Photo by Josh Bauer, NREL 61725

The Sensor Dilemma in Intelligent Transportation Systems

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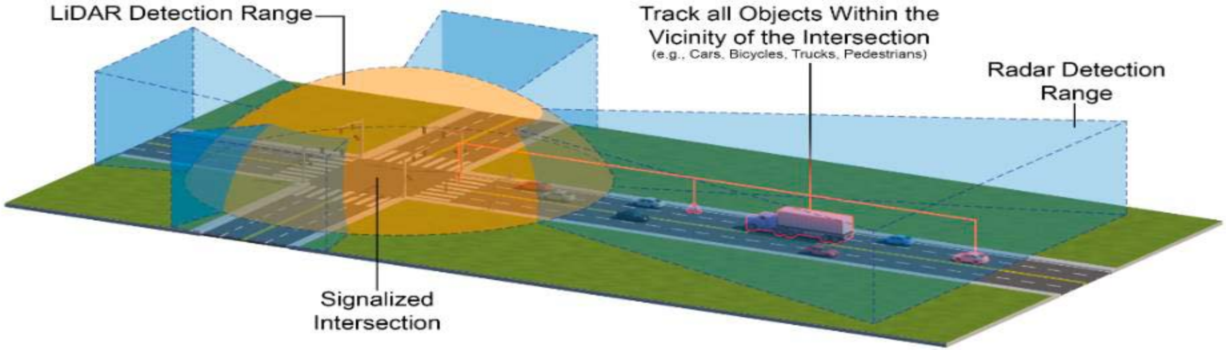
Background

- **Autonomous vehicles are the "Space Race" of this generation:**
  - Vast private capital on developing connected and automated vehicles.
  - However, most technology is behind corporate firewalls.
- Less attention on advances in smart, connected transportation infrastructure—i.e., **infrastructure perception and control (IPC)**.
  - 300,000 signalized intersections in the United States versus 300 million vehicles.
  - *Half of all crashes and excess fuel expended are at intersections.*[1]
  - Smart infrastructure could save lives and time, increase efficiency in the *near term, and enable next-generation automated public mobility.*
- **Challenge:**
  - **Create an open-source framework for infrastructure intelligence that is scalable, resilient, highly accurate… and affordable.**

[1] L. Wu, Y. Ci, J. Chu, and H. Zhang. 2015. "The Influence of Intersections on Fuel Consumption in Urban Arterial Road Traffic: A Single Vehicle Test in Harbin, China." *PLoS ONE* 10 (9): e013747. journals.plos.org/plosone/article?id=10.1371/journal.pone.0137477.

Objective/Hypothesis

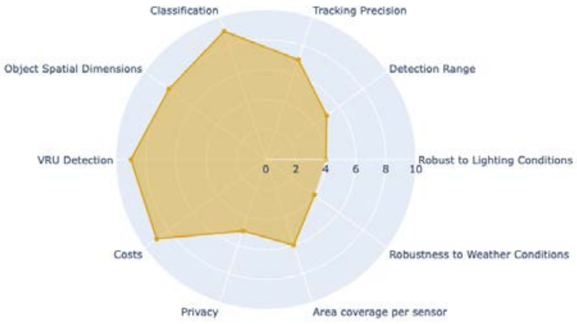
A lack of highly reliable, full state-space awareness of roadway situations is the current bottleneck for the incremental introduction of smart infrastructure control.



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 an open framework for processing and messaging of state space of all objects to accelerate benefits of IPC integrated with connected and automated vehicles, saving lives and energy.

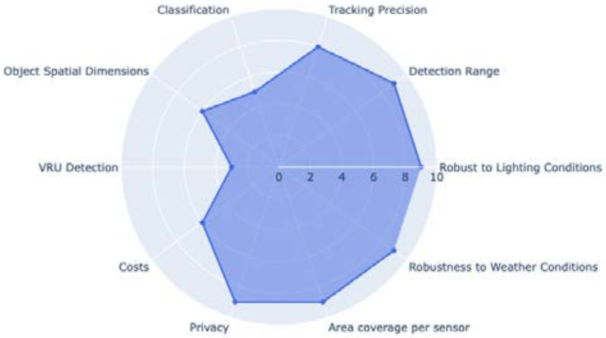
Comparing Camera, Radar, and Lidar

Camera



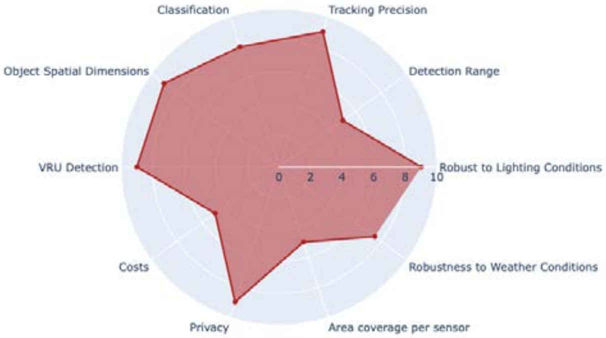
- Strong object classification with color and feature detection.
- Able to detect vulnerable road users.
- Affordable and easy infrastructure integration.
- Poor in fog, rain, and low light.
- Low detection range as objects.
- Privacy concerns.
- Detection and tracking depends on algorithms used.

Radar



- Superior detection range.
- Robust to fog, rain, and low light.
- No privacy concerns.
- High coverage per sensor.
- Poor vulnerable road user detection.
- Poor classification ability.
- Expensive cost (hardware, mounting, and software).

Lidar



- Strong object classification.
- Able to output accurate special object dimensions.
- Able to detect vulnerable road users.
- Expensive and somewhat difficult to integrate with infrastructure.
- Poor in adverse weather conditions.
- Low detection range.
- No privacy concerns.

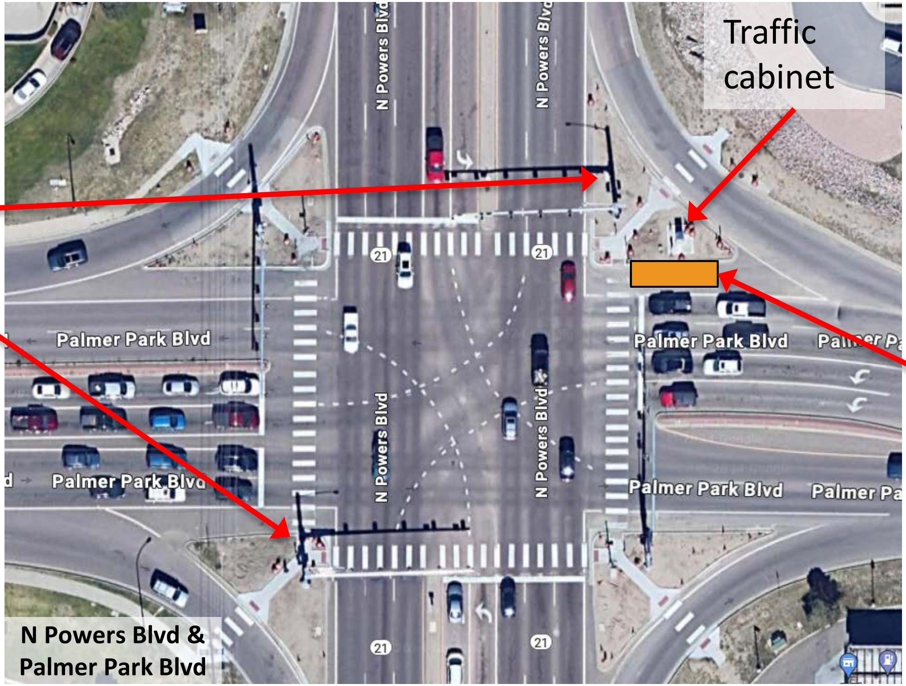
Data Collection

IPC Mobile Lab

Photos by Joe DelNero (NREL)

Data Collection at Intersection

Pole-mounted EVO Radar units

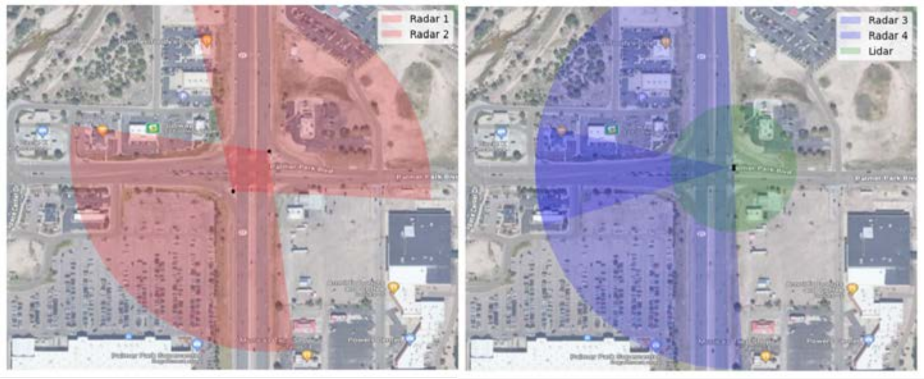


IPC Mobile Lab

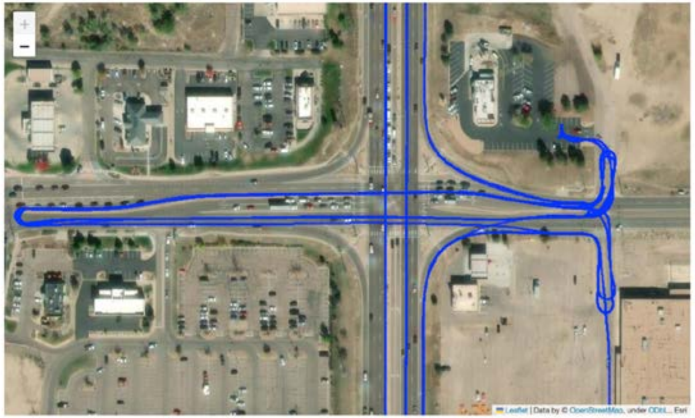
Traffic intersection in Colorado Springs

Sensor Deployment

Sensor field of view



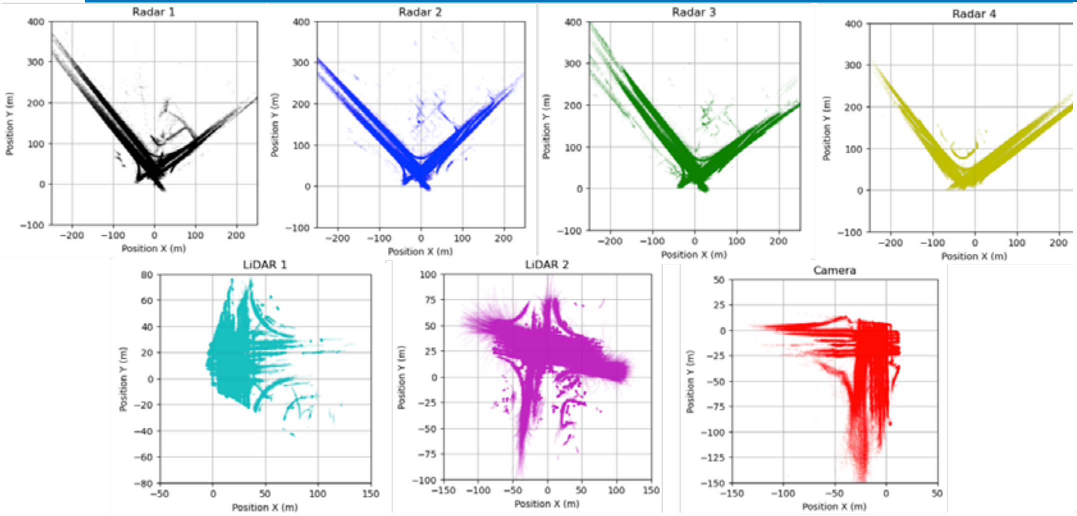
GPS vehicle tracks with post-processing kinematic correction

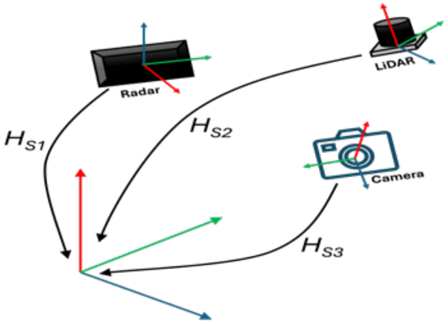


Perception Sensor Specifications

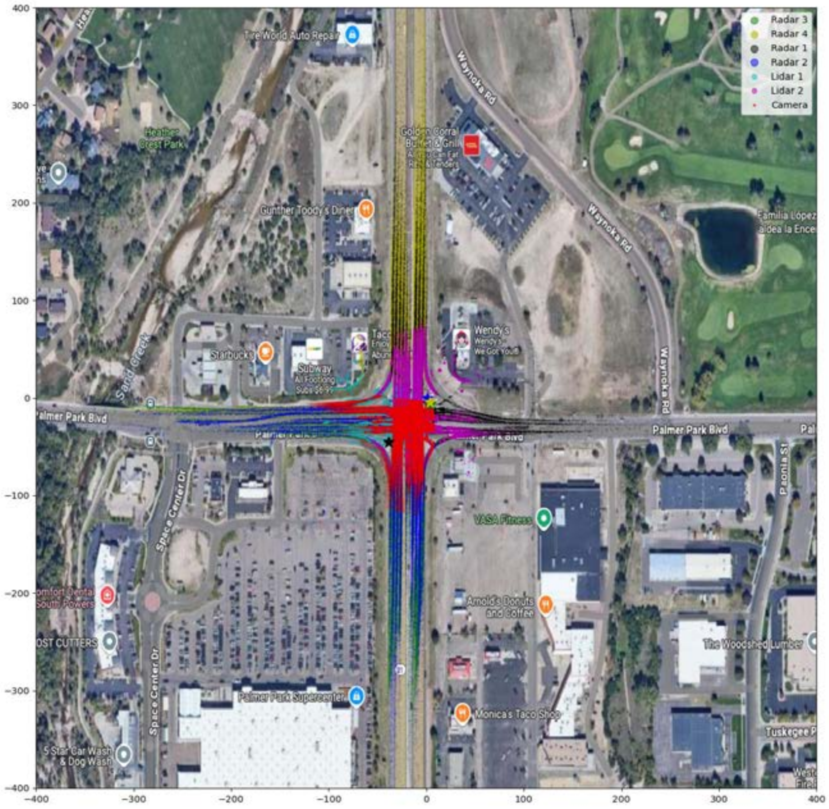
Properties	Radar	Lidar		Camera
Model	Econolite EVO	Ouster OS1	Cepton X90	Axis P3255-LVE
Range (m)	275	90	90	70–80
Field of view, horizontal (degrees)	110°	360°	90°	
Sampling rate (Hz)	10	10	10	10
Classification	Vehicles, nonmotorized, small trucks, big trucks	Cars, trucks, pedestrians, two-wheelers	Vehicles, pedestrians	Vehicles, pedestrians
Perception software	InnoSenT (ISYS-5220) API	Outsight Shift	Helius	Axis Analytics

Sensor Data Transformation

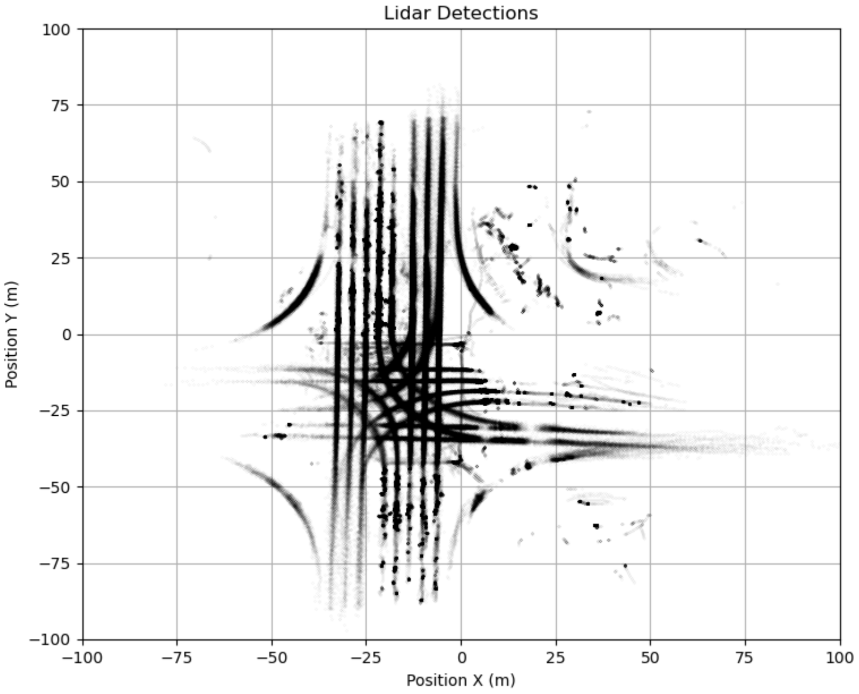


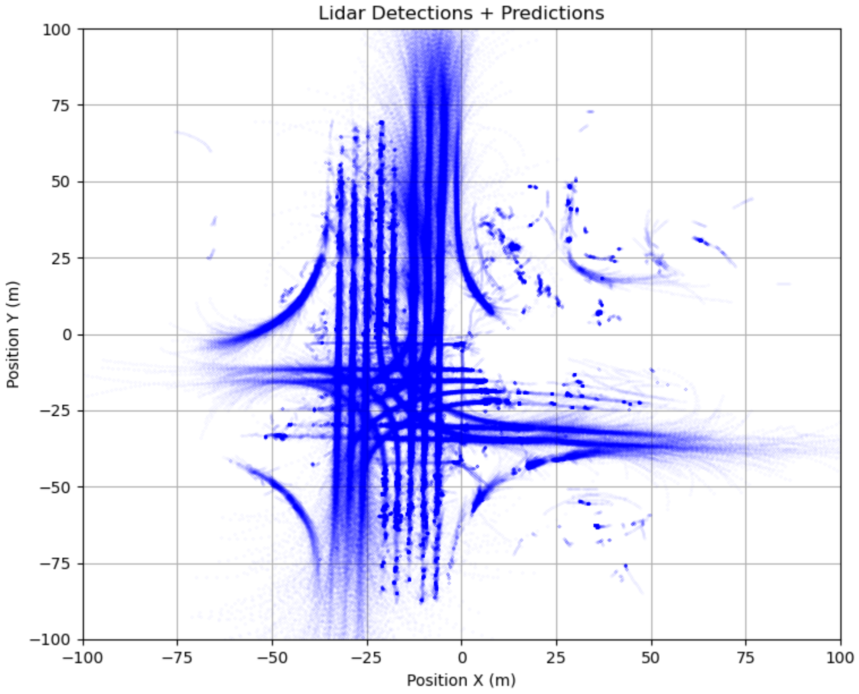


$$\begin{bmatrix} \hat{x} \\ \hat{y} \\ \hat{z} \\ 1 \end{bmatrix} = \underbrace{\begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix}}_{H_{Si}} \times \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

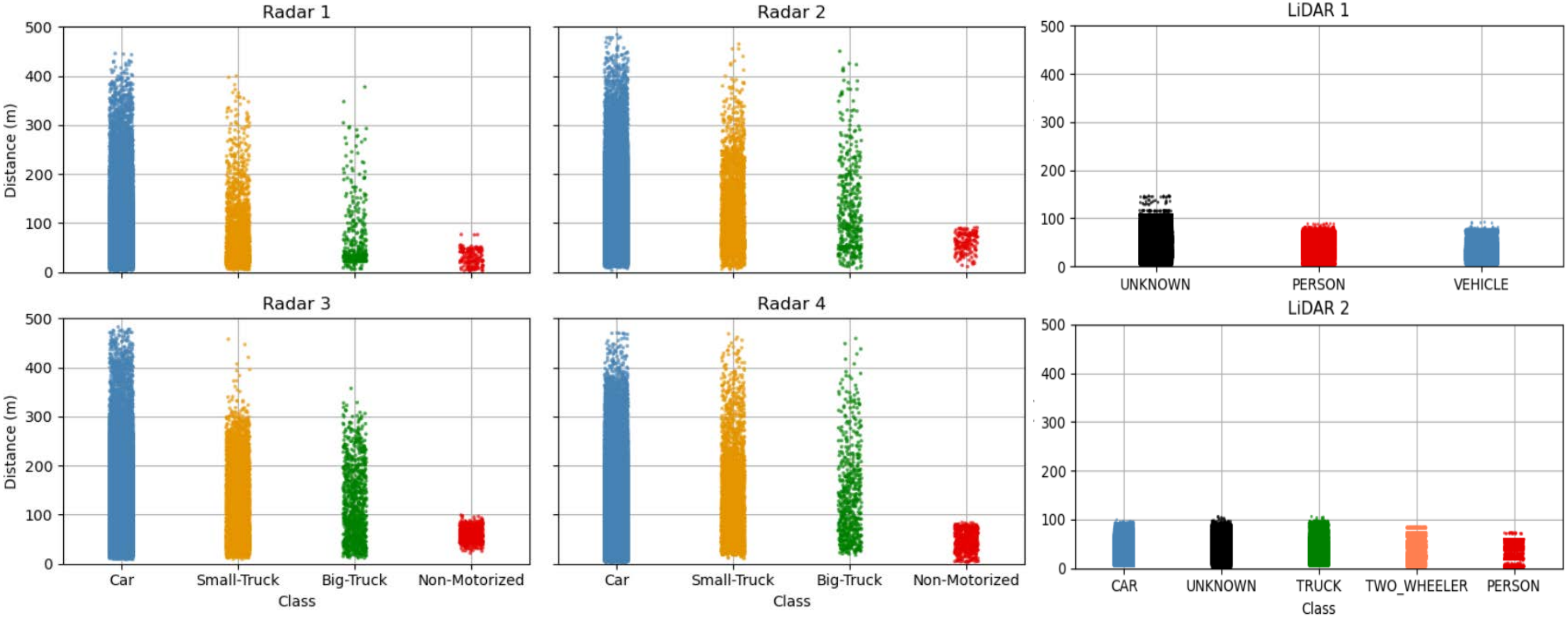


Filtering Algorithms

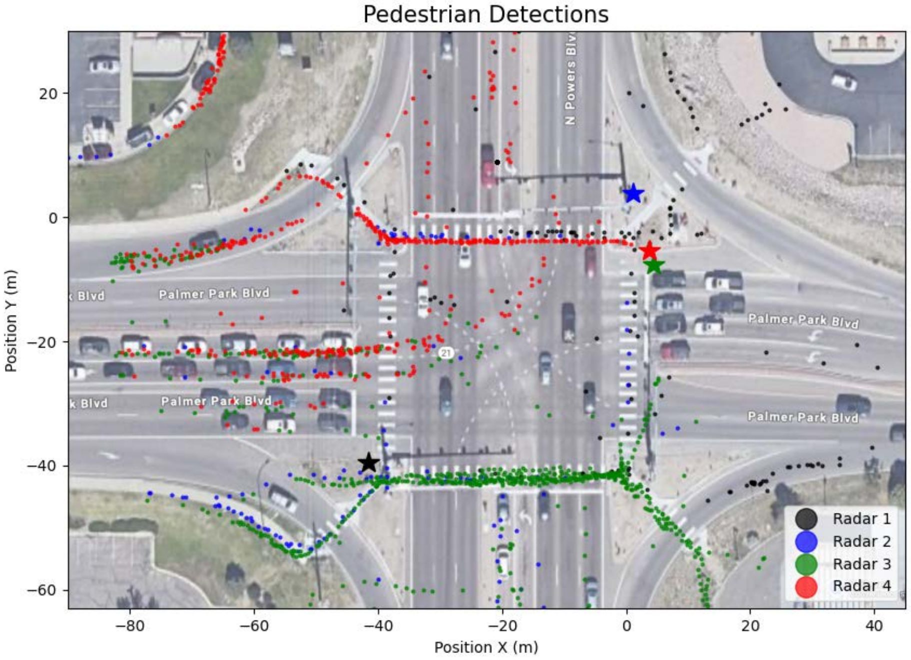


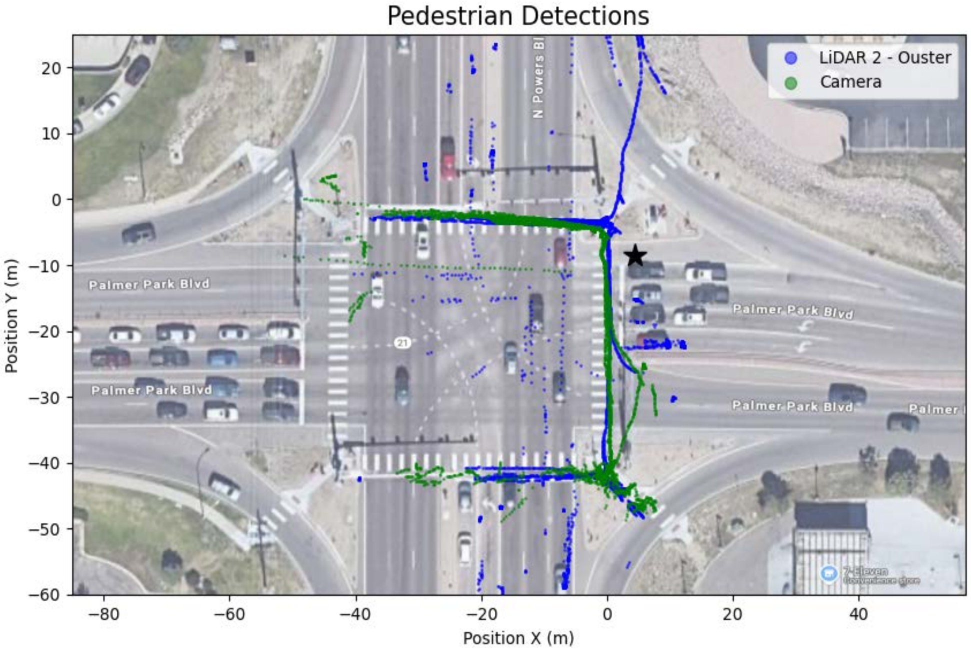


Sensor Range



Vulnerable Road User Detection





More vulnerable road user detection observed in Radars 3 and 4 due to higher elevation angle (pointed towards intersection) and a lot of incorrect detections

Fewer false positives observed; placing diagonally opposite pole would provide full intersection coverage

Key Takeaways

- Camera object detection confidence varies with different object detection algorithms—performance is highly dependent on training data.
- Cameras have issues with lens distortion.
- Lidar object detection is lower than the specification's nominal range.
- Multi-sensor lidar setup is difficult—manually required to align point clouds together. – Automated Calibration is needed.
- Lidar has high cost, and long-term reliability is questionable.
- Radar shows inconsistent object length/width dimensions—depends on radar cross section.

Limited overlap between sensors causes higher ID switches—leading to inconsistent object counts and classification inconsistency.

Objective

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.
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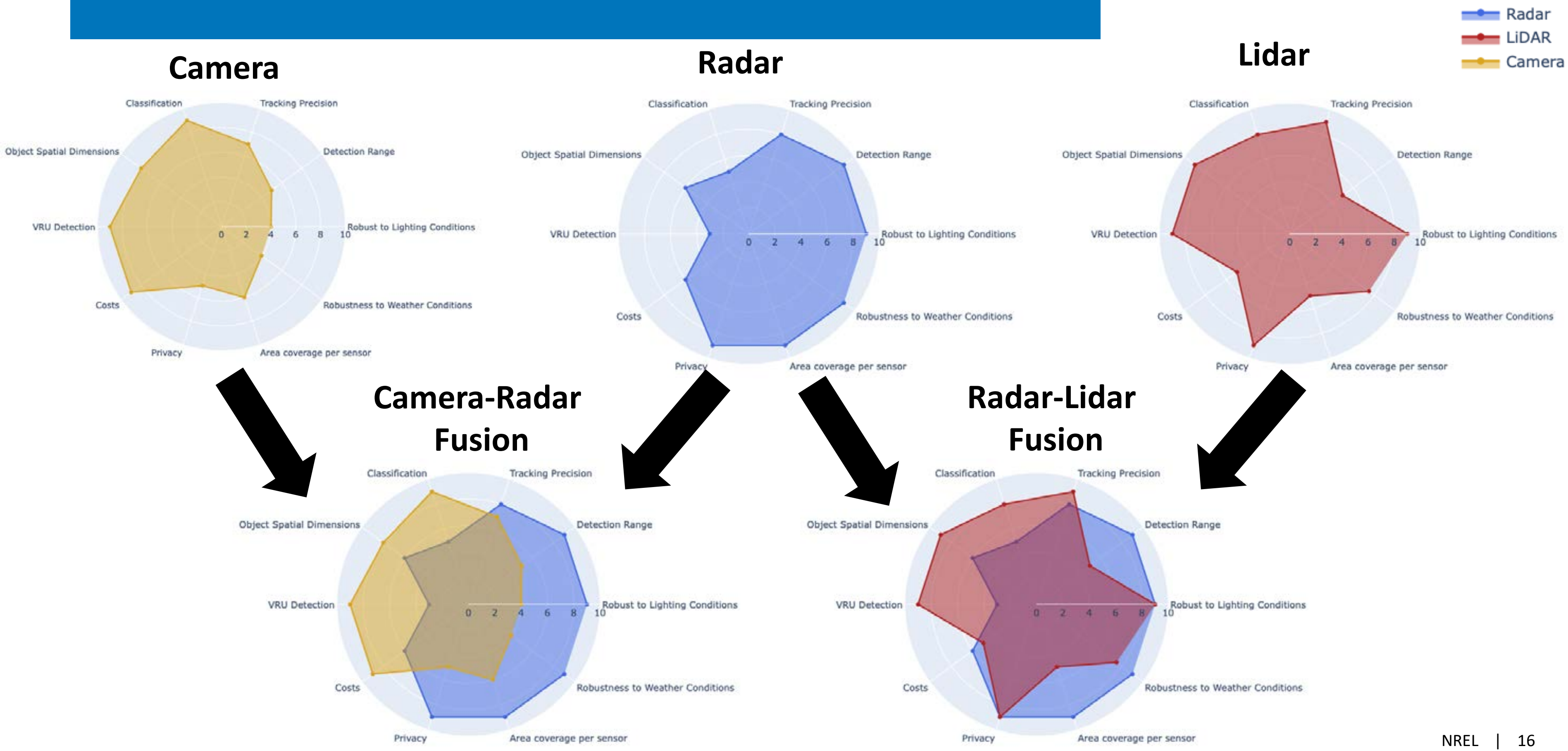
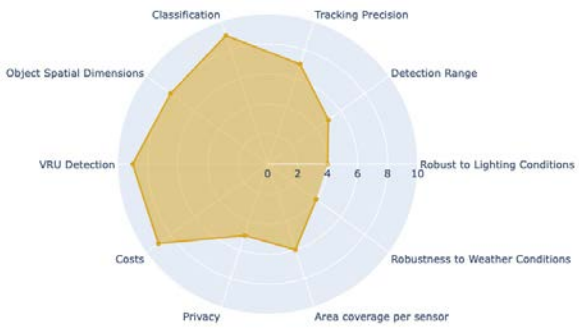
Multi-Sensor Data Fusion

Multi-Sensor Fusion

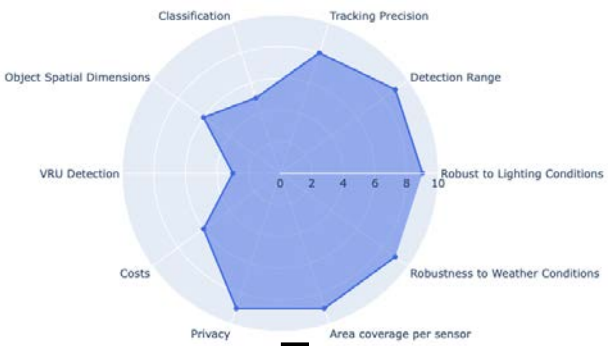


Multi-Sensor Fusion

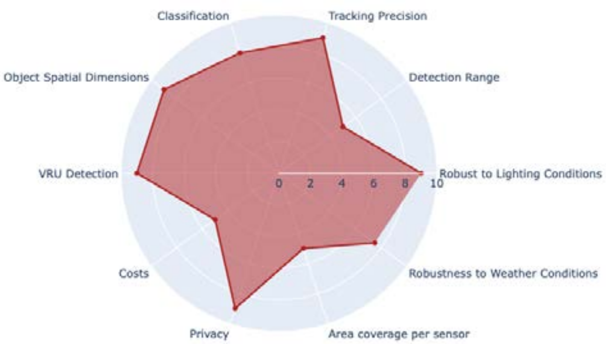
Camera

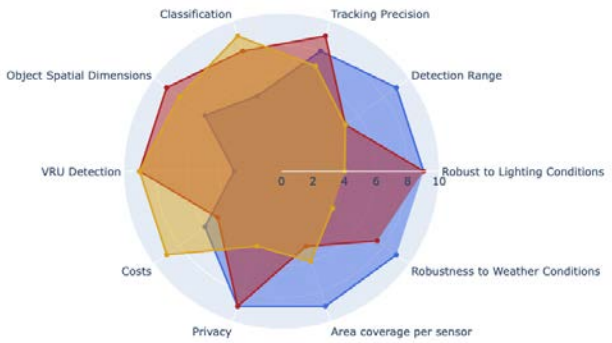


Radar



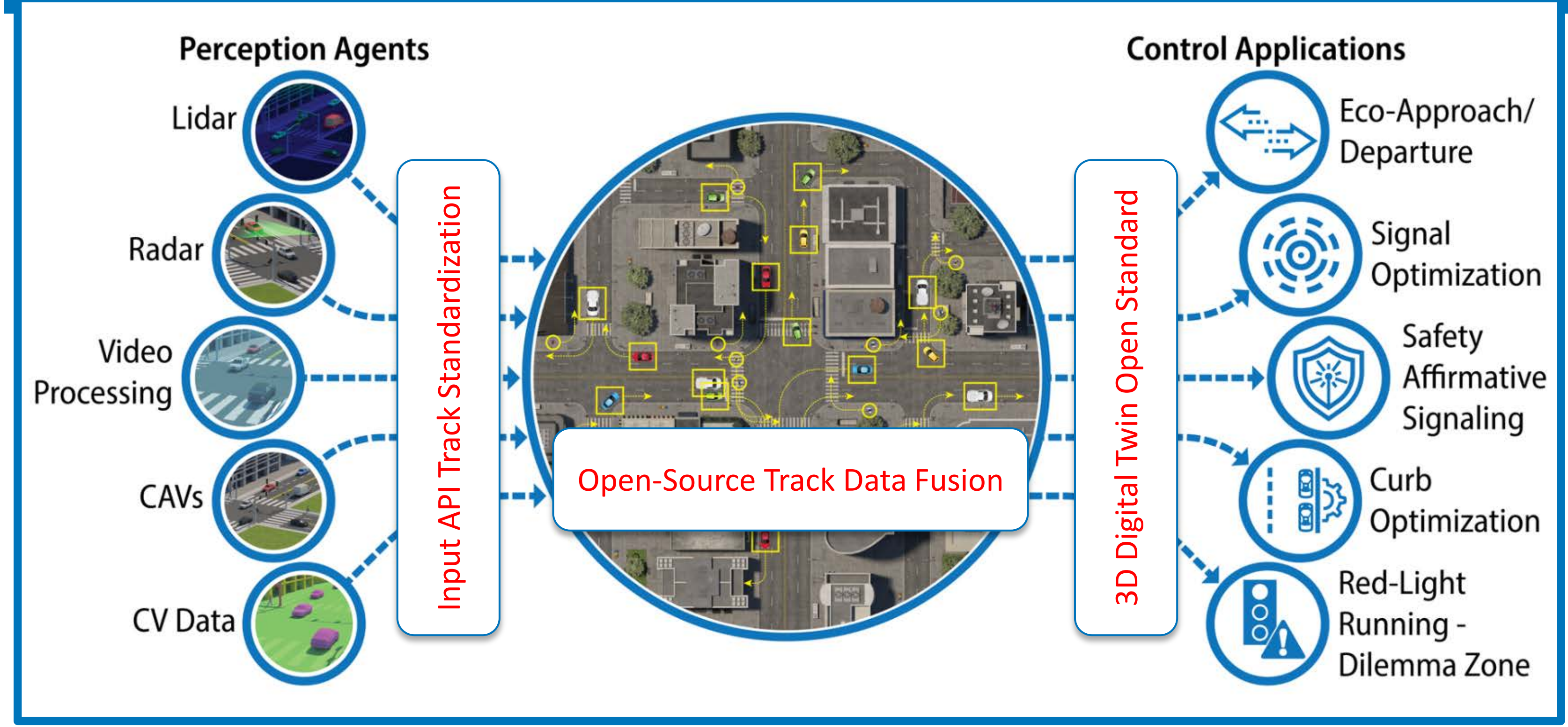
Lidar





Camera-Radar-Lidar Fusion

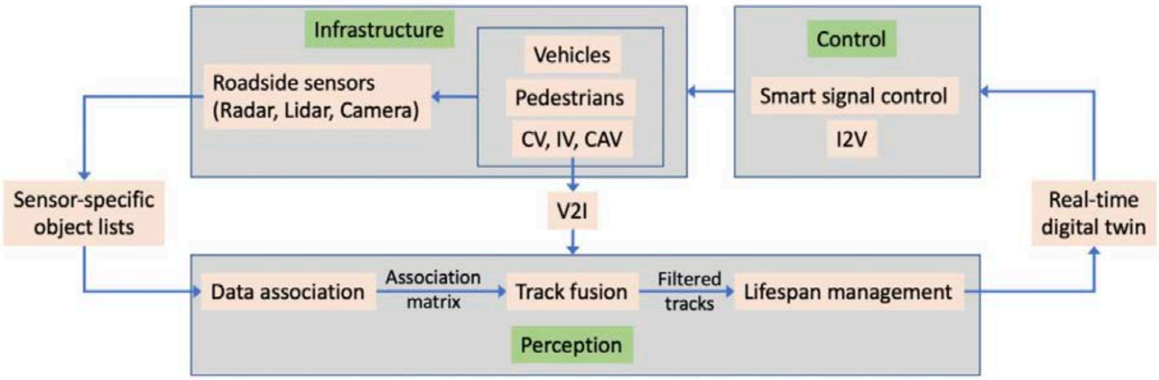
Overall Cooperative Perception Pipeline Summary



Data → **Information** → **Control**

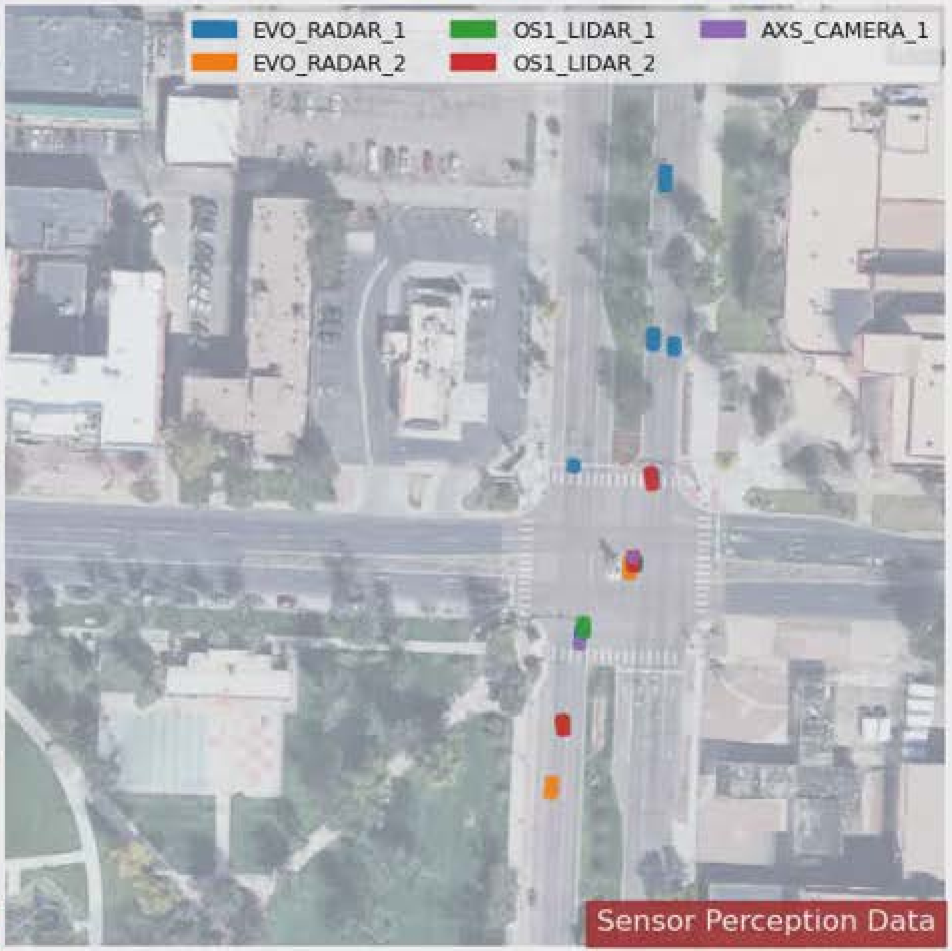
IPC Fusion Engine

1. **Spatial Transformation**
2. **Data Association**
3. **State Estimation**
4. **Lifespan Management**



Functional flow chart for IPC fusion engine

Fusion of Radar (2), Lidar (2), and Video (1)



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.
- **Context-aware fusion to improve performance.**
  - Dynamically re-weight sensor inputs based on conditions (e.g., range, environment).

ONE sensor tells a story—many tell the TRUTH!

Challenges and Research Areas

Fusion: Track persistence around occlusions.

Fusion: Track persistence within queues.

Automated calibration—hang it and go.

- Internal sensor consistency and connected vehicle data are key.

Automated validation (health monitoring).

- Internal sensor consistency and connected vehicle data are key.

Data standardization.

- Input (sensors) and output (digital twin).

Integration with vehicles and nonmotorized traffic.

NREL IPC Laboratory

IPC Multi-Sensor Object Tracking Dataset

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.

data.nrel.gov/submissions/287

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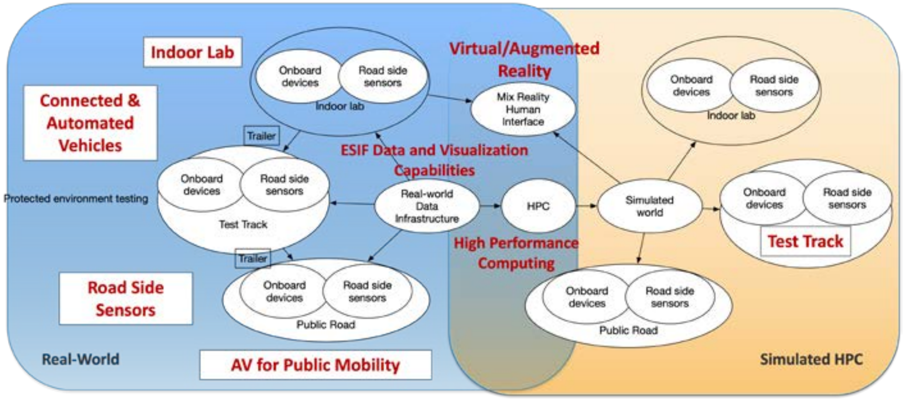

www.nrel.gov/transportation/ipc-lab

Thank You!

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