Multi-Sensor Fusion for Intelligent Transportation: A Robust Framework for Digital Infrastructure Deployment

MASITE 2025

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CENTER OF EXCELLENCE
on New Mobility and Automated Vehicles

Background

- **AVs are the space race of this generation** –
  - Vast private capital on developing CAVs, but …
  - Most technology is behind corporate firewalls
- Less attention on advances in smart, connected transportation infrastructure – **Infrastructure Perception & Control** (IPC)

  - 300,000 signalized intersections in the US vs 300M vehicle

  – *half of all crashes and excess fuel expended are at intersections**
  - Smart infrastructure could save lives, time and increase efficiency in the *near-term, & enable next generations automated public mobility.*

Challenge:

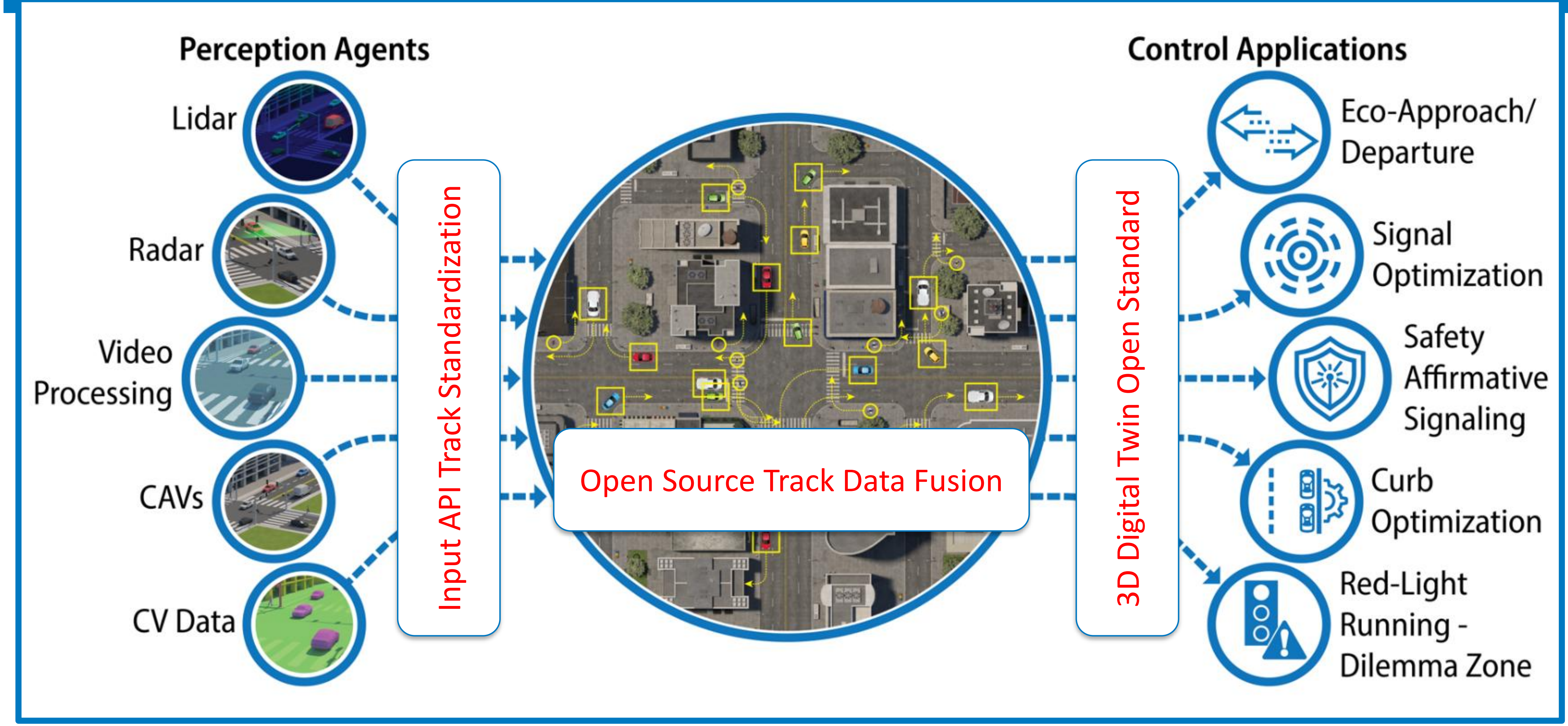
Create an open-source framework for infrastructure intelligence that is scalable, sustainable, resilient, highly-accurate ….. and affordable

https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0137477

Challenges and Goal

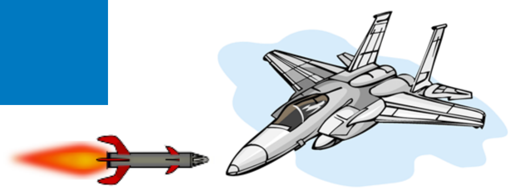
- **Problems to address:**
    - **Lack of full state-space awareness of all moving objects**
    - **Lack of confidence and reliability of state-space model**
  - Most research in this area is siloed and proprietary.
- **Goal: Develop IPC replicable to any infrastructure application to quantified levels of accuracy and confidence**
  - Fuse multi-modal sensor data to achieve quantifiably accuracy of state-space awareness (using AI, ML, and classical techniques)
  - Develop open-source mathematical framework for confidence/reliability, self-calibration/validation/health monitoring
  - Define open-source, normalized interfaces for 3D object tracks

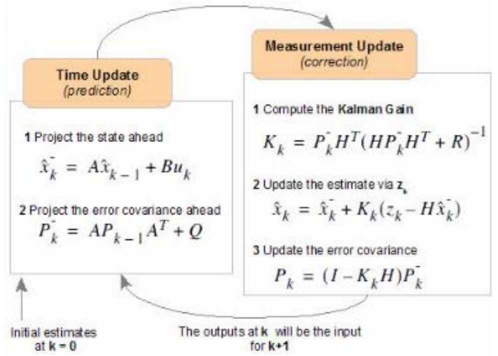
Infrastructure Perception and Control Framework



Data → **Information** → **Control**

Sensor Fusion – State Space Estimation





- Two camps:
  - Classical: Underlying formulation in terms of Bayesian inference. "Current belief about system state + New data = Statistically optimal new belief about system state"

    Full state-space – but not scalable

  - Modern: Based on modern AI, esp. deep neural networks. "Given available sensors, design a deep network that combines them (somehow), and train it on millions of labelled examples."

    Scalable – but not full state-space
- IPC goal is to combine, hybridize

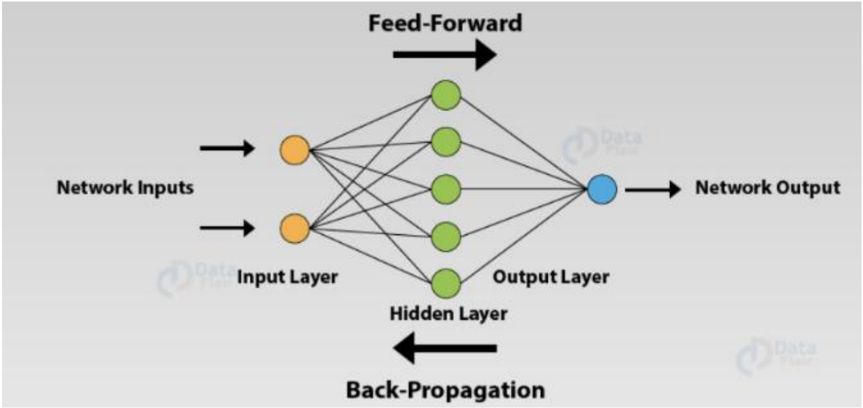
State = Process Model + Process Error

Observation = Measurement Model + Measurement Error

Objectives:

- Infer parameters by minimizing error
- Apply control to optimize system performance

+



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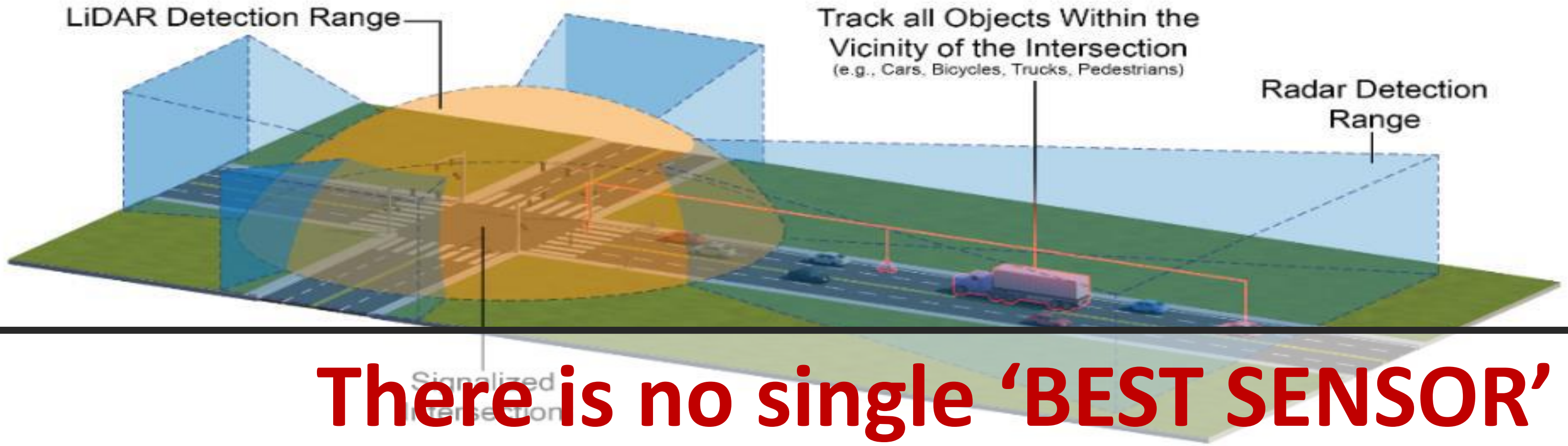
NREL Infrastructure Perception

Objective/Hypothesis

A lack of highly reliable, full state-space awareness of roadway situations is the current bottleneck for the incremental introduction of smart infrastructure control.



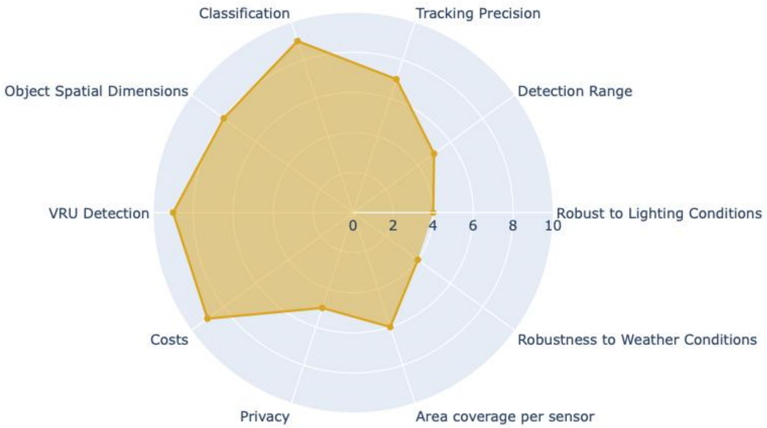
There is no single 'BEST SENSOR'

1. Lack of state space awareness of the surrounding traffic situation inhibits any kind of intelligent **mission-critical or safety-critical** infrastructure control today
2. Current attempts are fragmented, not integrated, and largely proprietary.
3. Sensor technology (radar, LiDAR, and video imaging) is maturing rapidly.
4. Objective: Develop and share open framework for processing and messaging of state-space of all objects to accelerate benefits of Infrastructure Perception and Control (IPC) integrated with CAVs, saving lives and energy.

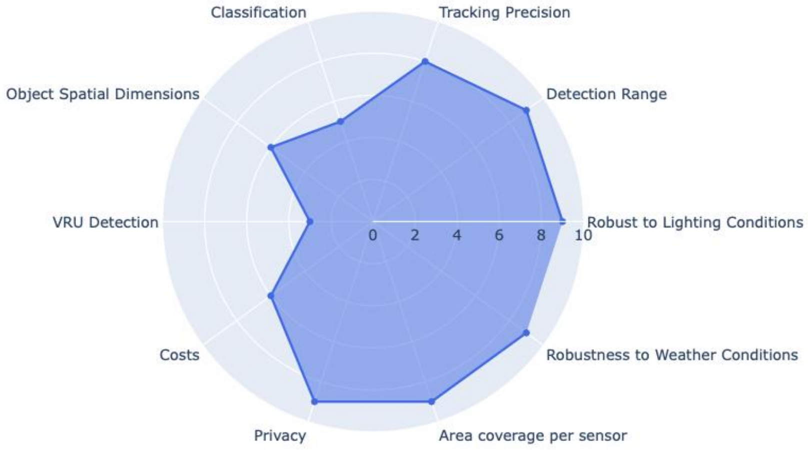
Comparing Camera, Radar, and Lidar

Radar
LiDAR
Camera

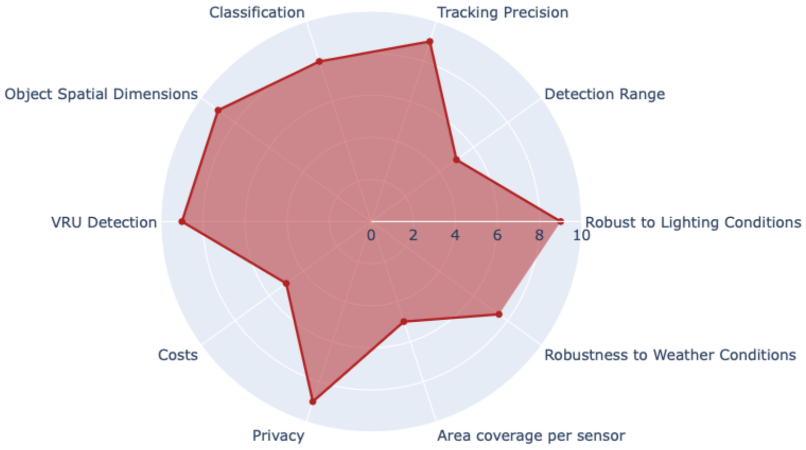
Camera



Radar



Lidar

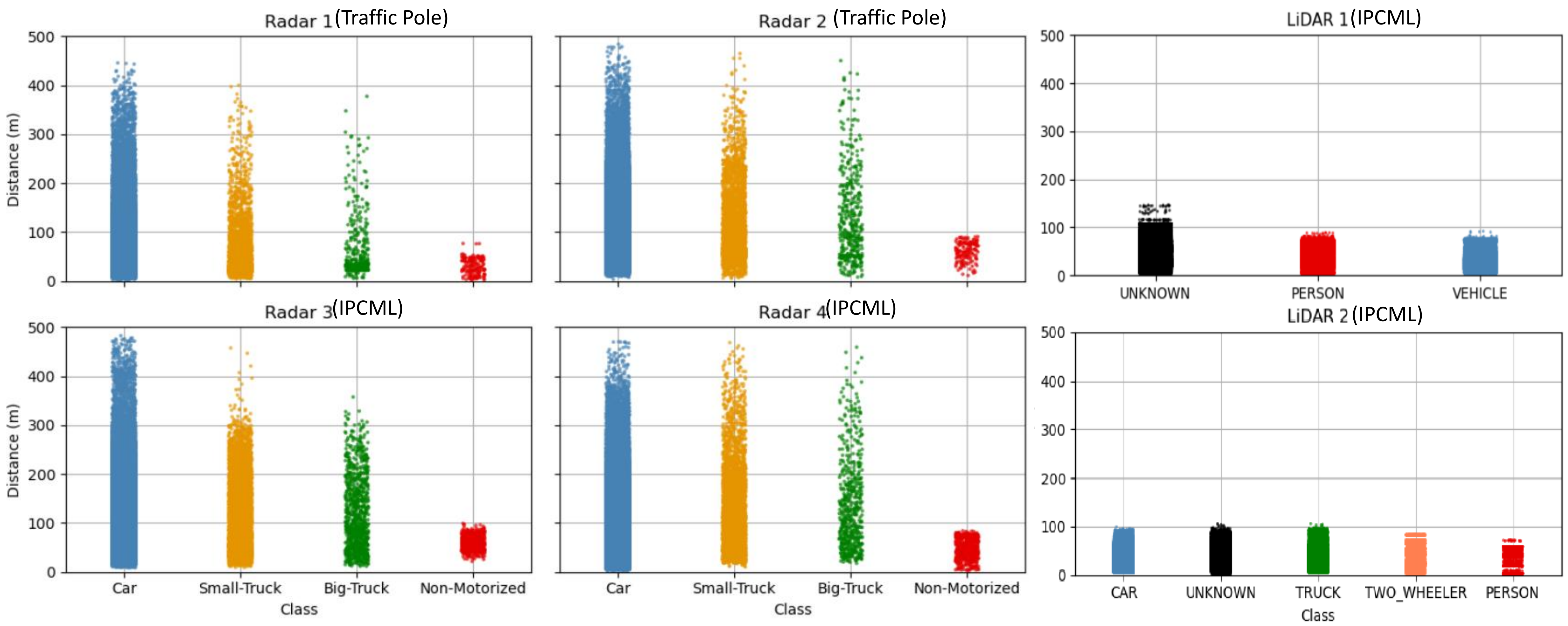


- Strong object classification with color and feature detection.
- Good vulnerable road user detection.
- Detection and tracking depends on algorithms used.

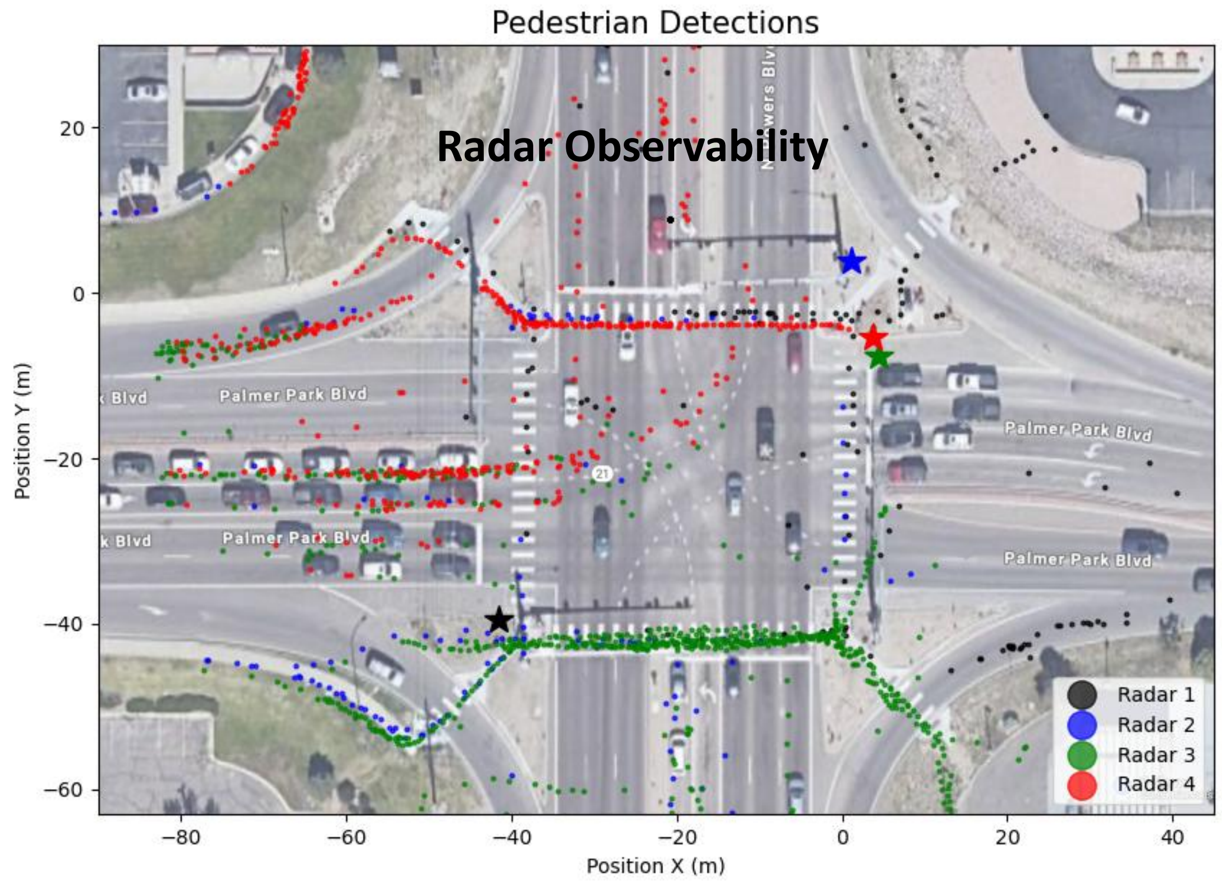
- Superior detection range.
- Robust to fog, rain, and low light.
- High coverage per sensor.
- Poor vulnerable road user detection.

- Strong object classification.
- Able to output accurate special object dimensions.
- Able to detect vulnerable road users.
- Low detection range.

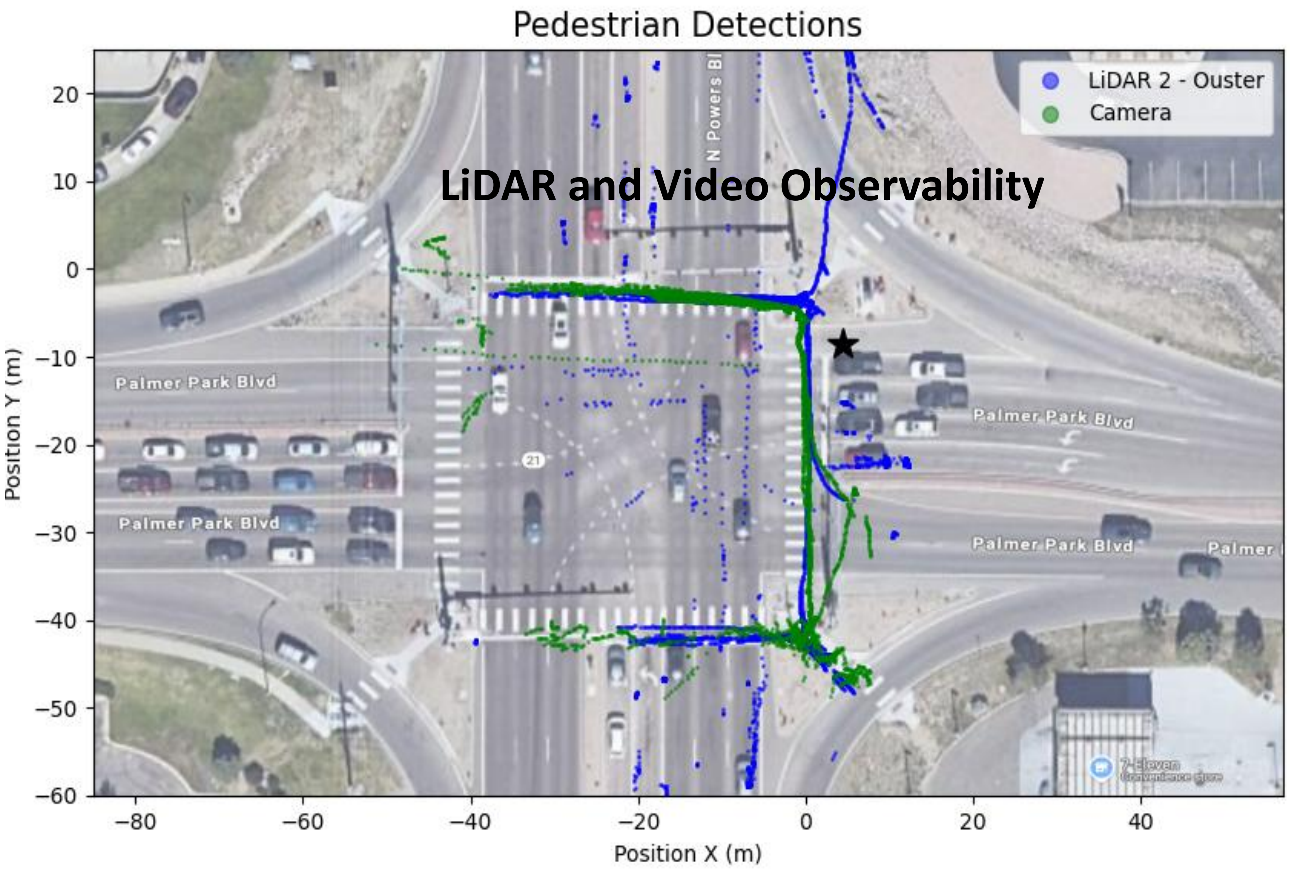
Testing and Verifying Sensor Range



Bike and Pedestrian Detection

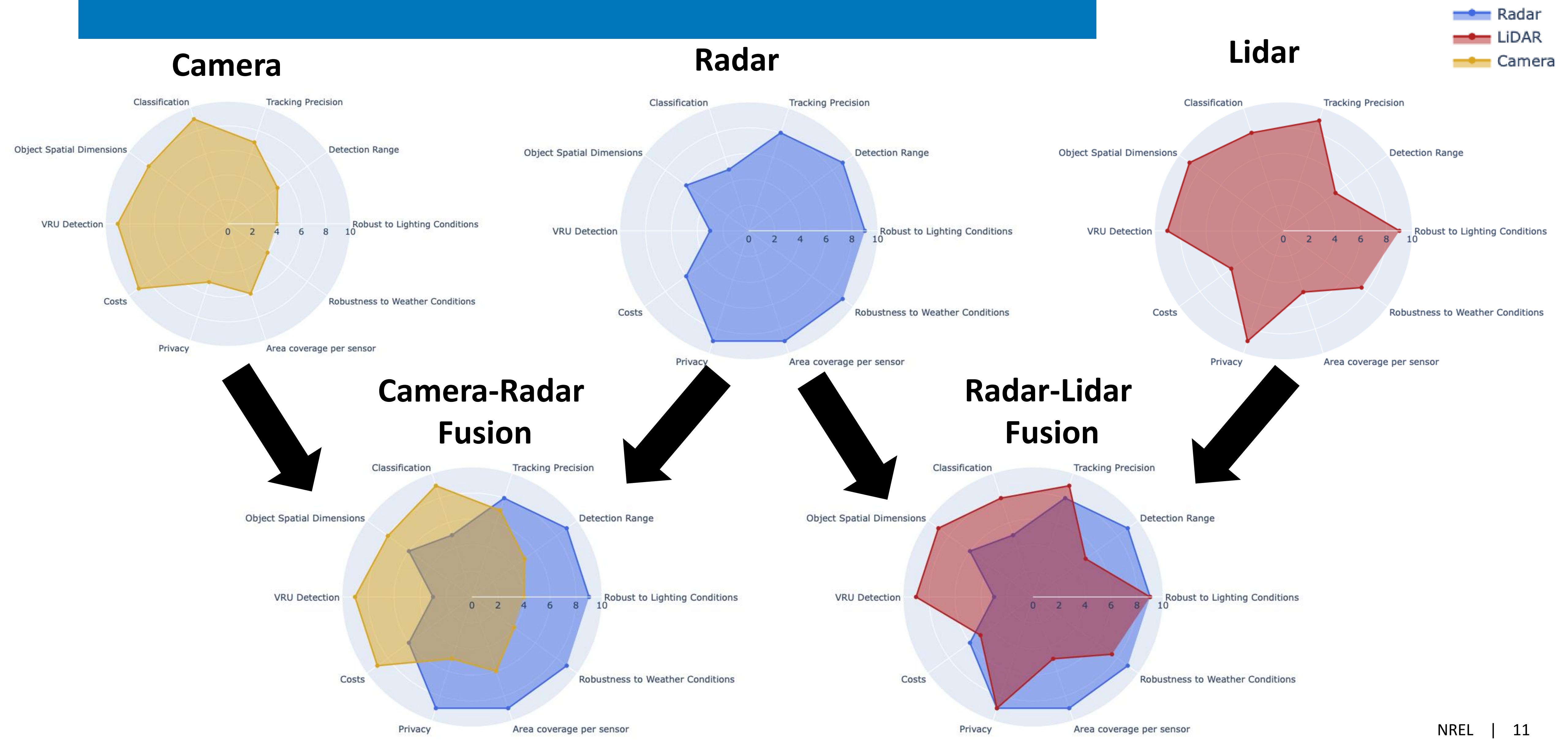


More bike and pedestrian tracks observed in Radars 3 and 4 due to higher elevation angle (pointed towards intersection) and a lot of incorrect detections

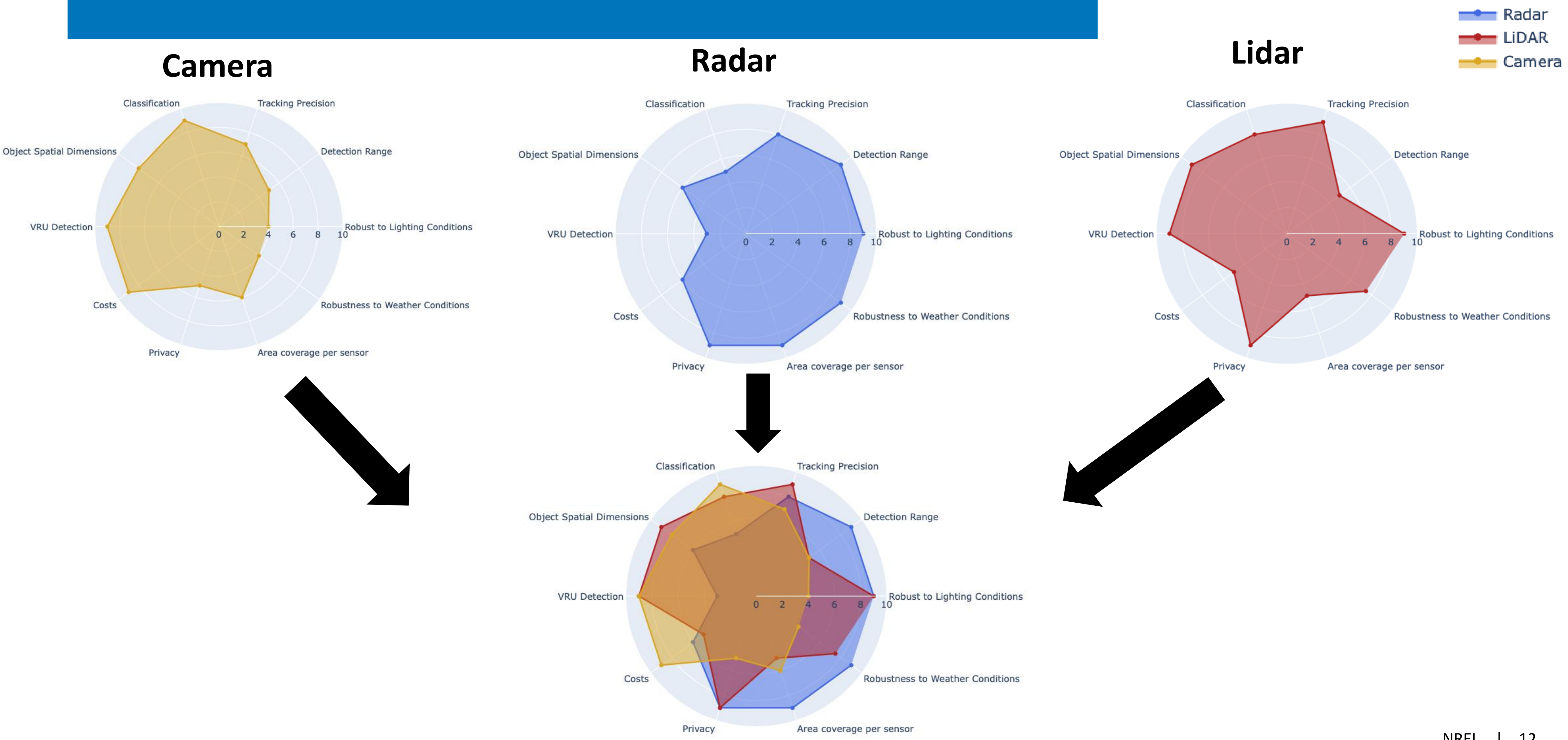


Fewer false positives observed for bike/ped traffic; placing diagonally opposite pole would provide full intersection coverage

Multi-Sensor Fusion



Multi-Sensor Fusion



Camera-Radar-Lidar Fusion

Key Takeaways

- **Sensor data fusion is critical.**
  - No single sensor is reliable in all conditions.
- **Accurate time and spatial synchronization is essential.**
  - Sensors have different latencies, update rates, and fields of view.
  - Use periodic GPS time-stamping and accurate calibration to avoid drift.
- **Standardization and interoperability are critical.**
  - Sensors from different vendors use different data formats and protocols.
- **No such thing as a 'silver bullet' sensor**

ONE sensor tells a story—many tell the TRUTH!

N Nevada Ave & E Platte Ave, Colorado Springs, CO, USA

N Nevada Ave &
E Platte Ave,
Colorado Springs,
CO, USA

Nov 22, 2024

N Nevada Ave & E Platte Ave, Colorado Springs, CO, USA

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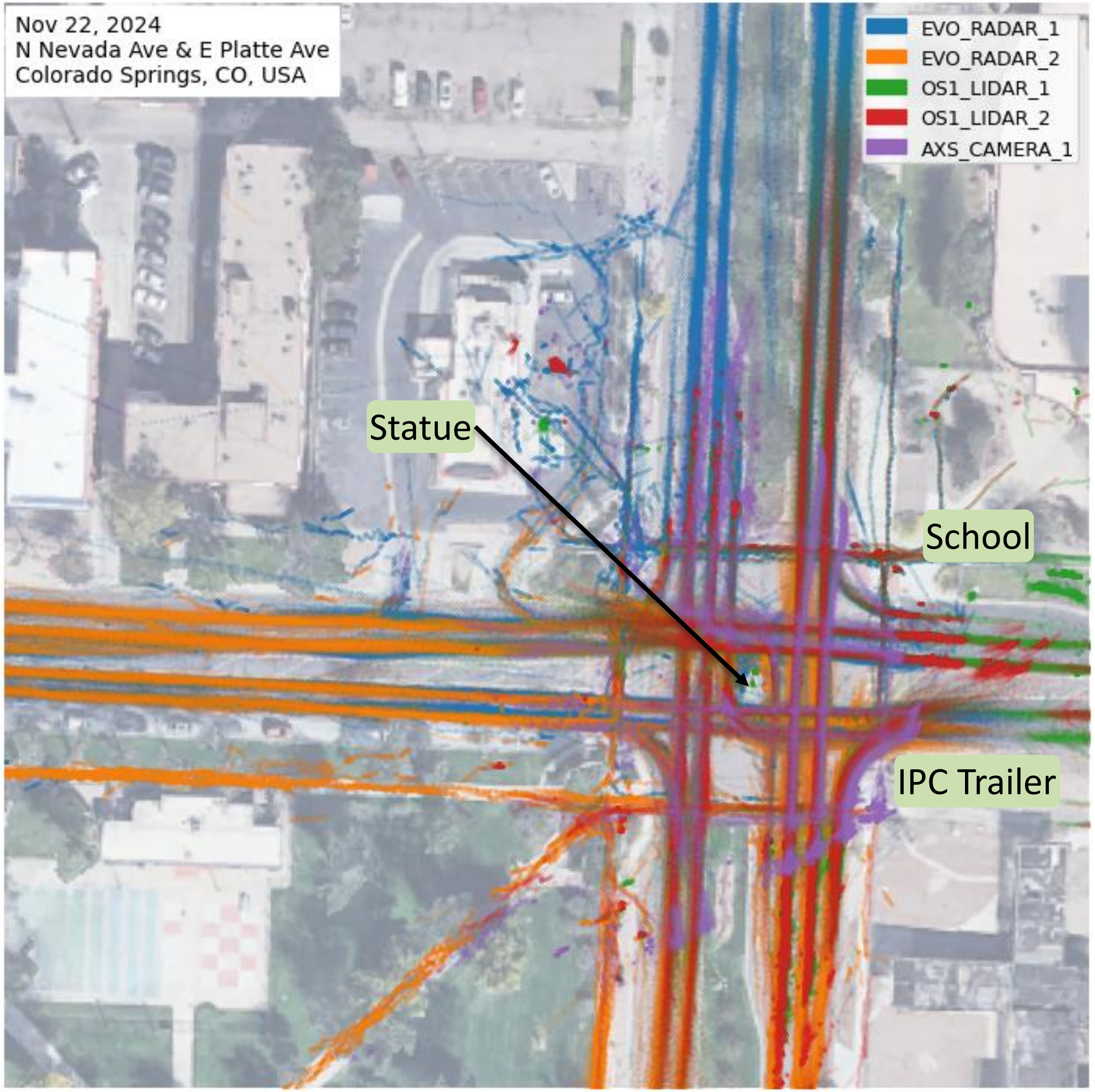


Field Data: Sensor Fusion

Real World Public Partners

Colorado Springs operates over 600 intersections.

- IPC Lab has the same traffic cabinet and associated devices
- NREL IPC Supports the CS SMART Grant

Track Testing CAV Technologies with AR

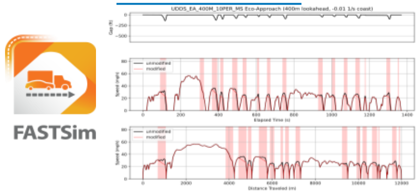
optional

Powertrain simulation model(s)

Data from previous testing

Previous analysis estimating real-world energy impacts

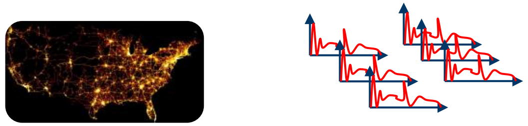
FASTSim + CAVs



Outcomes

- Estimated energy impacts by technology and driving condition
- A weighting scheme to combine impacts by driving condition
- Estimated national-scale impacts energy savings potential

Nationally representative drive cycles



KPI Pipeline

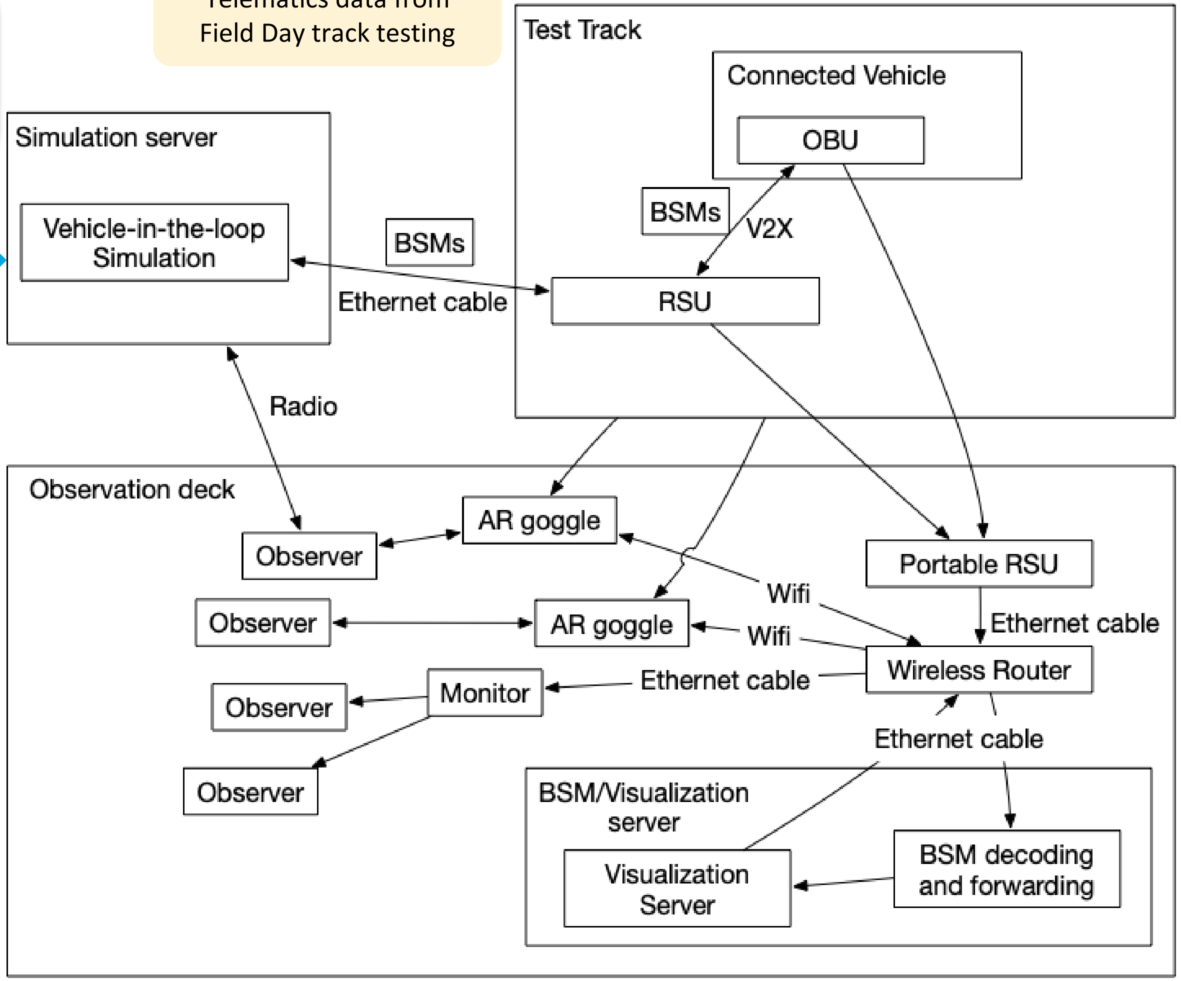
Sample VTD Drive Cycles

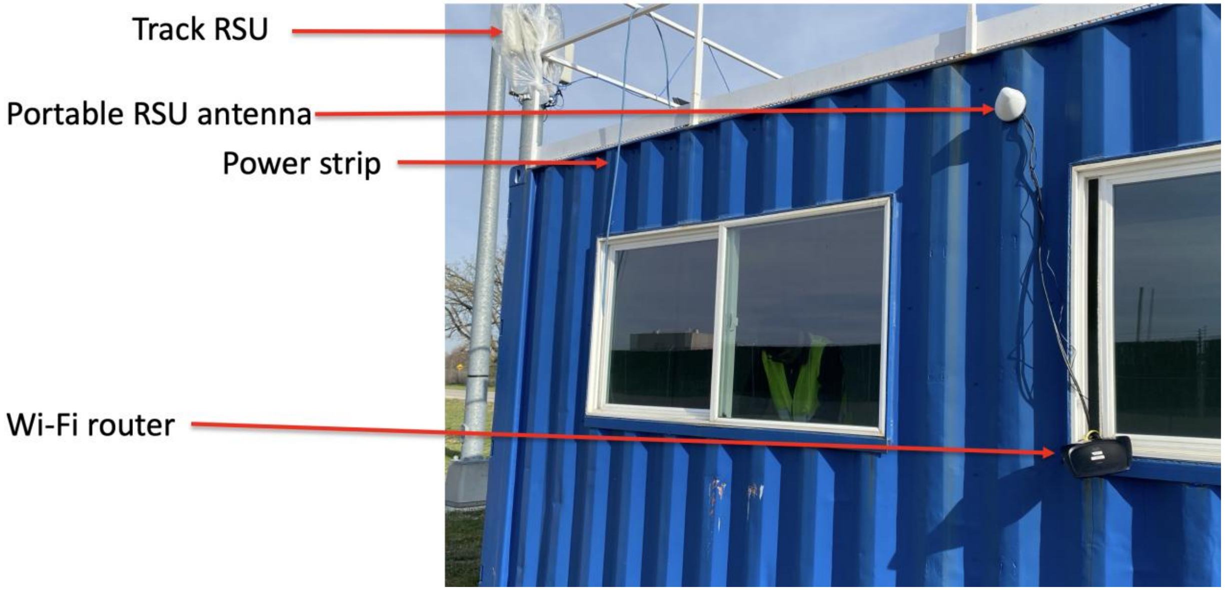
KPI Statistical Analysis and KNN Clustering

Adjustment of VTD Configuration informed by real-world drive cycles and KPI metrics

Calibration

Telematics data from Field Day track testing






Scott
SHOP

Take-Aways

Real World Deployments:

- **Multiple Sensors will be needed for robustness and fail-safe**
- **Automated procedures for calibration and validation are needed**
- **Sensor data interfaces need to be standardized**
- **Data from multiple sensors need to be fused with confidence measures**
- **Digital twin accuracy and fidelity known in real-time at all time, to drive multiple applications**
- **Infrastructure data needs Connected Vehicle data, and vice-versa**
- **Justified by business cases supported**
- **Augmented Reality integrated into a CV deployment provides observation into the digital world**

Into the future:

- Edge, real-time deployment of IPC Fusion software
- Enable multiple downstream applications
- Full integration of V2X data

Infrastructure Perception and Control Multi-Sensor Object Tracking Dataset (IPC-MSOT)

Processed and transformed sensor data collected across multiple days.

Publicly available at data.nrel.gov/submissions/287

F. MIR, R. SANDHU, S. YOUNG, Q. WANG, D. SINES and Z. SOSA, "Descriptor: Infrastructure Perception and Control: Multi-Sensor Object Tracking Dataset (IPC-MSOT)," in *IEEE Data Descriptions*,
doi: 10.1109/IEEEDATA.2025.3601080

NREL Data Catalog

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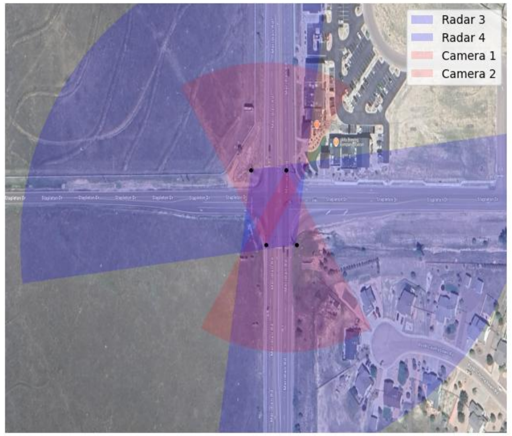
Multi-Sensor Object Detection Data from Infrastructure Sensors Deployed at Traffic Intersections in the City of Colorado Springs, Colorado, USA

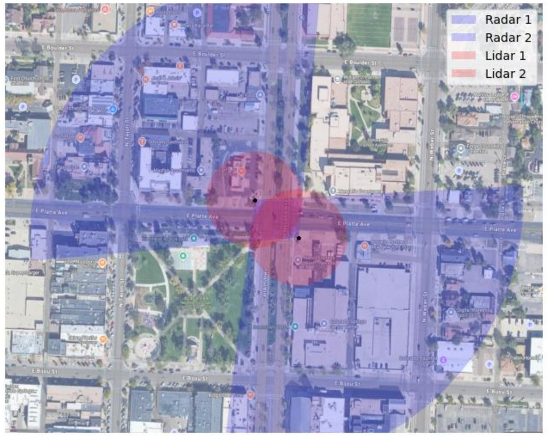
The dataset provided here was collected as a part of the US Department of Transportation (USDOT) Strengthening Mobility and Revolutionizing Transportation (SMART) project, where the City of Colorado Springs (Colorado, USA) and National Renewable Energy Laboratory (NREL) collaborated to collect object-level trajectory data from road users using multiple types of infrastructure sensors deployed at different traffic intersections. The data was collected in 2024 across multiple days at various intersections in and around the City of Colorado Springs. The goal of the data collection exercises was to learn various attributes about infrastructure sensors and to build a repository of high resolution object-level data that can be used for research and development (such as for developing multi-sensor data fusion algorithms).

Data presented here was collected from sensors either installed either on the traffic poles or hoisted on top of NREL's Infrastructure Perception and Control (IPC) mobile trailer. The state-of-the-art IPC trailer can deploy the latest generation of perception sensors at traffic intersections and capture real-time road user data. Sensors used for data collection include Econolite's EVO RADAR units, Ouster's OS1 LIDAR units and Axis Camera units. The raw data received from individual sensors is processed at the edge compute device located inside the IPC mobile Lab, and the resulting object-level data is then stored and processed offline. Each data folder contains all the data collected on the day. We have transformed (rotation then translation) the raw detections to ensure the data from all sensors is represented in the same cartesian coordinate system. The object list attributes impacted from the transformation are PositionX, PositionY, SpeedX, SpeedY and HeadingDeg. The rest of the data attribute remains untouched. Users should note that we do not claim that this transformation is perfect and there may be some misalignment among the different sensors.

N. Powers Blvd. and Palmer Park Blvd., Colorado Springs, Colorado



Stapleton Dr. and Meridian Dr., El Paso County, Colorado



N. Nevada Ave. and E. Platte Ave., Colorado Springs, Colorado

Published Papers

1. Stanley E. Young, Erik A. Bensen, Lei Zhu, Christopher Day, J. Sam Lott, Rimple Sandhu, Charles Tripp, and Peter Graf. Concept of Operations of Next-Generation Traffic Control Utilizing Infrastructure-Based Cooperative Perception, pages 93–104. American Society of Civil Engineers, 2022. doi: 10.1061/9780784484326.010. URL: https://ascelibrary.org/doi/abs/10.1061/9780784484326.010.
2. F. Mir, S. Young, R. Sandhu and Q. Wang, "Spatiotemporal Automatic Calibration of Infrastructure Lidar, Radar, and Camera with a Global Navigation Satellite System," 2024 IEEE 27th International Conference on Intelligent Transportation Systems (ITSC), Edmonton, AB, Canada, 2024, pp. 28-33, doi: 10.1109/ITSC58415.2024.10920024. https://ieeexplore.ieee.org/document/10920024
3. Mir, Faizan, Stanley Young, Rimple Sandhu, Qichao Wang, Charles Tripp, and Todd Osborn. 2024. *Infrastructure-Based Cooperative Perception at a Traffic Intersection: Overview and Challenges: Preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5400-92133. https://www.nrel.gov/docs/fy25osti/92133.pdf
4. Mir, F., Young, S., Sandhu, R., Wang, Q., Tripp, C., & Osborn, T. (2025). *Infrastructure-Based Cooperative Perception at a Traffic Intersection: Overview and Challenges.* National Renewable Energy Laboratory (NREL). https://www.nrel.gov/docs/fy25osti/91777.pdf
5. Young, S., Mir, F. Sines, D., Sosa, Z., Wang, Q., Sandhu, R., Tripp, C. & Osborn, T. *A Framework for the Robust Deployment of Digital Infrastructure.* IRF Global R2T Conference & Exhibition 2024. (in-press)
6. Faizan Mir, Rimple Sandhu, Stanley Young, Qichao Wang, and Todd Osborn. The Sensor Dilemma in Intelligent Transportation Systems: Evaluating Radar, Lidar, and Camera, pages 610–621. doi: 10.1061/9780784486191.055. https://ascelibrary.org/doi/abs/10.1061/9780784486191.055
7. F. MIR, R. SANDHU, S. YOUNG, Q. WANG, D. SINES and Z. SOSA, "Descriptor: Infrastructure Perception and Control: Multi-Sensor Object Tracking Dataset (IPC-MSOT)," in IEEE Data Descriptions, doi: 10.1109/IEEEDATA.2025.3601080

Q&A

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