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OPTIMIZING CROSS-SLOPE ESTIMATION USING AIRBORNE, MOBILE, AND STATIC LIDAR DATA

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2026 RPUG CONFERENCE ★ PITTSBURGH, PA ★ APRIL 28 - MAY 1

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- Background
- Problem statement and objectives
- Data and methodology
- Experimental observations
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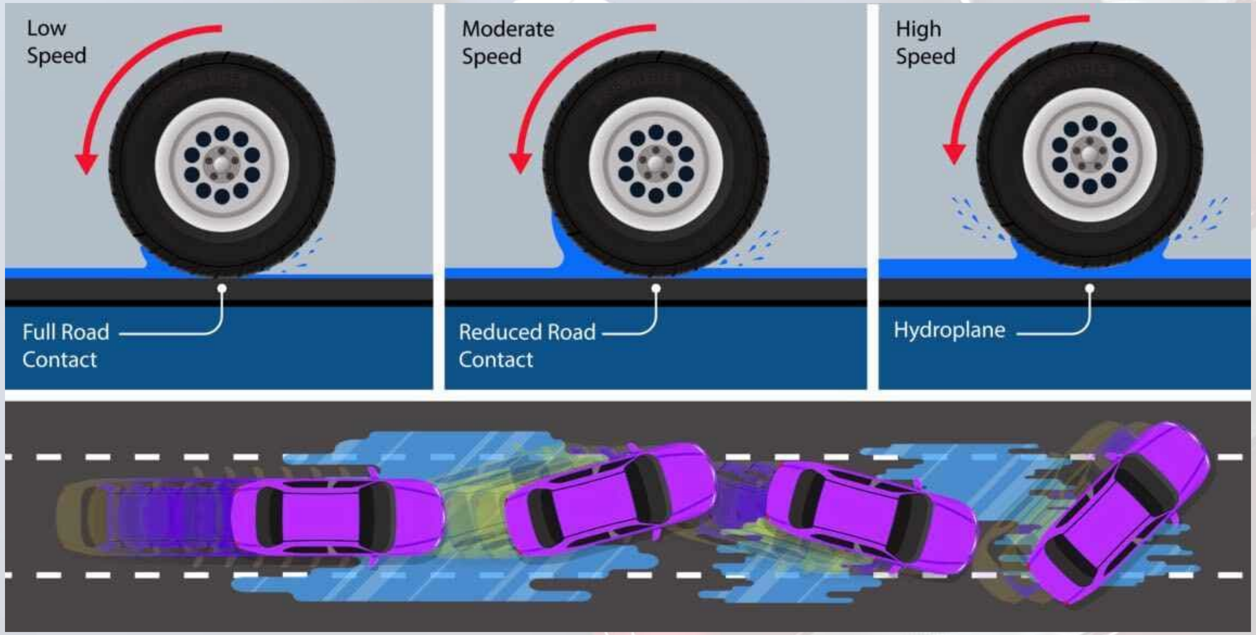
- Conclusion, limitations, and future direction

BACKGROUND

- Nearly 70% of weather-related crashes occur on wet pavement
- Around 1.2 million crashes annually are associated with wet conditions
- Hydroplaning can occur at water depths as low as 0.1 inch



Source: https://www.apollotyres.com

- Inadequate cross-slope reduces drainage and increases risk

PROBLEM AND MOTIVATION

- Cross-slope controls how water drains laterally across the pavement surface.
- Poor estimation can distort drainage assessment, ponding interpretation, and hydroplaning-related analysis.
- Agencies need methods that are both accurate enough for engineering decisions and scalable enough for corridor or network use.
- This study focuses on choosing and optimizing lidar-based workflows for that balance.

OBJECTIVE

Estimate roadway cross-slope from multiple LiDAR sources and optimize a patch-based plane fitting workflow for stable, interpretable results.

- A clear workflow that links pavement extraction, patch design, orientation control, and slope estimation.
- Validation-oriented and operational multi-source setups for network-level estimation.
- Practical guidance on when to use mobile LiDAR, static LiDAR, airborne LiDAR, and profile data together.

METHOD WORKFLOW

Train Set

USGS Data

Mobile LiDAR Data (Cyclomedia)

Data Linkage

Data Preprocessing

Analysis of Geometric Data (Cross-Slope and Grade) using plane or curve-fitting regression models

Validation Set

Static LiDAR Data

Auto-level or Total station Data

Conversion to .las format using X100Manager

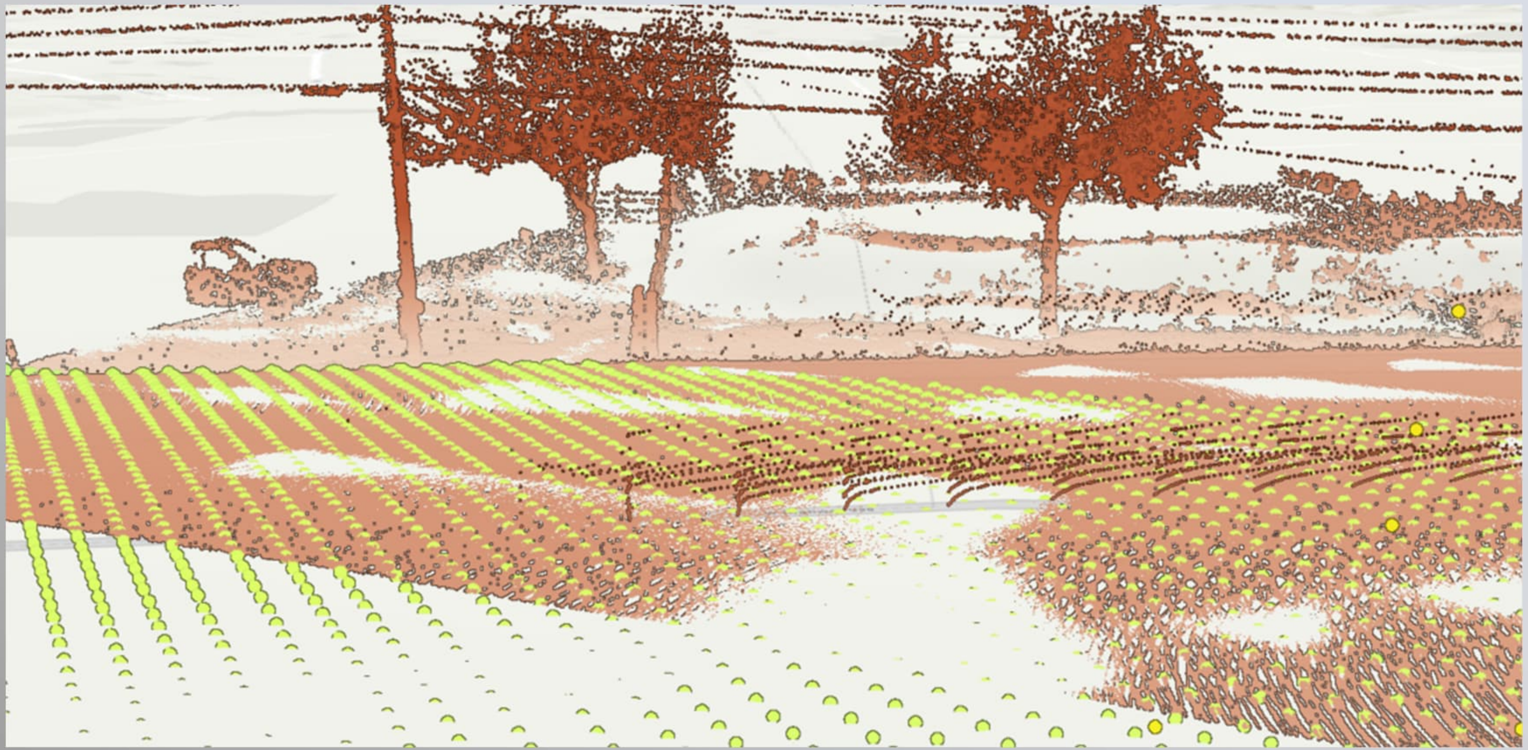
Pointcloud tile stitching, classification, geo-referencing and noise-reduction using CloudCompare, LP360 and Pix4D software

Elevation, cross slope and grade are calculated

Elevation, cross slope, and grade are calculated

Validation of elevation, cross-slope, and grade results by comparing them with validation data from selected sections using static LiDAR and auto-level measurements

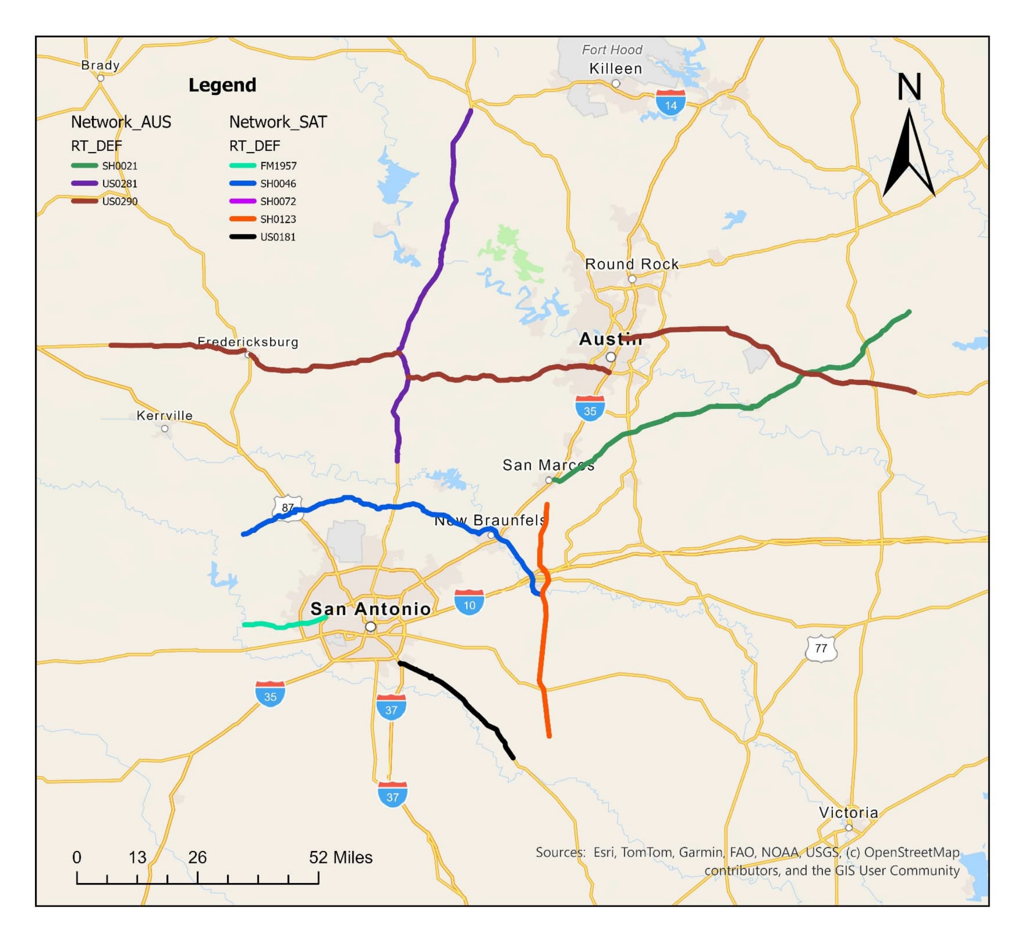
DATA SOURCES AND STUDY DESIGN



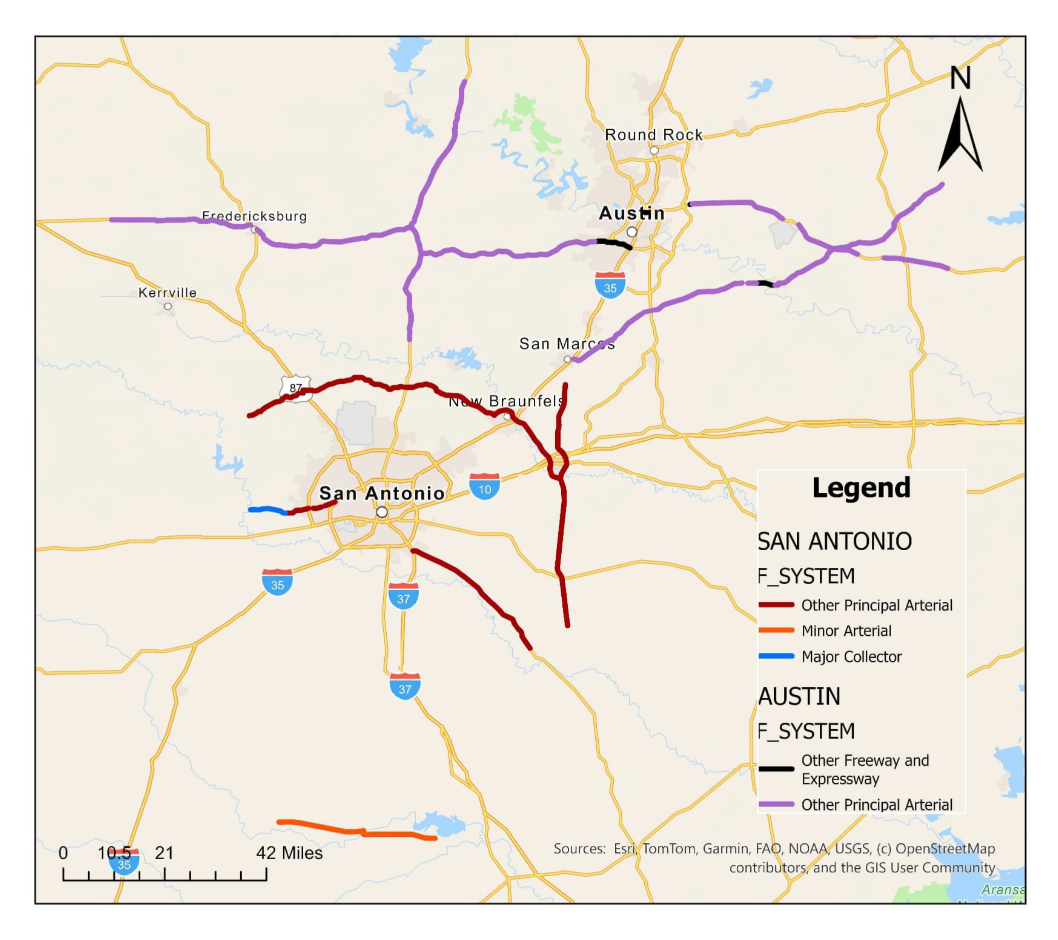
Mobile LiDAR derived point clouds (brown) compared to USGS LiDAR derived point clouds (yellow) for an area along the US290 highway in Austin, Texas.

- USGS Data Density: average 1-10 points/sq m
- Mobile LiDAR Data Density: average > 200 points/sq m
- Static LiDAR Data Density: average 200 points/sq m

DATA SOURCES AND STUDY DESIGN



Austin - 827.74 km roadway



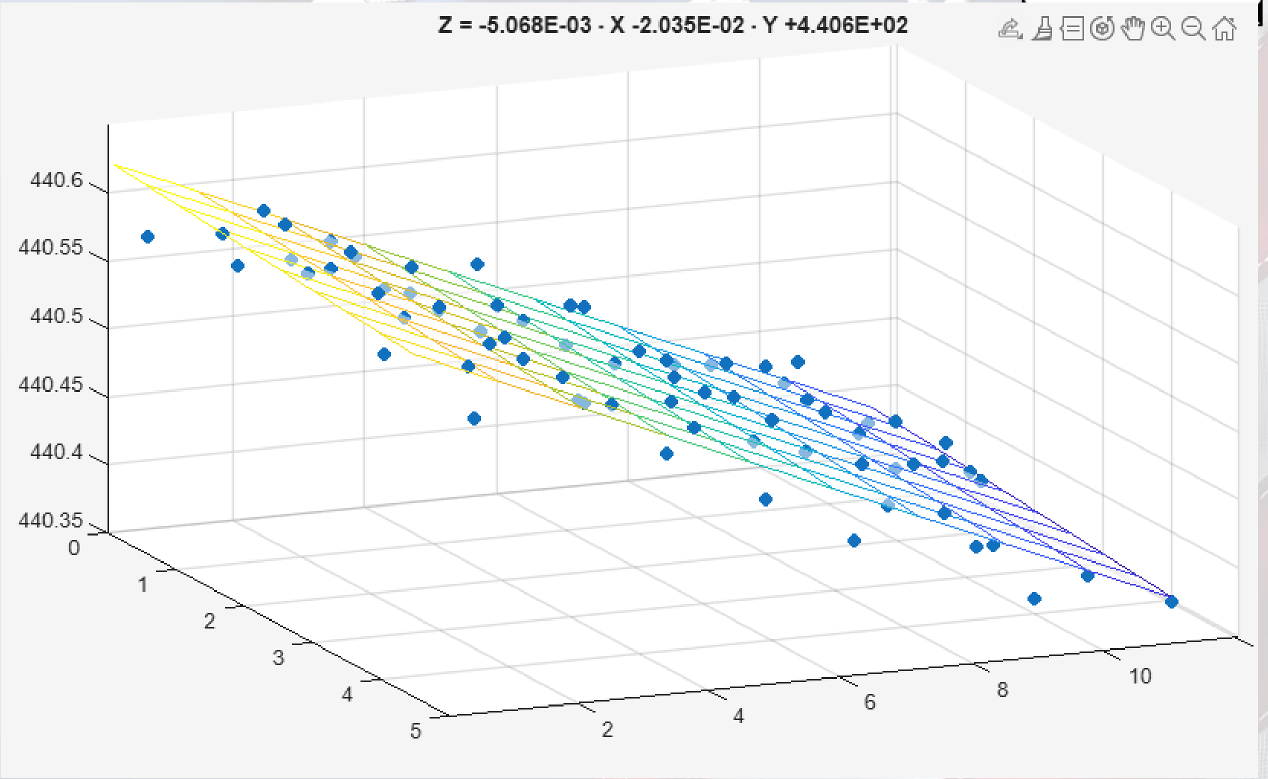
San Antonio - 452.09 km roadway

PLANE FITTING

- A local patch of pavement points is selected within each roadway segment.
- A least-squares plane is fitted to the patch to estimate local surface orientation.
- Roadway azimuth is used to separate the along-road direction from the transverse direction.
- Cross-slope is then derived from the fitted plane in the transverse direction.

PLANE FITTING

Patch fitting in SH0046 study area



Plane fit to calculate cross slope and elevation from point cloud geometries

$$z = a \cdot x + b \cdot y + c$$

$$a_{\parallel} = a \cdot \sin(\theta) + b \cdot \cos(\theta)$$

$$b_{\perp} = a \cdot \cos(\theta) - b \cdot \sin(\theta)$$

$$\theta = arctan2(\Delta y, \Delta x)$$

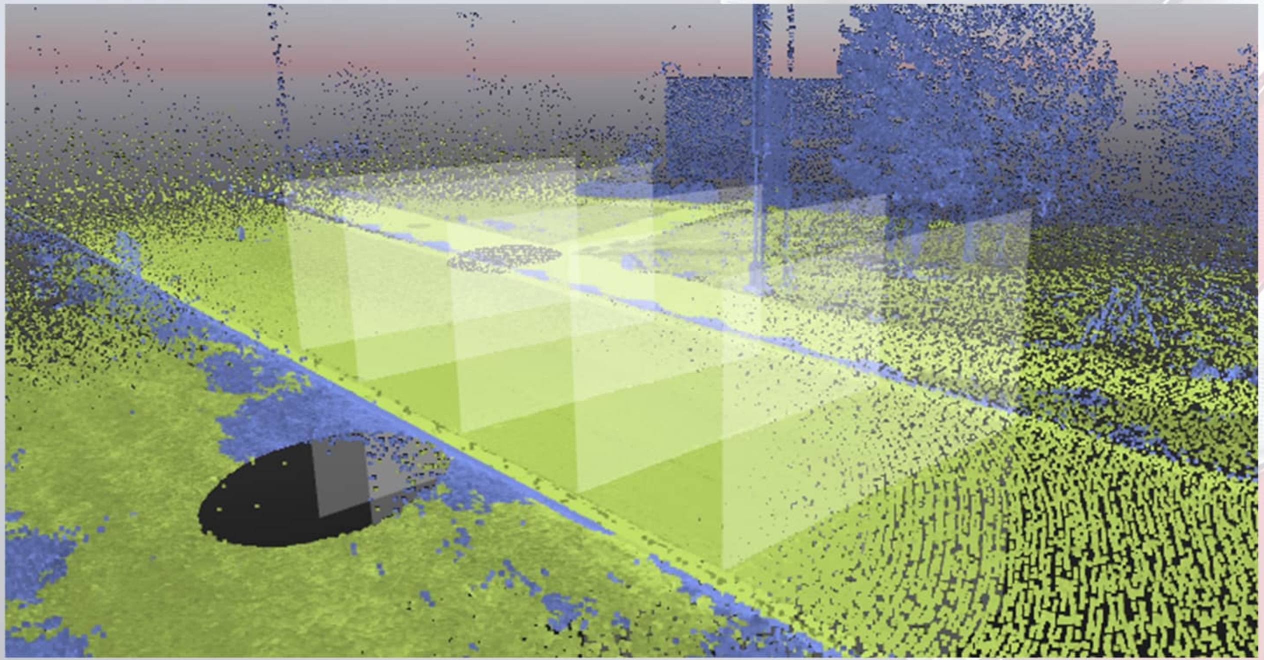
OPTIMIZATION FACTORS

- Patch Size: Too small can be noisy. Too large can smooth away local geometry.
- Orientation Control: Misaligned patches can bias the interpreted transverse slope.
- Noise Filtering: Filtering helps remove unstable or non-pavement points before fitting.
- Point Density: Dense data improve lane-level detail. Sparse data may need stronger smoothing.

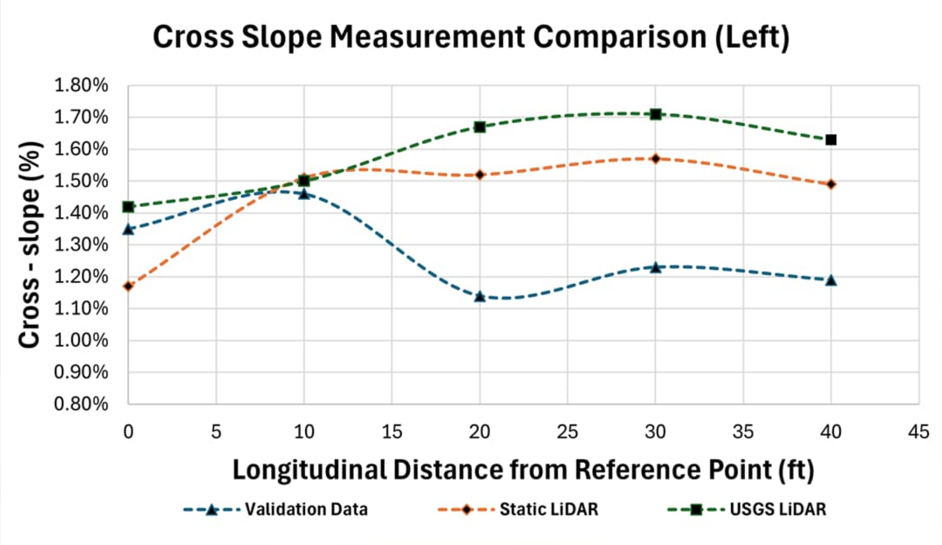
CASE STUDY A: VALIDATION-ORIENTED COMPARISON

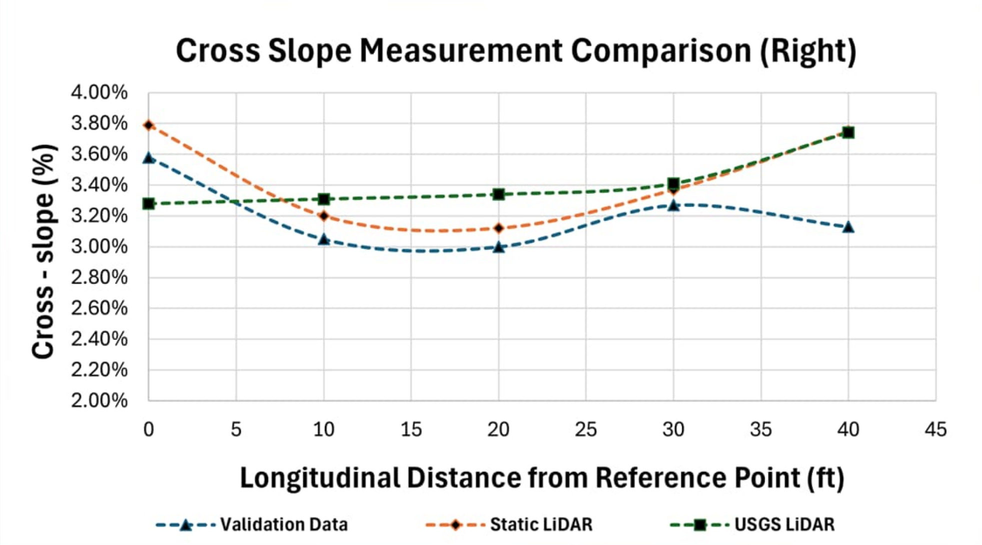
USGS LiDAR, Static LiDAR, Auto Level Measurement

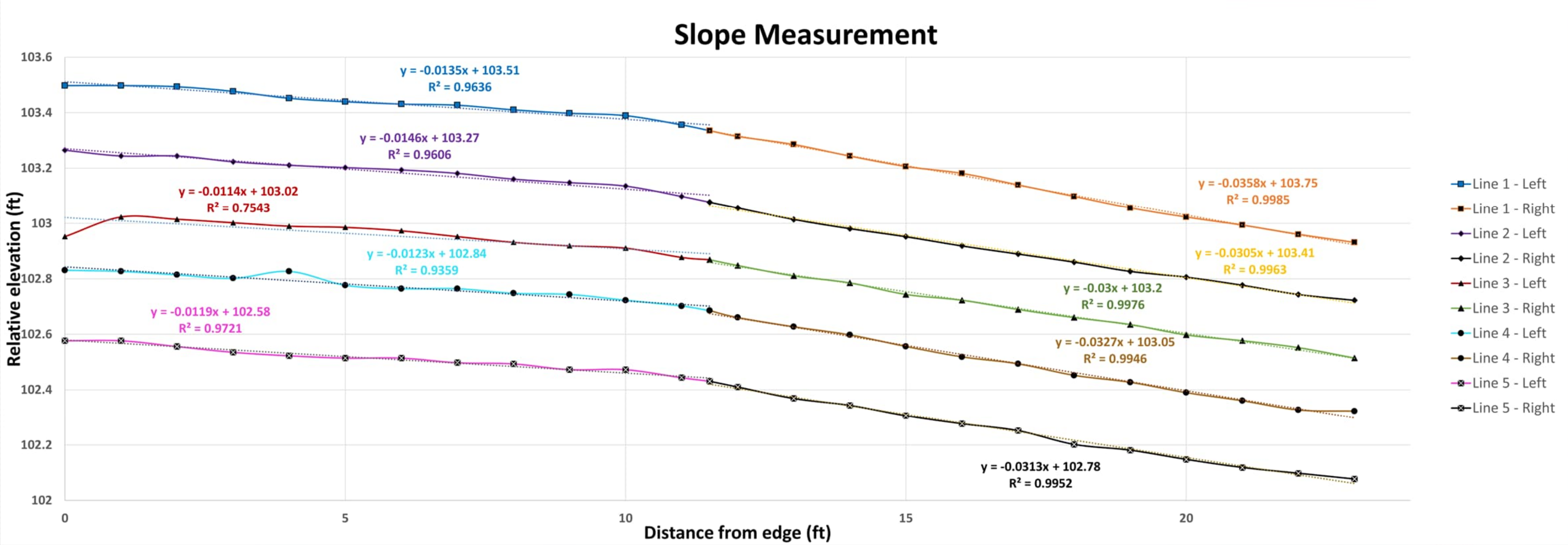
Case study roadway section (3055 Hunter Road). Transverse profiles were collected at 10 ft intervals along the longitudinal direction.



Point clouds acquired using static LiDAR (STONEX X100). Green denotes ground points, while blue represents non-ground points. Vertical sections indicate auto level data collection locations.

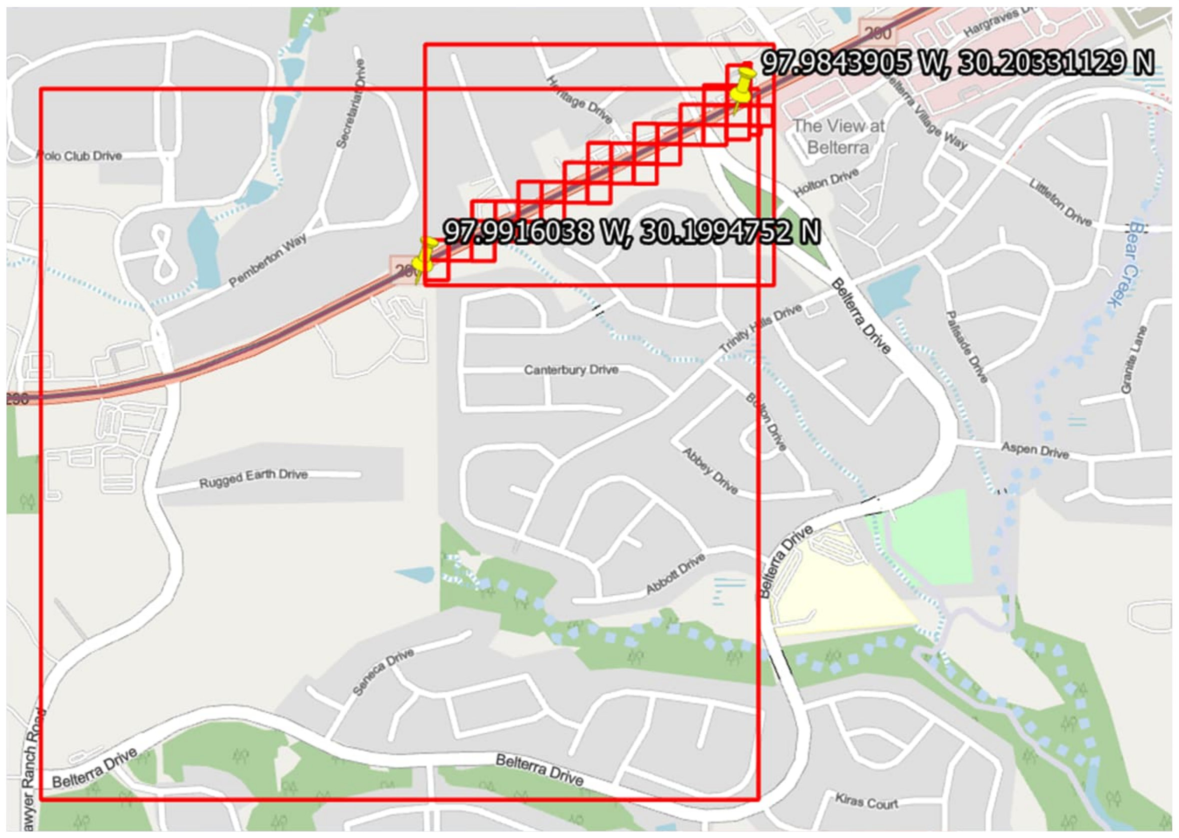

Cross Slope Measurement Comparison (Left)
Cross - slope (%)
1.80%
1.70%
1.60%
1.50%
1.40%
1.30%
1.20%
1.10%
1.00%
0.90%
0.80%
0 5 10 15 20 25 30 35 40 45
Longitudinal Distance from Reference Point (ft)
Validation Data
Static LiDAR
USGS LiDAR


Cross Slope Measurement Comparison (Right)
Cross - slope (%)
4.00%
3.80%
3.60%
3.40%
3.20%
3.00%
2.80%
2.60%
2.40%
2.20%
2.00%
0 5 10 15 20 25 30 35 40 45
Longitudinal Distance from Reference Point (ft)
Validation Data
Static LiDAR
USGS LiDAR

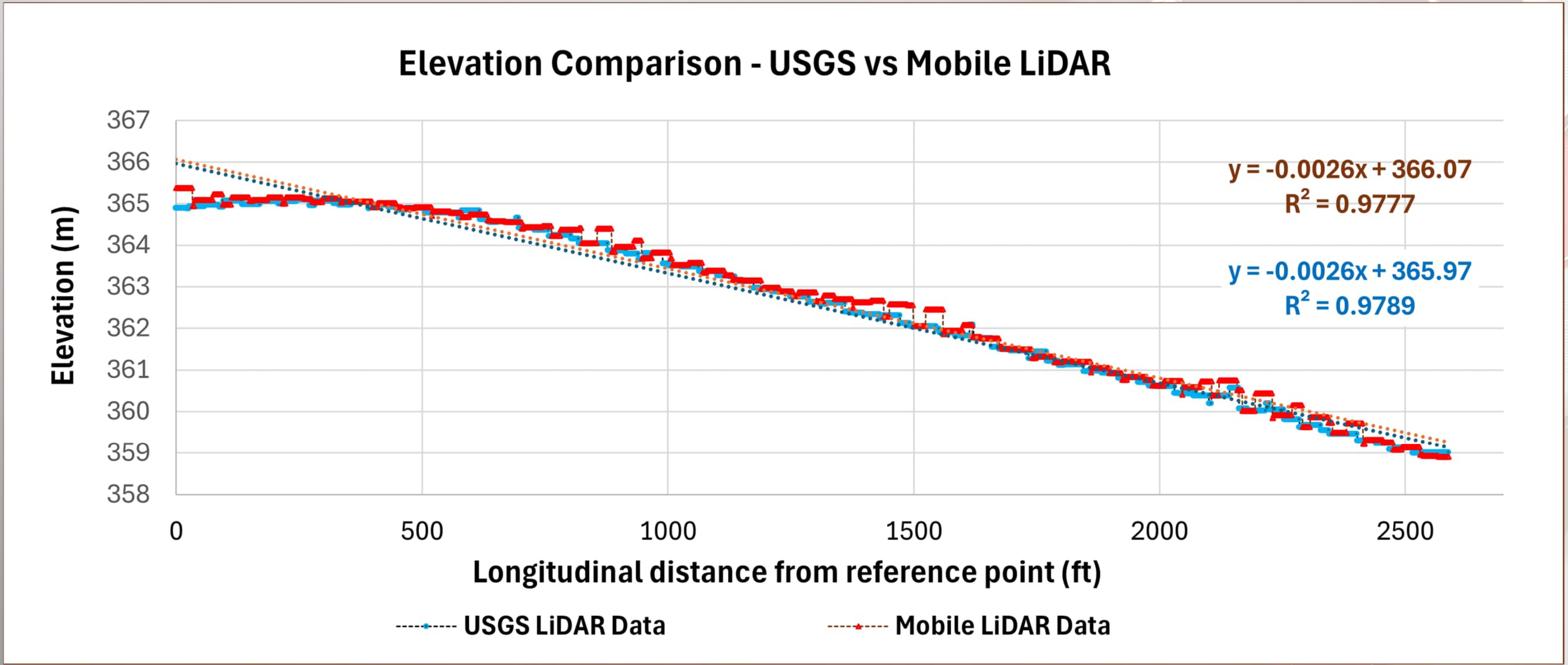

Slope Measurement
Relative elevation (ft)
103.6
103.4
103.2
103
102.8
102.6
102.4
102.2
102
0 5 10 15 20
Distance from edge (ft)
y = -0.0135x + 103.51
R² = 0.9636
y = -0.0146x + 103.27
R² = 0.9606
y = -0.0114x + 103.02
R² = 0.7543
y = -0.0123x + 102.84
R² = 0.9359
y = -0.0119x + 102.58
R² = 0.9721
y = -0.0358x + 103.75
R² = 0.9985
y = -0.0305x + 103.41
R² = 0.9963
y = -0.03x + 103.2
R² = 0.9976
y = -0.0327x + 103.05
R² = 0.9946
y = -0.0313x + 102.78
R² = 0.9952
Line 1 - Left
Line 1 - Right
Line 2 - Left
Line 2 - Right
Line 3 - Left
Line 3 - Right
Line 4 - Left
Line 4 - Right
Line 5 - Left
Line 5 - Right

CASE STUDY B

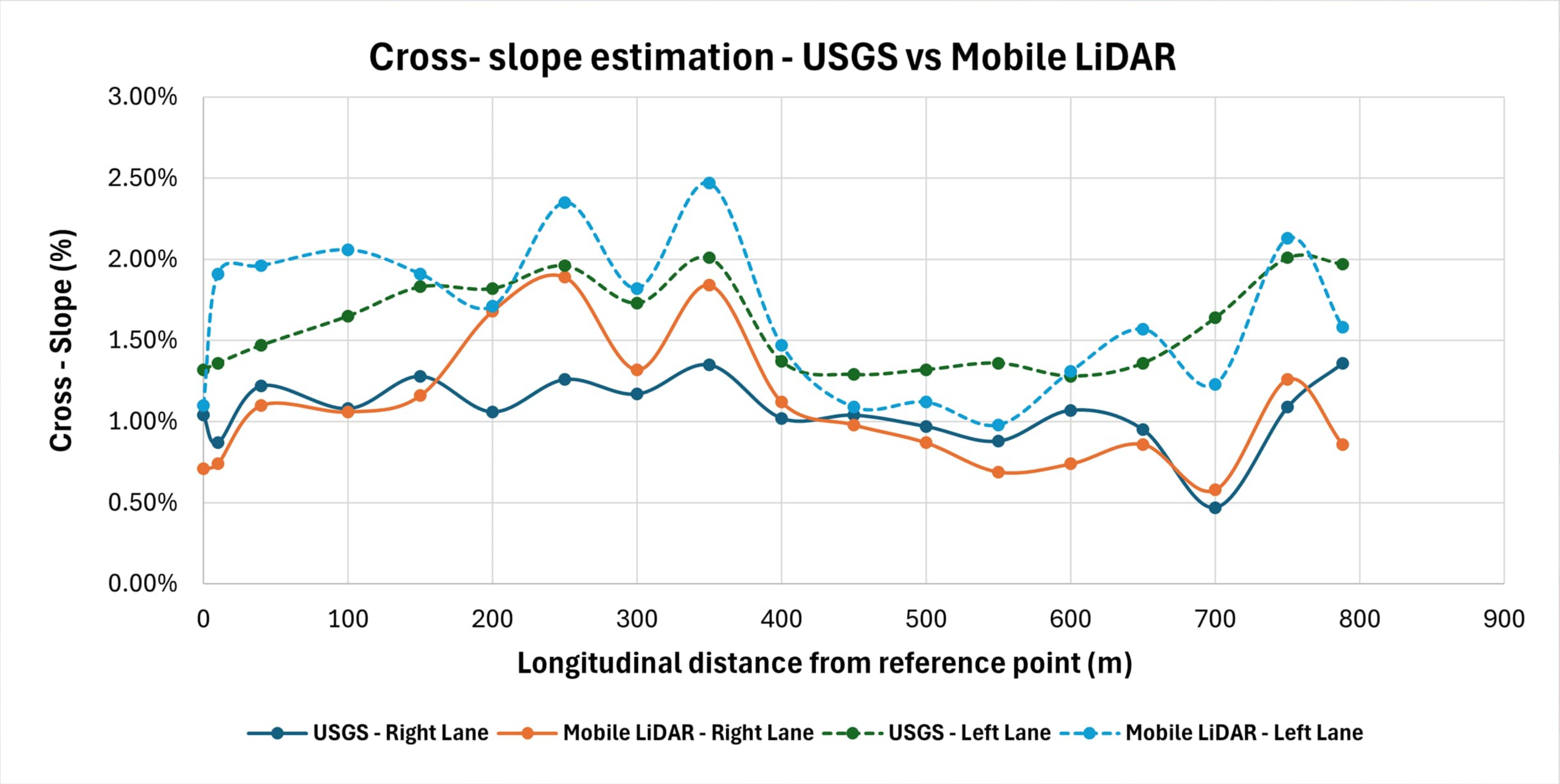
- USGS and Mobile LiDAR Data
- AOI: 2,588 ft roadway, US290
- USGS point cloud density: 7 points per square m, Point spacing 0.358 m
- Mobile LiDAR point cloud density: 69 points per square m, Point Spacing 0.121 m



Study area along US 290



Elevation Comparison - USGS vs Mobile LiDAR
y = -0.0026x + 366.07
R² = 0.9777
y = -0.0026x + 365.97
R² = 0.9789
Elevation (m)
367
366
365
364
363
362
361
360
359
358
0
500
1000
1500
2000
2500
Longitudinal distance from reference point (ft)
USGS LiDAR Data
Mobile LiDAR Data


Cross- slope estimation - USGS vs Mobile LiDAR
Cross - Slope (%)
3.00%
2.50%
2.00%
1.50%
1.00%
0.50%
0.00%
0
100
200
300
400
500
600
700
800
900
Longitudinal distance from reference point (m)
USGS - Right Lane
Mobile LiDAR - Right Lane
USGS - Left Lane
Mobile LiDAR - Left Lane

LIMITATIONS AND FUTURE DIRECTION

Limitations

- Validation methods vary across data sources and study settings
- Complex roadway conditions such as transitions, curves, and grade changes remain difficult
- Lower-density datasets still require stronger guidance for lane-level applications

Future Direction

- Test the workflow across more roadway types and geometric conditions
- Evaluate sensitivity to denoising and smoothing thresholds

CONCLUSIONS

- Patch-based plane fitting was effective for estimating roadway cross-slope from multiple LiDAR sources
- Static and mobile LiDAR produced more detailed and stable lane-level results
- USGS airborne LiDAR supported efficient large-area assessment with acceptable precision
- Optimization of patch size, orientation, and filtering improved slope consistency across datasets

ACKNOWLEDGEMENT

The authors sincerely acknowledge the Texas Department of Transportation (TxDOT) for funding this research under Project 0-7211. The authors also acknowledge the support of the CREATE University Transportation Center and thank Cyclomedia for providing data used in this study.

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