SPR 844

Evaluation of Curb Ramp Compliance: Review of Tools, Methods, and Time to Develop Error Tolerances

Northwest Transportation Conference

Oregon Department of Transportation

Rodger Gutierrez, Michael Olsen, Ezra Che, David Trejo, Caleb Ogbeta

COLLEGE OF ENGINEERING

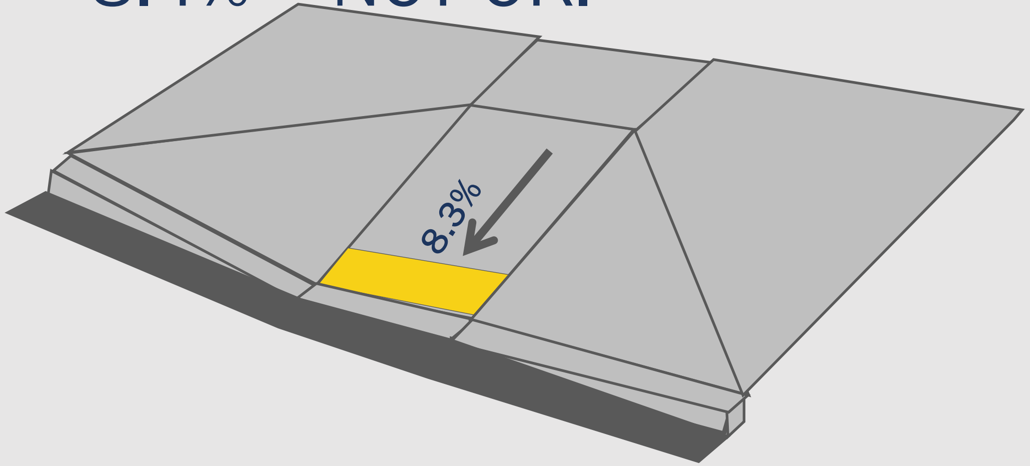
School of Civil and Construction Engineering

Oregon State University

ADA Standards for Curb Ramp Compliance

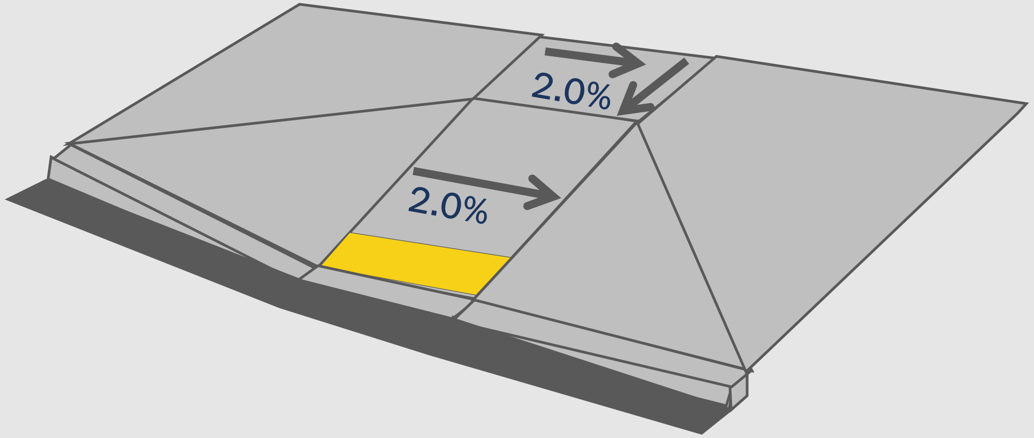
1:12 Max. Running Slope (8.3%)

- 8.3% = OK
- 8.4% = NOT OK.



1:48 Max. Cross Slope (2.1%)

- 2.0% = OK
- 2.2% = NOT OK.



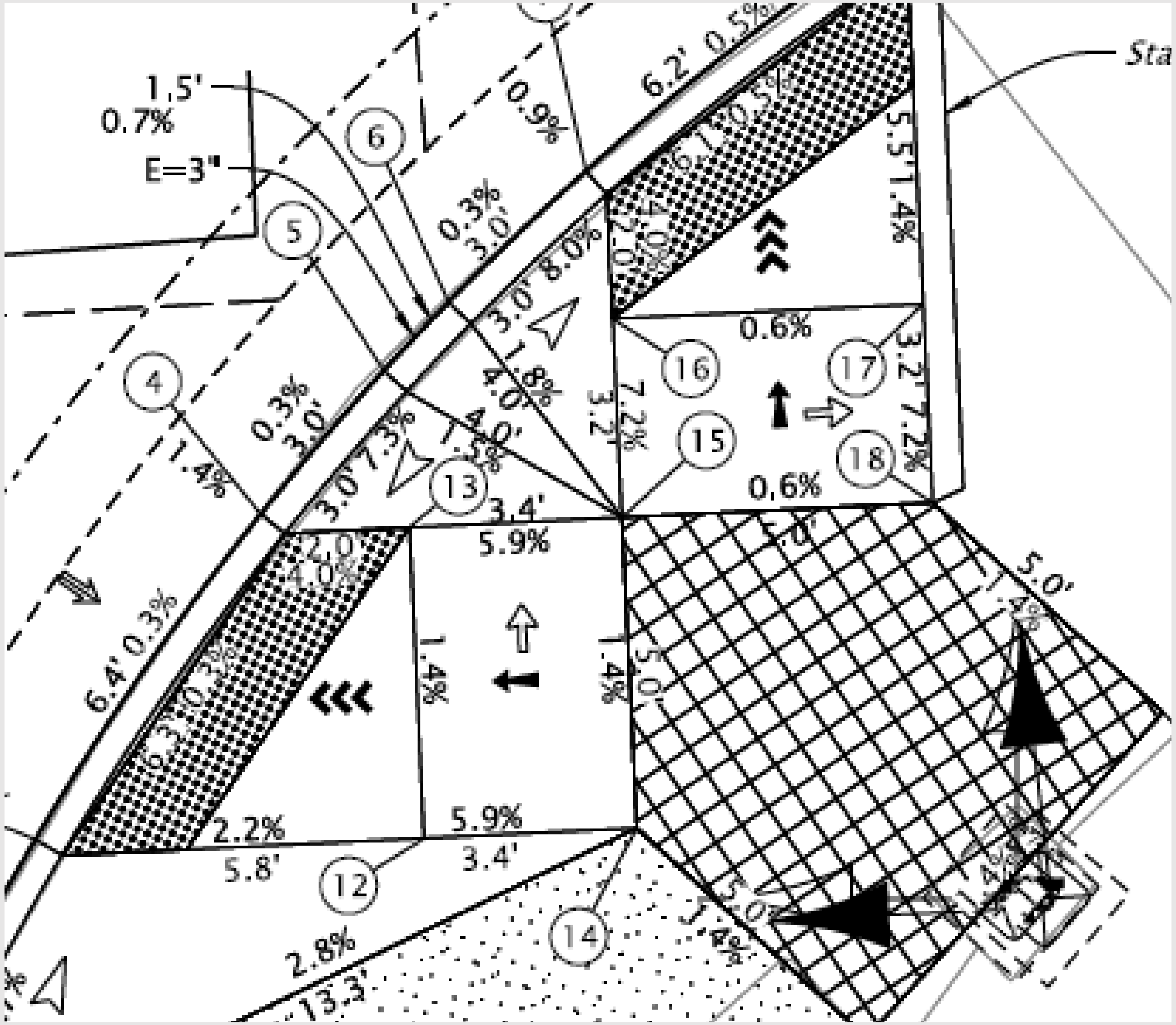
A TOLERANCE BEYOND A MAXIMUM VALUE IS NOT ALLOWED.
RECOMMENDED TO UNDER-DESIGN.

- *ODOT's Design Max. 7.5%*
- *ODOT's Design Max. 1.5%*

Oregon Department of Transportation

Tolerance = Contractor's Flexibility to Adjust?

"Contractor has wiggle room"



Example: Same Curb Ramp Inspected 3 times (altered adjacent ramp run, didn't alter landing)

- Landing Running Slope
- 1.4%

5/16/2019

- Landing Running Slope
- 1.2%

8/13/2019

- Landing Running Slope
- 1.3%

8/28/2019

Oregon Department of Transportation

The research question?

- 2011 US Access Board
  - Dimensional tolerances for concrete surfaces → under-design.
- 2017 ODOT Research Proposal
  - Selected → cancelled by ODOT (research not needed)
- ODOT Research SPR 844
  - What factors influence why measurements are inconsistent?

Oregon Department of Transportation

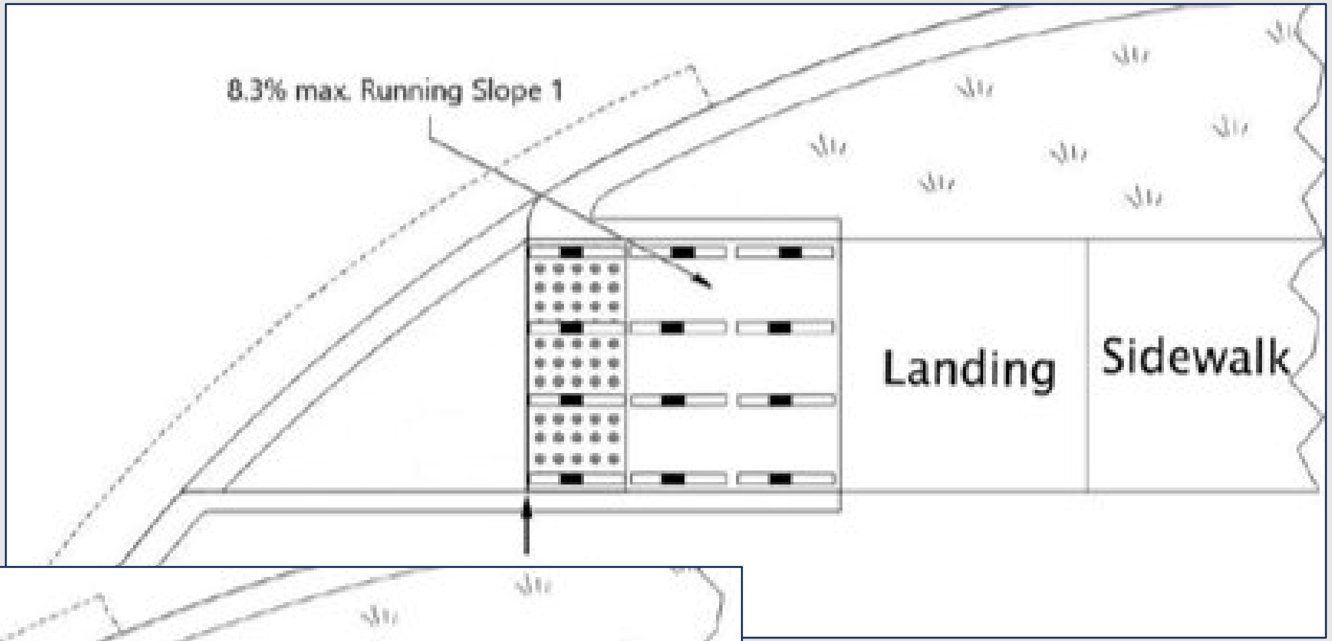
Measurement Error

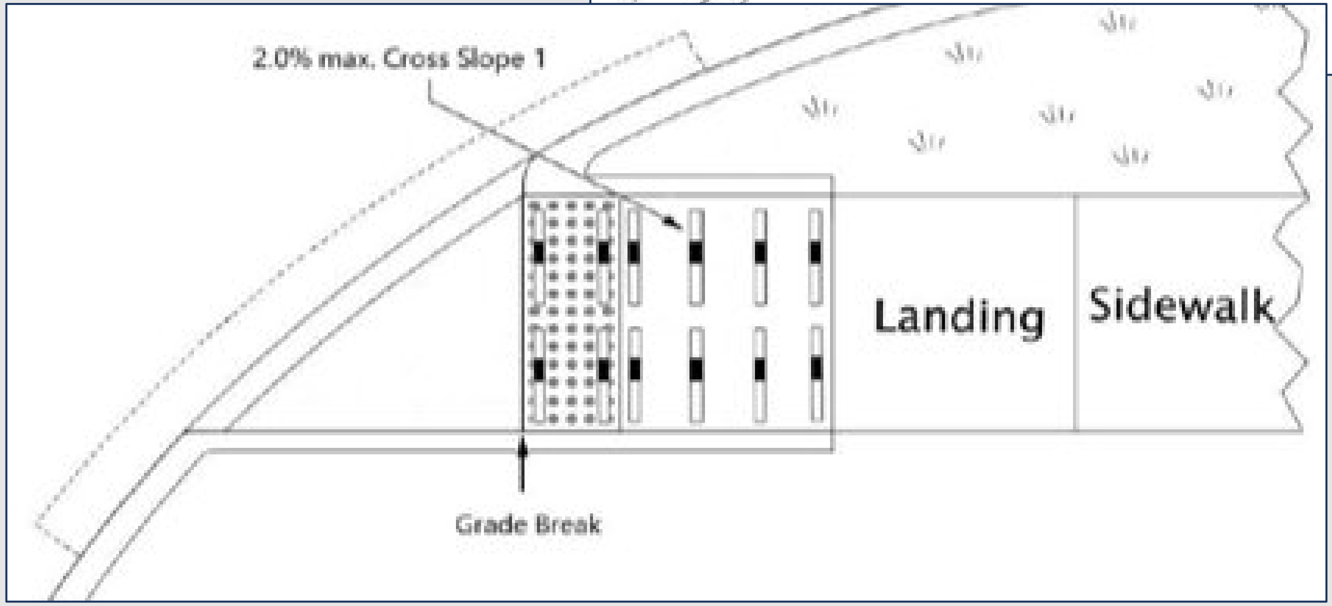
- Device error using digital levels
  - Calibration
- Human Error
  - Measure in the same place
  - Straightness of placement

Oregon Department of Transportation

Variation of the material itself or from workmanship

- Local variations of slope within a planar concrete surface
  - Lump & Slump
  - Bulging at Edges
  - Uniformity

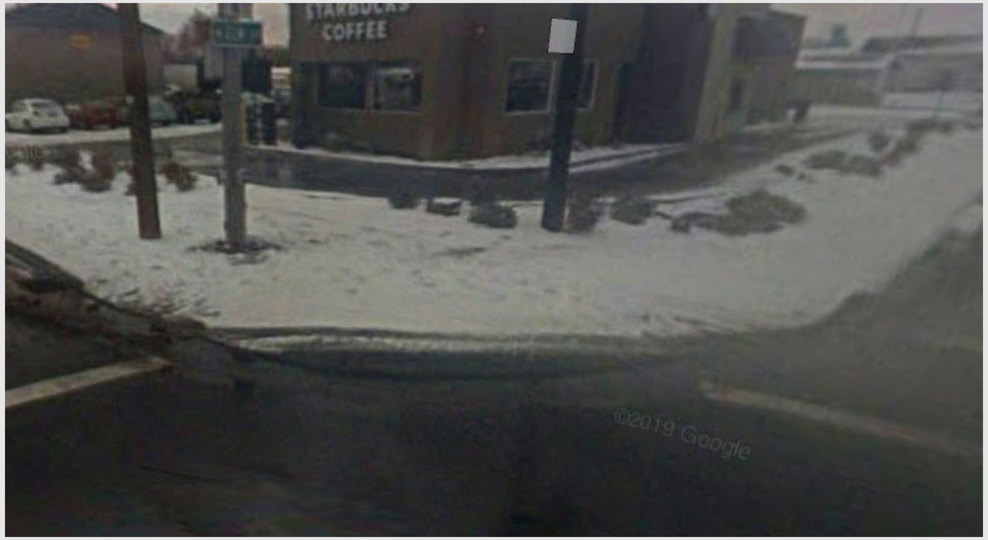




Potential movement of concrete surface over time

During curing

During freeze/thaw cycle



Effects of a point load
(from vehicles running over concrete)

Consolidation of foundation materials

DISCLAIMER

I have financial interests in the company EzDataMD LLC, and commercialization of technology involving point cloud data processing (e.g., EZProj). The conduct, outcomes, or reporting of this research could benefit EzDataMD LLC and could potentially benefit me.

Key Challenges

- Inherent device errors in the context of ADA assessment on curb ramps
- Unknown consistency in operation with many entities
  - ODOT has a rigorous process and training for inspectors.
- Single metric not considering a flatness index for surface variability
- Unknown field effects over time
- QA/QC measurements generally do not consider concrete curing processes.
- Most industry tolerances do not directly apply to curb ramps or rigorously consider the measurement errors.

Objectives

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

- Investigating lidar technologies for ADA compliance assessments to evaluate the performance of smart levels.
- Developing a research database of existing and newly-constructed curb ramps for testing and analysis
- Identifying the best combination(s) of tools and methods
- Identifying an appropriate overall flatness index
- 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.

Error Sources

Determined through a combination of theoretical modeling and experiments

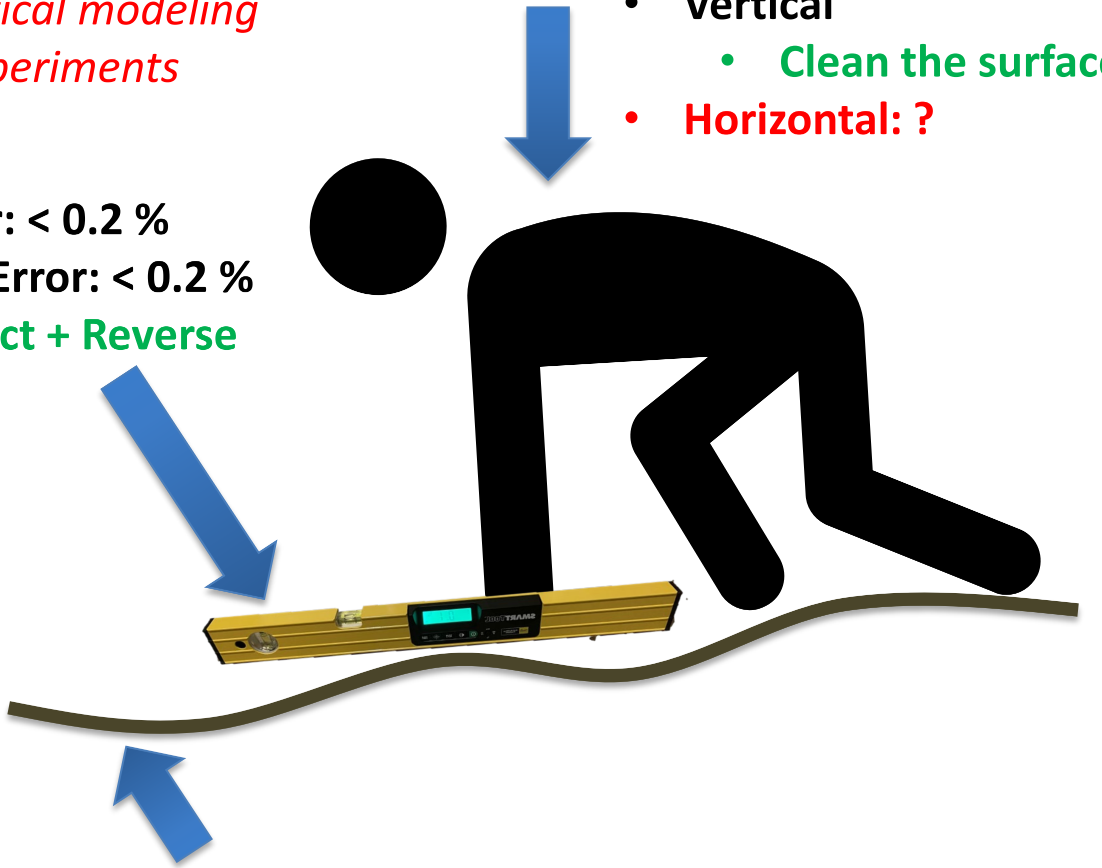
Operating Errors (misalignment):

- **Vertical**
  - **Clean the surface**
- **Horizontal: ?**

Device Error: < 0.2 %

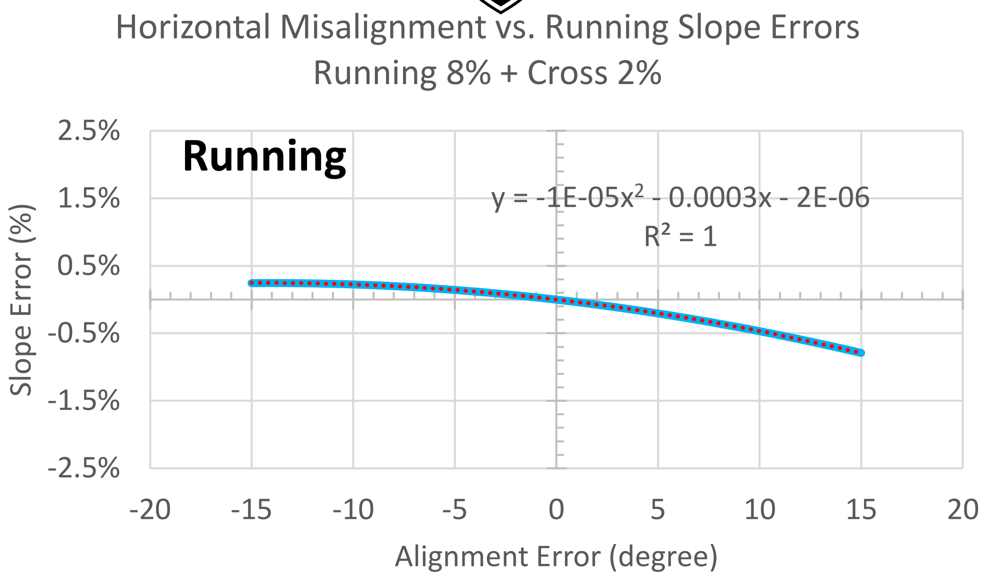
Calibration Error: < 0.2 %

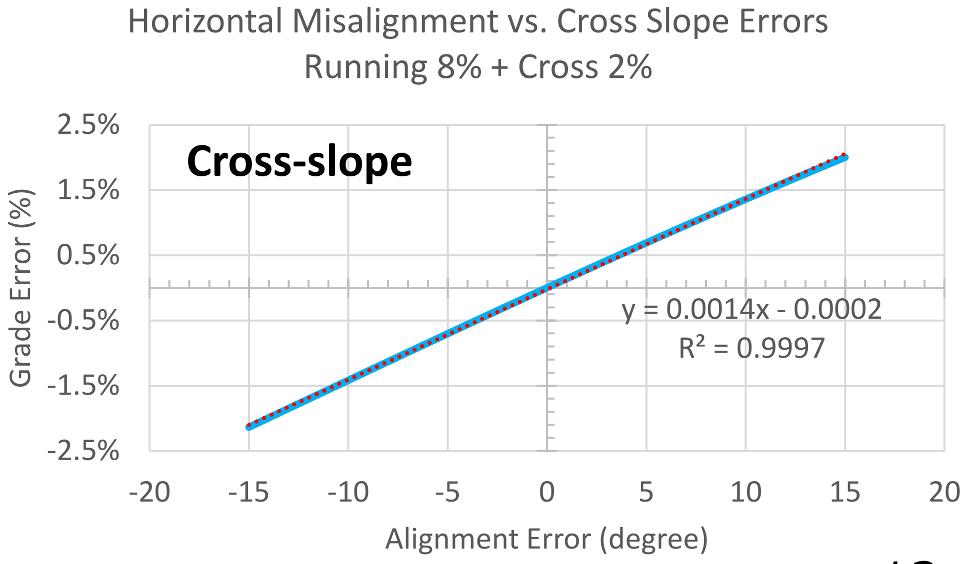
- **Direct + Reverse**



Surface roughness: varies.

- **Taking more samples**





Inspector Consistency

Oregon State University
College of Engineering

- ODOT Inspector Training Database (2022)
  - 64 ramps @ undisclosed location
  - 1942 running, 2114 cross slope measurements
- Ground Truth
  - ODOT Ground Truth
  - OSU Ground Truth

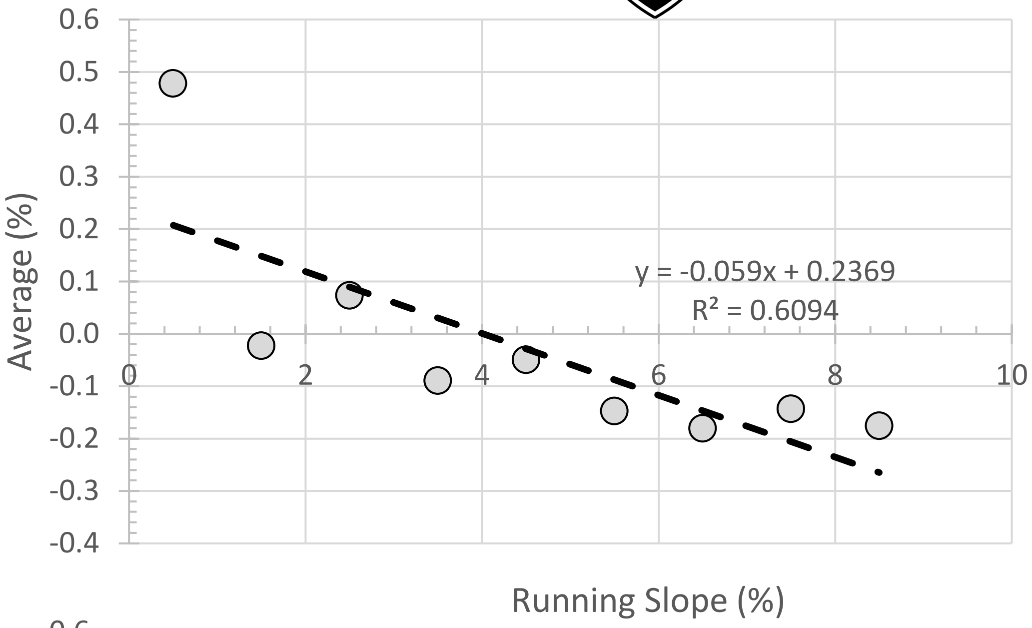
Photo is from different location to preserve anonymity of the site for certification tests.

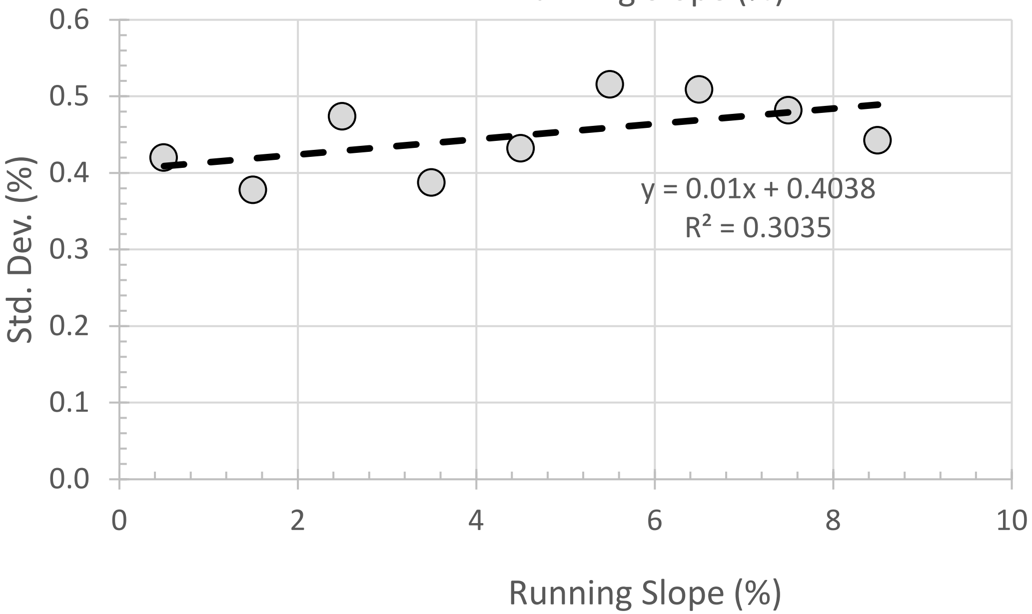
Running Slope (blunders removed)

Oregon State University College of Engineering

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**

- Variability is ~0.5 % (1-σ)
- May have some values of cross slope & running slope mixed up in 0-1 and 1-2% bins
- Std. Dev. Increases on steeper ramps- more sensitive to orientation\misalignments of smart level.
- Detectable Blunders Removed

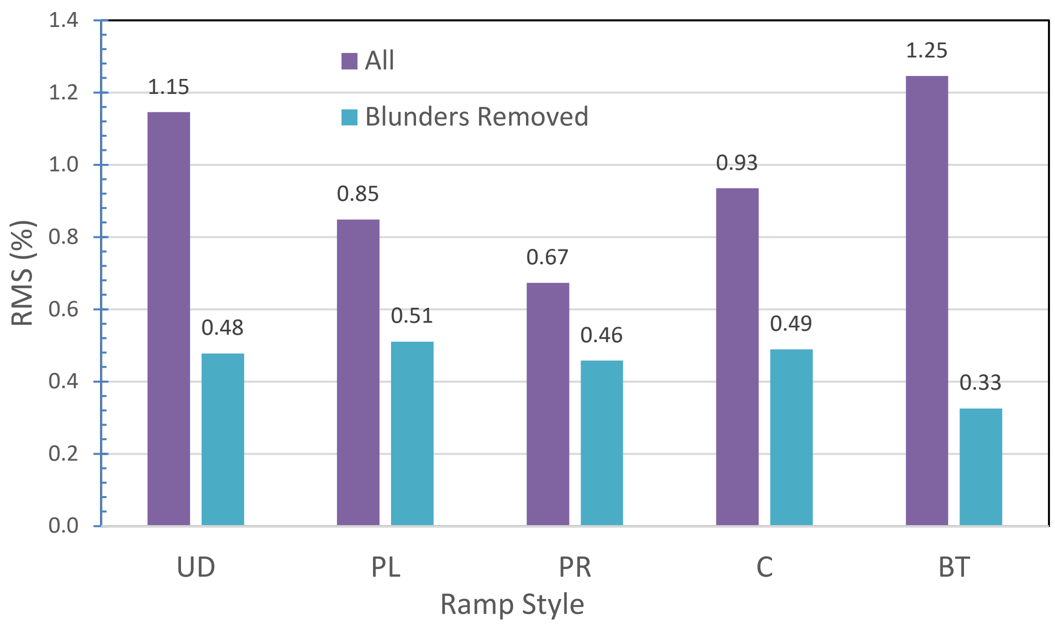




Ramp Style

Oregon State University College of Engineering

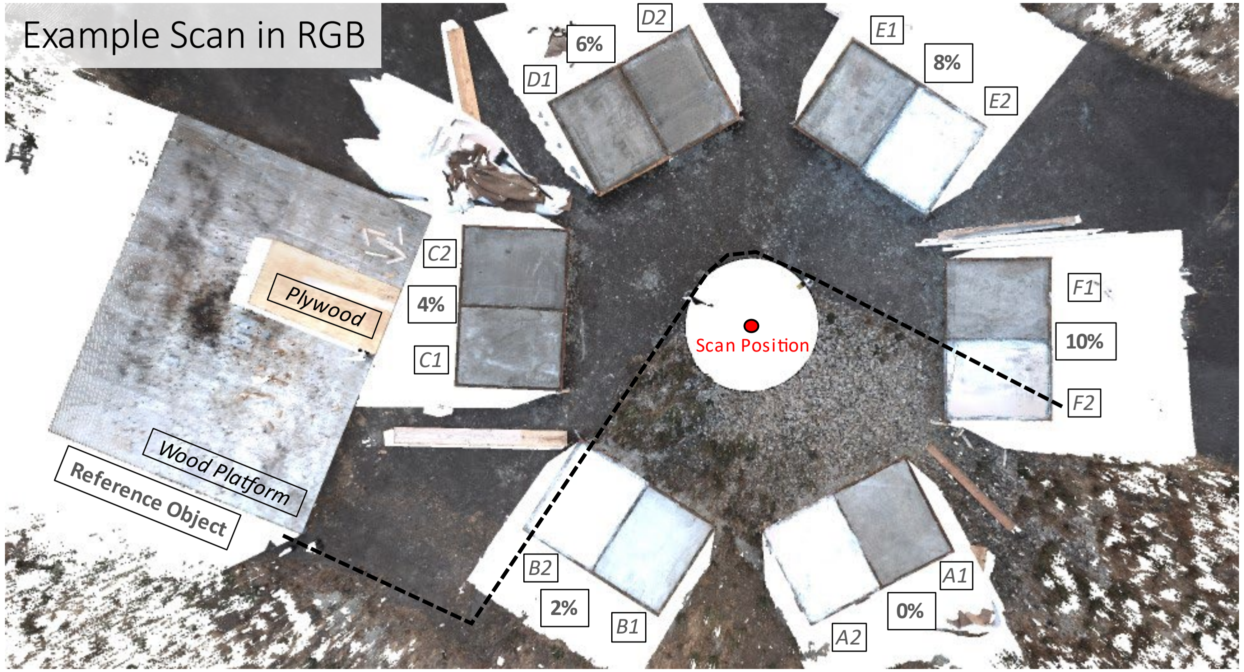
Statistic	UD	PL	PR	C	BT	All
Average	-0.13	-0.08	-0.18	-0.06	-0.16	-0.09
Std. Dev.	0.46	0.51	0.42	0.48	0.30	0.48
Min	-1.50	-1.50	-1.50	-1.50	-0.80	-1.50
Max	1.20	1.30	0.90	1.40	0.20	1.40
Median	-0.10	0.00	-0.10	0.00	-0.10	0.00
Count	143	371	237	1059	10	1821
RMS	0.48	0.51	0.46	0.49	0.33	0.49
Blunder Rate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



- UD= Unique Design, PL= Parallel, PR= Perpendicular, C= Combination, and BT = Blended Transition
- Ramp types (e.g., UD and BT) resulted in substantially more blunders (~9%) than other ramp types (2-7%)
- Once the blunders are removed, the average differences and standard deviations are more consistent across the ramp styles

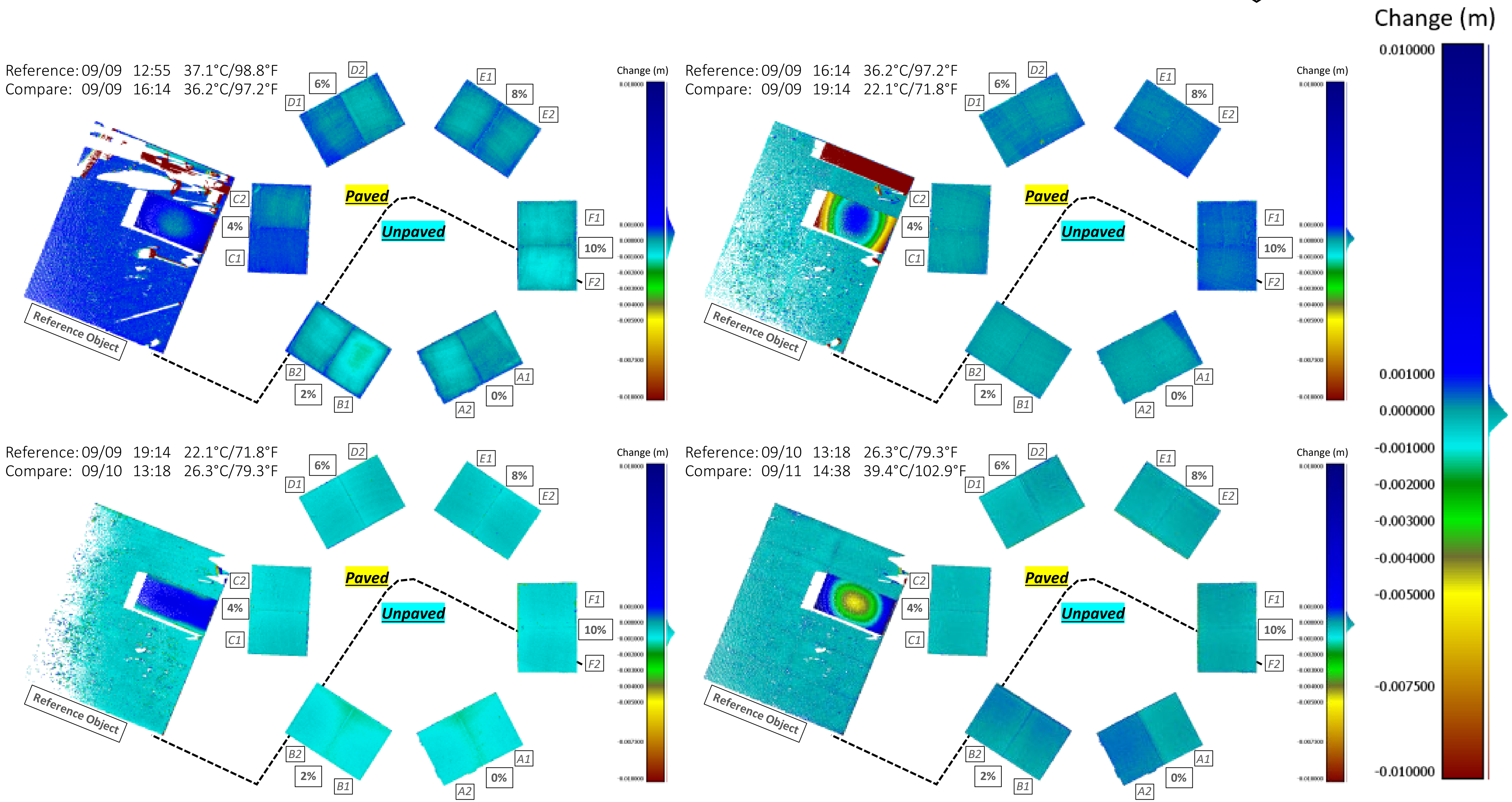
Concrete Testing

- 12 ramps with different curing methods and mixtures
- Running slope: 0% - 10%
- 13 epochs of monitoring with TLS
  - 09/09/21 – 10/31/21



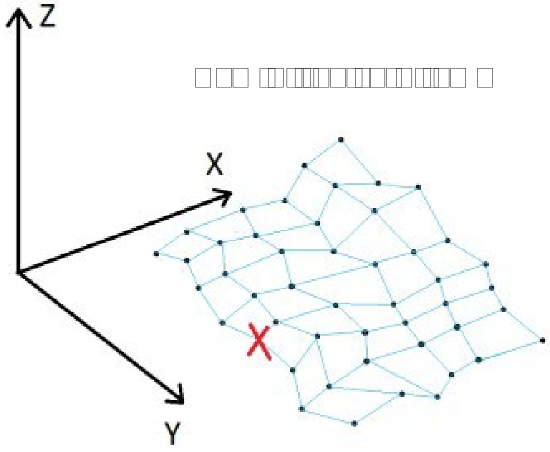
09/09/2021 – 09/11/2021

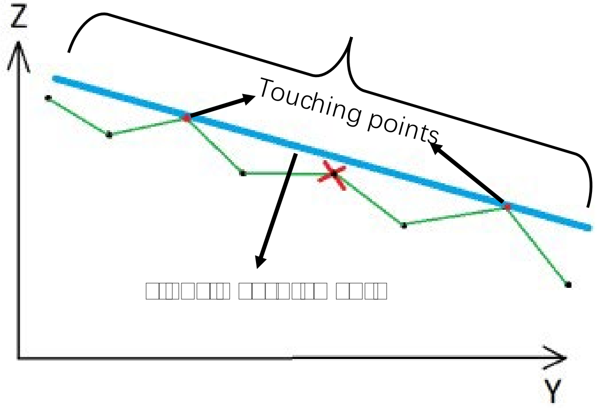
Oregon State University
College of Engineering



Virtual Smart Level

Oregon State University
College of Engineering





Method	Statistics of the mean slope (from 0% to 10%)					
	mean	std	min	max	median	RMSE
TP	-0.10%	0.16%	-0.38%	0.18%	-0.10%	0.18%

Watch for me in Caleb's presentation

Concrete Testing Summary

Oregon State University College of Engineering

- No drastic changes were observed beyond 7 days
- Very consistent roughness (dSTD)
- Hardening and curing process have little impact
- Temperature and humidity showed little impact
- Consolidation settlement can cause significant changes

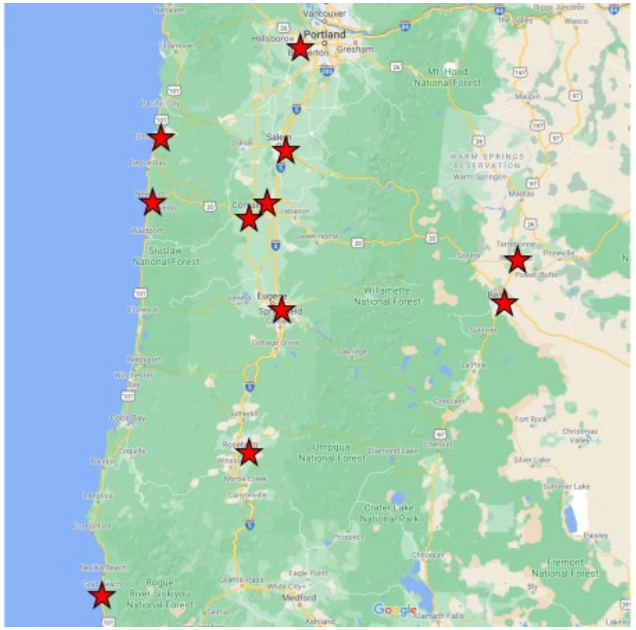
Change of Running Slope from 9/9 to 10/31 via virtual smart level program

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

In-Situ Data Collection and Analysis

Oregon State University
College of Engineering

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 & 6^{th} 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 13^{th} 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 11^{th} St (2)	09/17/2021	03/08/2022



Field Workflow

Oregon State University
College of Engineering

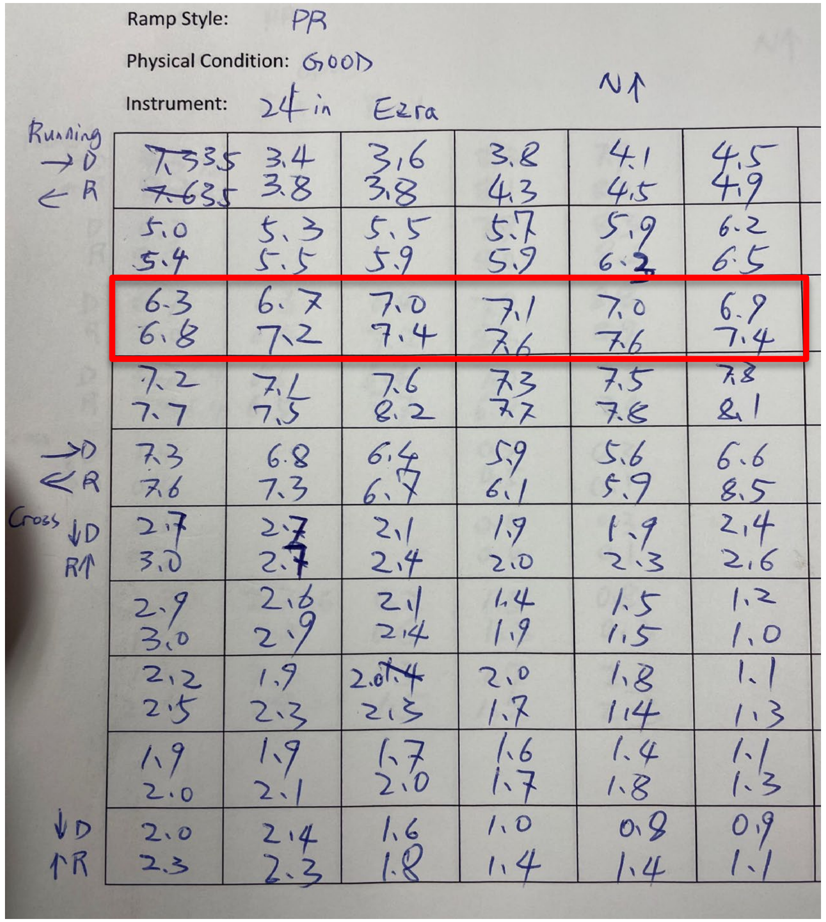
- Laser Scanning:
  - Capture each ramp with P40/50 lidar scans
  - Geo-reference each scan with GNSS measurement (ORGN)
- Smart Level:
  - Calibrate the smart levels before the survey
  - Clean the curb ramps with brooms and brushes.
  - Mark survey locations (grid pattern @ 1.5 ft)
  - Measure and record slope measurements in both direct and reverse face at each mark

Direct vs Reverse

- Collecting both direct and reverse:
  - Detects significant calibration residuals
  - Verifies and eliminate blunders
  - Minimizes calibration residuals & misalignment errors
- Just following the manual might not be enough

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

Example of calibration issues



Consistency of Field Surveys

Oregon State University College of Engineering

- 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

No detectable blunders!!!

Predicted Maximum Slope

Oregon State University
College of Engineering

- Considers Surface Roughness
  - AVG 0.7%, STD 0.4%

- Predicted MAX Slope = Slope AVG + C.I.
  - 68% C.I. = 1.00 × Slope STD
  - 90% C.I. = 1.65 × Slope STD
  - 95% C.I. = 1.96 × Slope STD
  - 99% C.I. = 2.58 × Slope STD

- Field Approximation:
  - Slope AVG = Slope MED
  - Slope STD = SF × (MAX Slope – MIN Slope)

SF Lookup

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

Evaluation of the predicted maximum slope (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

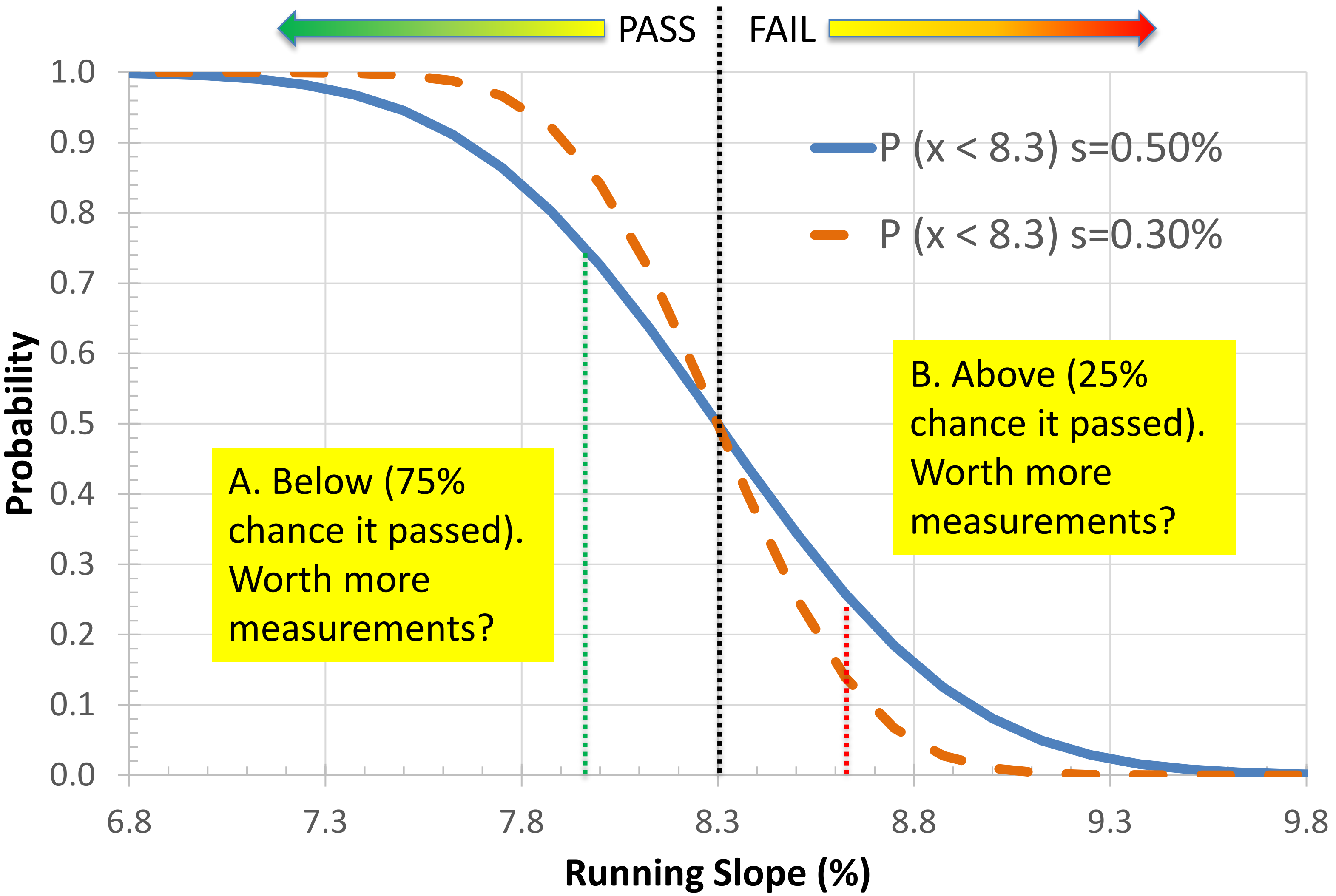
Repeatedly surveyed ramps only (196 samples)

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

Potential Workflow

Oregon State University College of Engineering

- Execute Phase I:
  - Implement "Current ODOT Process" to find max
  - Compute Probability.
- *If probability (S<8.3%) < desired probability (e.g., 95%),* execute Phase II:
  - Implement "Proposed Process" to estimate max (90% confidence)
- *If probability (S<8.3%) < desired probability (e.g., 95%)* execute Phase III: Do detailed scanning and more advanced statistics to determine compliance.



NEED TO DETERMINE ACCEPTABLE PROBABILITY THRESHOLDS!
(Different for if above vs below)

Key Takeaways

Oregon State University College of Engineering

- Smart Levels
  - Simple, inexpensive, easy to use but error prone.
  - **Calibration is critical. Obtain direct and reverse measurements.**
  - > 5 repeated observations at a single spot reduces the standard deviation from 0.3% to 0.1%.
  - Differ from ‘ground truth’ between -0.47%. and +0.36%.
  - **Improved sampling strategies can reduce standard deviations**

- Placement
  - Horizontal and vertical misalignment of the equipment => significant errors
  - Vertical misalignments (e.g., debris or bump) affect slope measurements more substantially than the horizontal.
  - Detectable warnings: difficult to clean the surface, more wear, and unstable setup
  - Repeat monitoring following the proposed procedure showed consistent results.

Key Takeaways

Oregon State University
College of Engineering

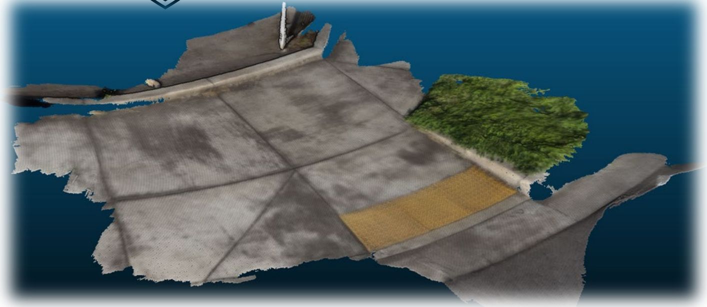
- High Inspector variability
  - 0.5% standard deviation for measurements by different trained inspectors. (Section 5)
  - Different interpretations of ramps. [1.25% if blunders aren't removed]
  - **The maximum slope (single measurement) as a metric is error prone. Stop Using!**
    - No guarantee that the inspector will find the maximum slope.
    - The maximum slope measurement can be artificially high and not representative of the ramp.

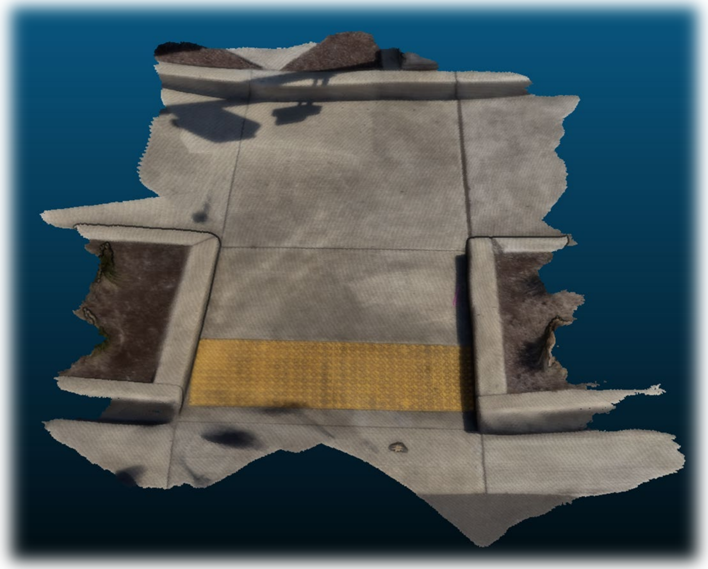
- Time-dependencies
  - Some settlement was observed after rainfall in the built-up curb ramps from consolidation. (Depends on site conditions)
  - Standard deviation from repeat measurements at field sites was ~0.35% using the proposed method (Settlement or measurement error?)
  - > 48 hours after placing concrete (cured & hardened). Slope changes of -0.33% to +0.28% observed while curing (Section 6).

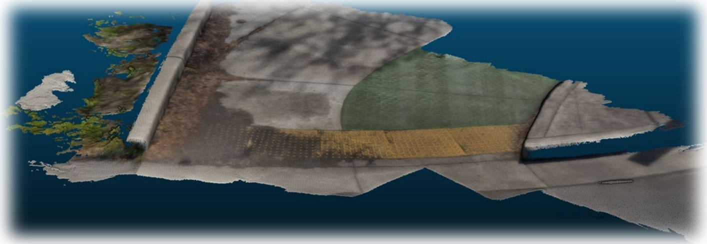
- Combined Error sources
  - Std. Dev. ~0.60% (inspector, field effects, curing processes)

Future Opportunities

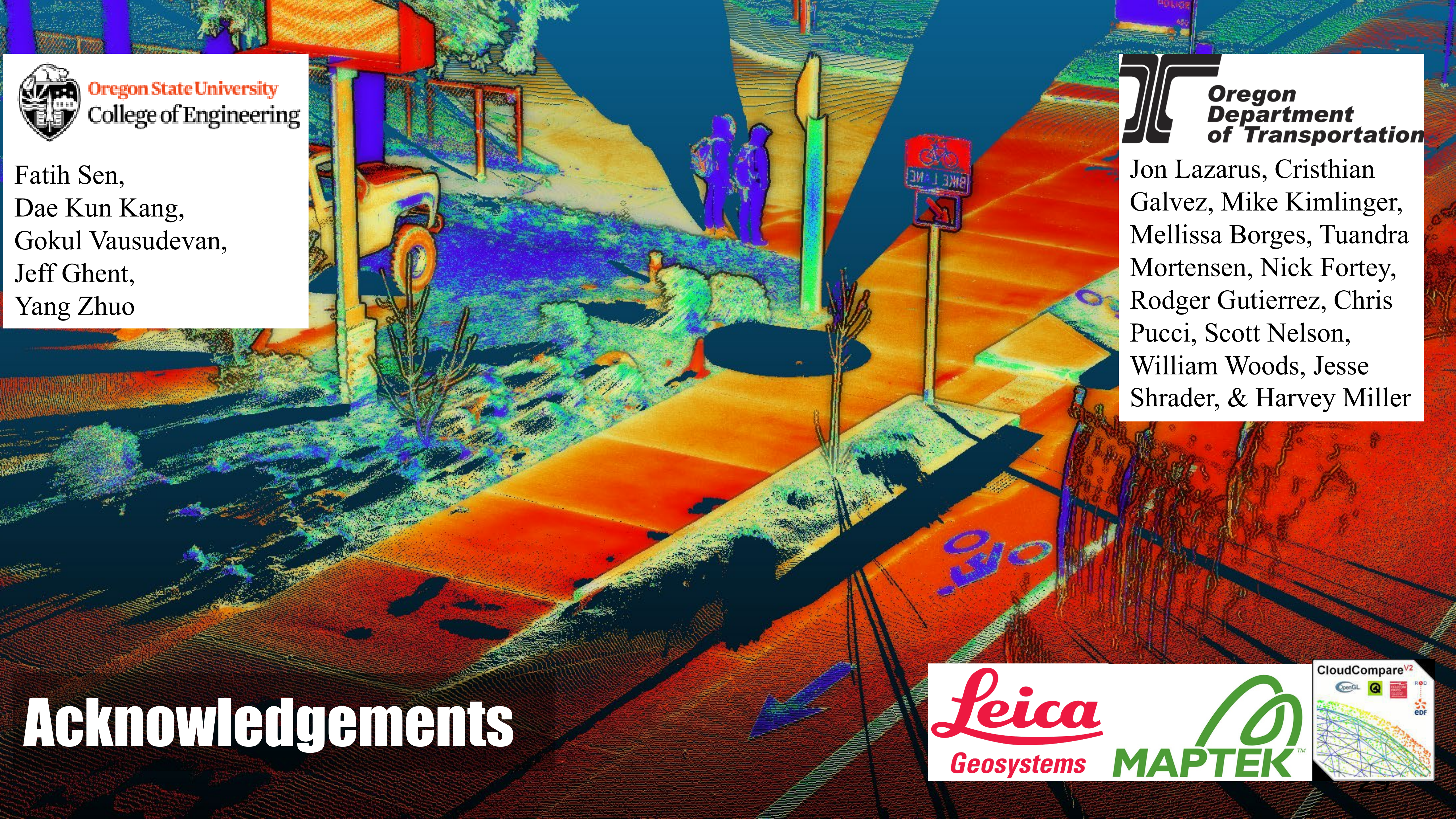
1. Possibility of a tolerance? (e.g., does the RS have to be less than 8.3 or can it be within a designated tolerance consider the variability (0.5%) of inspector measurements).
2. Incorporate future assessments to expand the database that encodes the individual measurements to continue to refine estimates 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 the inspections. (Smart App)
3. Consider exploring other methods to evaluate curb ramp compliance that are more directly inline with the navigability of the ramp and its intended purpose (e.g., inertial sensors in a wheelchair).
4. Provide 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. (Reduce mistakes and enable richer determinations of tolerances from the construction process). (Smart App)
5. Explore capabilities of iPhone Lidar Sensor. (Caleb presentation, FHWA project by EzDataMD)







Oregon State University
College of Engineering



Oregon State University
College of Engineering

Fatih Sen,
Dae Kun Kang,
Gokul Vausudevan,
Jeff Ghent,
Yang Zhuo

Oregon Department of Transportation

Jon Lazarus, Cristhian Galvez, Mike Kimlinger, Mellissa Borges, Tuandra Mortensen, Nick Fortey, Rodger Gutierrez, Chris Pucci, Scott Nelson, William Woods, Jesse Shrader, & Harvey Miller

Acknowledgements

Leica Geosystems

MAPTEK

CloudCompare V2

Recommendations

Oregon State University
College of Engineering

- Execute a tiered process to perform more rigorous smart level measurements when close to tolerances
  - Initial smart levels followed by laser scanning.
  - Less expensive than legal fees
  - Need to determine confidence intervals
- Modify field procedures to be more rigorous
  - Incorporate tolerances
  - All parties should use consistent methodology
  - More systematic measurements (Sampling & **Direct** + **Reverse)**
  - Incorporate roughness & not reliant solely on maximum (90%)
  - Execute and verify calibration!!!!!!
  - Develop a Smart App to perform calculations and ensure consistency. (Can log GNSS position data to minimize ramp confusion!)
- Timing of measurement
  - > 48 hours after placing concrete (cured & hardened). Slope changes of -0.33% to +0.28% observed while curing (Section 6).
  - Readings may be taken to assist contractors with compliance during construction but smart levels should not be placed on fresh concrete