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SYSTEMATIC LITERATURE REVIEW ON CROSS-SLOPE AND GRADE ESTIMATION METHODS

ANANNYA GHOSH TUSTI, GAURI RAVIKANT MAHAJAN, DR. XIAOHUA LUO, DR. FENG WANG
SMART TRANSPORTATION INFRASTRUCTURE MANAGEMENT LAB, TEXAS STATE UNIVERSITY

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

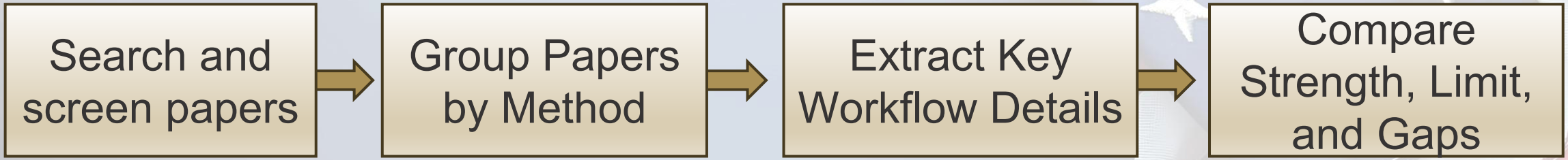
Modern 3D Methods

- 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

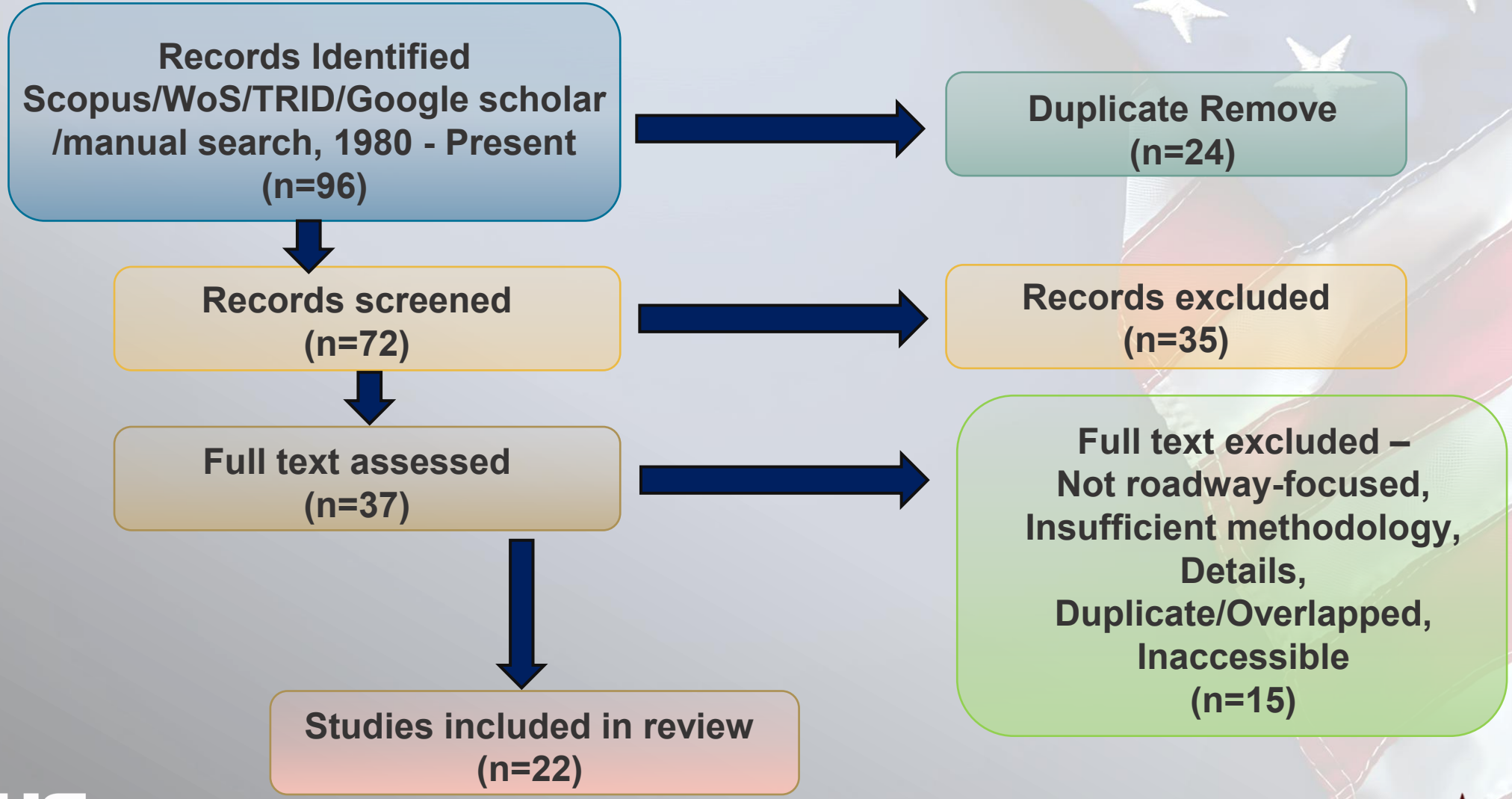


Example Selection: Liu et al (2018)

- Criteria: High accuracy grade calculation from the United States Geological Survey (USGS) Digital Elevation Model (DEM)
- Method Group: Sensors (3DEP Elevation Data),
- Key Workflow: Road buffer, surface extraction, cleaning and smoothing, validation with digital level

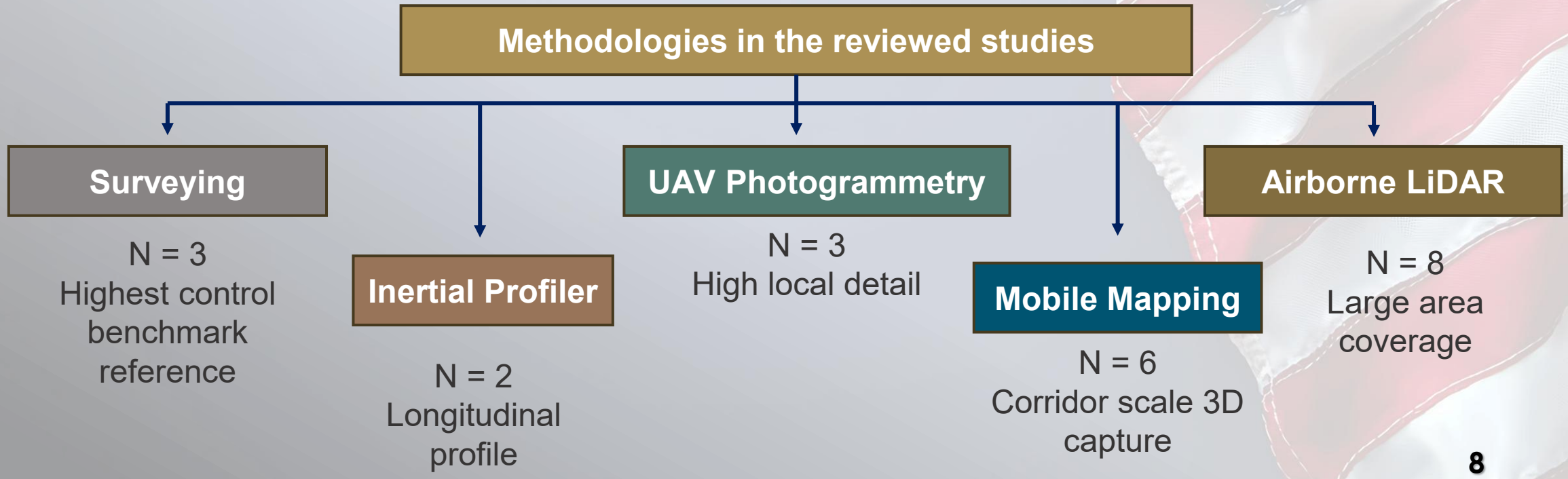
PRISMA PROTOCOL

Preferred Reporting Items for Systematic Reviews and Meta-Analyses – **Dr. David Moher**

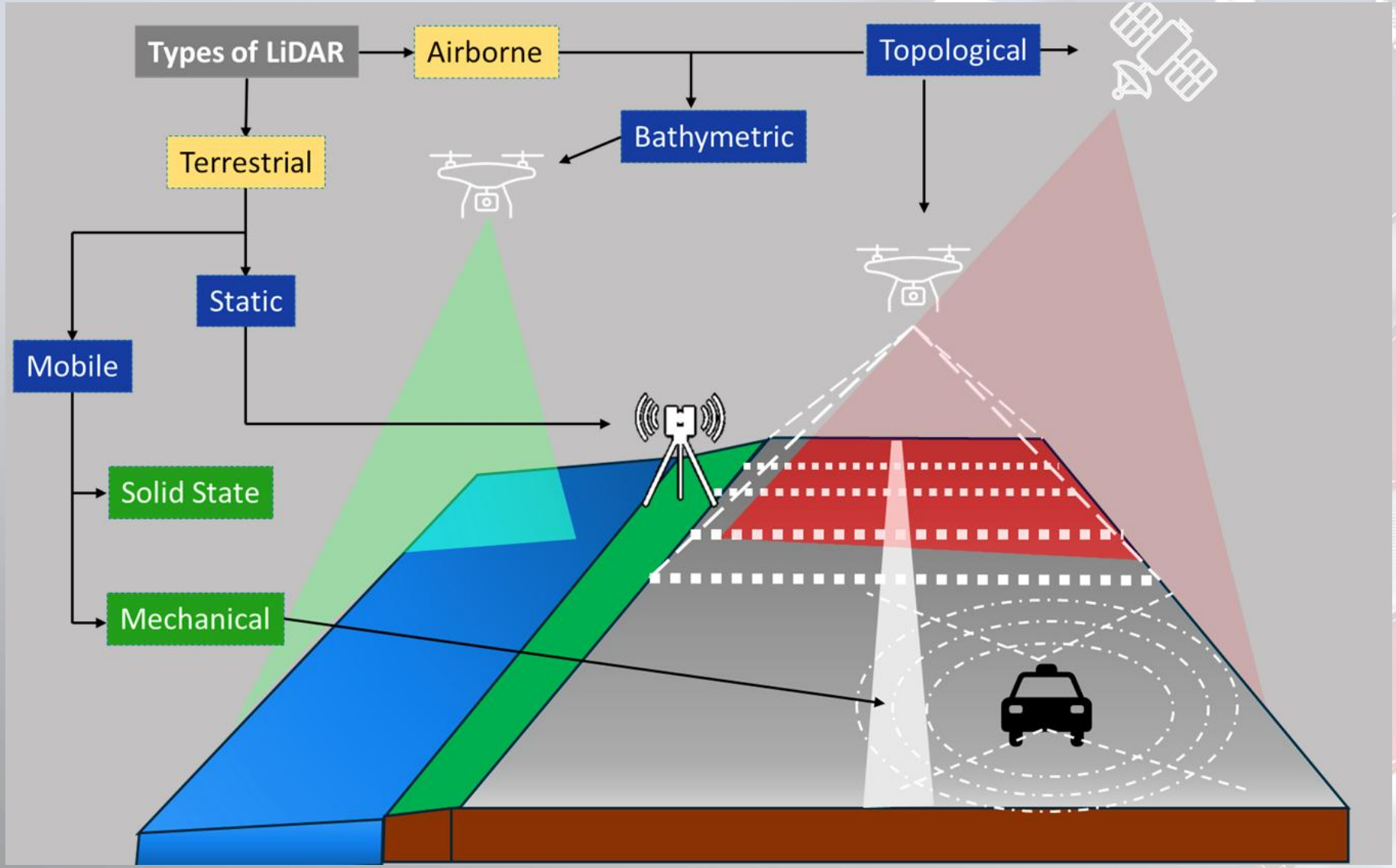


MAIN DATA SOURCES IN THE LITERATURE

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



TYPES OF LIDAR SYSTEMS



DOMINANT COMPUTATION STRATEGIES

Profile-based

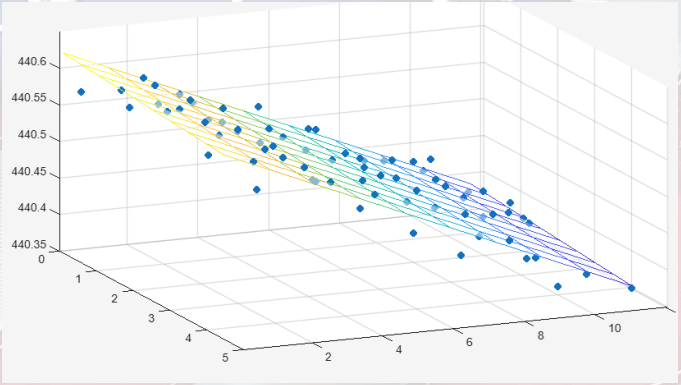
- Rise/run from sampled elevations.
- Strong for survey and profiler workflows

Regression-Based

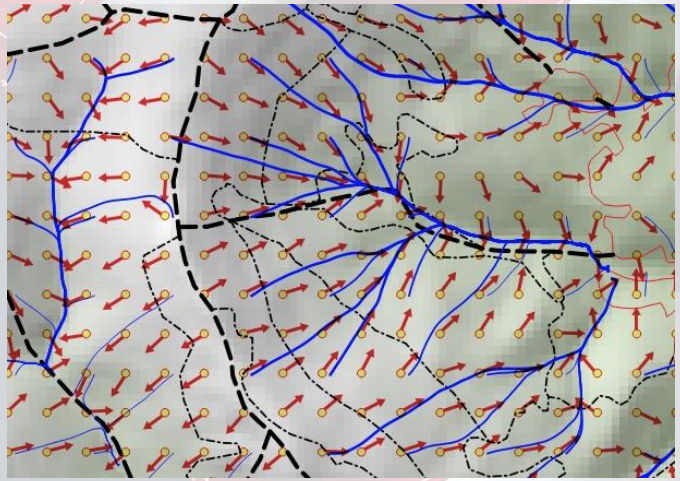
- Fit line or plane to selected points
- Sensitive to segmentation and point selection

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.

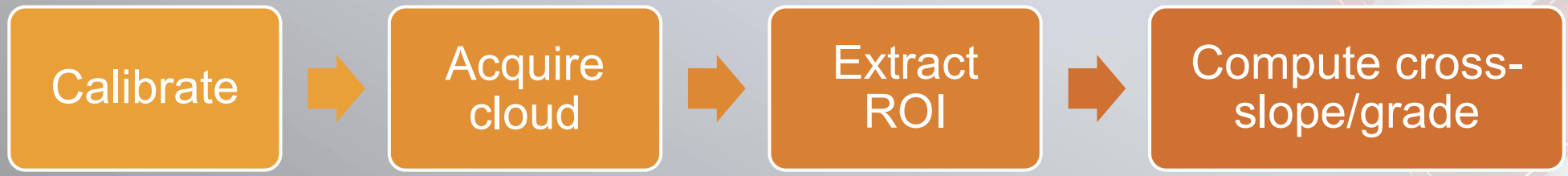
MOBILE LIDAR

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

Limitations

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

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

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

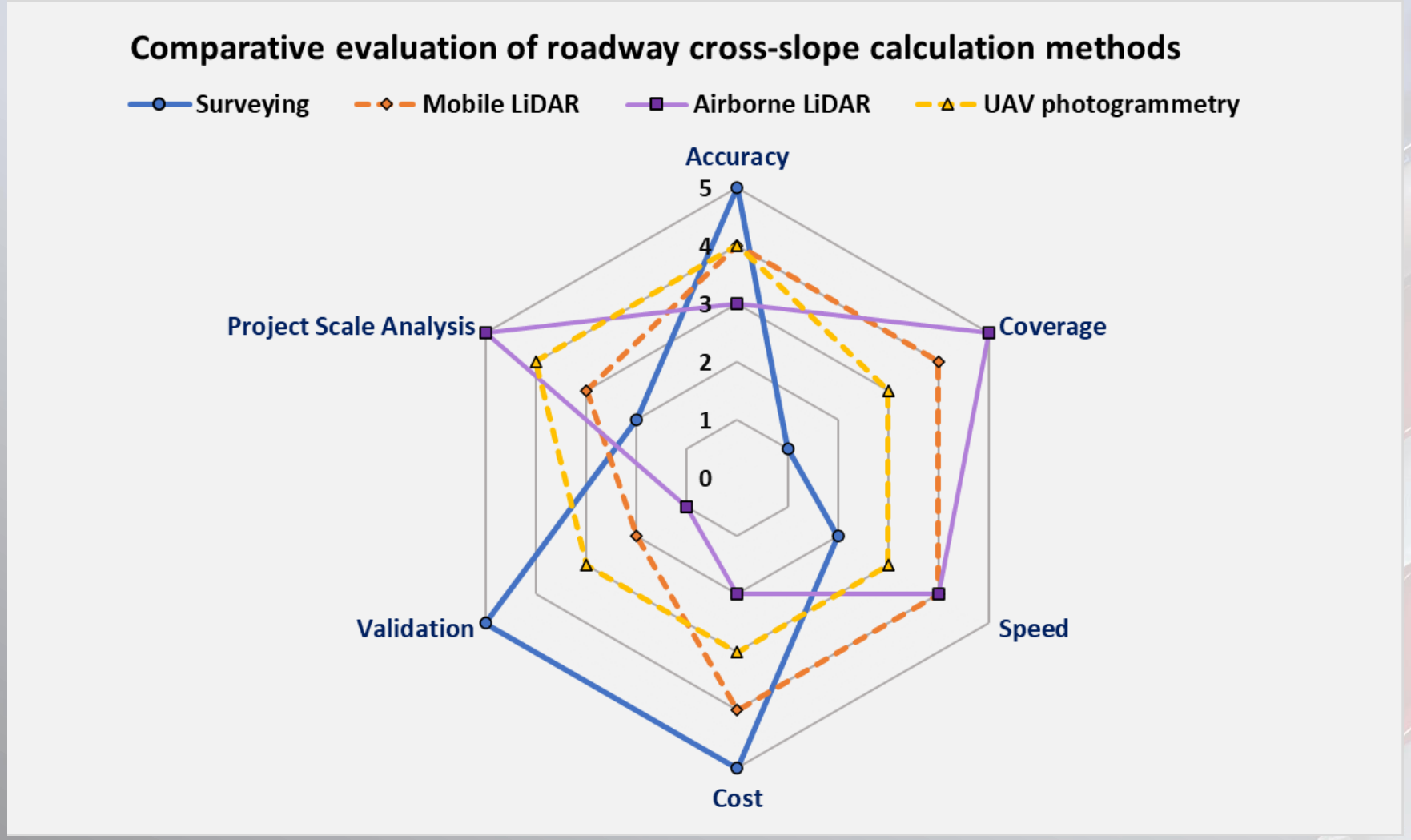
Comparative Use

- 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 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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REFERENCES

- Caroti, G., Piemonte, A., 2010. Measurement of cross-slope of roads: evaluations, algorithms and accuracy analysis. Survey Review 42, 92–104. https://doi.org/10.1179/003962610X12572516251484
- Cassule, L., Sarasua, W., Mahani, M., Burgett, J., Shams, A., Famili, A., 2021. Combined use of LiDAR and photogrammetry for highway cross-slope measurement.
- Liu, H., Li, H., Rodgers, M.O., Guensler, R., 2018. Development of road grade data using the United States geological survey digital elevation model. Transportation Research Part C: Emerging Technologies 92, 243–257. https://doi.org/10.1016/j.trc.2018.05.004

REFERENCES

- Luo, W., Wang, K.C., Li, L., 2016. Hydroplaning on sloping pavements based on inertial measurement Unit (IMU) and 1mm 3D laser imaging data. Periodica Polytechnica Transportation Engineering 44, 42–49. https://doi.org/10.3311/PPtr.8208
- Shams, A., Sarasua, W.A., Famili, A., J. Davis, W., H. Ogle, J., Cassule, L., Mammadrahimli, A., 2018. Highway Cross-Slope Measurement using Mobile LiDAR. https://doi.org/10.1177/0361198118756371
- Tsai, Y., Ai, C., Wang, Z., Pitts, E., 2013. Mobile cross-slope measurement method using lidar technology. Transportation research record 2367, 53–59. https://doi.org/10.3141/2367-06

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