Prototyping a Low-cost Roadside Device System for Cooperative Automated Driving

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CCAT Safety Working Group Meeting – October 24, 2025

Introduction

Challenges in Automated Driving and the Need for Cooperation

- Despite major progress in Automated Vehicles (AVs), safety and reliability remain uncertain in complex Operational Design Domains (ODDs).
- Key technical limitations:
  - Sensing and understanding dynamic environments
  - Predicting intentions of other road users
- USDOT's Automated Vehicles Comprehensive Plan emphasizes Cooperative Driving Automation (CDA) as a solution.
- CDA: Leverages communication among vehicles, infrastructure, and travelers to collectively enhance safety and mobility.
- FHWA's Safe System Approach: "Responsibility is shared" and "redundancy is crucial."

Introduction

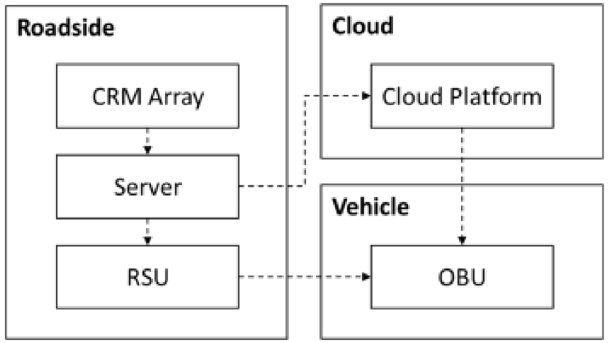
Why Infrastructure Matters

- SAE J3216 defines CDA classes but does not address vehicle-to-infrastructure interaction.
- Infrastructure-Based (IB) CDA enables cooperation between vehicles and intelligent roadside units (RSUs).
- Advantages of infrastructure-based systems:
  - No onboard power/space limits → more sensors, better computing.
  - Alternative viewing angles → cover vehicle blind spots.
  - Added redundancy → improved reliability.
  - Equity: serves all compatible vehicles, not just equipped CAVs.
- Current barriers:
  - No national system architecture
  - Unclear business model
  - High initial cost to reach critical mass

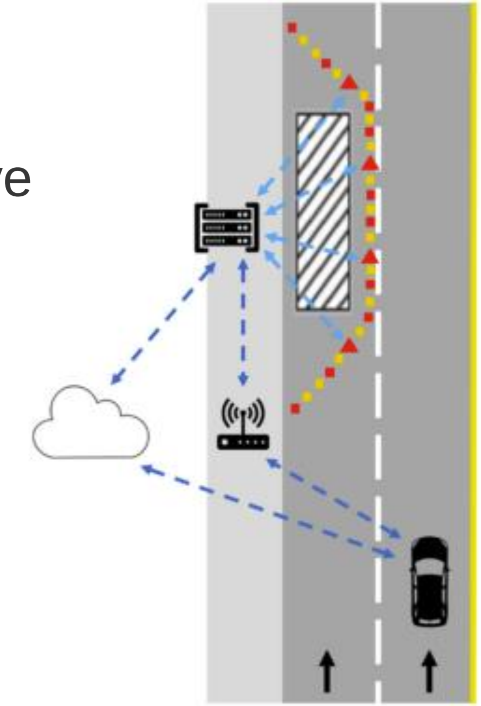
Introduction

Bridging the Deployment Gap

- FHWA developing Roadway Digital Infrastructure (RDI) strategy to define national architecture.
- To accelerate deployment before national rollout: focus on cost-effective critical-road use cases (e.g., intersections, work zones).
- Work zones identified by USDOT DAVI as top data-integration priority.
- Need for low-cost, scalable roadside systems to bootstrap IB-CDA deployment.



CRM System Architecture

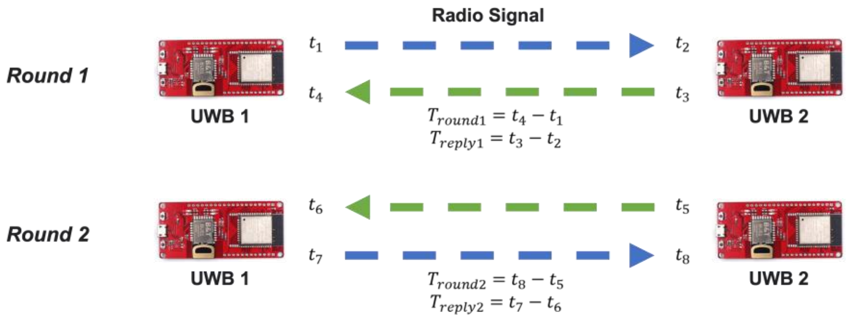


Work Zone Scenario

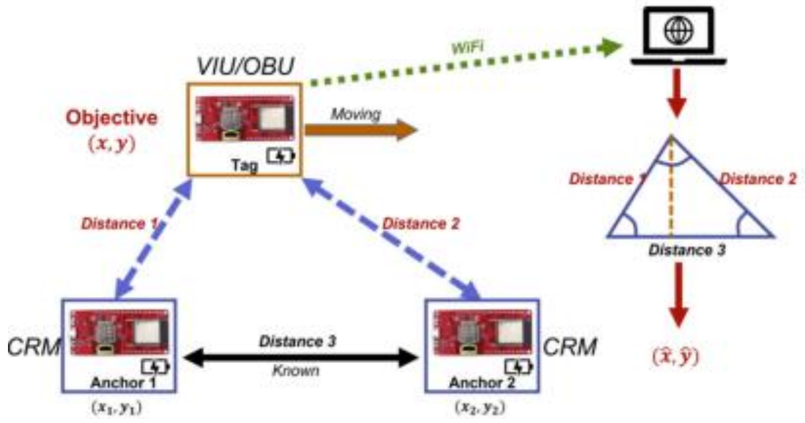
Introduction

Proposed Solution and Objectives

- CRM System: A low-cost roadside device network supporting CAV localization.
- Provides:
  - Real-time distance measurements via Ultra-Wideband (UWB)
  - High-resolution road geometry and work-zone boundary detection
- Serves as a gateway system for infrastructure-based CDA.
- Project objectives:
  - Evaluate CRM localization accuracy under diverse scenarios
  - Demonstrate CRM use for Work Zone Data Exchange (WZDx) data feeds
  - Provide insights for future large-scale field deployment
- Initial findings: Sub-decimeter static accuracy and sub-0.2 m dynamic accuracy, showing strong potential for reliable, low-cost CDA support.



UWB two-way ranging process used by the CRM distance-measurement module



CRM/Tag architecture for advanced triangular positioning

Literature Review

Overview

- **This literature review addresses three key areas relevant to work zone automation for autonomous vehicles:**
- **Work Zone Scenarios for Autonomous Driving:**
  - Challenges in automated vehicle deployment and cooperative driving automation approaches;
  - Recent academic advances in merge control, lane coordination, and communication strategies
- **Work Zone Data Exchange (WZDx) Standard:**
  - National USDOT initiative for standardizing real-time work zone information;
  - Current deployment challenges and recent solutions for improving data accuracy;
- **Connected Reference Marker (CRM) System:**
  - Low-cost infrastructure-based localization using ultra-wideband (UWB) technology;
  - High-resolution work zone boundary detection to enhance WZDx feeds.

Literature Review

Work Zone Scenarios for Autonomous Driving

- **Safety and Reliability Challenges:**
  - Automated vehicles face safety concerns from large-scale deployment experiences;
  - Work zones present challenging **operational design domains (ODDs)** with temporary lane closures, signage, and physical obstructions;
- **Cooperative Driving Automation (CDA) Approach:**
  - **USDOT** highlights CDA as key research focus in Automated Vehicles Comprehensive Plan;
  - CDA leverages **communication** between vehicles, infrastructure devices, and road users;
  - **FHWA CARMA** program demonstrates CDA improves work zone safety and mobility;
- **Recent Academic Research:**
  - Employ reinforcement learning, control algorithms, and traffic modeling techniques to optimize vehicle merging and traffic flow management in work zones, with platoon regulation and real-time traffic state prediction;
  - Complementary advances in vehicle detection, V2V/V2I communication, thermal imaging, and large language models (**LLM**) enhance situational awareness and enable adaptive decision-making for cooperative autonomous driving systems **navigating complex work zone scenarios**.

Literature Review

Work Zone Data Exchange (WZDx) Standard

- **USDOT National Initiative:**
  - WZDx designed to standardize **real-time work zone information** dissemination;
  - **Objective**: Enhance roadway safety and efficiency through harmonized data access;
- **Data Specification and Standards:**
  - Common data specification inspired by General Transit Feed Specification (GTFS);
  - Enables Infrastructure Owners and Operators (IOOs) to publish consistent **format data;**
  - U.S. DOT engaged ITE and SAE for standardization efforts
- **Current Deployment Challenges:**
  - Work zone data mostly derived from planning systems, **lacking reliable real-time geometric details**;
  - Smart work zone devices (GPS-equipped cones/boards) **expensive** and operationally challenging;
  - Significant **barriers to widespread deployment** due to transportation, setup, and activation costs.

Literature Review

Connected Reference Marker (CRM) System

- **CRM System Architecture:**
  - Three main components: **roadside unit**, **cloud service**, and **mobile unit;**
  - Roadside: CRM array with anchors, server for computation, RSU for data exchange;
  - Mobile: OBU (on-board unit) with CRM unit for vehicle-side localization;
- **Ultra-Wideband (UWB) Technology:**
  - Localization based on measuring distances between CRM array and CRM unit of OBU;
  - UWB is **low-cost** technology already widely used in mobile devices (e.g., Apple AirTag);
  - Enables real-time location, data transmission, and applications;
- **Key Capabilities:**
  - Real-time detection of accurate **work zone boundaries** at high resolution;
  - Embedding UWB units in work zone cones enables **precise cone localization**;
  - Enriched data stream improves infrastructure **communication** capabilities
  - Supports automated **path planning** for CAVs navigating narrow and non-standard **road geometries**;

System Building

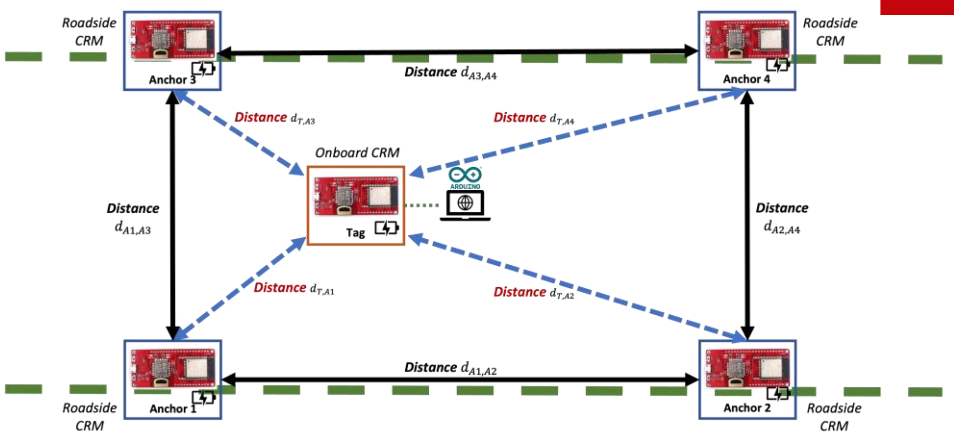
Overview

- The Connected Reference Marker (CRM) system integrates hardware, software, and algorithms to achieve low-cost, high-accuracy localization.
- Designed to support Cooperative and Automated Driving (CDA) and Work Zone Data Exchange (WZDx) standards.
- Development process includes three stages:
  - Prototype hardware construction using ESP32 UWB modules.
  - Developing and testing different localization algorithms and methods.
  - LLM-based semantic translation for WZDx integration.
- Goal: Build a scalable and field-deployable infrastructure enabling CAV localization and standardized data exchange.

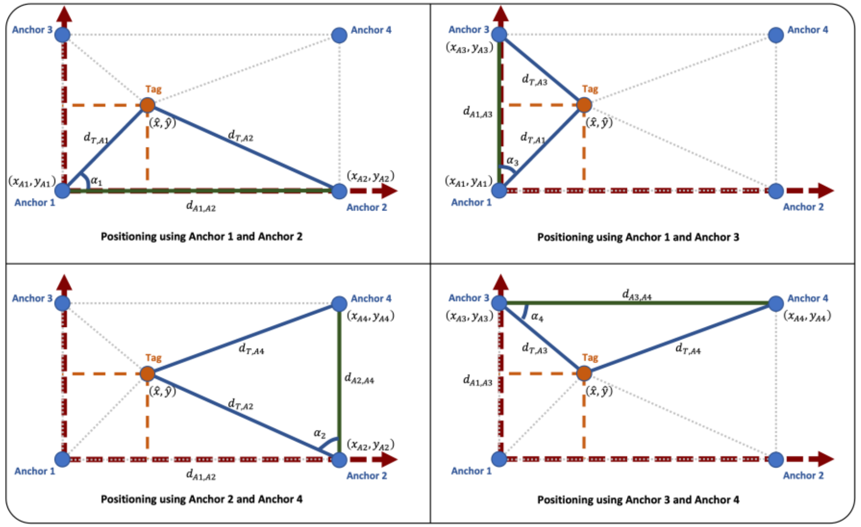
System Building

Hardware Implementation

- Anchors:
  - Stationary ESP32 UWB modules mounted on cones or roadside structures at known coordinates.
  - Two-anchor triangular setup and four-anchor rectangular layout for redundancy and accuracy.
- Tag: Mobile UWB module mounted on the vehicle under test, continuously exchanging ranging signals with anchors.
- Processing Unit: Laptop/PC connected via USB to collect distance data, run triangulation algorithms, and visualize positions in real time.
- Experimental Settings:
  - Static tests → sub-decimeter error.
  - Dynamic tests → ≈ 0.2 m average error.
- Conclusion: Proves the feasibility of a low-cost, scalable roadside localization system that can expand with additional anchors and nodes.



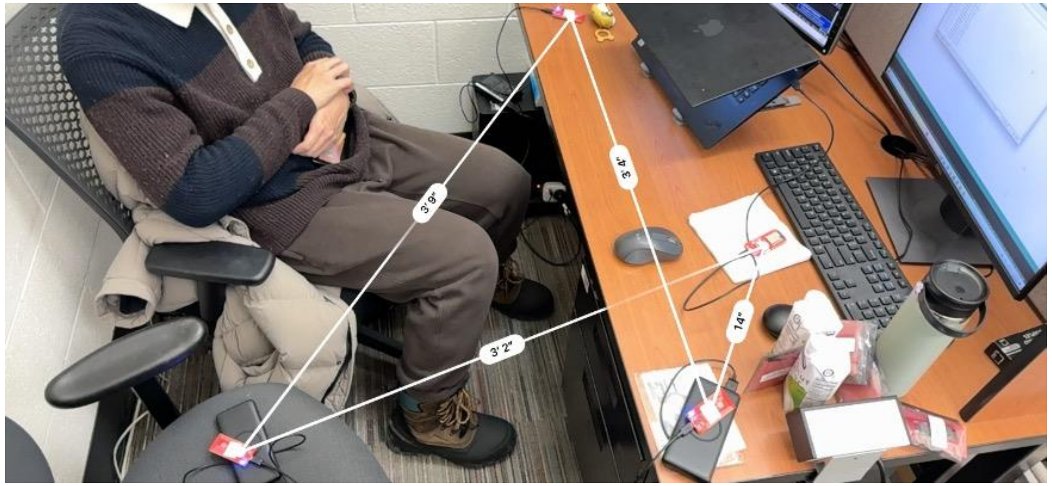
Four-anchor CRM/Tag architecture for advanced triangular positioning

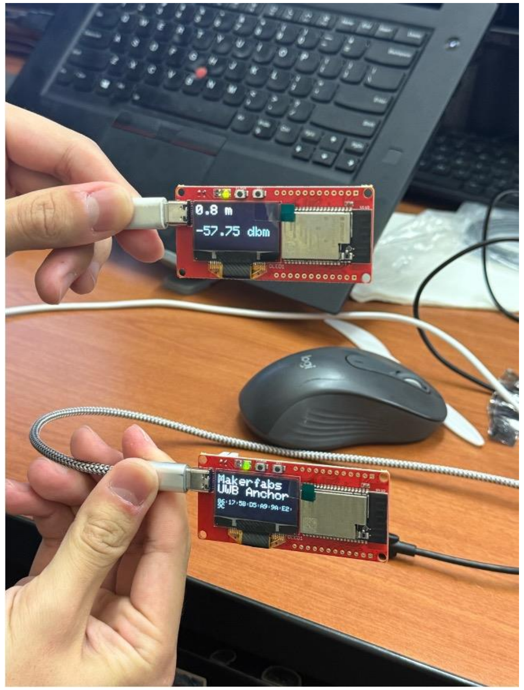


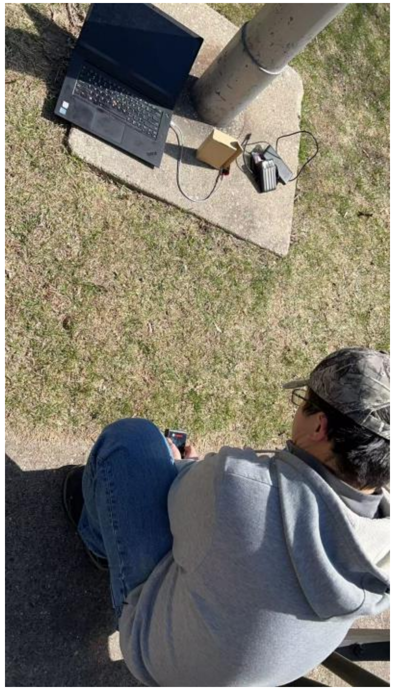
Four-anchor triangular positioning geometry and coordinate averaging

System Building

CRM Prototyping and Testing







System Building

Software and Algorithmic Framework (Part 1)

- Purpose: Transform raw UWB ranging signals into precise localization outputs.
- Distance Measurement:
  - Time-of-Flight (ToF) ranging implemented in single- and double-sided two-way modes.
  - Double-sided method reduces synchronization errors and improves robustness.
- Baseline Localization Framework:
  - Triangulation/Multilateration — solves geometric relationships between tag and anchors; averaging reduces noise.
  - Extended Kalman Filter (EKF) — applies a constant-velocity motion model to smooth trajectories and suppress outliers.
- Joint-Embedding Predictive Architecture-based method (proposed):
  - Predicts future embeddings from historical distance sequences.
  - Reconstructs denoised ranges to mitigate Non-Line-of-Sight (NLOS) errors.
  - Enables anchor self-calibration by minimizing trajectory–distance discrepancies, reducing dependence on surveyed coordinates.
- Outcome: The proposed method ensures continuous, robust localization for both static and dynamic tests.

System Building

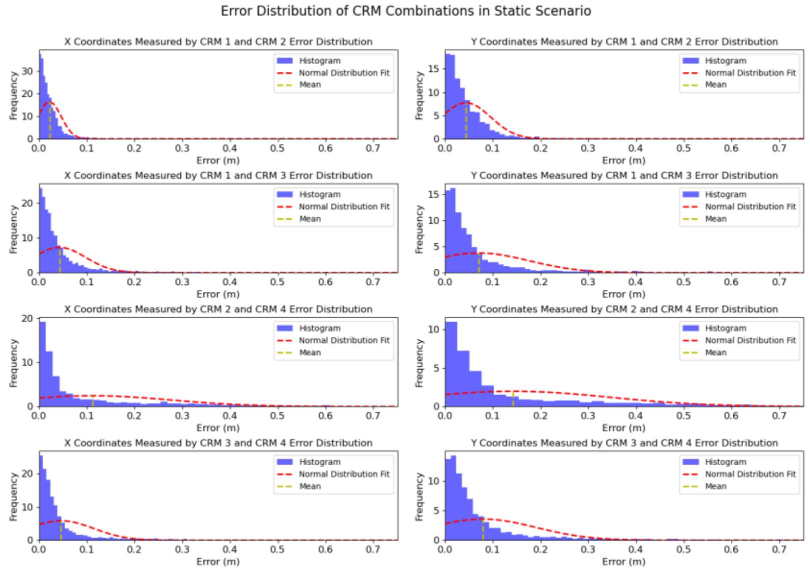
Software and Algorithmic Framework (Part 2)

- Objective: Translate high-resolution CRM geometry into standardized Work Zone Data Exchange (WZDx) feeds.
- Fusion Process:
  - Fuse CRM outputs (cone coordinates, lane geometry) with official WZDx inputs (polylines, lane lists, textual closures).
  - Use a Large Language Model (LLM) to interpret and align semantic work-zone descriptions with physical geometry.
- LLM Reasoning Tasks:
  - Identify open and closed lanes based on closure statements.
  - Align cone placements to generate accurate trapezoidal work-zone footprints.
  - Generate refined centerline polylines consistent with traffic direction and safety rules.
- Outputs:
  - Refined geometric data for drivable corridors.
  - Safe lane lists and concise navigation instructions for CAV and human drivers.
- Result: Serialized into WZDx-compliant feeds, ensuring interoperability and nationwide scalability for CDA deployment.

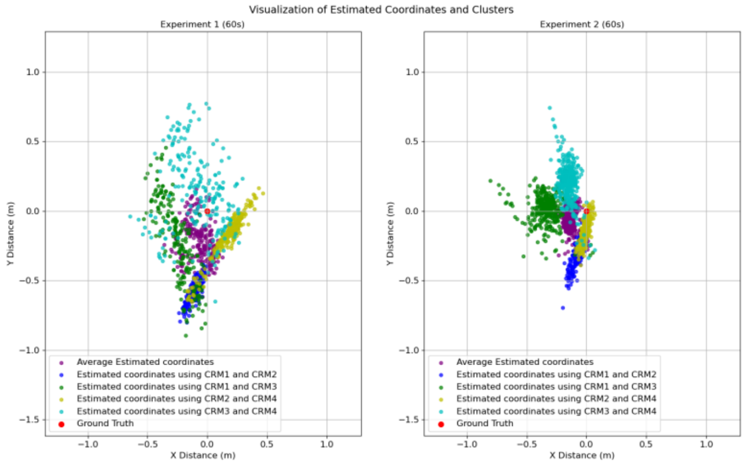
Localization Accuracy Evaluation

Static Scenario Performance and Error Analysis

- Experimental Setup:
  - Outdoor field 13.15 m × 7.5 m simulating road geometry.
  - Four anchors + one tag; two fixed points tested (8.4, 3.75) m and (4.0, 3.75) m, each 60 s.
- Distance Measurement Performance:
  - Right-skewed error distributions → most errors < 0.1 m.
  - Occasional overestimation due to signal reflection or minor interference.
- Two-Dimensional Positioning Performance:
  - Estimated positions cluster tightly around ground truth.
  - Minor lateral shift in Experiment 2 → possible calibration or environmental bias
  - Demonstrates sub-decimeter accuracy and high stability under static conditions.



Error distribution of CRM combinations in the static scenario

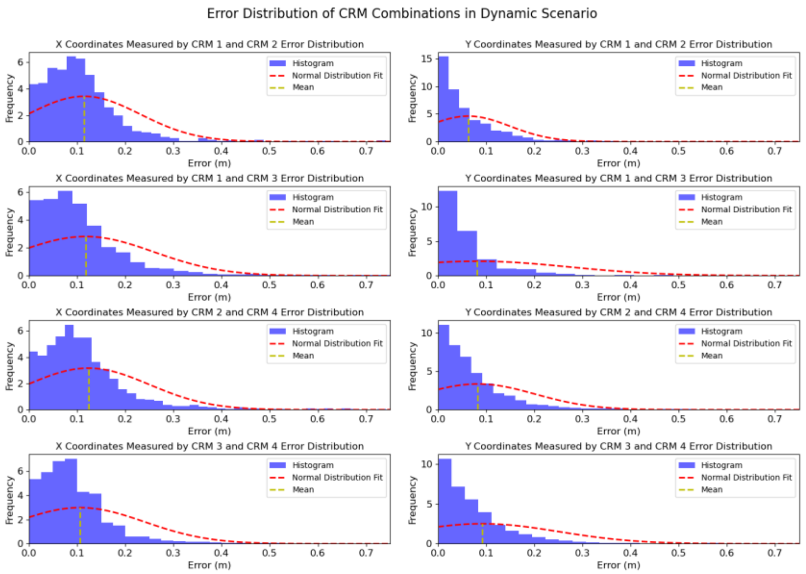


Static-scenario two-dimensional positioning clusters and ground-truth comparison.

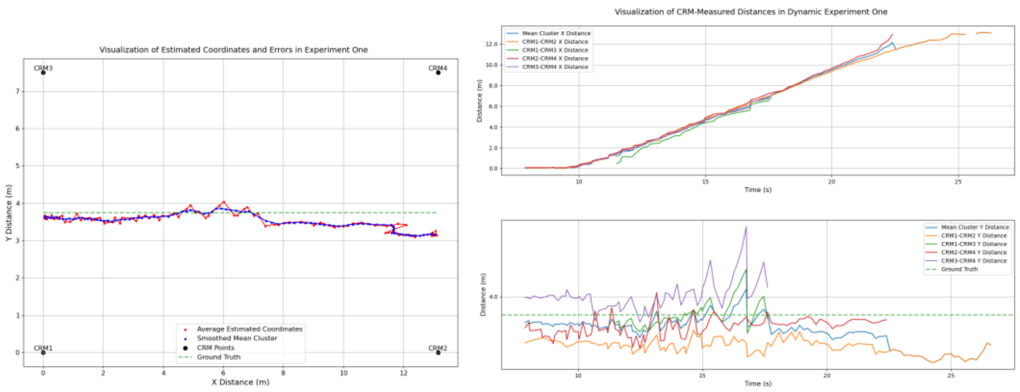
Localization Accuracy Evaluation

Dynamic Scenario Performance and Error Analysis

- Setup: Tag moved horizontally along Y = 3.75 m for 30 s at ≈ 0.48 m/s.
- Distance Error Distribution:
  - Mean error < 0.2 m in X & Y.
  - Occasional larger errors due to rapid motion or signal loss — indicates need for response-time optimization.
- Two-Dimensional Positioning:
  - Smoothed trace closely matches ground truth; deviations mainly in Y-axis.
  - Consistent X-axis tracking confirms system robustness.
  - Fluctuations suggest further refinement of signal processing and height compensation.
- Result:
  - Maintains ≈ 0.2 m average dynamic error — sufficient for real-time lane-level tracking.
  - Proves CRM robustness against short-term NLOS and motion disturbances.



Error distribution of CRM combinations in the dynamic scenario



Estimated moving trace in Dynamic Experiment

Simulation and Evaluation

Data simulation purpose

- **UWB data issues: UWB (Ultra-Wideband)** provides centimeter-level ranging but suffers from NLOS, multipath, and interference, which is relevantly **rare** in real data but highly influence the performance of estimation algorithm.

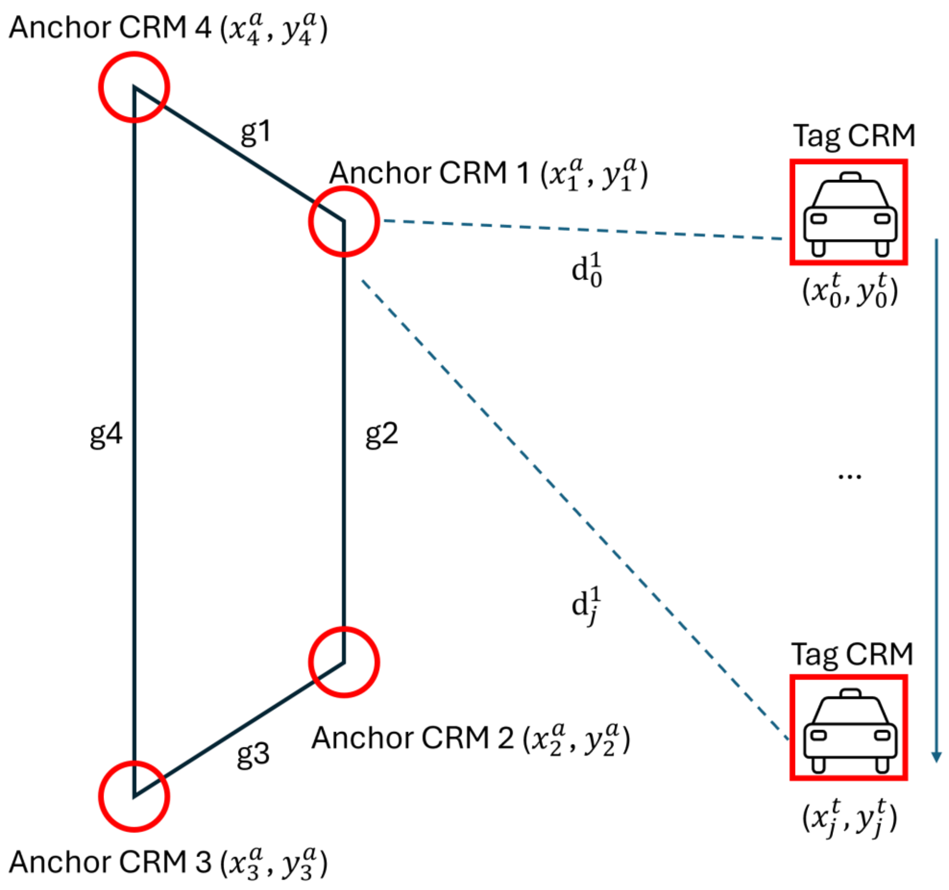
↓

- Simulated scenarios can help to test and improve the algorithm's performance and robustness in these complex situation.

Simulation and Evaluation

Simulation settings

- **Environment setup:**
  - Modeled an urban work-zone segment of **≈ 100 m × 200 m**.
  - **Four UWB anchors** placed at different positions to emulate varied work-zone geometries.
  - A **single UWB tag** represents a moving *worker* or *vehicle*.
- **Tag motion:**
  - Path combines **linear** and random movement for realistic motion.
  - Motion discretized into **T = 100 time steps** (≈ 10 s at 10 Hz update rate).

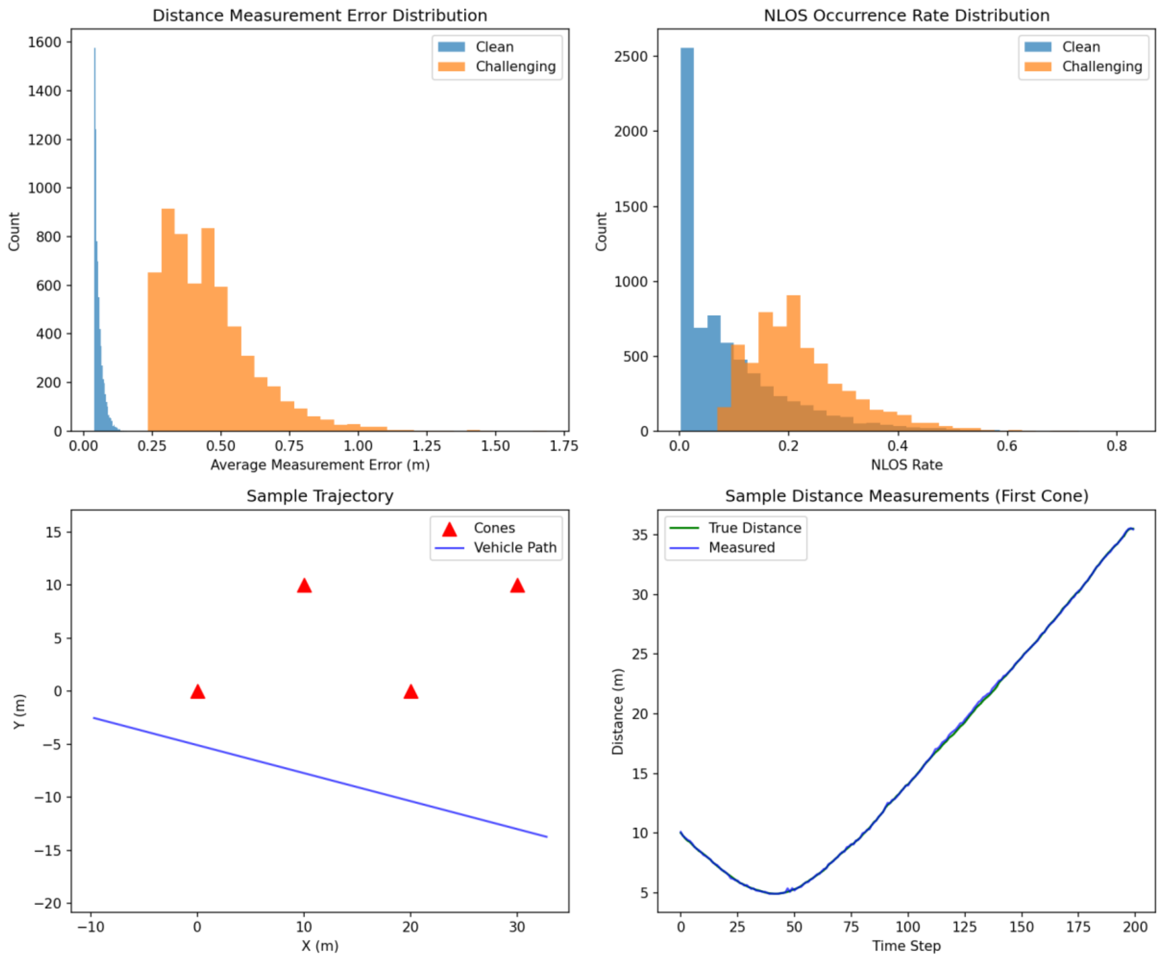


Simulation scenario illustration

Simulation and Evaluation

Simulation settings

- **Scenario design:**
  - **Measurement difficulty:** two scenario groups — *Clean* vs. *Challenging* .
  - **Work-zone shapes:** multiple realistic geometric configurations.
  - **Tag trajectories:** varied **initial speeds, directions, and accelerations**).
- **Measurement noise & outliers:**
  - Added **zero-mean Gaussian noise** to emulate normal UWB measurement uncertainty.
  - Introduced **sporadic NLOS outliers** (single-step large errors)to mimic signal blockage events.
  - Algorithms received **no prior knowledge** of outlier occurrences.



Statistical overview of the Clean and challenging scenarios simulated

Simulation and Evaluation

Algorithms

- Our method
  - **Encoder Q:** N distances → 128-Dimension embedding.
  - **Encoder K:** help with self-supervised process
  - **Predictor:** predicts next-step embedding from past K context(optimal K ≈ 3).
  - **Decoder:** reconstructs distances, denoising NLOS outliers.
- The pretrain phase help to understand the predictive potential structures, that is, **stable patterns of UWB ranging over time**. Train phase help to **recover clean distance values from stable embeddings.**

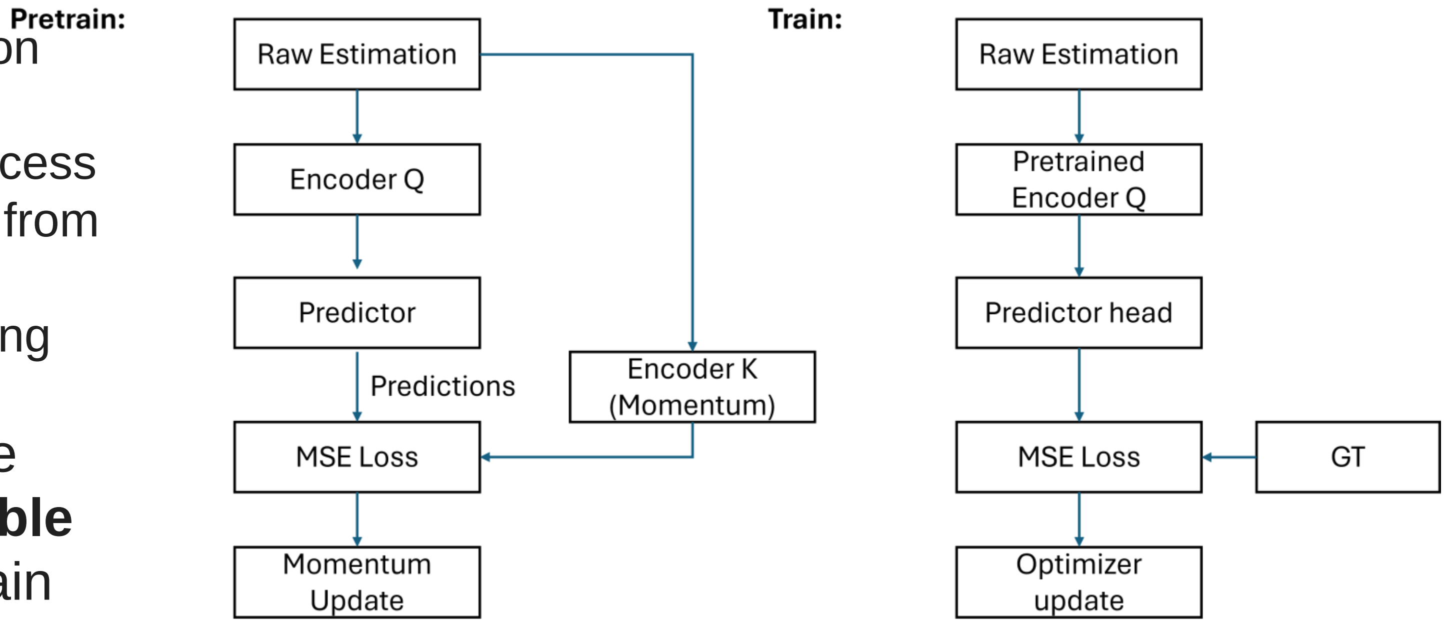
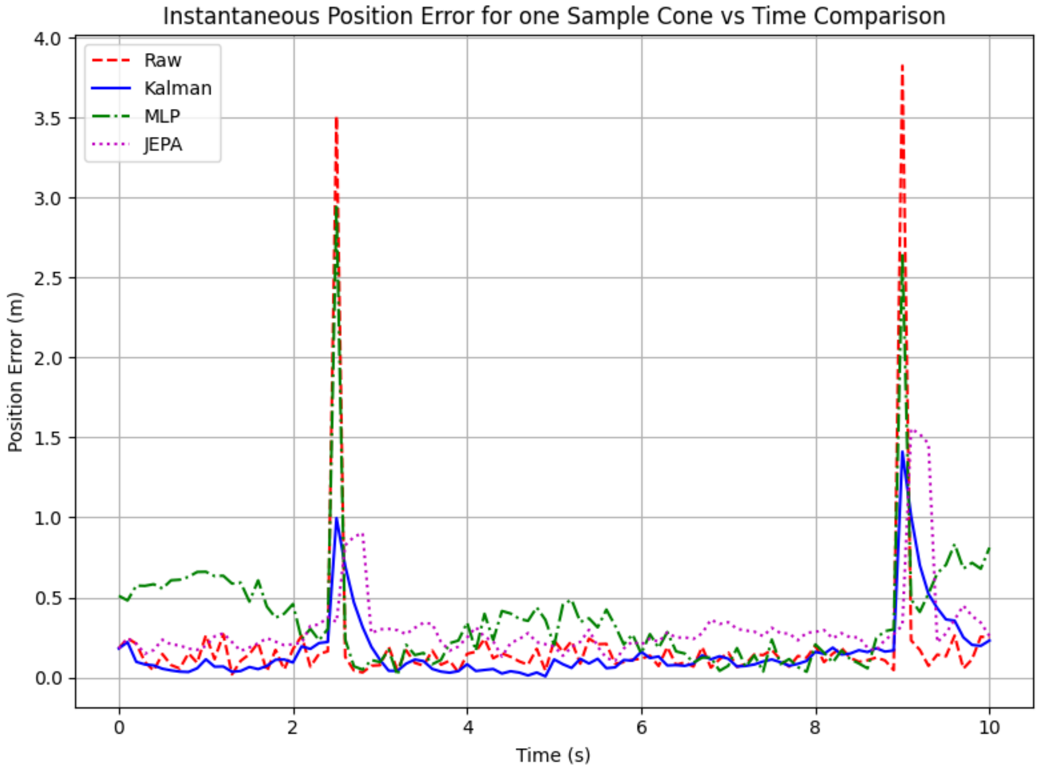


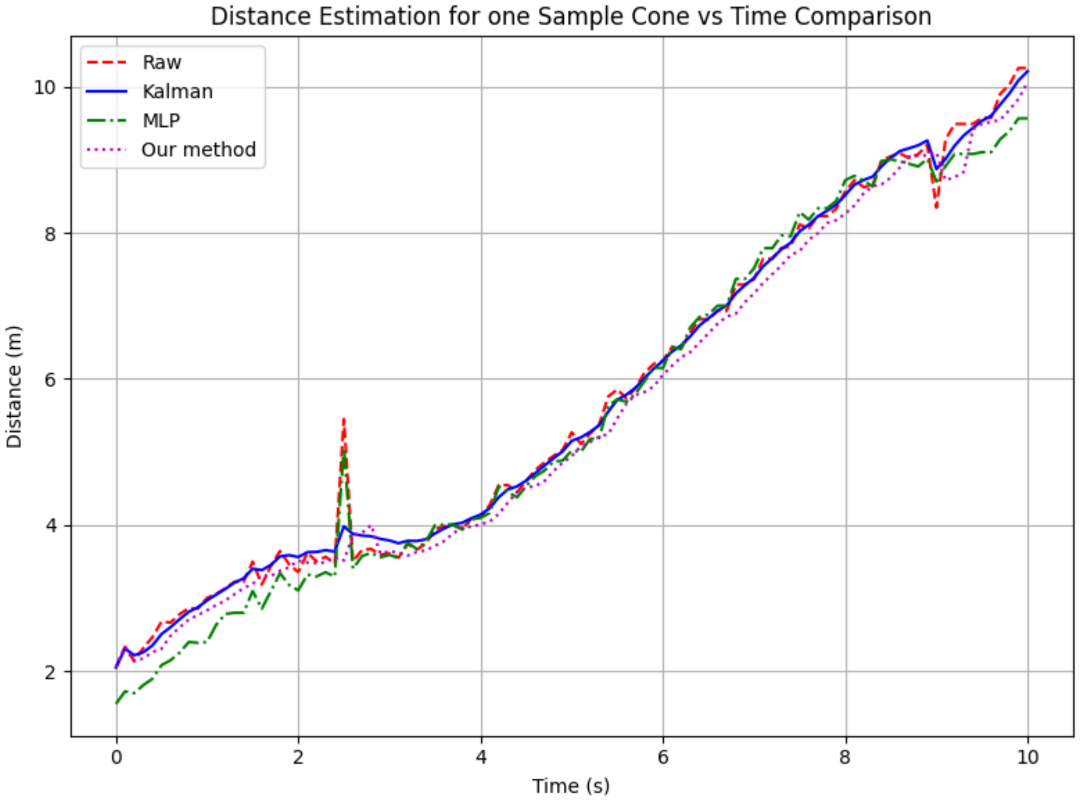
Illustration of our method

Simulation and Evaluation

Results



Position Error Comparison



Distance Error Comparison

LLM-Based WZDx

Problem Formulation and Framework

- **Objective**: Transform heterogeneous inputs into **high-fidelity** outputs for **autonomous driving navigation**
- **Five Input Components:**
  - (i) Vehicle **travel direction** D (e.g., northbound, westbound)
  - (ii) **Natural-language** WZDx closure description T
  - (iii) Structured lane list L indicating **status of each lane**
  - (iv) Official **polyline sketch** P outlining work zone
  - (v) CRM-derived cone/barrel **coordinates** C defining physical barricade geometry
- **Desired Outputs:**
  - Concise, interpretable **navigation instruction** summarizing lane usage and constraints
  - List of **recommended lanes** L safe identified as open and drivable
  - **Refined polyline** $\tilde{P}$ following centerline of open corridor with safe clearance from cones

LLM-Based WZDx

LLM Prompt Template Design

- **LLM Reasoning Tasks:**
  - Interpret WZDx policy language and validate consistency with CRM-observed cone layouts
- **Output refined geometric corridor** correcting offsets and aligning with traffic direction
- Identify intended closed and open lanes from WZDx text and structured lane metadata
- Align physical cone coordinates into trapezoidal work zone footprint
- **Generate centerline polyline** within declared open lanes
- Ensure refined polyline respects direction of travel and sampling intervals for AV planners
- **Data Encoding Format:**
  - **Cone and polyline coordinates** encoded in GeoJSON-style structures
  - **Textual** inputs follow WZDx standard
  - Consistent structure and format across all scenarios
  - **Single instruction** format encapsulating spatial, semantic, and rule-based reasoning

LLM Prompt Template

System Instruction:
You are a navigation assistant for autonomous vehicles operating in highway work zones. Given the structured inputs below, generate:

1. **Navigation Instructions**: a concise, human-readable summary describing which lanes to use, which to avoid, and any safety-critical constraints;
2. **Recommended Lanes**: a list of indices from the lane list indicating the open lanes safe for travel;
3. **Refined Polyline Coordinates**: a GeoJSON `LineString` that
   - connects the first and last cone pairs that bound the work-zone limits (upstream to downstream);
   - follows the vehicle's driving direction;
   - sits on the *longitudinal centre-line* of the travelled way—i.e. halfway between the left and right cone rows that form the trapezoidal work-zone footprint;
   - remains entirely within the open general-purpose lane(s);
   - uses the declared *number of lanes* and a nominal *lane-width* of 3.6 meters (around 0.000045 degree) to infer the correct centre offset when cones appear on only one side;
   - is smooth (no sharp jogs) and sampled roughly every 15–25 meters (0.00013–0.00022 degree) so downstream CAV/AV systems can interpolate reliably.

Important Note:
The `Polyline Coordinates` supplied in the input are only a *rough offset sketch* of the work-zone location and often sit beside the actual roadway alignment. Do **not** copy them verbatim. Instead, treat the `Cone/Barrel Coordinates` as CRM markers that bound a trapezoidal work-zone area and derive the **Refined Polyline Coordinates** as the centre-line of that trapezoid.

Input:

- **Direction** (D):
  A string indicating the vehicle's travel heading (e.g., "northbound", "westbound"), used to orient the inferred centerline.
- **WZDx Description** (T):
  A natural language lane closure description, specifying road segment, affected lanes, and temporal validity.
- **Structured Lane List** (L):

```
[
  {"order": i, "type": "shoulder"|"general", "status": "
     open"|"closed"}
]
```

- **Polyline Coordinates** (P):

```
{
  "type": "LineString",
  "coordinates": [ ... ]
}
```

- **Cone/Barrel Coordinates** (C):

```
[
  [lon_1, lat_1],
  [lon_2, lat_2],
  ...
]
```

LLM Prompt Template

LLM-Based WZDx

Experiment Setup and Data Sources

- **CRM Data:**
  - Derived from simulated **UWB measurements** with centimeter-level accuracy assumption;
  - Simulated coordinates placed precisely along known geometric alignments
  - Represents ground truth layout of physical work zones
  - Isolates **LLM reasoning capability** under idealized, high-fidelity spatial conditions
- **WZDx Scenarios:**
  - **Real WZDx feeds** sourced from **Wisconsin DOT public API**;
  - Two representative work zone configurations selected to test robustness
  - **Case 1:** Trapezoidal work zone with right-lane closure on state highway
  - **Case 2:** Curved segment with lateral cone offsets and multi-lane closure on interstate
- **Validation Method:**
  - Assess **LLM reliability** in interpreting lane closure intent;
  - Verify semantic-to-geometric alignment **accuracy**;
  - Evaluate **refined** centerline spatial accuracy and semantic validity;

LLM-Based WZDx

Case Study 1: Trapezoidal Work

- **Location**: State Highway 113 Northbound, COUNTY M WB to KENNEDY DR
- **Work Zone Configuration:**
  - Standard trapezoidal footprint with consistent lateral offset and longitudinal spacing
  - **Right-lane closure** on northbound highway segment
  - **Lane Status:** : Lane 1 (shoulder) open; Lane 2 (general) open; Lane 3 (general) closed; Lane 4 (shoulder) closed;
  - CRM-Derived Cone Coordinates: **8 anchor positions** precisely locating work zone boundary
- **LLM Output - Navigation Instructions:**
  - "Merge safely into Lane 2 before taper. Stay in that lane through work zone, keeping cone wall on your right. Proceed at reduced speed and watch for workers."
  - Recommended Lanes: [2]
  - **Refined Polyline**: Generated from CRM coordinates, replacing WZDx sketch
  - Key Finding: LLM correctly interprets closure semantics and produces centerline polyline aligned with both infrastructure constraints and policy declarations.

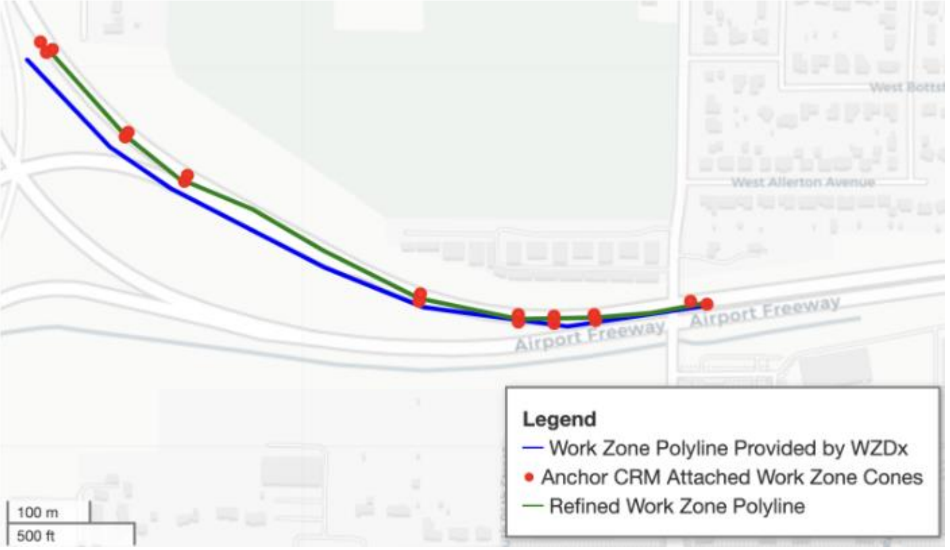
CRM-enhanced refinement of a WZDx right-lane closure: overview map.

CRM-enhanced refinement of a WZDx right-lane closure: zoomed map.

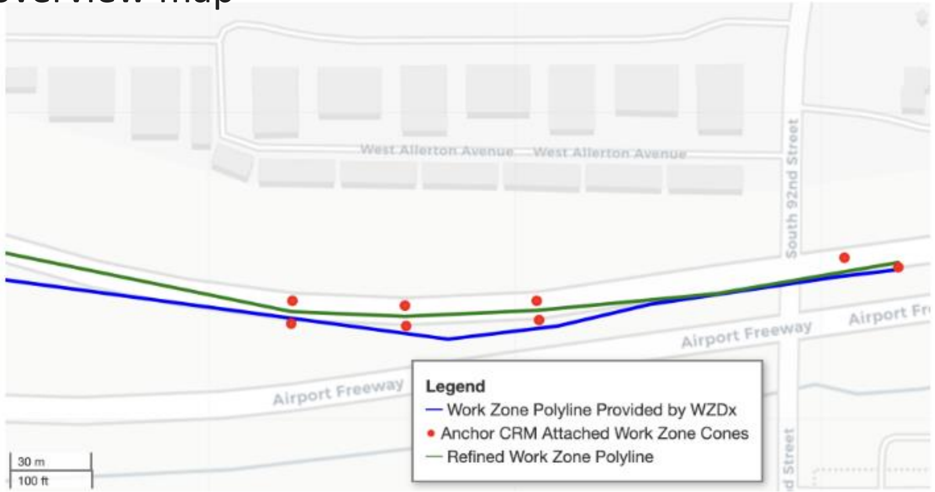
LLM-Based WZDx

Case Study 2: Complex Curved Work Zone

- **Location**: Interstate 41 Northbound, S 92ND ST to US 45 NB
- **Work Zone Configuration:**
  - **Curved segment with moderate curvature** and lateral cone offsets;
  - Multi-lane closure: Lanes 2, 3, 4 (general purpose) and Lane 1 (shoulder) closed;
  - Only Lane 5 (rightmost general purpose) remains open;
  - CRM-Derived Cone Coordinates: 16 anchor positions tracing outer boundary
- **LLM Output - Navigation Instructions:**
  - "Three left general-purpose lanes and left shoulder are closed. Travel exclusively in Lane 5, the rightmost open lane. Maintain clearance from cones/barrels marking work zone boundaries."
  - Recommended Lanes: [5]
  - Refined Polyline: Tracks longitudinal center of open lane with smoothed curvature
  - Key Finding: LLM **successfully interprets complex multi-lane closure semantics** and **generates refined polyline** aligning with actual lane geometry



CRM-enhanced refinement of a curved multi-lane closure: overview map



CRM-enhanced refinement of a curved multi-lane closure: zoomed map.

Conclusion

- **Problem & Approach:**
  - Safety/reliability gaps in complex ODDs motivate an equity-oriented, infrastructure-based CDA path. We prototype a **low-cost Connected Reference Marker (CRM)** roadside system to accelerate “critical mass” deployment by providing real-time ranging and high-resolution work-zone geometry for AV navigation.
- **What We Built & Learned:**
  - A low-cost roadside device network supporting CAV localization is developed. A simulation and evaluation pipeline of the algorithm within CRM system is developed. A LLM pipeline aligns CRM geometry with WZDx semantics is developed. Experiments show **sub-decimeter static** and **<0.2 m dynamic** accuracy, demonstrating practical, scalable localization.
- **Impact & Next Steps:**
  - CRM can enrich digital infrastructure (RDI) and enable reproducible, interoperable work-zone data for CDA—supporting safer paths and better planning. Next phases prioritize field deployments, end-to-end WZDx integration, and broader corridor evaluations.

Thank you!

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