NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

COMMUNICATIONS TECHNOLOGY LABORATORY

NIST Automated Vehicle Communications Overview

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Wesley Garey, Evan Black, Samantha Gamboa Quintiliani, Aziza Ben Mosbah, et al.

https://www.nist.gov/programs-projects/automated-vehicles-and-av-communications

AV Communications +

NIST COMMUNICATIONS TECHNOLOGY LABORATORY

Automated Vehicles and AV Communications

Summary

Automated vehicles (AVs) will significantly impact our daily lives and improve the competitiveness of our economy. Advances in communications capabilities – for wired and wireless onboard networks and offboard communications with other vehicles, infrastructure, and services in the driving environment – can drive innovation in vehicle automation. Measurement science and standards, including for AV communications, are essential to supporting safe and predictable operation of AVs and increasing consumer confidence. This project brings together expertise from the Communications Technology Laboratory to address AV system integration and communications challenges, in collaboration with the NIST-wide Automated Vehicles Strategic and Emerging Research Initiatives (SERI) program.

ORGANIZATIONS

- Communications Technology Laboratory
  - Smart Connected Systems Division
    - IoT Devices and Infrastructures Group
    - Transformational Networks and Services Group
  - Wireless Networks Division
    - Wireless Systems Innovation and Performance Group

DESCRIPTION

Automated vehicles (AVs), or Automated Driving Systems-equipped (ADS-equipped) vehicles, have great potential to improve our lives by freeing us from the stress of driving and reducing accidents caused by distractions or poor judgement. Connected, reliable, and safe AVs will spark significant improvements in our transportation systems and infrastructure and promote economic growth and innovation. Much effort is needed to realize this vision, including NIST activities to advance measurement methods and standardization to support AV development, operations, communications, and safety, in collaboration with our stakeholders. (See NIST Taking Measures blog "Cruising Toward Self-Driving Cars: Standards and Testing Will Help Keep Autonomous Vehicles Moving Safely on the Road" for additional context on NIST efforts to support automated vehicles.)

Operating Envelope Specification supports automated driving safety measurement, key to testing and public acceptance of automated vehicles
Credit: NIST

The safe and predictable operation of an AV depends on communications. A vehicle's awareness of its operating environment and ability to react to unsafe operating conditions depends on the communication networks both

NIST STAFF

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CONTACT

DATES

Started: October 2022

PROJECT STATUS

ONGOING

https://www.nist.gov/programs-projects/automated-vehicles-and-av-communications

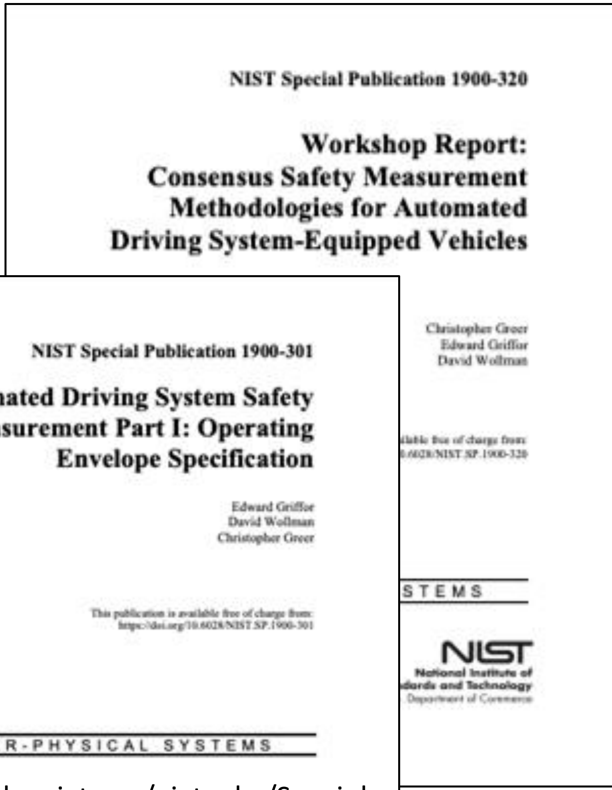
- Prior years' Automated Vehicle efforts (AV Safety Measurement, Operational Envelope Specification, Teleoperation, incl. workshops and stakeholder engagement) helped to establish foundation for NIST-wide AV effort.

- CTL team leads the AV Communications project within the NIST SERI program; CTL staff also contribute to other systems areas.
  - Co-simulation
  - Communications network modeling
  - Systems integration testbed design/demo
  - Teleoperation
  - Cyber/Communications protocols analysis
  - AI/Trustworthiness
  - Traffic infrastructure

Stakeholders: ADS Technical Working Group

- NIST (IoT) Cyber-Physical Systems organized two workshops
  - Consensus Safety Measurement Methodologies for Automated Driving System (June 2019)
  - Automated Driving System Safety Measurement and Operational Design Domain (July 2020)
- Automated Driving System Technical Working Group (ADS TWG) initiated in 2020, and has been meeting since to develop foundations for assessing AV performance (see Ed Griffor, lead)

https://www.nist.gov/publications/workshop-report-consensus-safety-measurement-methodologies-automated-driving-system


NIST Special Publication 1900-320

Workshop Report:
Consensus Safety Measurement Methodologies for Automated Driving System-Equipped Vehicles

Christopher Greer
Edward Griffor
David Wollman


NIST Special Publication 1900-301

Automated Driving System Safety Measurement Part I: Operating Envelope Specification

Edward Griffor
David Wollman
Christopher Greer

This publication is available free of charge from:
https://doi.org/10.6028/NIST.SP.1900-301

CYBER-PHYSICAL SYSTEMS

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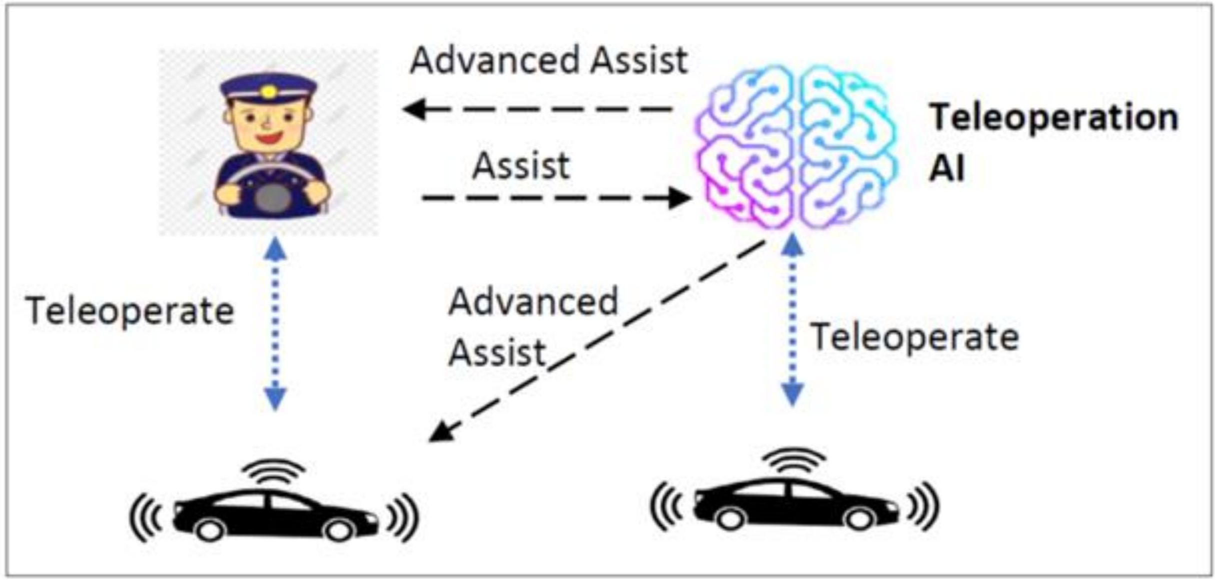
https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1900-301.pdf

- NIST introduced the concept of an *operating envelope specification* (OES), a structured description of the operating environment for driving.
  - The OES supports calculation-based reasoning for vehicle performance in that environment, with testing and certification applications and in real-time driving.

Stakeholders: Teleoperation Consortium

- NIST Vehicle Teleoperation Forum (November 2020) resulted in formation of Teleoperation Consortium.
- NIST has Board Member (Tao Zhang) on Teleoperation Consortium (Bob Bohn, NIST Liaison; Scott McCormick, Pres)
- Teleoperation Guidelines document on vocabulary, use cases, and communication technologies for Teleoperated Vehicles is anticipated to be published in December 2023.

https://www.nist.gov/news-events/events/2020/11/nist-vehicle-teleoperation-forum



https://www.teleoperation.org/

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NIST

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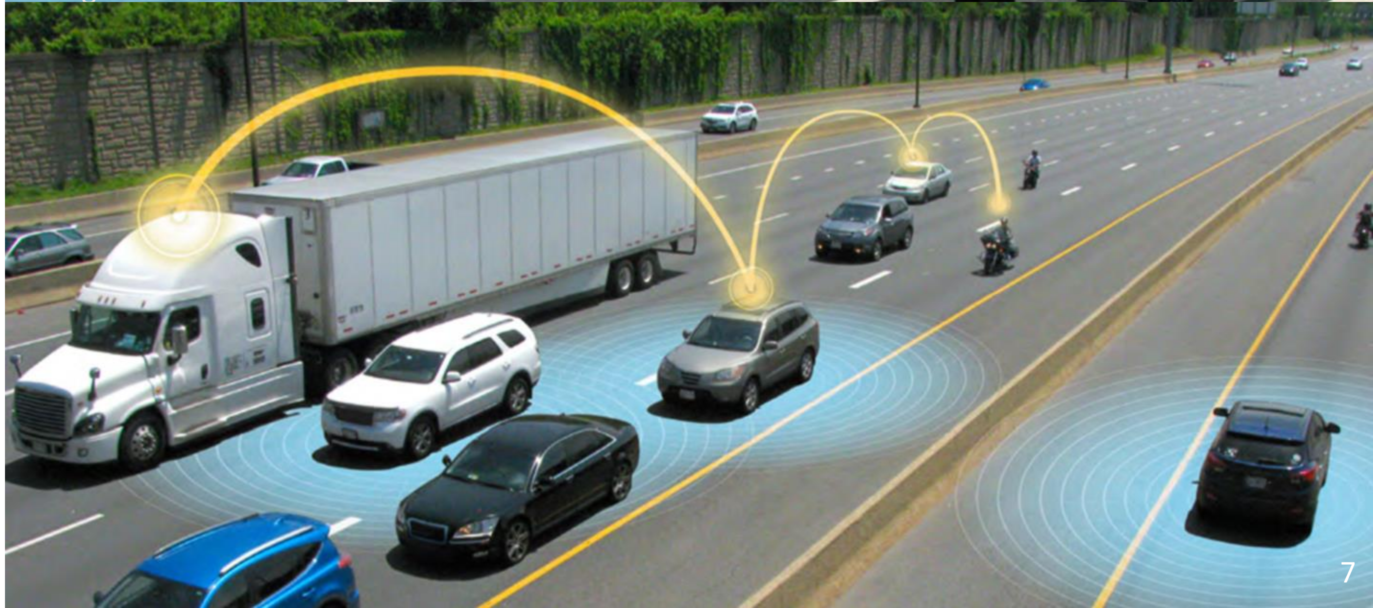
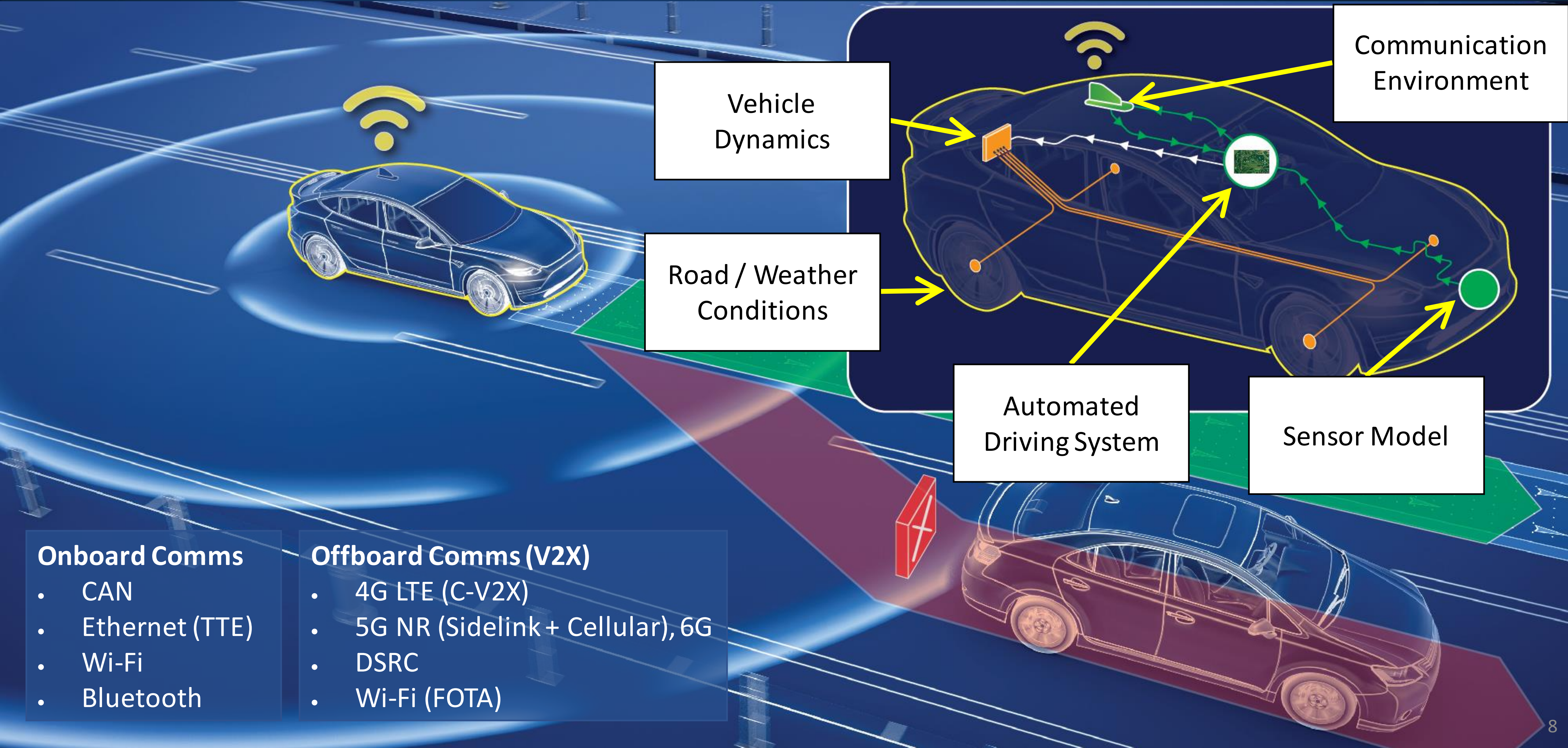
Perspectives on AV Communications

- Current Vehicles
  - Vehicle Operational Functions rely on onboard sensors for detection
  - Motivation for AV communications requires clear benefits/value, economics
- Leverage 20+ years of AV communications R&D
- Future Connected Automated Vehicles
  - Growing community agreement that communications will be increasingly important for safe AV operation and Cooperative Driving and Tactical Functions
  - Mixed environment (human drivers/AV) anticipated for a long time – safety
- Some AV and AV Communications Challenges
  - Timing and Latency Adequacy
  - Testing Methodology
  - Spectrum, Infrastructure, Smart Cities
  - Regulatory (incl. New Car Assessment Program)
  - Trustworthiness – Safety, Security, Privacy, Reliability, Resilience


Images: NHTSA



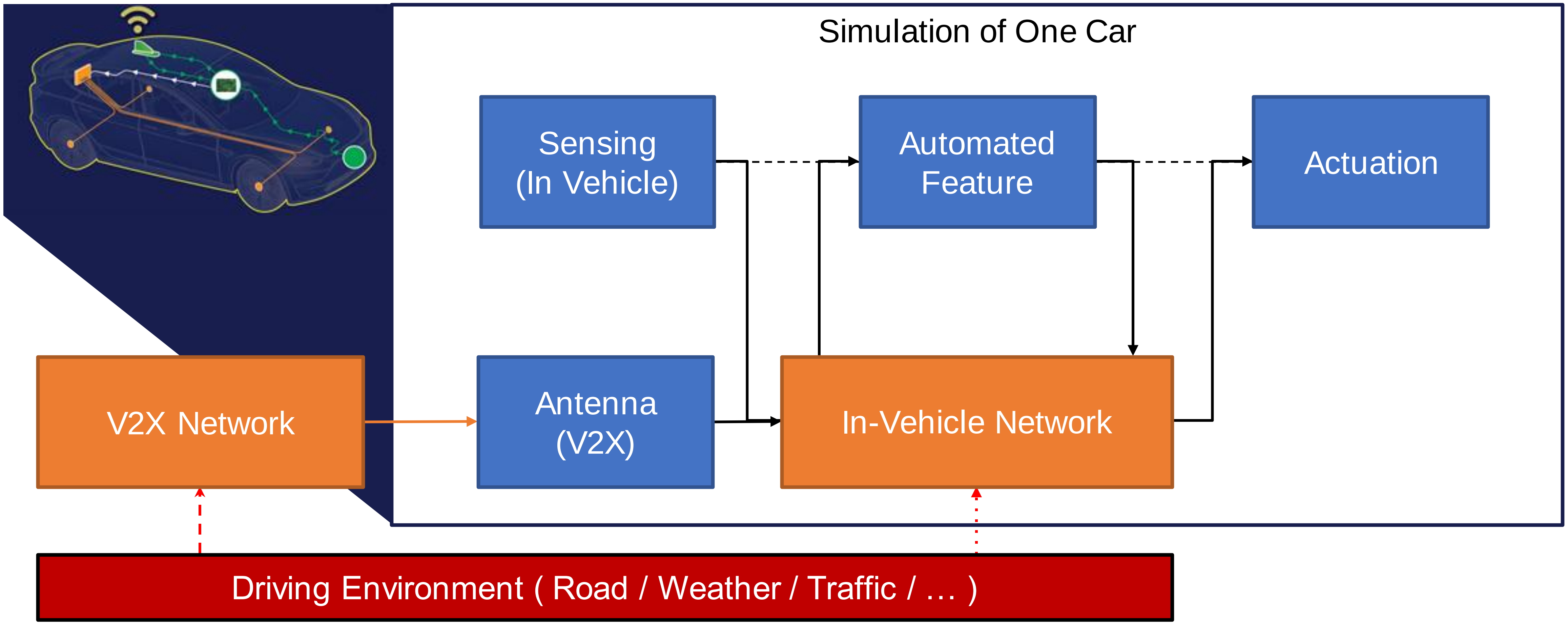
Systems in the Driving Environment



Onboard Comms
- CAN
- Ethernet (TTE)
- Wi-Fi
- Bluetooth

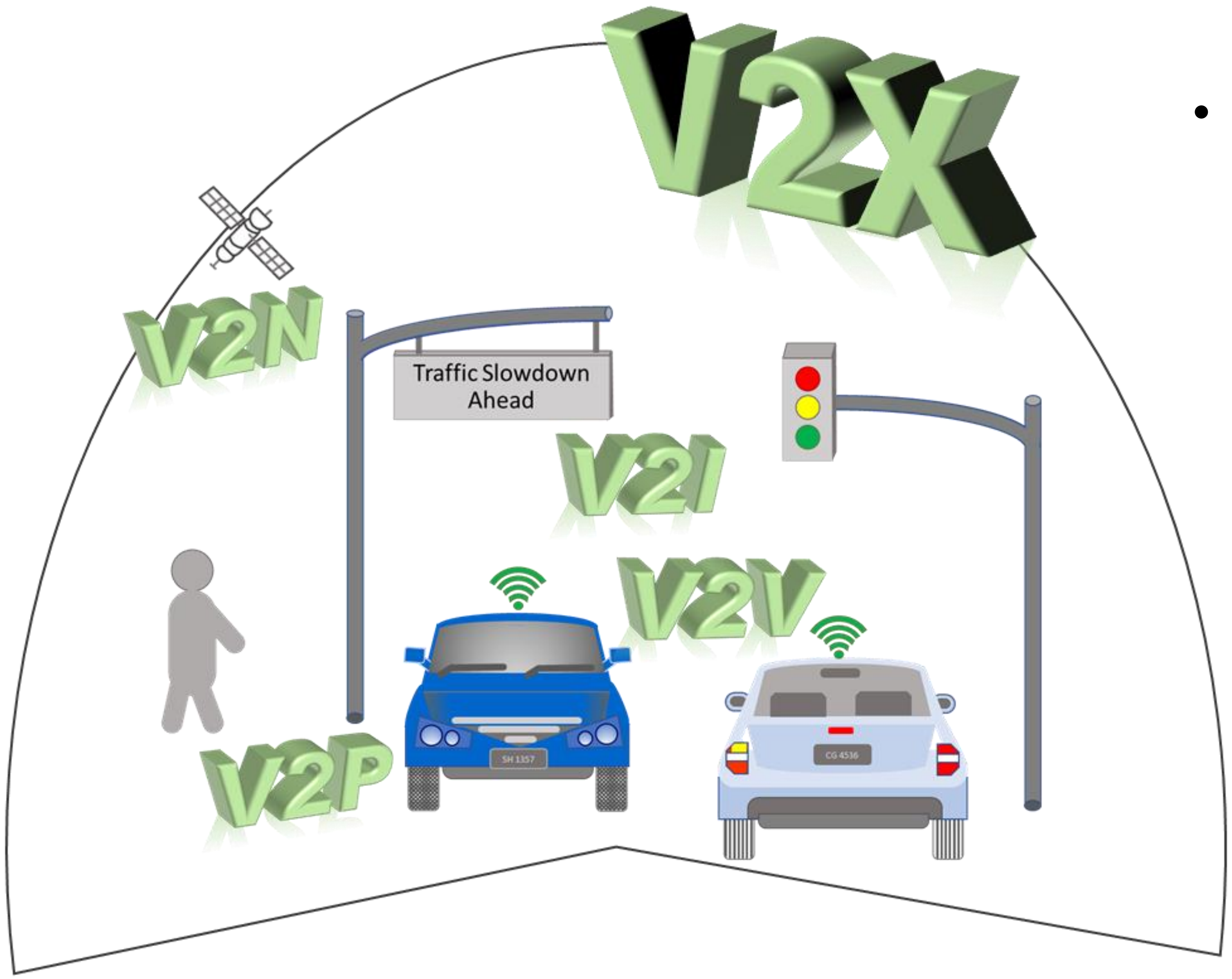
Offboard Comms (V2X)
- 4G LTE (C-V2X)
- 5G NR (Sidelink + Cellular), 6G
- DSRC
- Wi-Fi (FOTA)

Communication Paths in Vehicles



Sources of network interference (perturbations) in the driving environment will impact network performance and lead to an impact on overall vehicle performance.

V2X in AV from 4G LTE to 5G NR



- 3GPP specifies four V2X application types for 4G LTE [1]: V2V, V2P, V2I, and V2N.
- AV community envisions advanced use cases and services (e.g. [2]), and 3GPP specifies service requirements for 5G NR in six areas [3]:
  - General Aspects: interworking, communication-related requirements valid for all V2X scenarios
  - Vehicles Platooning
  - Advanced Driving
  - Extended Sensors
  - Remote Driving
  - Vehicle Quality of Service Support

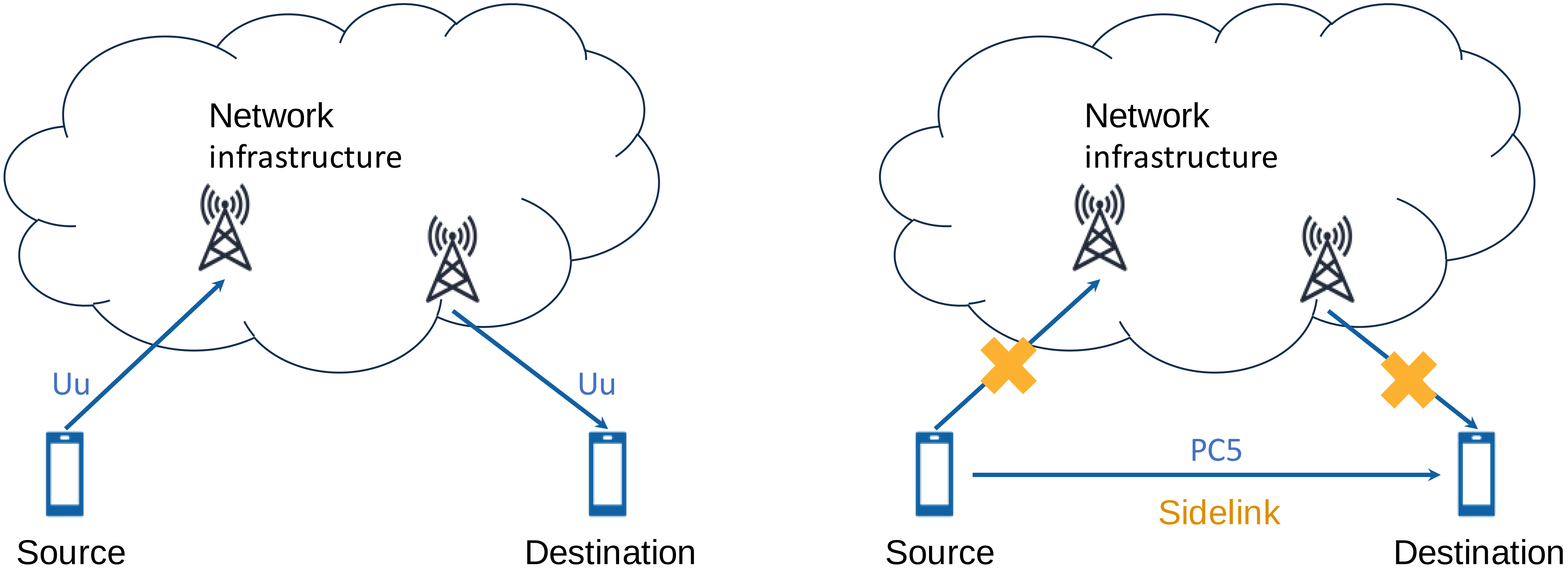
A GLOBAL INITIATIVE

1. 3GPP TS 22.185 V17.0.0. In *Technical Specification Group Services and System Aspects*; Service Requirements for V2X Services.

2. H. Bagheri *et al*., "5G NR-V2X: Toward Connected and Cooperative Autonomous Driving," in *IEEE Communications Standards Magazine*, vol. 5, no. 1, pp. 48-54, March 2021, doi: 10.1109/MCOMSTD.001.2000069.

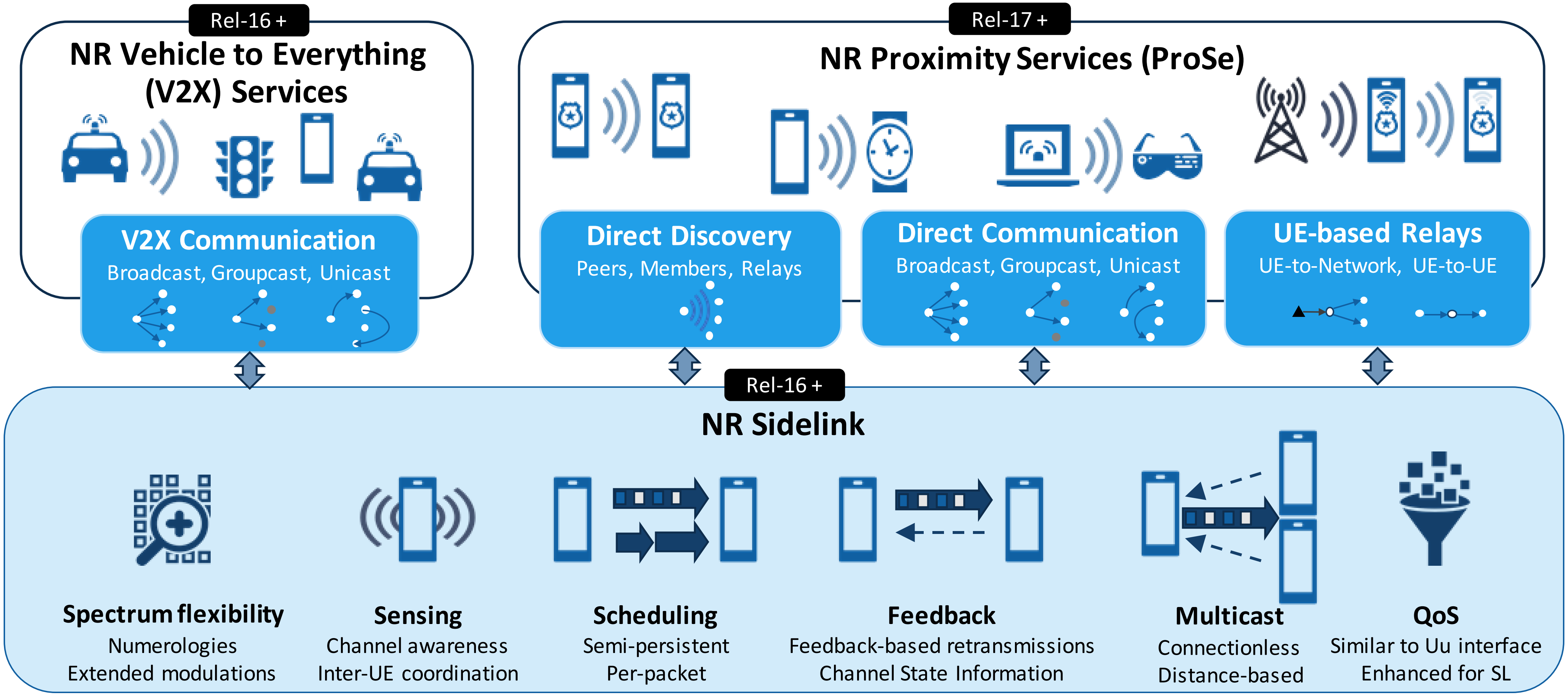
3. 3GPP TS 22.186 V17.0.0. In *Technical Specification Group Services and System Aspects*; Enhancement of 3GPP support for V2X scenarios.

Sidelink and Integrated V2X Communications



- 3GPP specifies sidelink for D2D and V2X communications, which provides direct link between vehicles.
  - Direct link enables ultra low latency communications, which is critical in V2X communications, and allows out-of-coverage communications.
- Sidelink and cellular network infrastructure can be integrated easily to serve a variety of AV use cases.

3GPP V2X Feature Evolution



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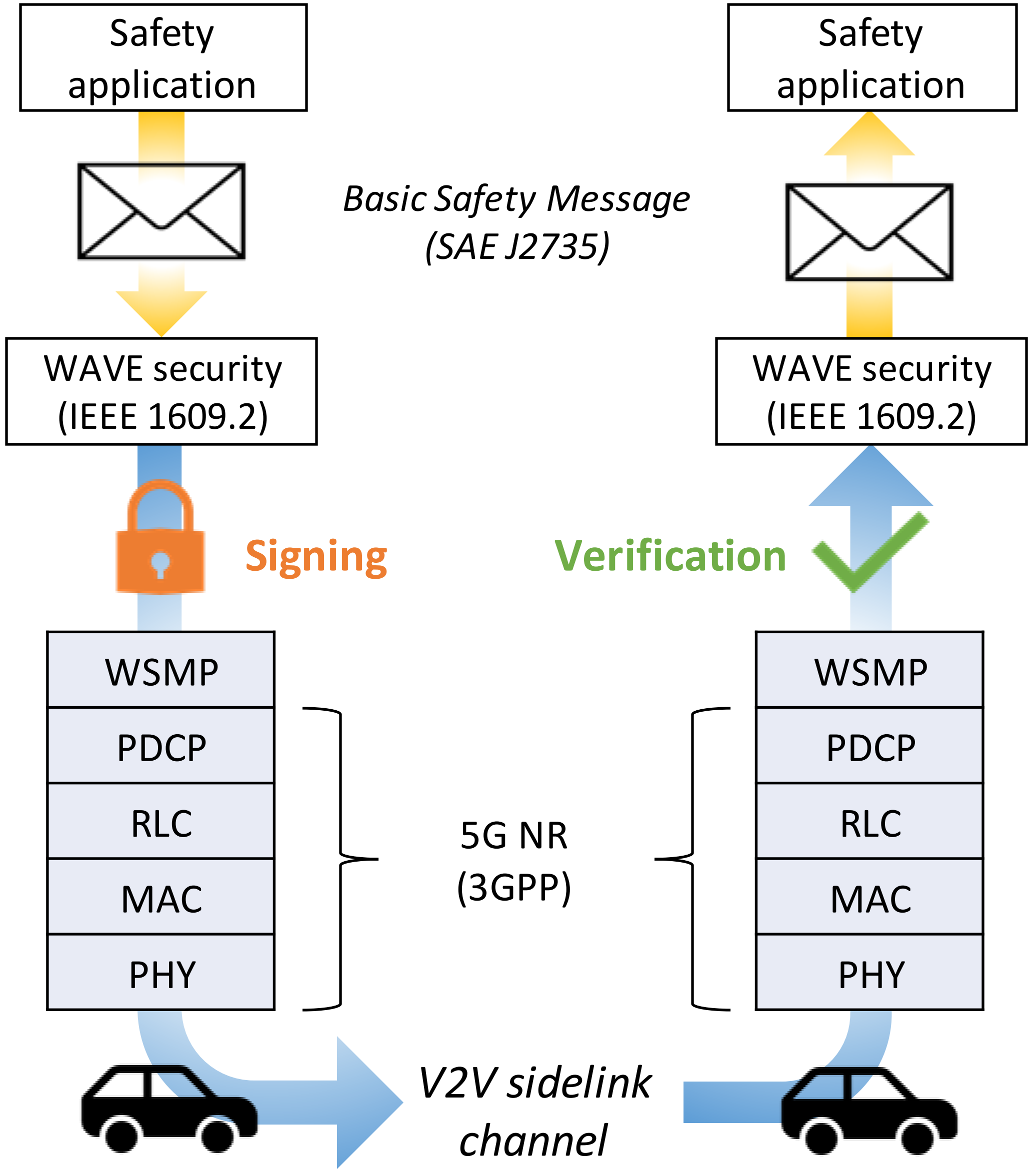
V2V Communications and Security/Privacy

Message Authentication

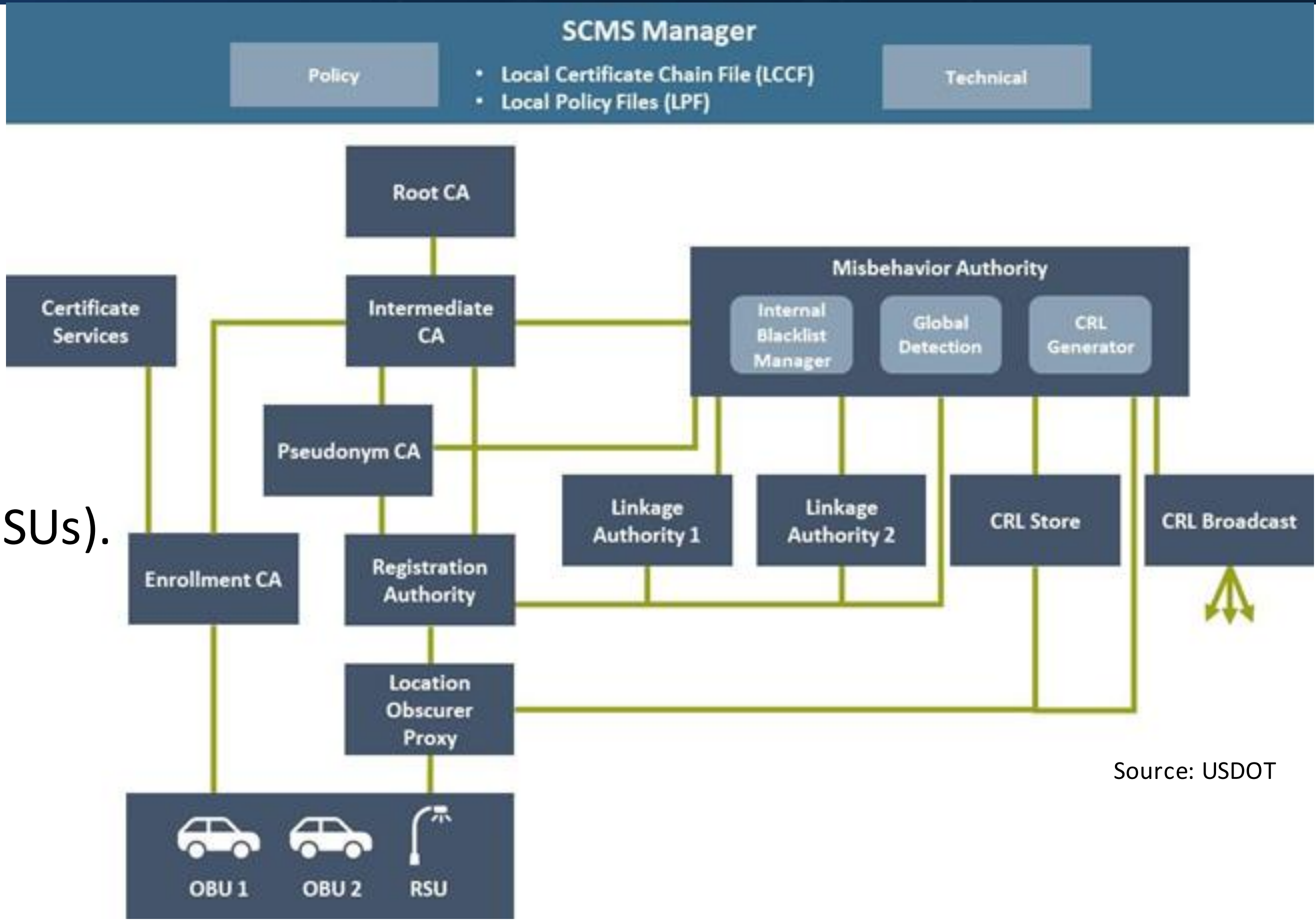
- Basic Safety Messages (BSMs) and Signal Phase and Timing (SPaT) messages from road infrastructure or other vehicles must be cryptographically signed to ensure integrity and authenticity
    - IEEE 1609.2 – WAVE Security Services
- All vehicles that receive a message must verify that it was signed by a valid certificate
    - Certificates are issued (and revoked) through the Security Credential Management System (SCMS)
- Signing and verification introduce delays due to computational cost of cryptographic operations
- Future Goal: studying the impact of BSM authentication on vehicle reaction time through co-simulations



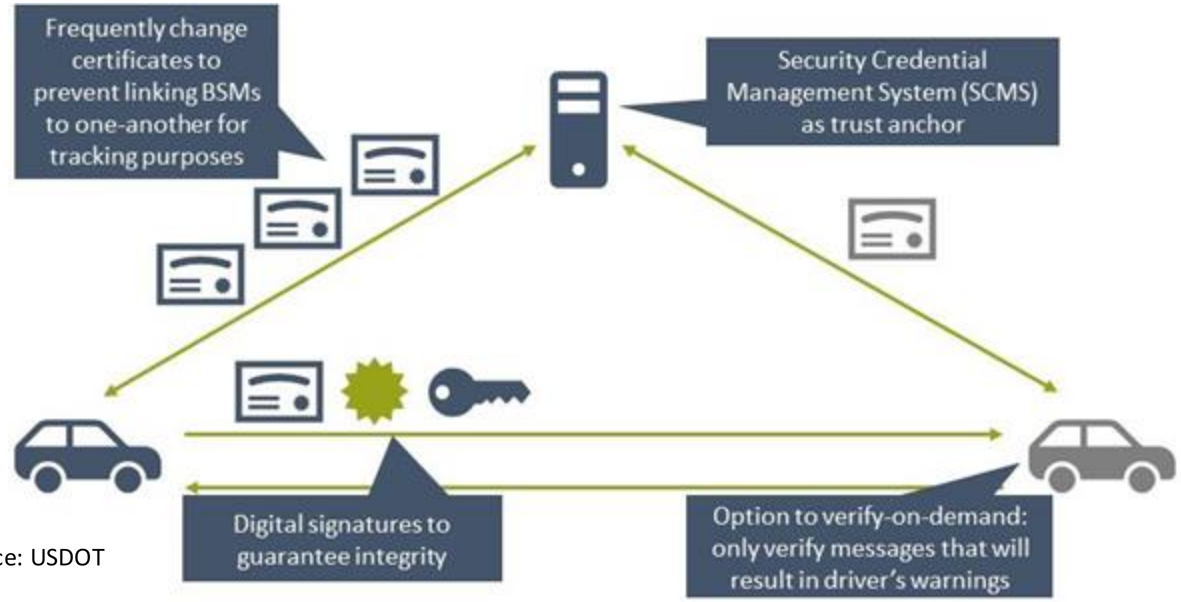
V2V Communications and Security/Privacy

Certificate Management

- The Security Credential Management System (SCMS) is responsible for issuing and revoking certificates of road users
  - It employs pseudonym certificates for the vehicles' onboard units (OBUs) to ensure the user's privacy.
  - Privacy not a large concern for Roadside Units (RSUs).



Source: USDOT



Source: USDOT

- Future Goal: Analyze the SCMS algorithms and protocols for potential privacy shortcomings and performance/scalability bottlenecks.

V2X Extension for Network Simulator (ns-3)

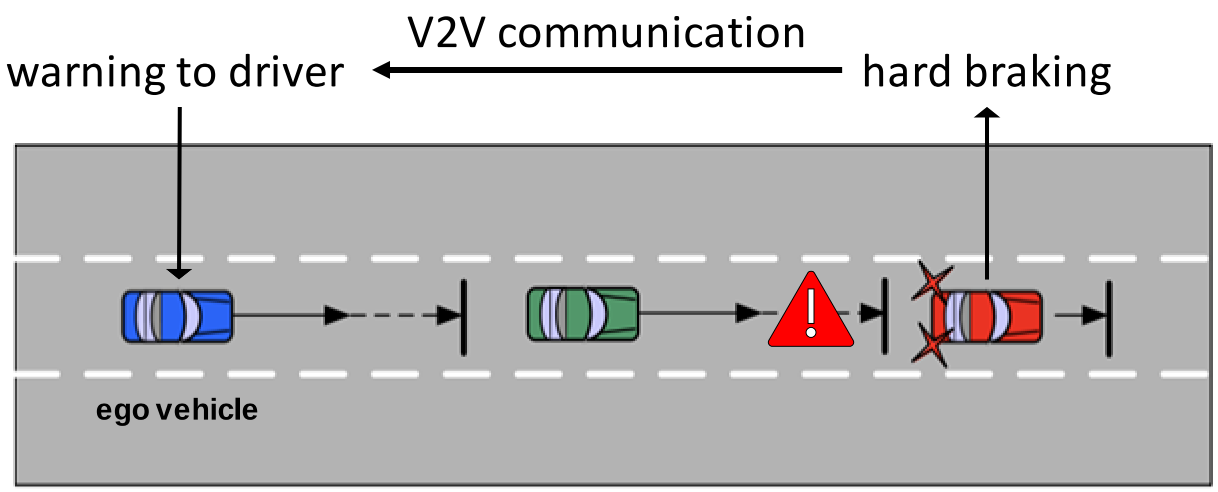
NIST

https://www.nsnam.org/

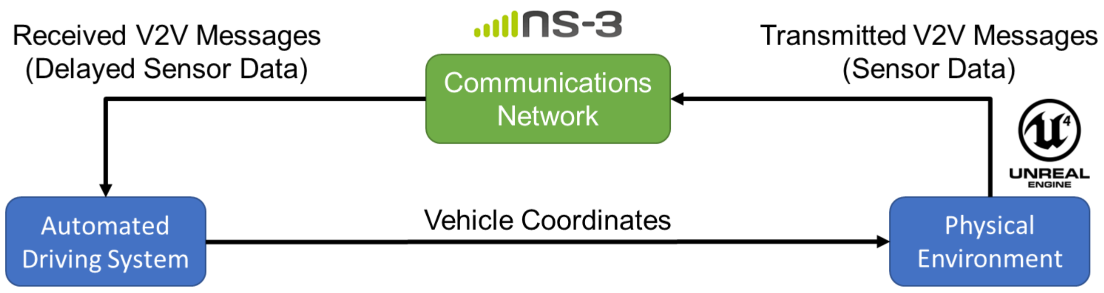
- ns-3 is a discrete-event network simulator that is:
  - open-source and maintained by a worldwide community
  - focused on the simulation of Internet and cellular systems
- A V2X extension for ns-3, available at https://apps.nsnam.org/app/nr/, was developed for 5G NR cellular networks and V2X communications which incorporates fundamental PHY-MAC NR features aligned with 3GPP NR Release 16:
  - NR frame structure
  - PSCCH and PSSCH multiplexing
  - resource allocation for NR V2X using mode 2 (autonomous resource selection)
  - both sensing-based semi-persistent and dynamic scheduling
  - blind- and feedback-based HARQ retransmissions
  - Sidelink Control Information (SCI) update
  - compliance with scenarios and channel models based on 3GPP TR 38.885 documentation
- A ROS extension for ns-3 was developed to enable these V2X features to be used in a co-simulation with automated driving simulators (such as CARLA, MathWorks Automated Driving Toolbox, …)

AV Communications Use Case Scenario

AV Communications Use Case Scenario: Emergency Electronic Brake Lights (EEBL)



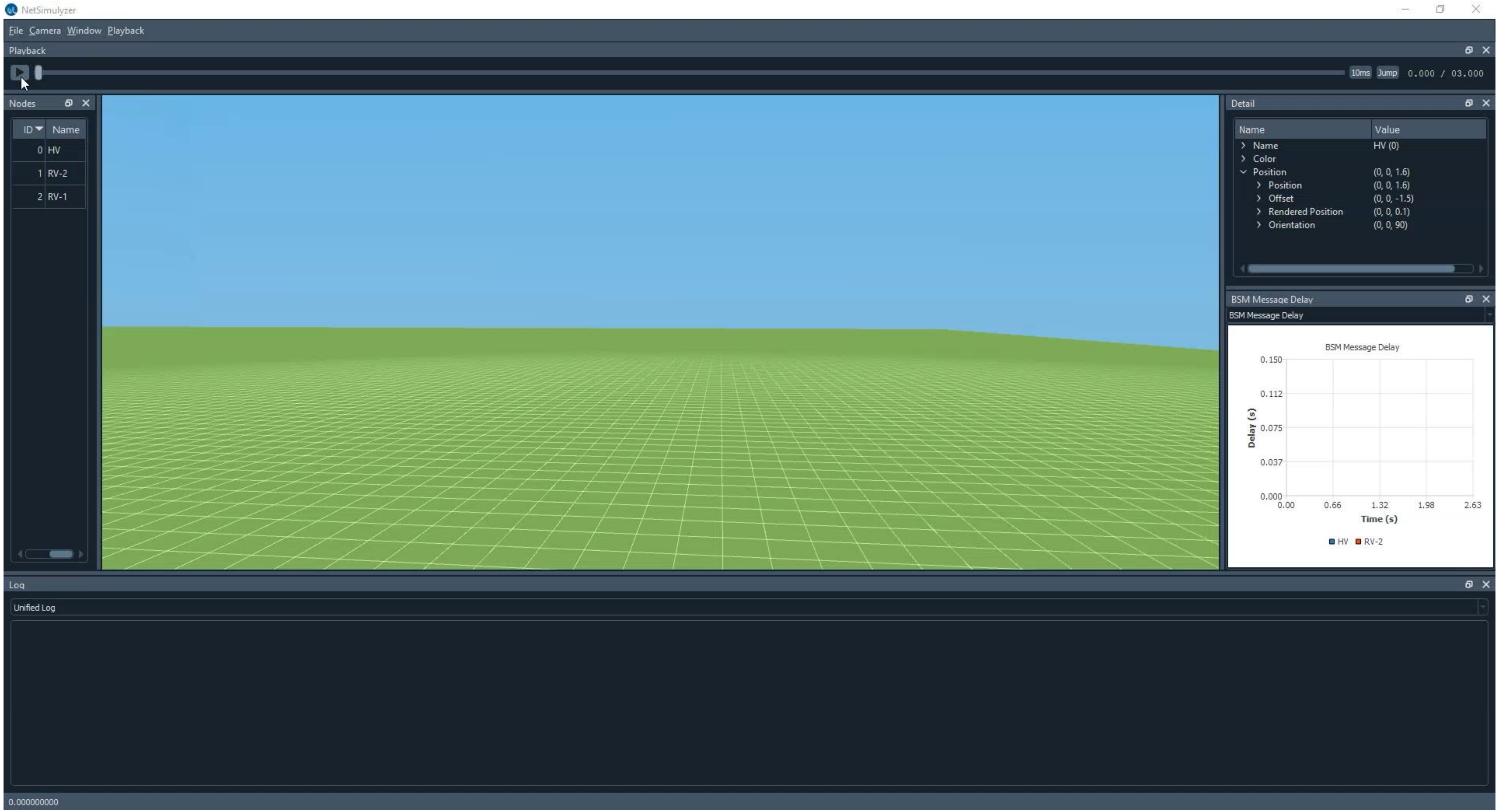
- Evaluating Emergency Electronic Brake Lights (EEBL) use case from SAE J2945/1 / ETSI TR 102 638 V1.1.1.
- Investigate ability of V2V to lower collision risk.
- Leverage previously-developed ns-3 simulation platform and link level simulator for 5G New Radio communications.
- Utilize co-simulation to incorporate onboard and offboard systems.



Status

Defined simulation scenario details.
Implemented the defined scenario.
Performing sensitivity analysis to network parameters.

Demo – Communication Only on for ALL Vehicles 250 ms Processing Delay



* Demo built upon Netsimulyzer, available at https://apps.nsnam.org/app/netsimulyzer/.

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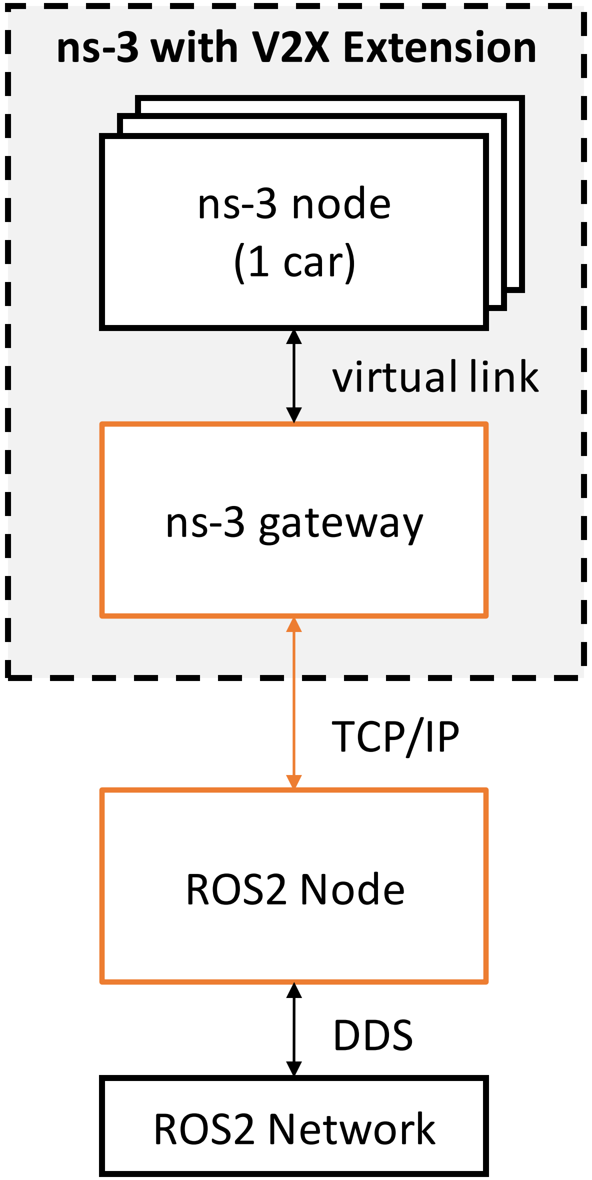
ROS2 Extension for ns-3

- A **ROS2 extension for ns-3** was developed to allow co-simulation of ns-3 models with different automated driving simulators:
  - bridges separate ns-3 and ROS2 processes using TCP/IP
  - synchronizes the ns-3 simulator time with the ROS2 /clock topic
  - uses virtual links (0 delay) to inject ROS2 messages into the ns-3 network
  - tracks vehicle positions (in ROS2) to update ns-3 node mobility models
  - integrated with the V2X extension and the EEBL scenario
- This extension was used to integrate ns-3 with Autoware and CARLA for the demo shown in the systems interaction presentation.
- The code is still being prepared for public release. When complete, it will be released as open-source software on the NIST GitHub (https://github.com/usnistgov)

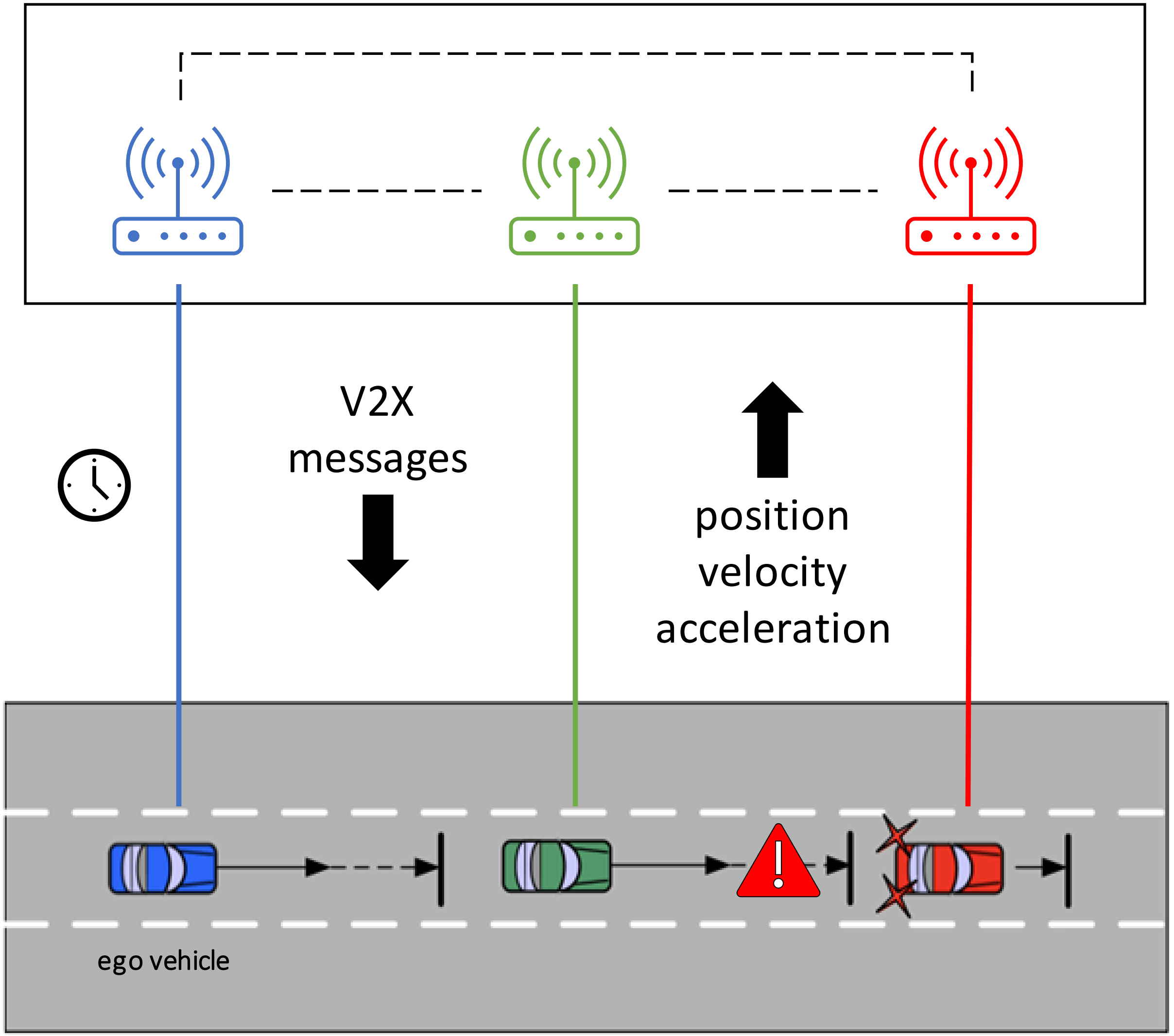


Co-Simulation of ns-3 using ROS

ns-3 NETWORK SIMULATOR

ROS (Robot Operating System 2)

Vehicle Simulator (CARLA + Autoware)

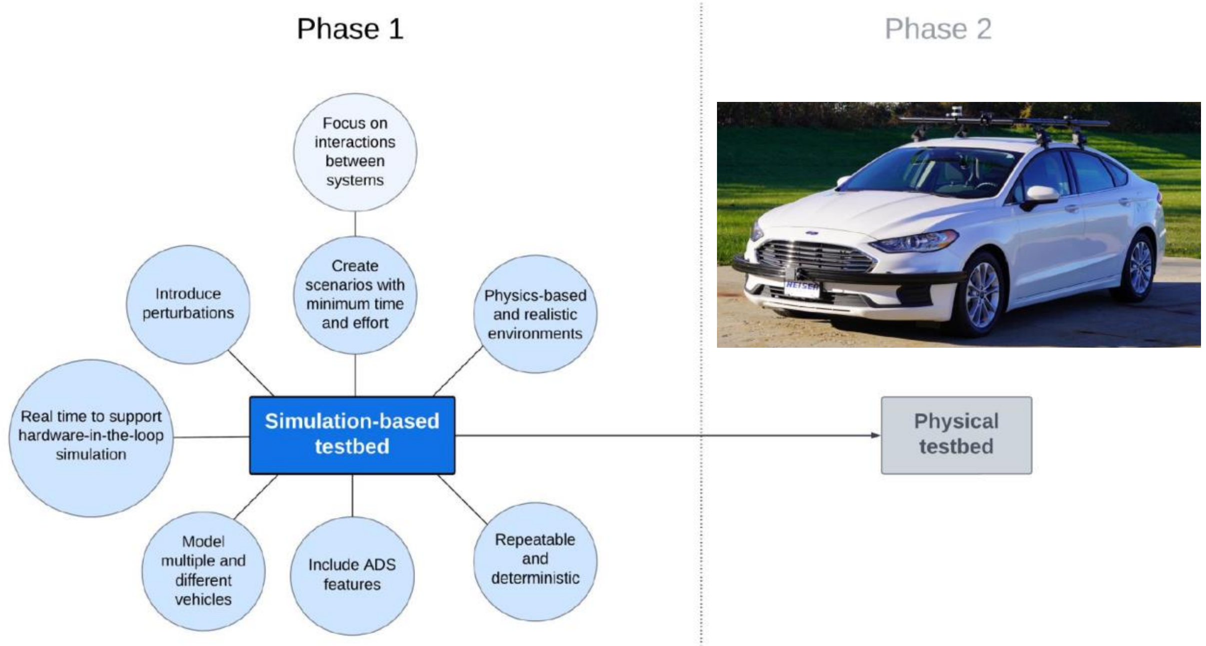


ns-3 models each car as a mobile node and simulates V2X (incl. V2V) communications using those nodes

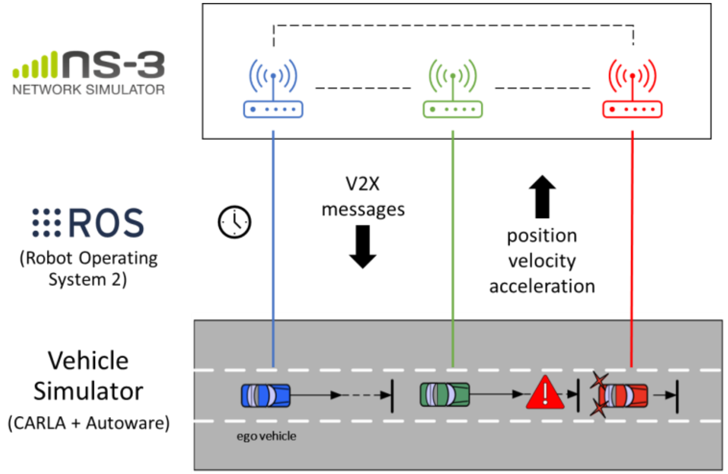
ROS 2 provides the time reference for ns-3 and manages data transfer between the different simulators

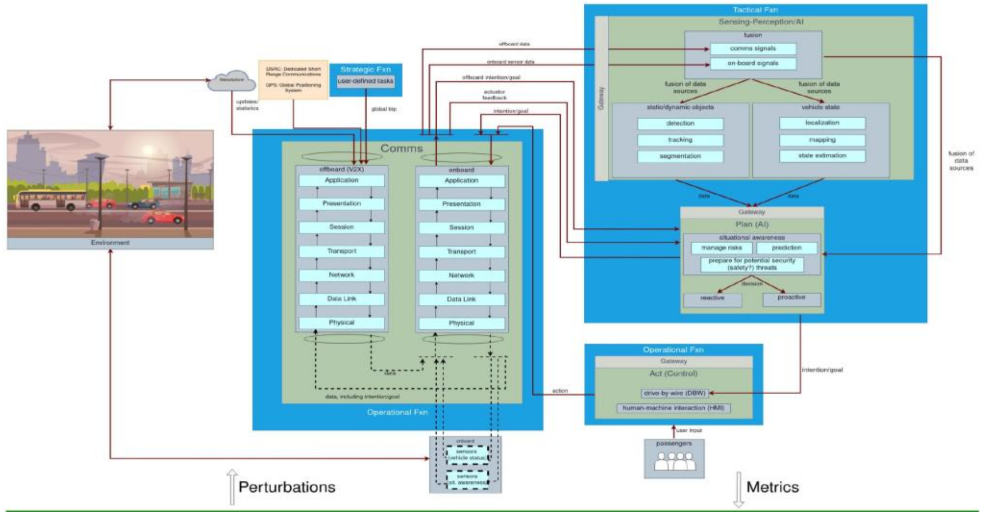
An automated driving simulator models the physical environment, control systems, and the physical response of each car

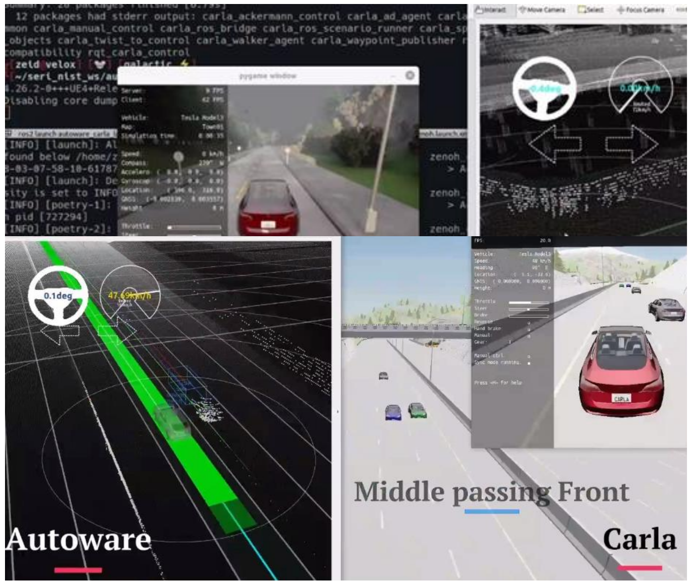
Integration with Systems Interaction Testbed



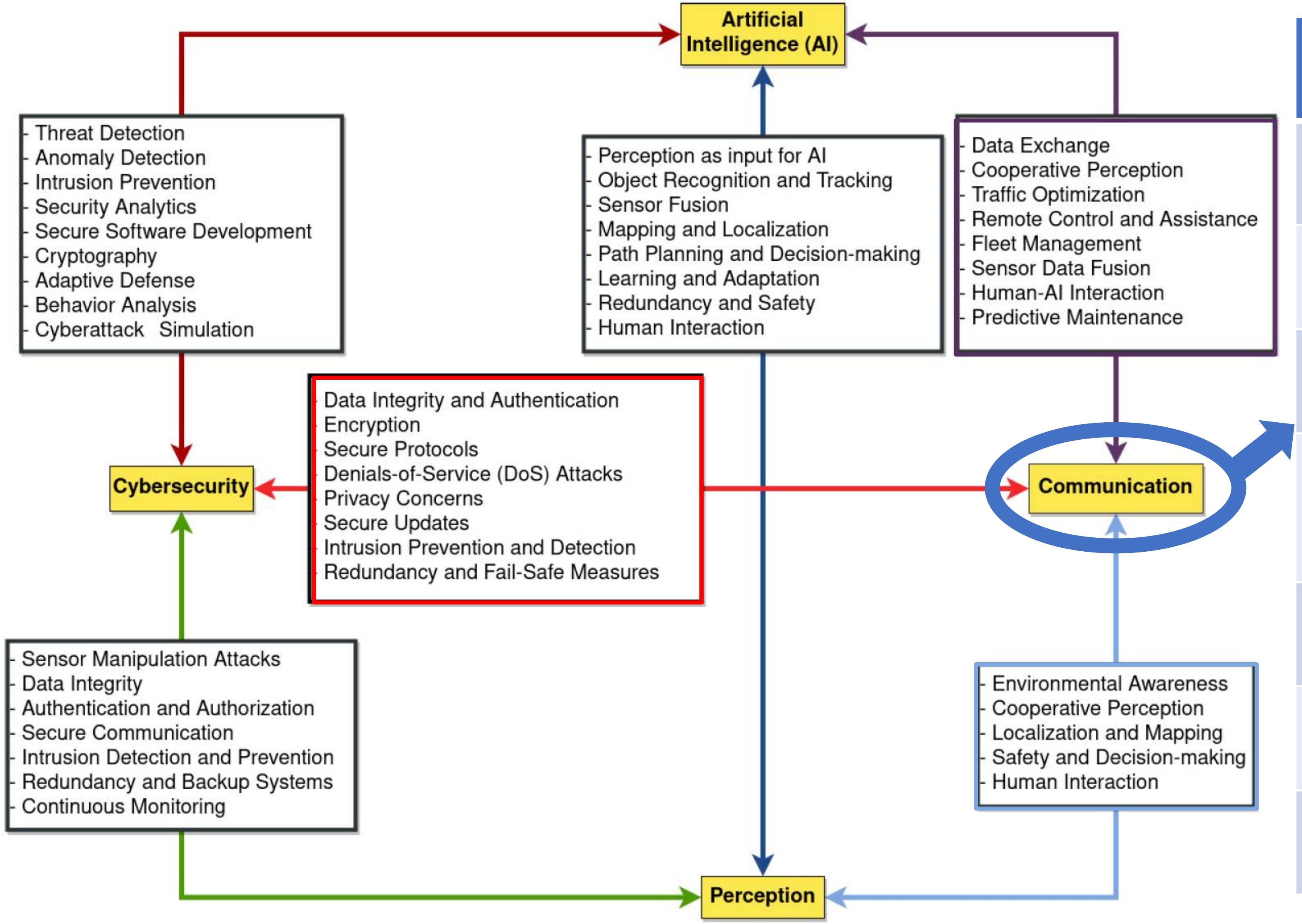
Goal: Integrate AV Communications network simulation capabilities and measurements into Systems Interaction Testbed (hardware in loop, development vehicle)







Integration with Systems Interaction Testbed



COMMUNICATIONS (ways comms impact performance)
Timing, frequency, latency to meet application requirements
Infrastructure, protocols, availability, coverage, more
Data requirements, information structure / comms
Trustworthiness (Security, Privacy, Safety, Resilience, Reliability)
Cooperative operations, remote control
Human and human-AI interactions, adaptability, AL/ML-federated learning
Environmental factors, impact on comms

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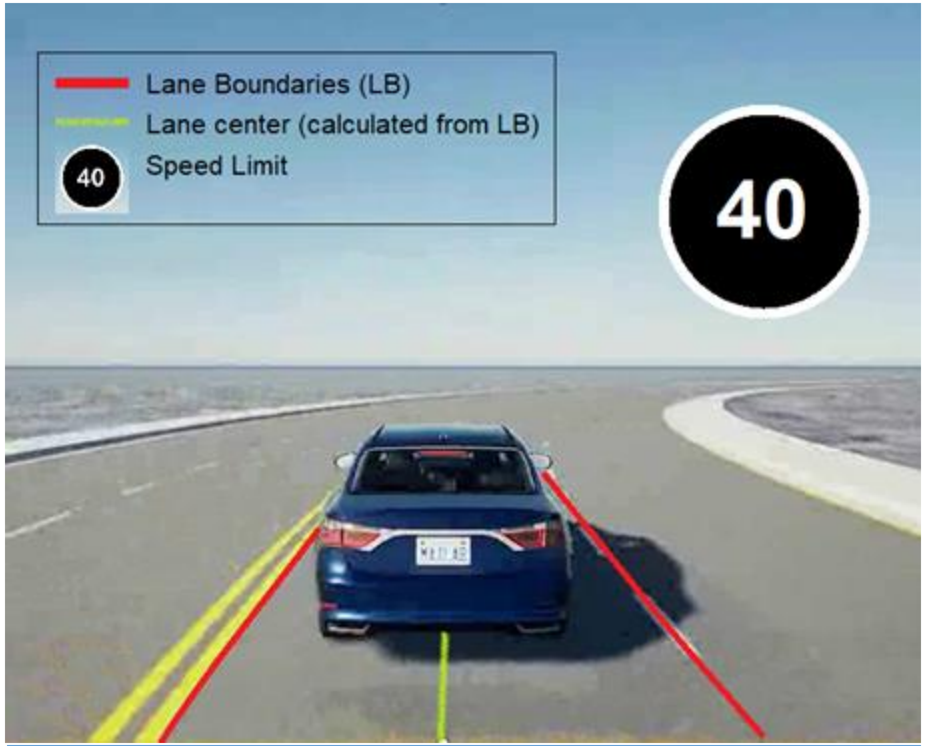
Behavioral Competency

- The **Automated Vehicle Safety Consortium (AVSC)** program of **SAE Industry Technologies Consortia (SAE ITC)** proposed a new safety methodology for automated vehicles based on an enumerable set of vehicle behaviors.
- The dynamic driving task can be considered a combination of vehicle behaviors, and a safety case can be constructed by demonstrating whether a vehicle has competency in all the behaviors required to execute its intended functions.

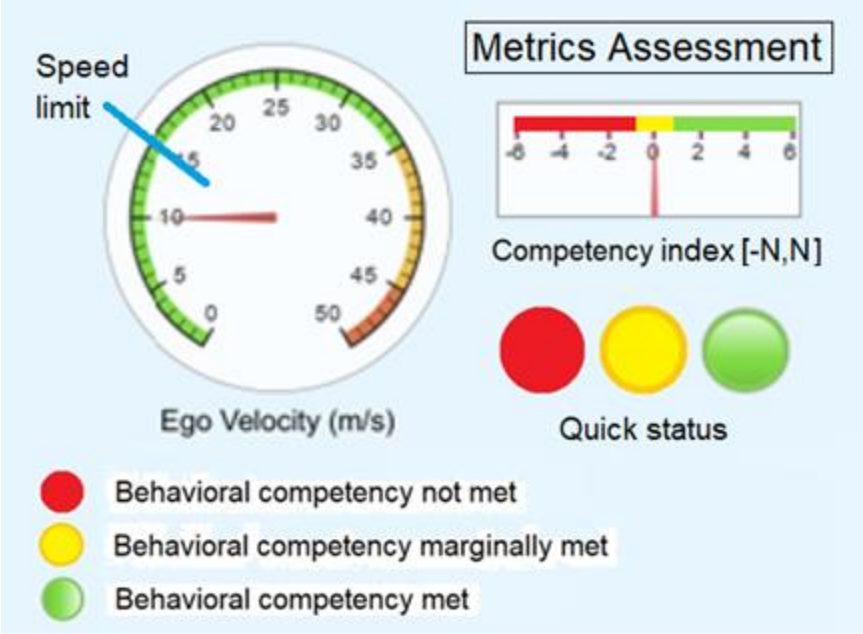
Example Behavior	Specification
Maintaining a lane	Driving along roads **predictably** and **consistently** maintaining proper lane position with respect to designated lane markings and speed limits.

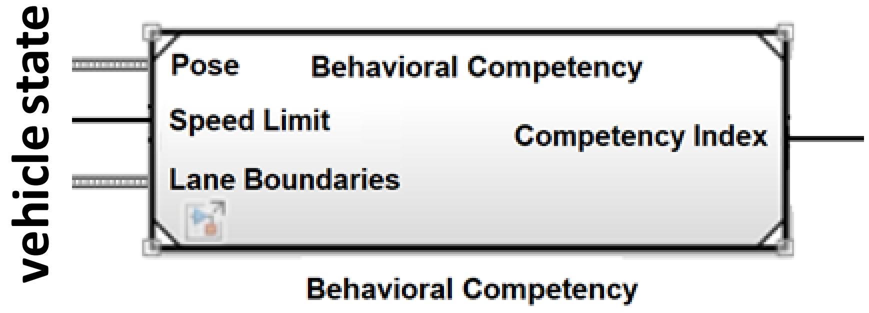
- **Behavioral Competency** in maintaining a lane, for example, may be demonstrated by acceptable "wandering distance" from the lane center and speed less than the speed limit



Concept cartoon indicating essential parameters for maintaining a lane

Measuring Behavioral Competency





- Signal temporal logic (STL) can be used to express a specification for a vehicle behavior
- For example, a simple STL specification for maintaining a lane:

$$\phi = \underbrace{\Box(v < v_{max})}_{\text{"Always maintain speed less than the speed limit"}} \wedge \underbrace{\Box(d_{center} < d_{threshold})}_{\text{"Always maintain distance from lane center less than the threshold"}}$$

STL Spec — "*Always* maintain speed less than the speed limit" AND "*Always* maintain distance from lane center less than the threshold"

- Vehicle performance can be assessed against the specification at either runtime or post-execution to measure competency
- Competency measured by ***competency index (n)***, a real number with range [-N,N], where the more positive the better
- The value of *N* depends on the system parameters

Future Directions

NIST

- Complete sensitivity analysis to V2X communication configurations and parameters for emergency braking scenario.
- Compare vehicle performance with perception only, communication only, and perception plus communication.
- Co-simulate both on-board and off-board communications.
- Explore 5G NR V2X communication mechanisms to enhance AV performance with focus on safety.
- Optimize the communication system to enhance AV performance.
- FY24 Milestone: Develop new capabilities in ns-3 network simulator required to study the effects of perturbations on AV communications and integrate these capabilities into the systems interaction testbed.
- FY24 Milestone: Develop and demonstrate measurement metrics and methods for analysis of AV communications impact on overall system performance using a representative use case in systems interaction testbed.