



SYSTEMATIC LITERATURE REVIEW ON CROSS-SLOPE AND GRADE ESTIMATION METHODS

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CONTENTS

- Background and Motivation
- Measurement Challenges and Data Sources
- Review Scope and Framework
- Dominant Methods and Technologies
- Comparative Insights
- Gaps, Limitations, and Future Directions



WHY SLOPE ESTIMATION MATTERS

- Controls pavement drainage and runoff path
- Affects ponding and hydroplaning risk
- Supports pavement performance analysis
- Important for roadway geometry inventory
- Needed for both project-level and network-level decisions



Crown reestablishment, Old El Mirage Road, San Bernardino, California

Road Maintenance



THE MEASUREMENT CHALLENGE



Traditional Methods

- Accurate
- Slow and labor-intensive
- Limited spatial coverage
- Strong for local checks

Modern 3D Methods

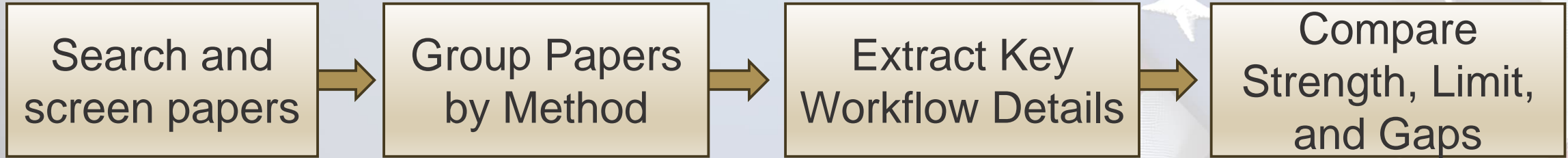
- Dense spatial coverage
- Faster for corridors
- Better for network analysis
- More processing-sensitive

REVIEW OBJECTIVE AND SCOPE



- Compare methods used to estimate cross-slope and grade
- Cover surveying, profilers, photogrammetry, mobile mapping, and airborne LiDAR
- Track analysis unit, surface extraction, and slope computation choices
- Identify gaps in consistency, validation, and complex-geometry handling

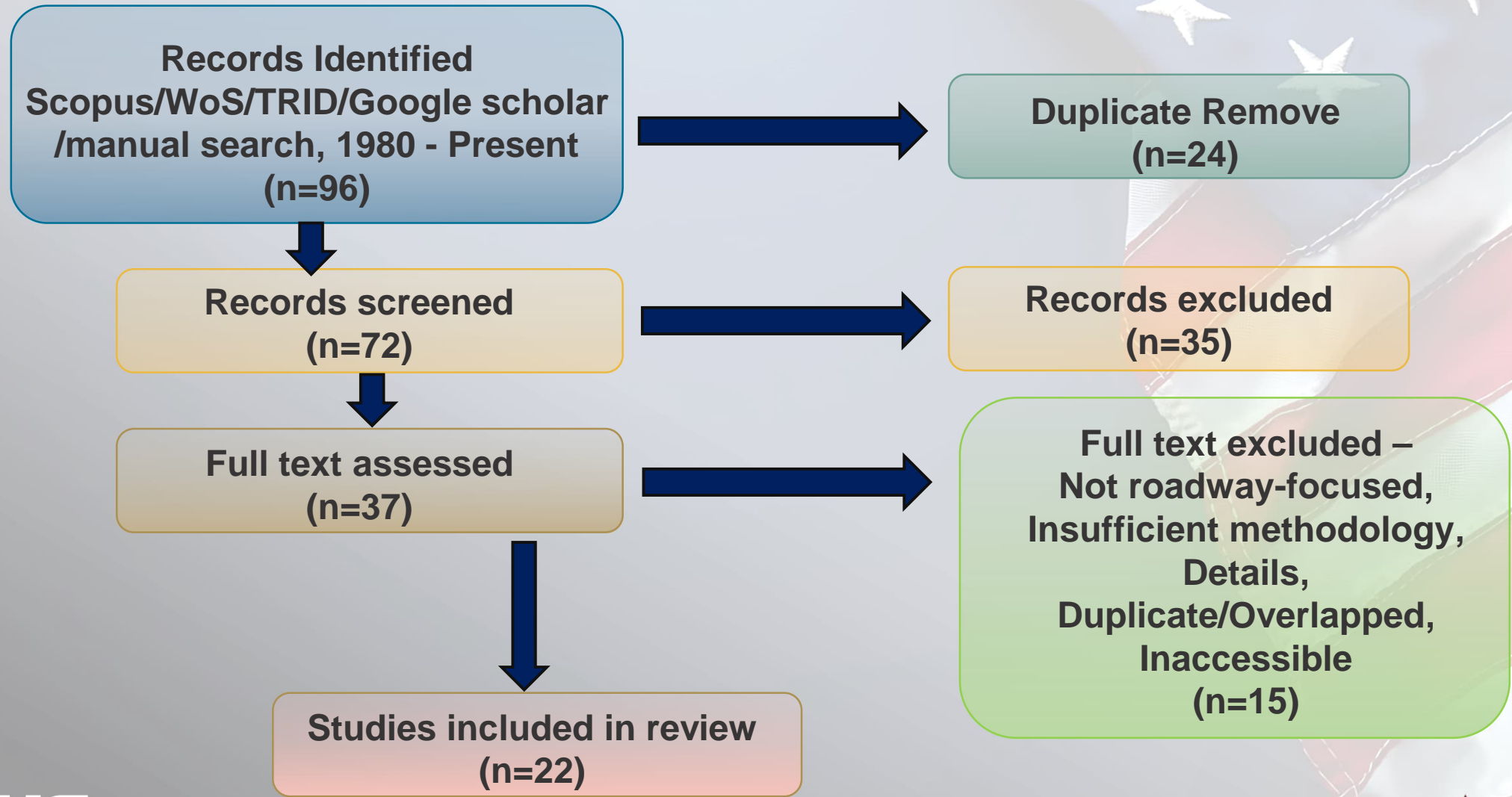
REVIEW FRAMEWORK



Example Selection: Liu et al (2018)

- Criteria: High accuracy grade calculation from USGS DEM.
- Method Group: Sensors (3DEP Elevation Data),
- Key Workflow: Road buffer, surface extraction, cleaning and smoothing, validation with digital level, smoothed distance-elevation profile

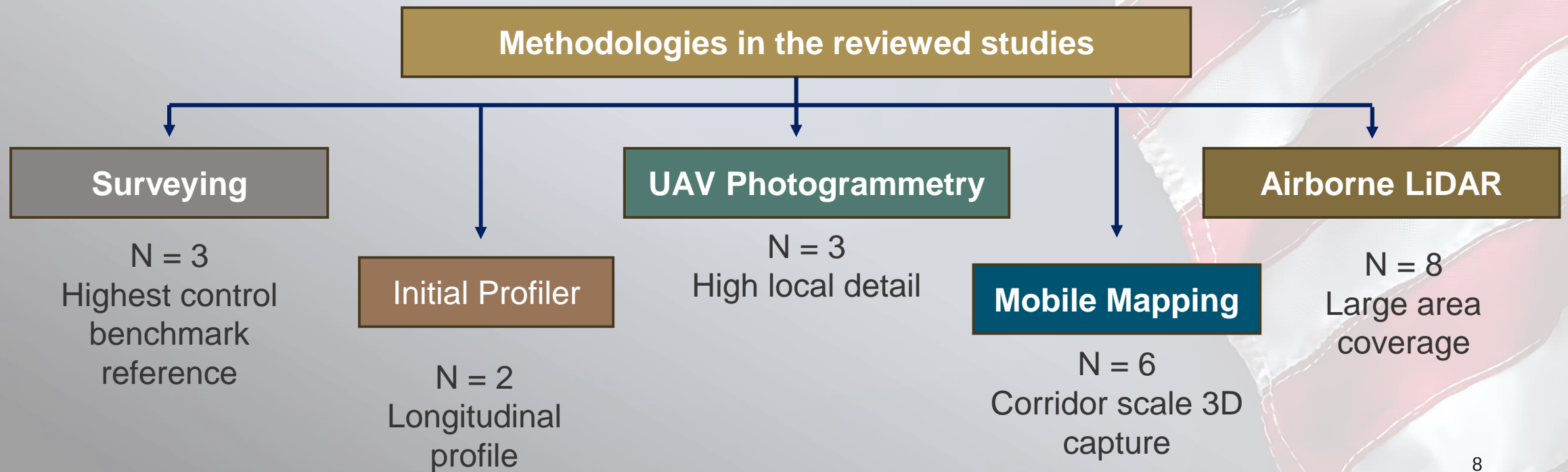
PRISMA PROTOCOL



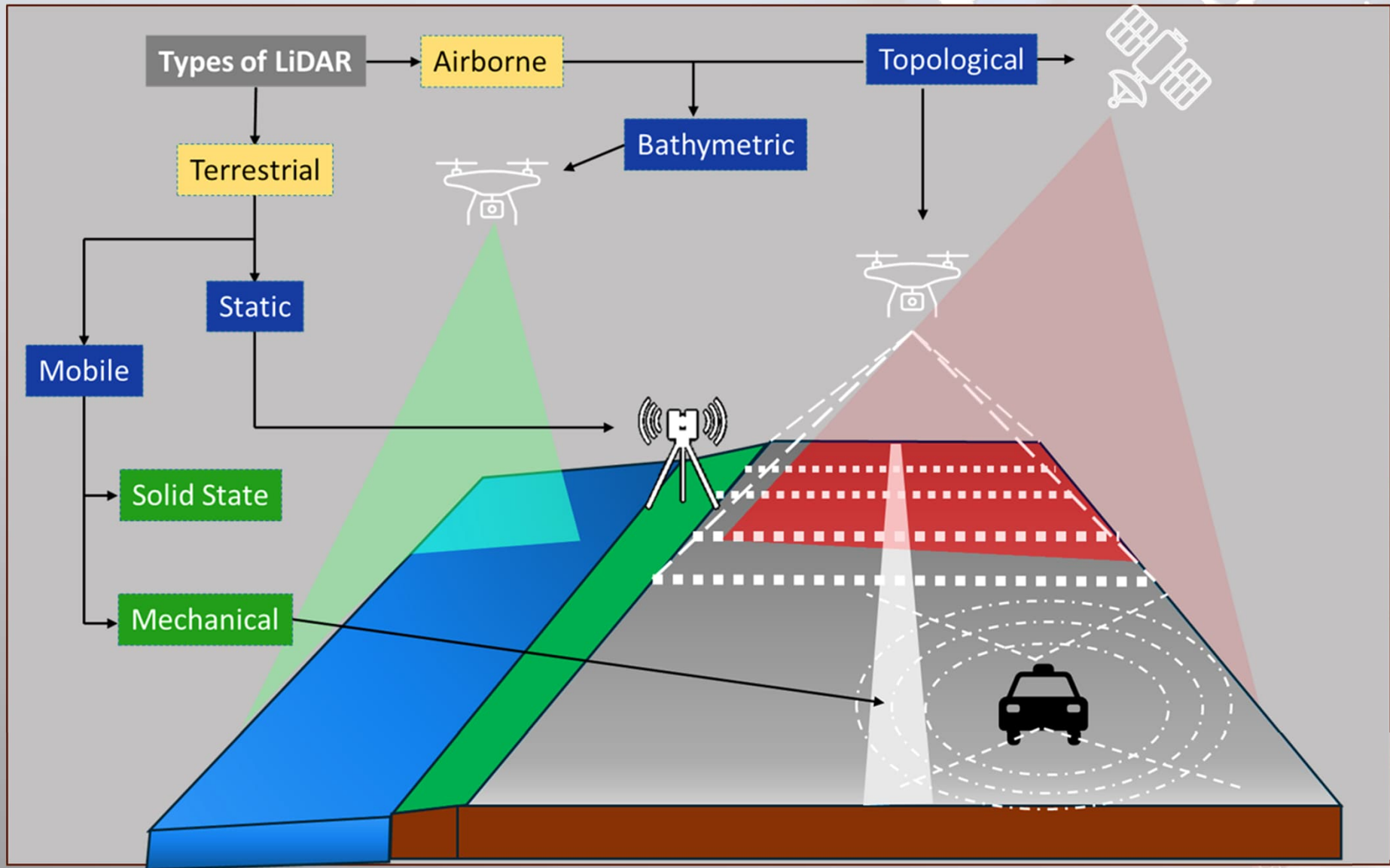
MAIN DATA SOURCES IN THE LITERATURE



Dense 3D data increase spatial coverage, but they also increase dependence on preprocessing choices.



TYPES OF LIDAR SYSTEMS



DOMINANT COMPUTATION STRATEGIES



Profile-based

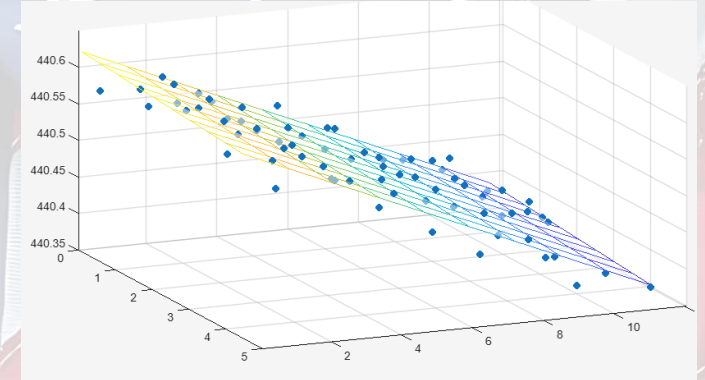
- Rise/run from sampled elevations.
- Strong for survey and profiler workflows

Regression-Based

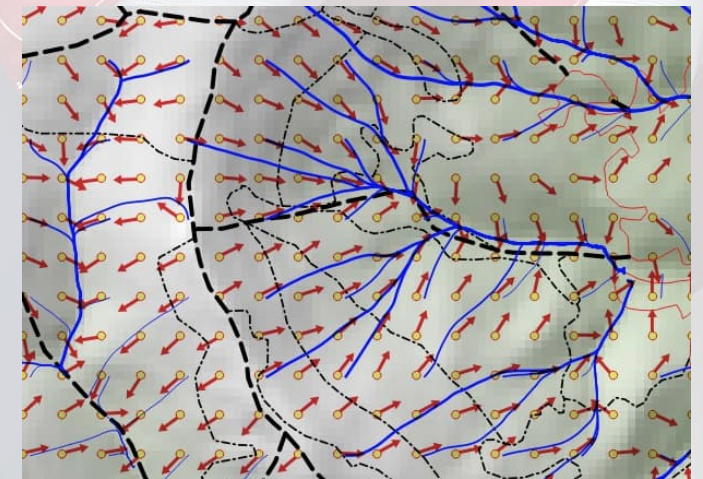
- Fit line or plane to selected points
- Sensitive to segmentation and point selection

Surface-based

- Estimate local pavement orientation
- Well suited to dense LiDAR and photogrammetry data



Plane fit for cross-slope



Slope direction on surface

CONVENTIONAL METHODS: SURVEYING AND PROFILERS



Strengths

- High control
- Strong benchmark for validation
- Clear interpretation
- Established field practice

Limitations

- Sample-based
- Labor intensive
- Traffic exposure in field work
- Not ideal for network-scale collection

Strong for longitudinal profile, but cross-slope extraction is less direct and more assumption-sensitive.

MOBILE LIDAR

Strengths

- Continuous corridor coverage
- Highway-speed data collection
- Strong fit for 3D surface workflows
- Useful for network-scale cross-slope measurement

Accuracy

Difference between adjusted LiDAR-derived cross-slopes and field surveying measurements < 0.19% at the 95% confidence level



AIRBORNE LIDAR

Strengths

- Broad-area coverage
- Existing datasets may already be available
- Useful for network screening and inventory

Earlier airborne LiDAR work: grade within about 1%, but cross-slope not yet practical from that surface model

Limitations

- Cross-slope is more sensitive than grade
- Depends on point density and extraction quality
- Needs stronger QA/QC for detailed use



UAV PHOTOGRAMMETRY AND HYBRID APPROACHES



Strengths

- High local detail
- Flexible for project-scale analysis
- Useful for validation and difficult sites
- Can complement LiDAR-based workflows

Comparative Use

- UAV photogrammetry often performs very well for local cross-slope determination and can rival high-control field methods in targeted studies.
- Best use: Detailed project-scale checks, verification, or hard-to-access sections.

METHOD PERFORMANCE DRIVERS

- Pavement surface extraction: Cloth Simulation Filter (CSF), Progressive TIN Densification (PTD), Centerline-based buffering & clipping
- Analysis unit definition: Lane-based segmentation, referencing
- Segment or patch length: sensitivity-based selection
- Noise and outlier handling
- Validation against independent ground truth

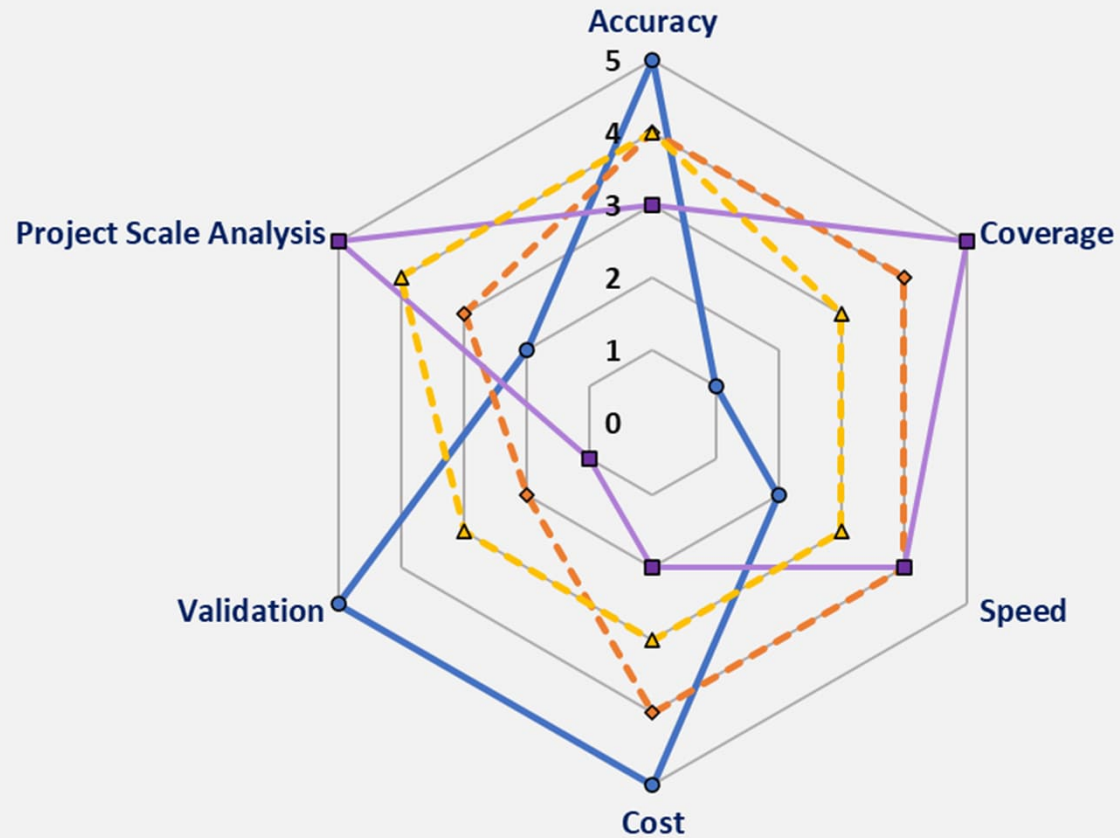


COMPARATIVE SYNTHESIS ACROSS METHODS



Comparative evaluation of roadway cross-slope calculation methods

—●— Surveying -◇- Mobile LiDAR -■- Airborne LiDAR -△- UAV photogrammetry



COMPARATIVE SYNTHESIS ACROSS METHODS



Methods	Accuracy	Coverage	Speed	Cost per sq mile	Best Use
Surveying	High	Low	Low	\$1,000-\$5,000	Benchmark / validation
Mobile LiDAR	High	High	High	\$500 – \$2,000	Corridor-scale cross-slope
Airborne LiDAR	Moderate	Very High	High	\$200-\$1,500	Network screening / inventory
UAV photogrammetry	High	Moderate	Moderate	\$200-\$800	Detailed project-scale analysis

GAPS AND FUTURE DIRECTIONS



Key Study Gaps

- No common standard for reporting workflow details
- Validation practices vary widely
- Complex transitions remain under-addressed

Future Directions

- Sensor/platform and point density
- Pavement extraction rule and segment length
- Slope model, filtering rules, and ground truth source

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