



# COARSE-TO-REFINED ROAD ALIGNMENT EXTRACTION AND PARAMETERIZATION FROM MLS POINT CLOUDS

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# PRESENTATION OVERVIEW



- WHY ROAD ALIGNMENT DATA MATTERS
- OUR COARSE-TO-REFINED FRAMEWORK
- ROAD GEOMETRY EXTRACTION
- ALIGNMENT IDENTIFICATION & PARAMETERIZATION
- RESULTS & VALIDATION
- CONCLUSIONS & FUTURE WORK

# WHY ROAD ALIGNMENT MATTERS



- > **25%** OF US ROADWAY DEATHS OCCUR ON CURVES (FHWA)
- SHARP CURVES & LONG TANGENTS: **VISIBILITY↓**, **DRIVER STRAIN↑**
- ROAD GEOMETRY DATA ESSENTIAL FOR SAFETY AUDITS, BIM, SIMULATION
- CURRENT REALITY: DESIGN RECORDS MISSING, OUTDATED, OR INACCURATE
- MANUAL SURVEYS: SLOW, LABOR-INTENSIVE, REQUIRE LANE CLOSURES



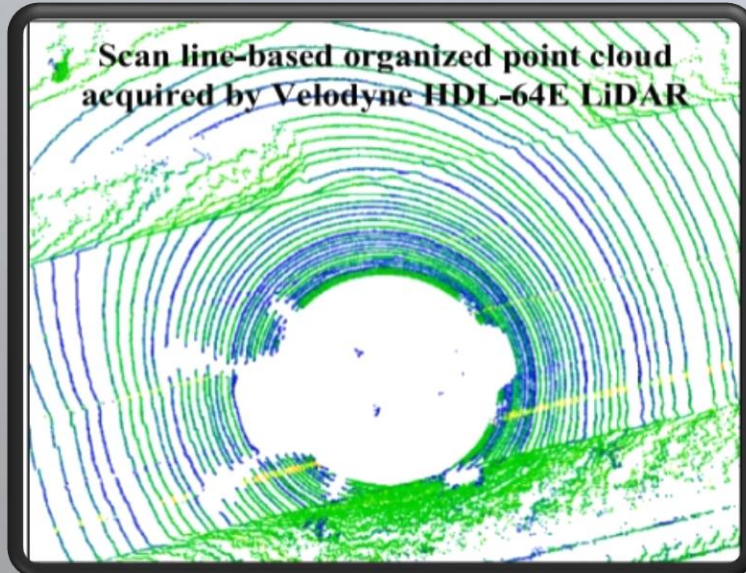
I-70 Glenwood Canyon

*Mobile Laser Scanning (MLS) offers a faster, safer alternative*

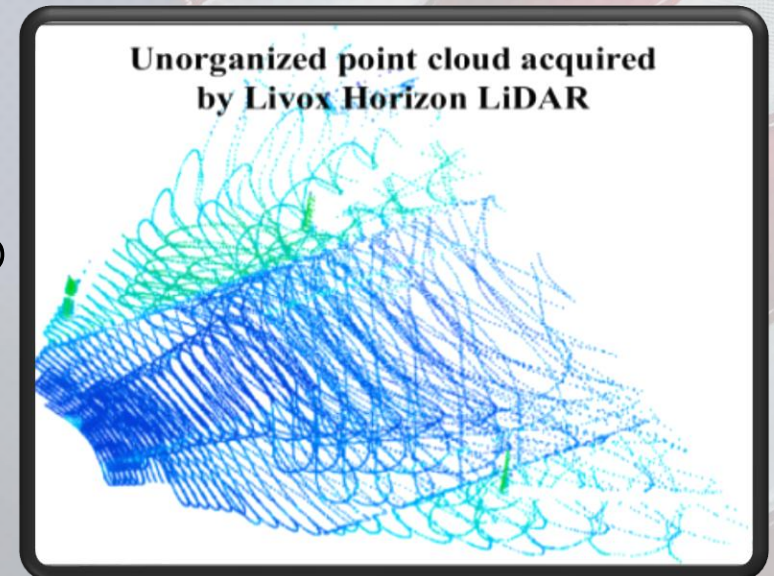
# THE DATA CHALLENGE



- TRADITIONAL MLS SYSTEMS: EXPENSIVE SCAN-LINE LIDAR
- SOLID-STATE LIDAR: AFFORDABLE — BUT PRODUCES **UNORDERED POINT CLOUDS**
- UNORDERED POINTS: TRADITIONAL METHODS FAIL (DESIGNED FOR SCAN-LINE DATA)
- EXISTING ALIGNMENT METHODS: LIMITED TO SIMPLE GEOMETRY (LINES + ARCS ONLY)



SCAN-LINE  
BASED



UNORGANIZED  
POINT CLOUD

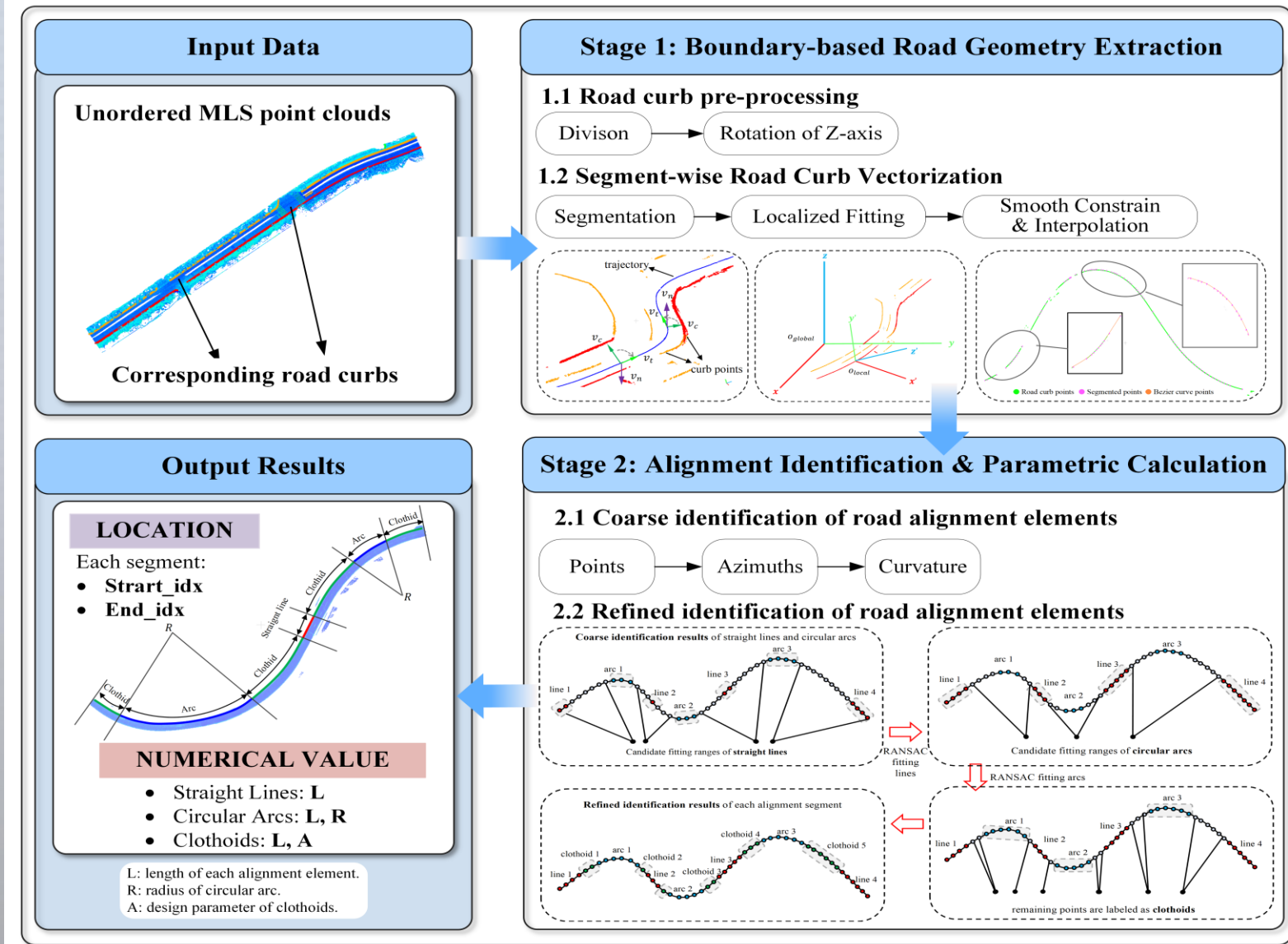
# OUR COARSE-TO-REFINED FRAMEWORK



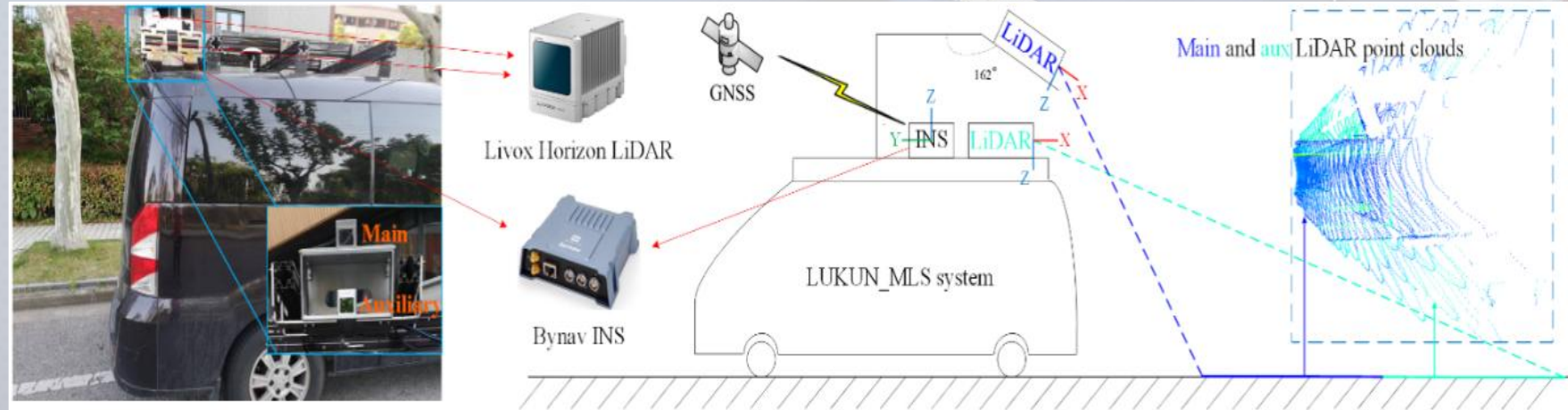
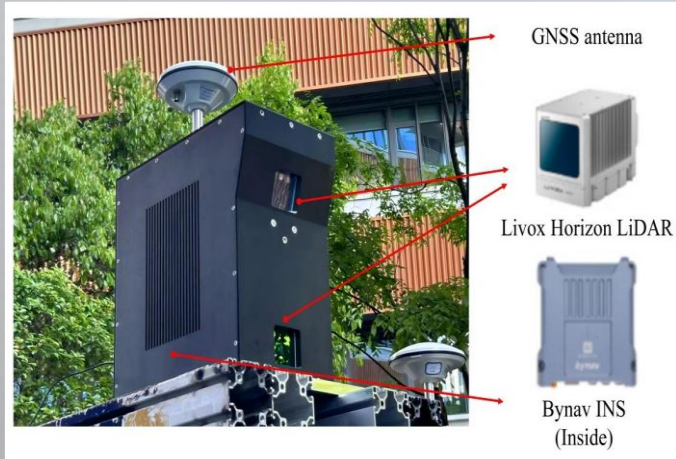
MLS POINT CLOUD → ROAD GEOMETRY EXTRACTION → ALIGNMENT IDENTIFICATION → PARAMETERS

TWO-STAGE APPROACH: COARSE ESTIMATION GUIDES REFINED MODEL FITTING

HANDLES ALL STANDARD ELEMENTS: LINES, CIRCULAR ARCS, CLOTHOIDS



# PROPOSED LIGHTWEIGHT MLS SYSTEM

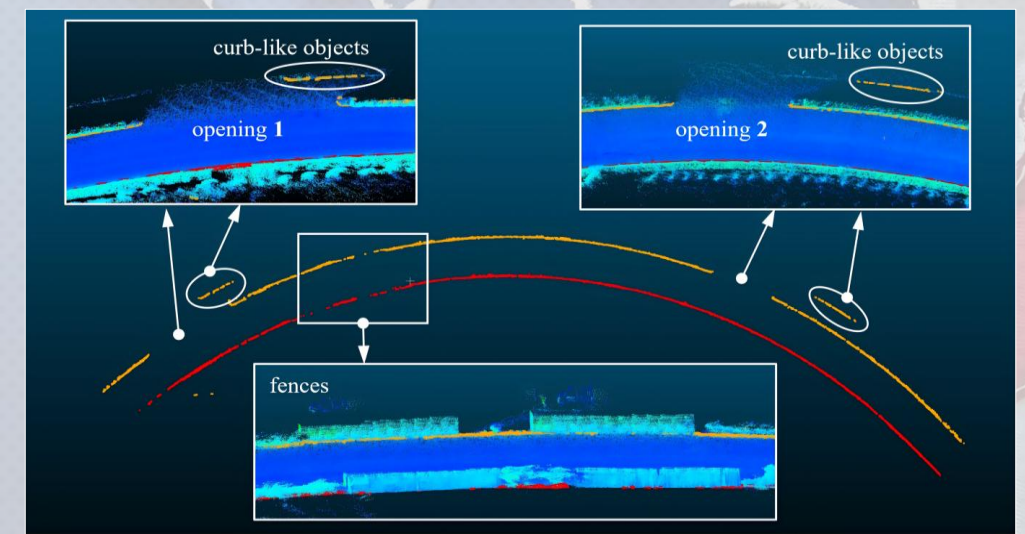
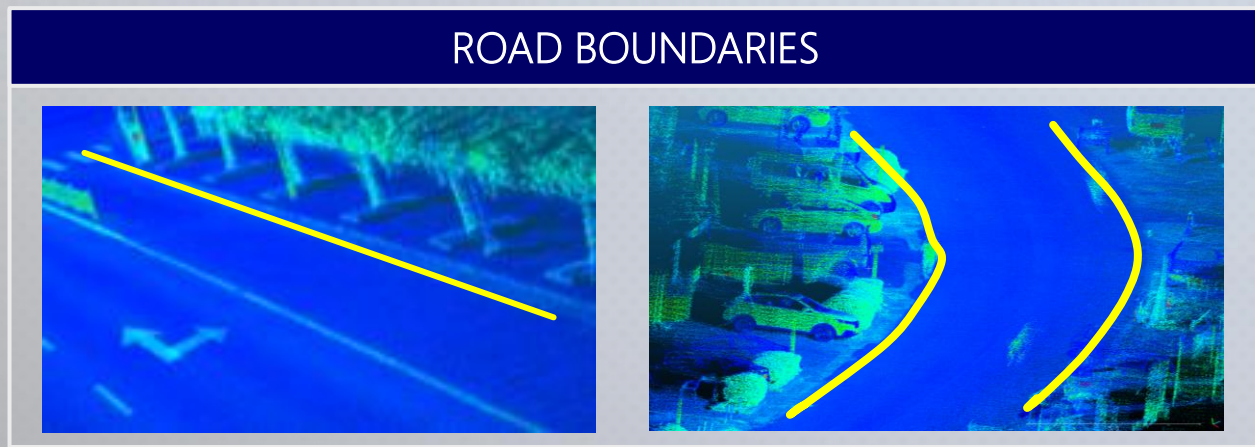


- **SELF-DEVELOPED SYSTEM:** 2 LIDARs + 1 INS UNIT
- **MAIN LIDAR:** HIGH-DENSITY PAVEMENT AND CURB SCANNING
- **AUXILIARY LIDAR:** SURROUNDING ROAD CONTEXT
- **INS:** PRECISE POSITION AND ORIENTATION FOR GEOREFERENCING

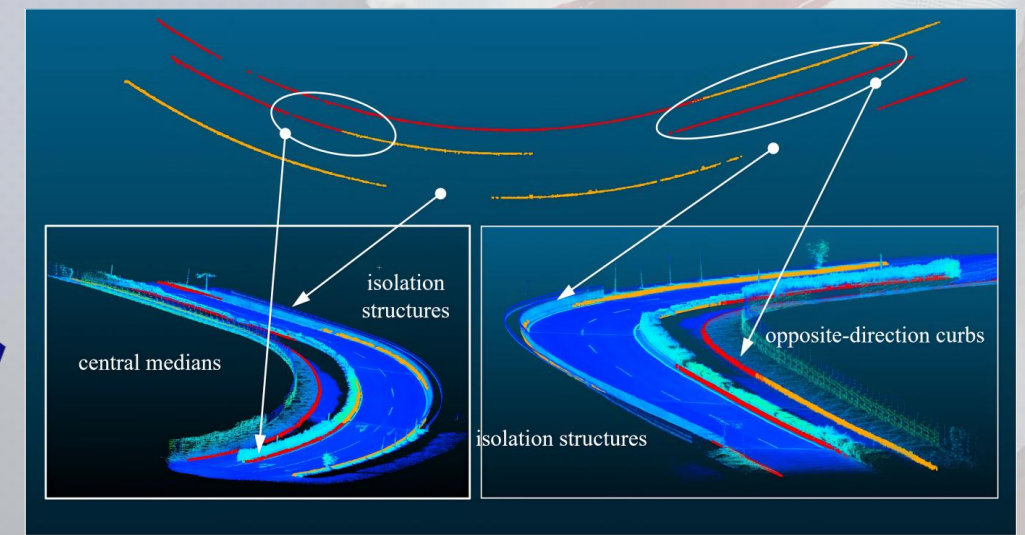
*Solid-state LiDAR: uniform coverage without scan-line assumption*

# STEP1: ROAD GEOMETRY EXTRACTION

## 1.1 ROAD CURB PRE-PROCESSING



- CURB-LESS SCENARIOS: CONTOUR-BASED BOUNDARIES
- UNORDERED POINT CLOUDS WITH SIMILAR GEOMETRIC PATTERNS
- ROBUST CURB EXTRACTION THROUGH DATA FUSION AND REGISTRATION <sup>1, 2</sup>
- PRE-SEGMENTED CURB POINT CLOUDS, BUT OCCASIONAL ERRORS:
  - INCOMPLETENESS AND NOISE
  - CURB MISASSOCIATION



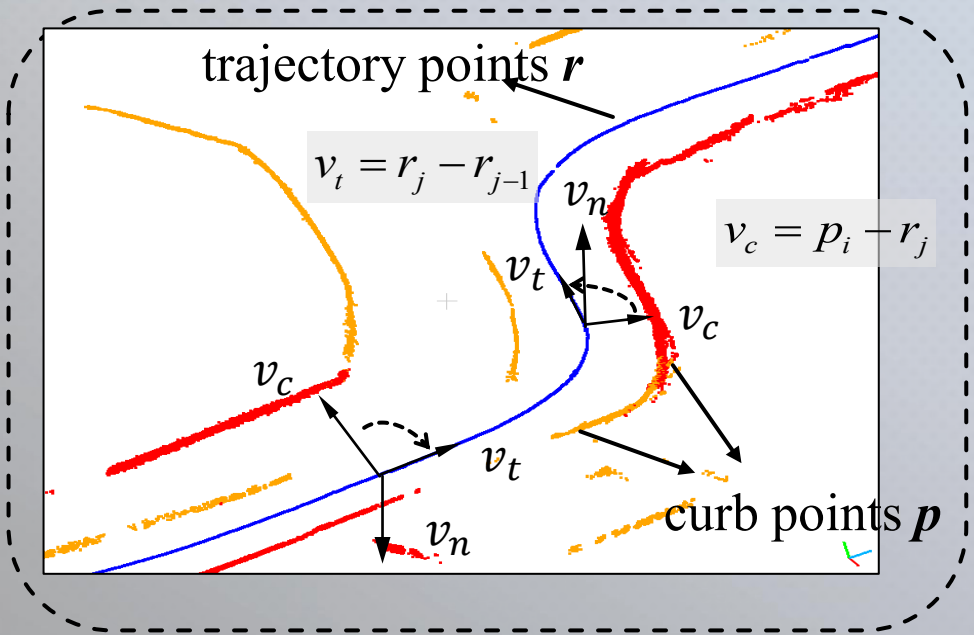
# STEP1: ROAD GEOMETRY EXTRACTION

## 1.1 ROAD CURB PRE-PROCESSING

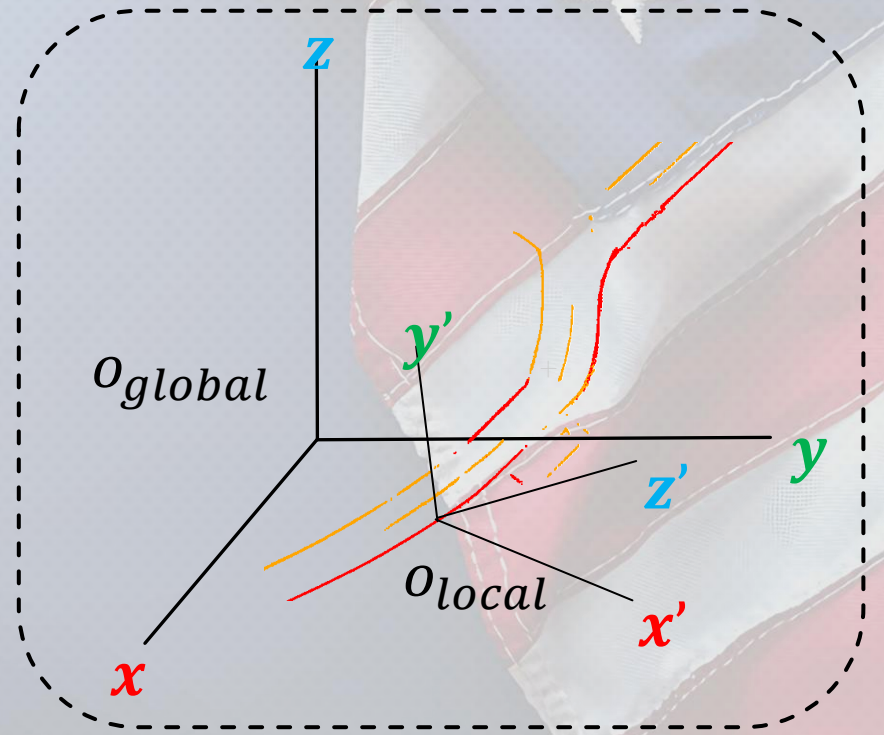
### a. DIVISION & SELECTION OF CURBS



### b. ROTATION OF Z-AXIS



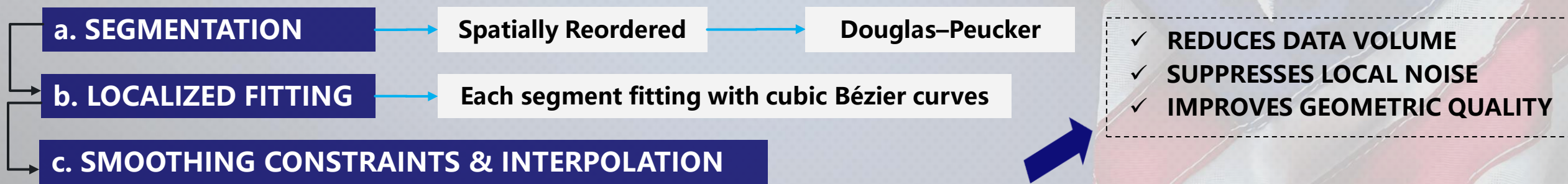
- $N_z$  OF CROSS PRODUCT INDICATES THE CURB SIDE:  
 $N_z > 0$ , RIGHT;  $N_z < 0$ , LEFT
- SELECT ONE SIDE:
  - MORE CONTINUOUS & COMPLETE COVERAGE



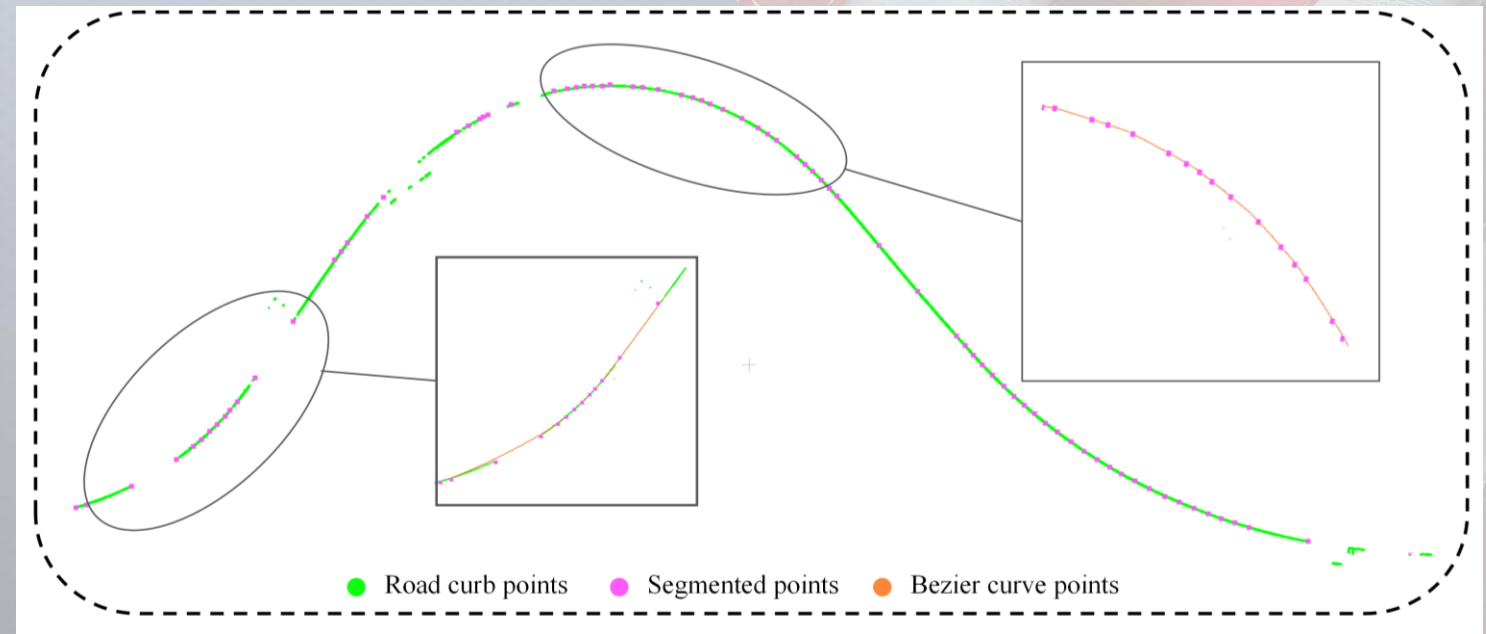
- ALIGNS THE Z-AXIS WITH THE PAVEMENT NORMAL
- NOT CHANGE THE 3D SHAPE OF THE CURB

# STEP1: ROAD GEOMETRY EXTRACTION

1.2 AFTER PRE-PROCESSING, THE CURB POINT CLOUD REMAINS DISCRETE, UNORDERED, AND CLUTTERED WITH NOISE AND GAPS



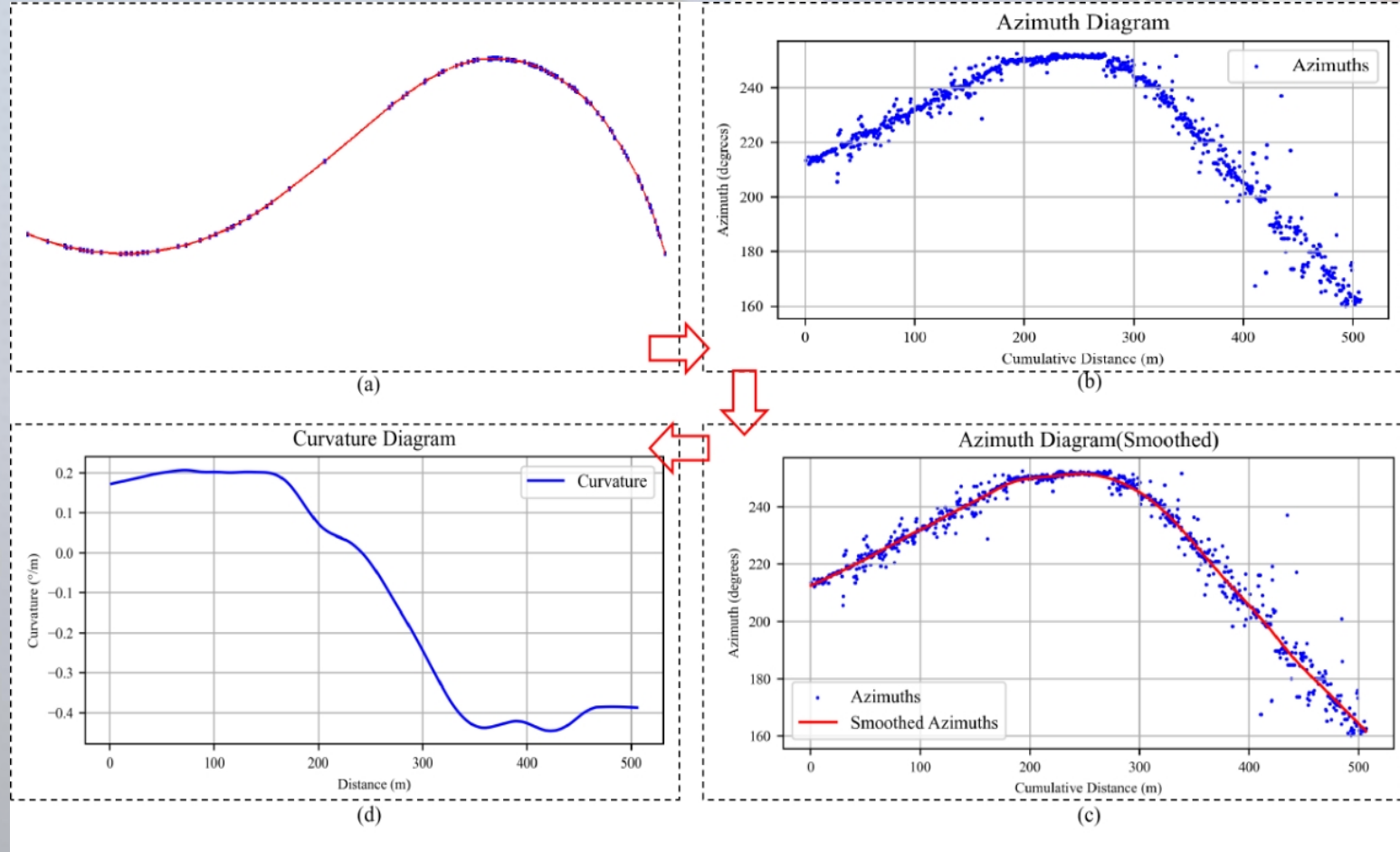
- **A LIGHTWEIGHT LOCAL OPTIMIZATION:**
  - ADJUSTS ONLY SHARED ENDPONTS TO ENFORCE  $C_1$  AND  $C_2$  CONTINUITY
- **OPTIMAL REPLACEMENTS:**
  - SEARCH AREA → POINTS WITHIN A 0.5 M RADIUS
  - SEARCH TARGET → MINIMIZE THE LOSS FUNCTION



# STEP2: COARSE ALIGNMENT ID.



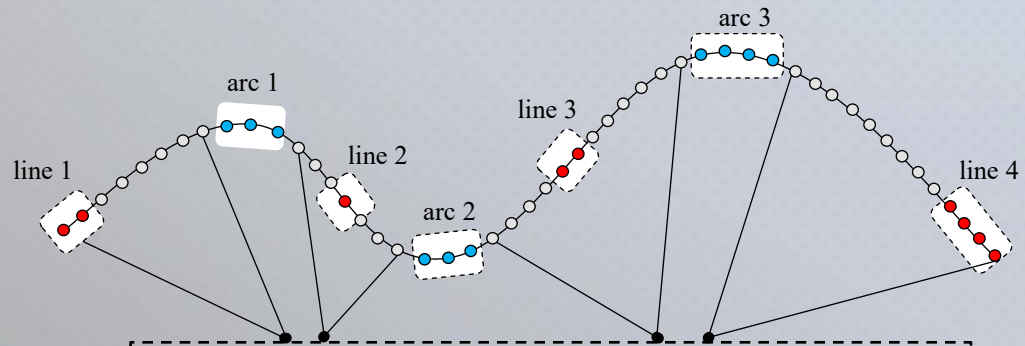
- COMPUTE **AZIMUTH** PROFILE FROM ROAD CURVE SEQUENCE POINTS
- COMPUTE **CURVATURE** PROFILE AFTER SMOOTHING AND OUTLIER REMOVAL
- AZIMUTH: CONSTANT SLOPE → STRAIGHT LINE
- CURVATURE: CONSTANT VALUE → CIRCULAR ARC
- CURVATURE: LINEAR CHANGE → CLOTHOID (TRANSITION CURVE)
- RULE-BASED CLASSIFIER ESTIMATES ELEMENT COUNT AND LOCATIONS



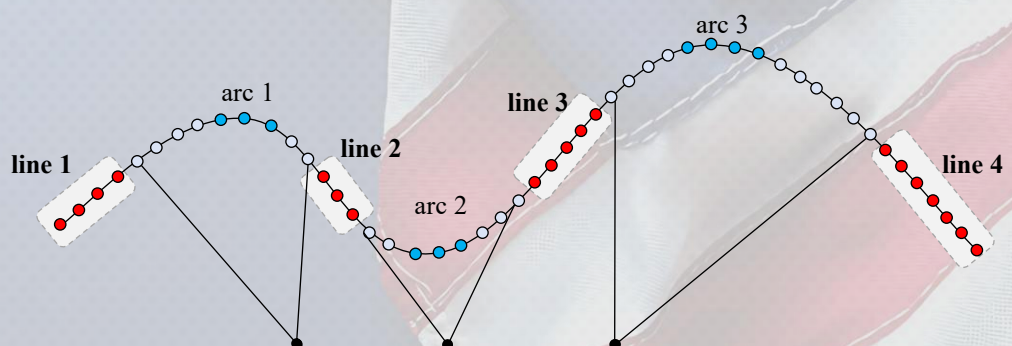
# STEP3: REFINED PARAMETERIZATION

- To **REFINE ELEMENT BOUNDARIES** AND **OBTAIN ACCURATE PARAMETERS**, WE ADOPT A **MODEL-FITTING STRATEGY** GUIDED BY THE **PRIOR GEOMETRIC ANALYSIS**.

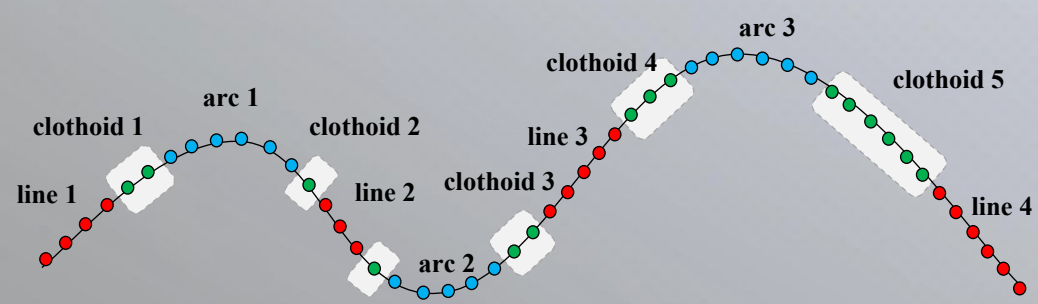
**Coarse identification results of straight lines and circular arcs**



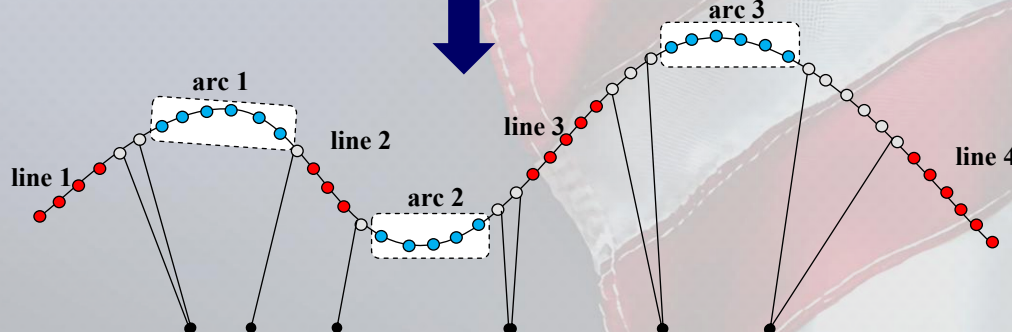
Candidate fitting ranges of **straight lines**



Candidate fitting ranges of **circular arcs**



**Refined identification results of each alignment segment**



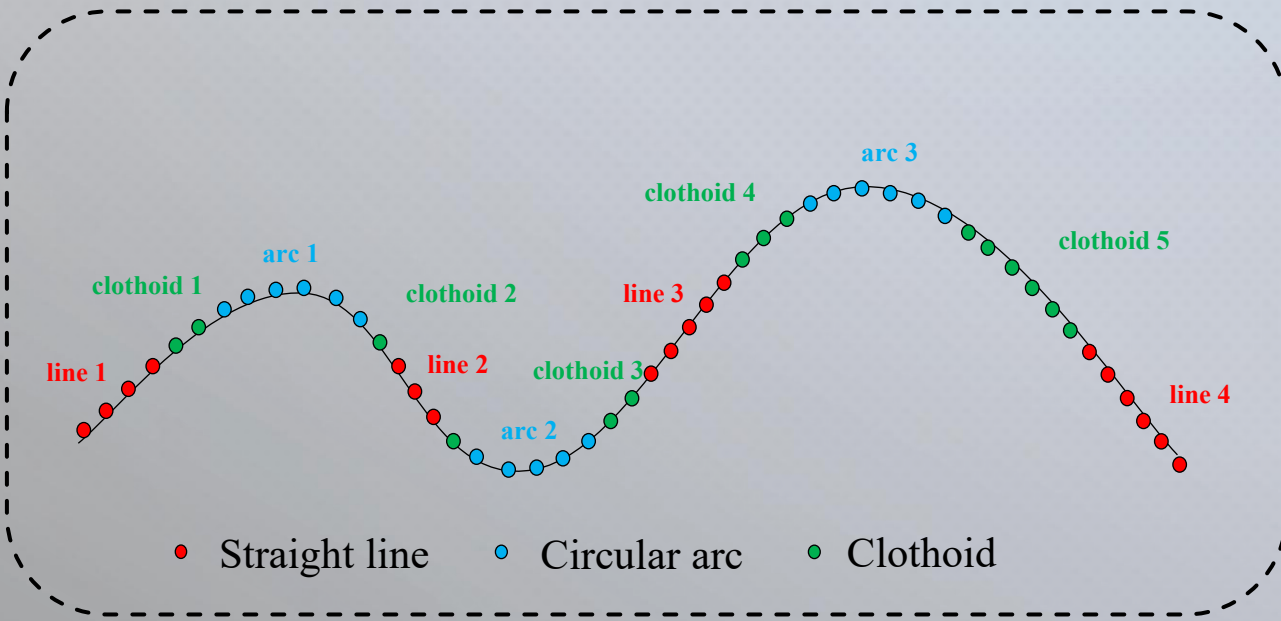
Remaining points are labeled as **clothoids**

- Straight line
- Circular arc
- Clothoid
- Unrecognized points
- ▭ Position range of each segment

# STEP 3: REFINED PARAMETERIZATION

- AFTER PRECISE IDENTIFICATION, **ALIGNMENT PARAMETERS** ARE THEN CALCULATED.

Refined identification results of each alignment segment

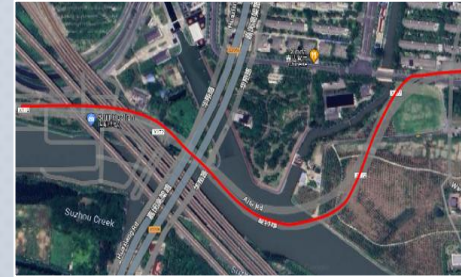


- **Straight Lines:**
  - Positions
  - Lengths
- **Circular Arcs:**
  - Positions
  - Lengths
  - Radius  $R_c^i$ :
    - ✓  $R_{c1}^i$  from **peak curvature of the diagram:**
    - ✓  $R_{c2}^i$  from **arc fitting outputs.**
    - ✓ the relative error < 1%,  $R_{c2}^i$  is chosen; otherwise,  $R_{c1}^i$  is used.
- **Clothoids:**
  - Positions
  - Lengths
  - Design parameter  $A_t^i$ :

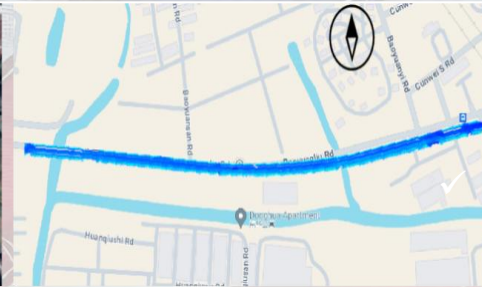
# TEST DATASET: REAL & SIMULATED ROADS



- REAL-WORLD DATA COLLECTED IN SHANGHAI
- AITE ROAD: 1,238 M — TYPICAL CIRCULAR ARCS
- BAOYUAN 6TH ROAD: 851 M — EXTRA-LARGE-RADIUS CURVE

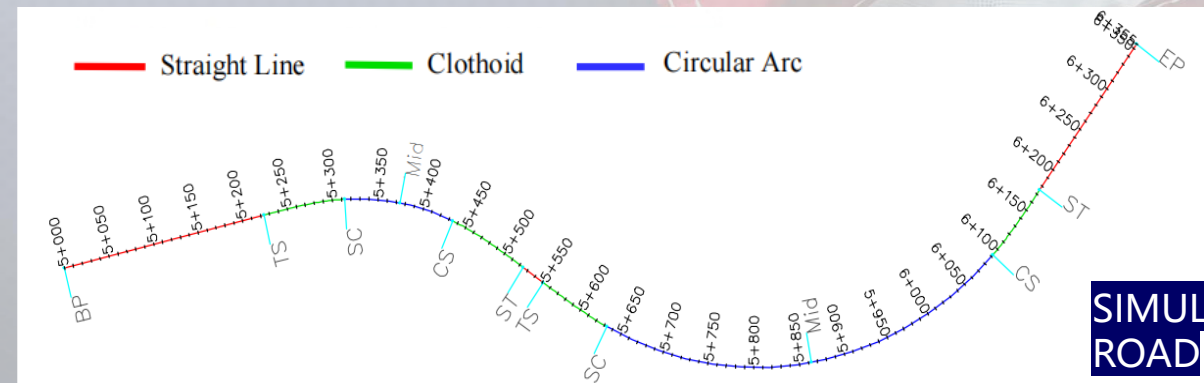


AITE ROAD



BAOYUAN ROAD 6TH

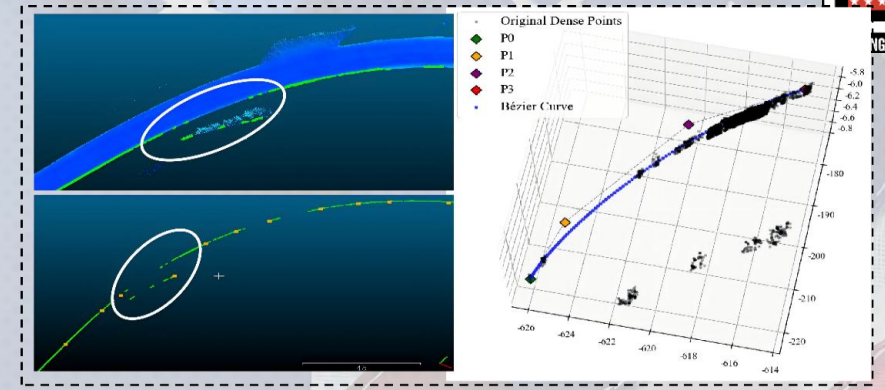
- SIMULATED DATA: 1,355 M ROAD IN AUTODESK CIVIL 3D
- 3 STRAIGHT LINES + 2 ARCS + 4 CLOTHOIDS (SAMPLED AT 0.5 M)
- GROUND TRUTH ALIGNMENT PARAMETERS PRECISELY CONTROLLED



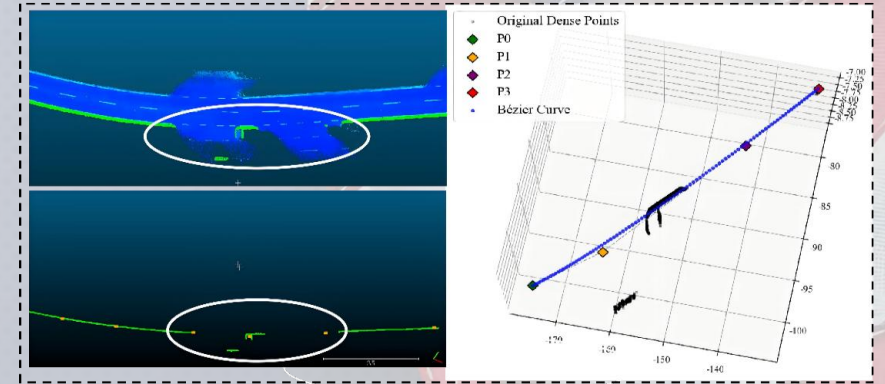
SIMULATED ROAD

# RESULTS: ROAD GEOMETRY QUALITY

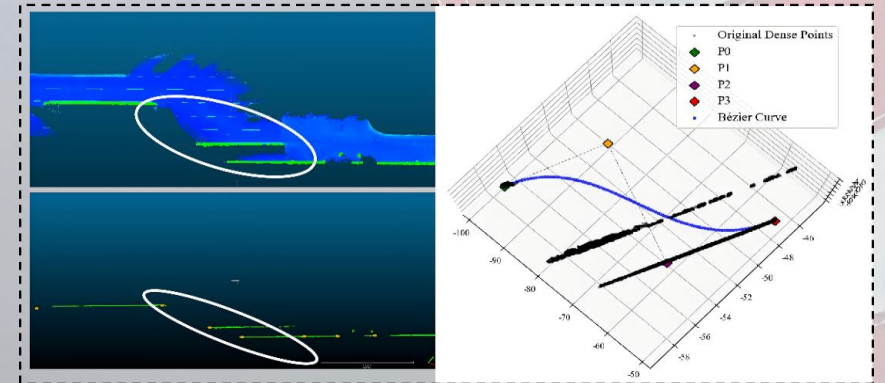
- THREE CHALLENGING REAL-WORLD SCENARIOS VALIDATED:
  - (A) DENSE FALSE POSITIVES FROM ROADSIDE OBJECTS → CORRECTLY SKIPPED
  - (B) POINT CLOUD GAPS → GEOMETRIC CONTINUITY MAINTAINED
  - (C) CURVATURE-VARYING SECTIONS → GLOBAL TREND PRESERVED
- QUANTITATIVE: **99.74%** CORRECTNESS, **99.41%** COMPLETENESS AT **50 CM** BUFFER



(a)



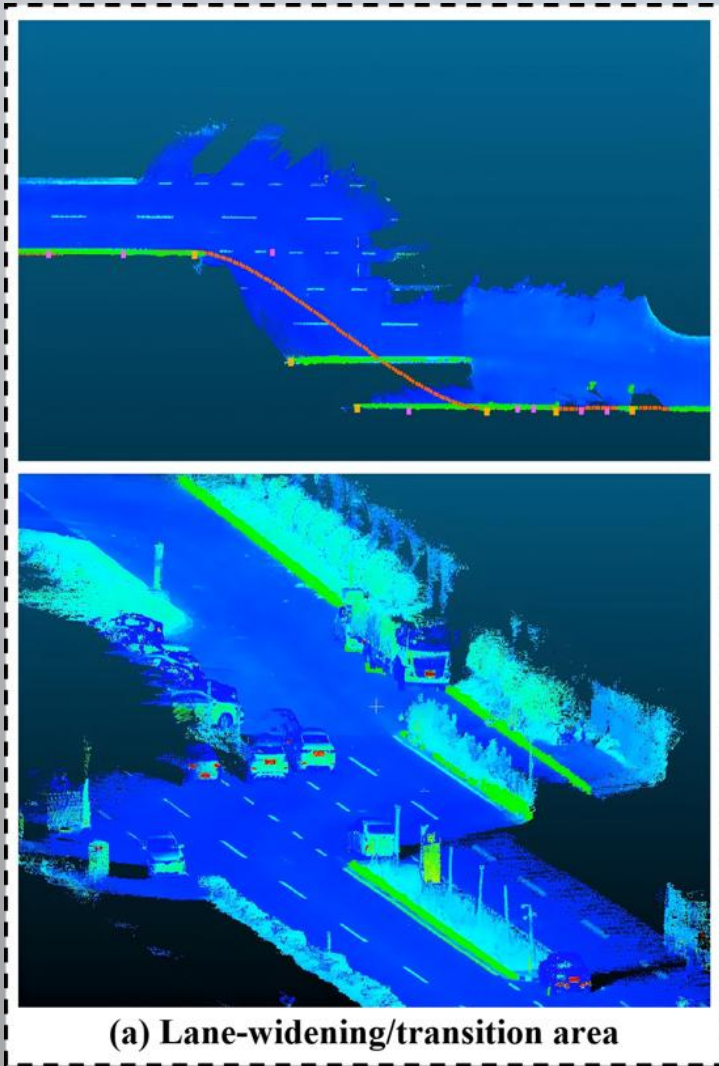
(b)



(c)

$W_b$ (cm)	Correctness (%)	Completeness (%)
10	61.26	60.98
20	89.51	89.10
30	97.38	97.02
40	98.87	98.51
50	99.74	99.41

# APPLICABILITY: LANE VARIATIONS

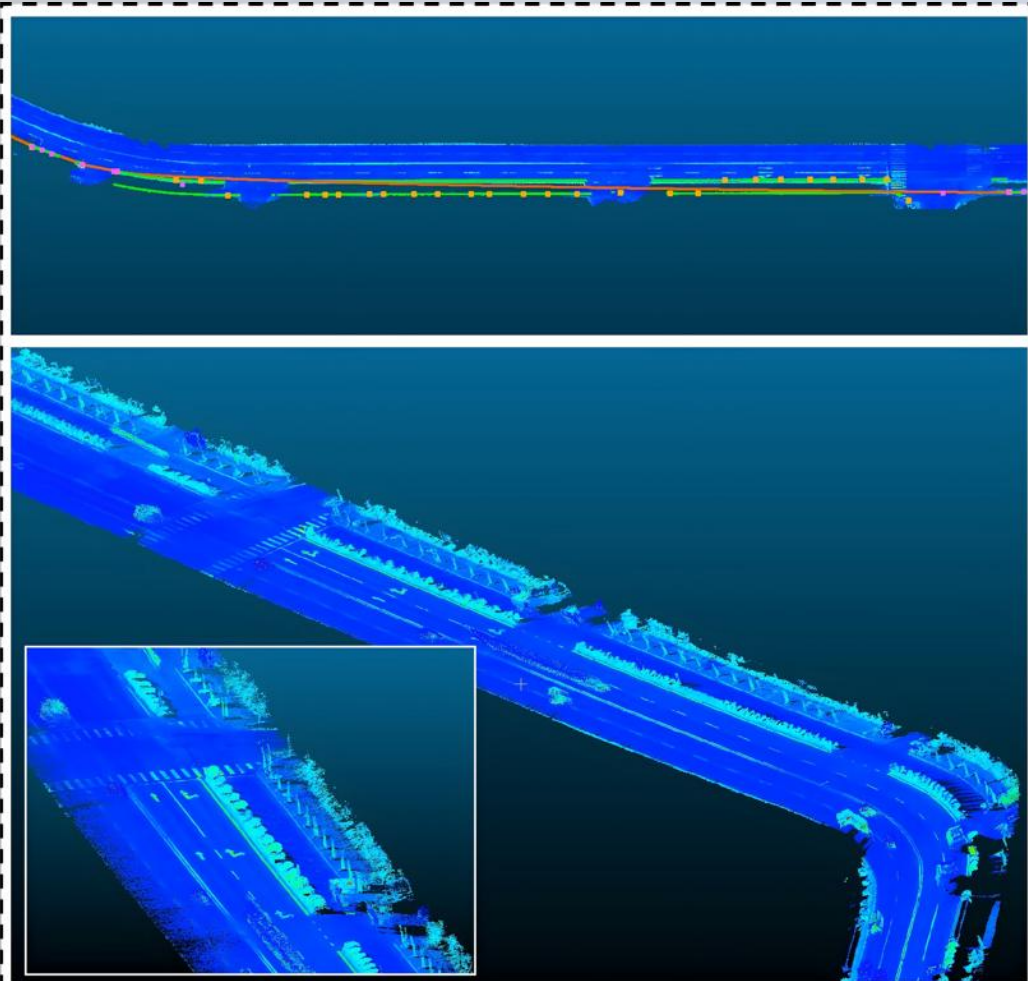


(a) Lane-widening/transition area

## (A) LANE-WIDENING / TRANSITION AREA

- CURB BOUNDARY SHIFTS Laterally THROUGH THE TRANSITION ZONE
- SINGLE-SIDE CURB INFERENCE MAY BIAS ALIGNMENT PARAMETERS WITHIN THAT ZONE
- **MITIGATION:** DUAL-SIDE CURB FUSION (BOTH LEFT AND RIGHT BOUNDARIES)

# APPLICABILITY: LANE VARIATIONS



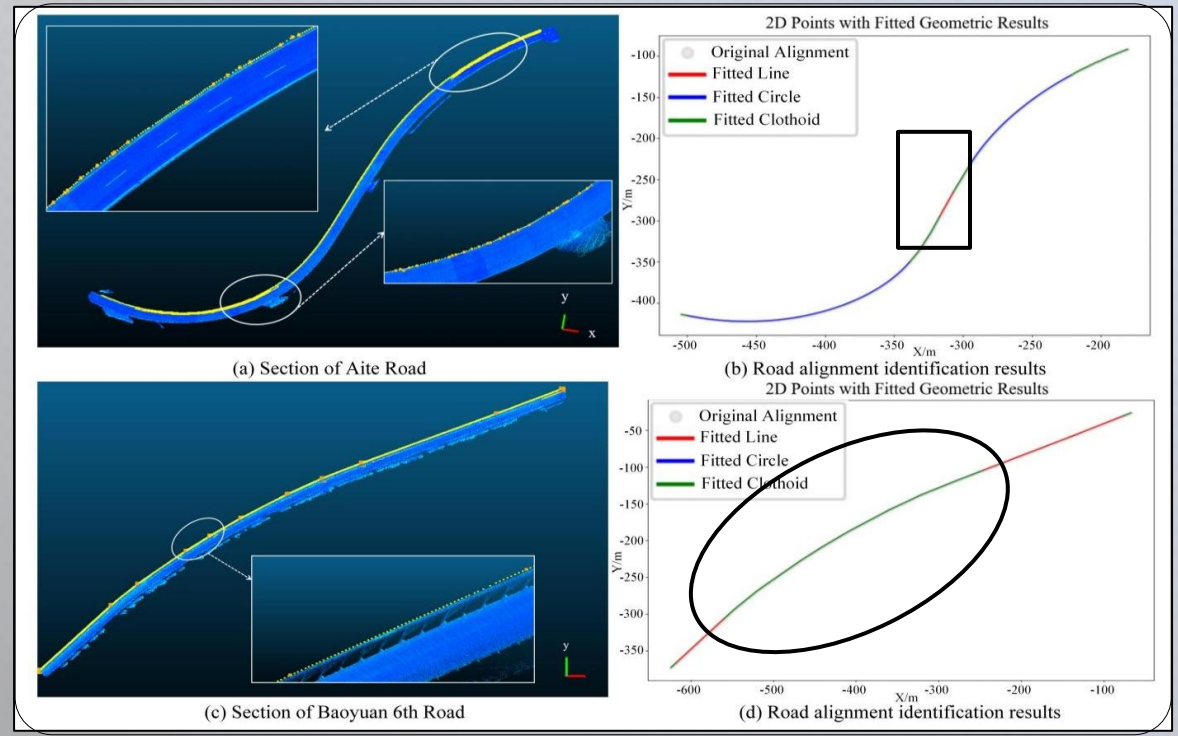
(b) Wide urban corridor with multiple curbs

## (B) WIDE CORRIDOR WITH MULTIPLE CURB-LIKE STRUCTURES

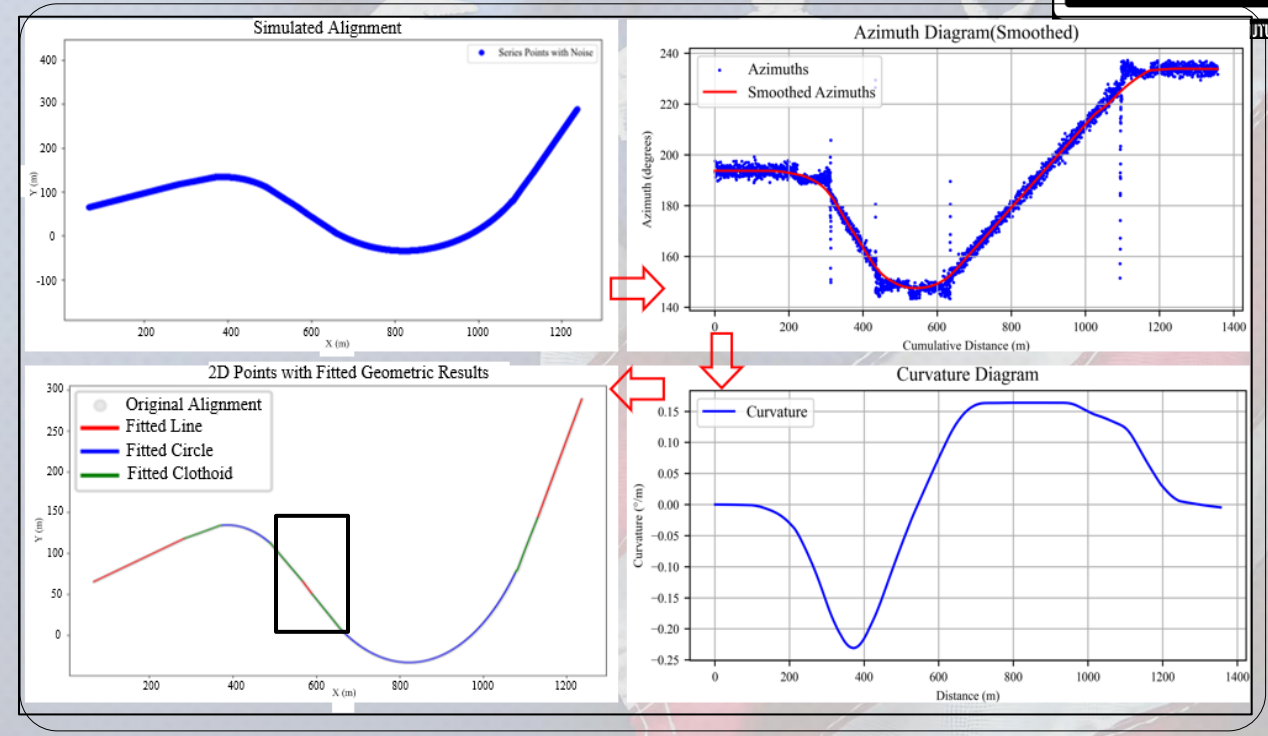
- MEDIANS AND PARTIAL COVERAGE CONFUSE LEFT/RIGHT CURB SEPARATION
- RESULT: SMOOTH BUT LATERALLY SHIFTED BOUNDARY REFERENCE
- **MITIGATION:** BIDIRECTIONAL / MULTI-PASS SCANNING + STRICTER BOUNDARY ASSOCIATION

BOTH CASES DEFINE THE CURRENT SYSTEM BOUNDARY FOR SINGLE-SIDE CURB SELECTION.

# RESULTS: ALIGNMENT IDENTIFICATION



Real-world data



Simulated Data

- BOTH REAL-WORLD AND SIMULATED ROADS CORRECTLY IDENTIFIED
- DETECTS INTERMEDIATE STRAIGHT SEGMENTS BETWEEN CLOTHOIDS IN S-CURVES
- CORRECTLY HANDLES EXTRA-LARGE-RADIUS CURVES (OFTEN MISIDENTIFIED)
- HIGH PRECISION: >97.8% PRECISION AND RECALL (SIMULATED DATA)
- LOW NUMERICAL ERROR FOR ALL ELEMENT TYPES (RELATIVE ERROR < 3%)



# RESULTS: TIME CONSUMPTION

- TIME CONSUMPTION EXPERIMENTS WERE CONDUCTED ON A SINGLE-CORE CPU SETTING OF THE TEST MACHINE (AMD RYZEN 9 6900HX, 3.30 GHZ) WITH REAL-WORLD DATA.

Stage	Real-world data		Mean Time (s/km)
	Aite Road	Baoyuan 6th Road	
Geometry Extraction	265.06 ± 8.09	247.43 ± 7.56	245.32 ± 7.49
Alignment Identification	30.13 ± 0.57	13.8 ± 0.26	21.03 ± 0.40

### GEOMETRY EXTRACTION:

- MORE TIME-INTENSIVE STAGE
- OPERATES ON DENSE CURB POINT CLOUDS
- ENCOMPASS MULTIPLE STEPS

### ALIGNMENT IDENTIFICATION:

- OPERATES ON A SIMPLIFIED AND UNIFORMLY RESAMPLED CURVE REPRESENTATION
- IMPORTANCE AND EFFECTIVENESS OF CURB VECTORIZATION IN ACCELERATING DOWNSTREAM MODELING

# CONCLUSION & FUTURE WORK



## WHAT WE ACHIEVED:

- COARSE-TO-REFINED FRAMEWORK: FIRST TO HANDLE LINES, ARCS AND CLOTHOIDS FROM AFFORDABLE MLS
- REAL-WORLD: >99% CORRECTNESS AND COMPLETENESS AT 50 CM BUFFER; DATA REDUCED TO LESS THAN 0.5% OF ORIGINAL SIZE
- SIMULATED: 97% MEAN IOU FOR SEGMENT IDENTIFICATION; AVERAGE PARAMETER ERROR BELOW 0.401%
- RUNTIME: 245 s/KM (GEOMETRY) + 21 s/KM (ALIGNMENT) ON SINGLE-CORE CPU - SUITABLE FOR OFFLINE PROCESSING
- OUTPUT: STANDARD HIGHWAY-DESIGN PRIMITIVES DIRECTLY COMPATIBLE WITH DIGITAL ROAD MODELING AND ASSET MANAGEMENT

## NEXT STEPS:

- VERTICAL ALIGNMENT EXTRACTION → FULL 3D ROAD PARAMETRIC MODEL
- COLLABORATION WITH US TRANSPORTATION AGENCIES FOR LARGE-SCALE VALIDATION
- INTEGRATION WITH BIM AND PAVEMENT MANAGEMENT WORKFLOWS

# THANK YOU!

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1. Zou, Z., H. Lang\*, J. Lu, and Q. Ma. Coarse-to-refined road curb segmentation from MLS point clouds. *Automation in Construction*, 2024, Vol. 166, p.105586.
2. Zou, Z., H. Lang\*, Y. Lou, and J. Lu. Plane-based global registration for pavement 3D reconstruction using hybrid solid-state LiDAR point cloud. *Automation in Construction*, 2023, Vol. 152, p.104907.
3. Chen, X., H. Lang\*, Zou, Z, Chen, Y, Jiang, Y. Coarse-to-refined Road Alignment Extraction and Parameterization from MLS Point Clouds, 2026, *Automation in Construction*.