Hi-Drive Summer School

Transport Systems & Logistics Laboratory

Safety Verification of Autonomous Vehicles via Edge Case Testing

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Outline

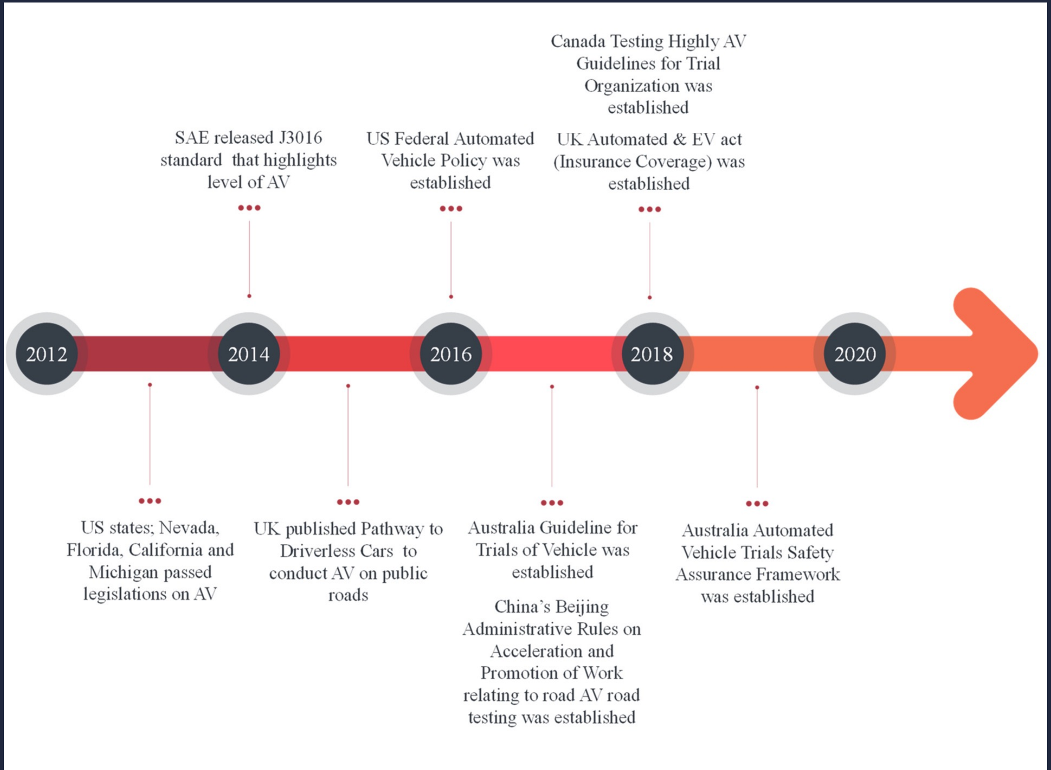
01 **Background**

02 **Edge case and virtual testing**

03 **Reality gap**

04 **Q&A**

History of AV Testing



https://encyclopedia.pub/entry/19560

Why AV Testing Matters

https://www.linkedin.com/pulse/whose-fault-when-someone-dies-autonomous-car-crash-few-sun-dahan/

Where We Are

Statistical Question	Benchmark Failure Rate		
How many miles (years[a]) would autonomous vehicles have to be driven...	**(A) 1.09 fatalities per 100 million miles?**	**(B) 77 reported injuries per 100 million miles?**	**(C) 190 reported crashes per 100 million miles?**
(1) without failure to demonstrate with 95% confidence that their failure rate is at most...	275 million miles (12.5 years)	3.9 million miles (2 months)	1.6 million miles (1 month)
(2) to demonstrate with 95% confidence their failure rate to within 20% of the true rate of...	8.8 billion miles (400 years)	125 million miles (5.7 years)	51 million miles (2.3 years)
(3) to demonstrate with 95% confidence and 80% power that their failure rate is 20% better than the human driver failure rate of...	11 billion miles (500 years)	161 million miles (7.3 years)	65 million miles (3 years)

[a] We assess the time it would take to compete the requisite miles with a fleet of 100 autonomous vehicles (larger than any known existing fleet) driving 24 hours a day, 365 days a year, at an average speed of 25 miles per hour.

https://www.rand.org/content/dam/rand/pubs/research_reports/RR1400/RR1478/RAND_RR1478.pdf/

AV Testing Method

Virtual Simulation

Use computer simulations and virtual environments to assess the performance, behaviour, and safety of self-driving systems.

Hardware-in-the-Loop

HIL focuses on testing the interaction between the hardware components in a controlled environment.

Use actual vehicle in a controlled and isolated environment to eliminate the potential risks associated with public road.

Closed Track

Assess the performance and capabilities of AVs interacting with dynamic environment in open-road conditions.

On-Road Trail

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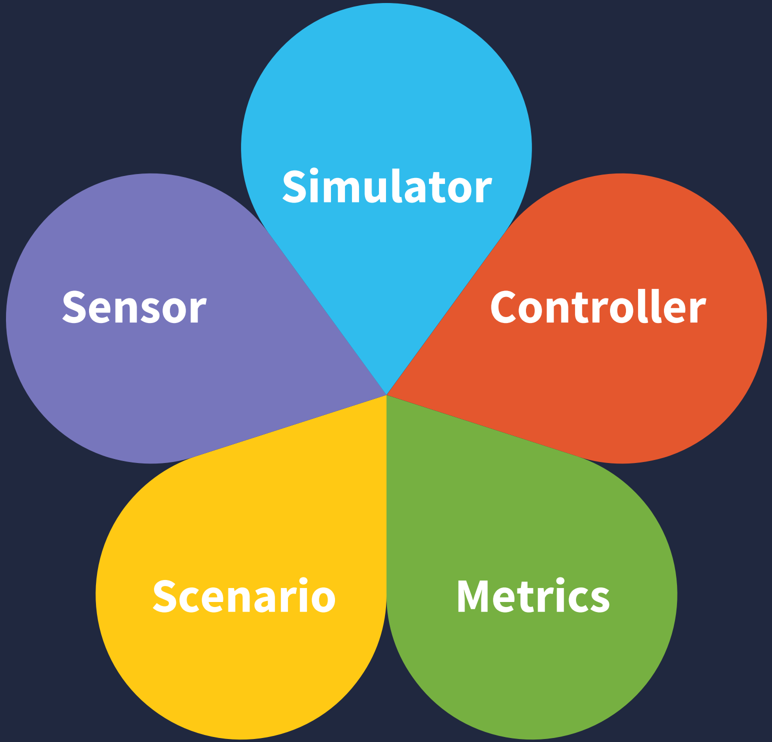
AV Testing Method

	Virtual Simulation	Hardware-in-the-Loop	Closed Track	On-Road Trail
Advantage	• Safety • Scalability • Reproducibility • Cost-efficiency	• Safety • Reduced cost • Reproducibility • Real hardware integration	• Safety • Reduced cost • Real vehicle dynamics • Controlled environment	• Adaptive learning • Scenario diversity • Human interaction • Real-world validation
Deficiency	• Limited realism • Unrealistic scenario • Less accurate sensor models	• Limited realism • Scalability challenges • Integration complexity • Simplified sensor inputs	• Overfitting • Testing scale • Simplified scenarios • Limited human interaction	• Safety concern • Scalability challenges • Limited reproducibility • Unpredictable scenarios

Edge Case

A rare or uncommon risky scenario that is outside the typical or expected conditions that an AV might encounter, but not beyond the realm of possibility.

Components of Virtual Simulation



Represent the physical environment where the vehicle operates.

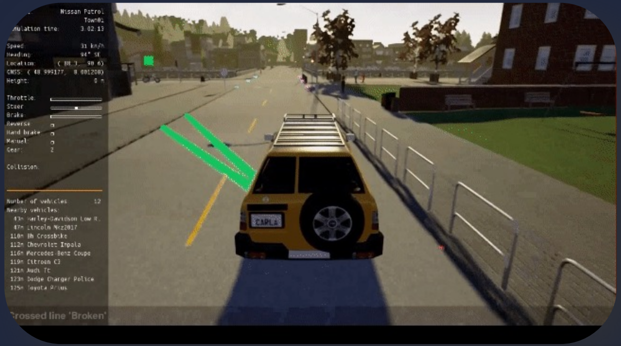
Representation of perception and localisation hardware.

Algorithms that interpret sensor inputs and generate action.

Definition and specification of tests to run.

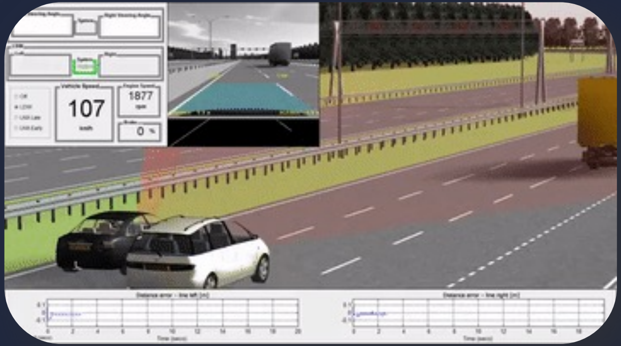
Models that help to evaluate the performance of controller.

Simulator



Carla

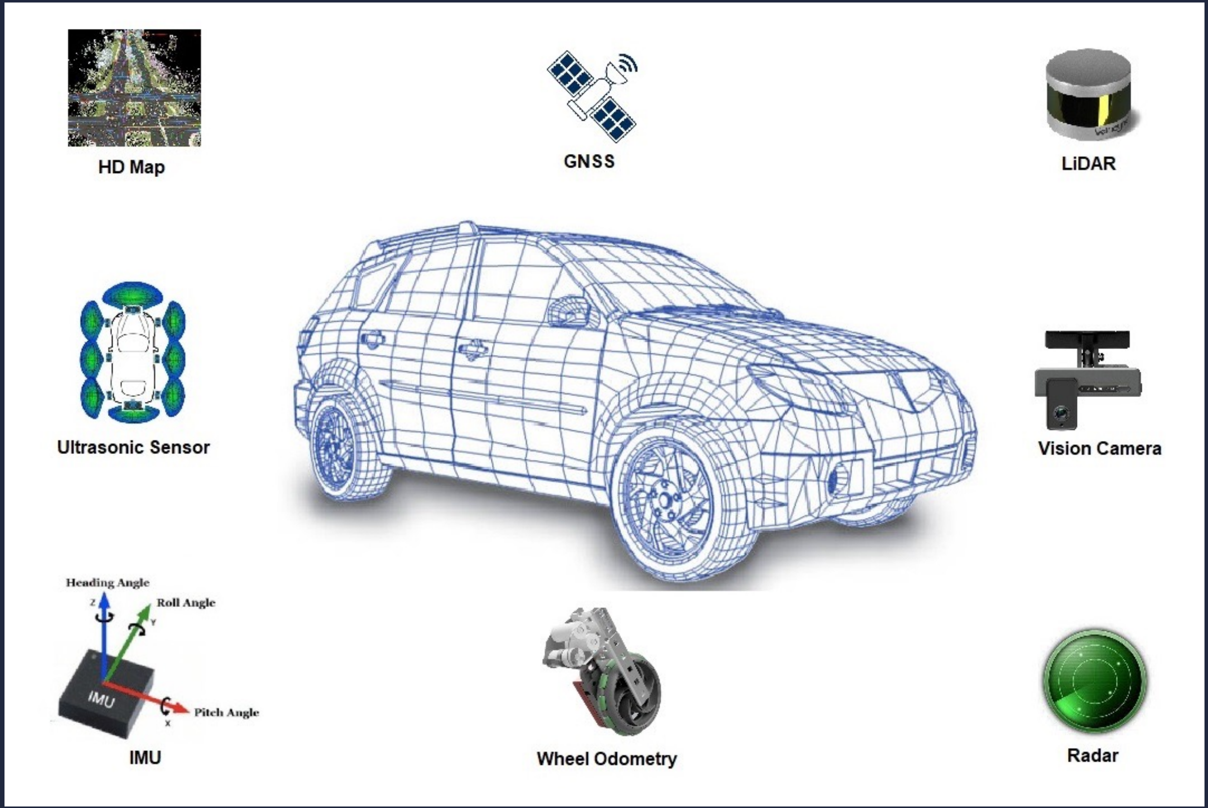
LGSVL



PreScan

AirSim

Sensor


HD Map
GNSS
LiDAR
Ultrasonic Sensor
Vision Camera
Heading Angle
Roll Angle
Pitch Angle
IMU
IMU
Wheel Odometry
Radar

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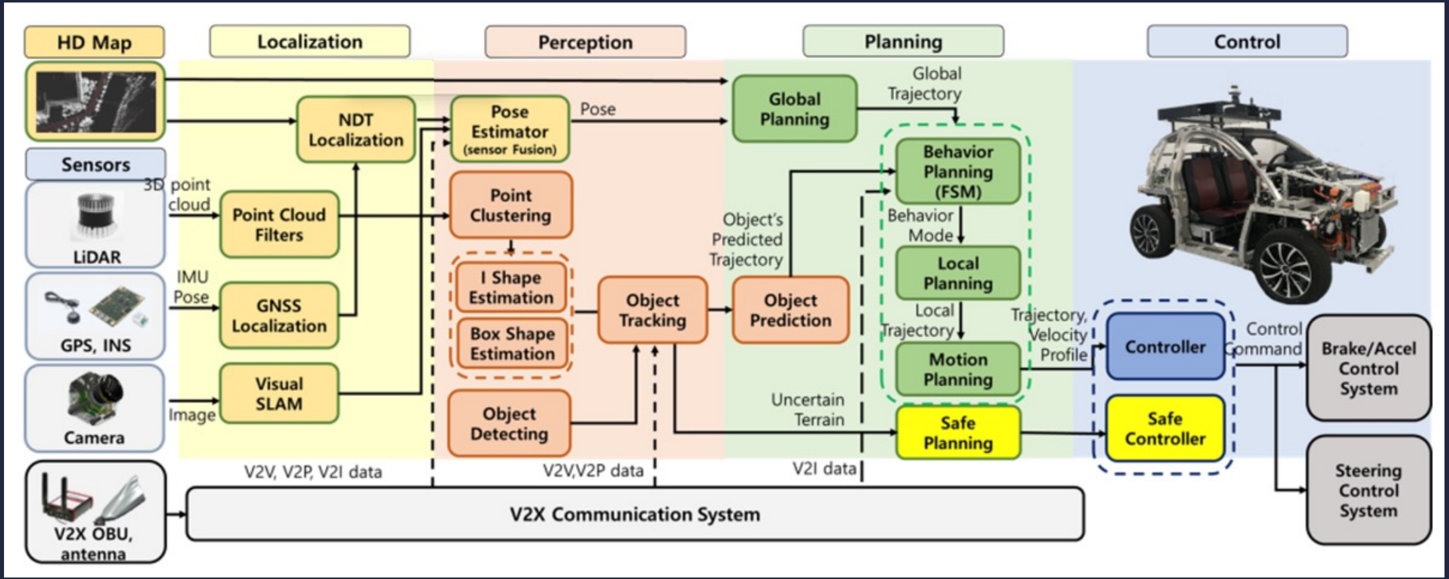
Controller



https://hmc.unist.ac.kr/research/autonomous-driving/

Autoware apollo ASLAN AUTONOMY openpilot

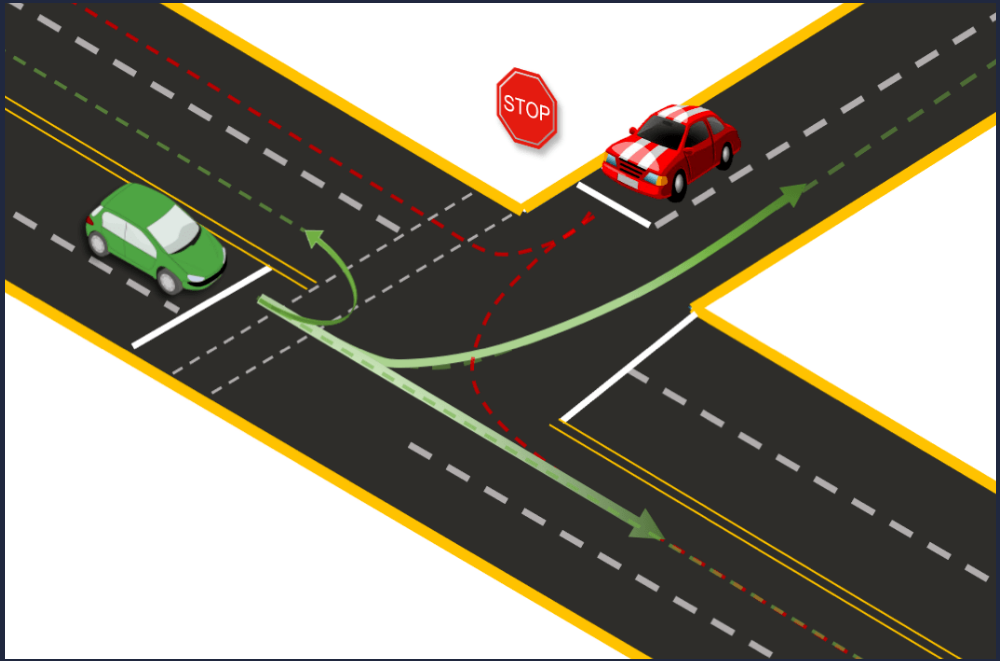
AV Testing Scenario

Scene

- Road, lane, and signals
- OpenDRIVE, Lanelet2

Scenario

- Motion of dynamic agent
- OpenSCENARIO, GeoScenario, SDL



Scene

ASAM OpenDRIVE defines a file format for the description of the road networks and their attributes.

It serves as a common data exchange format for sharing road information between various simulation tools, mapping software and AV platforms.


```xml
<OpenDRIVE>
    <road name="Road 1" length="2.5664892421878175e+1" id="1" junction="4">
        <link>
            <predecessor elementType="road" elementId="0" contactPoint="start"/>
            <successor elementType="road" elementId="3" contactPoint="start"/>
        </link>
        <planView>
            <geometry s="0.0000000000000000e+0" x="-5.7058023130732725e+0" y="2.2918871305676227e+1" hdg="4.2488480279107073e+0" length="2.1379679082546694e+0">
                <line/>
            </geometry>
            <geometry s="2.1379679082546694e+0" x="-6.6617266682988623e+0" y="2.1006512708599473e+1" hdg="4.2488480279107073e+0" length="1.0687328516700093e+1">
                <arc curvature="-3.0692654903585817e-2"/>
            </geometry>
            <geometry s="1.2825296424954761e+1" x="-1.2908857211963886e+1" y="1.2394203769607298e+1" hdg="3.9208255419063809e+0" length="1.0701541307682014e+1">
                <arc curvature="-2.8317873126663361e-2"/>
            </geometry>
            <geometry s="2.3526837732636775e+1" x="-2.1537303911266324e+1" y="6.1332832193376987e+0" hdg="3.6177806528956946e+0" length="2.1380546892413990e+0">
                <line/>
            </geometry>
        </planView>
        <elevationProfile/>
        <lateralProfile/>
        <lanes>
            <laneOffset s="0.0000000000000000e+0" a="0.0000000000000000e+0" b="0.0000000000000000e+0" c="0.0000000000000000e+0" d="0.0000000000000000e+0"/>
            <laneSection s="0.0000000000000000e+0">
                <left>
                    <lane id="1" type="driving" level="false">
                        <link>
                            <predecessor id="-1"/>
                            <successor id="1"/>
                        </link>
                        <width sOffset="0.0000000000000000e+0" a="3.5000000000000000e+0" b="0.0000000000000000e+0" c="0.0000000000000000e+0" d="0.0000000000000000e+0"/>
                        <roadMark sOffset="0.0000000000000000e+0" type="none" material="standard" color="white" laneChange="none"/>
                        <userData>
                            <vectorLane sOffset="0.0000000000000000e+0" laneId="{bb8e946c-b7d4-4bb1-bffe-5b3edfd8b2fc}" travelDir="backward"/>
                        </userData>
                    </lane>
                </left>
                <center>
                    <lane id="0" type="none" level="false">
                        <roadMark sOffset="0.0000000000000000e+0" type="none" material="standard" color="white" laneChange="none"/>
                        <userData/>
                    </lane>
                </center>
            </laneSection>
        </lanes>
    </road>
```


Example of a road segment

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Scenario

ASAM OpenSCENARIO defines a file format for the description of the dynamic content of driving and traffic simulators.

The primary use-case of OpenSCENARIO is to describe complex, synchronized maneuvers that involve multiple entities like vehicles, pedestrians and other traffic participants.

```xml
<OpenSCENARIO>
  <Storyboard>
    <Story name=" ">
      <Act name="Vehicle 0">
        <Sequence name="Vehicle 0" numberOfExecutions="1">
          <Actors>
            <Entity name="Vehicle 0"/>
          </Actors>
          <Maneuver name="Vehicle 0">
            <Event name="Vehicle 0:10.4409342" priority="overwrite">
              <Action name="SetTargetSpeed">
                <Private>
                  <Longitudinal>
                    <Speed>
                      <Dynamics shape="step" rate="0" time="0.1046572000000012"/>
                      <Target>
                        <Absolute value="0.29959452122063196"/>
                      </Target>
                    </Speed>
                  </Longitudinal>
                </Private>
              </Action>
              <StartConditions>
                <ConditionGroup>
                  <Condition name="StartCondition" delay="0" edge="rising">
                    <ByValue>
                      <SimulationTime value="10.4409342" rule="greater_than"/>
                    </ByValue>
                  </Condition>
                </ConditionGroup>
              </StartConditions>
            </Event>
```

Example of an event

Metrics

- Time-to-collision (TTC)
- Responsibility-Sensitive Safety (RSS)
- Deceleration Rate to Avoid a Crash (DRAC)
- Time Integrated Time-to-collision (TIT)
- Time Exposed Time-to-collision (TET)
- Bespoke risk index

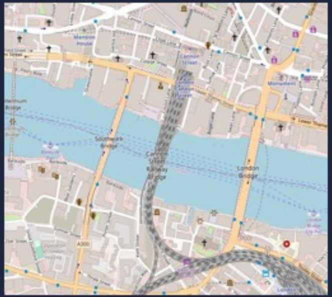
$$d^{lon}_{min} = \left[v_r\rho + \frac{1}{2}\rho^2 a_{max,accel} + \frac{(v_r + \rho a_{max,accel})^2}{2a_{min,brake}} - \frac{v_f^2}{2a_{max,brake}} \right]_+$$

$$d^{lon}_{min,brake} = \left[v_r\rho + \frac{1}{2}\rho^2 a_{r,\rho} + \frac{(v_r + \rho a_{max,accel})^2}{2A_{brake}} - \frac{v_f^2}{2a_{max,brake}} \right]_+$$

$$r_{lon} = \begin{cases} 0, & \text{if } d^{lon} \geq d^{lon}_{min} > 0 \\ 1 - \frac{d^{lon} - d^{lon}_{min,brake}}{d^{lon}_{min} - d^{lon}_{min,brake}}, & \text{if } d^{lon}_{min} \geq d^{lon} \geq d^{lon}_{min,brake} > 0 \\ 1, & \text{otherwise} \end{cases}$$

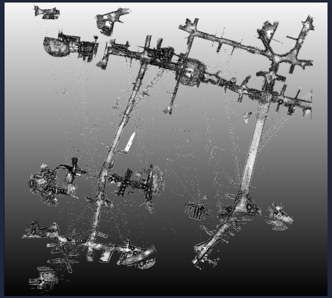
Proposed Pipeline

- Automatic map generation of real-world locations
- CV or parameterised traffic flow generation
- Autoware-controlled ego vehicle on customised maps
- Risk evaluation

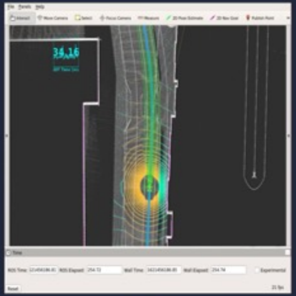

OpenStreetMap


3D Model


OpenDrive

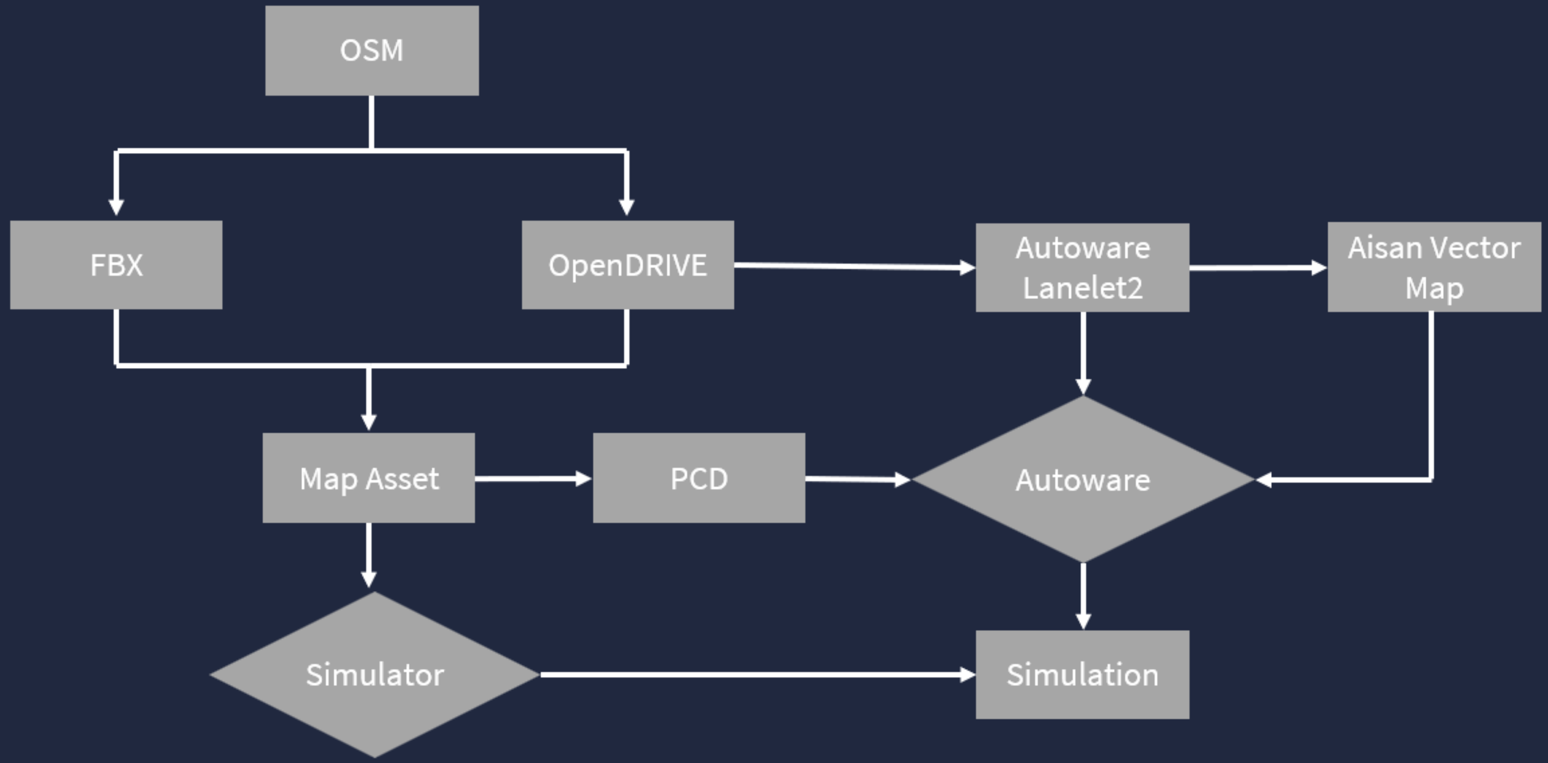

PCD


Simulation


Rviz

Y. Feng et al., "Rapid Procedural Generation of Real World Environments for Autonomous Vehicle Testing," *ICRA 2023 Workshop on Bridging the Lab-to-Real Gap: Conversations with Academia, Industry, and Government.*

Proposed Pipeline



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Example

Scenario Extraction

- Library of junction video footages from TfL
- Road agent detection and tracking
- Automated trajectory extraction
- Risk evaluation

d(risk)

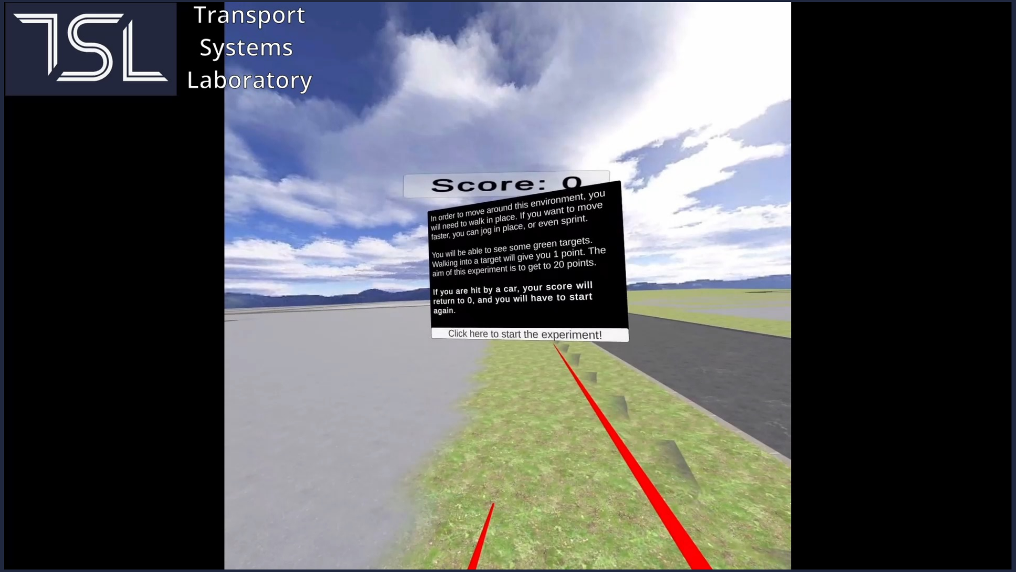
Scenario Replication

Live Evaluation

- Ego vehicle controlled via driving rig, traffic vehicles controlled by SUMO.
- Sensor detection with real-time risk metrics calculation.
- Live plot to give instant driving safety feedback.

Pedestrian Perception

- 97 participants
- 17 sessions
- 3-13 people in groups
- Walk-in-place locomotion
- Multiplayer setup



A. Shipman et al., "Novel trajectory prediction algorithm using a full dataset: comparison and ablation studies," *2022 IEEE International Conference on Intelligent Transportation Systems (ITSC).*

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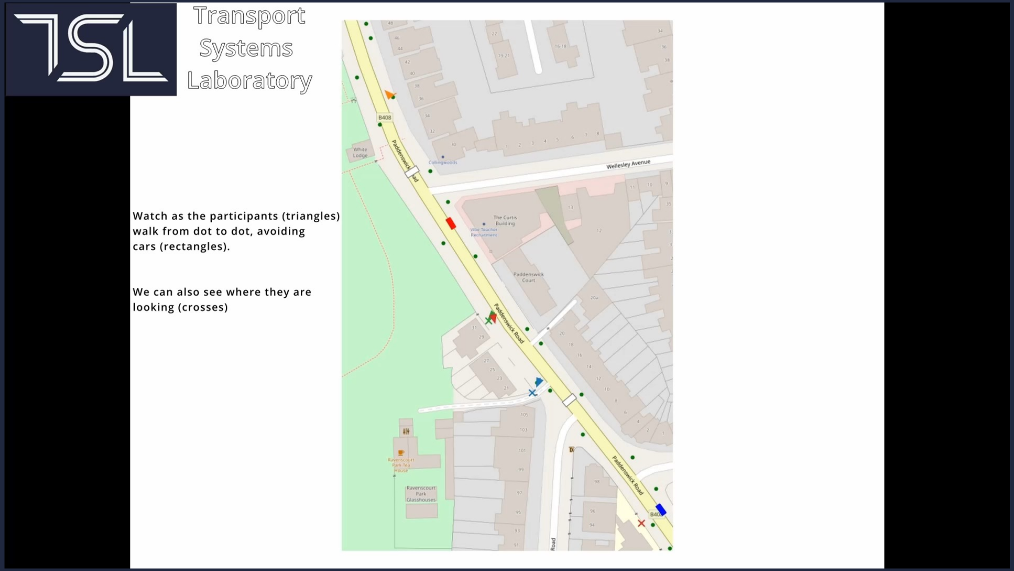
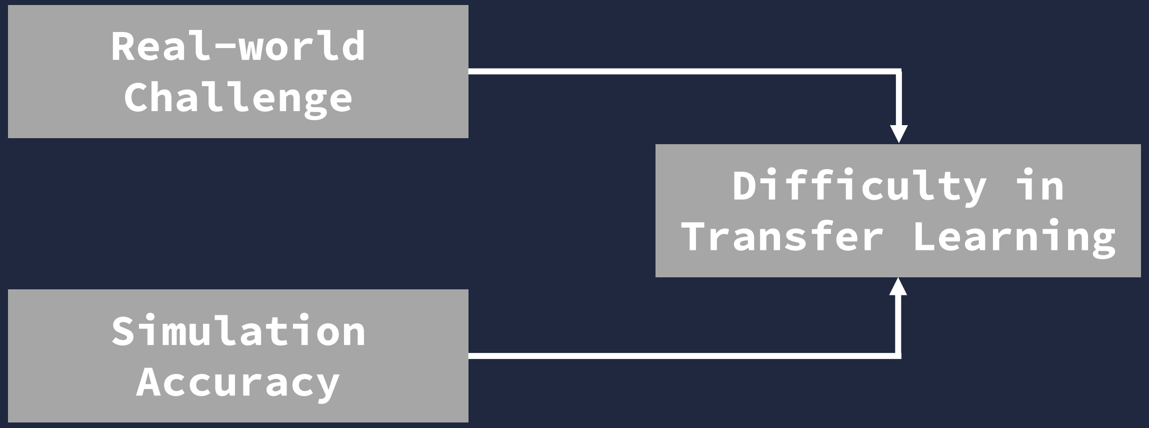
Pedestrian Perception

- Position
- Gaze point
- Destination
- TTC to incoming vehicle

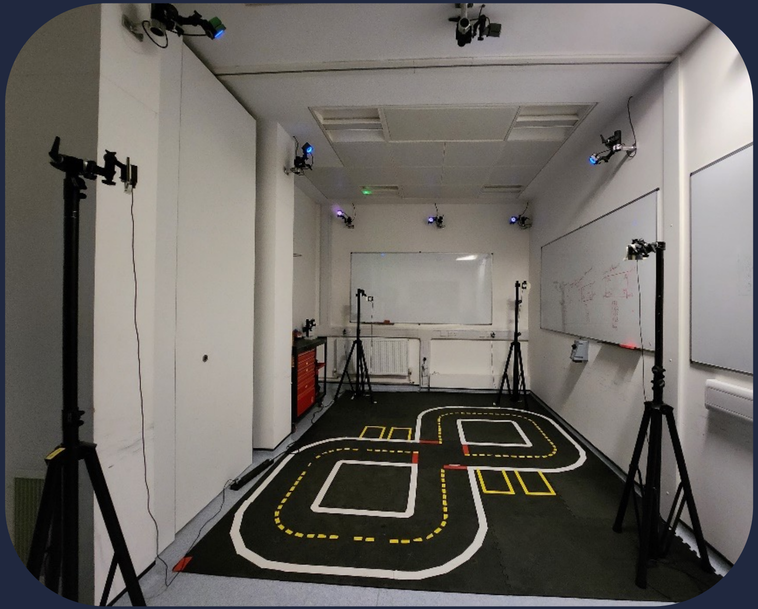


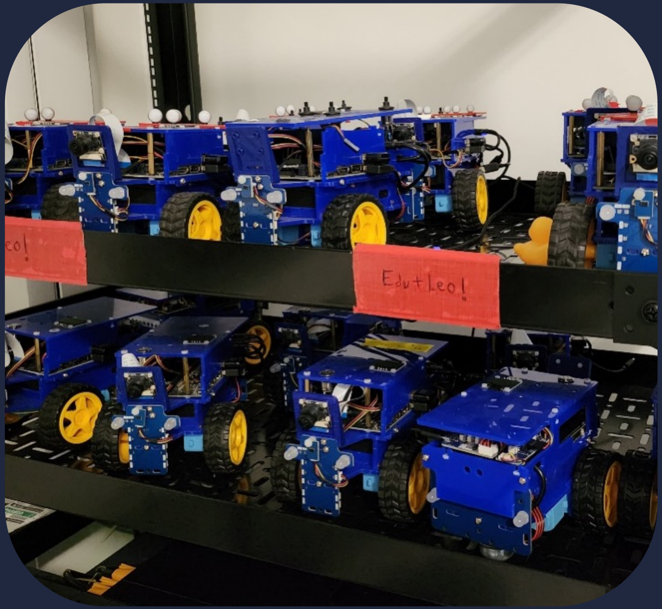
Reality Gap

The disparity or mismatch between performance or behavior observed in simulated environments and that observed in real-world.

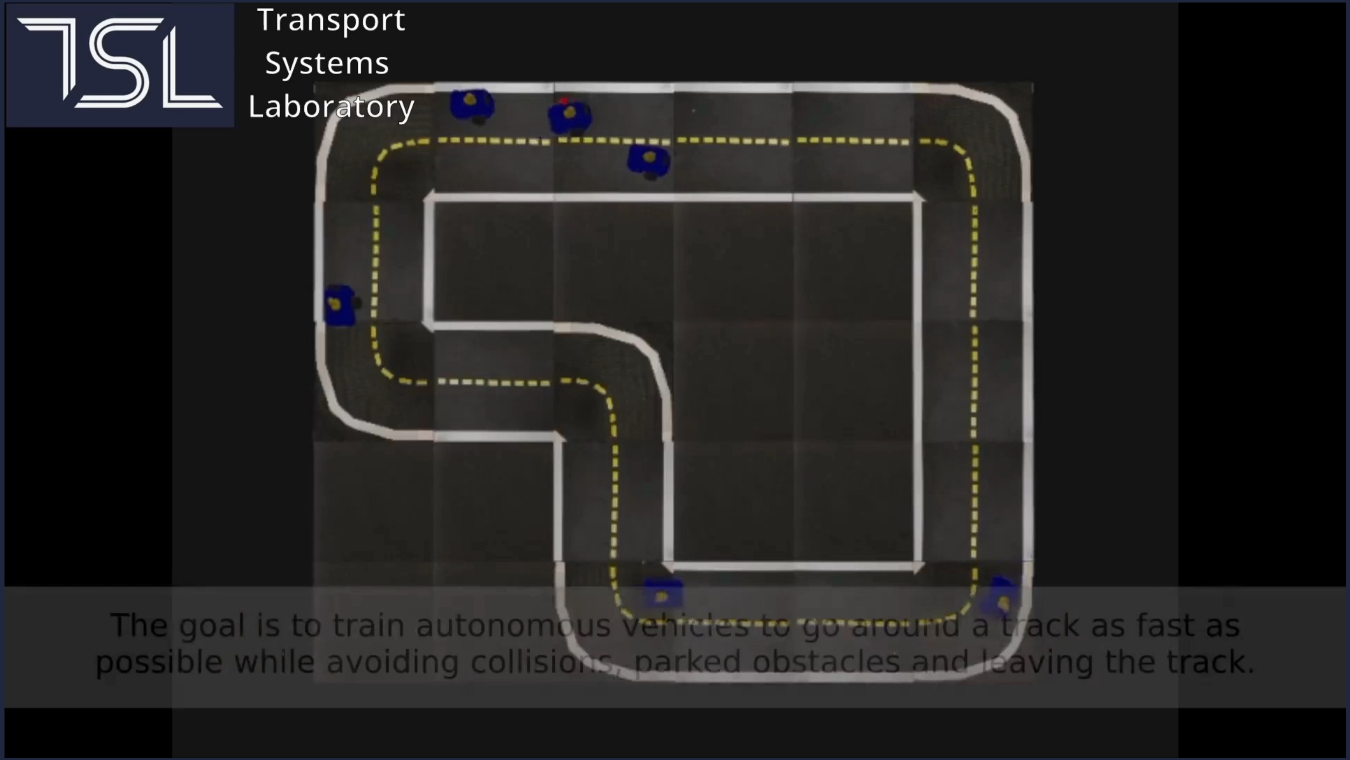


Reality Gap





Reality Gap



E. Candela et al., "Transferring Multi-Agent Reinforcement Learning Policies for Autonomous Driving using Sim-to-Real," *2022 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*.

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Thank you!

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