The U.S. Access Board published a report, "Dimensional tolerances in construction and for surface accessibility," that summarizes best practices for designers and the construction industry to improve compliance (Ballast, 2011). They also cover how to verify the compliance, specifications during pre-construction meetings, and construction observation with specified measurement protocols. This report also provided suggested tolerances (Table 2.1).

Table 2.1: Suggested Construction Tolerances For Curb Ramps In (Ballast, 2011)

Characteristic	Tolerances
Running slope	0.5% (also suggested to plan for a 7.5% running slope in an ideal case.)
Cross slope	0.5%
Landings	0.5%
Horizontal discontinuities and vertical alignments	0.125 in (3 mm)
Flatness for running slope	80% of the measurements not exceeding 8.3%. The remaining should not exceed 10% slope.
Flatness for cross slope	80% of the measurements not exceeding 2%. The remaining should not exceed 2.5% slope.

This report, however, evaluates the measurement protocols only considering the reported accuracy of the measuring device. In addition, the measurement method of flatness for running and cross slope is not explicitly considered in curb ramp design. This will be discussed in more detail in Section 2.4. ODOT adopted the suggested best practices for the design of curb ramps to provide tolerances to address potential construction errors, ultimately targeting more stringent thresholds than the ADA standards (Table 2.2) (ODOT, 2021). The best practices also include a clear statement of tolerances in the specification with all applicable industry standards listed.

ACI 117, "Specification for Tolerances for Concrete Construction and Materials and Commentary" outlines general standards for ramps, sidewalks, and intersections. For pavements and sidewalks, the ACI standard provides the following requirements in terms of the vertical deviation of surface:

1. Mainline pavements in longitudinal direction, the gap below a 10 ft (3 m) unleveled straightedge resting on high spots shall not exceed 1/8 in (3 mm).

2. Mainline the gap below a 10 ft (3 m) unleveled straightedge resting on high spots shall not exceed ¼ in (6 mm).

3. Ramps, sidewalks, and intersections, in any direction, the gap below a 10 ft (3 m) unleveled straightedge resting on high spots shall not exceed ¼ in (6 mm).

However, most curb ramps are shorter than 10 ft (3m). Thus, some modifications and adjustments need to be made if these measures are used to assess the construction quality. Similarly, there are also other measurements developed for the interior of a building that could potentially be adopted to perform curb ramp assessment with necessary modifications. For example, for evaluating the levelness of sloped floor surfaces, tolerances are defined by ASTM E1486. Survey lines are set across the floor. For each line, slopes parallel to the survey line are computed for successive 15-ft (4.57 m) segments of those lines. The root mean square (RMS) of those values is reported as the measure of levelness. Such standards clearly do not apply to curb ramps.

Table 2.2: ADA Standards Vs. ODOT Curb Ramp Design (ADA Curb Ramp Design Check List)

Characteristic	PROWAG	ODOT check list
Running slope	5.0 to 8.3%	5.0 to 7.5%
Cross slope	2.0% maximum	1.5% maximum
Counter slope	5.0% maximum	4.0% maximum
Clear width	48 in or 1.2 m, 60 in or 1.5 m (island)	54 in or 1.4 m, 66 in or 1.7 m (island)
Flares	10.0% maximum	10.0% maximum
Landing slope	2.0%	1.5%
Landing dimension	48 in or 1.2 m	54 in or 1.4 m
Gutter cross slope	2.0%	1.5%
Turning Space	48 in × 48 in or 1.2 m × 1.2 m minimum. 48 in × 60 in or 1.2 m × 1.5 m minimum when back is constrained. 2% maximum slope	54 in × 54 in or 1.4 m × 1.4 m minimum. 54 in × 66 in or 1.4 m × 1.7 m minimum when back is constrained. 1.5% maximum slope

Note that in ODOT specifications, blended transitions have a 5% maximum slope.

2.3 TOOLS AND METHODS

This section describes common and potential tools for assessing curb ramp compliance. All tools are vulnerable to user errors and blunders. Additionally, all tools should be periodically checked to ensure they are within calibration. The magnitude of errors and frequency of necessary calibration will vary across the different tools.

2.3.1 Metal measuring tapes

Measuring tapes (Figure 2.1) are the most common tools to measure distances because they are small and easy to use. The measurements can usually be obtained with a precision of 1/16 in or 2 mm. NIST tolerances for metal tapes are 1/32 in (1 mm) for a 6 ft (1.8 m) or less measuring tape. This precision is ordinarily sufficient for accessing the ADA compliance of a curb ramp in terms of dimension. There are several factors that could results in errors in dimensional measurement; however, given the 6 in (15 cm) tolerance in design (Table 2-2), most of these errors (with the exception of gross blunders) will be minimal. Some factors relate to user operation, such as not placing the tape directly on the surface and introducing sag, measuring from incorrect locations, and misalignment resulting in measurements obtained at a slight angle across the surface. These operating errors will typically result in larger reported values than the actual dimension. If the tape has been stretched with repeated usage or the metal hook is loose, the reported measurements will be smaller than the actual measurement.

Figure 2.1: Basic measuring tape.

2.3.2 Carpenter's levels

Carpenter's levels (Figure 2.2) are used to check level and plumb (some also have 45-degree inclination) in construction. They usually come with one or more physical level bubbles. To determine the slope of a curb ramp, they need to be used in combination with measuring tapes. However, this way of determining a slope can be highly error prone. Further the gradations on the level bubbles are often at very coarse intervals, resulting in poor precision in measurements.

Figure 2.2: Basic carpenter's level

2.3.3 Digital inclinometers (smart level)

Digital inclinometers (Figure 2.3), often referred to as a "smart level," are equipment used to measure the slope of a surface. (For purposes of clarity in this report we will refer to these digital inclinometers primarily as smart levels hereafter). They are commonly used to evaluate the ADA compliance of a curb ramp including the running, cross, flare, landing, counter, and gutter cross slope. They are simple to operate and have a nominal manufacturer reported accuracy of 0.1°

when the device is level/plumb and 0.2° when oriented at other angles. SmartTool® produces several models of smart levels as well as in several different lengths (e.g., 1, 2, and 4 ft, or 30, 60, 120 cm). All of the models, including Gen2 and Gen3, have the same sensor design and share the same accuracy. The "slope walker" model (Figure 2.4) is essentially a 1-ft (30-cm) smart level with a stand and handle to simplify the field effort as well as ensure the instrument is not placed on debris that could bias the readings.

Figure 2.3: Example SmartTool® digital inclinometer (2-ft or 60-cm length).

Figure 2.4: Slope walker digital inclinometer with handle.

2.3.4 Total Station

A total station (Figure 2.5) is a survey instrument that can precisely measure both angles (typically 1 – 5” [seconds of a degree] precision) and distances (typically 1 – 3 mm or 3/64 – 1/8 in). Total stations have a built-in level compensator that allows them to be precisely leveled to a few thousandths of a degree. A total station can observe the targets via a prism (Figure 2.5) mounted on a pole or tripod over the point of interest or in a reflectorless mode, which does not require physical contact with the objects. Slopes and dimensions can then be computed from the resulting coordinates on the points of interest at high accuracy.

There are several limitations in using the device routinely for compliance checks. First, a total station typically costs ($5,000 - $30,000) depending on the desired precision and features. Second, operating a total station requires a lot of training and experience. Third, setting up the instrument, including leveling, can be time-consuming. Fourth, it is somewhat heavy to carry from one setup location to another. Although it is not applicable for assessment on a regular basis, it is very suitable for controlled testing to obtain high accuracy baseline data. It could also be used in a more detailed investigation by a more experienced crew as a second check on the readings of a coarser smart level measurements when the curb ramp is on the border of passing and failing.

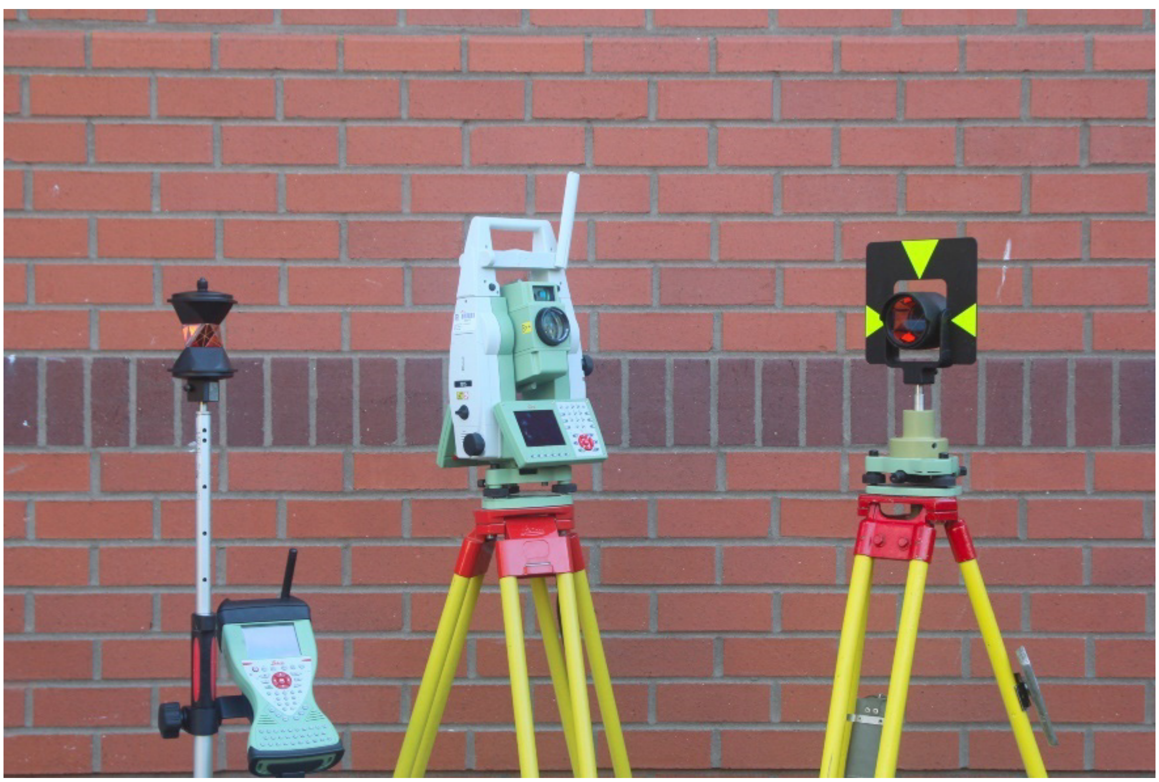


Figure 2.5: Total station, remote controller, and prism.

2.3.5 Global Navigation Satellite System (GNSS)

GNSS (Figure 2.6) is available in a range of devices from common mobile devices to survey grade GNSS receivers. GNSS can be used to determine the 3D global location of a point of interest. Depending on the GNSS unit, observation time, and the satellite visibility at a curb ramp, the accuracy of a measurement can be from the millimeter to meter level. In principle, GNSS can be used to determine the geometry of a curb ramp directly by observing a number of key points. Realistically, a GNSS measurement can achieve 3D accuracies of a few inches or centimeters if there is good satellite visibility during the survey. The error in the vertical is usually 2 – 3 times higher than the error in the horizontal. As a result, these larger vertical errors can significantly affect the ADA-compliance assessment, particularly for slope measurements. Nevertheless, although GNSS is not currently suitable to accurately measure slopes accurately over a small area (e.g., few feet or meters), GNSS can still be useful to georeference other local survey approaches and techniques. This geolocation is crucial for developing a usable sidewalk or curb ramp inventory database.

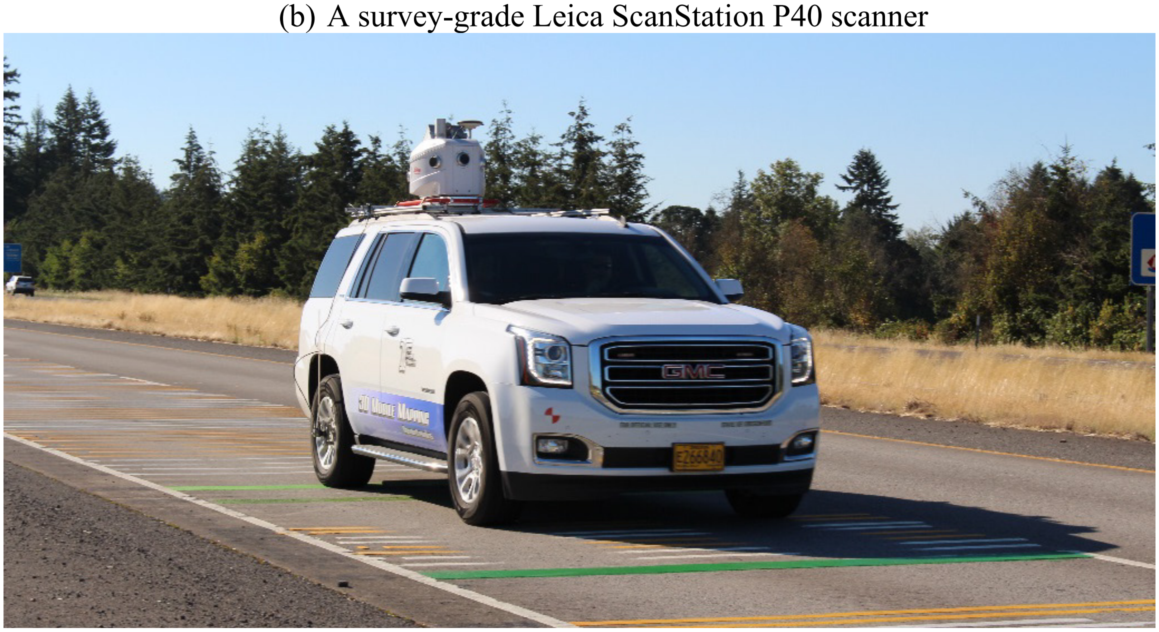
Figure 2.6: GNSS receivers mounted in different configurations.

2.3.6 Laser scanning

Laser scanning (Figure 2.7), also known as lidar- light detection and ranging, is a powerful data acquisition approach that can efficiently and accurately acquire a 3D point cloud (Figure 2.8: Example of point cloud data at a curb ramp collected by Leica Pegasus: Two mobile lidar systems) of a scene of interest at very high detail. Laser scanning has been widely adopted for various applications in transportation (Olsen et al. 2013) and can potentially be used for inventory and assessment of curb ramps. Not only can a laser scanner capture a curb ramp with thousands of measurements, but it also provides context of the surroundings, which can support more advanced and comprehensive analyses of a site without requiring repeat visits or extensive manual measurements in the field. Another key value to laser scanning is that measurements can be systematically extracted and visualized in context of the entire ramp. In the field, determining the precise center of the ramp to obtain measurements can be difficult. With a point cloud, the center can be located more precisely. The redundancy of measurements also improves the accuracy and precision of the resulting measurements. Nevertheless, the technology has not yet been proven fully for ADA compliance. There are some promising studies that have investigated the effectiveness of laser scanning to assess the ADA compliance of curb ramps that will be summarized in this section.

(a) a small, lightweight Leica BLK 360

(b) A survey-grade Leica ScanStation P40 scanner



(c) Leica Pegasus:Two mobile laser scanner

Figure 2.7: Examples of different platforms for laser scanners.

Figure 2.8: Example of pointcloud data at a curb ramp collected by Leica Pegasus: Two mobile lidar system.

Oh et al., 2018 proposed an approach to use terrestrial laser scanning data to evaluate the ADA-compliance of sidewalk and curb ramps. After the sidewalk and curb ramps were detected in the point cloud data, geometric information including slope, width, and length were extracted for the assessment. A curb ramp was considered as a plane and a plane fitting was performed. The normal vector of that plane was then utilized to calculate the slope. The slope measurement results were compared against field surveys using a measuring tape where the average difference was 0.13% (percentage slope). While this is promising and on par with the smart level, there are several limitations in this study to consider. First, because the estimated normal of a plane is a combination of running slope and cross slope, the study did not consider the cross slope of a curb ramp and running slope of a sidewalk separately as is needed for ADA compliance. Secondly, for the comparison, only 8 samples of curb ramps and sidewalks were used in total, which is not sufficient to draw a statistical conclusion (FGDC 2002). Third, utilization of tape measures introduces a significant amount of uncertainty, which was not further investigated in the study.

Oh et al. (2018) also tested an alternative approach by mounting a lidar sensor on a Segway scooter and demonstrated the effectiveness of the integrated system to capture sidewalks and extract the characteristics to assess the ADA compliance. A Velodyne V-16 lidar scanner was integrated with 3 cameras to capture point clouds and images with a 270-degree field of view. The focus in this work was to evaluate the feasibility of utilizing these data to detect static and dynamic objects. The system was able to capture objects such as sidewalks, signs, and grass. However, because the system does not include an IMU or GNSS receiver to get the position and orientation of the system in real time, it fails to assess the ADA compliance of the sidewalks and curb ramps.

Ai & Tsai (2019) used a mobile (vehicle) lidar system to help improve the process of developing a sidewalk and curb ramp inventory. To extract curb ramps from the mobile lidar point cloud data, an automatic curb ramp extraction and a web-based manual extraction process were introduced into the workflow. Once the curb ramps are isolated from the massive mobile lidar point cloud of the scene, the running slope of each extracted curb ramp is computed. In similar work done by Ai & Hou (2016), the accuracy of the running slope measurement from mobile lidar data was assessed at 20 curb ramps. The percentage slope errors ranged from -0.5% to 0.6% and the root mean square error was 0.3%. Although there is still room for improving the framework, such as adding more characteristics for ADA compliance assessment with more rigorous validation, overall, these studies showed promising results of utilizing laser scanning technology to evaluate curb ramp compliance.

2.3.7 Surface profiler

Some systems are built on a mobile platform (Figure 2.9) to measure the longitudinal slope, cross slope, flatness, and other characteristics for assessing the ADA compliance of primarily sidewalks. By building the sensors on a mobile platform, it makes it possible to cover the sidewalk across a large area efficiently with high resolution. For example, the Ultra-Light Inertial Profiler Sidewalks (ULIPs) device developed by Starodub, Inc. was used for the sidewalk inventory in Bellevue, WA. A comprehensive test of this system has been conducted and reported including distance measuring instrument (DMI) calibration, grade and cross slope validation, grade and cross slope averaging window size, rider stability. The test results were compared against digital inclinometer (smart level) readings and show that the accuracy of the system is adequate for assessing sidewalks. However, the tests at the curb ramps show significant discrepancies. One of the possible reasons for this is that at a curb ramp, there is more variation in terms of the surface characteristics comparing against the sidewalks, and the system is averaging measurement with a given interval to reduce noise in the raw measurements. There are also other similar systems such as the SSI CS8900 ADA Access Profiler, which can acquire surface characteristics including running slope, cross slope, evenness/roughness, and ride index.

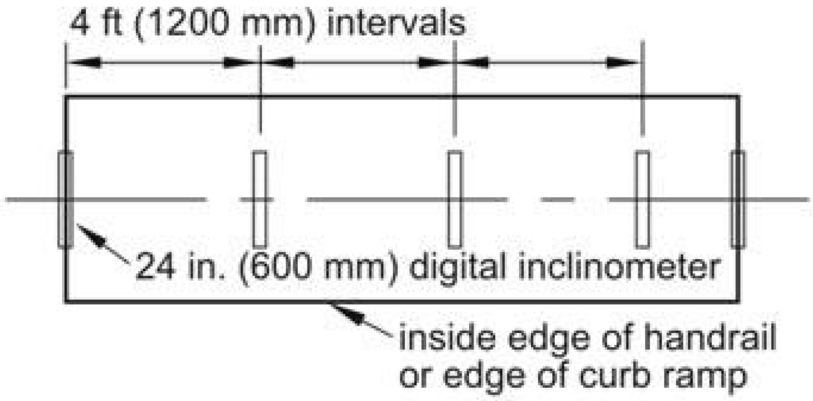
(a) ULIP- Ultra Light Inertial Profiler for sidewalk evaluation (Photograph from https://www.corada.com/products/starodub-inc-ultra-light-inertial-profiler-ulip-for-sidewalks)

(b) SSI CS8900 ADA Access Profiler from https://www.smoothroad.com/cs8900-ada-access-profiler

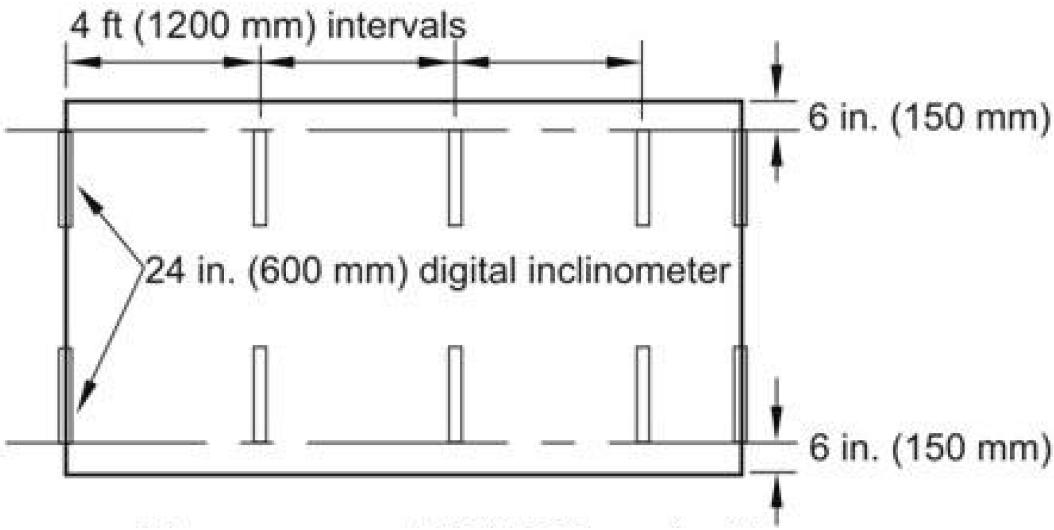
Figure 2.9: Examples of surface profiler systems.

2.4 FLATNESS EVALUATION

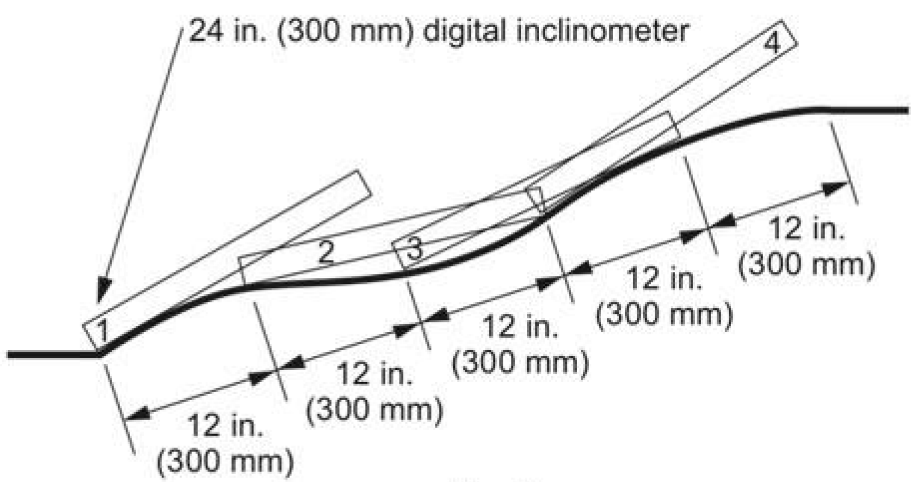
A smooth and flat surface is required to ensure the proper accessibility of a curb ramp. In PROWAG, there are requirements for the pedestrian access routes, in general, where the maximum vertical surface discontinuities (also referred as vertical fault or vertical lip) are 0.5 in. (13 mm). Other than the requirement on the vertical fault, the current ADA/ABA guidelines and other industry standards, specifications and measurement procedures do not specify the requirement of flatness for a curb ramp. Ballast (2011) introduced ways of measuring the flatness of the cross slope and running slope with straightedge and digital inclinometer inspired by ACI 117 in concrete construction. Nonetheless, the methods were designed for the ramps in buildings which are usually longer and wider than a curb ramp. For example, to measure the ramp flatness for cross slope, the intervals are spaced 4 ft (120 cm) along the travel direction. For measuring the flatness of local running ramp slope, a 2-ft (60-cm) smart level can be used to measure the steepest slope or spans between two high points every 1 ft (30 cm) (Figure 2.10). However, such measurements may only result in a few samples for most of the curb ramps. Hence, it would be challenging to calculate statistical metrics from such a small sample size. This literature review identified other potential metrics that could be adapted to evaluate the flatness of a curb ramp such as Floor Flatness, waviness index, International Roughness Index (IRI), and surface roughness.



(a) Cross slope for ramps up to and including 5 ft (1.5 m) wide.



(b) Cross slope for ramps over 5 ft (1.5 m) wide



(c) Running slope

Figure 2.10: Ramp flatness measurements for cross and running slope (from Ballast, 2011).

2.4.1 Concrete Slab Flatness Evaluation

In concrete construction, flatness is a referred to the degree to which a surface approximates a plane (ACI 117). Some standardized characteristics such as the F-number (e.g., floor flatness, F_F) and waviness index can be used to specify the standards for construction (Table 2.3).

ASTM E1155 specifies the standard test method for determining F_F. First, in each test section, straight lines are marked at key locations across the floor surface. Then along each line, elevations are measured every 12 in. The F_F for each test section can be then computed based on the variance of elevations and finally combined for the entire floor. However, it is challenging to directly adopt such standards in evaluating curb ramps. For example, each side of a test section is required to be no less than 8 ft while the area of each test section is no less than 320 ft^2 (30 m^2), which is impossible to achieve for a curb ramp given its limited size. Moreover, it also requires that the number of elevation measurements along each sample line should be no less than 12, which is also not applicable to the scale of a curb ramp. As a result, this method would require modification and validation of those modifications to be used for curb ramps.

Another common metric used in concrete construction is the waviness index specified in ASTM E1486. The basic concept of the waviness index is to measure the deviation between the floor surface and the mid-point of an imaginary straight edge (chord) at a number of sample points and adjust the root mean square of these deviations with the length of the chord. The length of the imaginary chord is 2, 4, 6, 8, and 10 ft (or 0.6, 1.2, 1.8, 2.4, and 3 m) Similar to the challenges in adopting floor flatness to curb ramps, it is difficult to meet the requirement due to the much smaller size of a curb ramp.

There are also recent research using other techniques (e.g., laser scanning) to use more complex metrics to assess the flatness of concrete slabs. For example, Puri et al. (2018) proposed a method using terrestrial lidar data to evaluate the flatness of a concrete slab via a 2D continuous wavelet transform. Given the very high resolution of the 3D pointcloud data collected by the terrestrial laser scanner and automated workflow, a large number of samples can be taken to complete the assessment throughout the scene efficiently.

Table 2.3: Features And Performance Of Existing Standard Methods And The Puri Et Al. Method For Measuring Floor Flatness (Puri, Valero, Turkan, & Bosché, 2018)

	Method	Straightedge	F-number	Waviness Index	2D CWT
Features	Periods of undulation detected	10'-20' (3.05-6.10 m)	1.5'-4' (0.46-1.22 m) (FF) 15'-80' (4.57-24.38') (FL)	2'-10' (0.61-3.05 m)	Any
	Output	Values in inches	FF and FL values	Values in inches	Map showing detected undulations for various periods.
	Types of errors	Random and systematic	Random	Random	Systematic (±3 to 6 mm)
	Approximate data acquisition efficiency (s/m2)	7	4	4	2
	Point Spacing	Along 1D non-parallel survey lines in 10-foot segments	Along 1D parallel survey lines in two orthogonal directions	Along 1D parallel survey lines in two orthogonal directions	Across 2D surface
Performance Criteria Achievement	Sparsity of Measurements	No	No	No	Yes
	Localization of defects	No	No	No	Yes
	Visualization of region of defects	No	No	No	Yes
	Repeatability	No	No	No	Yes

2.4.2 Pavement smoothness evaluation

For assessing the smoothness of pavement, there are several metrics that have been commonly used including the Pavement Serviceability Rating (PSR), Profile Index (PI), International Roughness Index (IRI), Mean Ride Index (MRI) and Half Car Ride Index (HRI) (Smith and Ram, 2016). These metrics are computed from the measurements along one or multiple profiles along or across the roadway. The specifications, as well as the relationships between these metrics, have been investigated and summarized in some previous work such as Smith et al. (2002).

These metrics, however, typically involve specialized equipment. For example, inertial profilers are commonly used in capturing road profiles to assess the smoothness of the road surface. Some sensors are designed to be mounted on a vehicle such that they are suitable for large-scale data collection (Perera et al., 2008). In prior research for ODOT, Chin and Olsen (2014) evaluated various technologies and instruments including a terrestrial laser scanner and instrument for road profile capturing to obtain the IRI. Additionally, although some of the instruments can be used to capture detailed surface information, these metrics are applied over a much larger scale compared against a curb ramp. For example, IRI is an index computed from a longitudinal profile measurement using a quarter-car simulation at a simulation speed of 50 mph (80 km/h) (ASTM E1926) where the unit of the IRI is in./mile or m/km and the required values are dependent to the designed speed of the roadway. The localized roughness is any 25 ft (7.6 m) segment that disproportionately affects the overall IRI while the IRI is sensitive to wavelengths from 4 – 98 ft (1.2 – 30 m) (Olsen et al., 2012). Such scale of measurement and analysis is not applicable to a curb ramp.

2.4.3 Roughness Metrics

In geomorphic studies, roughness or rugosity is commonly used to characterize a slope surface. For example, Berti et al. (2013) rigorously compared various approaches of computing surface roughness from a Digital Elevation Model (DEM) and evaluated their performance in identifying active landslides. The core to a reliable roughness metric is that the surface needed to be detrended (e.g., account for the general slope of the surface). It is worth noting that in all the approaches computing surface roughness, the surface roughness is always defined with a given scale (e.g., window size). The scale should match the feature(s) of interest. For example, roughness at the nanometer level would not significantly affect accessibility on a curb ramp; however, roughness at the centimeter (or inch) level would. Such definition of surface roughness provides flexibility to adapt data collected in different resolutions and the scale of the object of interest. As a result, some of the methods computing surface roughness can be adopted in characterizing the flatness of a curb ramp. For example, with a number of slope measurements on a curb ramp, the standard deviation of the slope measurements can be computed as the surface roughness for assessing its flatness. However, the optimal scale/window size and standardized sampling and measuring approach need to be further investigated before implementation. In addition to the direct slope measurements, laser scanning can also be used to model the surface and derive the roughness metrics.

3.0 ERROR ANALYSES

This section contains an assessment of error sources and magnitude for digital inclinometers. The section first presents passing rates for different parameters of interest based on prior studies. Next, it characterizes basic user or surface errors when obtaining measurements using a digital inclinometer as well as calibration protocols. The use of direct and reverse measurements is then explored. The following subsection discusses errors resulting from misalignments when placing the digital inclinometer on the surface. Lastly, the section describes theoretical accuracy improvements from obtaining several repeat measurements.

3.1 CURB RAMP INVENTORIES

In addition to construction tolerances (Section 2.2), measurements errors incurred when assessing the ADA compliance of a curb ramp also need to be considered in the design, construction, inspection, and service stages. Some public entities have conducted self-evaluations and inventory as part of the ADA transition plan (Table 3-1). Based on those results, the requirement of slopes (e.g., running slope, cross slope, etc.) have a significantly lower compliance rate in general compared against dimensions (e.g., landing dimensions, clear width, etc.). Given the fact that the slopes at a curb ramp are more likely to be non-compliant to ADAAG and that digital inclinometers (smart level) are the most commonly used equipment to measure the slope, it is important to investigate the error sources in the slope measurement.

Table 3.1: Examples Of Curb Ramp ADA Compliance Statistics For Several Locations. (Passing Rates Are Indicated In Parenthesis).

	Bellevue, WA	**Augusta, GA**	**Champaign-Urbana, IL**	**Totals**
Year	2009	2016	2016	-
Tools	Measuring tape, smart level	Measuring tape, smart level	Measuring wheel, smart level	-
Total curb ramps	3,511	3,214	12,717	19,442
Running slope	1,525 (43%)	2,251 (70%)	8,936 (70%)	12,712 (65%)
Cross slope	1,095 (31%)	1,496 (47%)	7,132 (56%)	9,723 (50%)
Counter slope	2,362 (67%)	1,999 (62%)	9,502 (80%)	13,863 (71%)
Landing slope	720 (21%)	2,987 (93%)	2,407 (30%)	6,114 (31%)
Gutter cross slope	1,302 (37%)	2,032 (63%)	8,424 (71%)	11,758 (60%)
Clear width	3,410 (97%)	3,186 (99%)	10,666 (84%)	17,262 (89%)
Landing dimension	2,276 (65%)	2,499 (78%)	6,640 (83%)	11,415 (59%)

3.2 BASIC CHARACTERIZATION OF A DIGITAL INCLINOMETER

3.2.1 Manufacturer Accuracy Testing

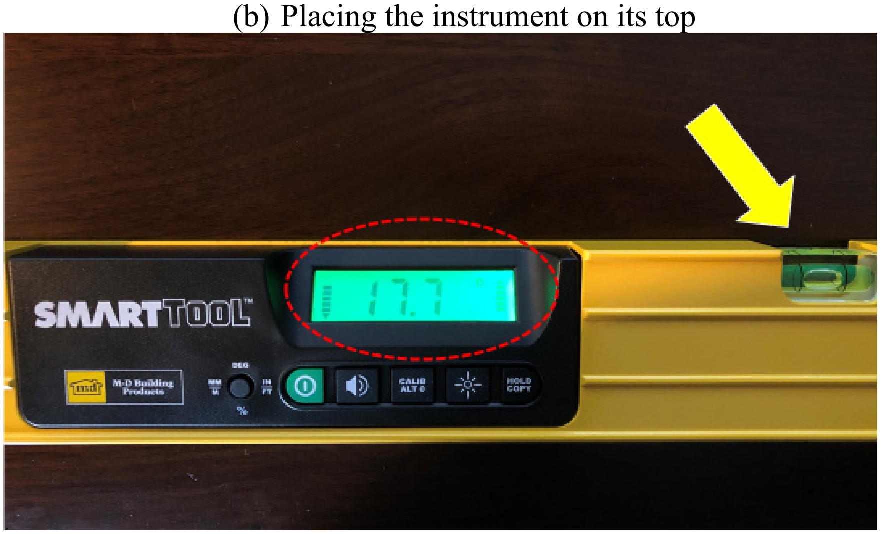
To evaluate and report the accuracy of the SmartTool digital inclinometer (Gen2 and Gen3), the manufacturer performs a series of rigorous laboratory tests. The tests are conducted at temperatures of 14°F, 75°F, and 122°F (or -10°C, 24°C, and 50°C) to validate the performance of their products under different environmental conditions. For this test, they set up a board that can be rotated to a given angle precisely and fix it in place with the smart level mounted at that orientation for a measurement. The board is rotated a full 360° both clockwise and counterclockwise at a distinct interval (2.8125°). The tests result in hundreds of smart level readings under different circumstances to compare against the ground truth. The accuracy of the SmartTool digital inclinometer (Gen2 and Gen3) is reported as 0.1° at level (plumb) and 0.2° at other angles. In practice, to achieve the accuracy in the specification, the smart level needs to be calibrated properly to account for different situations. For example, the tool needs to be recalibrated if it is dropped or the temperature is more than 20°F (11°C) different from the latest calibration.

3.2.2 Instrument Orientation

The smart level device is also sensitive to the orientation at which it is placed on the surface. It should be operated by attaching its top or bottom side to the surface to be measured. Although it is convenient to place it on its back for readability, this orientation results in invalid readings. Figure 3.1 shows examples of measurements taken on the top, bottom, and back. When placed on its back, the device displays an invalid measurement, despite the physical bubble indicating that it is level.

(a) Placing the instrument on its bottom

(b) Placing the instrument on its top



(c) Placing the instrument on its back

Figure 3.1: Valid measurements can be acquired by placing the smart level on its bottom and top while placing it on its back provides invalid readings.

3.2.3 Instrument Tilting

To further investigate the impact of tilting the smart level at smaller angles more reflective of curb ramps, the research team designed and conducted a simple test for a 2-ft (60-cm) SmartTool digital inclinometer (hereinafter referred to as smart level). A smart level was placed on a board that can be tilted to a large range of angles. To measure the exact tilting angle of the smart level, a smaller, but more precise digital inclinometer (DANIU DXL360S) was placed perpendicular to the smart level (Figure 3.2). The DXL360S is less than 3 in (8 cm) long and the slope measurement from has an accuracy of 0.05° and a resolution of 0.01°.

The tilting angle ranged from 0% to 20% approximately. The testing results show that there is no significant error in the smart level reading in such range (Table 3.2). The absolute variation of the smart level readings was within 0.1% which was on par with the precision of the equipment. Thus, as long as the smart level is operated properly, the tilt caused by the sloped surface should not affect the accuracy of the slope readings for slopes less than 20°.

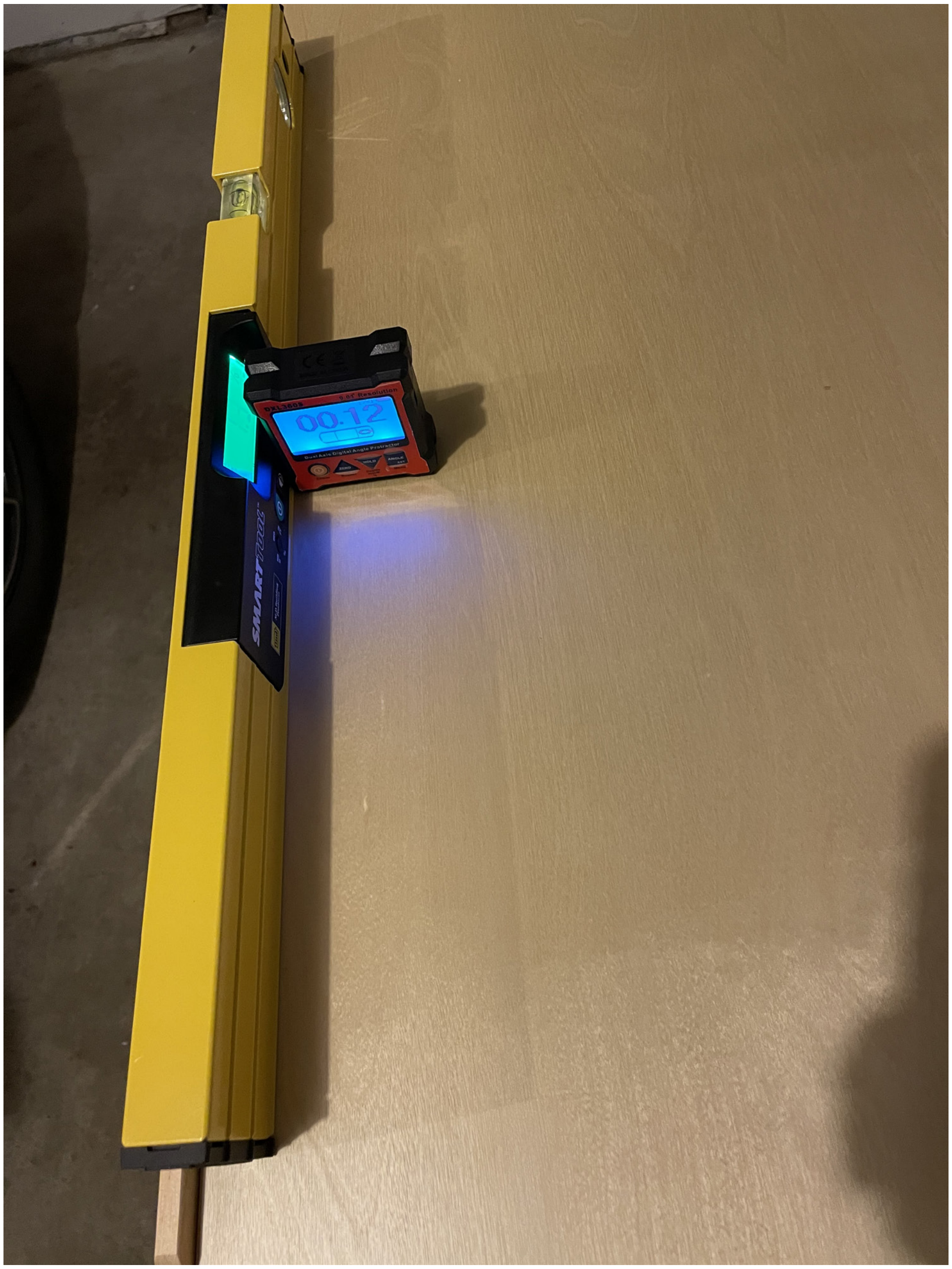


Figure 3.2: Example test setup with the smart level and high precision digital inclinometer.

Table 3.2: Stability Of Smart Level Readings With Different Tilt Angles On The Perpendicular Axis.

Tilt Angle (%slope)	Smart Level Reading (%slope)
0.10	1.3
2.16	1.3
4.33	1.3
6.16	1.4
8.30	1.4
10.17	1.4
11.76	1.4
14.51	1.4
16.01	1.4
17.21	1.3
18.53	1.4
20.43	1.4

3.2.4 Scale of Flatness, Smoothness and Roughness

Based on the summary provided in the literature review, it can be seen the measuring scale and sampling interval are critical in defining a metric that can reliably evaluate the flatness, smoothness, and roughness of a surface. To measure the slope on a curb ramp, a digital inclinometer or smart level is commonly used. Because the smart levels have different size options (e.g., 1 ft, 2 ft, 4 ft, or 30 cm, 60 cm, 120 cm), the slope is actually measured from different scales. This can cause some discrepancies in slope measurement where a shorter smart level can capture more detailed information (e.g., roughness) of a slope whereas the longer one can yield a more representative slope measurement. For example, in a test conducted by the research team, a 2-ft (60-cm) smart level was placed on a board which is visually flat, meaning there is no gap observable below the bottom of the smart level (Figure 3.3).

Figure 3.3: Example setup with a smart level and smaller digital inclinometer.

Then the research team used a smaller digital inclinometer, DXL360S, to measure the same surface in the same direction but at different positions. The test resulted in 8 readings of the smart level at the same position whereas the smaller digital inclinometer measured the same slope from 8 different positions. Table 3.3 shows the comparison between the readings from different digital inclinometers where the position refers to the distance from the DXL360S to the left end of the slope in Figure 3.3. It can be seen that with a smaller scale, the slope measurement has more variation. Thus, depending on the specified scale of computing flatness, smoothness, and roughness, the equipment should be chosen based on its accuracy, precision, and dimension.

Table 3.3: Comparison Of Smart Level And DXL360S Slope Readings At Different Locations Along The Table.

Position of DXL360S		DXL360S (%slope)	Smart Level Reading (%slope)
in	cm		
0	0	1.13	1.0
3	8	1.16	1.1
6	15	1.04	1.1
9	23	0.94	1.1
12	30	0.83	1.1
15	38	0.66	1.1
18	46	0.57	1.0
21	53	0.48	1.0

3.3 CALIBRATION OF DIGITAL INCLINOMETERS

The SmartTool® digital inclinometer needs to be calibrated to achieve the accuracy reported in the specification. To calibrate a smart level, the following steps need to be followed:

1. Place the smart level on a flat surface close to level with the screen facing the user, and press and hold the "calibrate" button until "Cal 1" shows on the display.

2. Turn the smart level 180° horizontally to make the back of the instrument face the user, and press and hold the "calibrate" button until "Cal 2" shows on the display.

3. Place the smart level upside down and let the screen face the user, and press and hold the "calibrate" button until "Cal 3" shows on the display.

4. Turn the smart level 180° horizontally to make the back of the instrument face the user, and press and hold the "calibrate" button until "Cal 4" shows on the display.

5. Then follow the similar steps (step 1 – 4) to calibrate the smart level on a vertical surface for the plumb measurement. However, vertical surfaces are beyond the scope of this report.

It is worth noting that given the smart level needs to be re-calibrated with a temperature variation or shock and the information about the most recent calibration cannot be retrieved on the instrument. In practice, it is recommended to perform calibration before a project.

3.4 DIRECT AND REVERSE MEASUREMENT

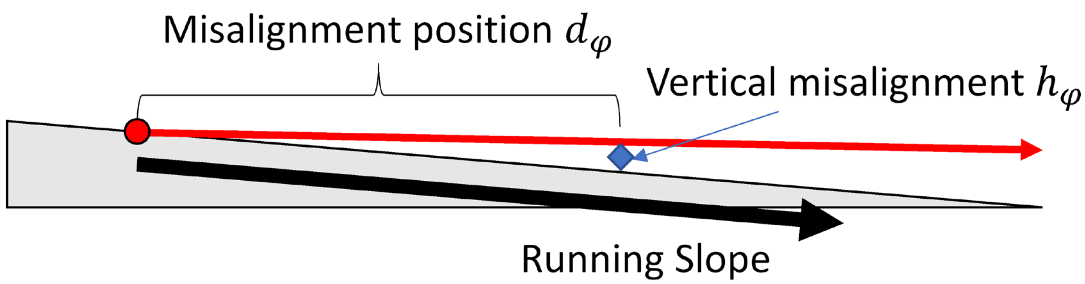
A common surveying procedure is to perform both direct and reverse measurement to eliminate some systematic errors. The core concept is that a bias in the measurement in the direct orientation should be nearly equal but opposite in sign in the reverse orientation and thus would cancel out when the two measurements are averaged. A similar practice can also be used in slope measurement with the smart level. The instrument can be placed to measure the target slope followed by turning it 180° horizontally and average these two readings. In principle, the calibration should eliminate such systematic errors and the direct and reverse measurements can yield the same readings. The research team tested a calibrated smart level on a surface with various slopes and recorded both direct and reverse readings (Table 3.4). The result shows that there are still some discrepancies between the direct and reverse readings. Because the difference between the direct and reverse measurements are within 0.2%, which is on par with the accuracy of the smart level, these discrepancies are likely caused by the residuals of the calibration as well as the precision of the sensors. Hence, obtaining a direct and reverse measurement would be a good practice to reduce these systematic errors as well as provide a check.

Table 3.4: Comparison Of Direct, Reverse And Average Slopes Measured With The Smart Level.

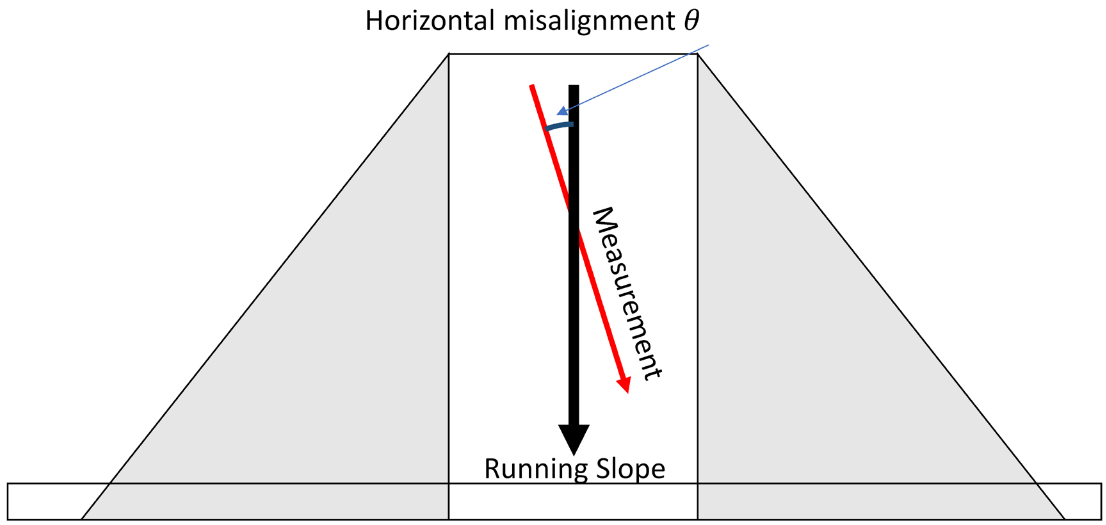
Smart level direct (%slope)	Smart level reverse (%slope)	Average (%slope)
0.0	0.0	0.0
2.2	2.0	2.1
3.9	3.8	3.9
6.1	6.1	6.1
8.3	8.1	8.2
10.3	10.3	10.3
12.1	12.0	12.1

3.5 MISALIGNMENT ERRORS

In addition to the precision of the instrument, errors can also be introduced from the operation and how the instrument is oriented when placed on the surface. First of all, the instrument needs to be attached to the surface to be inspected for measuring the slope. However, sometimes small debris and other objects may be present that might be under the digital inclinometer during the observation. This can cause the misalignment between the instrument and the surface in the vertical direction (Figure 3.4). Secondly, in ADAAG, all the slope requirements are associated with directions. For example, the running slope is the slope along the travel direction while the cross slope is measured perpendicular to the running slope. While these are straightforward to identify in a schematic, the exact direction and location can be difficult to precisely locate in the field when placing the smart level. When there is no clear indication of the precise direction of a slope to measure, there can be errors in the horizontal alignment (Figure 3.4). The research team modeled these two types of errors and investigated the impact of each type of error on the slope measurement under different scenarios.



(a) Example of vertical misalignment



(b) Example of horizontal alignment

Figure 3.4: Schematic to show example situations of vertical and horizontal misalignment.

3.5.1 Vertical Misalignments

To model the error of slope measurement caused by vertical misalignment of the instrument, two variables need to be considered, the vertical misalignment height h_φ and the misalignment position d_φ. Assuming there is an object under the instrument, h_φ would be the height of this object while d_φ represents the horizontal distance from this object to one end of the digital inclinometer that is attached to the slope surface. The error (σ_φ) caused by such vertical misalignment in percentage slope follows the equation below:

$$\boldsymbol{\sigma_\varphi = \pm \frac{h_\varphi}{d_\varphi}}$$

(3-1)

The correlations between h_φ, d_φ, and σ_φ are shown in Figure 3.5 and Figure 3-6. When the debris or other objects are larger or closer to the end point of the smart level, the measurement error increases. Notably, a longer smart level has the advantage in terms of mitigating vertical misalignment. Additionally, it is also worth noting that d_φ should be longer than half of the length of the smart level such that it can be stably placed on the surface. A key practical consideration based on ADAAG is that the truncated domes on the detectable warnings are specified as 0.2 in (5 mm) and trip hazards are defined as a change in height over 0.25 in (6 mm) The measurement errors with such vertical displacement are significant and exceed the tolerances for design and construction. Thus, it is necessary to avoid placing the instrument partially on the truncated domes or other objects.

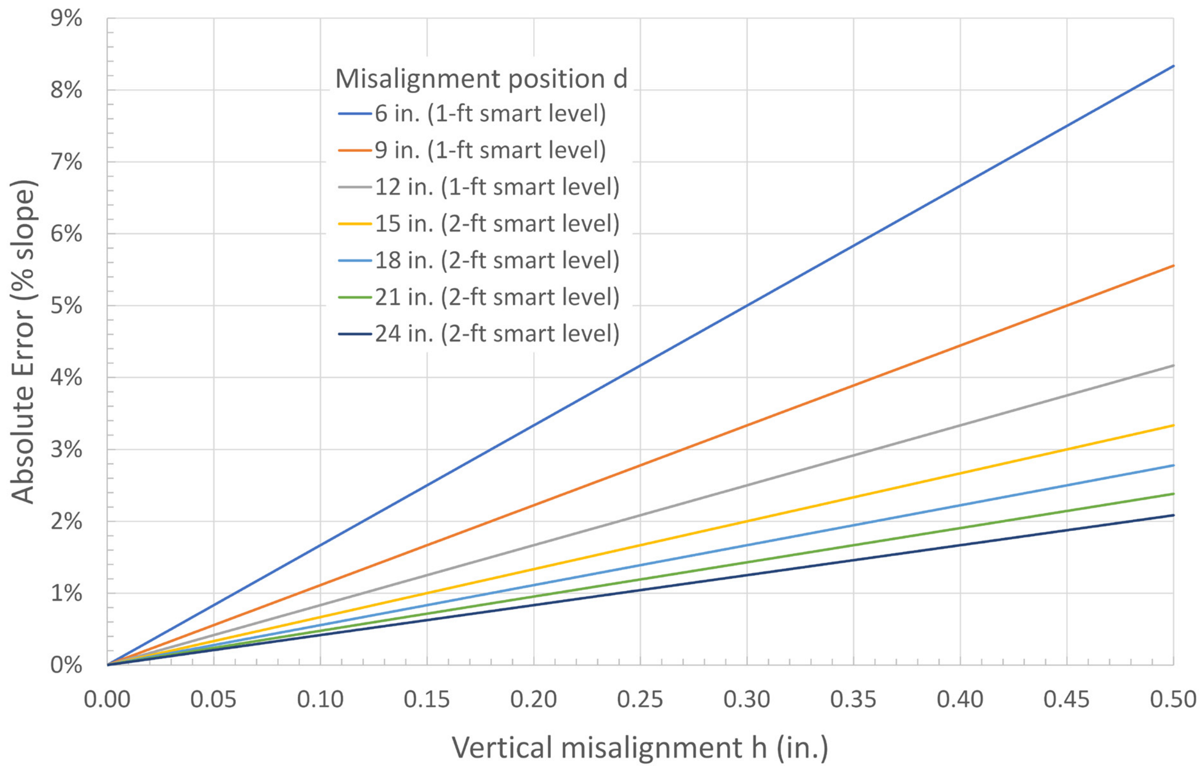


Figure 3.5: Correlation between vertical misalignment and absolute error in the slope measurement.

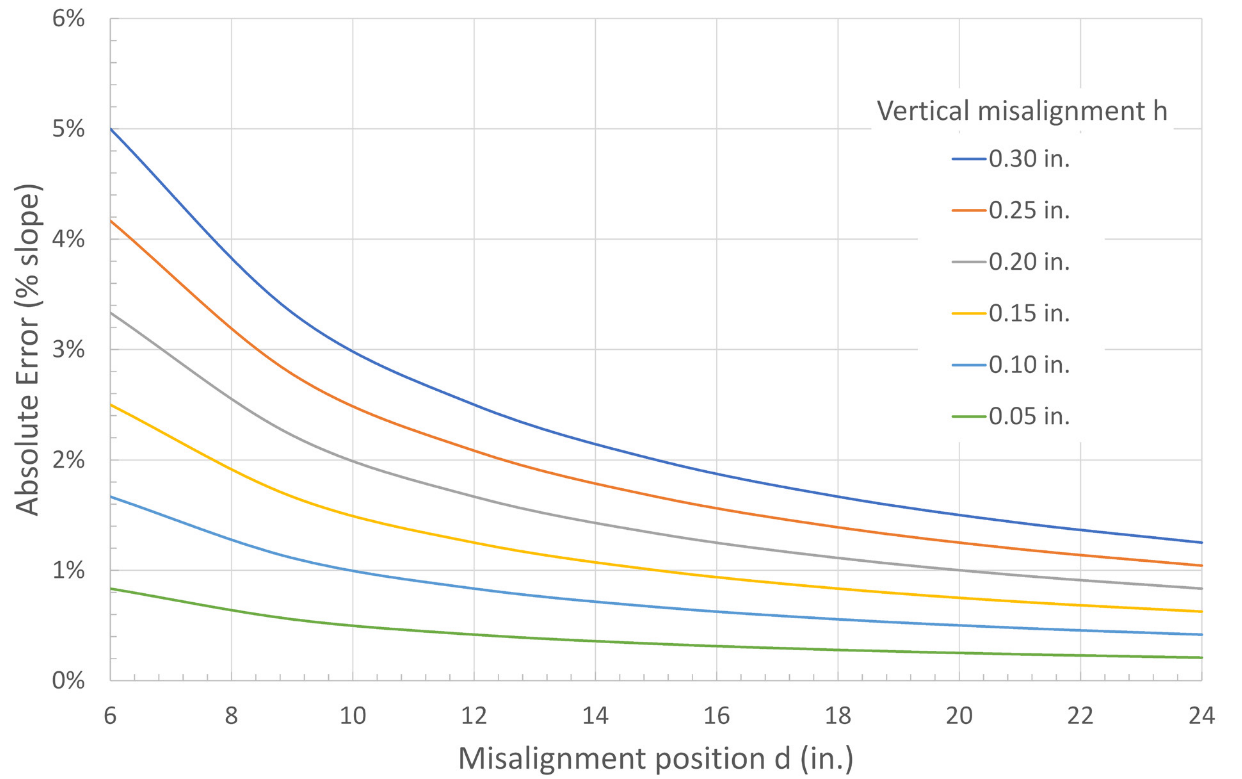


Figure 3.6: Correlation between vertical misalignment position and absolute error in slope measurement.

3.5.2 Horizontal Misalignments

Modeling errors caused by horizontal misalignment σ_θ are more complicated. In addition to the horizontal misalignment, θ, the running slope α_r (% slope) and cross slope α_c (% slope) of the curb ramp need to be considered. The errors also depend on whether the running slope or the cross slope is the target slope to be surveyed. First, we define the coordinate system for a curb ramp where y-axis is pointing down-hill along with the travel direction and the z-axis is pointing up. Given the running slope and cross slope of the curb ramp, the vectors of the running slope $\boldsymbol{V_r}$ and cross slope $\boldsymbol{V_c}$ can be computed:

$$\boldsymbol{V_r} = \begin{bmatrix} \mathbf{0} \\ \mathbf{cos(tan^{-1}}\,\boldsymbol{\alpha_r}) \\ \mathbf{sin(tan^{-1}}\,\boldsymbol{\alpha_r}) \end{bmatrix} \tag{3-2}$$

$$\boldsymbol{V_c} = \begin{bmatrix} \mathbf{cos(tan^{-1}}\,\boldsymbol{\alpha_c}) \\ \mathbf{0} \\ -\mathbf{sin(tan^{-1}}\,\boldsymbol{\alpha_c}) \end{bmatrix} \tag{3-3}$$

Then the surface of the curb ramp can be defined as a plane where the normal vector $\boldsymbol{N}$ can be obtained by computing the cross product of $\boldsymbol{V_c}$ and $\boldsymbol{V_r}$:

$$\boldsymbol{N} = \boldsymbol{V_c} \times \boldsymbol{V_r} = \begin{bmatrix} \cos(\tan^{-1}\alpha_r)\cdot\sin(\tan^{-1}\alpha_c) \\ -\cos(\tan^{-1}\alpha_c)\cdot\sin(\tan^{-1}\alpha_r) \\ \cos(\tan^{-1}\alpha_c)\cdot\cos(\tan^{-1}\alpha_r) \end{bmatrix}$$

(3-4)

Assuming the measurement takes place on the slope surface, the actual measuring vector $\boldsymbol{M}$ for a cross slope with a horizontal misalignment θ can be derived as:

$$\boldsymbol{M} = \begin{bmatrix} \cos(\theta) \\ \sin(\theta) \\ \dfrac{\sin(\theta)\cdot\cos(\tan^{-1}\alpha_c)\cdot\sin(\tan^{-1}\alpha_r) - \cos(\theta)\cdot\cos(\tan^{-1}\alpha_r)\cdot\sin(\tan^{-1}\alpha_c)}{\cos(\tan^{-1}\alpha_c)\cdot\cos(\tan^{-1}\alpha_r)} \end{bmatrix}$$

(3-5)

Then $\boldsymbol{M}$ is normalized to unit vector $\widehat{\boldsymbol{M}}$ and the error σ_θ can be computed:

$$\sigma_\theta = \left|\tan\left(\sin^{-1}\left(\begin{bmatrix}0 & 0 & 1\end{bmatrix}\cdot\widehat{\boldsymbol{M}}\right)\right)\right| - \alpha_c$$

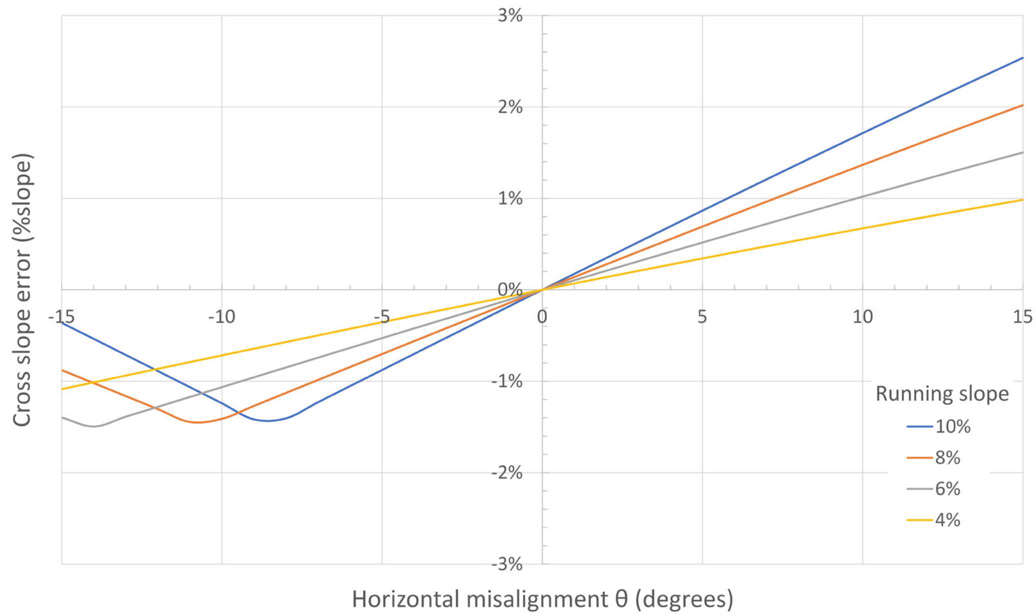
(3-6)

Similarly, the theoretical errors caused by horizontal misalignment for a running slope can be calculated as:

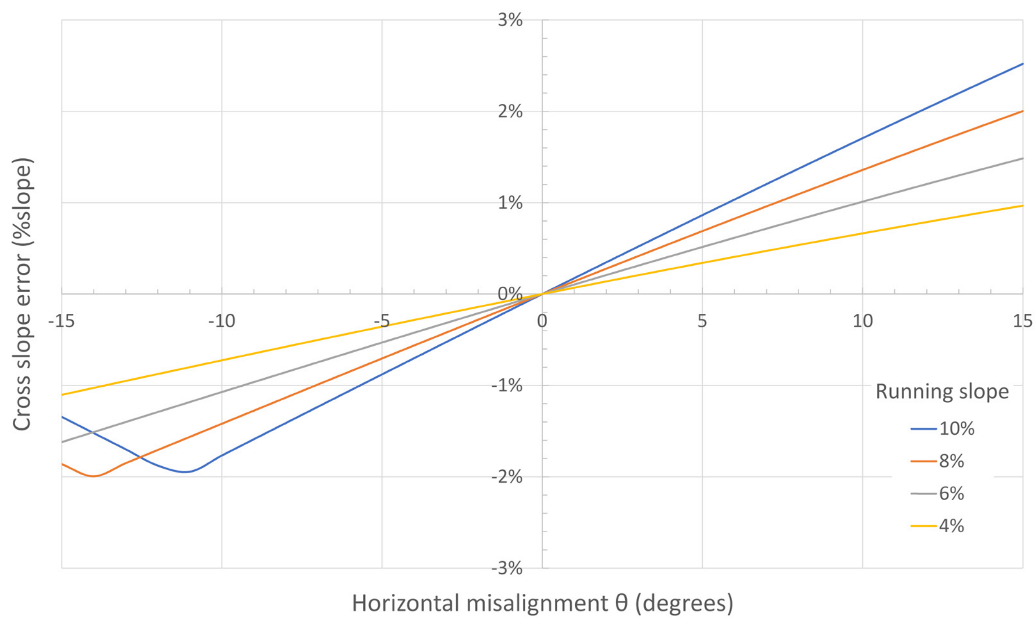
$$\sigma_\theta = \left|\tan\left(\sin^{-1}\left(\begin{bmatrix}0 & 0 & 1\end{bmatrix}\cdot\widehat{\boldsymbol{M}}\right)\right)\right| - \alpha_r$$

(3-7)

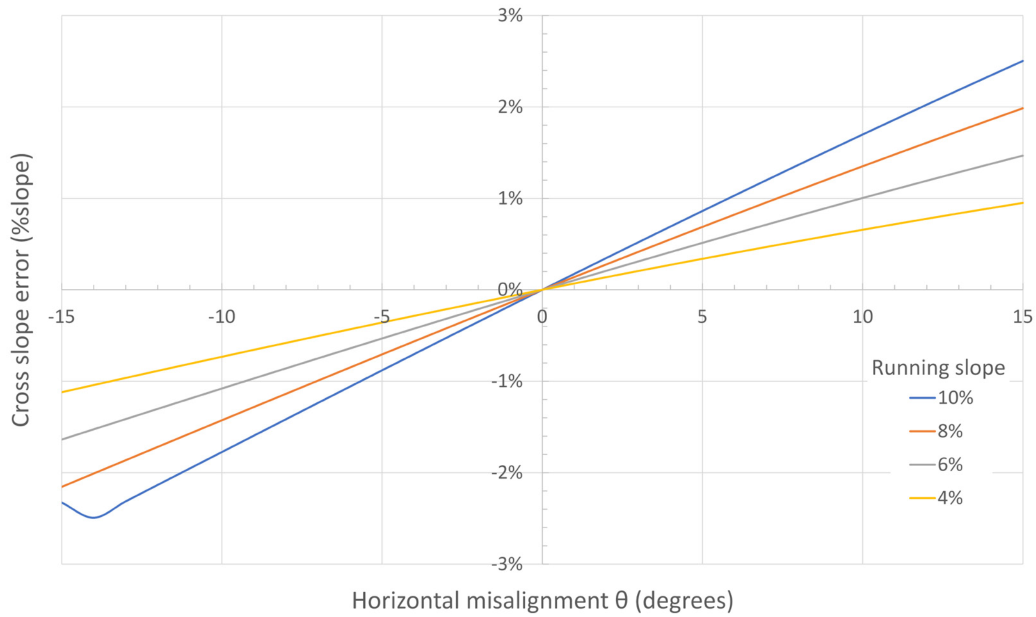
The correlation between the horizontal misalignment and slope measurement errors for cross slope and running slope under different combinations are shown in Figure 3.7 and Figure 3.8, respectively. In general, the impact of horizontal misalignment on running slope is less than on cross slope. Additionally, a larger difference between running slope and cross slope is more likely leading to a significant error caused by horizontal misalignment.



(a) Cross slope = 1.5%

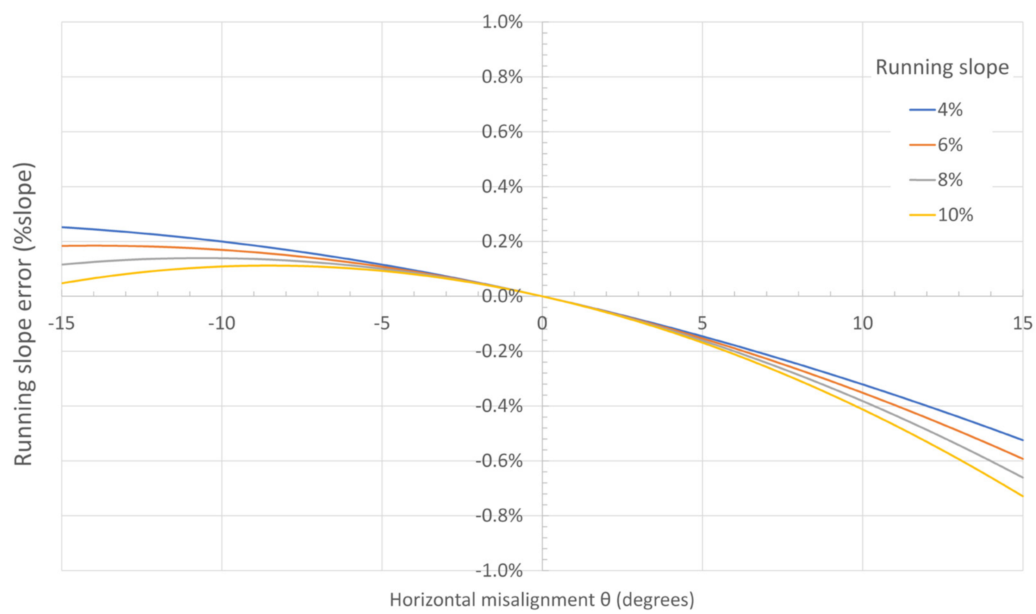


(b) Cross slope = 2.0%

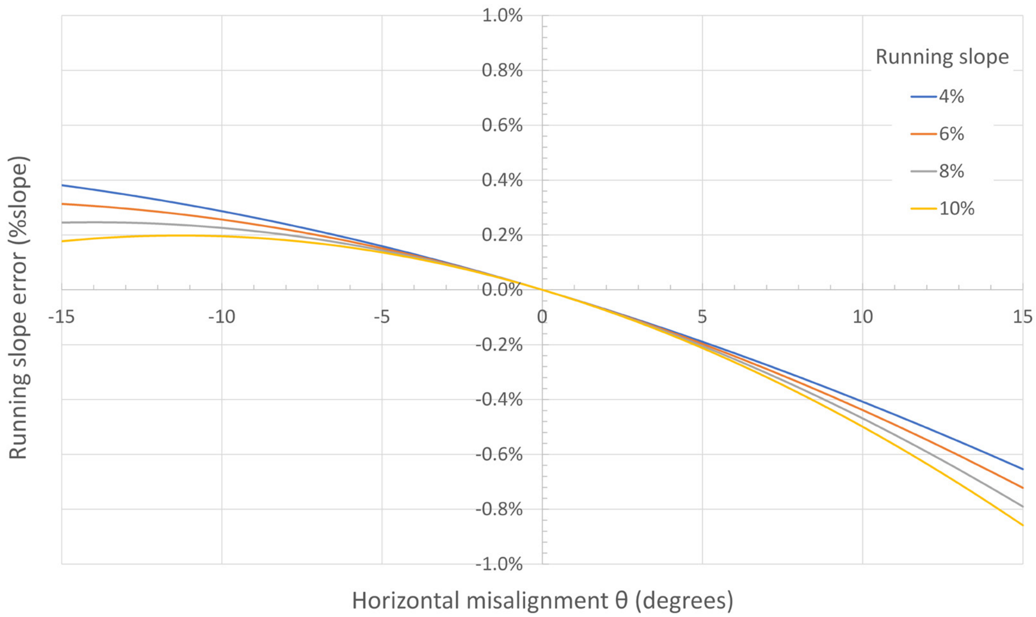


(c) Cross slope = 2.5%

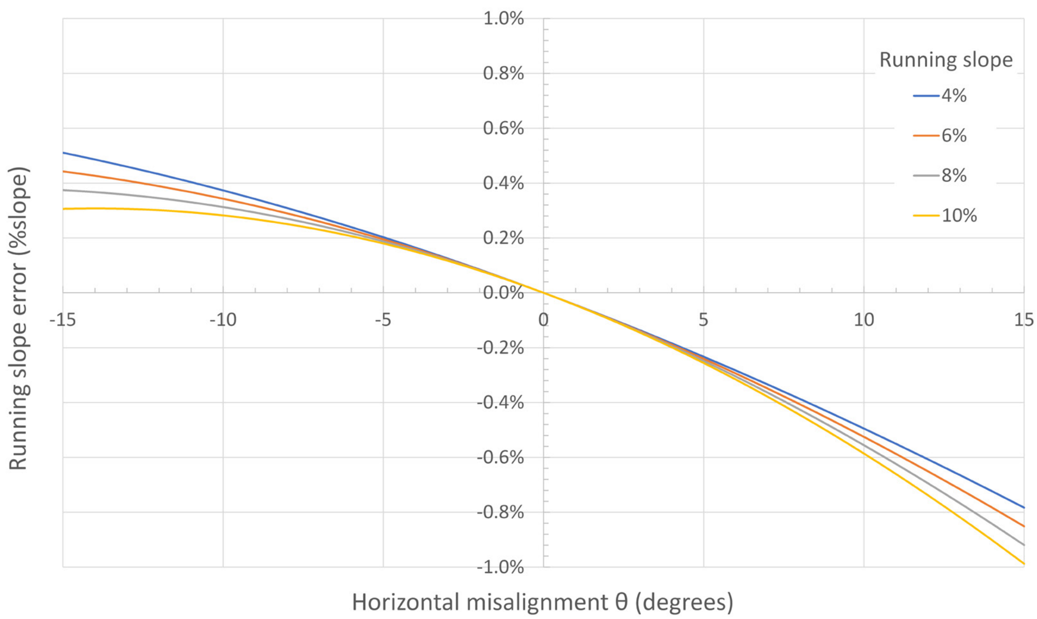
Figure 3.7: Correlation between horizontal misalignment and cross slope error.



(a) Cross slope = 1.5%



(b) Cross slope = 2.0%



(c) Cross slope = 2.5%

Figure 3.8: Correlation between horizontal misalignment and running slope error.

3.6 REPEAT MEASUREMENT ACCURACY IMPROVEMENTS

Repeated measurement is a common approach to reduce random errors as well as blunders in survey (Ghilani, 2017). Regarding the blunders, repeated measurement provides redundancies that can help detect blunders in the observations resulting in a more robust measurement. The random errors can come from the precision of the instrument, as well as other sources (e.g., misalignment for the slope measurement in previous sections). Taking the precision of the instrument as an example, the precision of the smart level is ±0.1° (0.2%) for level and plumb and ±0.2° (0.3%) for other angles. In other words, the error is within ±0.2% or ±0.3% for a single slope measurement. To improve the accuracy of the slope measurement, one can make repeating observations and take the average value. Because all the observations can be considered independent to each other, the standard deviation of the average can be computed with the following equation.

$$\boldsymbol{S} = \pm\frac{\boldsymbol{\sigma}}{\sqrt{\boldsymbol{n}}}$$

(3-8)

where S is the standard deviation (i.e., precision) of the average slope, σ is the precision for each observation, and n is the number of observations. With an increasing number of observations, the standard deviation of the average follows the trend in Figure 3.9. Despite that the accuracy of the slope measurement can keep being improved with more observations, given the resolution of smart level readings is 0.1%, in theory, an accuracy of 0.1% slope measurement can be achieved by taking average value from 2 observations for level or plumb and 5 observations for other angles. When the number of observations reach 17 and 37, the accuracy of the slope measurement can be higher than 0.1%.

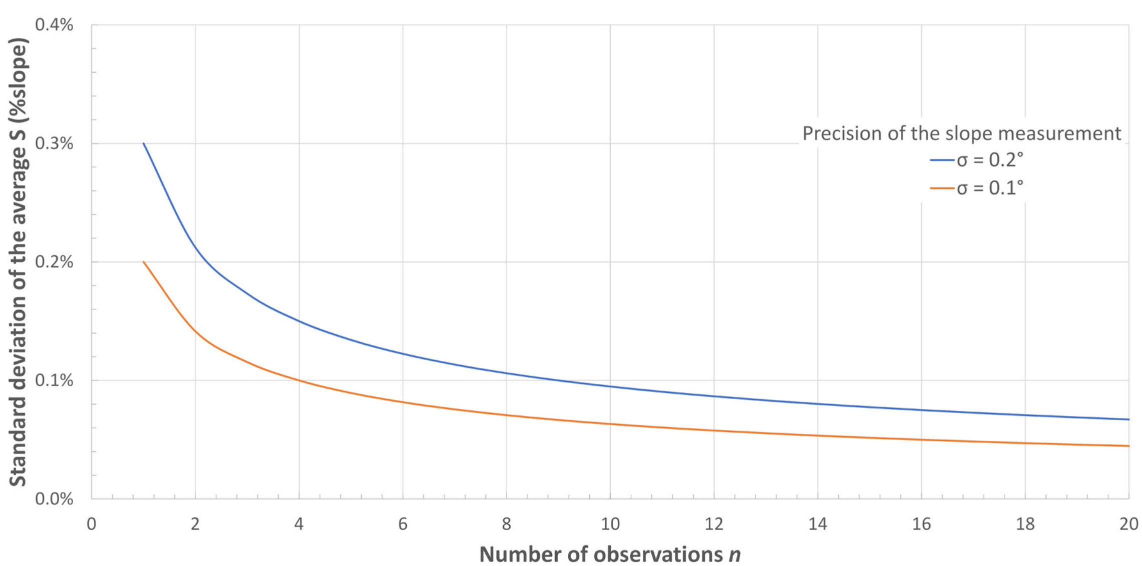


Figure 3.9: Theoretical accuracy improvement based on measurement repetition.

The research team further tested the repeatability of the smart level (Table 3.5). The surface slope was set at approximately 0%, 2%, 4%, 6%, 8%, and 10%, and 10 measurements were made for each slope. The result showed that the smart level was very precise given the standard deviation was less than 0.1% for all the slope settings.

Table 3.5: Repeatability Measurements And Summary Statistics Of Measuring Slope Of Surfaces Sloped Nominally From 0-10%.

Reading ID	Smart level reading (%slope)						
1	0.2	2.1	4.0	6.0	8.0	10.1	12.1
2	0.2	2.1	4.0	6.0	8.0	10.2	12.1
3	0.2	2.1	4.0	6.0	8.0	10.2	12.1
4	0.2	2.2	4.0	6.1	8.0	10.2	12.1
5	0.2	2.2	4.0	6.0	8.1	10.2	12.1
6	0.2	2.2	4.0	6.1	8.0	10.2	12.1
7	0.2	2.2	4.0	6.0	8.0	10.2	12.1
8	0.2	2.2	4.0	6.0	8.0	10.2	12.1
9	0.2	2.2	4.0	6.0	8.0	10.2	12.1
10	0.2	2.2	4.0	6.1	8.0	10.2	12.1
Average	0.2	2.2	4.0	6.0	8.0	10.2	12.1
Standard deviation	0.00	0.05	0.00	0.05	0.03	0.03	0.00
Minimum	0.2	2.1	4.0	6.0	8.0	10.1	12.1
Maximum	0.2	2.2	4.0	6.1	8.1	10.2	12.1
Median	0.2	2.2	4.0	6.0	8.0	10.2	12.1

3.7 SUMMARY OF KEY FINDINGS

The highlights of the error analysis are summarized below:

1. The smart level can provide accurate slope measurements with its bottom or top attached to the surface. Laying it on its back will result in invalid readings.

2. The smart level needs to be calibrated before usage to meet its specifications.

3. Averaging direct and reverse readings of a smart level can eliminate some systematic errors.

4. Errors caused by horizontal and vertical misalignment of the equipment can be significant, particularly in context of assessing the ADA compliance of a curb ramp. The vertical misalignment (e.g., debris or bump) affects the slope measurement more substantially than the horizontal misalignment.

5. At least 5 repeated observations at the same spot can reduce the standard deviation of the average slope measurement performed with a smart level from 0.3% to 0.1%.

4.0 CALIBRATION TESTING

This section describes the work performed for testing and evaluating different tools and measurement methods for assessing the ADA compliance of curb ramps. The proposed testing sites, tools, and data acquisition procedures will be described in detail for each test.

4.1 OBJECTIVES

Calibration testing was first be implemented to rigorously evaluate the capabilities of the instruments as well as the variability with measurement methods to identify a subset of devices and methods to obtain measurements for a curb ramp compliance database. Specific objectives of the calibration testing include:

1. Evaluate the consistency between several devices such as smart levels (different sizes), total stations, laser scanners, and total stations in reliably measuring the slopes of a curb ramp for ADA compliance.

2. Assess the suitability of measurements extracted from the pointclouds collected from terrestrial laser scanners to serve as reference measurements.

3. Compare the direct and reverse observations of a smart level to assess the precision of its calibration, and

4. Compare different modes and quantities of measurements with a smart level to determine the most reliable approaches.

The tools that are used and evaluated in this test are summarized briefly, as follows (Table 4-1).

Table 4.1: Summary Of Equipment Used In The Calibration Testing.

Type of Equipment	Model	Roles in calibration test
Digital Level	Leica LS15	Verify the total station measurements
Total Station	Leica TS15P	Collect ground truth data for slope measurements.
Laser Scanners	Leica ScanStation P40, Leica BLK 360	Capture 3D geometric details on the curb ramp and be compared against total station survey for evaluation.
Smart Level	2-ft (60 cm) Smart level (Gen 3)	Measure the surface slope and be compared against total station survey for evaluation using different methods.

4.2 OVERVIEW OF THE FIELD DATA COLLECTION

The data collection for the calibration testing was performed on March 3rd, 2021. For this testing, two curb ramps were selected at the intersection between SW 14th and SW Campus Way at the Oregon State University Campus in Corvallis, OR (Figure 4.1).

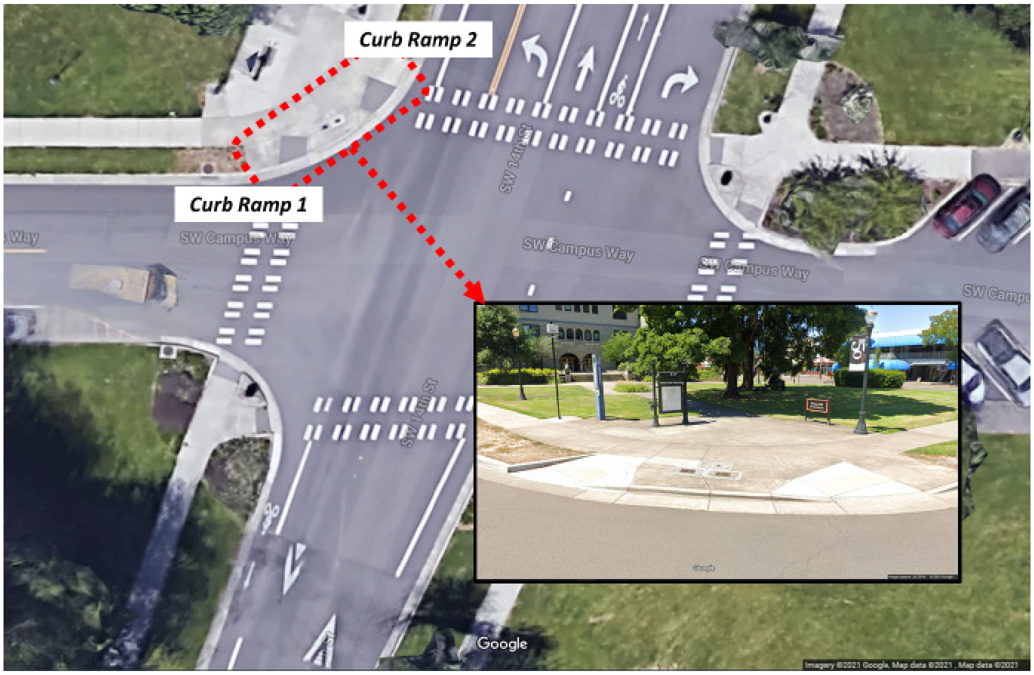


Figure 4.1: Overview of the area of interest for calibration.

4.2.1 Site Preparation

The research team first cleaned the surface of both curb ramps to remove dust, leaves, and other debris to eliminate potential noise and associated errors. Painter's tape was then applied to the curb ramps to mark the measurement locations of the smart level for measuring the running slope and cross slope (Figure 4.2). The marks were spaced at 1 ft (0.3 m) intervals with 2-ft (60 cm) strips of tape to match the size of the smart level. Further, because the widths of the painter's tape and smart level are similar, the direct and reverse observations could be aligned to the same orientation to reduce the errors caused by horizontal misalignment. There were 18 marks on Curb Ramp 1 and 25 marks on Curb Ramp 2, resulting in 36 and 50 survey points, respectively. It is worth noting that all of the marks cross the gaps between slabs. Next, the research team marked finely marked survey points on the tapes at both ends of each smart level, which facilitated the survey by the total station and the digital level to establish ground truth data.

4.2.2 Total Station and Leveling

After setting up these pre-marks of survey points, the total station data were collected with a Leica TS15P in conjunction with a Leica 360 prism. The prism was mounted on a prism pole supported by a bipod to reduce the centering and leveling errors (Figure 4.3). Once all of the survey points were acquired by the total station, we further surveyed a number of these points using a digital level (i.e., Leica LS15) to verify the vertical accuracy of the total station measurements. The research team also completed a full loop with the digital level survey to evaluate closure at the benchmark point used as the initial backsight. The elevation at the benchmark closed at 0.004 in. (0.1 mm).

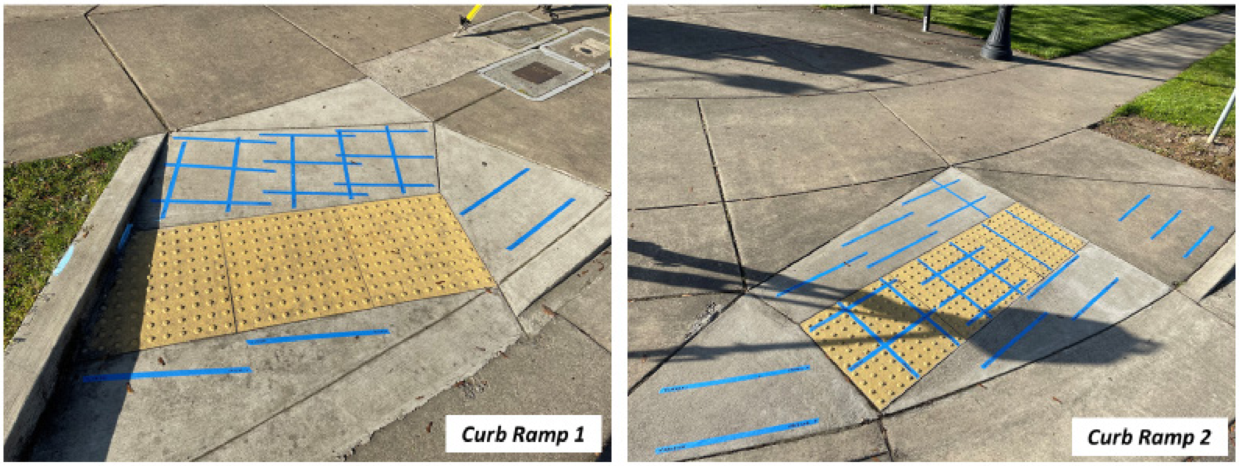


Figure 4.2: Grid marks for survey points and smart level measurements.

Figure 4.3: Total station measurement using Leica 360° prism with a bipod.

4.2.3 Terrestrial Laser Scanning

Two terrestrial laser scanners including the Leica Scanstation P40 and Leica BLK360 were used to collect data for each ramp. The Leica P40 scanner is a very high-quality system capable of high precision measurements. The BLK360 is a relatively inexpensive laser scanner (approximately $20,000 USD) with reasonable accuracy and quality. The research team set up the BLK360 scanner at the turning space of each slope while the P40 was set up on the sidewalk between the two ramps (Figure 4.4). To capture the targets setup in the field for post-processing, the horizontal field of view of both scanners was 360° and the angular resolutions were 0.029° and 0.038° for BLK360 and P40, respectively. Both scanners collected images with the 3D pointcloud data such that the pointclouds contain color information (Figure 4.5) to provide context to the measurements. The typical point spacing within the pointclouds collected by each scanner was less than 0.4 in (1 cm) across the curb ramps and surrounding area.

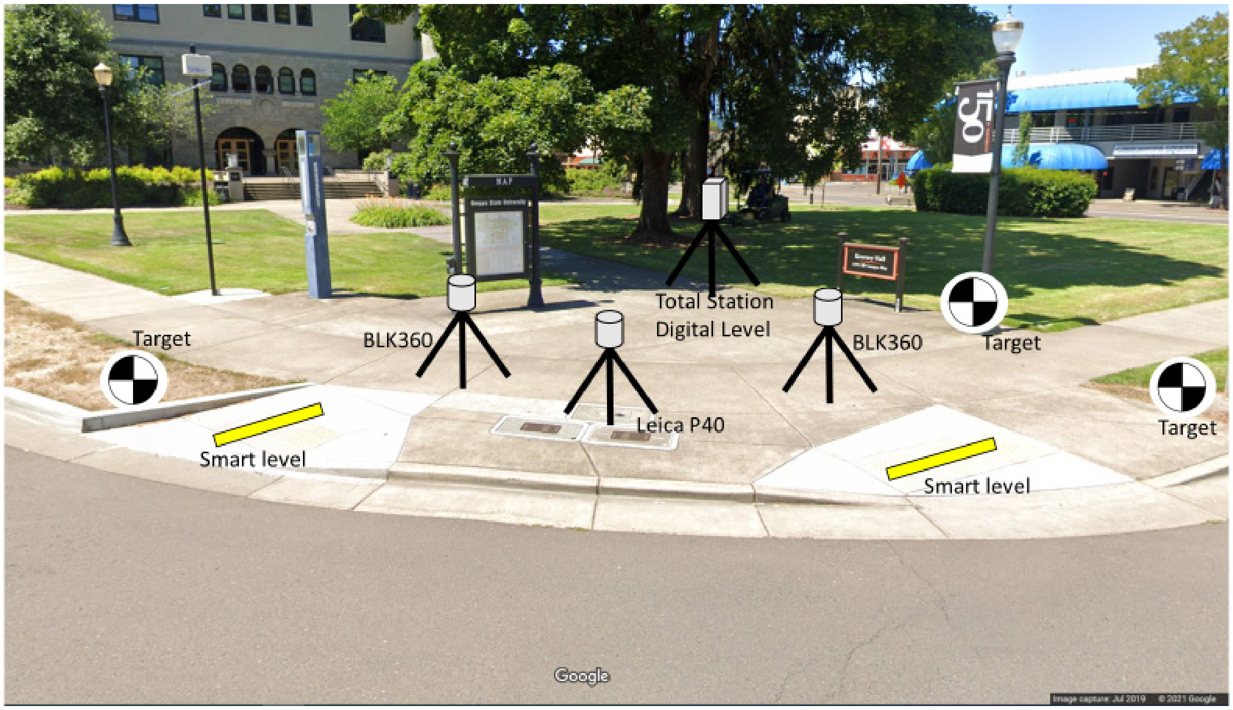


Figure 4.4: Layout of the instrument setup for data collection of the calibration testing.

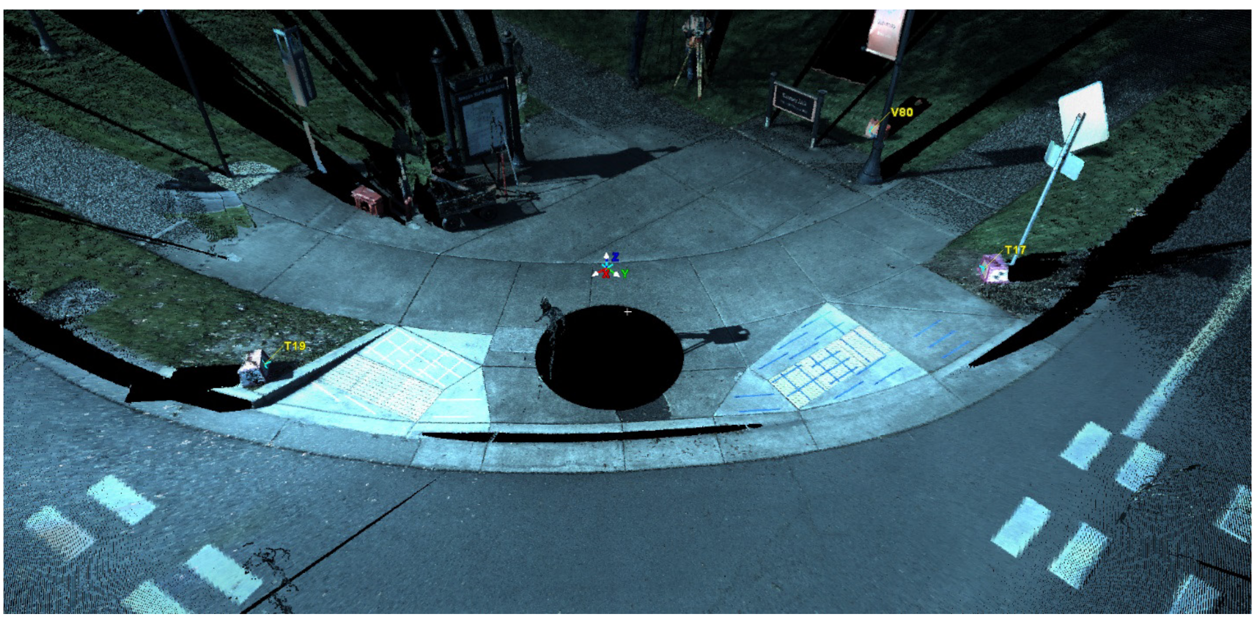


Figure 4.5: Example pointcloud collected with the Leica ScanStation P40.

4.2.4 Smart Level Measurements

A 2-ft (60 cm) smart level was used to collect data for all marks across both ramps. The smart level was calibrated before the field data collection following manufacturer protocols. The smart level was precisely positioned to align with a pre-marked location and left in place for a few seconds until the reading stabilized. After the reading was recorded, it was moved to the next mark to repeat the same procedure. Once all of the marks were measured, the field crew completed a second round of measurements with the smart level facing the opposite direction, which is referred to as a reverse observation in this report. The reason for avoiding a direct observation from being immediately followed by its reverse observation is to ensure that all the readings are independent.

4.3 DATA PROCESSING

The dataset collected for this calibration testing was processed in a local coordinate system defined by the total station setup. The data from digital level and smart level can be registered to the total station data via the point ID. The terrestrial laser scanning data was imported into Leica Cyclone 2020 software with the total station data. The scans were registered via the targets in conjunction with cloud-to-cloud registration, and the residuals of the targets were used to assess the accuracy of the registration as a quality check (Table 4.2). There is a total of 18 target pairs included in the registration. The 3D root-mean-squared-error (RMSE) is under 0.1 in. (3 mm) while the accuracy at 95% confidence level (CL) is under 0.2 in. (5 mm). The registration was also evaluated qualitatively by visualizing the registered pointclouds with the total station survey points to evaluate if clear biases were present in the results (Figure 4.6). In the registration, the scans were constrained to be level based on the device level compensator (P40) or inclination sensor (BLK360). This way the leveling bias of the system could be considered when it is used as a standalone device without a control survey with a total station or other device.

Table 4.2: Statistical Summary Of Pointcloud Registration For Terrestrial Laser Scanning Data (N = 18).

	Vertical Error	Horizontal Error	3D Error
Mean	0.0000 m	0.0010 m	0.0021 m
Standard Deviation	0.0024 m	0.0005 m	0.0014 m
Minimum	-0.0040 m	0.0000 m	0.0004 m
Maximum	0.0042 m	0.0019 m	0.0046 m
Median	0.0000 m	0.0010 m	0.0017 m
RMSE	0.0024 m	0.0011 m	0.0026 m
Accuracy @ 95% CL	0.0050 m	0.0025 m	0.0058 m

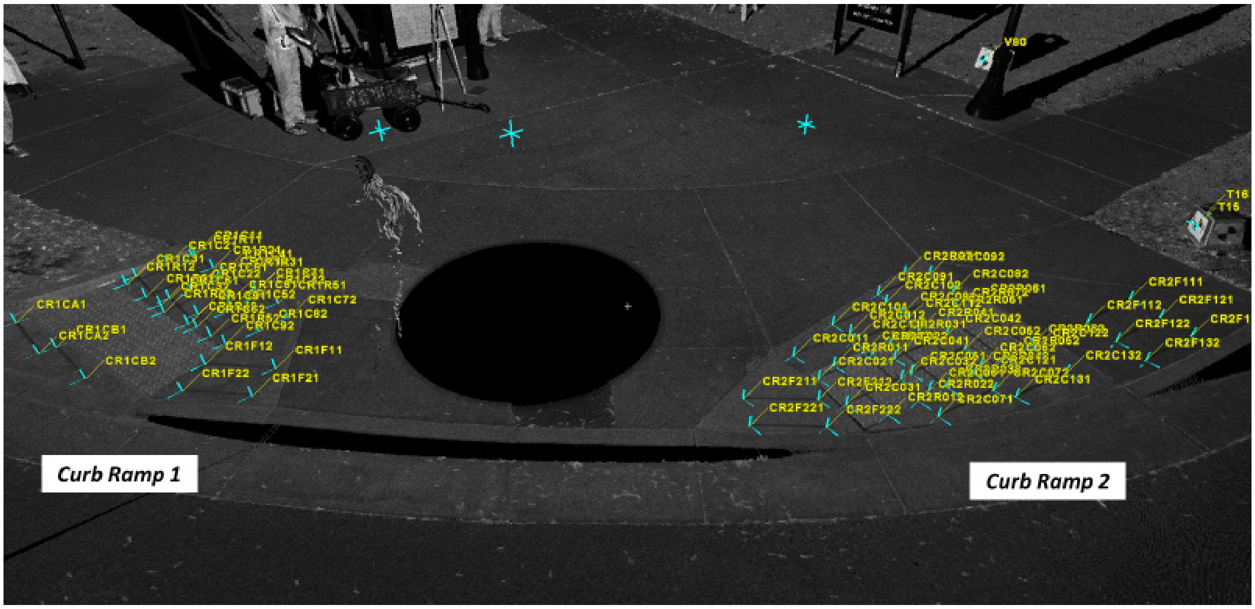


Figure 4.6: Example of the registered pointclouds and total station measurements.

4.4 VALIDATION OF TOTAL STATION MEASUREMENTS

To validate the relative accuracy of the total station measurements, the total station observations were compared against elevations measured by a survey-grade digital level (Leica LS15) with sub-mm measurement precision. Because this project focuses on the slope measurement, the differences in elevation, dH, between two ends of each mark were calculated and compared (Table 4.3). The statistical summary shows that the accuracy at 95% confidence level is close to 0.03 in. (0.7 mm). Hence, it can be concluded that the accuracy of the total station measurement is sufficient to serve as ground truth to assess the accuracy of the terrestrial laser scanning and smart level data.

Table 4.3: Comparison Between Total Station And Digital Level Measurements.

PID1	PID2	Total Station (m)	Survey Grade Digital Level (m)	Error (m)
		dH	dH	
CR1C51	**CR1C52**	-0.0209	-0.0212	0.0003
CR1CB1	**CR1CB2**	-0.0115	-0.0116	0.0001
CR1F11	**CR1F12**	-0.0265	-0.0268	0.0003
CR1R31	**CR1R32**	-0.0387	-0.0380	-0.0007
CR2C051	**CR2C052**	0.0007	0.0004	0.0003
CR2C071	**CR2C072**	0.0010	0.0014	-0.0004
CR2C111	**CR2C112**	0.0016	0.0019	-0.0002
CR2F121	**CR2F122**	-0.0338	-0.0332	-0.0006
CR2F211	**CR2F212**	-0.0340	-0.0339	-0.0001
CR2R071	**CR2R072**	-0.0396	-0.0394	-0.0002

Table 4.4: Statistical Summary Of Accuracy Assessment For Total Station Measurements.

Parameter	Value
Mean	-0.0001 m
Standard Deviation	0.0004 m
Minimum	-0.0007 m
Maximum	0.0003 m
Median	-0.0001 m
RMSE	0.0004 m
Accuracy @ 95% CL	0.0008 m

4.5 ACCURACY ASSESSMENT OF TLS DATA

The pointclouds collected by terrestrial laser scanners have a very high point density and were registered to the total station measurements with a high accuracy (a few millimeters). An open-source software, CloudCompare, was utilized to compute the nearest distance from each total station measurement to the pointcloud acquired by each scanner (Table B.0-1 and Table B.0-2 for the Leica BLK360, and Table B.0-4 for the Leica P40). A statistical analysis was then performed on each scanner and curb ramp where Curb Ramp 1 and Curb Ramp 2 contain 36 and 50 survey points, respectively. First, the blunders need to be removed based on the errors. One set of measurements (“CR2F121” and “CR2F122”) in total was excluded from the statistical summary of the BLK360 data capturing Curb Ramp 2 due to the high error of about 0.4 in. (0.01

m). The high error value of this particular point is caused by low point density due to occlusions in the scan (Figure 4.7), leading to incorrect values when compared against the nearest neighbor.

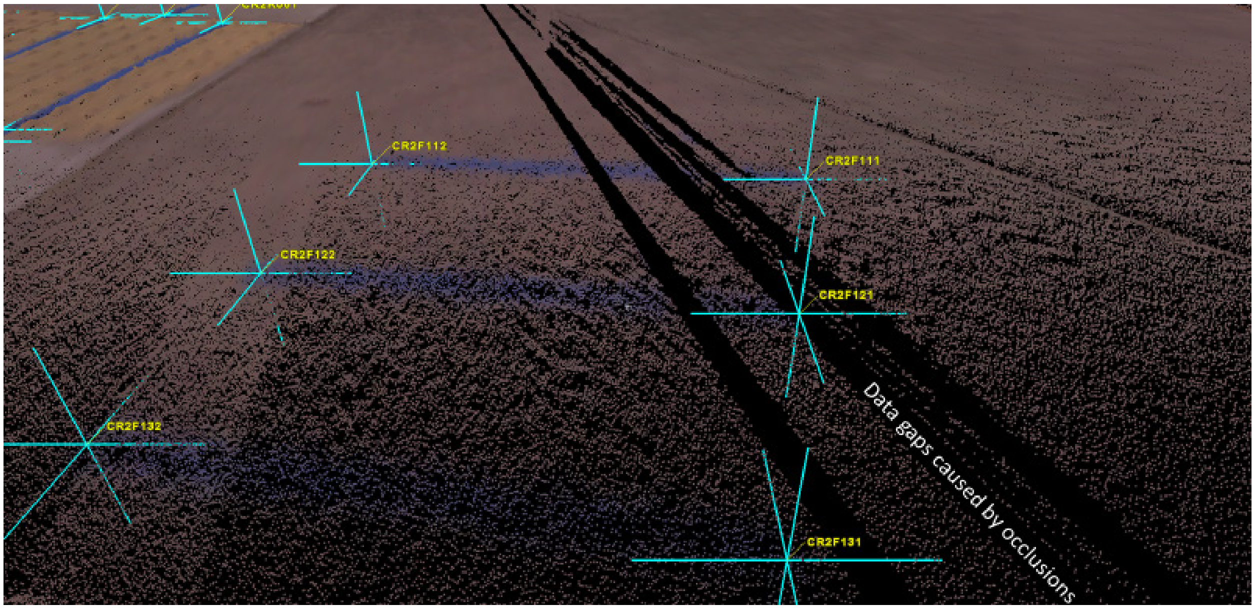


Figure 4.7: Example of data gaps due to occlusions resulting in measurement errors.

Table 4.5: Statistical Summary For The Leica BLK360 In Capturing Curb Ramps With Single Points Extracted From The Pointcloud Using The Total Station Measurement.

	Curb Ramp 1 (36 points)	Curb Ramp 2 (48 points)
Mean	0.0023 m	0.0032 m
Standard Deviation	0.0013 m	0.0015 m
Minimum	0.0007 m	0.0017 m
Maximum	0.0062 m	0.0083 m
Median	0.0017 m	0.0048 m
RMSE	0.0026 m	0.0050 m
Accuracy @95% CL	0.0042 m	0.0081 m

Table 4.6: Statistical Summary For The Leica P40 In Capturing Elevations On Curb Ramps With Single Points Extracted From The Pointcloud Using The Total Station Measurement As Reference

	Curb Ramp 1 (36 points)	Curb Ramp 2 (48 points)
Mean	0.0022 m	0.0010 m
Standard Deviation	0.0006 m	0.0010 m
Minimum	0.0014 m	0.0010 m
Maximum	0.0043 m	0.0061 m
Median	0.0023 m	0.0025 m
RMSE	0.0024 m	0.0029 m
95% Confidence Level	0.0039 m	0.0048 m

Slope measurements were then derived from the elevations obtained from the laser scanners (Table 4.7) and compared with the smart level readings. The BLK360 data showed a high RMSE (0.40%) while the P40 showed a highly accurate RMSE of 0.09%. The accuracy could further be improved by plane fitting instead of relying on a single point measurement.

Table 4.7: Statistical Summary For The Leica P40 And BLK 360 In Capturing Curb Ramp Slopes With Single Points Extracted From The Pointcloud Using The Total Station Measurement As Reference.

	BLK360	P40
Mean	-0.05%	0.00%
Standard Deviation	0.41%	0.09%
Minimum	-0.97%	-0.17%
Maximum	0.58%	0.16%
Median	0.05%	-0.01%
RMSE	0.40%	0.09%
95% Confidence Level	0.78%	0.17%

Comparing the Leica ScanStation P40 and Leica BLK360, the P40 demonstrates better and more consistent performance in capturing the curb ramps. This is attributed to three characteristics of the P40 sensor compared with the BLK360. First of all, the Leica P40 has improved ranging accuracy than the BLK 360, which can result in a more precise measurement. The Leica P40 nominally has a ranging accuracy of 0.02 in. (0.4 mm) at 32.8 ft (10 m) while the BLK360 has a ranging accuracy of 0.16 in. (4 mm) at the same range. Notably, the actual accuracy will be impacted by a variety of factors such as range, surface reflectivity, angle of incidence, and so forth. This is particularly important given that the curb ramps are relatively oblique to the scanner. Second, the Leica P40 needs to be physically leveled when set up and the dual-axis digital compensator will precisely correct each scan line individually during the scan. Thus, the pointcloud is less likely to be tilted compared against the Leica BLK 360 which solely relies on the internal digital compensator. The stated accuracy of the compensator is 1.5 seconds (0.00042°) according to the product specifications of Leica ScanStation P40 while the leveling accuracy of the Leica BLK 360 is typically much coarser at 0.05° based on several tests conducted previously by the research team in comparison to Leica P40 data. Lastly, because the setup of the Leica P40 is higher above the ground than the BLK360 in the filed data collection, the angle of incidence at the ground points is generally lower in the P40 pointclouds, leading to additional degradation of the ranging measurements from the oblique angle.

The statistical summary shows that both scanners can achieve a high accuracy where the accuracy at 95% confidence level is typically on the order of a few millimeters. Nevertheless, such error propagating to the slope measurement will result in a significant slope error. For example, using the theoretical error model developed in Section 3.5, the slope error caused by 6 mm (0.24 in.) of total vertical error can cause a slope error of around 1% for a 2-ft (60 cm) smart level. This accuracy is not sufficient for evaluating a smart level with an accuracy of 0.2%. However, it should be noted that in this test, only the closest point from the total station measurements was used for the initial evaluation. Given the high point density that can dramatically increase the sampling size and reduce noise, there are several approaches that can be utilized to improve the accuracy of slope measurement, including:

1. Generate a digital terrain model (DTM) such that the local elevation can be calculated from a large number of points within a small cell. The elevation of the given 2D coordinates can be then extracted from the terrain model. For example, using the median value of the points of the cell can be more robust against noise compared with using the elevation from a single point.

2. Extract a cross section from the pointcloud at the location used to measure the slope. A regression line can be fit to the points to obtain a more robust slope value.

3. Combine the aforementioned two approaches. The terrain model can be first generated, and the regression line will be fit to the terrain model for measuring the slope.

This analysis determines whether the BLK 360 and P40 can be effectively used to provide ground-truth measurements of curb ramp slopes as well as provide detailed measurements for flatness evaluations for the curb ramp.

4.6 ACCURACY ASSESSMENT OF SMART LEVEL

4.6.1 Discrete slope measurement comparison

The 2-ft (60 cm) smart level measurements obtained over the pre-marked survey points were compared against the ground truth values of slope derived from total station measurements to assess accuracy. Because each mark was measured by the smart level in direct and reverse face, in addition to the single measurement of the slope, the average between the direct and reverse readings was also considered. In the results on Curb Ramp 1 (Table 4.8) and Curb Ramp 2 (Table 4.9), there were two outliers removed ("*CR1C2*" and "*CR1C6*") from the statistical analysis because the difference between the direct and reverse readings were significantly higher than other readings as well as the precision of the instrument according to its specification. (Validation of removal of these measurements will be discussed in Section 4.62). All other direct and reverse readings were within 0.2%, which verifies the quality of the calibration process in this test. The statistical analysis (Table 4.10) shows that the smart level behaves consistently on both curb ramps resulting in similar accuracy and precision with all three approaches, considering the fact that the resolution of the readings on the smart level is 0.1%. Because the smart level is well calibrated and the orientation of the setup can be referred to by the marks, averaging the direct and reverse readings does not provide substantial improvement for the slope measurement. However, in practice, using an average of the direct and reverse readings at the same spot can be potentially beneficial because it can help mitigate the calibration errors, blunders, and errors caused by horizontal misalignment.

Table 4.8: Accuracy Assessment Of The 2-Ft (60 Cm) Smart Level Measurements On Curb Ramp 1.

PID	Direct	Reverse	Diff.	Average	Ground Truth	Error		
						Direct	Reverse	Mean
CR1C1	3.8%	3.9%	0.1%	3.85%	3.71%	0.09%	0.19%	0.14%
CR1C2	3.9%	4.3%	0.4%	4.10%	3.94%	-0.04%	0.36%	0.16%
CR1C3	3.0%	3.1%	0.1%	3.05%	2.93%	0.07%	0.17%	0.12%
CR1C4	3.5%	3.6%	0.1%	3.55%	3.59%	-0.09%	0.01%	-0.04%
CR1C5	3.8%	3.9%	0.1%	3.85%	3.86%	-0.06%	0.04%	-0.01%
CR1C6	2.6%	3.3%	0.7%	2.95%	3.07%	-0.47%	0.23%	-0.12%
CR1C7	1.9%	1.9%	0.0%	1.90%	1.99%	-0.09%	-0.09%	-0.09%
CR1C8	2.4%	2.5%	0.1%	2.45%	2.32%	0.08%	0.18%	0.13%
CR1C9	2.6%	2.6%	0.0%	2.60%	2.61%	-0.01%	-0.01%	-0.01%
CR1CA	2.2%	2.4%	0.2%	2.30%	1.90%	0.30%	0.50%	0.40%
CR1CB	1.7%	1.7%	0.0%	1.70%	2.07%	-0.37%	-0.37%	-0.37%
CR1F1	4.6%	4.7%	0.1%	4.65%	4.60%	0.00%	0.10%	0.05%
CR1F2	5.0%	5.0%	0.0%	5.00%	5.02%	-0.02%	-0.02%	-0.02%
CR1R1	7.6%	7.6%	0.0%	7.60%	7.48%	0.12%	0.12%	0.12%
CR1R2	7.3%	7.3%	0.0%	7.30%	6.94%	0.36%	0.36%	0.36%
CR1R3	6.5%	6.5%	0.0%	6.50%	6.58%	-0.08%	-0.08%	-0.08%
CR1R4	6.4%	6.4%	0.0%	6.40%	6.54%	-0.14%	-0.14%	-0.14%
CR1R5	6.5%	6.5%	0.0%	6.50%	6.49%	0.01%	0.01%	0.01%

Table 4.9: Accuracy Assessment Of The 2-Ft (60 Cm) Smart Level Measurements On Curb Ramp 2.

PID	Direct	Reverse	Diff.	Average	Ground Truth	Error		
						Direct	Reverse	Mean
CR2C01	0.0%	0.1%	0.1%	0.05%	0.00%	0.00%	0.10%	0.05%
CR2C02	0.5%	0.6%	0.1%	0.55%	0.70%	-0.20%	-0.10%	-0.15%
CR2C03	1.0%	1.1%	0.1%	1.05%	1.02%	-0.02%	0.08%	0.03%
CR2C04	0.2%	0.1%	-0.1%	0.15%	0.10%	0.10%	0.00%	0.05%
CR2C05	0.1%	0.1%	0.0%	0.10%	0.12%	-0.02%	-0.02%	-0.02%
CR2C06	0.3%	0.3%	0.0%	0.30%	0.25%	0.05%	0.05%	0.05%
CR2C07	0.2%	0.2%	0.0%	0.20%	0.17%	0.03%	0.03%	0.03%
CR2C08	0.2%	0.3%	0.1%	0.25%	0.03%	0.17%	0.27%	0.22%
CR2C09	0.1%	0.1%	0.0%	0.10%	0.13%	-0.03%	-0.03%	-0.03%
CR2C10	0.1%	0.2%	0.1%	0.15%	0.38%	-0.28%	-0.18%	-0.23%
CR2C11	0.1%	0.2%	0.1%	0.15%	0.27%	-0.17%	-0.07%	-0.12%
CR2C12	0.1%	0.1%	0.0%	0.10%	0.17%	-0.07%	-0.07%	-0.07%
CR2C13	0.3%	0.2%	-0.1%	0.25%	0.61%	-0.31%	-0.41%	-0.36%
CR2F11	4.5%	4.6%	0.1%	4.55%	4.94%	-0.44%	-0.34%	-0.39%
CR2F12	6.2%	6.1%	-0.1%	6.15%	5.87%	0.33%	0.23%	0.28%
CR2F13	6.2%	6.2%	0.0%	6.20%	6.18%	0.02%	0.02%	0.02%
CR2F21	6.3%	6.2%	-0.1%	6.25%	6.15%	0.15%	0.05%	0.10%
CR2F22	7.8%	7.9%	0.1%	7.85%	7.71%	0.09%	0.19%	0.14%
CR2R01	7.7%	7.7%	0.0%	7.70%	7.84%	-0.14%	-0.14%	-0.14%
CR2R02	7.5%	7.5%	0.0%	7.50%	7.54%	-0.04%	-0.04%	-0.04%
CR2R03	7.5%	7.5%	0.0%	7.50%	7.30%	0.20%	0.20%	0.20%
CR2R04	7.6%	7.5%	-0.1%	7.55%	7.54%	0.06%	-0.04%	0.01%
CR2R05	7.9%	7.9%	0.0%	7.90%	7.67%	0.23%	0.23%	0.23%
CR2R06	7.8%	7.8%	0.0%	7.80%	7.65%	0.15%	0.15%	0.15%
CR2R07	7.2%	7.2%	0.0%	7.20%	7.02%	0.18%	0.18%	0.18%

Table 4.10: Statistical Summary For The Smart Level In Measuring Slopes.

	Curb Ramp 1			Curb Ramp 2		
	Direct	Reverse	Average	Direct	Reverse	Average
Mean	0.01%	0.06%	0.04%	0.00%	0.01%	0.01%
Standard Deviation	0.17%	0.20%	0.18%	0.18%	0.17%	0.17%
Minimum	-0.37%	-0.37%	-0.37%	-0.44%	-0.41%	-0.39%
Maximum	0.36%	0.50%	0.40%	0.33%	0.27%	0.28%
Median	0.00%	0.03%	0.00%	0.02%	0.02%	0.03%
RMSE	0.16%	0.20%	0.18%	0.18%	0.17%	0.17%
95% RMSE	0.35%	0.44%	0.39%	0.37%	0.34%	0.35%

4.6.2 Slope variability assessment

The research team further investigated the two measurements with large discrepancy between direct and reverse readings, which were removed from the statistical analysis. Because the impact of calibration errors and errors caused by horizontal misalignment were proven to be neglectable, the pointcloud collected by Leica P40 was used to analyze these measurements to provide enhanced geometric information of that portion of the curb ramp. For each of the survey markers under analysis, four discrete slope measurements were obtained by evenly dividing the distance between two survey points into four increments. The slope measurement between "*CR1C21"* and "*CR1C22*" (Figure 4.8), calculated from the total station measurements is 3.94%. Meanwhile, the slope measurement for the four sections ranges from 2.62% to 4.23%. Both the direct and reverse readings (i.e., 3.9% and 4.3%) fall into this range, explaining the large difference between the direct and reverse readings. Similarly, the slope between "*CR1C61*" and "*CR1C62*" ranges from 1.89% to 4.05% (Figure 4.9) when discretized in a similar fashion while the direct and reverse readings from the smart level are 2.6% and 3.3%, respectively. Such phenomenon shows that the impact of the flatness or roughness of the surface can significantly impact the accuracy of the smart level readings. Section 5.2 discusses approaches that will be used to evaluate the flatness of curb ramps.

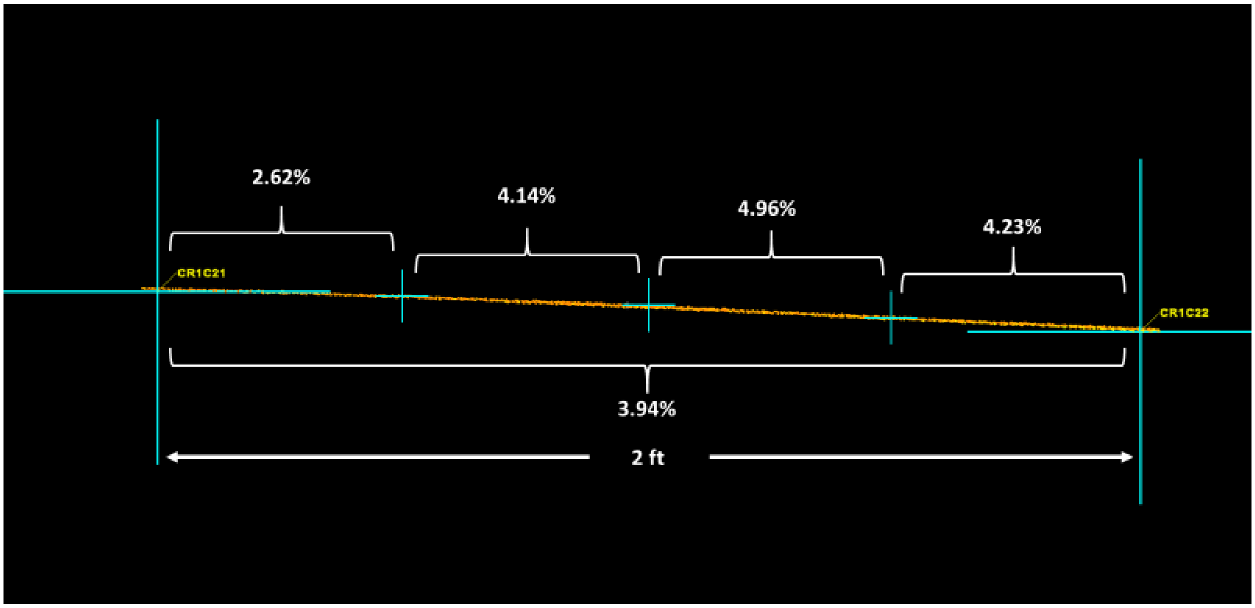


Figure 4.8: Detailed slope measurements in pointclouds for slope "CR1C2".

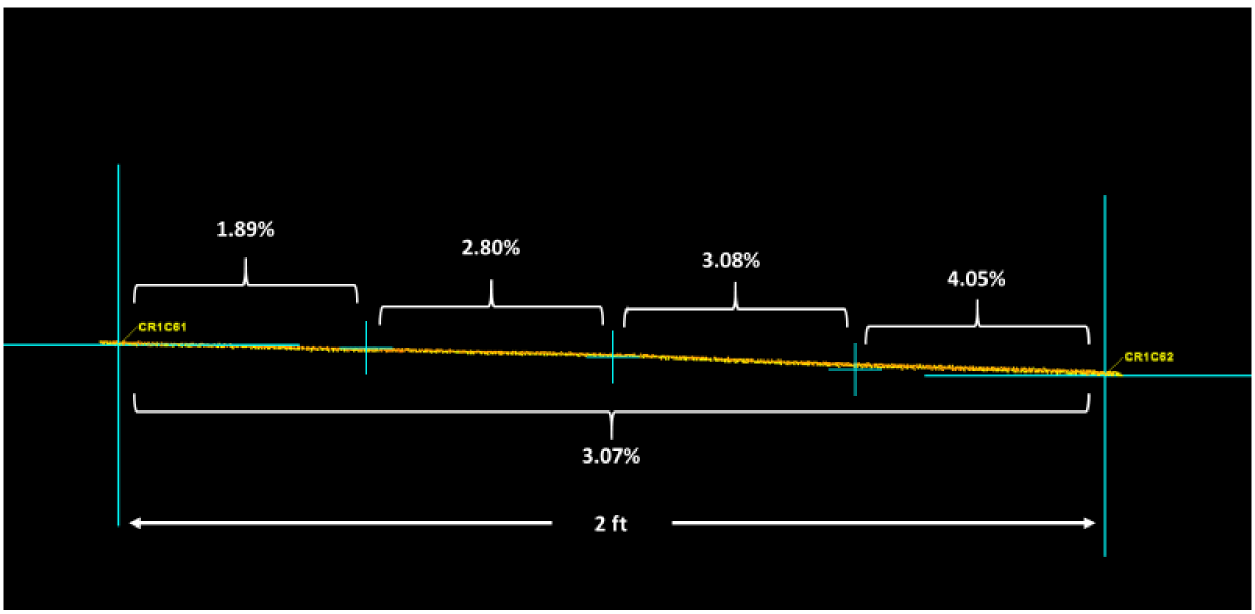
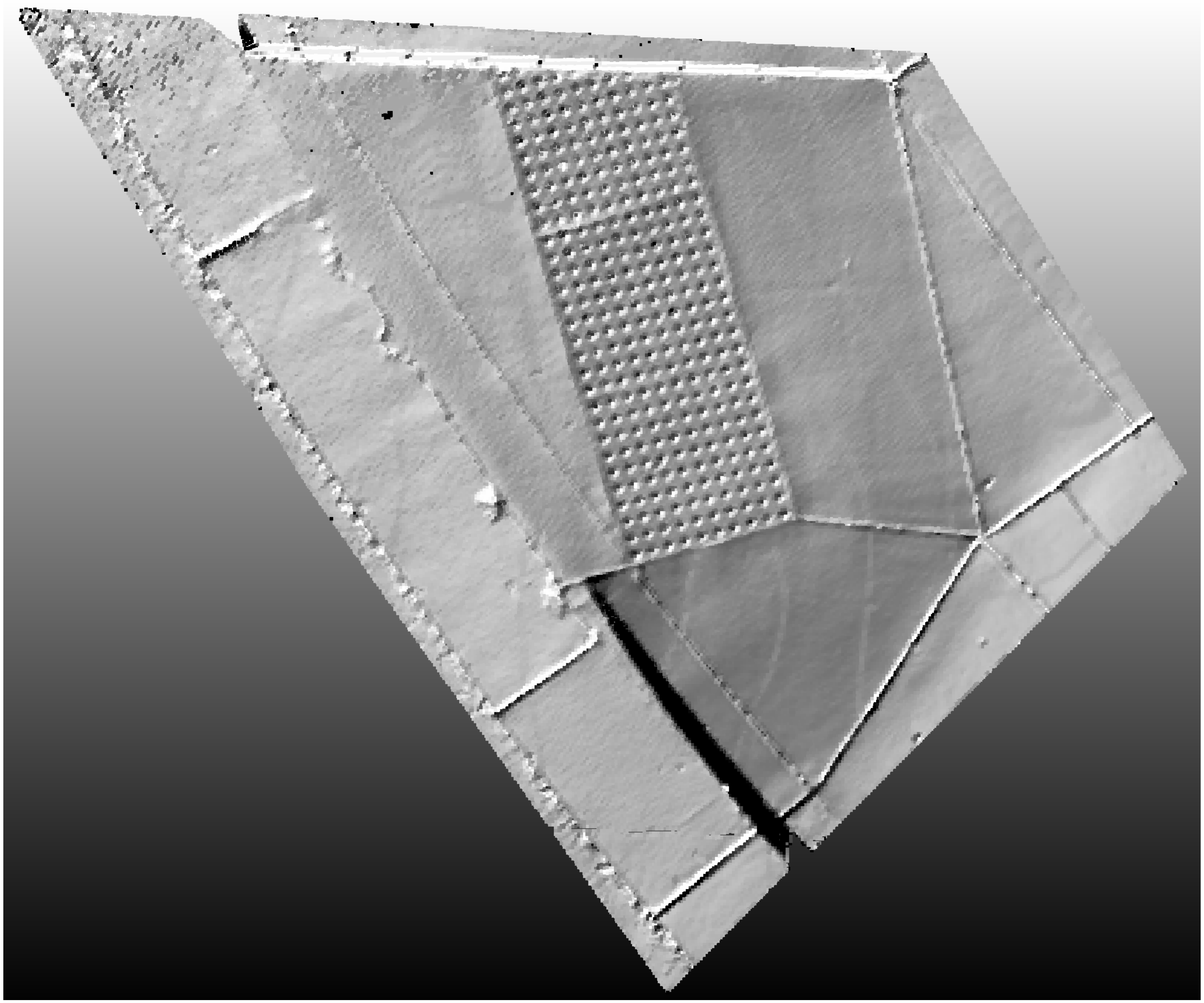


Figure 4.9: Detailed slope measurements in pointclouds for slope "CR1C6".

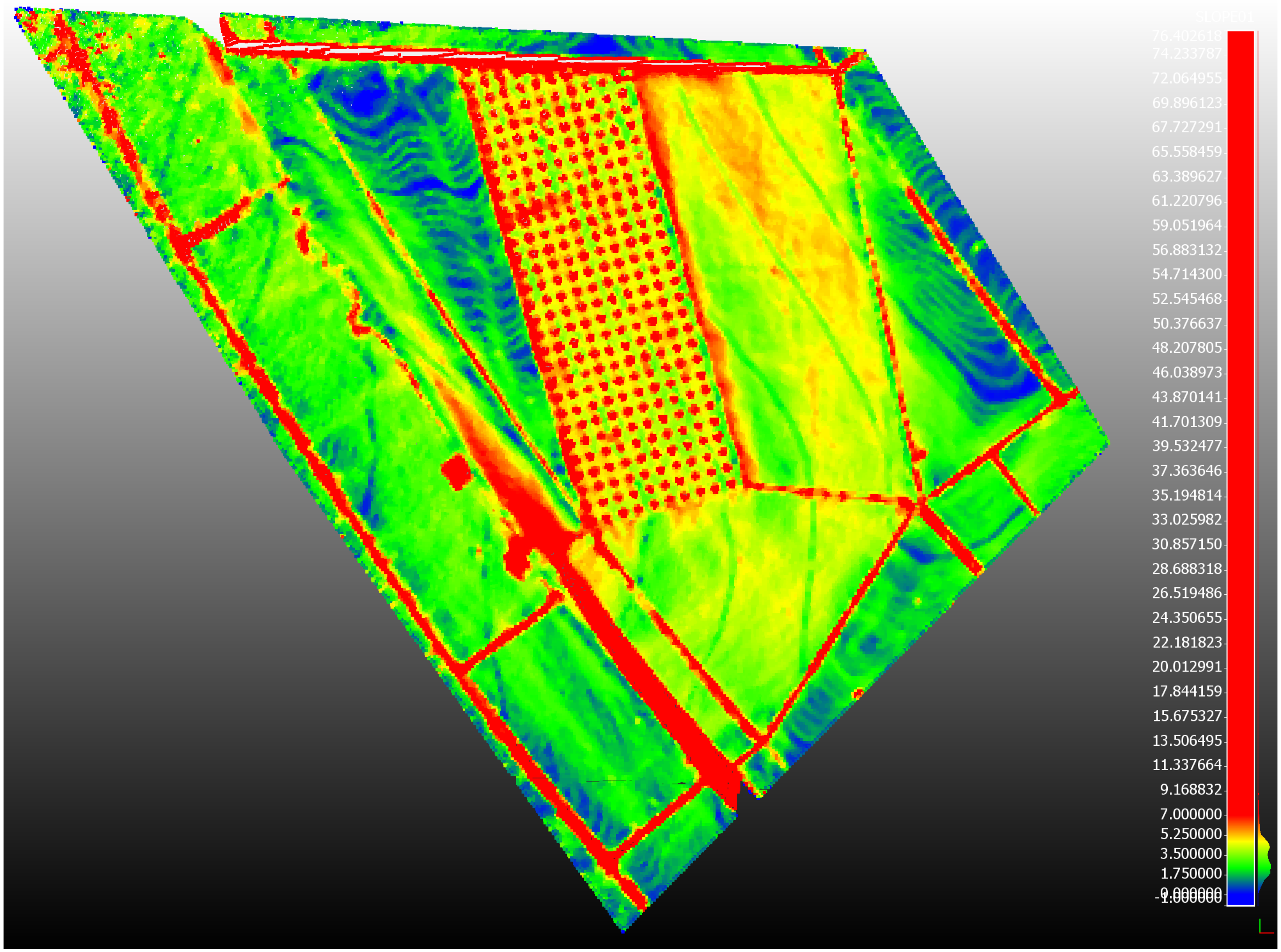
4.7 FLATNESS/ROUGHNESS EVALUATION

In the tests described in Section 3, the precision and repeatability specifications of the smart level have been validated. The research team also conducted a more rigorous calibration test (Section 4) to assess the performance of the 2-ft (60 cm) smart level on two curb ramps. The results show that the vast majority of the smart level readings are accurate when compared with a total station, with just a few outliers. When the research team further investigated these outliers, they found the primary cause for the discrepancy results from differences in the flatness/roughness of the surface of the curb ramp. Hence, the evaluation procedures for curb need to consider the local variability into account during inspection.

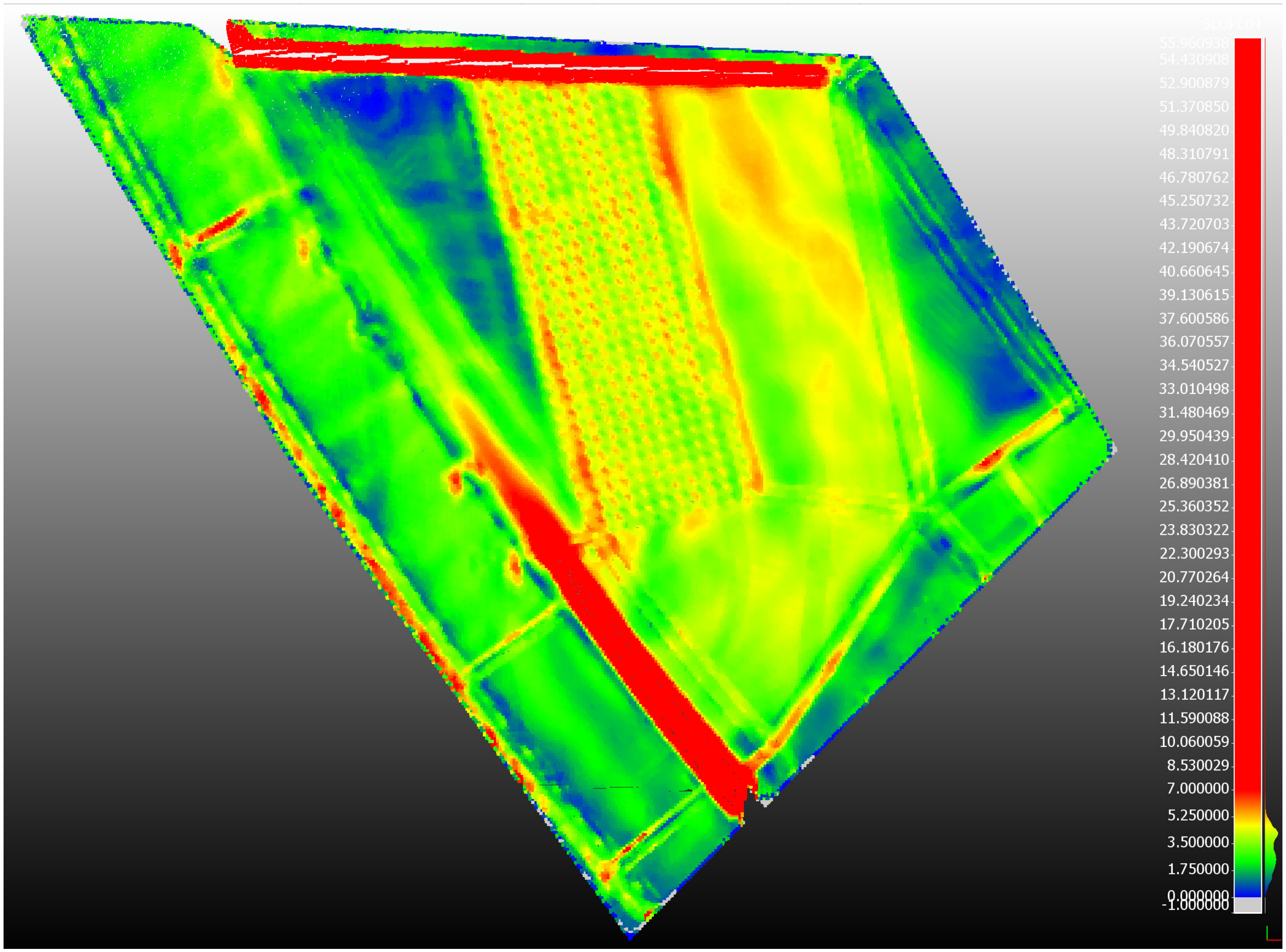
The pointcloud data from the calibration tests were analyzed using the RAMBO software previously developed by the research team (Olsen et al., 2020) to evaluate the surface morphology including slope variability and roughness of the surface. Results are shown in Figure 4.10. Note that both slope and roughness values are dependent on the scale or window size of interest.



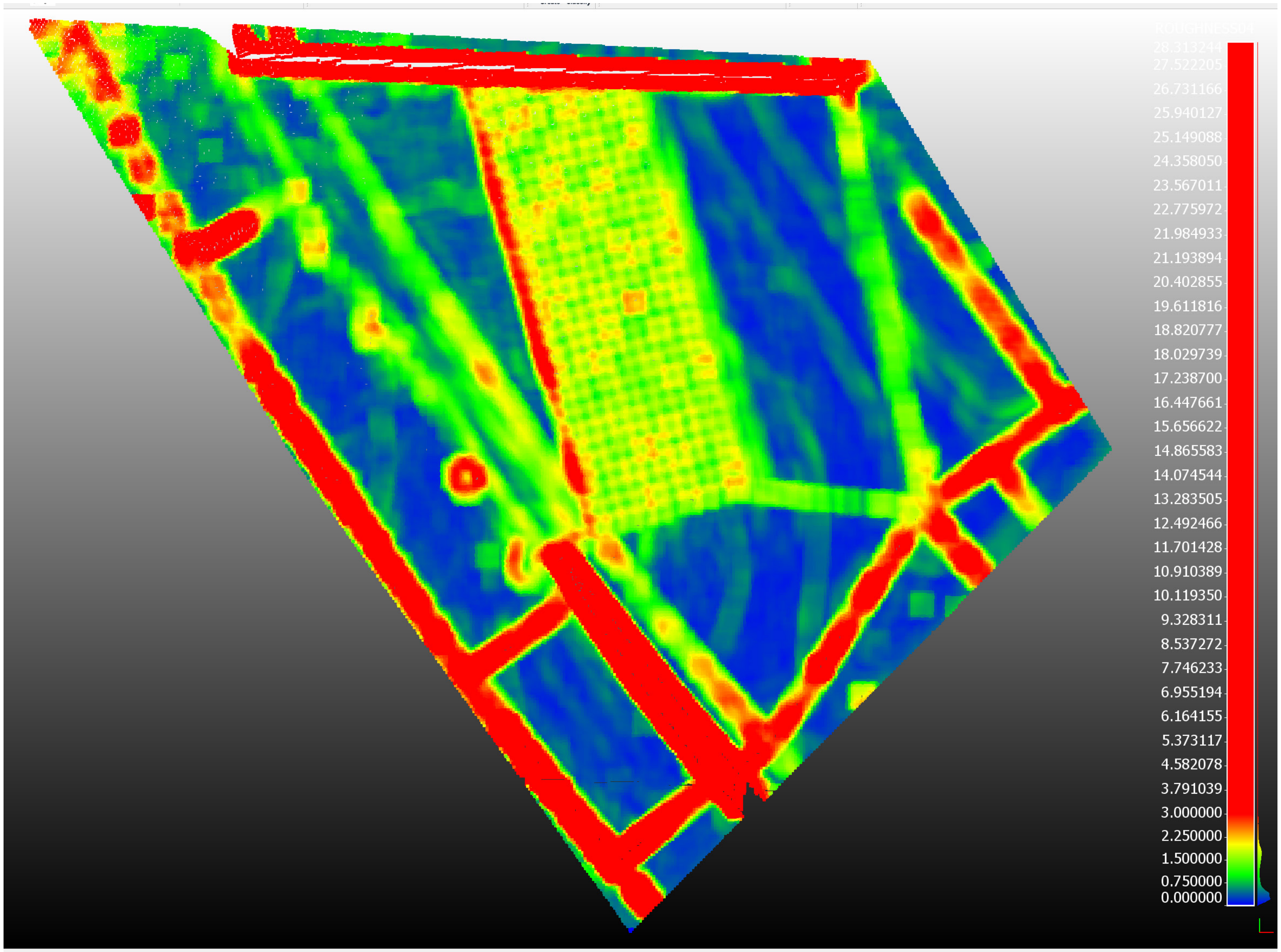
(a) Hillshade



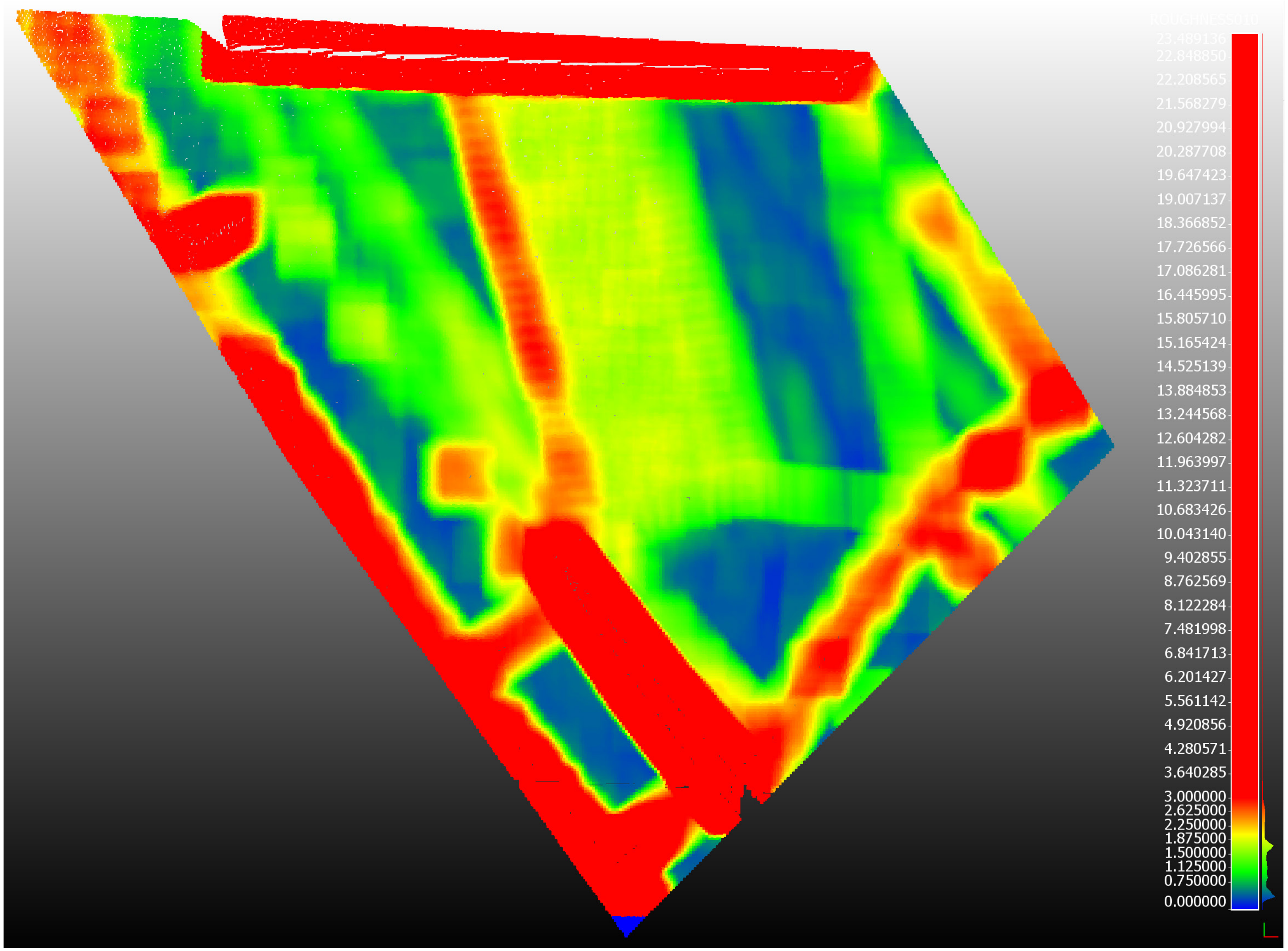
(b) Slope (window size = 1.2 in. x 1.2 in. (3 cm x 3 cm)). Units: Degrees



(c) Slope (window size = 3.5 in. x 3.5 in. (9 cm x 9 cm)) Units: Degrees



(d) Roughness (3.5 in. x 3.5 in. (9 cm x 9 cm) window size) Units: Degrees



(e) Roughness (8.2 in. x 8.2 in. (21 cm x 21 cm) window size) Units: Degrees

Figure 4.10: Morphological analysis results for Curb Ramp 1. The cell size for the analysis was 0.4 in. (1 cm).

5.0 OPERATOR VARIABILITY TESTING

5.1 OPERATOR VARIABILITY

In the previous tests, the research team eliminated operational errors (e.g., misalignment errors) from the smart level measurements by defining the position and orientation of the device placement precisely. Nonetheless, as analyzed in the theoretical model (Section 3), the misalignment errors can play a substantial role in the slope measurement with a smart level. Therefore, an operator variability test was conducted based on inspection data obtained from inspector training test.

The test was performed on OSU campus. The center of a "flat" slab was marked to indicate where to place the smart levels. Each operator was instructed to place a smart level over the center mark with the goal of aligning it parallel to the slab edges (Figure 5-1). To measure the "true" target orientation, a number of points along the edges of the slab were measured with a total station prior to the test.

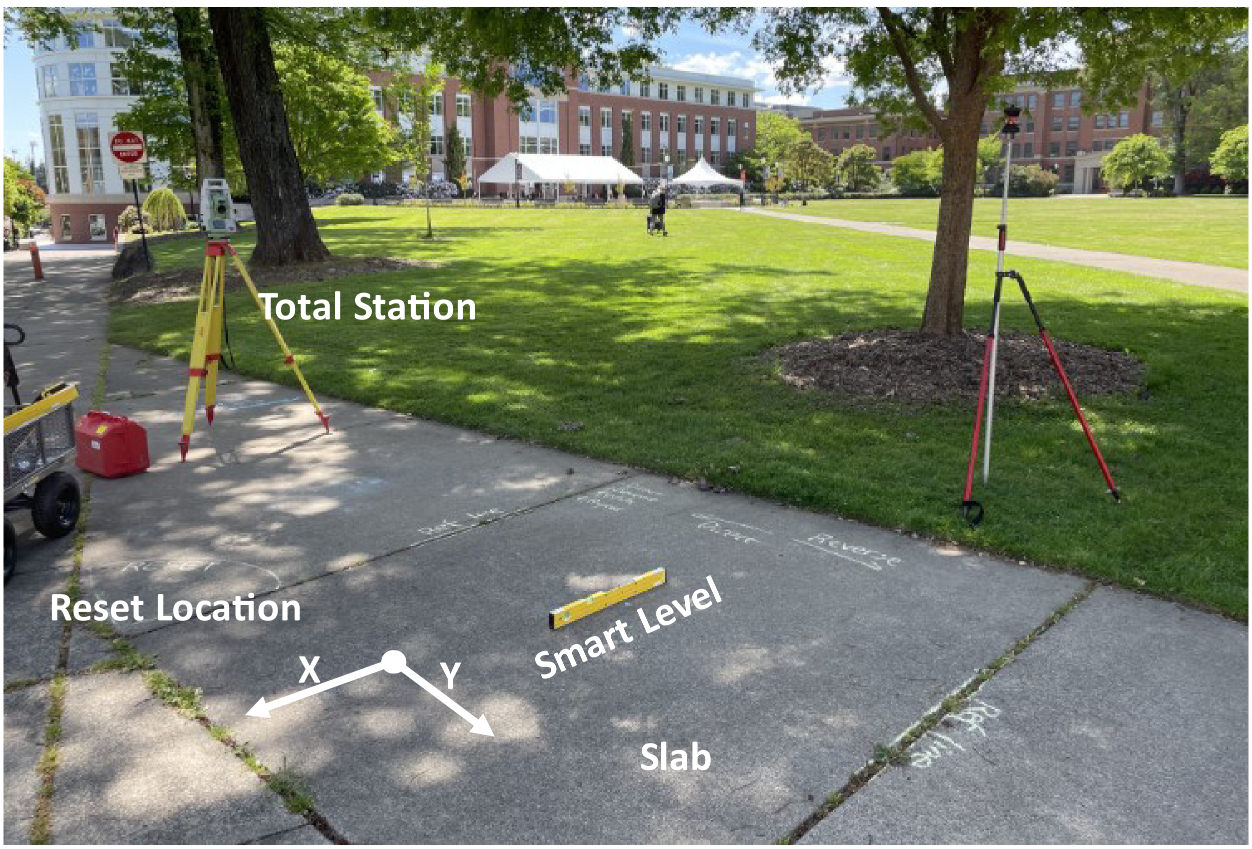


Figure 5.1: Schematic illustrating the operating variability testing.

Each operator was instructed to place the smart level on its direct and reverse face for each set observations. The operator then left the slab and walked to the "reset" area before making another set of observations to keep each set of readings independent. Three instruments were tested in this experiment including a 6-inch, 2-ft, and 4-ft smart level. Both ends of each smart level were marked with targets so that that the position and orientation of the smart level could be precisely measured with total station during the test (Figure 5.2).

Figure 5.2: Smart levels used in the operator variability test with end points marked.

Three participants performed the measurements. Each participant acquired 15 direct and 15 reverse readings with 6-inch smart level and 2-ft smart level, as well as 3 direct and 3 reverse readings with 4-ft smart level. The research team then analyzed all of the total station measurements of the smart level position and orientation to provide reference data (Table 5.1) to compare with the participants' observations.

Table 5.1: Statistical Summary Of The Operator Variability Test Regarding The Horizontal Alignment.

	Statistical metrics	Participant 1	Participant 2	Participant 3	All
6-inch smart level	Average	-1.17°	-2.89°	-3.16°	-2.41°
	Std. Dev.	1.65°	2.35°	1.45°	2.04°
	RMSE	1.20°	3.70°	3.46°	3.15°
2-ft smart level	Average	-1.60°	-0.35°	0.12°	-0.61°
	Std. Dev.	1.47°	1.90°	0.71°	1.61°
	RMSE	2.16°	1.90°	0.71°	1.71°
4-ft smart level	Average	-1.54°	-0.72°	-0.91°	-1.06°
	Std. Dev.	0.76°	1.87°	1.07°	1.29°
	RMSE	1.69°	1.85°	1.34°	1.64°

The results in Table 5.1 show that all operators have significant bias and variation in running all three instruments regarding the horizontal alignment. The magnitudes of the average and standard deviation vary from person to person significantly. In general, the 6-inch smart level resulted in a larger horizontal misalignment compared with the 2-ft and 4-ft smart levels. One of the primary reasons for this could be the fact that the longer smart level provides a better visual reference for the inspectors to align with the concrete slab. However, a tradeoff is that the longer smart level is more difficult to work with, especially for small curb ramps.

Next, to provide more context of the analysis, the distribution of the horizontal misalignment errors for each participant was also plotted to further show the variability between different operators in placing the smart levels (Figure 5.3). A similar case can be found in the centering errors in this test as well (Figure 5.4) where results are more similar between Participants 1 and 2 compared with participant 3. Note that higher centering errors occur in the X direction.

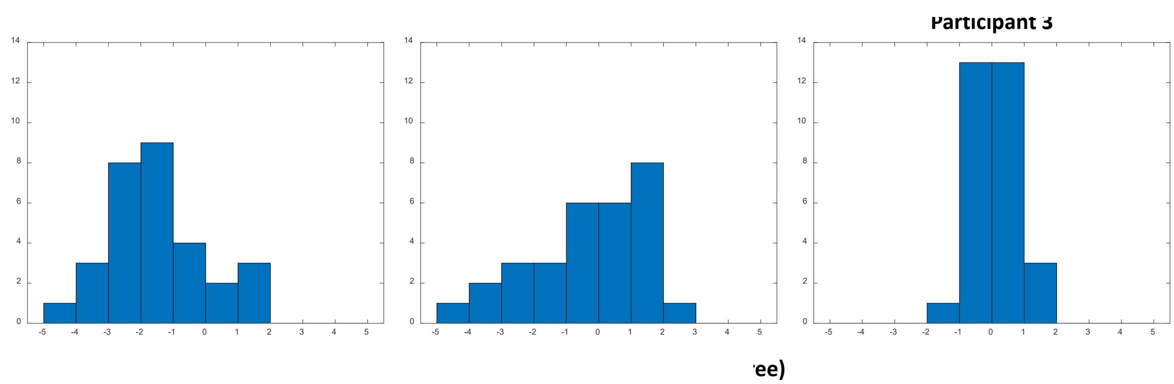


Figure 5.3: Distribution of horizontal misalignment errors for each participant.

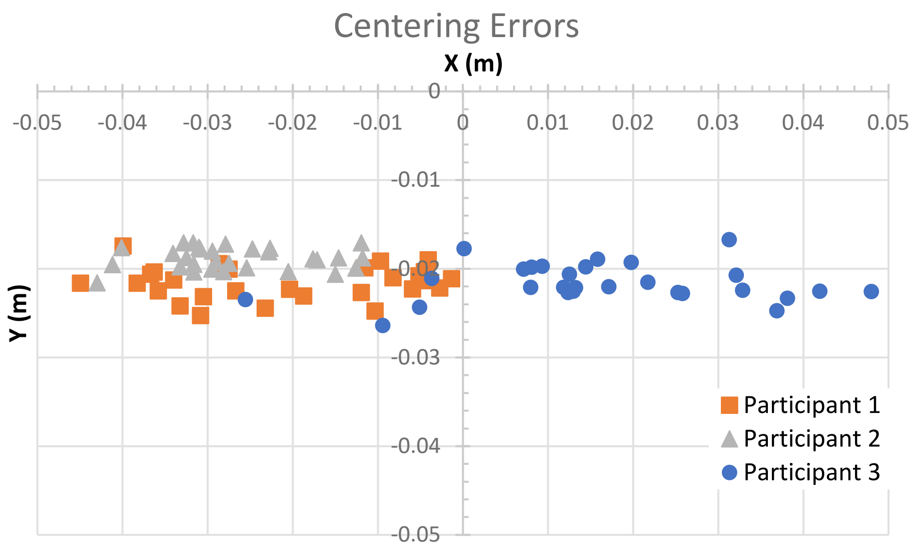


Figure 5.4: Centering errors in the operator variability test.

5.2 INSPECTOR CONSISTENCY TESTING

One of the challenges in curb ramp inspection is that although there is a general procedure to be followed, inspectors often need to make adjustments based on the actual field situation and their experience. As a result, sometimes the inspection process can be subjective because the inspection procedures themselves do not guarantee that the maximum slope on the curb ramp can be captured. For this test, the research team analyzed data provided by ODOT from their inspector certifications completed during 2022. As part of the certification process, a qualified inspector from ODOT obtained reference measurements for 64 different ramps at several intersections across the inspection site following standard procedures. The inspectors undergoing certification then performed evaluations. A total of 1942 and 2114 running and cross slope measurements, respectively, were obtained by these inspectors undergoing certification for evaluation. Inspectors did not indicate when direct or reverse measurements were used.

5.2.1 Running slope measurements

All data from runs 1, 2, and 3 were combined and the differences between the inspectors undergoing certification and the ground truth measurements were compared for different slope bins in 1% increments. Table 5.2 provides a statistical analysis of these differences for each of the bins and the dataset as a whole. Figure 5.5 plots the average and standard deviation values for each bin. Notably, a strong trend is observed with the average difference. Substantial differences are observed between the values recorded by the inspectors undergoing certification compared with the ground truth. These inspectors undergoing certification tend to record much higher values on shallow ramps and much lower values on steeper ramps. High standard deviation values (~0.8%) are observed across all slope bins.

Table 5.2: Statistical Analysis Of Differences (%) Between Inspectors Undergoing Certification And Ground Truth For All Running Slope Measurements.

Slope Bins	0.0-1.0%	1.0-2.0%	2.0-3.0%	3.0-4.0%	4.0-5.0%	5.0-6.0%	6.0-7.0%	7.0-8.0%	8.0-9.0%	All
Average	0.66	0.11	0.18	-0.15	-0.14	-0.34	-0.36	-0.30	-0.32	-0.17
Std. Dev.	0.86	0.82	0.94	0.49	0.75	0.85	1.00	0.89	0.91	0.91
Min	-0.30	-1.10	-3.50	-1.90	-3.50	-4.10	-6.10	-6.60	-5.50	-6.60
Max	5.90	6.40	5.40	1.00	4.00	1.80	2.30	1.40	1.60	6.40
Median	0.45	0.00	0.10	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	0.00
Count	60	284	135	58	252	240	379	387	147	1942
RMS	1.08	0.83	0.95	0.51	0.76	0.91	1.07	0.94	0.96	0.92

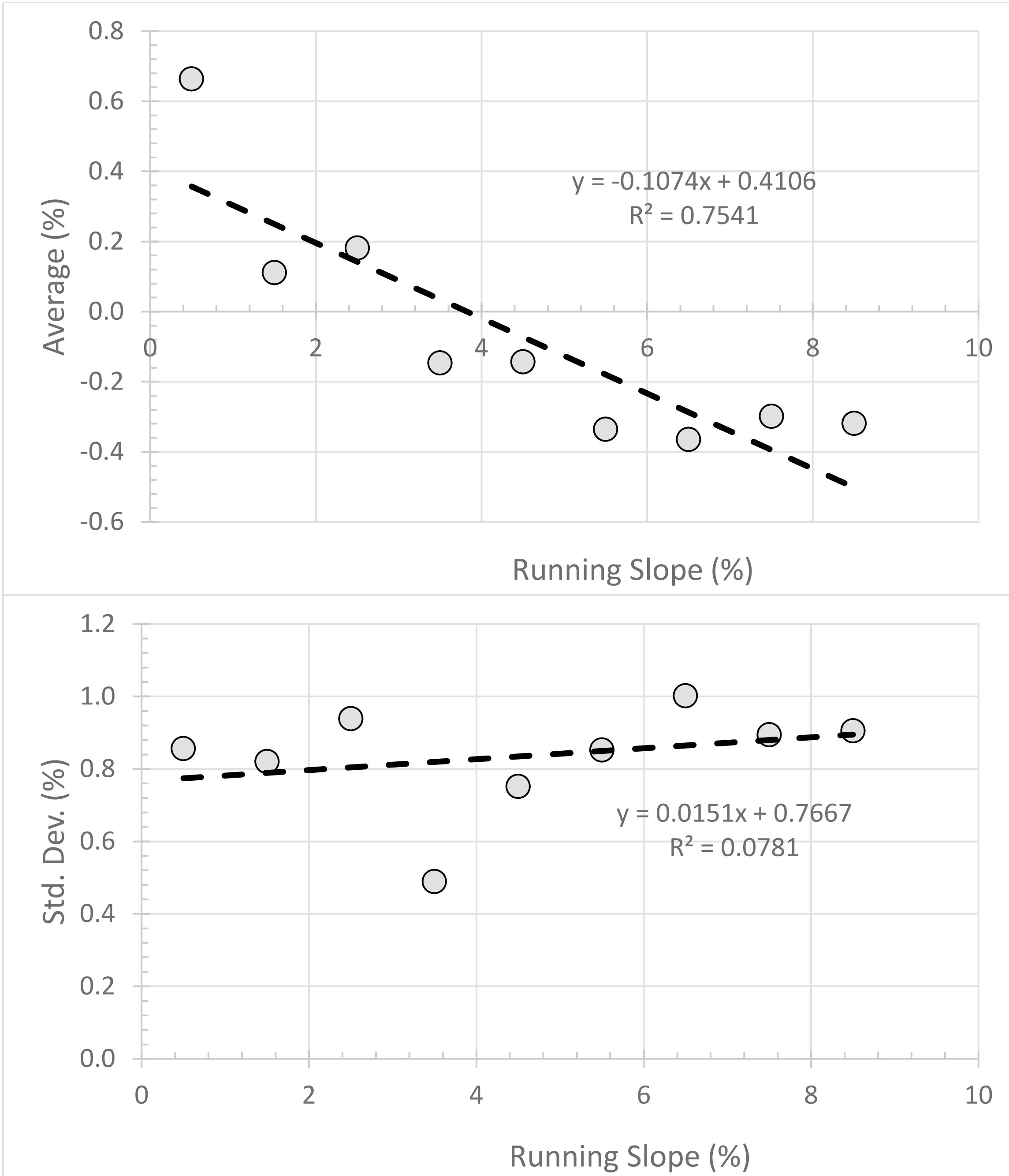


Figure 5.5: (a) Average And (B) Standard Deviation Of Differences In Running Slope Measurements Between Inspectors Undergoing Certification And Ground Truth Measurements In 1% Bin Increments.

5.2.2 Filtered running slope measurements

Given that the inspectors were still in training and had varying levels of expertise, blunder detection was performed to provide a more realistic estimate of the variability of certified inspectors. A 3-sigma test was performed to remove values higher than the average plus 3 standard deviations and values lower than the average plus 3 standard deviations. Then the average and standard deviations were recomputed, and the test was performed again. This process was repeated for several iterations until no more values were removed. The 3-sigma values were -1.5 and 1.35%. While this process removes large blunders, it is still likely that some misread or mis recorded values still remain to a limited degree. Several of these blunders were identified to be caused by the inspectors undergoing certification mixing up the cross and running slopes.

Following the 3-sigma test, data were plotted in the same format as in Section 5.2.1 with Table 5.3 providing a statistical analysis of these differences for each of the bins and the dataset as a whole and Figure 5.6 plotting the average and standard deviation values for each bin. The same trends of higher values of slope for shallower ramps and lower values of slope for steeper ramps are observed, but with a lower correlation. Overall, the average difference is -0.09% which is within the specifications of the smart level. However, the standard deviation remains relatively high at 0.48%. The higher variability is likely a result of (1) differences in equipment used, (2), differences in calibration, and (3) differences in inspector procedures and measurement locations.

Table 5.3: Statistical Analysis Of Differences (%) Between Inspectors Undergoing Certification And Ground Truth For Running Slope Measurements With Blunders Removed.

Slope Bins	0.0-1.0%	1.0-2.0%	2.0-3.0%	3.0-4.0%	4.0-5.0%	5.0-6.0%	6.0-7.0%	7.0-8.0%	8.0-9.0%	All
Average	0.48	-0.02	0.07	-0.09	-0.05	-0.15	-0.18	-0.14	-0.18	-0.09
Std. Dev.	0.42	0.38	0.47	0.39	0.43	0.52	0.51	0.48	0.44	0.48
Min	-0.30	-1.10	-1.10	-1.40	-1.50	-1.50	-1.50	-1.50	-1.50	-1.50
Max	1.30	1.30	1.10	1.00	0.90	1.10	1.10	1.20	1.10	1.30
Median	0.40	0.00	0.00	-0.10	-0.05	-0.10	-0.10	-0.10	-0.10	0.00
Count	54	273	129	56	236	219	353	366	137	1823
RMS	0.63	0.38	0.48	0.39	0.43	0.54	0.54	0.50	0.47	0.49

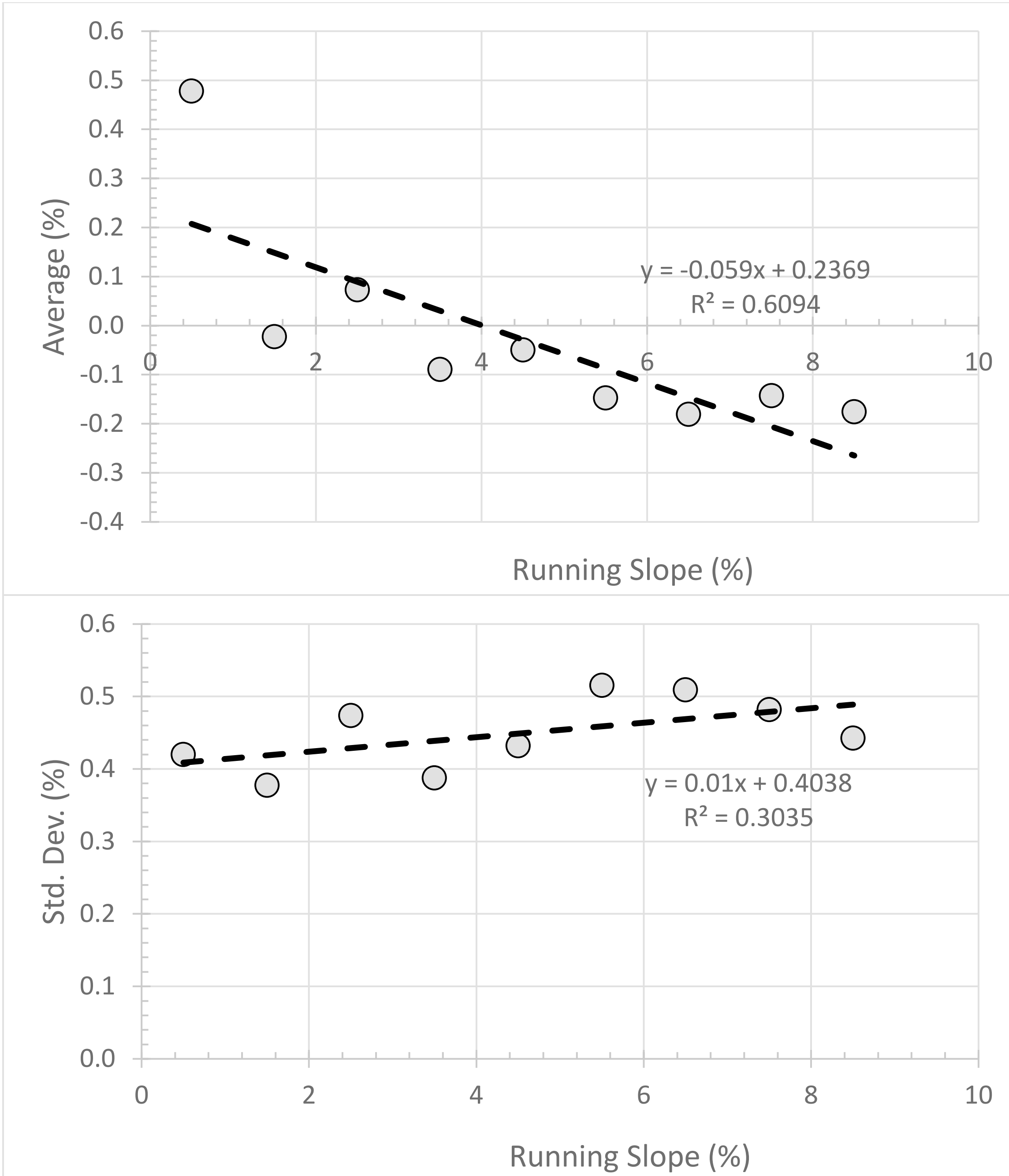


Figure 5.6: (a) Average and (b) Standard Deviation of differences in running slope measurements between inspectors undergoing certification and ground truth measurements in 1% bin increments with blunders removed.

5.2.3 All cross-slope measurements

The same process completed for the running slope in Section 5.2.1 was completed for the cross slopes. Notably, these values have a much smaller range, so the bin size was adjusted to 0.3% increments except for the first bin which ranged from 0-0.1%. Table 5.4 provides a statistical analysis of these differences for each of the bins and the dataset as a whole and Figure 5.6 plots the average and standard deviation values for each bin. Similar trends were observed for the running slope with higher average differences for shallower slopes. A standard deviation of 0.74% was obtained for all data points.

Table 5.4: Statistical Analysis Of Differences (%) Between Inspectors Undergoing Certification And Ground Truth For Cross Slope Measurements Without Blunders Removed.

Slope Bins	0.0-0.1%	0.1-0.4%	0.4-0.7%	0.7-1.0%	1.0-1.3%	1.3-1.6%	1.6-1.9%	1.9-2.2%	2.2-2.5%	All
Average	1.33	0.57	0.32	0.20	0.04	-0.01	-0.08	-0.22	0.00	0.08
Std. Dev.	0.50	0.71	0.67	0.31	0.47	0.61	0.57	0.80	0.38	0.74
Min	0.00	-0.60	-0.50	-0.40	-1.20	-1.10	-1.50	-1.70	-0.90	-1.70
Max	4.00	2.60	3.70	1.00	3.90	6.40	6.40	12.80	0.80	12.80
Median	1.30	0.40	0.10	0.10	0.00	0.00	-0.10	-0.20	0.00	0.00
Count	178	62	53	70	257	482	542	432	37	2114
RMS	1.42	0.91	0.74	0.37	0.47	0.61	0.57	0.83	0.38	0.74

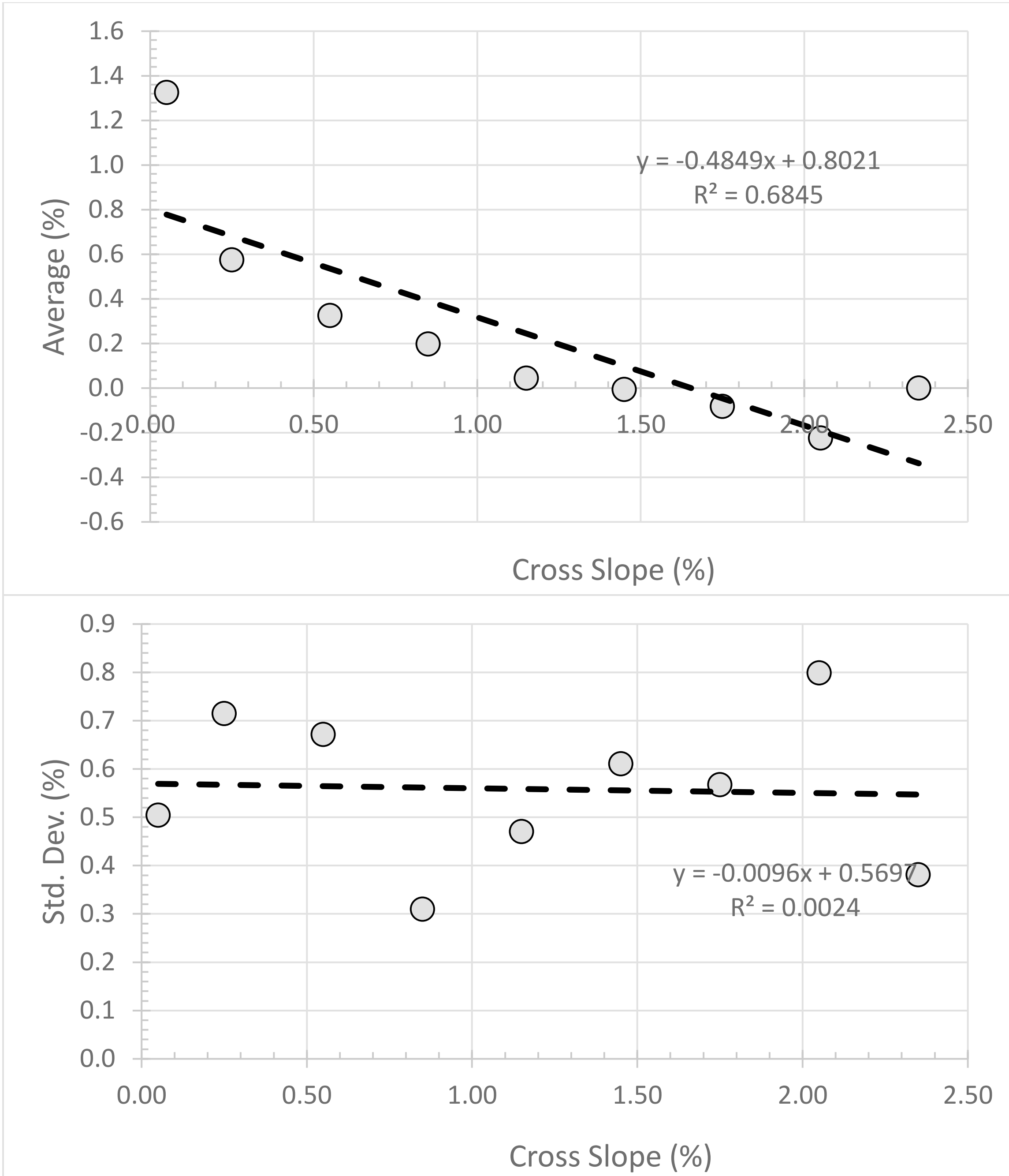


Figure 5.7: (a) Average and (b) standard deviation of differences in cross slope measurements between inspectors undergoing certification and ground truth measurements in 0.3% bin increments.

5.2.4 Filtered cross slope measurements

The same 3-sigma test as described in Section 5.2.2 was applied to remove large blunders. The 3-sigma thresholds used were -1.35 and 1.25%. Several of these blunders were identified to be caused by the inspectors undergoing certification mixing up the cross and running slopes. Following the 3-sigma test, data were plotted in the same format as in Section 5.2.3 with Table 5.3 providing a statistical analysis of these differences for each of the bins and the dataset as a whole and Figure 5.6 plotting the average and standard deviation values for each bin. Similar trends with the running slope are observed with a strong correlation for the average. Overall, the average difference is -0.04% which is within the specifications of the smart level. The standard deviation remains relatively high at 0.45% similar to the running slope and is likely due to the same factors described in Section 5.2.2. Interestingly, a trend with high correlation is observed for the standard deviation; however, the standard deviation values do not differ substantially (0.30 to 0.43) across the bins.

Table 5.5: Statistical Analysis Of Differences (%) Between Inspectors Undergoing Certification And Ground Truth For Cross Slope Measurements With Blunders Removed.

Slope Bins	0.0-0.1%	0.1-0.4%	0.4-0.7%	0.7-1.0%	1.0-1.3%	1.3-1.6%	1.6-1.9%	1.9-2.2%	2.2-2.5%	All
Average	0.91	0.29	0.20	0.20	0.02	-0.06	-0.12	-0.24	0.00	-0.04
Std. Dev.	0.30	0.37	0.35	0.31	0.38	0.39	0.37	0.43	0.38	0.45
Min	0.00	-0.60	-0.50	-0.40	-1.20	-1.10	-1.30	-1.30	-0.90	-1.30
Max	1.20	1.00	1.20	1.00	1.20	1.20	1.20	1.00	0.80	1.20
Median	1.00	0.20	0.10	0.10	0.00	0.00	-0.10	-0.20	0.00	0.00
Count	75	51	50	70	254	475	536	420	37	1969
RMS	0.95	0.47	0.40	0.37	0.38	0.39	0.39	0.49	0.38	0.45

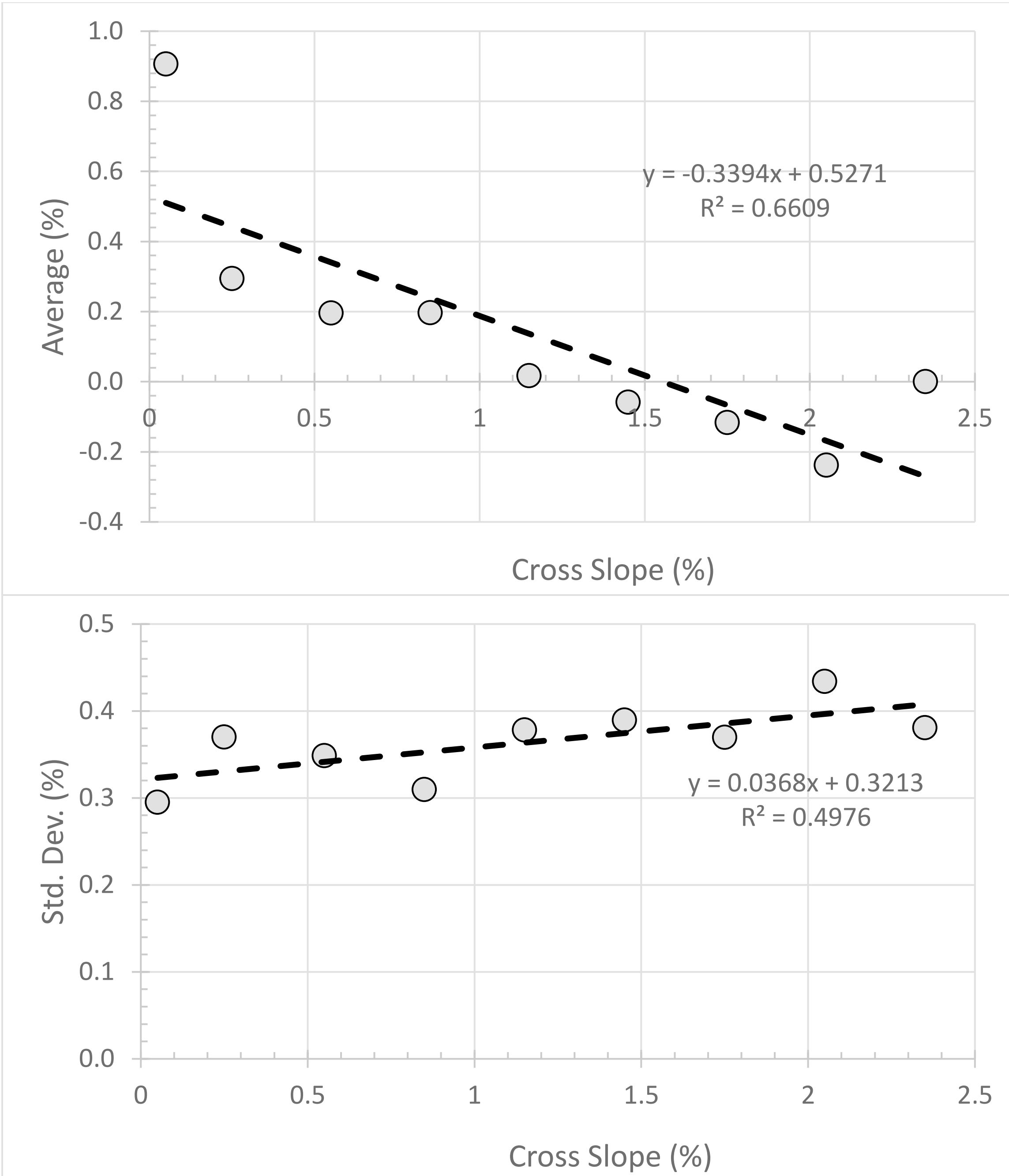


Figure 5.8: (a) Average and (b) Standard Deviation of differences in cross slope measurements between inspectors undergoing certification and ground truth measurements in 0.3% bin increments with blunders removed.

5.2.5 Ramp Style

The dataset was then categorized by Ramp Style (UD= Unique Design, PL= Parallel, PR= Perpendicular, C= Combination, and BT = Blended Transition) and statistics were calculated for each ramp style to determine if the style of ramp lead to more uncertainty for all values (Table 5.6) and with blunders removed (Table 5.7). It is noted that some ramp types (e.g., UD and BT) resulted in substantially more blunders (~9%) than other ramp types (2-7%), resulting in much higher RMS values (Figure 5.9). This is likely due to more confusion when the inspector is determining where and how to obtain the smart level measurements. In some cases, they may be measuring the turning space instead of the ramp. However, once the blunders are removed, the average differences and standard deviations are more consistent across the ramp styles. Hence, it is possible that the less experienced inspectors commit more errors on some ramp types.

Table 5.6: Statistical Analysis Of Differences (%) Between Inspectors Undergoing Certification And Ground Truth For Running Slope Measurements Based On Ramp Design Type.

Statistic	UD	PL	PR	C	BT	All
Average	-0.33	-0.12	-0.24	-0.16	0.22	-0.17
Std. Dev.	1.10	0.84	0.63	0.92	1.29	0.91
Min	-6.00	-5.90	-6.10	-6.60	-0.80	-6.60
Max	1.90	4.00	0.90	6.40	4.00	6.40
Median	-0.10	0.00	-0.10	0.00	0.00	0.00
Count	156	391	242	1136	11	1939
RMS	1.15	0.85	0.67	0.93	1.25	0.92

Table 5.7: Statistical Analysis Of Differences (%) Between Inspectors Undergoing Certification And Ground Truth For Running Slope Measurements Based On Ramp Design Type With Blunders Removed.

Statistic	UD	PL	PR	C	BT	All
Average	-0.13	-0.08	-0.18	-0.06	-0.16	-0.09
Std. Dev.	0.46	0.51	0.42	0.48	0.30	0.48
Min	-1.50	-1.50	-1.50	-1.50	-0.80	-1.50
Max	1.20	1.30	0.90	1.40	0.20	1.40
Median	-0.10	0.00	-0.10	0.00	-0.10	0.00
Count	143	371	237	1059	10	1821
RMS	0.48	0.51	0.46	0.49	0.33	0.49
Blunder Rate	8.3%	5.1%	2.1%	6.8%	9.1%	6.1%

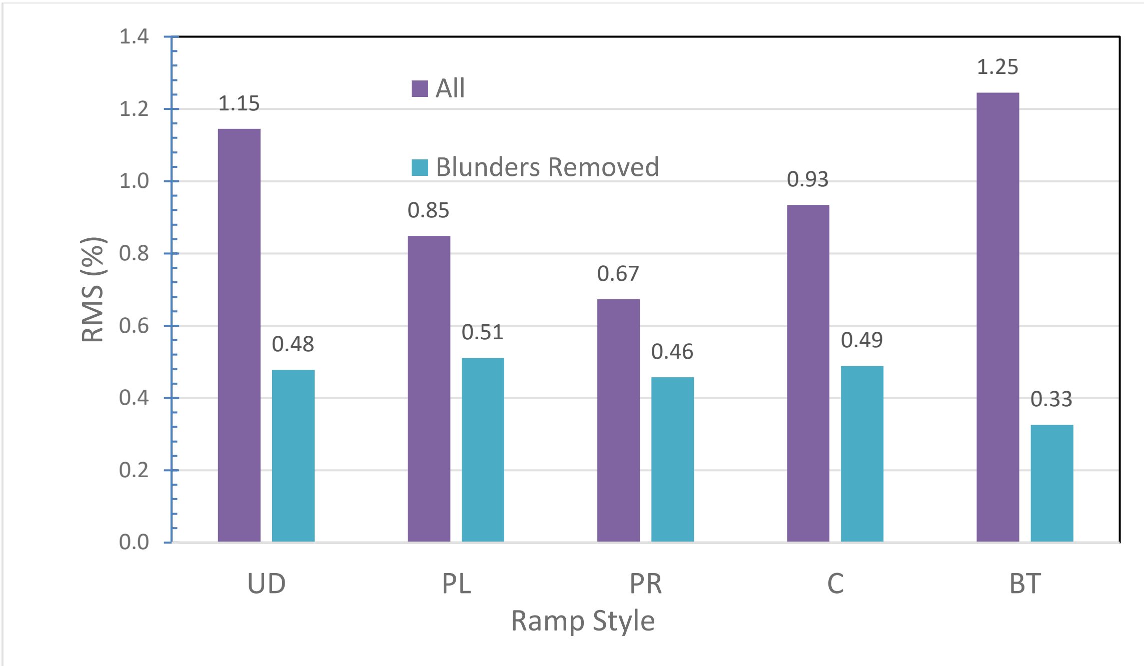


Figure 5.9: RMS differences in running slope measurements between inspectors undergoing certification and ground truth measurements categorized by ramp style with and without blunders removed. Note that BT contains relatively few measurements (11) and so it may not be statistically significant.

5.2.6 Comparison of Ground Truth Measurements

In February 2023, the research team performed smart level measurements on the curb ramps following the procedures outlined in Section 7.3.2. These were then compared to the ODOT ground truth measurements for the ramps for the running slope (Table 5.8, Table 5.9) and cross slope (Table 5.11). The average, median, and maximum measurements obtained by the research team were used for comparison. In addition, the proposed running slope (using the methods outlined in Sections 7.2.2 and 8.3.3) was used in the comparison. Note that the maximum and proposed statistics are most comparable to ODOT as the inspectors only provide the maximum measurement from several measurements taken on the slope.

Two blunders were detected and removed from the running slope measurements in (Table 5.10). No blunders were detected for the cross-slope. The standard deviations of 0.48% (running slope) and 0.54% (cross-slope) between the research team's measurements and the ODOT ground truth is very consistent with that observed from the inspectors undergoing certification and the ODOT ground truth.

Lastly, for some ramps, the research team obtained measurements on the detectable warning instead of the flat portion to evaluate the differences between those measurements. The statistical comparison for the running and cross slope measurements are provided in Table 5.11 and Table 5.12, respectively. Measurements obtained on the detectable warning have a higher RMS value given the increased difficulty in reliably placing the smart level.

Table 5.8: Statistical Analysis Of Differences (% Slope) Between The Ground Truth Running Slope Measurements Derived By ODOT And The Research Team.

Statistic	Average	Median	Max	Proposed
Average	-0.86	-0.84	-0.20	-0.08
Min	-2.72	-2.60	-2.20	-1.88
Max	3.90	3.98	4.80	4.85
Std. Dev.	0.88	0.88	0.90	0.90
Median	-0.88	-0.90	-0.3	-0.20
Count	45	45	45	45
RMS	1.22	1.21	0.92	0.89

Table 5.9: Statistical Analysis Of Differences (% Slope) Between The Ground Truth Running Slope Measurements Derived By ODOT And The Research Team With Blunders Removed.

Statistic	Average	Median	Max	Proposed
Average	-0.93	-0.91	-0.27	-0.16
Min	-2.16	-2.00	-1.15	-1.25
Max	-0.11	-0.10	0.50	0.72
Std. Dev.	0.42	0.42	0.40	0.43
Median	-0.88	-0.90	-0.3	-0.20
Count	43	43	43	43
RMS	1.02	1.00	0.48	0.45

Table 5.10: Statistical Analysis Of Differences (% Slope) Between The Ground Truth Running Slope Measurements Derived By ODOT And The Research Team On The Detectable Warnings With Blunders Removed.

Statistic	Average	Median	Max	Proposed
Average	-0.95	-0.93	-0.23	-0.11
Min	-1.97	-2.00	-1.15	-1.25
Max	-0.11	-0.10	0.50	0.72
Std. Dev.	0.43	0.46	0.47	0.52
Median	-0.98	-1.01	-0.23	-0.05
Count	16	16	16	16
RMS	1.04	1.03	0.79	0.74

Table 5.11: Statistical Analysis Of Differences (% Slope) Between The Ground Truth Cross Slope Measurements Derived By ODOT And The Research Team.

Statistic	Average	Median	Max	Proposed
Average	-0.58	-0.60	0.02	0.06
Min	-1.63	-1.60	-1.20	-1.17
Max	0.61	0.38	1.80	1.74
Std. Dev.	0.45	0.46	0.54	0.52
Median	-0.61	-0.60	0.00	0.01
Count	45	45	45	45
RMS	0.73	0.75	0.54	0.52

Table 5.12: Statistical Analysis Of Differences (% Slope) Between The Ground Truth Cross Slope Measurements On Detectable Warnings Derived By ODOT And The Research Team.

Statistic	Average	Median	Max	Proposed
Average	-0.63	-0.68	0.07	0.09
Min	-1.06	-1.20	-0.50	-0.41
Max	0.37	0.35	1.00	0.95
Std. Dev.	0.39	0.43	0.46	0.42
Median	-0.70	-0.73	-0.10	0.01
Count	17	17	17	17
RMS	0.74	0.80	0.87	0.84

6.0 CONCRETE TESTING

6.1 OVERVIEW OF SETUP

To evaluate the potential local variability of a planar, concrete surface as well as the impact of curing and hardening, a total of 12 ramps were built with different slopes (i.e., 0%, 2%, 4%, 6%, 8%, 10%) as outlined in Table 6.1 and Figure 6.1. These tests were conducted at the OSU O.H. Hinsdale Wavelab Facility at Oregon State University. Two ramps were built side by side for each slope (Figure 6.2) with a width of 4.5 feet, length of 6 feet, and thickness of 6 inches. The research team constructed the ramp specimens with different combinations of curing methods (i.e., wet burlap vs type 2 curing compound (CC) with 1 gallon per 150 sf) and concrete mixture (i.e., ODOT standard vs. minimum paste). Commercial Grade Concrete (CGC) requirements are 4-7% air, slump less than 5 inches, minimum 3000 psi (28 days) and placement temperature between 50 and 90 °F. The maximum aggregate size is not limited. Hence, the test also provides information on whether minimizing paste content in concrete could minimize potential shrinkage and planar movements.

Table 6.1: Summary Of The Ramp Specimen For Concrete Evaluation.

Ramp Specimen ID	Slope	Cure	Concrete Mixture
A1	0%	Wet Burlap	ODOT Standard
A2		Type 2 Curing Compound	ODOT Standard
B1	2%	Wet Burlap	ODOT Standard
B2		Type 2 Curing Compound	ODOT Standard
C1	4%	Type 2 Curing Compound	ODOT Standard
C2		Type 2 Curing Compound	Minimum Paste
D1	6%	Wet Burlap	ODOT Standard
D2		Wet Burlap	Minimum Paste
E1	8%	Wet Burlap	ODOT Standard
E2		Type 2 Curing Compound	ODOT Standard
F1	10%	Wet Burlap	ODOT Standard
F2		Type 2 Curing Compound	ODOT Standard

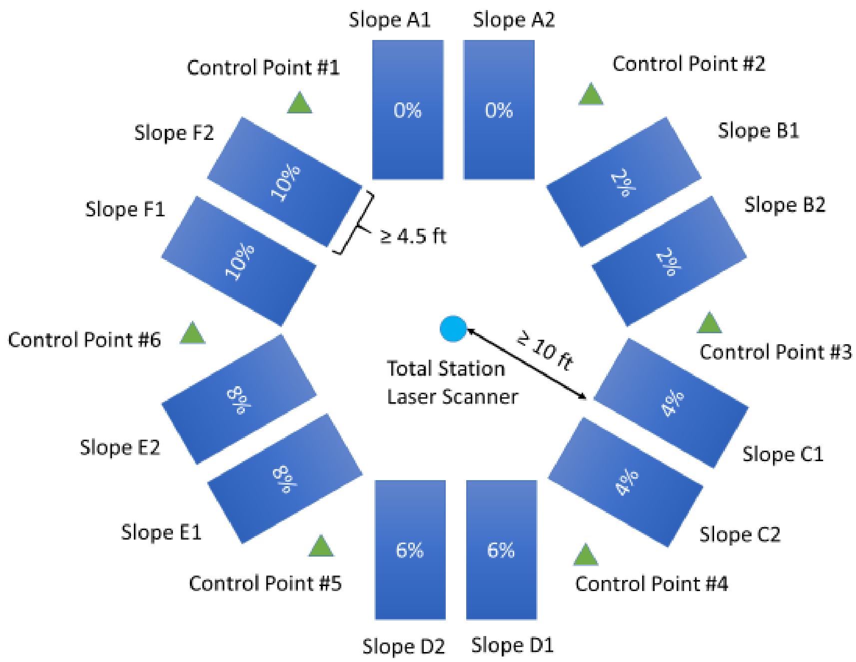


Figure 6.1: Planned ramp construction and survey configuration of the lab test for the concrete evaluation.

Figure 6.2: Ramp construction and survey configuration of the lab test for the concrete evaluation.

6.2 DATA COLLECTION

6.2.1 Laser scanning monitoring data

Once the construction was finished, the Leica ScanStation P50 was used to obtain high-precision point cloud data to monitor the ramps. The laser scanning is based on remote sensing technologies that can acquire high quality readings without making physical contact with the specimen. To ensure the consistency of the survey, the research team set up the laser scanner at the same location and height by marking the position of each tripod leg and using the same tripod with its full length for all the surveys. Such approach was demonstrated to be effective as the 3D root-mean-square-deviation (RMSD) of the scan origin location is 1.4 cm (0.55 inch) for all 13 epochs (Table 6.2) over the entire monitoring period (a total of 52 days). Photographic color information was also captured with the scan to provide more context of the specimen and surrounding environment (Figure 6.1).

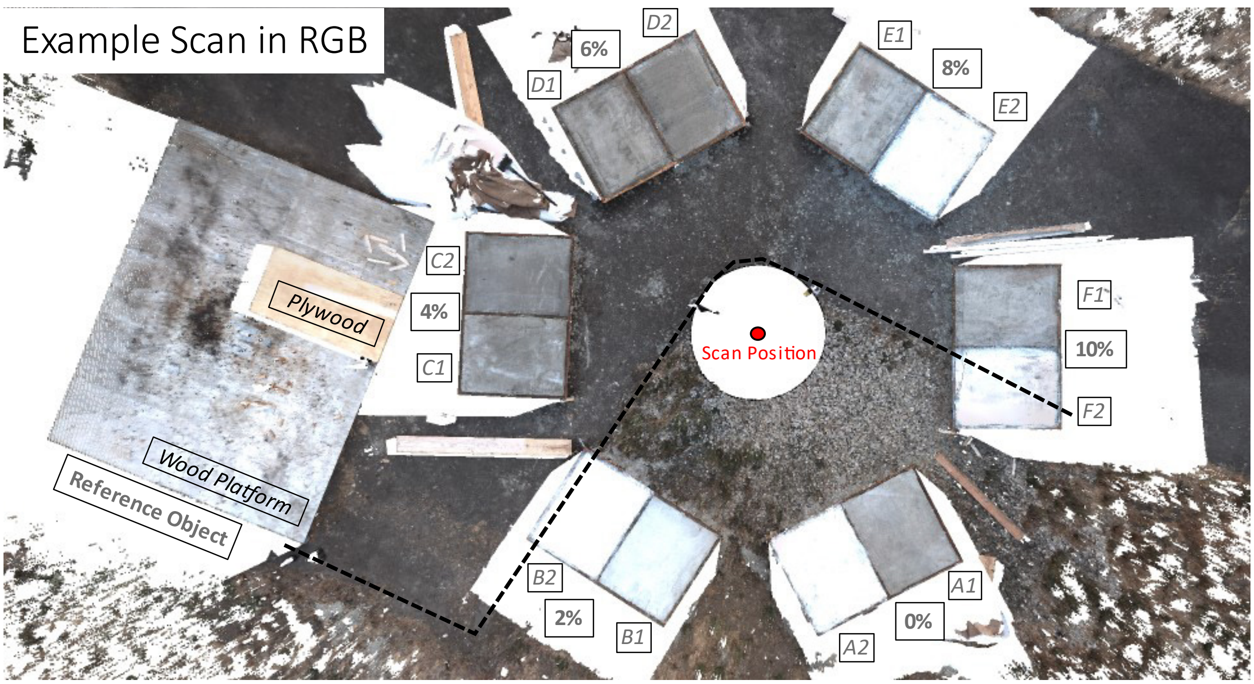


Figure 6.3: Example scan shown in RGB color.

Setting up permanent targets in a proper geometric configuration on the site is challenging due to the lack of stable objects (e.g., buildings) in a relatively close range. As a result, the point cloud registration in the post processing was based on cloud-to-cloud constraints leveraging iterative closest point (ICP) technique with the assistance of a few targets to initialize the scan alignment. The accuracy of registration from such a process can achieve sub-centimeter level registration quality. However, to be able to track changes on millimeter level, the registration process needs to eliminate the contributions from the points on the ramps as well as other moving objects present in the scene which are moving/settling during the test. Thus, the research team cropped each scan to only preserve the objects that are assumed to be fixed (e.g., stable buildings, paved road, etc.) and performed the ICP registration on these cropped point clouds. The root-mean-square-error (RMSE) of a total of 78 cloud-to-cloud constraints was found to be 0.6 mm (0.02 inch) while the RMSE at each scan ranges from 0.4 mm to 0.8 mm (Table 6.2). The resulting transformation parameters of each scan were applied to each scan to ensure geometric alignment for the subsequent change analysis.

Table 6.2: Summary Of The Laser Scanning And Point Cloud Registration Results

ScanID	Date	Time	X (m)	Y (m)	Z (m)	Cloud-to-Cloud RMSE (m)
01	09/09/2021	12:55	0.0000	0.0000	0.0000	0.0005
02	09/09/2021	16:14	0.0028	-0.0063	0.0005	0.0007
03	09/09/2021	19:14	0.0037	-0.0028	0.0006	0.0004
04	09/10/2021	13:18	-0.0027	-0.0056	0.0057	0.0005
05	09/11/2021	14:38	-0.0071	-0.0074	0.0036	0.0005
06	09/12/2021	19:21	-0.0049	-0.0036	0.0038	0.0004
07	09/13/2021	19:39	-0.0036	-0.0128	-0.0188	0.0007
08	09/14/2021	19:20	-0.0055	-0.0078	-0.0051	0.0004
09	09/15/2021	19:16	-0.0033	-0.0075	0.0027	0.0006
10	09/16/2021	16:14	0.0036	-0.0217	-0.0082	0.0006
11	09/23/2021	17:24	-0.0018	-0.0106	-0.0036	0.0007
12	10/07/2021	14:33	0.0077	-0.0197	0.0027	0.0008
13	10/31/2021	14:28	0.0035	0.0033	-0.0040	0.0008

6.2.2 Environmental condition data

In addition to the laser scans, the research team also collected environmental data with a set of Kestrel DROP D2/D3 sensors. One unit was placed at each wooden platform and logged data throughout the monitoring (Table 6.3) with the exception of the last epoch on 10/31/2021 where data were obtained from the Corvallis Municipal Airport. The units recorded temperature and humidity readings every 30 minutes. The average and standard deviation of the temperature readings from all 6 units were computed at the moment of the survey and compared with the data recorded from the weather station at the Corvallis Municipal Airport (Figure 6.4 and Figure 6.5). The data from the environment sensors in this study share the same overall trend as the readings from the weather station. The difference in the temperature readings as well as the range between the two can be explained by the fact that the recordings were from different instruments. Additionally, the units used in this study were much closer to the ground and hence affected more by the ground surface temperature, which varies significantly more than the air temperature. Furthermore, each unit at the testing site can be impacted by the heat from the curing process, especially when the ramp is covered since the unit is attached to the wood frame. The research team also collected cumulative rainfall recordings from the Hyslop weather station to track the rainfall between epochs.

Table 6.3: Summary Of The Environment Readings From The Field And The Reference Stations.

ScanID	Field Temperature (°F)	Field Relative Humidity	Reference Temperature (°F)	Reference Relative Humidity	Reference Accumulative Rainfall (inch)
01	98.8	35.4%	77	52%	0.00
02	97.2	32.9%	77	52%	0.00
03	71.8	62.1%	68	78%	0.00
04	79.3	43.8%	68	59%	0.00
05	102.9	22.6%	76	37%	0.00
06	66.2	50.4%	65	58%	0.00
07	66.7	45.6%	64	59%	0.00
08	72.0	54.8%	73	61%	0.00
09	64.0	41.3%	63	49%	0.00
10	88.3	16.5%	69	30%	0.00
11	88.0	33.0%	71	52%	1.38
12	79.0	40.4%	58	51%	1.64
13	-	-	58	56%	2.59

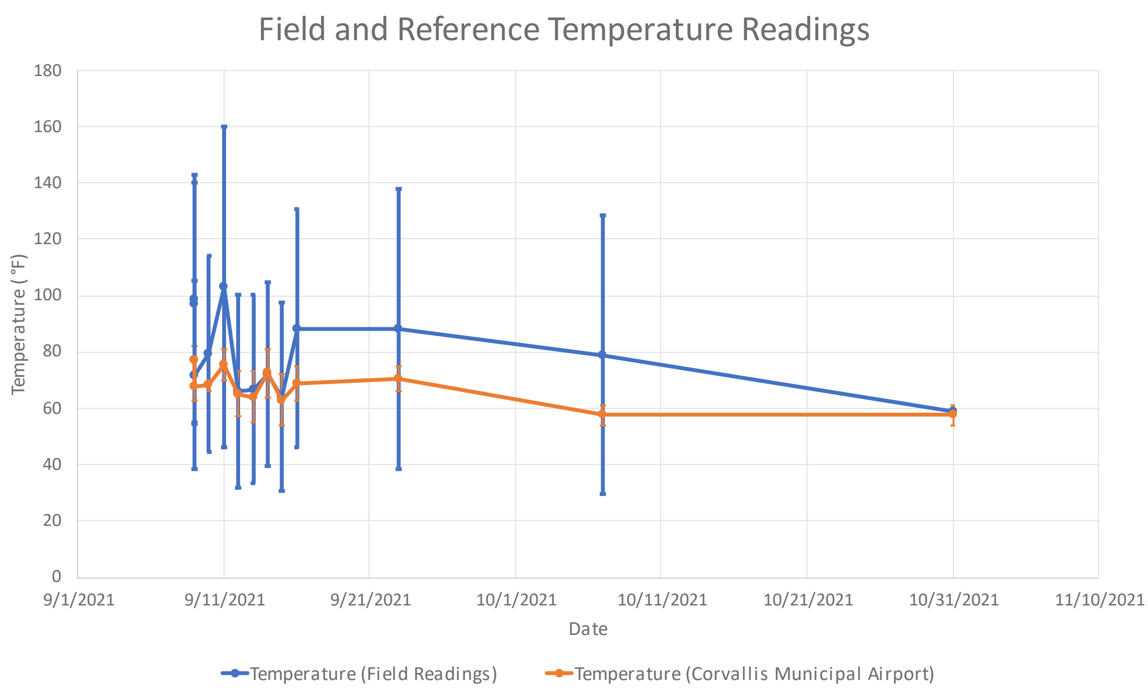


Figure 6.4: Temperature recordings in the field and from the weather station at Corvallis Municipal Airport.

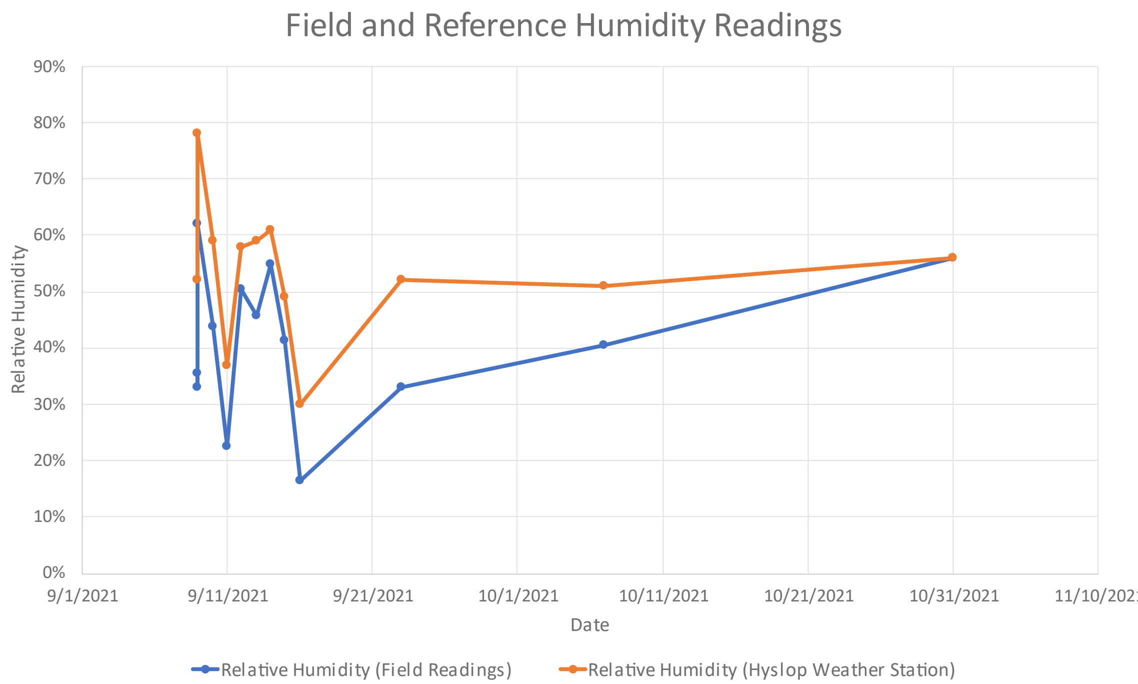


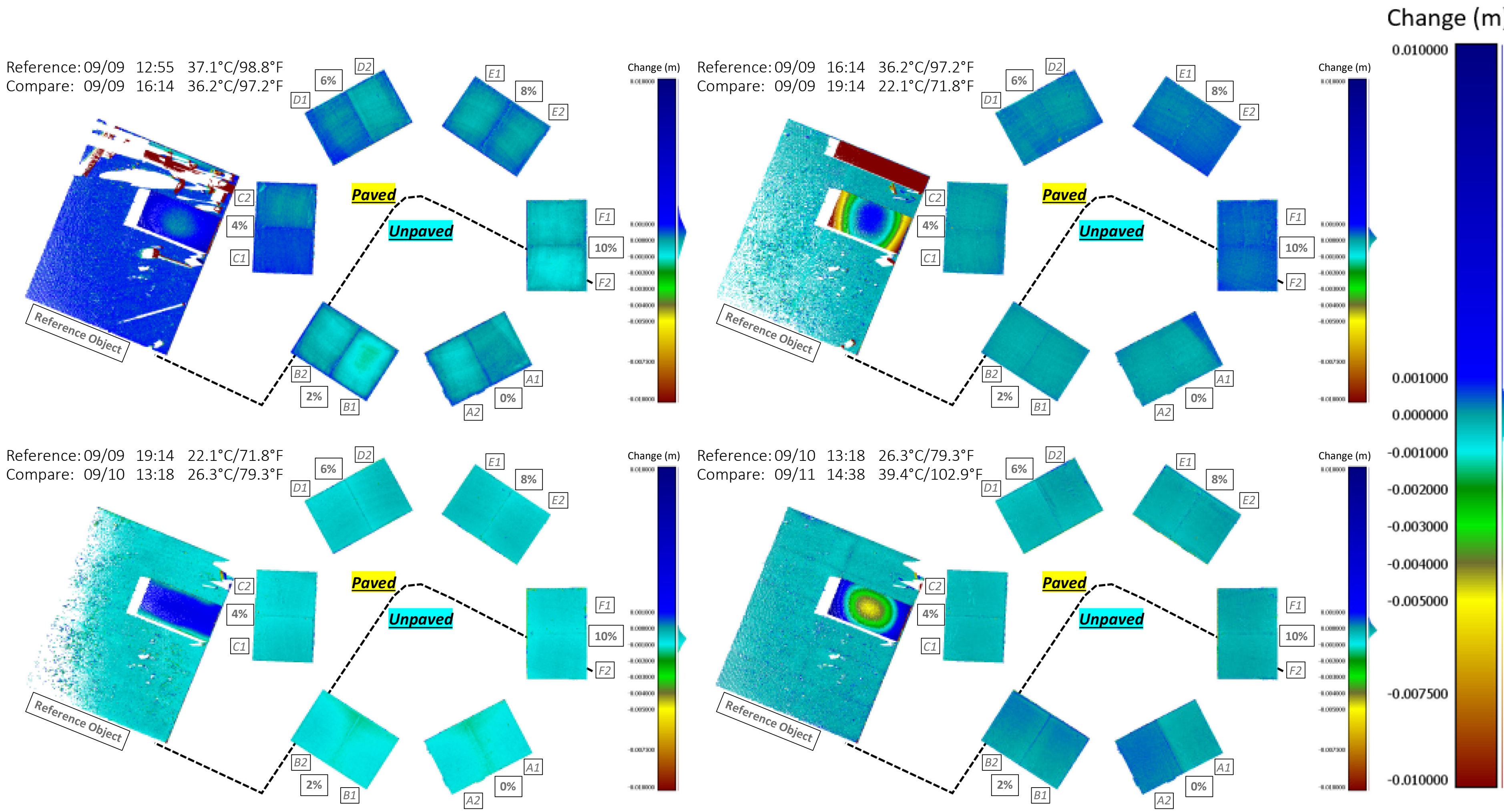
Figure 6.5: Humidity recordings in the field and from the Hyslop weather station.

6.2.3 Smart Level Readings

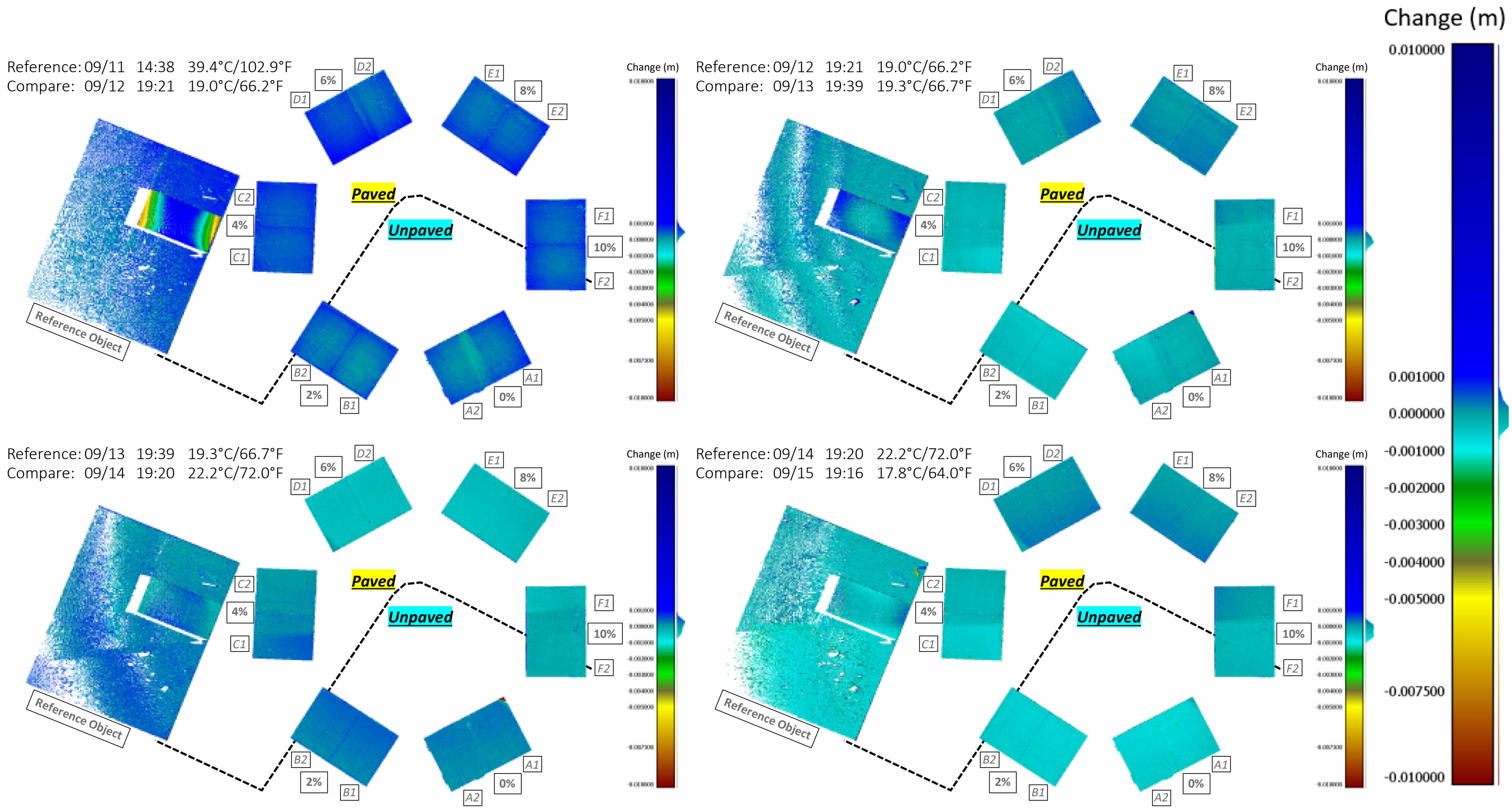
After completion of the scanning of the last epoch in this test, the research team measured the running slope of each specimen with a 24-inch smart level using the same methodology applied in the in-situ ramp data collection (Section 7.0) to determine the final slopes. The smart level data was also used to validate the program developed by the research team through Pactrans Research that can take virtual slope measurements in the point cloud.

6.3 CONCRETE MONITORING

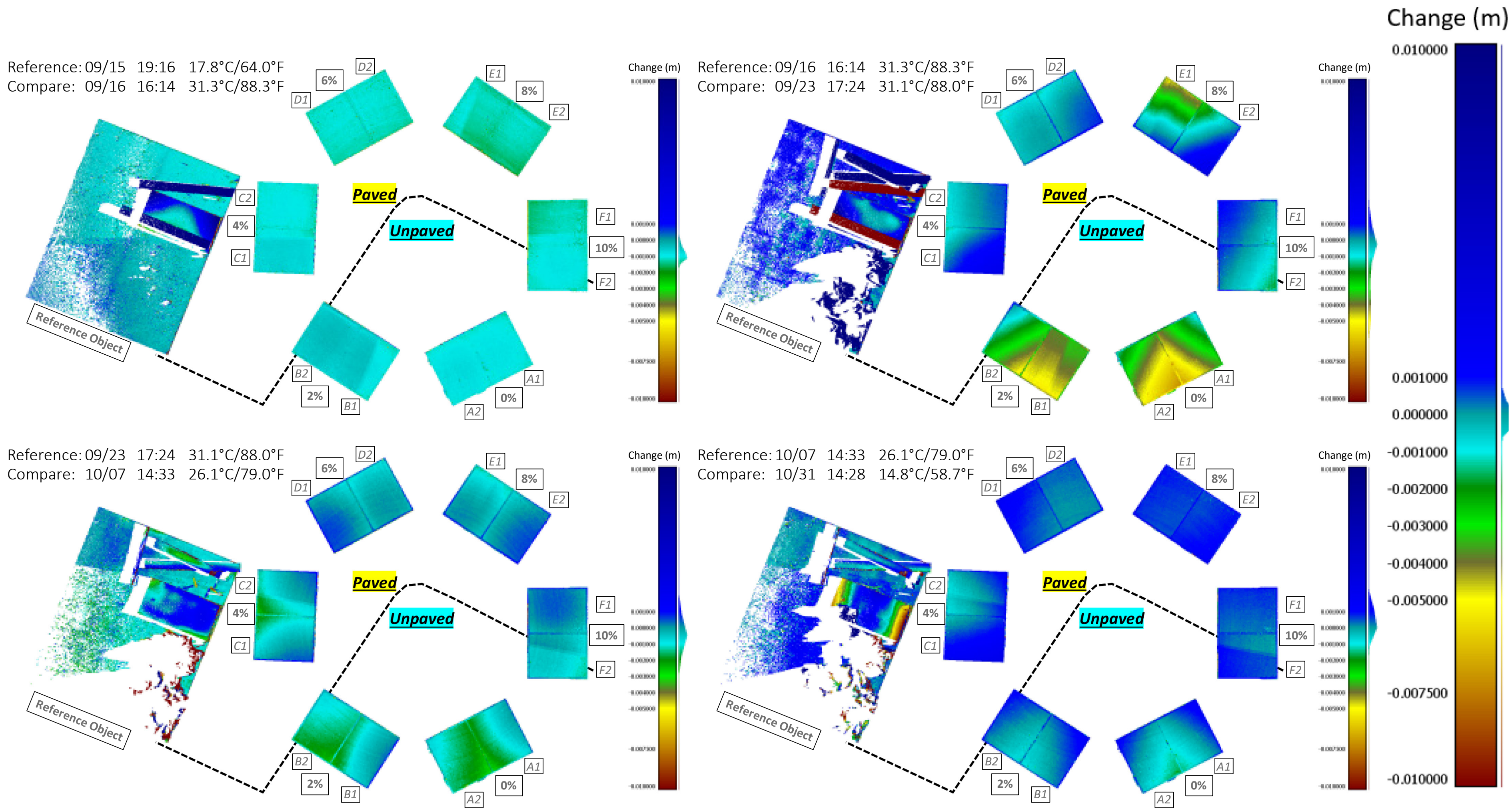
To conduct change analysis, the point cloud data from all epochs was cropped and a digital terrain model (DTM) was generated using RAMBO software with a cell size of 1 cm (0.4 inch). The grid points from each epoch were then exported. It is worth noting that in such a process, most noise can be filtered by taking the median elevation in each cell of the terrain model when generating the grid point. Then the grid points from each epoch were compared with its prior epoch using CloudCompare and the changes in Z-axis were visualized and analyzed (Figure 6.6). A large wood platform and a piece of plywood on it were placed near the specimen throughout the test to serve as reference objects to validate the changes detected in the analysis. As shown in the results, the changes on the wood platform indicate the bias and background noise of the monitoring. The changes tracked from the plywood effectiveness of the monitoring as its shape is also impacted by the temperature. For example, in the upper left figure of Figure 6.6(a), the center of the plywood is raised up while its edges lower when it cools down. The bottom left shows the opposite pattern of change when the plywood heats up. Nevertheless, the figures on the left in Figure 6.6(a) do not show significant change when the temperature readings from two epochs are relatively close.



(a) 09/09/2021 to 09/11/2021



(b) 09/11/2021 to 09/15/2021



(c) 09/15/2021 to 10/31/2021

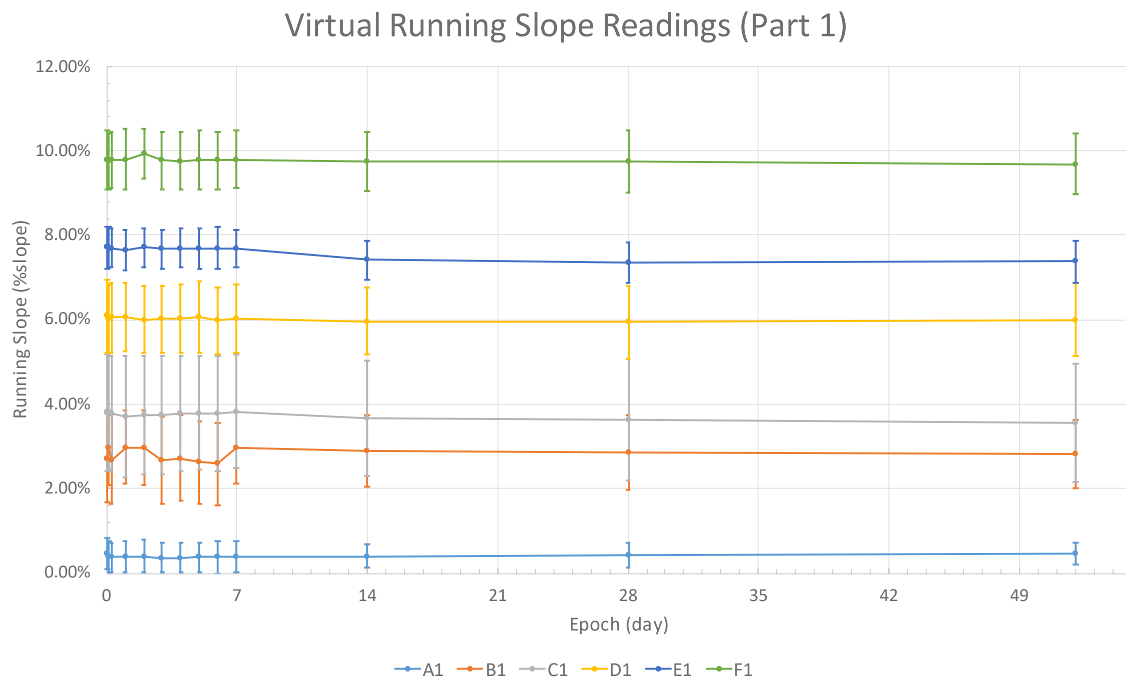
Figure 6.6: Change analysis of the DTM for each epoch.

It can be seen from the analysis results that most of the ramps did not have substantial local changes throughout the test where the changes between two epochs are within a few millimeters. Some noticeable changes took place from 09/16 to 10/31 (Figure 6.6 (c)), which show clear correlation with the rainfall occurring during the same period (Figure 6.5). This is likely caused by the consolidation settlement because the local changes on ramp A1, A2, B1, and B2 built on the unpaved gravel are significantly higher than the others on the surface paved with asphalt. Ramp E1 also shows some noticeable changes from 09/16 to 09/23. However, the ramp next to it, E2, does not share the same trend and neither ramp has significant changes for the following epochs. Thus, the single incidence of settlement on ramp E1 could be caused by settlement on part of the frame. Similar phenomena can be found on F2 in the same epoch where the corner of the wood frame settled more than the other parts and the settlement did not continue to the following epochs.

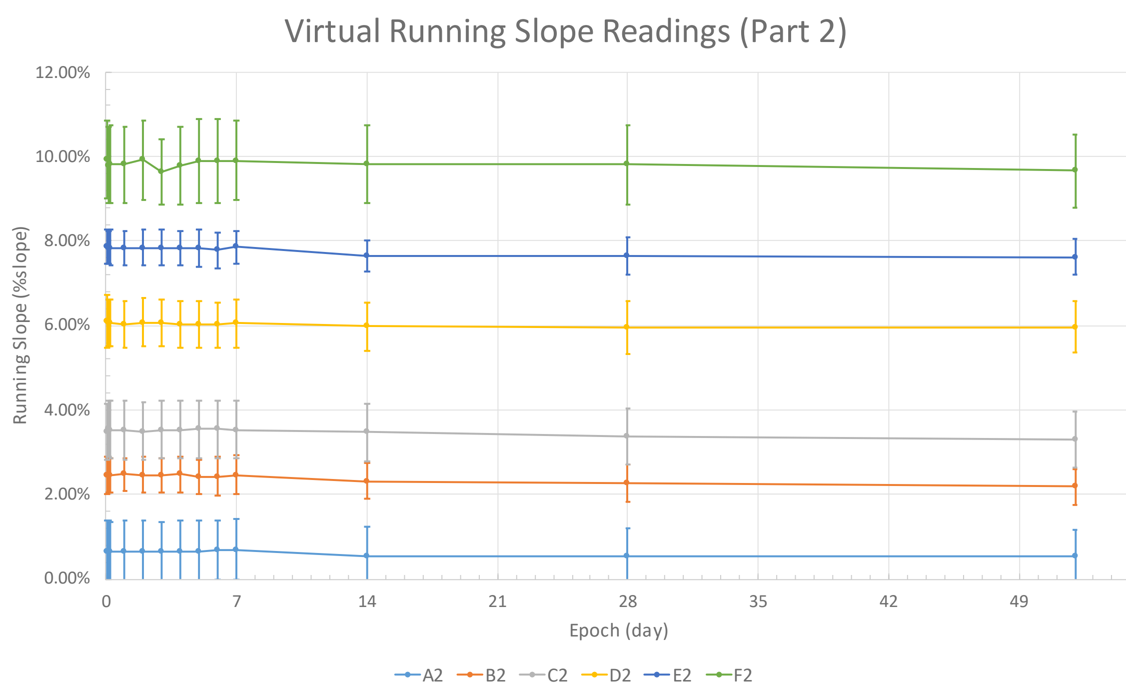
6.4 SLOPE CHANGE ANALYSIS

To further measure and analyze the impact of the local changes on the surface to the slope measurements with smart level, a program developed by the research team was deployed to acquire virtual slope readings in the point clouds for each epoch on all the specimen such that minimal physical contact to the specimen can be achieved. The virtual smart level program takes 3D point cloud as input, and first generates a DTM with a user-given cell size. Then the sampling locations are determined in a grid pattern with the same sampling distance used in the field data collection (45 cm/1.5 ft). For each sample, the program mimics the smart level by defining the length of the equipment in the DTM and search for two supporting points along the virtual equipment on the surface assuming the bottom of the smart level is flat while its center of gravity aligns with its centroid. Such approach considers the roughness and flatness of the ramp surface better and outperforms other techniques (e.g., linear regression, surface normals) in terms of accuracy in estimating average slope, surface roughness (standard deviation of the slope readings), and maximum slope (standard inspection procedure). The RMSE of the average slope, surface roughness, and maximum slope in the accuracy assessment conducted in the prior work by comparing with smart level survey are 0.18%, 0.14%, and 0.32%, respectively, which are on par with the specified accuracy of the smart level (0.2%).

The overall trend of the running slope and roughness on each ramp shows to be stable and there is no drastic change taking place (Figure 6.6). The differences in slope metrics between the first and last epoch including average slope (dAVG), standard deviation of slope (dSTD), minimum slope (dMIN), maximum slope (dMAX), and median slope (dMED), and number of samples (dN) were summarized for both running and cross slope (Table 6.4 and Table 6.5). It is worth noting that the number of samples (N) is determined in the virtual smart level measurement program. The research team tracked the changes in the number of samples (dN) to validate the consistency of the point cloud editing and computation. As seen in the overall changes, there is no clear correlation between the change in the slope metrics and the designed slope of the ramps in both cases of running and cross slope. Thus, a statistical analysis is carried out to describe the changes detected in the virtual slope measurements quantitatively (Table 6.6 and Table 6.7). Based on the root-mean-squared-deviation (RMSD) of the slope metrics, there is no significant difference between running and cross slope where all the RMSD values are under 0.3%. It is also noticeable that the surface roughness is very consistent throughout the testing period which indicates that the local changes detected in the point cloud discussed in the previous section have minimal impact on the roughness readings. However, for the maximum and average slope readings, the changes on the surface have a significant impact.



(a) Ramps on the left side of the wood frame.



(b) Ramps on the right side of the wood frame.

Figure 6.7: Virtual running slope monitoring where the error bars represent the roughness/standard deviation.

Table 6.4: Difference Of The Virtual Running Slope Readings Between The First And Last Epoch (09/09/2022 - 10/31/2022).

ID	dAVG	dSTD	dMIN	dMAX	dMED	dN
A1	0.00%	-0.10%	0.03%	-0.21%	-0.01%	0
A2	-0.08%	-0.13%	0.01%	-0.31%	-0.11%	0
B1	0.10%	-0.23%	0.63%	-0.26%	0.15%	-1
B2	-0.26%	-0.01%	-0.28%	-0.18%	-0.26%	0
C1	-0.24%	0.01%	-0.29%	-0.36%	-0.28%	0
C2	-0.21%	0.00%	-0.20%	-0.23%	-0.19%	0
D1	-0.08%	0.00%	-0.08%	-0.09%	-0.09%	0
D2	-0.12%	-0.01%	-0.12%	-0.12%	-0.08%	0
E1	-0.34%	0.01%	-0.38%	-0.39%	-0.36%	0
E2	-0.24%	0.01%	-0.29%	-0.20%	-0.24%	0
F1	-0.11%	0.03%	-0.22%	-0.17%	-0.12%	0
F2	-0.28%	-0.04%	-0.16%	-0.24%	-0.38%	-1

Table 6.5: Difference Of The Virtual Cross Slope Readings Between The First And Last Epoch (09/09/2022 - 10/31/2022).

ID	dAVG	dSTD	dMIN	dMAX	dMED	dN
A1	0.44%	0.09%	0.35%	0.60%	0.38%	0
A2	0.31%	0.05%	0.24%	0.39%	0.23%	0
B1	0.13%	-0.05%	0.33%	0.19%	0.06%	0
B2	0.36%	0.04%	0.08%	0.38%	0.39%	0
C1	0.37%	0.04%	-0.03%	0.17%	0.55%	0
C2	-0.08%	-0.05%	-0.04%	-0.12%	0.00%	-1
D1	0.13%	0.00%	0.09%	0.16%	0.13%	0
D2	-0.08%	-0.02%	-0.02%	-0.15%	-0.11%	0
E1	0.03%	-0.14%	0.29%	-0.10%	-0.01%	0
E2	0.34%	0.00%	0.38%	0.33%	0.36%	0
F1	0.05%	0.02%	0.33%	0.30%	-0.06%	0
F2	0.02%	-0.01%	0.03%	-0.02%	0.04%	0

Table 6.6: Statistical Summary Of The Virtual Running Slope Metric Variations Between The First And Last Epoch (09/09/2022 - 10/31/2022).

Stats	dAVG	dSTD	dMIN	dMAX	dMED	dN
AVG	-0.15%	-0.04%	-0.11%	-0.23%	-0.16%	-0.2
STD	0.13%	0.08%	0.27%	0.09%	0.15%	0.4
MIN	-0.34%	-0.23%	-0.38%	-0.39%	-0.38%	-1.0
MAX	0.10%	0.03%	0.63%	-0.09%	0.15%	0.0
MED	-0.16%	0.00%	-0.18%	-0.22%	-0.16%	0.0
RMSD	0.20%	0.09%	0.29%	0.25%	0.22%	0.4

Table 6.7: Statistical Summary Of The Virtual Cross Slope Metric Variations Between The First And Last Epoch (09/09/2022 - 10/31/2022).

Stats	dAVG	dSTD	dMIN	dMAX	dMED	dN
AVG	0.17%	0.00%	0.17%	0.18%	0.16%	-0.1
STD	0.19%	0.06%	0.17%	0.24%	0.21%	0.3
MIN	-0.08%	-0.14%	-0.04%	-0.15%	-0.11%	-1.0
MAX	0.44%	0.09%	0.38%	0.60%	0.55%	0.0
MED	0.13%	0.00%	0.17%	0.18%	0.10%	0.0
RMSD	0.25%	0.06%	0.24%	0.30%	0.27%	0.3

The research team further investigated the changes in average and maximum slope in each epoch by generating a statistical summary of the deviations (Table 6.8, Table 6.9, Table 6.10, and Table 6.11). Looking at the average difference of the average and maximum slope (-0.11% and -0.14%) detected from the point cloud data, the epoch from 09/16/2021 to 09/23/2021 stands out in most of the metrics especially for running slope measurements. This period is also when the rainfall during that week caused most of the consolidation settlement. The trend of the change in running slope also matches the results of the change analysis in the point cloud where all significant changes due to consolidation settlement are near the top of the ramps and would lower the overall slope. In summary, the impact of the concrete hardening and curing process along with the temperature during the survey to the slope measurements is usually not significant considering the accuracy of the smart level (0.2%). However, the consolidation settlement of the curb ramp can cause significant changes in running and cross slope, which could lead to discrepancies between the slope measurements performed at substantially different times.

Table 6.8: Statistical Analysis Of The Change In Virtual Average Running Slope Readings In Each Epoch.

Date/Time	AVG	STD	MIN	MAX	MED	RMSD
09/09/2021 12:55	-	-	-	-	-	-
09/09/2021 16:14	0.00%	0.09%	-0.14%	0.25%	-0.01%	0.09%
09/09/2021 19:14	-0.02%	0.09%	-0.29%	0.04%	-0.01%	0.09%
09/10/2021 13:18	0.01%	0.09%	-0.06%	0.30%	-0.01%	0.10%
09/11/2021 14:38	0.02%	0.06%	-0.06%	0.13%	0.02%	0.06%
09/12/2021 19:21	-0.07%	0.12%	-0.30%	0.03%	-0.02%	0.13%
09/13/2021 19:39	0.03%	0.05%	-0.02%	0.17%	0.02%	0.06%
09/14/2021 19:20	0.00%	0.05%	-0.09%	0.11%	0.00%	0.05%
09/15/2021 19:16	-0.01%	0.03%	-0.08%	0.03%	0.00%	0.03%
09/16/2021 16:14	0.05%	0.11%	-0.02%	0.38%	0.03%	0.12%
09/23/2021 17:24	-0.11%	0.07%	-0.26%	0.02%	-0.09%	0.13%
10/07/2021 14:33	-0.03%	0.03%	-0.11%	0.03%	-0.02%	0.04%
10/31/2021 14:28	-0.03%	0.06%	-0.15%	0.06%	-0.04%	0.07%

Table 6.9: Statistical Analysis Of The Change In Virtual Average Cross Slope Readings In Each Epoch.

Date/Time	AVG	STD	MIN	MAX	MED	RMSD
09/09/2021 12:55	-	-	-	-	-	-
09/09/2021 16:14	0.01%	0.02%	-0.02%	0.04%	0.01%	0.02%
09/09/2021 19:14	-0.01%	0.03%	-0.05%	0.04%	0.00%	0.03%
09/10/2021 13:18	0.00%	0.02%	-0.03%	0.05%	0.01%	0.03%
09/11/2021 14:38	0.00%	0.04%	-0.08%	0.06%	0.01%	0.04%
09/12/2021 19:21	0.00%	0.03%	-0.07%	0.05%	0.00%	0.03%
09/13/2021 19:39	0.00%	0.04%	-0.07%	0.08%	0.00%	0.04%
09/14/2021 19:20	0.00%	0.02%	-0.02%	0.05%	0.00%	0.02%
09/15/2021 19:16	0.01%	0.02%	-0.03%	0.04%	0.01%	0.02%
09/16/2021 16:14	0.01%	0.03%	-0.03%	0.07%	0.00%	0.03%
09/23/2021 17:24	0.05%	0.09%	-0.08%	0.19%	0.02%	0.10%
10/07/2021 14:33	0.05%	0.06%	-0.08%	0.13%	0.04%	0.08%
10/31/2021 14:28	0.04%	0.05%	-0.04%	0.14%	0.04%	0.07%

Table 6.10: Statistical Analysis Of The Change In Virtual Maximum Running Slope Readings In Each Epoch.

Date/Time	AVG	STD	MIN	MAX	MED	RMSD
09/09/2021 12:55	-	-	-	-	-	-
09/09/2021 16:14	-0.01%	0.09%	-0.27%	0.08%	0.02%	0.09%
09/09/2021 19:14	-0.02%	0.12%	-0.31%	0.21%	-0.01%	0.12%
09/10/2021 13:18	0.02%	0.06%	-0.10%	0.12%	0.02%	0.06%
09/11/2021 14:38	0.00%	0.04%	-0.06%	0.09%	-0.02%	0.04%
09/12/2021 19:21	-0.08%	0.19%	-0.66%	0.07%	-0.04%	0.20%
09/13/2021 19:39	0.07%	0.19%	-0.05%	0.67%	0.01%	0.21%
09/14/2021 19:20	0.01%	0.04%	-0.06%	0.08%	0.00%	0.04%
09/15/2021 19:16	-0.02%	0.06%	-0.13%	0.04%	0.00%	0.06%
09/16/2021 16:14	0.03%	0.06%	-0.06%	0.16%	0.01%	0.07%
09/23/2021 17:24	-0.14%	0.08%	-0.31%	-0.02%	-0.13%	0.16%
10/07/2021 14:33	-0.02%	0.05%	-0.11%	0.06%	-0.02%	0.06%
10/31/2021 14:28	-0.06%	0.05%	-0.14%	0.01%	-0.08%	0.08%

Table 6.11: Statistical Analysis Of The Change In Virtual Maximum Cross Slope Readings In Each Epoch.

Date/Time	AVG	STD	MIN	MAX	MED	RMSD
09/09/2021 12:55	-	-	-	-	-	-
09/09/2021 16:14	-0.03%	0.07%	-0.17%	0.07%	-0.04%	0.08%
09/09/2021 19:14	0.00%	0.07%	-0.09%	0.17%	0.00%	0.07%
09/10/2021 13:18	-0.01%	0.06%	-0.17%	0.07%	0.00%	0.06%
09/11/2021 14:38	0.00%	0.05%	-0.08%	0.09%	0.00%	0.05%
09/12/2021 19:21	0.05%	0.07%	-0.03%	0.17%	0.03%	0.09%
09/13/2021 19:39	-0.02%	0.05%	-0.10%	0.04%	0.00%	0.05%
09/14/2021 19:20	0.02%	0.05%	-0.03%	0.17%	0.01%	0.06%
09/15/2021 19:16	-0.02%	0.10%	-0.33%	0.06%	0.00%	0.10%
09/16/2021 16:14	0.03%	0.08%	-0.06%	0.20%	0.01%	0.08%
09/23/2021 17:24	0.05%	0.14%	-0.11%	0.28%	0.01%	0.15%
10/07/2021 14:33	0.04%	0.11%	-0.22%	0.18%	0.05%	0.12%
10/31/2021 14:28	0.06%	0.05%	-0.03%	0.13%	0.07%	0.08%

6.5 COMPARISON TO DESIGN

The average measured slopes were compared to the design values for running (Table 6.12) and cross (Table 6.13) slopes for the initial and final laser scan surveys of the test. As mentioned previously, prior to the construction of the ramp, the wood frames were carefully measured to ensure that they were at the desired cross slope. However, variances on the order of 0.20% were observed in the readings across the frame due to the smart level measurement error and variances in the frame itself. The standard deviations for the running slope are similar to the tolerance of 0.50% recommended by Ballast et al. (2011) for the construction. Larger deviations and an overall bias were also observed in the cross-slope measurements compared to the running slope.

Smart level readings were obtained for the running slope at the end of the test. The maximum values from the laser scanning virtual smart level analysis were also computed for comparison (Table 6.14 and Table 6.15). The deviations tended to be higher at the end of the test due to the curing process and settlement of the frame that occurred during the monitoring period. Notably there is more variance in the smart level readings of the running slope compared to the laser scanning data. However, it is also observed that when looking at the maximum values compared with the design values, deviations of 1% or more were observed, likely owing to imperfections in the frame as well as the local surface roughness during the finishing process. The maximum reading is highly sensitive to the surface roughness.

Table 6.12: Comparison Of The Average Measured Running Slopes On Concrete Test Ramps To The Design Value Based On Laser Scanning.

		Laser Scanning (Virtual Smart Level)			
Ramp ID	**Design**	**Initial**	**Δ**	**Final**	**Δ**
A1	0%	0.45%	0.45%	0.45%	0.45%
B1	2%	2.72%	0.72%	2.82%	0.82%
C1	4%	3.80%	-0.20%	3.56%	-0.44%
D1	6%	6.09%	0.09%	6.00%	0.00%
E1	8%	7.72%	-0.28%	7.38%	-0.62%
F1	10%	9.79%	-0.21%	9.69%	-0.31%
A2	0%	0.63%	0.63%	0.55%	0.55%
B2	2%	2.45%	0.45%	2.19%	0.19%
C2	4%	3.50%	-0.50%	3.29%	-0.71%
D2	6%	6.08%	0.08%	5.96%	-0.04%
E2	8%	7.85%	-0.15%	7.62%	-0.38%
F2	10%	9.93%	-0.07%	9.66%	-0.34%
Average			**0.09%**		**-0.07%**
Std. Dev.			**0.38%**		**0.47%**

Table 6.13: Comparison Of The Average Measured Cross Slopes On Concrete Test Ramps To The Design Value Based On Laser Scanning Data. (No Smart Level Readings Were Obtained For Cross Slope). The Design Value For The Cross Slopes Was 0%).

Ramp ID	Laser Scanning (Virtual Smart Level)	
	Initial	Final
A1	0.26%	0.71%
B1	0.82%	0.95%
C1	0.54%	0.91%
D1	0.35%	0.48%
E1	0.56%	0.59%
F1	0.98%	1.04%
A2	0.93%	1.24%
B2	0.98%	1.34%
C2	0.32%	0.23%
D2	0.40%	0.33%
E2	0.79%	1.13%
F2	0.47%	0.49%
Average	**0.62%**	**0.79%**
Std. Dev.	**0.26%**	**0.35%**

Table 6.14: Comparison of maximum measured running slopes on concrete test ramps to the design value based on laser scanning and smart level data.

Ramp ID	Design	Laser Scanning (Virtual Smart Level)				Smart Levels (Field Survey)			
		Initial	Δ	Final	Δ	Final (current)	Δ	Final (proposed)	Δ
A1	0%	1.15%	1.15%	0.94%	0.94%	1.45%	1.45%	1.26%	1.26%
B1	2%	3.88%	1.88%	3.62%	1.62%	3.80%	1.80%	4.32%	2.32%
C1	4%	5.40%	1.40%	5.04%	1.04%	5.25%	1.25%	5.76%	1.76%
D1	6%	7.12%	1.12%	7.03%	1.03%	7.25%	1.25%	7.51%	1.51%
E1	8%	8.35%	0.35%	7.95%	-0.05%	7.85%	-0.15%	7.95%	-0.05%
F1	10%	10.72%	0.72%	10.56%	0.56%	10.70%	0.70%	10.80%	0.80%
A2	0%	2.21%	2.21%	1.89%	1.89%	1.95%	1.95%	1.68%	1.68%
B2	2%	3.02%	1.02%	2.83%	0.83%	3.40%	1.40%	3.17%	1.17%
C2	4%	5.02%	1.02%	4.79%	0.79%	4.85%	0.85%	4.46%	0.46%
D2	6%	7.04%	1.04%	6.92%	0.92%	6.60%	0.60%	6.66%	0.66%
E2	8%	8.38%	0.38%	8.18%	0.18%	8.20%	0.20%	8.37%	0.37%
F2	10%	11.44%	1.44%	11.21%	1.21%	11.05%	1.05%	11.35%	1.35%
Average			**1.14%**		**0.91%**		**1.03%**		**1.11%**
Std. Dev.			**0.52%**		**0.52%**		**0.60%**		**0.65%**

Table 6.15: Comparison of maximum measured cross slopes on concrete test ramps to the design value based on laser scanning data. (No smart level readings were obtained for cross slope). The design value for the cross slopes was 0%).

Ramp ID	Laser Scanning (Virtual Smart Level)	
	Initial	Final
A1	0.96%	1.56%
B1	1.33%	1.53%
C1	1.50%	0.55%
D1	0.74%	0.90%
E1	0.86%	0.90%
F1	2.21%	2.52%
A2	1.83%	2.22%
B2	2.52%	2.90%
C2	0.67%	0.55%
D2	0.79%	0.65%
E2	1.02%	1.35%
F2	1.57%	1.56%
Average	**1.33%**	**1.43%**
Std. Dev.	**0.58%**	**0.75%**

7.0 IN-SITU CURB RAMP DATABASE

7.1 OVERVIEW

Based on the results of the calibration testing, the research team developed a database of measures from a variety of in-service or recently constructed curb ramps encompassing many types of curb ramps. Applicable fields from existing data measured by ODOT field inspectors available in TransGIS were also evaluated and integrated into the research database.

7.2 FIELD DATA COLLECTION

7.2.1 Site Selection

For the in-situ measurement testing, the research team collected data on curb ramps in multiple locations (Table 7.1) that are in 9 cities across the state of Oregon (Figure 7.1) to cover curb ramps that were built at different times and in different conditions leveraging the information provided on TransGIS platform. There were 17 intersections and approximately 100 curb ramps that were surveyed for testing measurements using different methods. Approximately half of the curb ramps were selected for repeated survey approximately 6 months after the first in-situ measurements based on their conditions and level of ADA compliance. For example, one curb ramp in Salem (Figure 7.2) was in poor condition and was clearly not ADA compliant in its design. Given that it probably will be replaced soon, the research team did not perform a repeated survey as it does not properly reflect the current design and construction practices for curb ramps by ODOT and would bias the analysis. No significant change was detected in the six-month survey, so additional surveys were deemed unnecessary.

Table 7.1: Cities, locations, and dates of the data collection for in-situ testing.

City	Location (number of intersections)	Date of initial survey	Date of repeated survey
Corvallis, OR	Hwy 99W & SW Madison Ave (2)	09/01/2021	-
Albany, OR	Hwy 20 & First Ave SW (2)	09/01/2021	03/03/2022
Springfield, OR	Pioneer Pkwy & C St (2)	10/17/2021	-
Roseburg, OR	Hwy 138 & NE Jackson St (1)	10/07/2021	03/05/2022
Gold Beach, OR	Hwy 101 & 6th St (1)	10/01/2021	03/05/2022
Newport, OR	Hwy 101 & SW Lee St (2)	09/02/2021	03/03/2022
Lincoln City, OR	Hwy 101 & NE 13th St (1)	09/02/2021	-
Salem, OR	Hwy 99E & Pine St NE (2)	09/16/2021	-
Tigard, OR	Hwy 141 & SW Oleson Rd (1)	09/16/2021	-
Bend, OR	Hwy 20 & NE Revere Ave (1)	09/17/2021	-
Redmond, OR	Hwy 126 & SW 11th St (2)	09/17/2021	03/08/2022

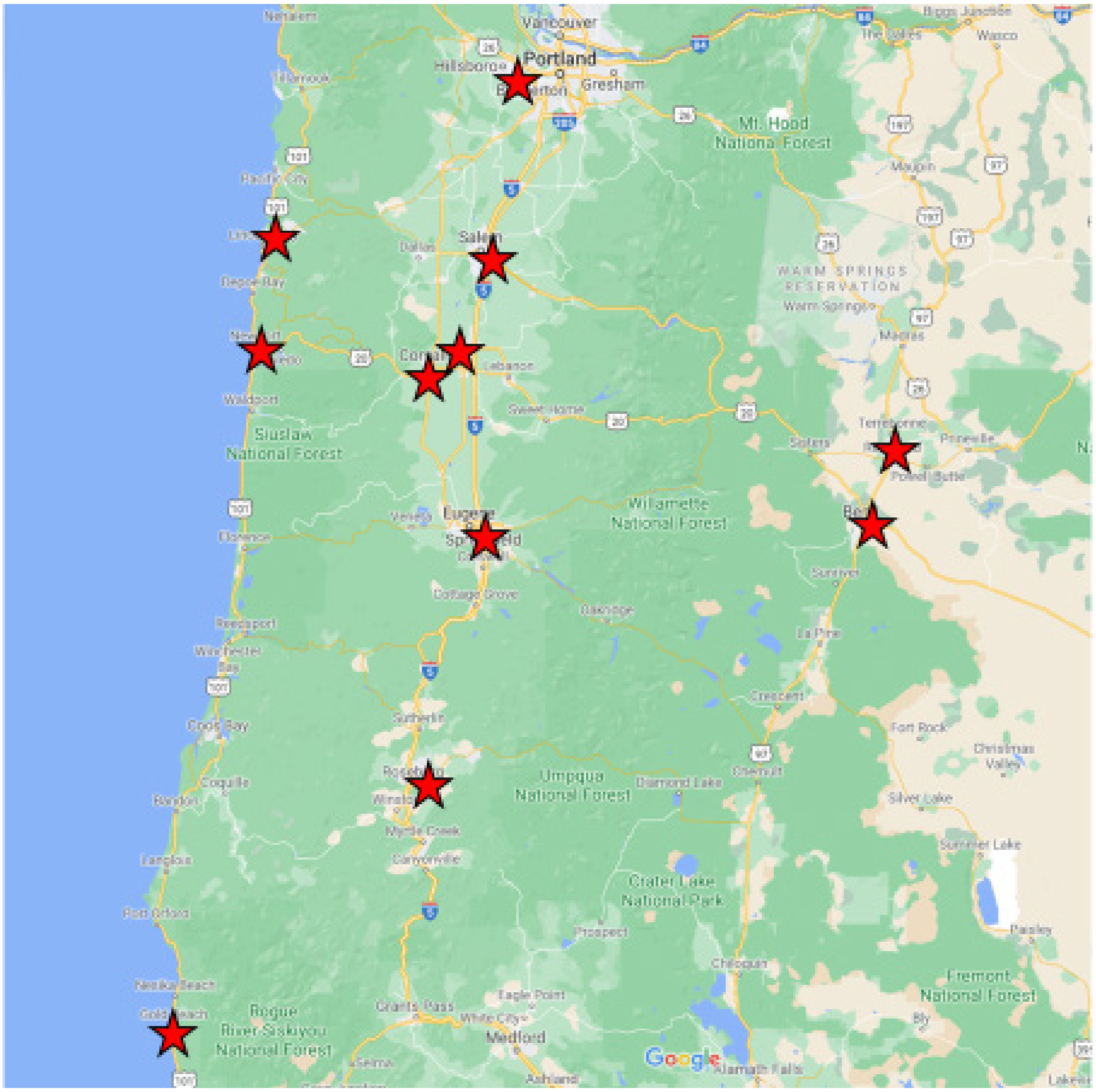


Figure 7.1: Locations of the data collection for in-situ testing.

Figure 7.2: Example of a non-compliant curb ramp at the site of Salem, OR.

7.2.2 Field Procedures

7.2.2.1 Smart level readings

For the in-situ measurements, the research team focused on measuring the running slope and cross slope in detail. There are several other items to be inspected that are related to slope measurement (e.g., counter slope, gutter flow slope, curb running slope, etc.). However, for slope measurements in a narrow area (e.g., gutter flow slope and curb running slope), there are only a few samples that can be taken with a limited choice of instrument. On the other hand, while measuring the slope of the landing or turning space is similar with the running slope and cross slope, the survey on landing and turning space tend to be impacted by less factors than running and cross slope because a larger horizontal misalignment can be tolerated (see discussions in Section 3.5) on a landing or turning space where the slope on both directions is relatively low (less than 2%).

In the operating test (see Section 5.0), the research team tested 6-inch (15 cm), 24-inch (60 cm), and 48-inch (120 cm) smart levels to investigate if the size of the smart level would impact the inspectors' capacity in aligning the equipment to the target direction when measuring running slope and cross slope. The result shows that the misalignment errors for a 6-inch smart level are significantly higher than the other two. On the other hand, although 48-inch smart levels provide more consistent placements and readings, it is challenging in a lot of cases to fit such a long instrument at a given point on a curb ramp. Therefore, the research team selected the 24-inch (60 cm) smart level as the primary slope measurement instrument in the in-situ curb ramp testing.

The actual field procedure is described as follows:

1. Equipment calibration: All smart levels were calibrated before each survey by following the procedure outlined in the user manual. The goal of such system calibration is to eliminate the systematic errors between direct and reverse measurements. To achieve the sensor's specified accuracy, the calibration process was conducted on a flat surface (e.g., desk, floor) with a mark to ensure each measurement in the calibration procedure was placed at the precisely the same location (usually by putting a mark on the surface using tape) to mitigate the impact of the flatness of the surface. The calibration should result in a difference within 0.2% slope between direct and reverse measurement at the same position. If not, the calibration process is repeated.

2. Marking the sampling grid on the curb ramp: To provide a good coverage for a run on a curb ramp, the research team took samples on the curb ramp in a grid pattern with a preset spacing. The research team first made tape measurements to determine the dimensions of a slab. Then the numbers of rows and columns were calculated respectively using a 1.5 ft (45 cm) spacing. The 1.5 ft spacing was found to be a good balance between field effort and level of details (Yang, Under Review). Once the dimension of the sampling grid was determined, the research group marked the grid at the center of the slab with the center of the grid as the reference point (Figure 7.3). Note that these sampling points were used for both running and cross slope. It is also worth noting that the research team did not mark or measure the slope on the detectable surface because those slope readings can be unreliable and inaccurate. Placing the smart level on the crowns of the domes can be challenging and unstable while the space between the domes is too narrow to fit the equipment (Figure 7.4), resulting in tilt biases.

Figure 7.3: Example sampling grid marked with chalk for slope measurements.

Figure 7.4: Tilting from placement of a smart level on the detectable warning surface.

3. Smart level measurements: The field crew used the 24-inch smart level to measure running and cross slope at each pre-marked location, and recorded the readings to a field form that was specially designed for this study (Figure 7.5). In addition to the basic information of the survey site (e.g., date, site, temperature) and the curb ramp (e.g., corner/ramp position, ramp condition), both direct and reverse readings were recorded at each pre-marked location. In this study, the direct and reverse face of the equipment are pre-defined with respect to the curb ramp and sampling grid where is also indicated in the field form (arrow represents the direction that the screen of the smart level is facing to). To make a smart level measurement, the center of the instrument was placed to the mark. The survey crew also adjusted the actual survey location from the marks that are close to the boundary of the slab in its survey direction to ensure the whole smart level does not cross any edges. It is also worth noting that the index of the corner, ramp, and run follows the convention for ODOT curb ramp inspection procedure. Additionally, the row and column indices of the sampling grid shown in the field form correspond to the orientation of the curb ramp. For example, for a survey crew standing at the bottom of a curb ramp and facing the curb ramp, sample [01, 01] corresponds to the mark at the bottom left corner.

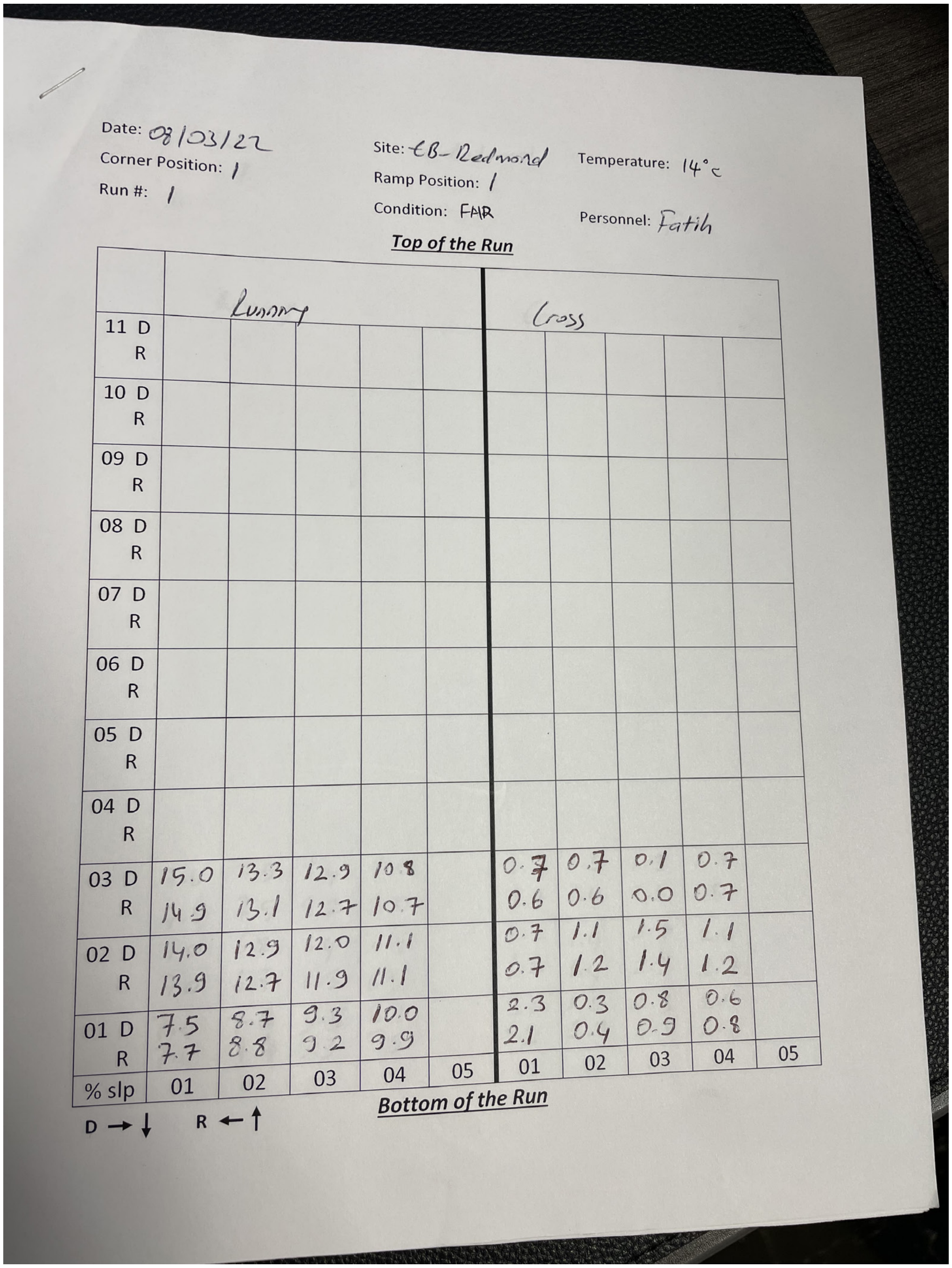


Figure 7.5: Example of a field survey form.

7.2.2.2 Laser scanning data

In addition to the smart level measurements, the research team also collected terrestrial laser scanning data with the Leica ScanStation P50 for each ramp (Figure 7.6). The scan resolution was typically set to ensure the scans, to result in a terrain model at centimeter level resolution which provides sufficient detailed information to support the analysis that requires surface characteristics (e.g., roughness). For mapping the curb ramps of interest to the geodatabase, a GNSS receiver (e.g., Leica GS14) was mounted on top of the scanner to obtain the 3D location via ORGN.

Figure 7.6: Terrestrial laser scanning data collection at a curb ramp.

7.3 DATABASE ESTABLISHMENT

7.3.1 Ramp information from ODOT TransGIS

After the research team selected all the curb ramps to survey, a spreadsheet was created to record the basic information and previous inspection results related to the slope measurements of the in-situ curb ramps (Table 7.2). This form can be linked to the in-situ survey data via the location, corner position, and ramp position. Notice that TransGIS only provides the ADA compliance of a curb ramp or the reasons for its incompliance but does not have the actual measurements. As a result, this form was developed to serve as a reference and provide context of the curb ramps. It was not used as ground truth to evaluate the field measurements by the research group.

Table 7.2: Ramp Information From Transgis Included With The In-Situ Curb Ramp Database.

Field Name		Value Type	Description
Ramp ID		Integer	The index that will be used internally to track ramps.
City		Text	The city that the ramp is located at.
Linear Reference Method Key		Text	The linear reference method key referred to the highway ID.
Milepoint		Float	Location of the intersection
Cross Street		Text	The cross street of the curb ramp
Corner Position		Integer	Count the corner counterclockwise when facing the increasing mileage direction and starting from right hand side with the lower mileage.
Ramp Position		Integer	Follow the corner position and count the ramp counterclockwise.
Ramp Style		Text	PR – perpendicular PL – parallel C – combination UD – unique design CT – cut through
Ramp Physical Condition		Text	Good, Fair, Poor
Last Inspection Year		Integer	The year that the ramp last inspected.
Run 1	Running Slope Compliance	Text	Whether running slope is compliant (run 1)
	Cross Slope Compliance	Text	Whether cross slope is compliant (run 1)
Run 2	Running Slope Compliance	Text	Whether running slope is compliant (run 2)
	Cross Slope Compliance	Text	Whether cross slope is compliant (run 2)
Run 3	Running Slope Compliance	Text	Whether running slope is compliant (run 3)
	Cross Slope Compliance	Text	Whether cross slope is compliant (run 3)

7.3.2 Smart level data

After each field data collection, the field forms for the smart level slope measurements were immediately organized based on the site and verified the records with field crews. All of the data in each form including date, site, temperature, corner ID, ramp ID, run ID, ramp style, concrete type, condition, instrument, personnel, number of rows and columns, and direct and reverse readings in percentage slope was then tabulated into a spreadsheet stored in csv format (Table 7.3). Note the slope readings from the smart level were entered row by row in the order of the sampling grid indices starting from (1, 1) such that the approximate location of the measurement can be retrieved by following the same marking and measuring procedures.

Table 7.3: Summary Of Information Fields Included In The Survey Table In The Database For In-Situ Ramp Measurements (Completed By The Research Team).

Field Name	Value Type	Description
Survey Date	Text	Year and date of the data collection by the research team.
Site ID	Text	An index that will indicate the survey date and site to internally link to other tables and data sheets.
Temperature	Float	The temperature during the survey
Corner Position	Integer	Count the corner counterclockwise when facing the increasing mileage direction and starting from right hand side with the lower mileage.
Ramp Position	Integer	Follow the corner position and count the ramp counterclockwise.
Ramp Style	Text	PR – perpendicular, PL – parallel, C – combination, UD – unique design, CT – cut through
Run Position	Integer	Count the run counterclockwise.
Slope Type	Text	R – running slope C – cross slope
Concrete Type	Text	EX – Exposed aggregate TR – troweled finish
Device	Text	The device used in slope measurement: SL24 – 24-inch (60 cm) smart level SL06 – 6-inch (15 cm) smart level SL48 – 48-inch (120 cm) smart level P50 – Leica Scanstation P50
Personnel	Text	Personnel that take measurements
Number of Rows	Integer	Number of rows in the sampling grid.
Number of Columns	Integer	Number of columns in the sampling grid.
Direct Slope Readings	Float Array	All of the direct readings in percentage slope in the sampling grid index order.
Reverse Slope Readings	Float Array	All of the direct readings in percentage slope in the sampling grid index order.

The name of csv file is given based on the corner, ramp, and run number as well as slope type (cross or running). For example, C3R12R and C3R12C indicate that the data is collected at corner #3, ramp #1, and run #2 that measures running and cross slope, respectively. All the csv files storing data at an intersection were kept in a folder named with the site ID (e.g., "Albany_20EB"). There are two reasons why such folder structure and naming convention are followed. First of all, such an approach makes it much easier to organize data and develop scripts to aggregate the data and perform analysis. Additionally, because the same information embedded in the file and folder structure appears in the spreadsheet, it can be used to implement QA/QC mechanism to spot errors during tabulation process.

Then the research team developed a script that reads each csv file and combined all the data into one single spreadsheet for further analysis. All the basic information about the site and survey were copied over including the folder/file structure (Table 7.4). Regarding the actual slope readings, the research team calculated three types of slope measurements: direct, reverse, and average (averaging direct and reverse readings at a single sampling location). For each type of readings, the average, standard deviation, minimum, maximum, and median values were calculated and written to the "analysis results" spreadsheet.

Table 7.4: Summary Of Information Fields Included In The Analysis Table In The Database For In-Situ Ramp Measurements.

Field Name		Value Type	Description
Survey Folder		Text	Name of the folder that stores the data
Site Folder		Text	Site ID indicated by the folder name
Corner Position from File		Integer	Corner position indicated by the file name.
Ramp Position from File		Integer	Ramp position indicated by the file name.
Run Position from File		Integer	Run position indicated by the file name.
Slope Type from File		Text	Slope type indicated by the file name.
Survey Date		Text	Year and date of the data collection by the research team or inspectors.
Site ID		Text	An index that will indicate the survey date and site, and be used internally to link to other tables and data sheets.
Temperature		Integer	The temperature during the survey (Celsius)
Corner Position		Integer	Count the corner counterclockwise when facing the increasing mileage direction and starting from right hand side with the lower mileage
Ramp Position		Integer	Follow the corner position and count the ramp counterclockwise
Ramp Style		Text	PR – perpendicular PL – parallel C – combination UD – unique design CT – cut through
Run Position		Integer	Count the run counterclockwise
Slope Type		Text	R – running slope C – cross slope
Concrete Type		Text	EX – Exposed aggregate TR – troweled finish
Ramp Physical Condition		Text	Good, Fair, Poor
Device		Text	The device used in slope measurement (SL24 – 24-inch (60 cm) smart level)
Personnel		Text	Personnel that take measurements
Number of Rows		Integer	Number of rows in the sampling grid.
Number of Columns		Integer	Number of columns in the sampling grid.
Total Number of Readings		Integer	Total number of samples
Direct	Average Reading	Float	Average slope reading
	Reading Standard Deviation	Float	Standard deviation of the readings

Field Name		Value Type	Description
	Minimum Reading	Float	Minimum slope reading
	Maximum Reading	Float	Maximum slope reading
	Median Reading	Float	Median slope reading
Reverse	Average Reading	Float	Average slope reading
	Reading Standard Deviation	Float	Standard deviation of the readings
	Minimum Reading	Float	Minimum slope reading
	Maximum Reading	Float	Maximum slope reading
	Median Reading	Float	Median slope reading
Average	Average Reading	Float	Average slope reading
	Reading Standard Deviation	Float	Standard deviation of the readings
	Minimum Reading	Float	Minimum slope reading
	Maximum Reading	Float	Maximum slope reading
	Median Reading	Float	Median slope reading

7.3.3 Terrestrial Laser Scanning data

The point cloud acquired by the Leica Scanstation P50 was processed and used as a source of ground truth reference data because it has a higher accuracy and can provide much denser samples from the curb ramps (e.g., Figure 7.7). The GNSS data collected at each scan position was used to georeference the point cloud while the local alignment was achieved mostly by adding cloud-to-cloud constraints in Cyclone software. Because the local alignment needs to be prioritized to ensure the accuracy of the geometric details, the typical weight of a cloud-to-cloud constraint was set 1.0 while the GNSS observations were given 0.05 as the weight. As a result, the relative registration accuracy is within a few millimeters for all the terrestrial laser scanning data and the absolute georeferencing errors are within a few centimeters. Note that relative accuracy is the most applicable metric given that slope measurements are relative measurements. The data were finally exported as both ASTM E57 and ASPRS LAZ formats for subsequent analyses.

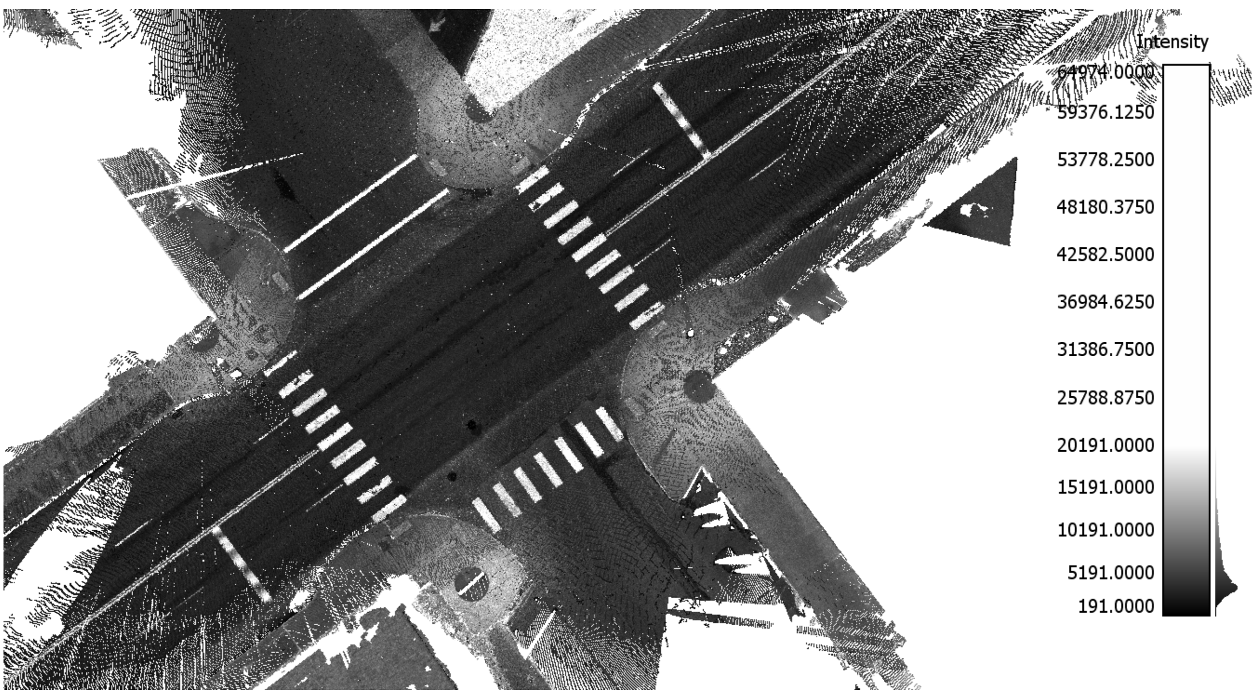


Figure 7.7: Example of the georeferenced terrestrial laser scanning data.

8.0 IN-SITU DATA ANALYSIS AND MONITORING

8.1 ANALYSIS OVERVIEW

The research team analyzed the research database described in the prior sections to evaluate the following aspects: (1) survey precision in terms of the direct and reverse observations, (2) consistency of the new method proposed by the research team, and (3) surface roughness metrics. This analysis will further validate the proposed method for field data collection and demonstrate its effectiveness quantitatively.

8.2 FIELD SURVEY PRECISION

As discussed in Section 3.0, the precision of the slope observations with a smart level on a curb ramp can be impacted by a variety of factors including the sensor precision, calibration residuals, and misalignment. Despite the rigorous effort by the research team to model the theoretical errors, the field measurement can still be challenging to predict with the theoretical error models in the context of assessing the ADA compliance of a curb ramp. For example, the lab test comparing the direct and reverse observations in Section 3.4 shows that the discrepancy between the direct and reverse observations is almost always within 0.2% for a well calibrated smart level, which falls within the accuracy specification of the smart level. In the calibration testing, the difference between direct and reverse observations follows the same trend with only a few outliers up to 0.7%. It is worth noting that in the calibration testing, the research team placed tape on the curb ramp surface to minimize errors resulting from inconsistent placement of the smart level in terms of both location and orientation. However, to maintain efficiency in the field survey, the research team only marked the position of each sample point, which can introduce additional misalignment errors. Further, in practice, the aggregated slope metrics are more important than the individual observations when assessing the ADA compliance of the curb ramp.

Thus, the research team leveraged the research database developed from the in-situ data collection to analyze the difference between direct and reverse readings (Table 8.1). Note that the cross slope and running slope of the same curb ramp are separated and considered as two curb ramps in the analysis to cover a wider range of slope with a larger number of data samples (a total of 295 samples). In this summary table, each column presents a slope metric on an individual curb ramp level from the research database while each row presents a statistical metric calculated from the difference between the direct and reverse readings. For example, the research team calculated the average slope (AVG Slope) for each curb ramp with all the direct readings and reverse readings separately (the number of slope readings are the same as indicated in the NSLOPE column), and the difference between them. The differences from all the curb ramps were then used to compute the statistical metrics where the RMSD of such difference is 0.11%.

Table 8.1: Comparison Of Slope Metrics Derived From Direct And Reverse Readings.

All	Difference between Direct and Reverse Readings (% slope)					
	NSLOPE	AVG Slope	Slope STD	MIN Slope	MAX Slope	MED Slope
AVG	0.0	0.02	0.00	0.01	0.01	0.02
STD	0.0	0.11	0.09	0.20	0.19	0.17
MIN	0.0	-0.50	-0.68	-0.80	-0.70	-0.95
MAX	0.0	0.50	0.38	1.70	0.80	0.60
MED	0.0	0.01	0.00	0.00	0.00	0.00
RMSD	0.0	0.11	0.09	0.20	0.19	0.17

Overall, the statistical analysis shows a very high level of agreement between the direct and reverse readings in terms of average, standard deviation, minimum, maximum, and median slope values, where the RMSDs are all within 0.2%. That being said, it is noticeable that there are substantial outliers indicated by the minimum and maximum of the differences for all the metric where the average slope and slope standard deviation are less sensitive to the blunders than the minimum and maximum slope. It is also worth noting that because all data were collected following the new method developed by the research team, there was a rigorous QA/QC directly process embedded in the field procedure. When the survey crew records both direct and reverse readings at the pre-marked location, if a large discrepancy is spotted, additional readings are made for verification. On the other hand, when following the current ODOT field procedure, this analysis can be seen as a very conservative estimate of the consistency for a curb ramp inspection only considering the variation in the orientation of the smart level and sensor precision. Moreover, despite the fact that in some cases the direct or reverse readings can be more accurate, there is no consistent trend and the orientations of the direct and reverse can be arbitrary as there is no standard in the existing measurement procedure.

In summary, capturing and averaging both direct and reverse observations for each sample point can be beneficial because it:

- Helps inspectors detect significant calibration residuals when there is a large systematic bias between direct and reverse readings.
- Enables inspectors to verify measurements so they can spot and eliminate blunders more systematically in the field.
- Minimizes the calibration residuals and the misalignment errors to some degree through the averaging process.

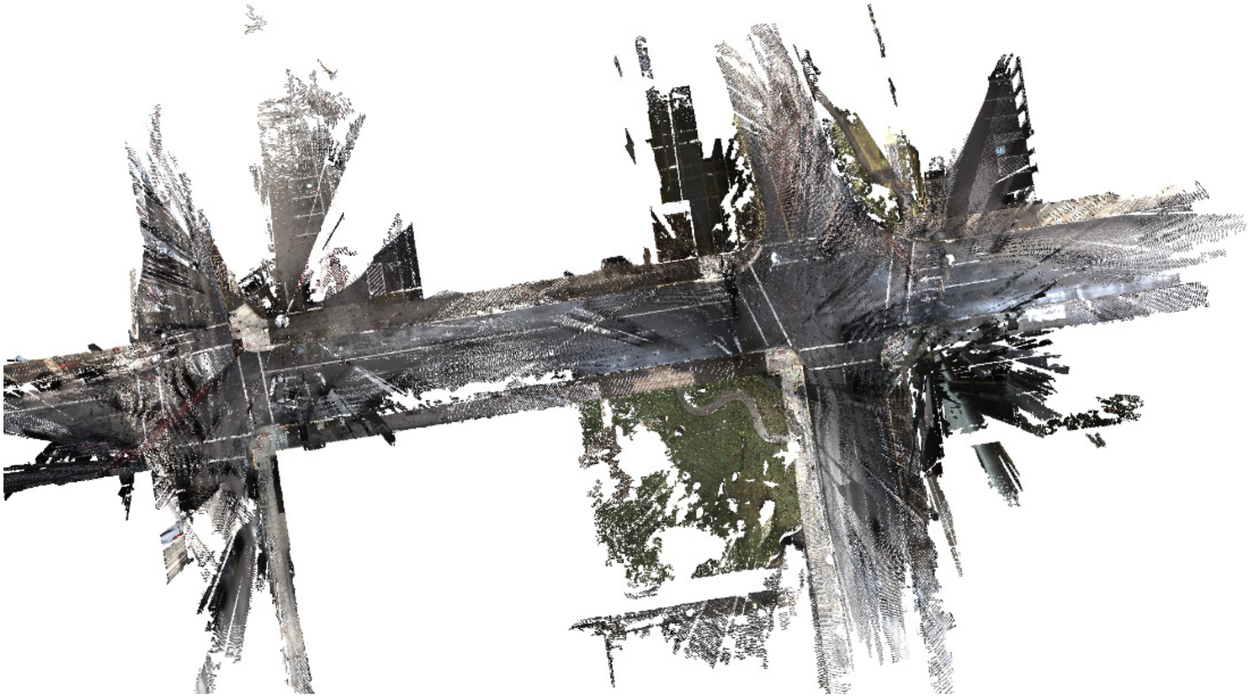
8.3 SURVEY CONSISTENCY FOR REPEATED SURVEYS

8.3.1 Change analysis from point clouds

To further evaluate the effectiveness of the proposed field method, the repeated surveys in the research database can be used to analyze the consistency of the survey techniques as well as the performance of different metrics. Before such an analysis, however, the ground truth needs to be developed to ensure that there is no significant change on the curb ramp surface during the monitoring period. In this study, the TLS scans were considered as the reference data source because the scanner has been demonstrated through calibration testing to be a more reliable sensor to capture detailed geometric information of the surface (Section 4.0). The surrounding area covered by the scans can also provide more context for verification in case major changes are detected in the monitoring survey.

The geo-referenced point cloud for each site and epoch was first downsampled to 0.01 m to: (1) reduce data volume and computation complexity, (2) normalize the point density to remove bias in statistical analysis, (3) reduce some local errors, and (3) increase consistency in the comparison. The down-sampling process was performed with EZVox, a commercial point cloud processing toolkit, originally developed by the research team at OSU. The downsampling program organizes the point cloud data into 3D voxels (i.e., 0.01 m cubes) and then samples the point closest to the voxel center in each cube to achieve a relatively even distribution while preserving the original measurements rather than taking an aggregated value (e.g., centroid) that can artificially smooth the surface (Che & Olsen, 2023). Then Vo-SmoG ground filtering (Che et al., 2021) was applied to each downsampled point cloud to separate the ground including the curb ramp surface and the non-ground objects (e.g., buildings, cars, pedestrian, etc.).

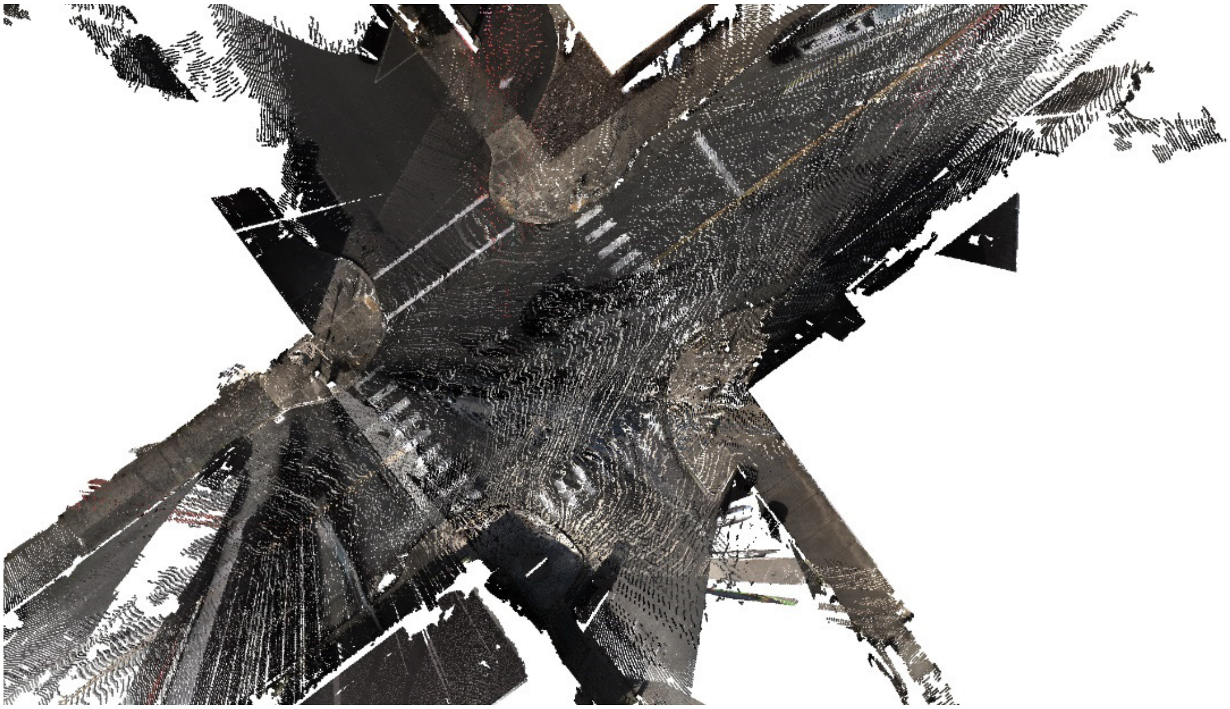
The open-source software, Cloud Compare was utilized to compare the down-sampled ground points for each site through change analysis. The difference histogram from the change analysis was further fit to a Gaussian distribution to compute the average and standard deviation of the vertical difference for visual and quantitative analysis (Figure 8.1, Figure 8.2, Figure 8.3, Figure 8.4, Figure 8.5).



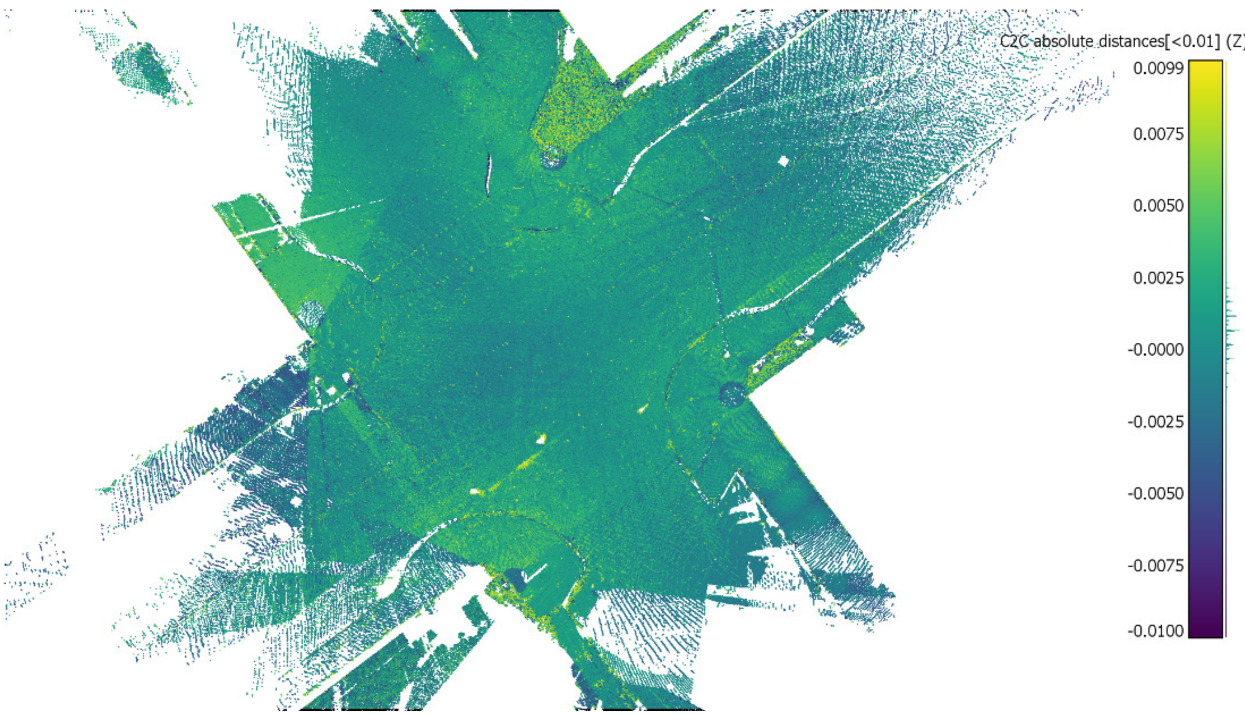
(a) Point cloud in RGB color

(b) Cloud-to-cloud comparison result (m)

Figure 8.1: Change analysis in point clouds for repeated survey at the Albany, OR site including two intersections where the average and standard deviation of the cloud-to-cloud comparison for the intersection on the left (West) are 0.8 mm and 2.4 mm, respectively, while the one on the right (East) is 0.3 mm and 1.6 mm.

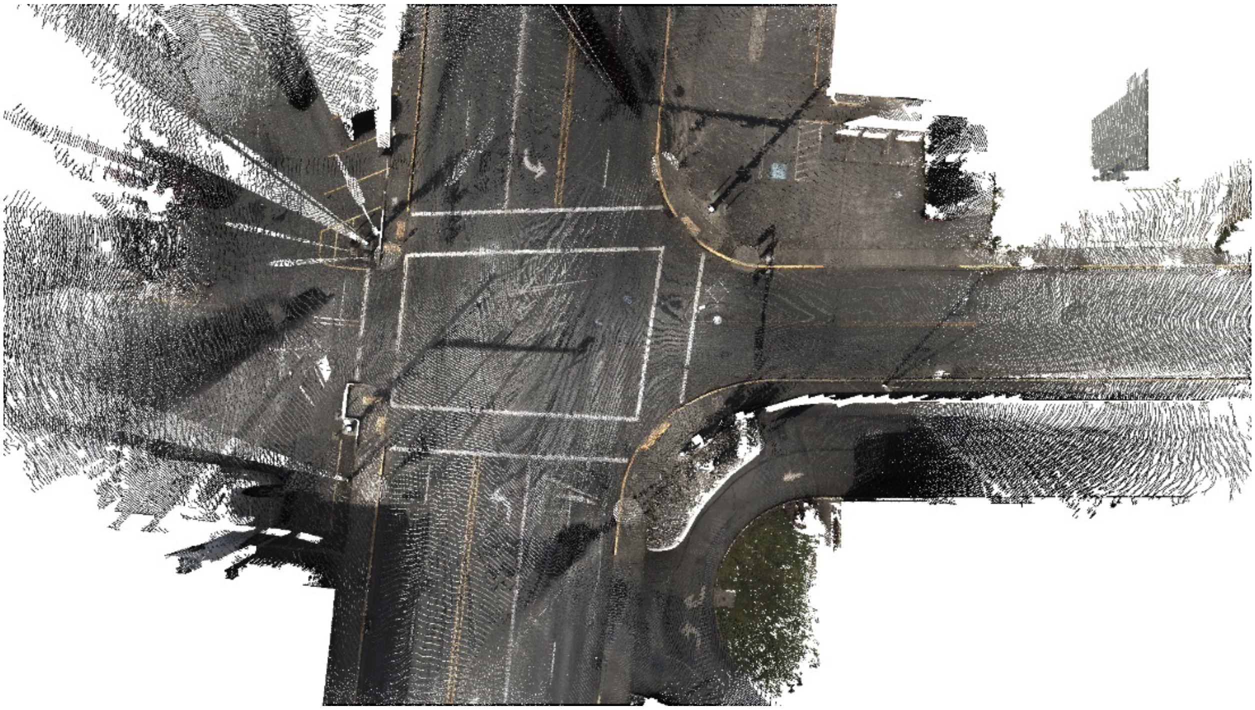


(a) Point cloud in RGB color

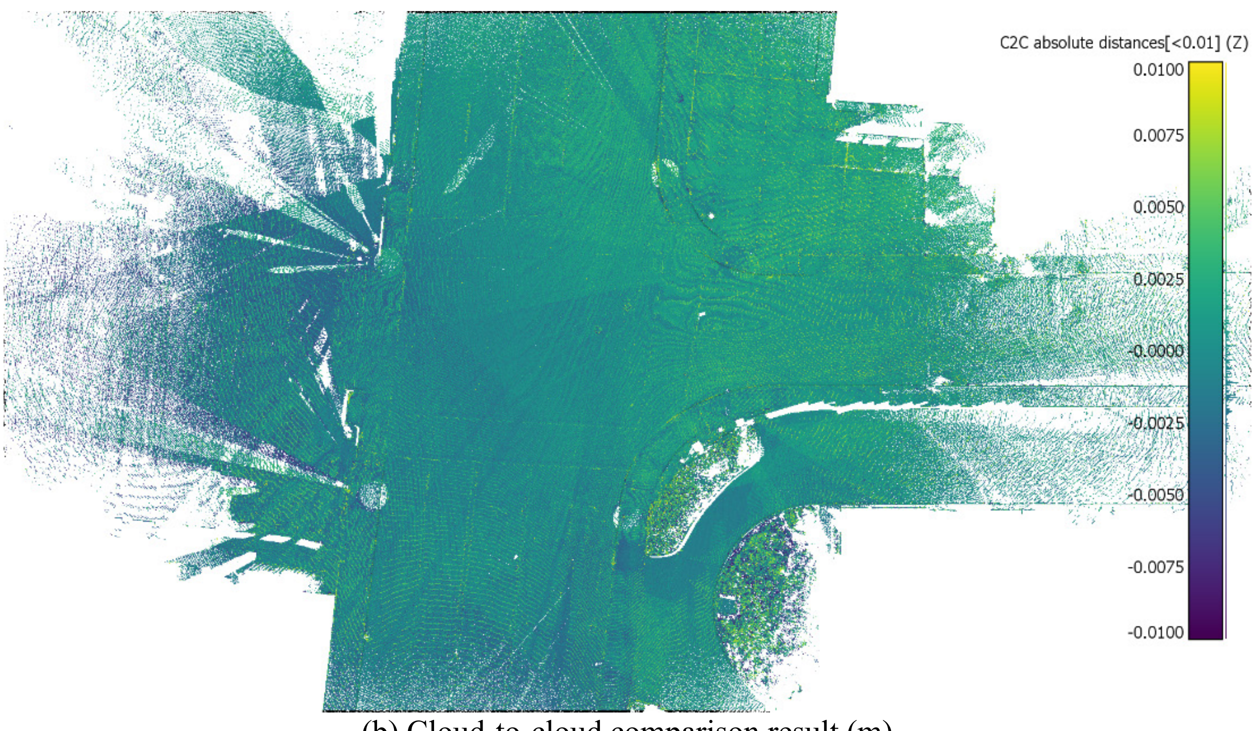


(b) Cloud-to-cloud comparison result (m)

Figure 8.2: Change analysis in point clouds for repeated survey at the site in Newport, OR including one intersection where the average and standard deviation of cloud-to-cloud comparison for the intersection are 0.6 mm and 1.7 mm, respectively.

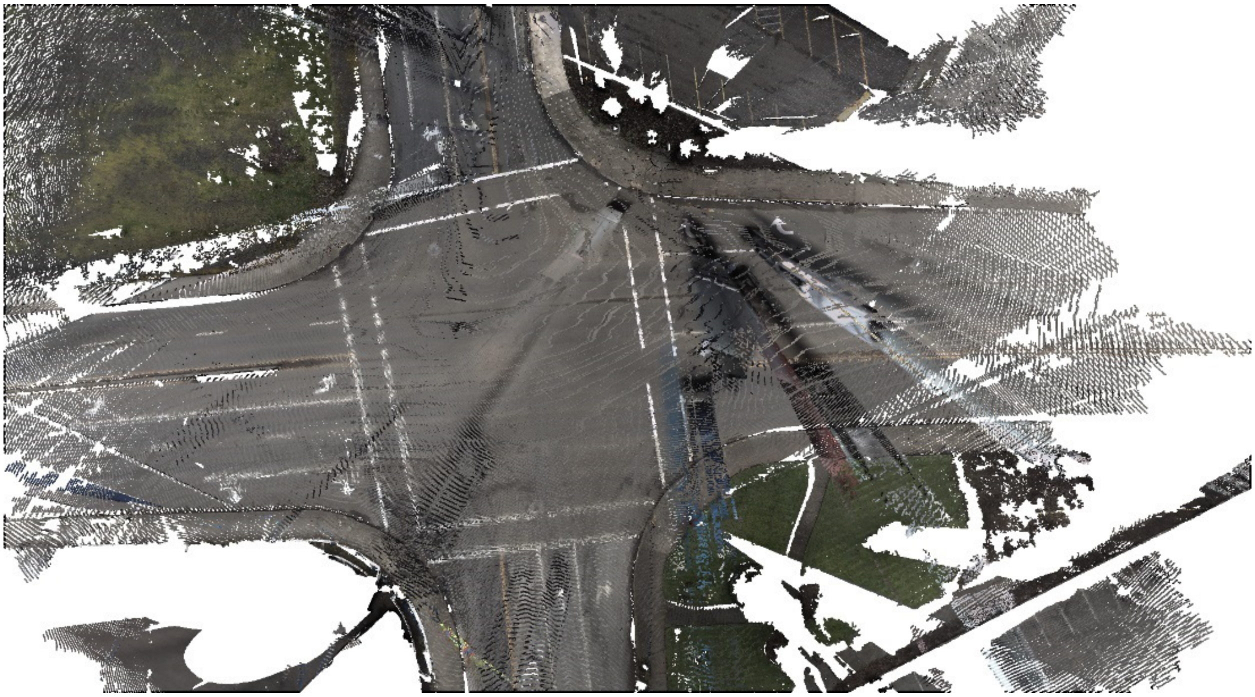


(a) Point cloud in RGB color

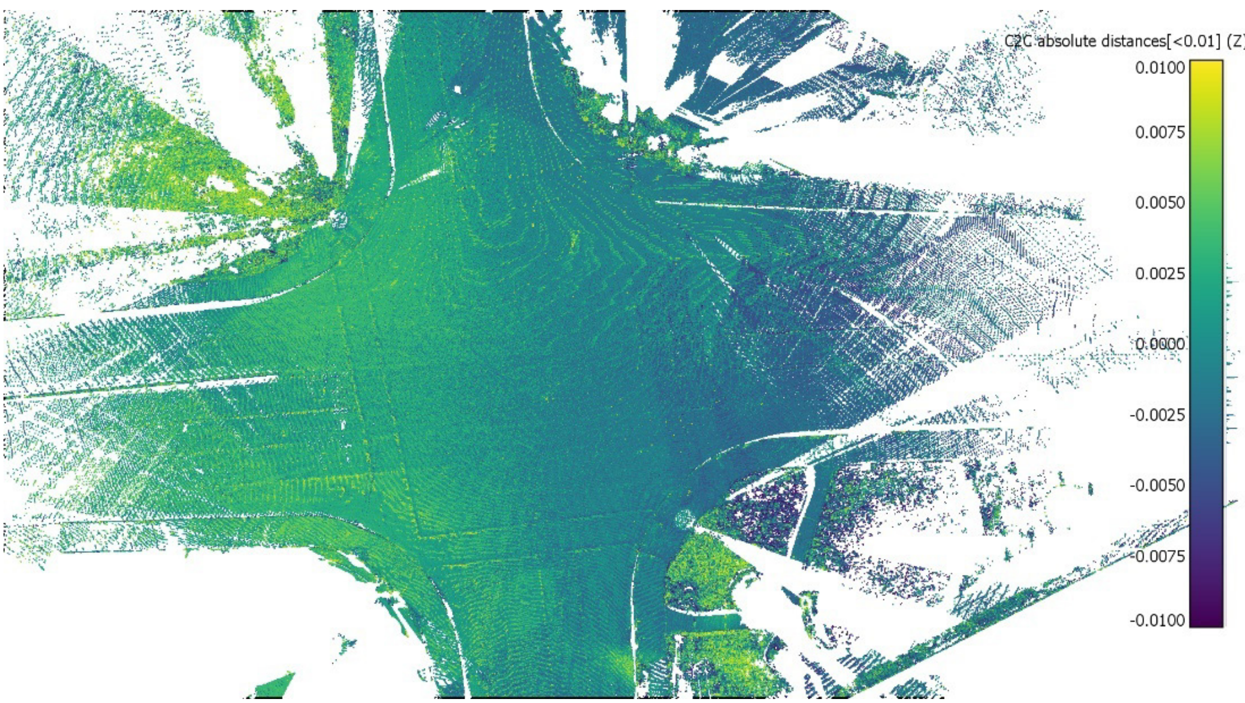


(b) Cloud-to-cloud comparison result (m)

Figure 8.3: Change analysis in point clouds for repeated survey at the site in Gold Beach, OR including one intersection where the average and standard deviation of cloud-to-cloud comparison for the intersection are -0.6 mm and 1.9 mm, respectively.



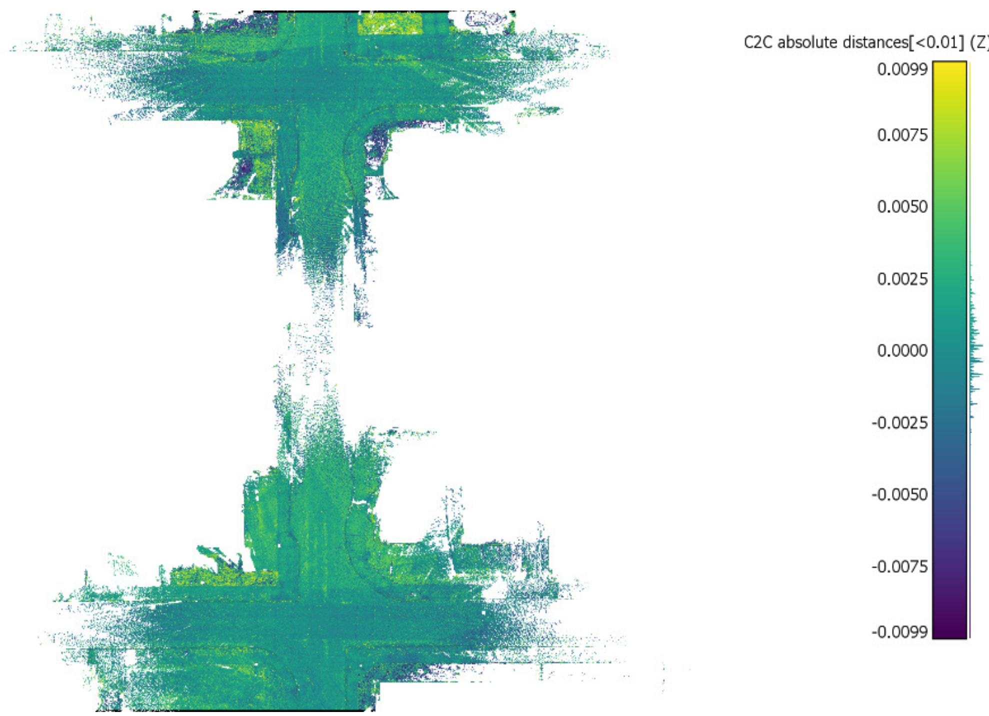
(a) Point cloud in RGB color



(b) Cloud-to-cloud comparison result (m)

Figure 8.4: Change analysis in point clouds for repeated survey at the site in Roseburg, OR including one intersection where the average and standard deviation of cloud-to-cloud comparison for the intersection are -0.3 mm and 2.5 mm, respectively.

(a) Point cloud in RGB color



(b) Cloud-to-cloud comparison result (m)

Figure 8.5: Change analysis in point clouds for repeated survey at the site in Redmond, OR including two intersections where the average and standard deviation of cloud-to-cloud comparison for the intersection at the top (North) are 0.3 mm and 1.8 mm, respectively, while the one at the bottom (South) is -0.0 mm and 2.1 mm.

It can be seen from the results that the average change for all the sites is on the level of sub-millimeter showing no significant bias in the registration. The standard deviation of the vertical change between epochs is consistently within 3 mm, which is on par with the accuracy reported in the calibration testing (Table 4.6). Therefore, it can be concluded that there is no significant change in all the sites under monitoring in this study. Considering this finding, the ideal repeated inspections should produce similar results, and hence the performance metrics will be computed based on the same assumption.

8.3.2 Measurement Consistency

In the prior section, the point clouds collected from the in-situ curb ramp survey were analyzed and showed no significant difference between the two epochs approximately three months apart. This section will focus on the smart level measurements and analyze the effectiveness of the proposed field method and slope metrics.

8.3.2.1 Individual Site Analysis

As discussed in Section 8.2, the average value of the direct and reverse reading at a sampling point was taken as a slope measurement (the number of sampling points is presented as NSLOPE). All averaged values were then used to compute the slope metrics for either type of slope (i.e., cross slope or running slope) including the average slope (AVG Slope), slope standard deviation (Slope STD), minimum slope (MIN Slope), maximum slope (MAX Slope), and median slope (MED Slope). The difference in these metrics from two epochs were computed and the RMSE calculated from all the curb ramps from each site is summarized in Table 8.2 with the cloud-to-cloud comparison result as a reference.

All metrics generally follow the same trend where the minimum and maximum slope fluctuate significantly more compared with the other metrics as they are more sensitive metrics to outliers or blunders. It is noticeable that the largest errors occur at Albany 1 where the RMSE for the average slope and slope standard deviation are 0.46% and 0.38%, respectively. These errors can be largely explained by the difference in the number of slope samples with an average number of samples around 11. The sample size was lower as Albany is one of the first sites that the research team visited and part of the training process for the team to test and adopt the new field data collection method. It can be seen later on at the other sites, the discrepancies in the total number of samples are minimal and the RMSE is typically less than 1, demonstrating the consistency of the proposed sampling approach.

Table 8.2: Summary Of The Comparison Between Two Epochs Of In-Situ Curb Ramp Surveys For TLS And Smart Level Using The Proposed Field Method.

	TLS Gaussian Distribution Fitting in Cloud-to-Cloud Comparison (m)		RMSE derived from the difference between the Field Survey and Repeated Monitoring (% slope) with the Smart Levels					
	AVG	**STD**	**NSLOPE**	**AVG Slope**	**Slope STD**	**MIN Slope**	**MAX Slope**	**MED Slope**
Albany 1	0.0008	0.0024	3.8	0.46	0.38	1.20	0.48	0.39
Albany 2	0.0003	0.0016	1.5	0.25	0.19	0.42	0.52	0.21
Newport	0.0006	0.0017	0.0	0.16	0.19	0.20	0.53	0.14
Gold Beach	-0.0006	0.0019	0.8	0.38	0.28	0.86	0.41	0.43
Roseburg	-0.0003	0.0025	0.0	0.35	0.21	0.46	0.50	0.41
Redmond 1	0.0003	0.0018	0.0	0.25	0.21	0.67	0.34	0.37
Redmond 2	-0.0000	0.0021	1.2	0.13	0.13	0.36	0.27	0.34

8.3.2.1 Combined Site Analysis

Another consideration in this analysis is that even though most of the sites behave relatively consistently, the sample size (number of curb ramps, running slope + cross slope) for each site can be small (12 – 16). To ensure that the analysis can support general discussion and recommendations for the methods and metrics, the research team combined the data from all the listed sites together and performed a more detailed statistical summary (Table 8.3). The average and median errors (AVG and MED) of all the metrics are minimal (0.1 for samples, under 0.1% for slope), illustrating that there is no bias introduced into the repeat survey, particularly considering the fact that the smart level only provides slope values to the nearest 0.1%. There are some reasonable variations in the standard deviation of errors (STD) and minimal blunders as indicated in the minimum and maximum errors (MIN and MAX). Regarding the individual slope metrics, the average slope and slope standard deviation tend to provide the most consistent results while the maximum slope is associated with more significant deviation. The median would have provided a more reliable estimate of the surface slope if there are blunders with abnormally large errors in the smart level measurements with sufficient samples. However, in this case, the blunders of individual smart level readings can be screened and fixed in the field when surveying with both direct and reverse faces. Moreover, the curb ramp surface is relatively small with 11 sampling points, on average, with a reasonable sampling spacing (1.5 ft). Thus, the median slope tends to fluctuate more than the average slope.

Table 8.3: Statistical Summary Of The Difference Between Two Epochs Of Smart Level Survey (98 Samples In Total).

All	Differences between the Field Survey and Repeated Monitoring (% slope)					
	NSLOPE	AVG Slope	Slope STD	MIN Slope	MAX Slope	MED Slope
AVG	-0.1	-0.03	-0.06	0.05	-0.09	-0.04
STD	1.7	0.29	0.23	0.66	0.43	0.33
MIN	-6.0	-1.21	-1.24	-2.05	-1.60	-1.10
MAX	6.0	1.05	0.59	4.00	1.00	0.85
MED	0.0	-0.02	-0.03	0.05	-0.05	-0.03
RMSE	1.7	0.29	0.24	0.66	0.44	0.33

8.3.2.1 Running slope vs cross-slope analysis

An additional analysis was conducted by separating the running and cross slope and running slope measurements because: (1) the cross slope (<2°) is usually substantially smaller than the running slope (6-8°); (2) the construction tolerances built into the design for running and cross slope are different; and (3) the horizontal misalignment errors affect the running and cross slope differently. Comparing the comparison results of running and cross slope (Table 8-4 and Table 8-5), the number of slope samples, average slope, slope standard deviation, and median slope are quite consistent where the difference (within 0.1%) is within the precision of the smart level readings. Much larger difference occurs in the minimum slope where the RMSE of the minimum running slope and cross slope is 0.89% and 0.30%, respectively. The difference in the maximum slope for running slope is slightly lower than the cross slope where the RMSE is 0.32% and 0.53%, respectively. Based on the theoretical error model in Section 3.5.2 developed for the horizontal misalignment, the cross slope should be impacted more than the running slope. However, no such trend has been shown in this analysis and in some cases, the opposite appears true. Thus, the horizontal misalignment appears to play a minimal role in the slope measurements, at least in this study where measurements were very consistent given that the directions of the running and cross slope were marked with the sampling grid in the crossing marker. The field survey crew could use those markers as a guidance of the position and orientation of each smart level observation.

The use of maximum slope per the current ODOT inspection procedure can result in 0.32% to 0.53% differences for running and cross slope, respectively, as shown in this study. Nevertheless, these results are likely better than typical practice as such performance is achieved with the enhancement of the proposed field method which provides more samples, more QA/QC in the field, and more consistent sampling than is currently implemented by inspectors. The current ODOT design guidelines for the curb ramps have a maximum slope of 7.5% and 1.5% for running and cross slope, which leaves a buffer of 0.8% and 0.5%, respectively, for construction and inspection tolerances. Unfortunately, even with the proposed field method, the use of the maximum slope per the current ODOT inspection procedure can easily lead to false positives and false negatives in determining the ADA compliance of a curb ramp, especially for the more sensitive cross slope measurement. Unlike running slope, which can vary a lot depending on the circumstances with much more flexibility in the design, cross slope is usually designed to be 1.5% which makes its tolerance tight. As shown in this study, the consistency of the survey itself can bring in enough errors leading to incorrect inspection conclusions of the ADA compliance. The same issue applies to the running slope in the case of a relatively steep curb ramp in challenging terrain.

Table 8.4: Statistical Summary Of The Difference Of Running Slope Between Two Epochs Of Smart Level Survey (49 Samples In Total).

Running	Differences between the Field Survey and Repeated Monitoring (% slope)					
	NSLOPE	AVG Slope	Slope STD	MIN Slope	MAX Slope	MED Slope
AVG	0.0	-0.04	-0.05	0.07	-0.07	-0.09
STD	1.7	0.34	0.27	0.89	0.31	0.33
MIN	-6.0	-1.21	-1.24	-2.05	-0.90	-1.10
MAX	6.0	1.05	0.59	4.00	0.45	0.60
MED	0.0	-0.03	-0.03	0.10	0.00	-0.05
RMSE	1.7	0.34	0.28	0.89	0.32	0.34

Table 8.5: Statistical Summary Of The Difference Of Cross Slope Between Two Epochs Of Smart Level Survey (49 Samples In Total).

Cross	Differences between the Field Survey and Repeated Monitoring (% slope)					
	NSLOPE	AVG Slope	Slope STD	MIN Slope	MAX Slope	MED Slope
AVG	-0.1	-0.01	-0.06	0.03	-0.11	0.01
STD	1.6	0.24	0.18	0.30	0.52	0.32
MIN	-6.0	-0.66	-0.56	-1.05	-1.60	-0.90
MAX	6.0	0.57	0.37	0.75	1.00	0.85
MED	0.0	-0.02	-0.03	0.00	-0.10	0.00
RMSE	1.6	0.24	0.19	0.30	0.53	0.32

8.3.2.2 Blunders

The research team further investigated the measurements associated with large errors. For example, in the running slope (Table 8.4), the measurements corresponding to the minimum and maximum error in average slope (-1.21% and 1.05%) were located. Considering the fact that the cross slope at the sample curb ramps with the same sampling locations does not have large errors, these errors were likely caused by the shifting of the entire sampling grid over the curb ramp. As both measurements happened to be at the Albany 1 site, which was the first site the research team surveyed where the crew went through the training process, these two instances can be seen as outliers and do not reflect the effectiveness and consistency of the metrics nor the proposed field method. Instead, it shows the local variability of the curb ramp surface and necessity of considering the sampling method in the field. After removing these two data points, the RMSE for all the metrics (NSLOPE, AVG Slope, Slope STD, MIN Slope, MAX Slope, MED Slope) are 1.5, 0.25%, 0.21%, 0.63%, 0.30%, and 0.30% (47 samples), respectively. All the metrics are almost identical with the results in cross slope except for the MIN Slope and MAX Slope.

8.3.2.3 Conclusions

In summary, the use of a single maximum value can be highly error prone and inconsistent. The metrics of average slope and slope standard deviation statistically describe different aspects of the ramp surface very consistently while the proposed field method provides a more consistent and uniformed sampling in the field with enhanced QA/QC capacity.

9.0 PROPOSED SLOPE MEASUREMENTS

9.1.1 Proposed slope metric considering roughness.

In Section 8.3.2, the slope standard deviation, a metric describing the surface roughness, has been proven to be consistent as it is on par with the average slope and shows better consistency than the maximum slope. In this section, the research team investigates the effectiveness of the roughness metrics derived from the slope standard deviation. The variation of the slope across a small portion of the surface demonstrated in Section 4.6.2 is difficult to capture within a single measurement with a smart level. Thus, in addition to solely evaluating slope measurements, in the field tests, the research team developed and tested appropriate flatness/roughness metrics to tackle this challenge. The proposed metrics are designed to meet the following requirements:

1. They should be able to describe the flatness or roughness of a surface effectively considering the geometry of the curb ramps (e.g., dimensions, slope).

2. They can be derived from the data collected by an instrument commonly used in ADA compliance assessment (e.g., smart level).

3. The effort to perform the requisite measurements and computations should be reasonable.

The proposed method is implemented as follows:

- A number of slope measurements (averaging direct and reverse readings is recommended) with the smart level are evenly distributed across a surface at a fixed interval, including both its running slope and cross slope. The field procedure is described in detail in Section 7.2.2.1.

- The average and standard deviation of those slope measurements are calculated. This should be done for running and cross slopes independently.

- The average or median slope is the most representative value of the general slope of the ramp but does not consider roughness.

- The roughness of this surface's running slope can be defined as the standard deviation of the individual slope measurements, which ultimately statistically describes the deviations in the flatness of the surface.

- A slope value considering flatness can be computed by scaling the roughness (standard deviation) values to a desired confidence level (e.g., 90% confidence) and adding it to the average. It can be computed using the following equation where CISF is a scale factor to the appropriate confidence interval (e.g., 1.65 for 90% confidence).

$$\textbf{Reported Slope} = \textbf{Slope AVG} + \textbf{CISF} \times \textbf{Slope STD}$$

(8-1)

- If the slope at 90% confidence level does not meet the requirements, then a more detailed inspection is necessary to verify compliance.

The instrument used and the sampling interval are the two key variables that can impact the effectiveness of the proposed roughness metrics. Amongst the different types of smart levels, the research team focused the flatness evaluation on the 2-ft (60 cm) smart levels because they are the most commonly used by ODOT inspectors to assess the curb ramps after installation. Additionally, because the slope measurements should not cross multiple concrete slabs, the area available for evaluation for a 4-ft (120 cm) smart level would be too small because any place that is closer than 2 ft (60 cm) to the edge of the surface cannot be surveyed effectively. Although increased sampling leads to more precise assessment results, the practicality of the proposed method was considered to ensure productivity in the field. As a result, the research team tested the flatness in the in-situ measurements where different tools and sampling intervals can be efficiently tested to determine an optimal sampling interval. The assessment results were then compared with the ground truth results following ODOT's method.

9.1.2 Confidence Intervals

Assuming that the slope measurements of a curb ramp surface follow a Gaussian distribution, the confidence intervals (C.I.) can be computed from the standard deviation of the samples via scale factors. In this study, the 68%, 90%, 95%, and 99% confidence intervals were calculated with the following 1D equations based on error probability theory (US Air Force, 1962):

$$\textbf{68\% C.I.} = \textbf{1.00} \times \textbf{Slope STD}$$

(Equation 8-2a)

$$\textbf{90\% C.I.} = \textbf{1.65} \times \textbf{Slope STD}$$

(Equation 8-2b)

$$\textbf{95\% C.I.} = \textbf{1.96} \times \textbf{Slope STD}$$

(Equation 8-2c)

$$\textbf{99\% C.I.} = \textbf{2.58} \times \textbf{Slope STD}$$

(Equation 8-2d)

Note that these equations assume a gaussian distribution and a sufficient number of samples (e.g., 20+) to be statistically significant.

Each confidence interval is added to the average slope to predict the actual maximum slope. (The assumption with this approach is that the maximum slope measured may not actually be the maximum slope on the ramp due to sampling bias). To evaluate and analyze the performance, the predicted maximum slope values were first compared with the observed maximum readings from all curb ramps and epochs (Table 9.1). The result shows that the 68% C.I. consistently underestimates the maximum slope while 95% and 99% C.I tend to result in overestimations. The average error for 90% C.I. is 0.10% showing that the predicted value only slightly above the maximum observation. It also has the lowest RMSE illustrating a better performance overall. It is worth noting that although 95% and 99% C.I. have larger average errors and RMSE, they most likely lead to a more conservative assessment of the ADA compliance of the curb ramp. Lastly, the data were divided into running slope and cross slope (Table 9.2, Table 9.3). Overall, the same trend can be observed where the 90% C.I. yields the best performance in terms of predicting the maximum slope.

Table 9.1: Evaluation Of The Predicted Maximum Slope For All The Ramps (295 Samples In Total).

ALL	68% C.I.	90% C.I.	95% C.I.	99% C.I.
AVG	-0.36	0.10	0.33	0.77
STD	0.34	0.34	0.42	0.62
MIN	-2.98	-1.99	-1.50	-0.55
MAX	0.32	1.82	2.91	5.04
MED	-0.30	0.08	0.25	0.62
RMSE	0.49	0.36	0.53	0.99

Table 9.2: Evaluation Of The Predicted Maximum Slope For The Running Slope Of All The Curb Ramps (148 Samples In Total).

Running	68% C.I.	90% C.I.	95% C.I.	99% C.I.
AVG	-0.37	0.14	0.39	0.88
STD	0.42	0.41	0.49	0.74
MIN	-2.98	-1.99	-1.50	-0.55
MAX	0.32	1.82	2.91	5.04
MED	-0.30	0.10	0.31	0.69
RMSE	0.56	0.43	0.63	1.15

Table 9.3: Evaluation Of The Predicted Maximum Slope For The Cross Slope Of All The Curb Ramps (147 Samples In Total).

Cross	68% C.I.	90% C.I.	95% C.I.	99% C.I.
AVG	-0.34	0.07	0.27	0.66
STD	0.24	0.25	0.31	0.45
MIN	-1.12	-0.76	-0.59	-0.25
MAX	0.17	0.95	1.37	2.19
MED	-0.31	0.05	0.21	0.54
RMSE	0.42	0.26	0.41	0.80

On one hand, note that the analysis discussed above has a potential bias: The maximum values used as reference in the evaluation are also used in computing the predicted maximum slope. This can potentially lead to bias in the evaluation results especially considering that the sample size is usually small on an individual curb ramp (~11 on average). On the other hand, for the same reason, excluding the maximum value from the calculation of the confidence interval can be error prone. Additionally, removing a data point from a curb ramp can affect the distribution of the sampling as well. Therefore, to further validate the findings and ensure this bias is minimal, all of the repeatedly surveyed curb ramps were extracted to establish independent datasets to compare against. For a curb ramp that is repeatedly surveyed in this study, the data collected from the first epoch is treated as reference data while the second epoch is used to predict the maximum slope. Then the roles of these two epochs can be flipped to generate another sample in the analysis. In such a way, the roughness metrics can be evaluated from two independent datasets from the same site. The results (Table 9.4, Table 9.5, Table 9.6) mostly show similar trends and correlations with the exception of the reduced discrepancy between the running and cross slope measurements. In this test, the roughness metrics provide very similar performance for the running and cross slope unlike the previous tests.

Table 9.4: Evaluation Of The Predicted Maximum Slope For All The Slope Readings Of The Repeatedly Surveyed Curb Ramps (196 Samples In Total).

All	68% C.I.	90% C.I.	95% C.I.	99% C.I.
AVG	-0.34	0.09	0.31	0.72
STD	0.42	0.48	0.56	0.75
MIN	-1.75	-1.52	-1.41	-1.20
MAX	0.84	1.97	3.06	5.19
MED	-0.35	0.08	0.28	0.68
RMSE	0.54	0.49	0.64	1.04

Table 9.5: Evaluation Of The Predicted Maximum Slope For The Running Slope Readings Of The Repeatedly Surveyed Ramps (98 Samples In Total).

Running	68% C.I.	90% C.I.	95% C.I.	99% C.I.
AVG	-0.34	0.15	0.39	0.86
STD	0.38	0.44	0.55	0.81
MIN	-1.39	-0.98	-0.87	-0.66
MAX	0.78	1.97	3.06	5.19
MED	-0.41	0.10	0.35	0.75
RMSE	0.51	0.47	0.67	1.18

Table 9-6: Evaluation Of The Predicted Maximum Slope For The Cross Slope Of The Repeatedly Surveyed Ramps (98 Samples In Total).

Cross	68% C.I.	90% C.I.	95% C.I.	99% C.I.
AVG	-0.34	0.04	0.22	0.58
STD	0.46	0.52	0.56	0.66
MIN	-1.75	-1.52	-1.41	-1.20
MAX	0.84	1.40	1.67	2.29
MED	-0.32	0.08	0.25	0.56
RMSE	0.57	0.52	0.60	0.88

There is another interesting finding when comparing the two sets of analysis results. In the first test, where all the curb ramps are analyzed, a noticeable difference can be found between running slope and cross slope in the standard deviation of errors and RMSE (Table 9.2, Table 9.3). The reason can be a combination of a few factors. To demonstrate these factors, a summary table (Table 9.7) was created by averaging the key characteristics of the curb ramps for each site. First of all, given the fact that the length of a curb ramp is generally larger than its width, it would be more challenging to ensure the surface is constructed flat in the travel direction. Thus, the surface roughness (Slope STD, or 68% C.I.) for the running slope is significantly larger than the cross slope in most cases. Nevertheless, the roughness metrics behave very consistently for running slope and cross slope in the second test when only the repeatedly surveyed curb ramps are included. Thus, the research group also grouped the sites into two categories and compared the difference between those in the attempt to explain such discrepancy. Both categories cover a variety of number of slope samples (also indicating the dimension of the curb ramp), average slope, surface roughness, and maximum slope whereas the monitored group tended to be in a better condition than the other group. In addition to the wear and degradation on the curb ramps from usage and weathering that results in more local variation and irregularity, the condition also provides an indicator of the time when they were built to reflect the construction material and standard at the time. Thus, the surface condition might exacerbate the slope variation for the running slope, which did not follow the proposed roughness model as precisely as the cross slope or compared to the newly built ramps in good condition.

Table 9.7: Summary Of The Curb Ramp Characteristics (Average Values) At Each Site.

	Site	Condition	NSLOPE	Running (%slope)			Cross (%slope)		
				AVG Slope	Slope STD	MAX Slope	AVG Slope	Slope STD	MAX Slope
Monitored	Albany	Good	13.1	5.45	0.73	6.54	0.98	0.52	1.90
	Newport	Good	10.9	3.63	0.67	4.60	0.89	0.46	1.67
	Gold Beach	Good	14.0	7.26	0.81	8.55	1.93	0.58	2.91
	Roseburg	Fair	9.0	9.25	0.55	10.01	1.00	0.57	1.90
	Redmond	Fair/Good	8.0	9.33	0.94	10.62	1.38	0.74	2.39
Surveyed Once	Corvallis	Fair	12.7	2.09	0.70	3.28	1.25	0.52	2.12
	Lincoln City	Fair	7.7	4.85	0.85	6.01	2.92	1.25	4.72
	Salem	Poor/Fair	8.4	9.42	1.12	10.96	1.66	1.03	3.08
	Springfield	Fair	9.8	5.30	0.71	6.30	1.88	0.60	2.71
	Bend	Poor/Fair	8.8	4.05	0.78	5.18	1.76	0.54	2.56
	Tigard	Fair	9.0	6.25	1.41	8.48	1.41	0.78	2.60

9.1.2.1 Standard Deviation Approximation Method

Finally, given the challenge of having to compute the aforementioned slope metrics, this study also provides approximation approaches to help improve the feasibility of using such metrics in the field by the inspectors with limited access to computing resources. First of all, calculating the average slope can be challenging when a large number of slope readings are recorded. In these cases, the median slope can be used instead as an approximation of the average slope. Additionally, the standard deviation can be difficult and time consuming to derive in the field without the aid of a computational device. To cope with it, an improved empirical rule of thumb (Ramirez & Cox, 2012) can be utilized to estimate the standard deviation with the following equation:

$$\boldsymbol{Slope\ STD} = \frac{\boldsymbol{MAX\ Slope - MIN\ Slope}}{\boldsymbol{3\sqrt{\ln NSLOPE} - 1.5}}$$

(Equation 8-3)

To further simplify the formula, a lookup table (Table 9.8) can be generated to determine the scale factor (SF) applied to the range of the slope readings to obtain different confidence intervals. This reduces the computation to:

$$\boldsymbol{Slope\ STD = SF * (MAX\ Slope - MIN\ Slope)}$$

(Equation 8-4)

where the SF is computed as:

$$\boldsymbol{SF} = \frac{\boldsymbol{1}}{\boldsymbol{3\sqrt{\ln NSLOPE} - 1.5}}$$

(Equation 8-5)

Table 9.8: Lookup Table For Scale Factors That Are Applied To The Range Of The Slope (MAX Slope – MIN Slope) To Estimate The Confidence Interval (Unit: %Slope).

NSLOPE	68% C.I.	90% C.I.	95% C.I.	99% C.I.
6	2.5	4.1	8.1	20.9
12	3.2	5.3	10.4	26.8
15	3.4	5.7	11.1	28.5
18	3.6	5.9	11.6	29.9
21	3.7	6.1	12.0	31.0
24	3.8	6.3	12.4	32.0
27	3.9	6.5	12.7	32.8
30	4.0	6.6	13.0	33.5

To evaluate the accuracy of the proposed approximation, the estimated values of average slope (EST AVG Slope) and slope standard deviation (EST Slope STD) using the median slope and range of the slope, respectively, were compared against the actual average slope and slope standard deviation (Table 9.9). The results show that there is no significant bias in the proposed estimation approaches given that the RMSE for the average slope and slope standard deviation are 0.22% and 0.10%, respectively. It is worth noting that some of the samples only contain a few measurements, which can cause large errors in the approximation. That being said, the uncertainty shown in the result can be acceptable in most cases to determine whether the slope of a curb ramp is a clearly within ADA compliance or not. Regardless of whether the approximation equation is used, more detailed and high-accuracy surveys (e.g., leveraging TLS data) are recommended to investigate the border-line cases due to the variety of error sources in the smart level measurements.

Table 9.9: Accuracy Assessment Of The Approximation Of Average Slope And Slope Standard Deviation (Unit: %Slope).

	All (295 samples)		Running (148 samples)		Cross (147 samples)	
	EST AVG Slope	EST Slope STD	EST AVG Slope	EST Slope STD	EST AVG Slope	EST Slope STD
AVG	-0.01	0.00	0.02	0.00	-0.04	0.09
STD	0.22	0.10	0.25	0.10	0.16	0.09
MIN	-0.83	-0.52	-0.61	-0.37	-0.83	0.09
MAX	2.02	0.28	2.02	0.28	0.40	0.09
MED	-0.02	0.01	0.00	0.01	-0.03	0.09
RMSE	0.22	0.10	0.26	0.10	0.17	0.13

10.0 ASSESSMENT PROCEDURES

10.1 INTRODUCTION

As demonstrated in the previous sections, many error sources contribute to the error in each slope measurement, which can impact the overall assessment process. Additionally, more rigorous techniques can reduce this error and provide higher levels of confidence in the assessment. This section describes a tiered assessment workflow that can be implemented to balance personnel costs for assessment with costs due to construction rework of non-compliant ramps.

10.2 COMBINED ERROR SOURCES

The standard law of the propagation of variance can be used to combine the error sources associated with measurement (m), construction (c), and field effects (f) into a single standard deviation (σ_{CO}). This assumes that the variables are independent.

$$\boldsymbol{\sigma_{CO} = \sqrt{\sigma_M{}^2 + \sigma_C{}^2 + \sigma_F{}^2}}$$

(Equation 10-1)

Standard deviations were compiled from the many tests completed in this research and are compiled in Table 10.1 for running slope, cross slope, and general use (i.e., combination of the running and cross slope data).

Table 10.1. Estimated Standard Deviations And Calculations Of Combined Standard Deviations.

Type	s	Parameter	Running Slope	Cross Slope	General	Comments
Measurement	σ_{ISL}	Inspector measurement with smart level following ODOT process of obtaining several measurements and reporting the maximum.	0.48%	0.45%	0.46%	Data from Table 5-3 (Running Slope) and Table 5-5 (Cross Slope). Includes variability inherent to smart level and of the inspectors in performing the measurements.
	σ_P	Inspector measurement with smart level following the proposed process to estimate maximum with direct and reverse measurements and collected on a grid.	0.41%	0.25%	0.34%	Values from Table 9-1 (General), Table 9-2 (Running) and Table 9-3 (Cross). Includes the roughness of the surface directly in the measurement metric. Based on the repeat measurements at the field sites.
	σ_{LS}	Slope measurements obtained from the laser scanner (Leica Scanstation P40/50).	0.09%	0.09%	0.09%	Data from Table 4.7. The variability of the laser scanner data compared with a survey grade level (0.3mm elevation accuracy or ~0.05% slope for a 2 ft smart level).
Field	σ_F	Field variability observed based on ramp condition and changes over time.	0.34%	0.24%	0.29%	Measured variability from the in-situ field tests. Includes the variability associated with the laser scanner.
Construction	σ_C	Variability associated with concrete curing and hardening processes	0.13%	0.19%	0.23%	Data from Tables 6-6 (Running), Table 6-7 (Cross), and Tables 6.4 and 6.5 (Combined) from the concrete test. Includes the variability associated with the laser scanner.
Combined	σ_{Ico}	Combined variability considering measurement, field effects, and construction effects obtained using current ODOT procedures with a smart level.	0.59%	0.53%	0.58%	Computed using Eqn. 10-1 using σ_{ISL}, σ_F, and σ_C.

Type	s	Parameter	Running Slope	Cross Slope	General	Comments
	σ_{Pco}	Combined variability considering measurement, field effects, and construction effects obtained using the proposed process with a smart level.	0.53%	0.37%	0.49%	Computed using Eqn. 10-1 using σ_P, σ_F, and σ_C.
	σ_{LSco}	Combined variability considering measurement, field effects, and construction effects obtained using a laser scanner	0.35%	0.29%	0.36%	Computed using Eqn. 10-1 using σ_{LS}, σ_F, and σ_C.

Note that the analysis results show that the measurement standard deviation (σ_P) of the proposed approach is approximately 0.12% lower than the current ODOT procedures (σ_I). Assuming that both procedures achieve sufficient coverage of the ramps to capture the maximum slope, this difference in the standard deviations is most likely attributed to the fact that the proposed method considers both direct and reverse readings at each sampling location and uses the average of both readings for reporting the assessment results. In other words, the proposed approach is adding a repeated observation to the assessment for the same curb ramp. In principle, such repeating will improve the accuracy according to the following equation (see more detailed discussion of repeat measurements in Section 3.6).

$$\boldsymbol{\sigma}' = \pm\frac{\boldsymbol{\sigma}}{\sqrt{\boldsymbol{n}}}$$

(Equation 10-2)

where σ' is the standard deviation (i.e., precision) of the average slope, σ is the precision for each observation, and n is the number of observations. In this case, n is two and repeating the survey would decrease the standard deviation from 0.46% to 0.32%, which is consistent with the result determined from the proposed approach (0.34%). Nevertheless, it can be challenging to implement the repeat survey with the current ODOT process as such equation only applies when the repeated measurements are taken at the same sampling locations at a ramp. Additionally, the accuracy of the smart level stated in its specification is 0.2%. Hence, this error will also affect the accuracy of the calibration. Because the proposed approach averages the direct and reverse readings, it can mitigate the associated systematic errors in calibration.

10.3 COMPUTING PROBABILITIES

Probabilities of a ramp passing or failing compliance thresholds can be computed assuming a normal distribution with the combined standard deviations in Table 10.1 depending on the methods employed. First, the Z-Score is computed.

$$\boldsymbol{Z} = \frac{\boldsymbol{S_{ADA}} - \overline{\boldsymbol{S}}}{\boldsymbol{\sigma_{Ico}}}$$

(Equation 10-3)

The Z-score is then input into the normal distribution probability density function to determine the probability that the ramp slope is less than the 8.33% slope threshold. Table 10.2 shows computed maximum running slope values computed for different probabilities and standard deviations. As an example, if a 95% probability of passing is desired and the inspector is using the current ODOT procedure (σ_{Ico} = 0.59%), then the maximum slope measurement should be less than 7.35%. However, if the laser scanner is used instead (σ_{LSco} = 0.36%), then the maximum obtained slope measurement should be less than 7.74% to have a 95% probability of being less than 8.33%. Table 10.3 provides the corresponding values for cross slope. Figure 10.1 and Figure 10.2 provide a graphical representation based on these measurement methods for running and cross slope, respectively.

Table 10.2. Threshold Maximum Measured Slope Values Computed For Different Probabilities Of A Curb Ramp Running Slope Being Less Than 8.33% And Slope Thresholds For Different Values Of Standard Deviations.

Probability	σ=0.3	σ =0.4	σ =0.5	σ =0.6	σ =0.7
5%	8.83%	8.99%	9.16%	9.32%	9.48%
10%	8.72%	8.85%	8.97%	9.10%	9.23%
15%	8.64%	8.75%	8.85%	8.96%	9.06%
25%	8.54%	8.60%	8.67%	8.74%	8.81%
50%	8.33%	8.33%	8.33%	8.33%	8.33%
75%	8.13%	8.06%	8.00%	7.93%	7.86%
85%	8.02%	7.92%	7.82%	7.71%	7.61%
90%	7.95%	7.82%	7.69%	7.56%	7.44%
95%	7.84%	7.68%	7.51%	7.35%	7.18%

Table 10.3. Threshold Maximum Measured Slope Values Computed For Different Probabilities Of A Curb Ramp Cross Slope Being Less Than 2.0% And Slope Thresholds For Different Values Of Standard Deviations.

Probability	σ=0.3	σ =0.4	σ =0.5	σ =0.6	σ =0.7
5%	2.49%	2.66%	2.82%	2.99%	3.15%
10%	2.38%	2.51%	2.64%	2.77%	2.90%
15%	2.31%	2.41%	2.52%	2.62%	2.73%
25%	2.20%	2.27%	2.34%	2.40%	2.47%
50%	2.00%	2.00%	2.00%	2.00%	2.00%
75%	1.80%	1.73%	1.66%	1.60%	1.53%
85%	1.69%	1.59%	1.48%	1.38%	1.27%
90%	1.62%	1.49%	1.36%	1.23%	1.10%
95%	1.51%	1.34%	1.18%	1.01%	0.85%

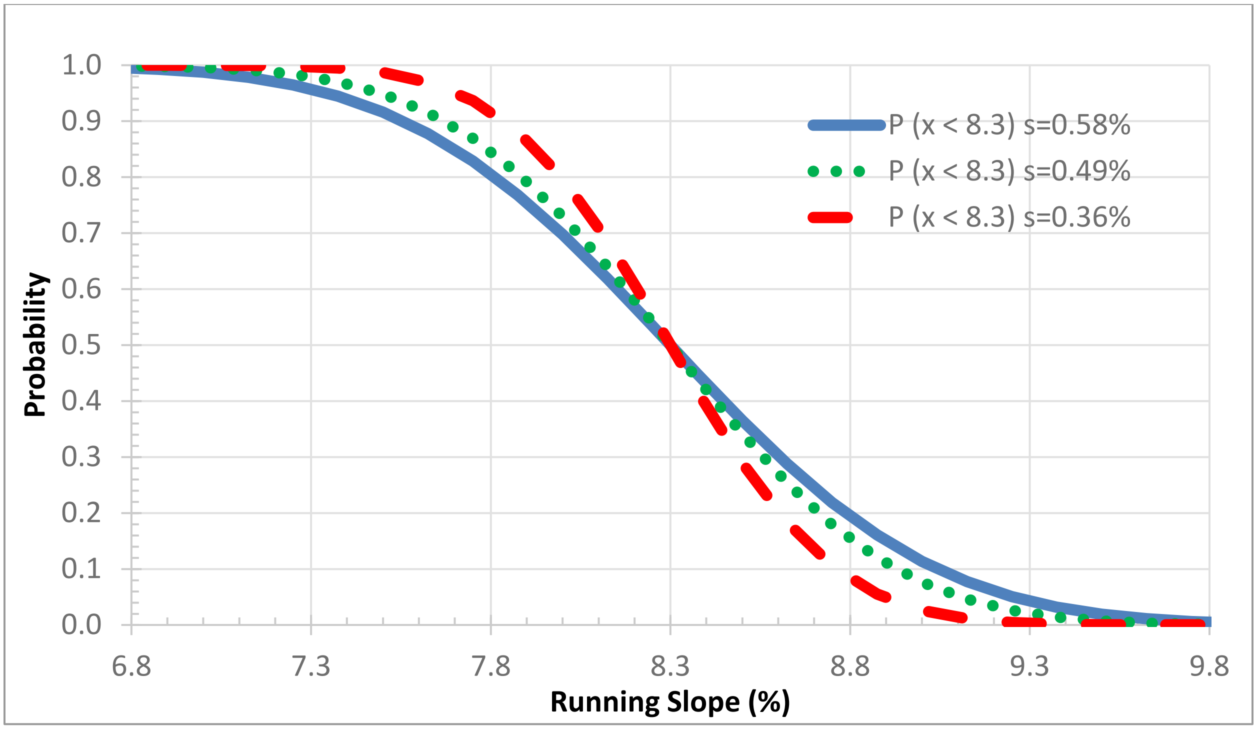


Figure 10.1. Example cross slope probability curve based on different standard deviations.

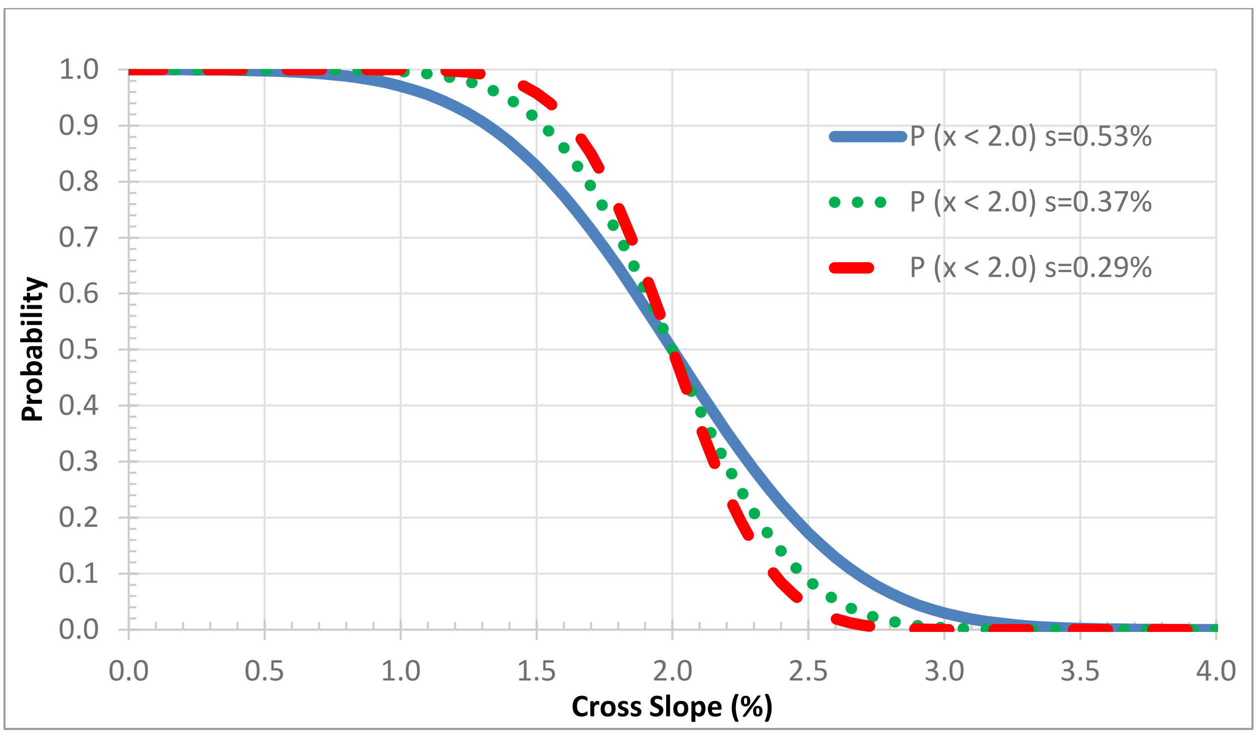


Figure 10.2. Example cross slope probability curve based on different standard deviations.

10.4 EXAMPLE TIERED ASSESSMENT WORKFLOW

Given the uncertainties in the assessment process and the cost of ramp removal, in borderline cases, it is prudent to implement more rigorous assessment techniques rather than solely rely on a single maximum measurement that is not repeatable as is done in practice. This will provide more confidence in the assessment process and the results should an issue arise in the future.

In order to execute this workflow, ODOT should determine appropriate thresholds to determine when to proceed to each phase of detailed measurement. The specific thresholds should balance the optimal use of their staff and resources with the costs of reconstruction/modification of curb ramps. This approach builds in tolerances for measurement error, construction processes, and typical field effects. The following sections provide an example of a tiered assessment process ODOT could implement. This example assumes running slope, but the same process can be implemented based on cross slope by substituting the appropriate values from Table 10.1. The general standard deviations were used.

10.4.1.1 Measurement Phase I (Default)

- Continue with the "current" ODOT inspection procedure where inspectors obtain multiple measurements to determine the maximum slope on the ramp. Perform both direct and reverse observations and average them to reduce error in the measurement and verify equipment is in calibration.

- Compute a Z-score using Eq. 10-3:

$$\boldsymbol{Z = \frac{S_{ADA} - \bar{S}}{\sigma_{Ico}}}$$

(Equation 10-3)

where Z is the Z-score for a normal distribution, S_{ADA} is the maximum allowable running slope (8.33% or 1:12), S is the maximum slope measured in the field, and σ_{Ico}= 0.58 from Table 10-1 for general use. Alternatively, the specific running or cross slope values can be used. Note that typically average values would be used in computing a Z-score. However, given that the assessment process is based on maximum values, those are used in lieu of averages, which is conservative.

- Once the Z-score is known, the probability that the ramp slope is less than the 8.33% threshold can be determined from the normal distribution function (Figure 10.3).

- If the probability is less than the desired confidence level (e.g., 95%), then the inspector should proceed with Measurement Phase II unless the probability is very low (e.g., 25% or less). In that case it is very unlikely to pass and not worth the inspector's time to acquire additional measurements. The ramp either needs to be reconstructed or modified.

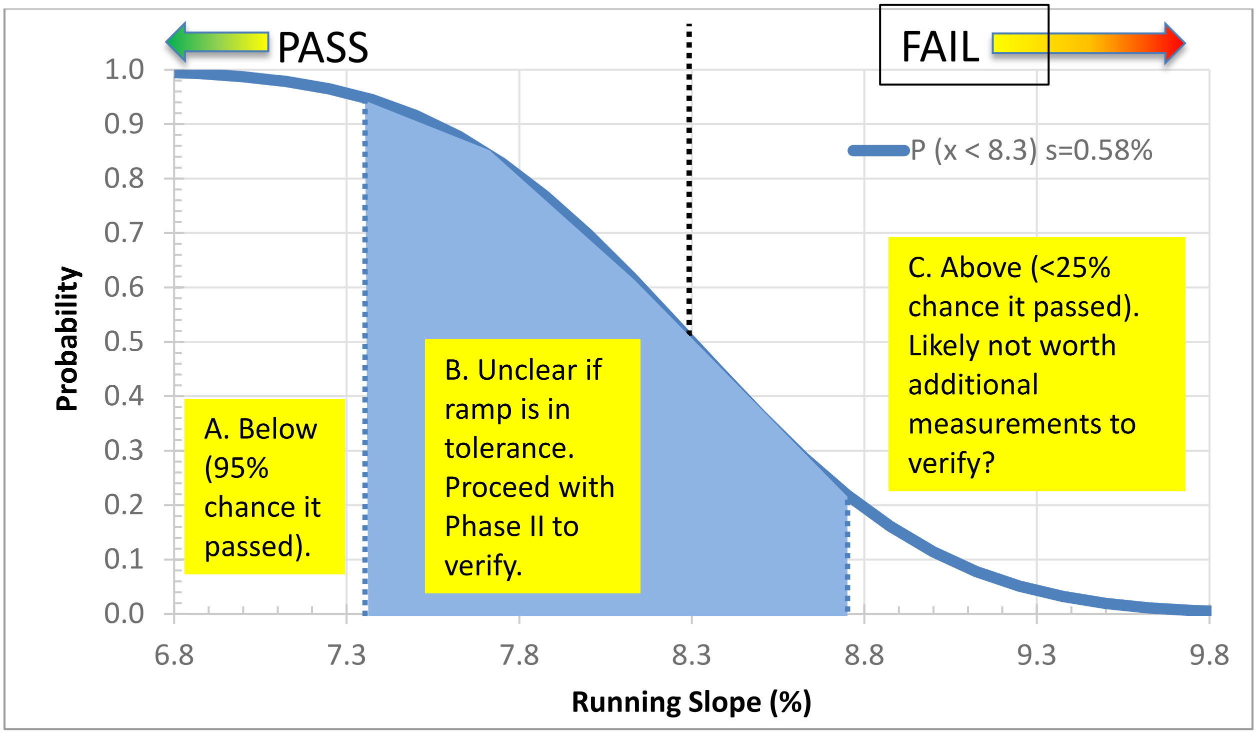


Figure 10.3. Example running slope compliance assessment for Measurement Phase I with the smart level.

10.4.2 Measurement Phase II (Proposed)

Should the initial measurement in Phase I not provide sufficient confidence (i.e., *probability (S<8.3%) < desired probability (e.g., 95%))*, then Phase II can be implemented:

- Obtain smart level readings using "Proposed Process" in Section 9.0 for more detailed, systematic measurements to estimate the maximum slope on the ramp.
- For the Z-score computation, use this new maximum slope from the proposed method and σ_{Pco}= 0.49% from Table 10.1 for general use. Alternatively, the specific running or cross slope values can be used.
- If the resulting probability (S<8.3%) of compliance (Figure 10.4) is less than the desired probability (e.g., 95%) but still within a reasonable chance of passing (e.g., 25%), execute Phase III for a detailed assessment.

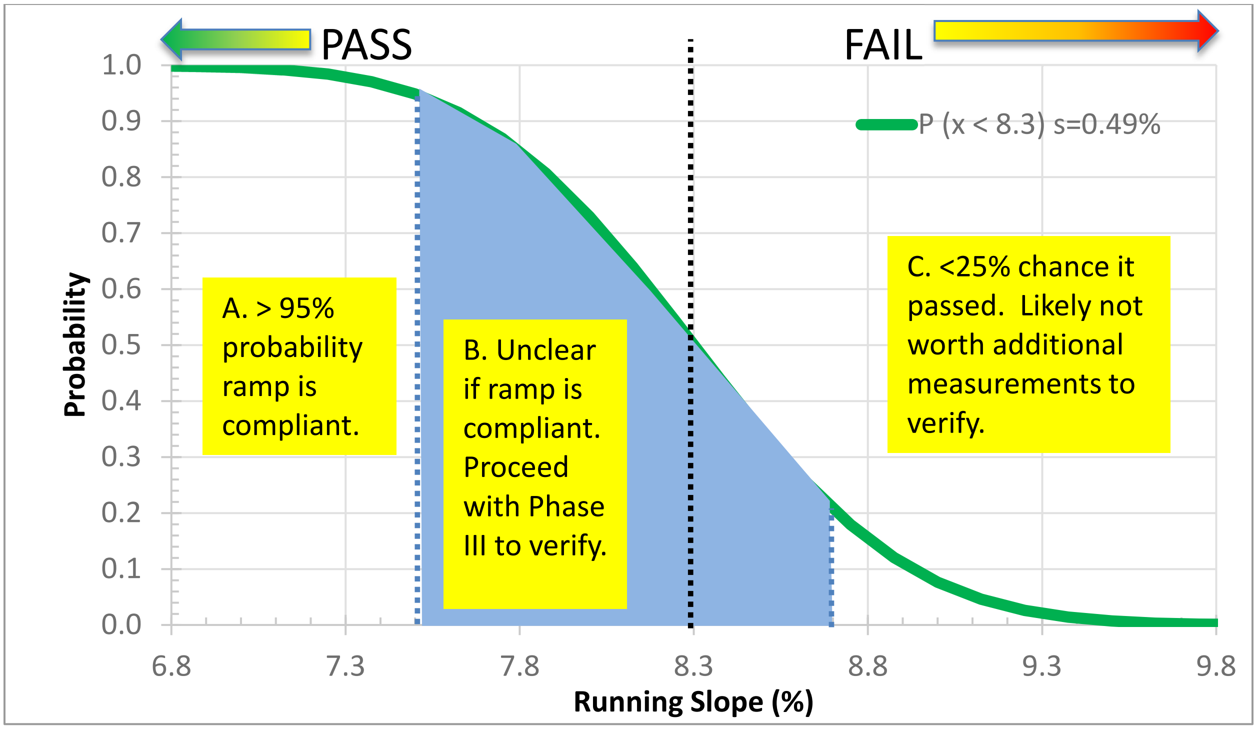


Figure 10.4. Running slope compliance assessment for Measurement Phase II with the proposed method using the smart level.

10.4.3 Measurement Phase III (Laser Scanning)

Should sufficient uncertainty remain after Phase II, perform a detailed investigation using advanced techniques.

- Use an appropriate laser scanner (e.g., Leica ScanStation P40 with the level compensation activated or Leica RTC360 with high accuracy tilt compensator enabled).
- Perform more advanced analysis and statistics to determine compliance to find the likely maximum (Similar to the methods employed in Section 6.4 using the virtual smart level analysis (Yang et al., Under Review).
- For the Z-score computation, use this new maximum slope from the laser scanning method and σ_{LSco}= 0.36% from Table 10-1 for general use. Alternatively, the specific running or cross slope values can be used.
- If the *probability (S<8.3%) is less than the desired probability (e.g., 95%),* then the ramp is deemed non-compliant and may need to be modified or reconstructed (Figure 10.5).

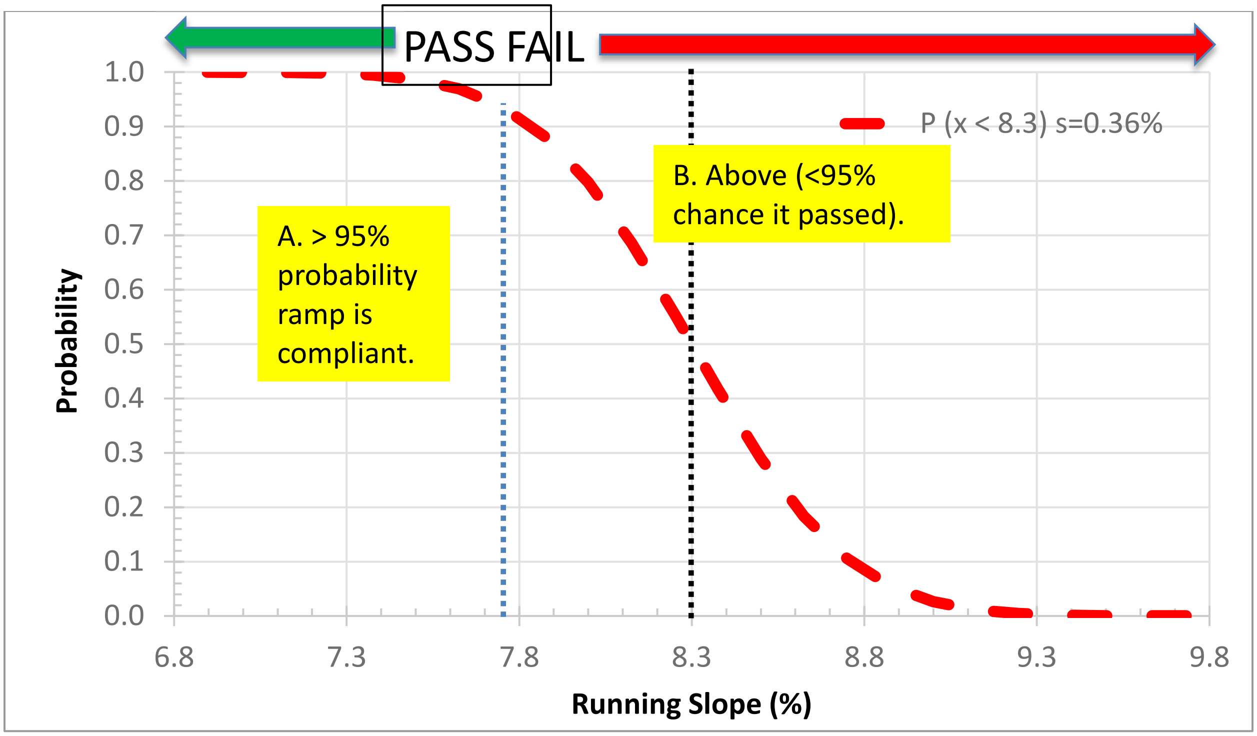


Figure 10.5. Running slope compliance assessment for Measurement Phase III with the laser scanner. In this case, the final pass or fail decision could be reached based on a 95% compliance threshold.

11.0 CONCLUSIONS AND RECOMMENDATIONS

11.1 CONCLUSIONS

Overall, the error modeling, experiments, and analysis have confirmed there is substantial variability in curb ramp slope measurements in practice. These differences are caused by many sources including sensor errors, inspector variability, measurement locations, quantity of measurements, and surface variability.

11.1.1 Challenge #1: Smart level calibration and operation

- Smart levels are ubiquitous, inexpensive, simple, and easy to use.
- Calibration of the smart level following manufacturer procedures is critical to obtain reliable results. To achieve the best possible accuracy, additional instructions should be followed (e.g., measuring at the exact same point during calibration).
- Some inspectors do not properly follow the calibration process. Additionally, the calibration process can be error prone when a flat surface is not available. Verification of the calibration is important.
- Direct and reverse observations improved the quality of the smart level readings by removing some systematic errors and improving the precision. It can also verify the calibration.
- Errors caused by horizontal and vertical misalignment of the equipment can be significant, particularly in context of assessing the ADA compliance of a curb ramp.
- The vertical misalignment (e.g., debris or bump) affects the slope measurement more substantially than the horizontal misalignment.
- Smart level measurements differed from ground truth measurements between -0.47%. and +0.36%. (Section 4)

11.1.2 Challenge #2: Inspector variability

- Improved sampling strategies and averaging direct and reverse observations can reduce standard deviations. (The proposed method reduced from standard deviations from ~0.5% to 0.3%)
- At least 5 repeated observations at the same spot can reduce the standard deviation of the average slope measurement performed with a smart level from ~0.3% to 0.1% (Section 3).
- High variability is observed in measurements (0.5% standard deviation) by different trained inspectors (Section 5). Note that one standard deviation represents about 68%

of the observations. Hence, 32% of the time, one would expect curb ramp measurements to differ by more than one standard deviation (0.5%). When blunders are not removed (e.g., inspectors mix up which ramp the measurements are taken from, the standard deviation increases to 1.25%).

- Using the maximum slope as a metric can also be error prone. Firstly, there is no guarantee that the inspector will find the maximum slope. Second, given the uncertainty in the measurement itself, that maximum slope measurement can be artificially high and not representative of the ramp or its navigability for mobility devices. Thus, repeat measurements by different inspectors can disagree by a wide margin.

- Measuring detectable warnings can be challenging because it can be difficult to clean the surface, they are easier to wear, and it is challenging to set up the smart level stably to measure the surface.

- Repeat monitoring at the OSU database sites following the proposed procedure showed consistent results, indicating that the proposed methodology is consistent and robust. The combined standard deviation from repeat measurements at field sites was reduced to from ~0.58% to 0.49% using the proposed measurement method.

11.1.3 Challenge #3: Flatness index for surface variability

- Except in cases of poor construction or damage, curb ramp surfaces generally can be considered planar within the tolerances of the typical measurement devices (e.g., smart level). However, this assumption should be validated through multiple measurements across the ramp. Notably, in the concrete test described in Section 6.0, the average slope of the ramp was very consistent with the design; however, the maximum slopes were found to be, on average, almost 1% higher for the constructed ramps due to localized surface roughness. Similar observations were made at the field sites.

- Smart levels are a highly efficient, simple method of obtaining slope measurements. Other techniques such as laser scanners, levels, and total stations can provide higher quality measurements. Laser scanners are particularly advantageous in that they provide detailed coverage of the ramp and can capture the variability of the ramp.

- Systematic methods are necessary to ensure consistent results. Applying a different methodology can result in substantial deviations in readings given the surface texture and variability.

- Detectable warning domes pose challenges in obtaining reliable measurements as they tilt the smart level and do not provide a stable setup. Although newer domes have wider spacing, the domes may not necessarily line up with the running slope direction (Section 5).

- Vertical misalignments (e.g., debris or bump) affect slope measurements more substantially than horizontal (Section 3).

11.1.4 Challenge #4: Field effects

- Some settlement was observed after rainfall in the built-up curb ramps from consolidation. The magnitude can vary due to different site soil conditions and other circumstances.

11.1.5 Challenge #5: Tolerances

- The industry does not yet have established tolerances for measurement. Construction tolerances, however, have been proposed. Ballast et al. recommend a 0.5% tolerance for the constructability. ODOT uses a 0.8% and 0.5% buffer in design to account for construction.

- This research quantified the precision of the measurements as well as deviations from concrete curing and field effects that can be used to establish tolerances for the measurements.

11.1.6 Challenge #6: Construction processes

- Curb ramp slope measurements are affected by curing processes and construction settlement. Slope changes of -0.33% to +0.28% were observed while curing (Section 6).

- Some settlement was observed after rainfall in the built-up curb ramps from consolidation that can affect the slope of the ramp. The type of soil and wetting processes as well as other environmental factors can influence how long these processes take to occur.

11.2 RECOMMENDATIONS

The research team provides several recommendations based on the findings of this research.

11.2.1 Challenge #1: Smart level calibration and operation

- Obtaining both direct and reverse readings of the smart level can be beneficial to remove the bias in calibration, bias in placing the device, and as a way for QA/QC in the field. Given that this practice is straightforward to implement with minimal cost, it should be made part of the standard of practice.

- Execute a tiered process to perform more rigorous measurements when close to tolerances. Smart levels are an adequate tool for determining if a ramp is very clearly within tolerance or clearly out of tolerance. However, for ramps close to tolerance, it is recommended to use a terrestrial laser scanner (e.g., Leica P50 or RTC360) with sufficient leveling quality to verify the ramp. While a laser scanner is more expensive than a smart level, use of a laser scanner to obtain a more reliable measurement will be less expensive and more sustainable (less concrete waste) than removing the ramp or legal costs. Given that only relative measurements are needed, the scanning process and analysis is straightforward to implement. ODOT's Engineering Automation has extensive experience with laser scanning and thus has the capabilities.

- With the proposed tiered process, ODOT should determine appropriate confidence intervals as to when a more detailed inspection process is warranted that balances inspector time with the construction costs associated with ramp removal.

- Given that detectable warning domes result in unstable setups, it is recommended to align the domes with the running slope direction, provide adequate spacing for a smart level within the dome, and/or discuss the possibility of a thinner smart level with manufacturers.

11.2.2 Challenge #2: Inspector variability

- Systematic methods should be followed by all parties involved to obtain consistent results. Applying a different methodology can result in substantial variability in readings.

- Given impacts of blunders, time to train personnel, and many measurements to be acquired, the research the team recommends ODOT consider the development of an app or as a minimum a modified in-field written procedure to ensure more systematic assessment. A basic smart app could support the field data collection process, perform the statistical analyses to walk through the workflow and determine if sampling is sufficient, and implement basic checks such as provide warnings of potential blunders in data. The app could also log GNSS positioning data to minimize ramp confusion by the inspectors.

11.2.3 Challenge #3: Flatness index for surface variability

- Use the proposed slope measurement and reporting method to capture systematic measurements across each ramp for a more rigorous assessment, particularly when it is questionable if the ramp is in compliance. This process directly considers roughness and determines a more representative value (90% confidence) for the curb ramp rather than relying on a single maximum value that can be error prone. The ODOT curb ramp inspection form (Appendix A) could be updated to allow the inspectors to record this information. A basic smart app or intelligent form could perform the computations for the inspector.

- Perform more rigorous research to determine appropriate roughness window evaluation sizes relevant to mobility assistant devices (e.g., wheel size), impact of roughness on navigability, and appropriate roughness tolerances.

11.2.4 Challenge #4: Field effects

- Incorporate future assessments to expand the database that encodes the individual measurements to continue to refine estimates of measurement uncertainty as well as evaluate other factors that may result in curb ramps no longer being in compliance (e.g., damage, settlement) when monitoring a curb ramp. This database can also be used as a quality control check on inspections.

11.2.5 Challenge #5: Tolerances

- Tolerances in design and evaluating if a curb ramp is in compliance should consider the variability (0.5%) of inspector measurements and construction processes. This tolerance determined through rigorous testing is similar to the recommendation of Ballast (2011) – See Table 2.1. However, the recommendation by Ballast is a tolerance based on inconsistencies in construction, not in the measurements itself, so both tolerances should be considered. Notably, the measurement tolerance should be considered in evaluating whether an in-service ramp should be removed in a situation where a high reading is obtained at a later date from the construction time and may simply be the result of variability in the placement and operation of the smart level.

11.2.6 Challenge #6: Construction processes

- Smart level readings for compliance should be taken after 48 hours after placing concrete when concrete has had several days to adequately cure and harden. Readings may be taken to assist contractors with compliance during construction, but smart levels should not be placed on fresh concrete.

11.2.7 Other

- Work with various stakeholders to move away from using a single maximum slope as the acceptance criteria and utilize the average and standard deviation of the measurements for a more holistic assessment of the ramp. Many of the tolerances and uncertainties could be reduced with this approach, resulting in higher confidence of the suitability of the ramp. As part of these discussions, work with stakeholders to allow for recognized industry construction and manufacturing tolerances as outline in Section 104 of the ADA standards (U.S. DOJ, 2010) to be considered in specified values such that the 8.33% running and 2.0% cross slopes are not strict cutoffs and provide tolerance for the measurement error.

- Investigate the possibility of using pocket lidar technology to measure slope. A current FHWA project is investigating this technology in transportation construction applications. While this technology is not as accurate as static or mobile terrestrial laser scanning, the cost of implementation is minimal both in terms of the availability of the technology (many inspectors have smart devices to complete their work) and the training required given the simplicity of the apps.

- Consider exploring other methods to evaluate curb ramp compliance that are more directly in line with the navigability of the ramp and its intended purpose. For example, a wheelchair-based sensor system could be designed that could directly measure the forces required to navigate the ramp and the forces acting on the occupant of the wheelchair could provide a more meaningful indication of the suitability of a ramp compared with direct measurements of geometric properties. Some mobile measurement devices are now available for sidewalks but are challenging to implement on curb ramps given they are too short for the device to initialize.

- Consider exploring the possibility of having design information (e.g., plans, specifications, ramp style, run direction) available to the inspectors during the evaluation of new and existing curb ramps to aid the assessment process. This will help reduce mistakes (e.g., measuring the wrong ramp). Additionally, incorporating design information into the database established in this research would allow additional analyses to support refinement of construction and measurement tolerances.

- Present the findings of this research to the ADA community directly and engage in discussions about measurement capabilities (e.g., National ADA symposium in 2024).

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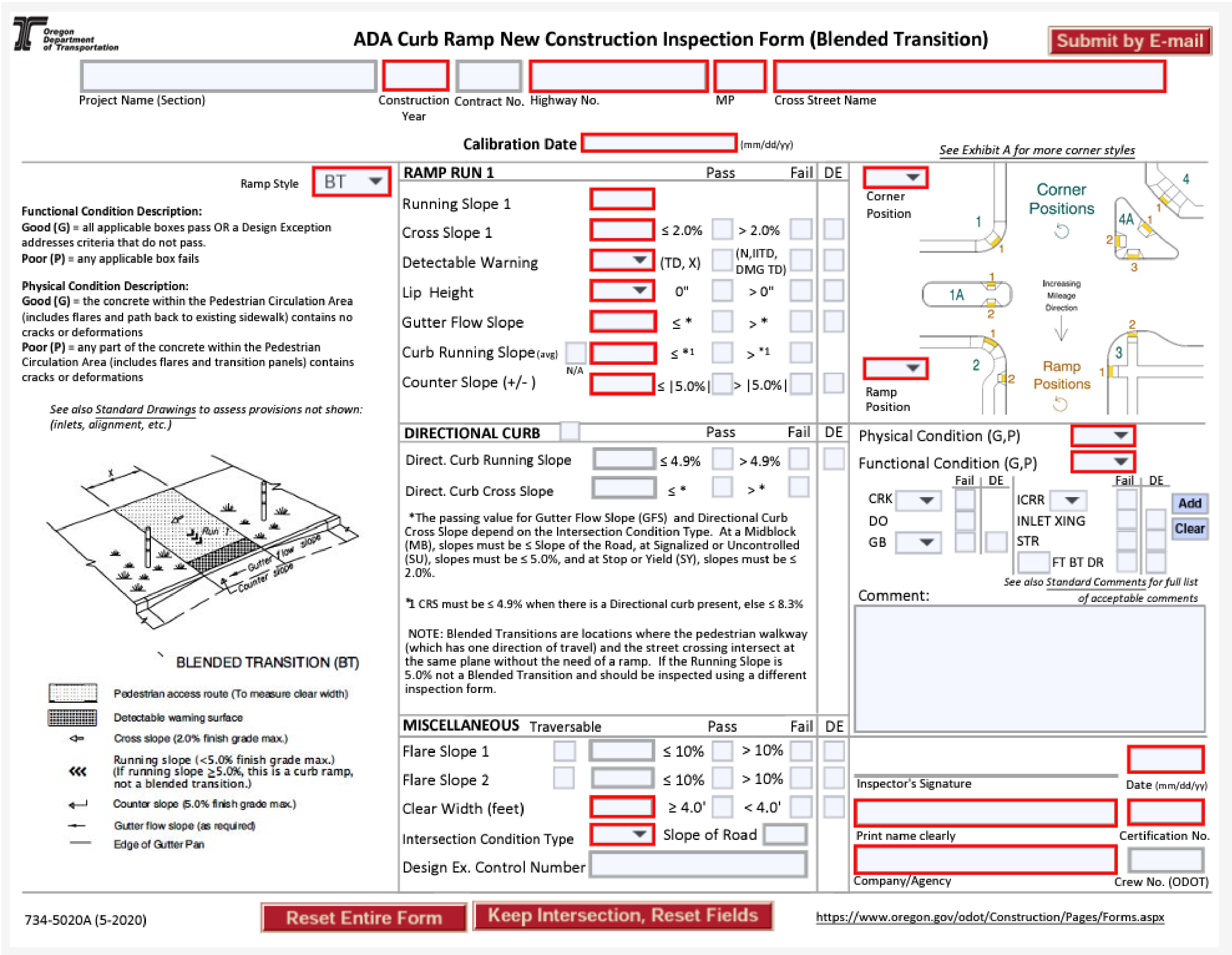
APPENDIX A
CURB RAMP NEW CONSTRUCTION INSPECTION FORMS



Oregon Department of Transportation

ADA Curb Ramp New Construction Inspection Form (Blended Transition)

Submit by E-mail

Project Name (Section) | Construction Year | Contract No. | Highway No. | MP | Cross Street Name

Calibration Date (mm/dd/yy)

See Exhibit A for more corner styles

Ramp Style: BT

Functional Condition Description:
Good (G) = all applicable boxes pass OR a Design Exception addresses criteria that do not pass.
Poor (P) = any applicable box fails

Physical Condition Description:
Good (G) = the concrete within the Pedestrian Circulation Area (includes flares and path back to existing sidewalk) contains no cracks or deformations
Poor (P) = any part of the concrete within the Pedestrian Circulation Area (includes flares and transition panels) contains cracks or deformations

See also Standard Drawings to assess provisions not shown: (inlets, alignment, etc.)

BLENDED TRANSITION (BT)

- Pedestrian access route (To measure clear width)
- Detectable warning surface
- Cross slope (2.0% finish grade max.)
- Running slope (<5.0% finish grade max.) (If running slope ≥5.0%, this is a curb ramp, not a blended transition.)
- Counter slope (5.0% finish grade max.)
- Gutter flow slope (as required)
- Edge of Gutter Pan

RAMP RUN 1		Pass		Fail	DE
Running Slope 1					
Cross Slope 1		≤ 2.0%		> 2.0%	
Detectable Warning		(TD, X)		(N, IITD, DMG TD)	
Lip Height		0"		> 0"	
Gutter Flow Slope		≤ *		> *	
Curb Running Slope (avg)	N/A	≤ *1		> *1	
Counter Slope (+/-)		≤ |5.0%|		> |5.0%|	

DIRECTIONAL CURB		Pass		Fail	DE
Direct. Curb Running Slope		≤ 4.9%		> 4.9%	
Direct. Curb Cross Slope		≤ *		> *	

*The passing value for Gutter Flow Slope (GFS) and Directional Curb Cross Slope depend on the Intersection Condition Type. At a Midblock (MB), slopes must be ≤ Slope of the Road, at Signalized or Uncontrolled (SU), slopes must be ≤ 5.0%, and at Stop or Yield (SY), slopes must be ≤ 2.0%.

*1 CRS must be ≤ 4.9% when there is a Directional curb present, else ≤ 8.3%

NOTE: Blended Transitions are locations where the pedestrian walkway (which has one direction of travel) and the street crossing intersect at the same plane without the need of a ramp. If the Running Slope is 5.0% not a Blended Transition and should be inspected using a different inspection form.

MISCELLANEOUS	Traversable		Pass		Fail	DE
Flare Slope 1			≤ 10%		> 10%	
Flare Slope 2			≤ 10%		> 10%	
Clear Width (feet)			≥ 4.0'		< 4.0'	
Intersection Condition Type			Slope of Road			
Design Ex. Control Number						

Corner Position

Corner Positions

Increasing Mileage Direction

Ramp Position

Ramp Positions

Physical Condition (G,P)

Functional Condition (G,P)

	Fail	DE		Fail	DE
CRK			ICRR		
DO			INLET XING		
GB			STR		
			FT BT DR		

Add | Clear

See also Standard Comments for full list of acceptable comments

Comment:

Inspector's Signature | Date (mm/dd/yy)

Print name clearly | Certification No.

Company/Agency | Crew No. (ODOT)

734-5020A (5-2020)

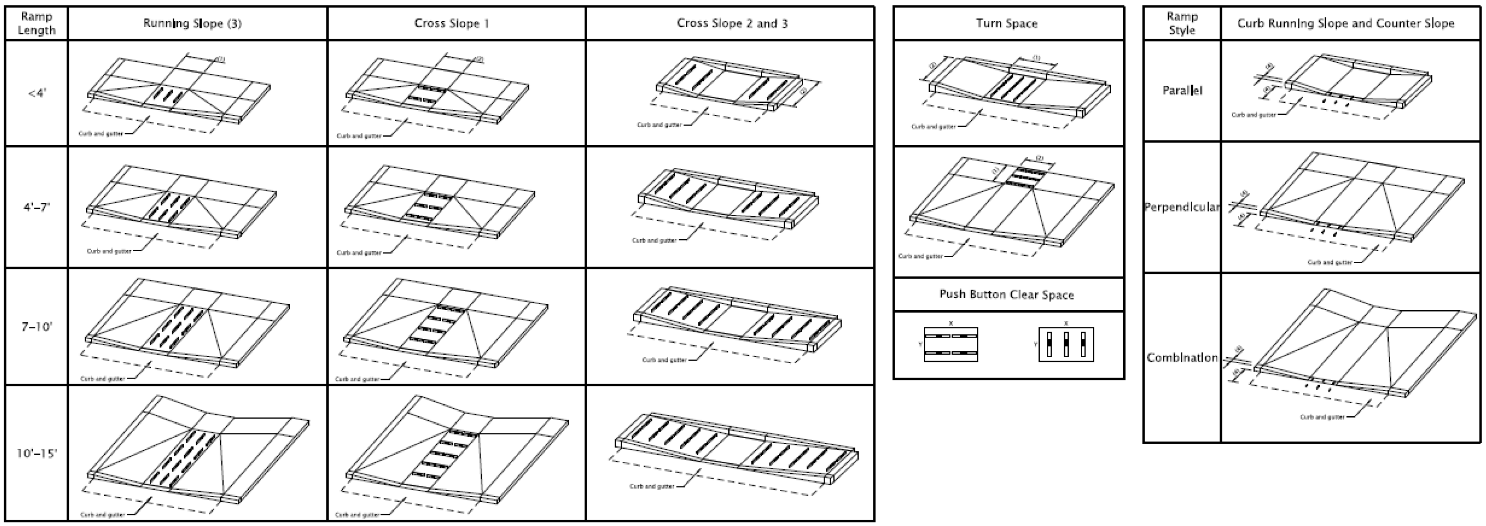
Reset Entire Form | Keep Intersection, Reset Fields

https://www.oregon.gov/odot/Construction/Pages/Forms.aspx

Figure A.0.1: ODOT curb ramp assessment form (from ODOT's inspector training materials).

RAMP SLOPE MEASUREMENTS

IMPORTANT: VISUALLY INSPECT THE RAMP FOR ANY NOTICEABLE SURFACE IRREGULARITY AND MEASURE/RECORD THE HIGHEST MEASURED VALUE



NOTES

(1) For ramp width greater than 5.0', add a row of measurements for each additional 2.0' width.
(2) For ramp width greater than 7.0', add one additional measurement for each additional 2.0' width.
(3) Applies to Running Slopes on ramp runs 2, 3 for parallel and combination ramps.
(4) Measure Curb Running Slope and Counter Slope consistent with the number of running slope columns measured, with a minimum of three. Measure Gutter Flow Slope consistent with the number of Cross Slope 1 measurements taken.
(5) Level placement locations shown are minimums. Specified slopes shall be compliant when measured anywhere on the ramp.
(6) Do not place level across two adjacent surfaces (truncated domes/concrete, curb/truncated dome, and gutter pan/ACP).

Figure A.0.2: Ramp slope measurement requirements (from ODOT's inspector training materials).

APPENDIX B
SUPPLEMENTAL DATA

Table B.0.1 Accuracy Assessment For Leica BLK360 On Curb Ramp 1.

PID	dX (m)	dY (m)	dZ (m)	Error (m)
CR1C11	-0.0016	0.0006	-0.0002	0.0017
CR1C12	-0.0012	0.0002	0.0021	0.0024
CR1C21	0.0006	0.0004	0.0000	0.0007
CR1C22	-0.0007	-0.0002	0.0016	0.0017
CR1C31	0.0004	0.0002	-0.0005	0.0007
CR1C32	0.0008	0.0001	-0.0003	0.0009
CR1C41	-0.0016	-0.0001	0.0028	0.0032
CR1C42	0.0006	-0.0017	0.0037	0.0041
CR1C51	0.0002	0.0001	0.0017	0.0017
CR1C52	-0.0006	-0.0006	0.0028	0.0029
CR1C61	-0.0001	0.0008	0.0004	0.0009
CR1C62	0.0021	-0.0002	0.0016	0.0026
CR1C71	-0.0026	0.0000	0.0029	0.0039
CR1C72	-0.0032	0.0014	0.0051	0.0062
CR1C81	-0.0001	0.0010	0.0009	0.0014
CR1C82	-0.0010	-0.0006	0.0012	0.0017
CR1C91	0.0006	0.0002	0.0012	0.0013
CR1C92	0.0003	0.0007	0.0023	0.0024
CR1CA1	-0.0036	-0.0017	-0.0019	0.0044
CR1CA2	-0.0021	-0.0005	0.0002	0.0022
CR1CB1	-0.0008	-0.0005	0.0004	0.0010
CR1CB2	-0.0001	0.0013	-0.0011	0.0017
CR1F11	-0.0001	0.0007	0.0006	0.0009
CR1F12	0.0005	0.0015	0.0011	0.0019
CR1F21	0.0002	0.0001	0.0010	0.0010
CR1F22	0.0001	0.0013	-0.0009	0.0016
CR1R11	-0.0002	-0.0010	0.0017	0.0020
CR1R12	0.0008	-0.0012	0.0004	0.0015
CR1R21	0.0000	-0.0012	0.0022	0.0025
CR1R22	-0.0010	-0.0006	-0.0006	0.0013
CR1R31	0.0003	-0.0001	0.0036	0.0036
CR1R32	-0.0008	0.0009	0.0009	0.0015
CR1R41	0.0004	0.0008	0.0041	0.0042
CR1R42	0.0005	-0.0014	0.0009	0.0017
CR1R51	-0.0037	-0.0009	0.0033	0.0050
CR1R52	-0.0022	0.0011	0.0023	0.0034

Table B.0.2 Accuracy Assessment For Leica BLK360 On Curb Ramp 2.

PID	dX (m)	dY (m)	dZ (m)	Error (m)
CR2C011	-0.0011	-0.0028	0.0011	0.0032
CR2C012	-0.0023	-0.0013	0.0051	0.0057
CR2C021	0.0005	0.0029	0.0017	0.0034
CR2C022	-0.0007	-0.0001	0.0036	0.0037
CR2C031	0.0003	-0.0021	0.0045	0.0050
CR2C032	-0.0033	0.0023	0.0041	0.0057
CR2C041	-0.0024	-0.0004	0.0027	0.0036
CR2C042	-0.0005	-0.0011	0.0043	0.0045
CR2C051	-0.0018	0.0003	0.0040	0.0044
CR2C052	-0.0029	-0.0005	0.0037	0.0047
CR2C061	-0.0004	0.0020	-0.0002	0.0020
CR2C062	0.0014	0.0006	0.0032	0.0036
CR2C071	0.0001	-0.0004	0.0056	0.0056
CR2C072	-0.0027	-0.0024	0.0036	0.0051
CR2C081	-0.0031	0.0020	0.0075	0.0083
CR2C082	0.0001	-0.0021	0.0063	0.0066
CR2C091	0.0002	-0.0057	0.0050	0.0076
CR2C092	-0.0007	-0.0045	0.0058	0.0074
CR2C101	-0.0010	-0.0039	0.0058	0.0071
CR2C102	-0.0022	-0.0030	0.0071	0.0080
CR2C111	0.0010	-0.0019	0.0053	0.0057
CR2C112	-0.0026	-0.0004	0.0059	0.0064
CR2C121	-0.0008	-0.0031	0.0035	0.0047
CR2C122	0.0002	0.0002	0.0036	0.0036
CR2C131	0.0002	-0.0018	0.0045	0.0049
CR2C132	-0.0013	0.0030	0.0040	0.0051
CR2F111	-0.0008	0.0024	0.0000	0.0025
CR2F112	0.0020	0.0006	-0.0005	0.0022
CR2F121	0.0103	0.0037	0.0014	0.0111
CR2F122	-0.0012	0.0015	0.0016	0.0025
CR2F131	-0.0022	-0.0007	0.0017	0.0028
CR2F132	-0.0023	-0.0006	0.0034	0.0041
CR2F211	0.0025	-0.0005	0.0044	0.0051
CR2F212	0.0000	0.0000	0.0044	0.0044
CR2F221	-0.0023	-0.0010	0.0034	0.0042
CR2F222	0.0012	-0.0002	0.0011	0.0017
CR2R011	0.0010	-0.0006	0.0028	0.0030
CR2R012	0.0006	0.0013	0.0043	0.0045

Table B.0.3 Accuracy Assessment For Leica P40 On Curb Ramp 1.

PID	dX (m)	dY (m)	dZ (m)	Error (m)
CR1C11	0.0009	-0.0011	-0.0017	0.0022
CR1C12	0.0003	-0.0015	-0.0014	0.0021
CR1C21	0.0001	-0.0023	-0.0015	0.0028
CR1C22	0.0018	-0.0009	-0.0019	0.0028
CR1C31	0.0009	-0.0025	-0.0020	0.0033
CR1C32	0.0003	-0.0016	-0.0018	0.0024
CR1C41	-0.0001	0.0022	-0.0007	0.0023
CR1C42	0.0001	0.0006	-0.0018	0.0019
CR1C51	0.0007	-0.0016	-0.0018	0.0025
CR1C52	-0.0001	-0.0013	-0.0017	0.0021
CR1C61	0.0014	-0.0019	-0.0011	0.0026
CR1C62	0.0006	0.0001	-0.0019	0.0020
CR1C71	-0.0001	-0.0017	-0.0016	0.0023
CR1C72	0.0003	0.0007	-0.0024	0.0025
CR1C81	0.0004	0.0003	-0.0016	0.0016
CR1C82	-0.0005	-0.0003	-0.0013	0.0014
CR1C91	0.0011	-0.0005	-0.0013	0.0018
CR1C92	0.0008	-0.0010	-0.0012	0.0018
CR1CA1	0.0029	-0.0004	-0.0024	0.0038
CR1CA2	-0.0036	0.0008	-0.0023	0.0043
CR1CB1	0.0017	-0.0002	-0.0021	0.0027
CR1CB2	-0.0026	-0.0004	-0.0016	0.0031
CR1F11	0.0004	0.0000	-0.0019	0.0019
CR1F12	0.0000	-0.0002	-0.0024	0.0024
CR1F21	-0.0003	0.0014	-0.0025	0.0028
CR1F22	-0.0004	-0.0004	-0.0014	0.0015
CR1R11	0.0003	0.0003	-0.0018	0.0018
CR1R12	0.0003	0.0001	-0.0021	0.0021
CR1R21	0.0005	0.0021	-0.0013	0.0025
CR1R22	0.0015	-0.0013	-0.0021	0.0029
CR1R31	0.0008	0.0002	-0.0019	0.0020
CR1R32	-0.0003	-0.0008	-0.0016	0.0018
CR1R41	-0.0011	0.0001	-0.0014	0.0018
CR1R42	-0.0020	-0.0001	-0.0016	0.0025
CR1R51	0.0008	0.0004	-0.0022	0.0023
CR1R52	-0.0007	0.0014	-0.0012	0.0019

Table B.0.4 Accuracy Assessment For Leica P40 On Curb Ramp 2.

PID	dX (m)	dY (m)	dZ (m)	Error (m)
CR2C011	0.0004	0.0006	-0.0007	0.0010
CR2C012	-0.0008	0.0001	-0.0017	0.0019
CR2C021	0.0010	-0.0007	-0.0021	0.0024
CR2C022	-0.0002	0.0013	-0.0012	0.0017
CR2C031	-0.0002	-0.0007	-0.0023	0.0024
CR2C032	0.0012	-0.0013	-0.0017	0.0024
CR2C041	-0.0009	0.0010	-0.0011	0.0017
CR2C042	0.0010	-0.0027	-0.0025	0.0038
CR2C051	-0.0013	0.0017	-0.0018	0.0028
CR2C052	-0.0014	-0.0001	-0.0031	0.0034
CR2C061	0.0001	-0.0006	-0.0020	0.0021
CR2C062	-0.0011	0.0020	-0.0016	0.0028
CR2C071	-0.0004	0.0010	-0.0022	0.0024
CR2C072	0.0018	0.0000	-0.0022	0.0028
CR2C081	-0.0016	-0.0006	-0.0023	0.0029
CR2C082	0.0016	0.0003	-0.0015	0.0022
CR2C091	-0.0013	0.0017	-0.0018	0.0028
CR2C092	0.0008	-0.0011	-0.0020	0.0024
CR2C101	-0.0005	0.0015	-0.0020	0.0025
CR2C102	0.0013	-0.0006	-0.0017	0.0022
CR2C111	0.0005	-0.0005	-0.0015	0.0016
CR2C112	0.0009	-0.0010	-0.0019	0.0023
CR2C121	0.0017	-0.0017	-0.0023	0.0033
CR2C122	0.0027	0.0006	-0.0022	0.0035
CR2C131	-0.0003	-0.0034	-0.0013	0.0037
CR2C132	-0.0008	0.0004	-0.0028	0.0029
CR2F111	0.0017	-0.0012	-0.0028	0.0035
CR2F112	-0.0005	0.0010	-0.0023	0.0025
CR2F121	-0.0052	0.0021	-0.0024	0.0061
CR2F122	-0.0037	0.0029	-0.0022	0.0052
CR2F131	0.0013	0.0007	-0.0021	0.0025
CR2F132	0.0042	-0.0002	-0.0014	0.0044
CR2F211	0.0000	0.0009	-0.0024	0.0025
CR2F212	0.0015	0.0004	-0.0014	0.0020
CR2F221	0.0002	0.0014	-0.0014	0.0019
CR2F222	0.0007	-0.0008	-0.0017	0.0020
CR2R011	-0.0005	0.0008	-0.0020	0.0022
CR2R012	0.0001	0.0007	-0.0025	0.0026