Verified Artificial Intelligence and Autonomy

Sanjit A. Seshia

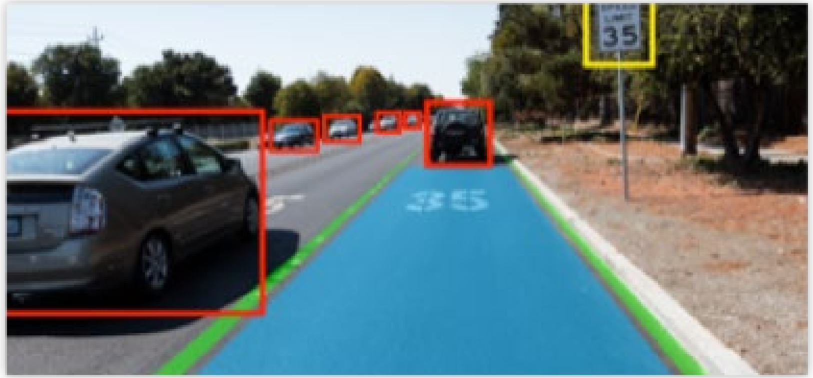
Professor

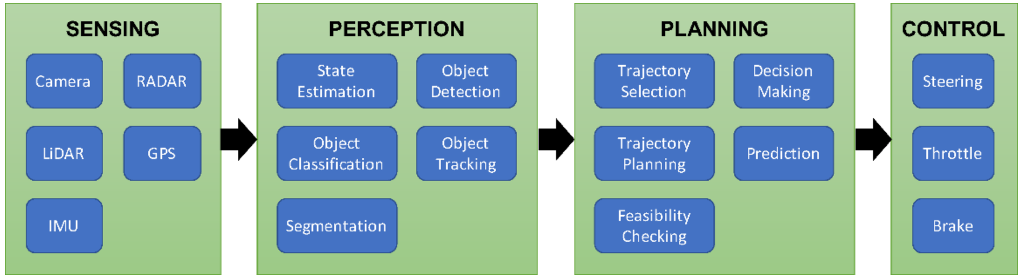
EECS Department, UC Berkeley

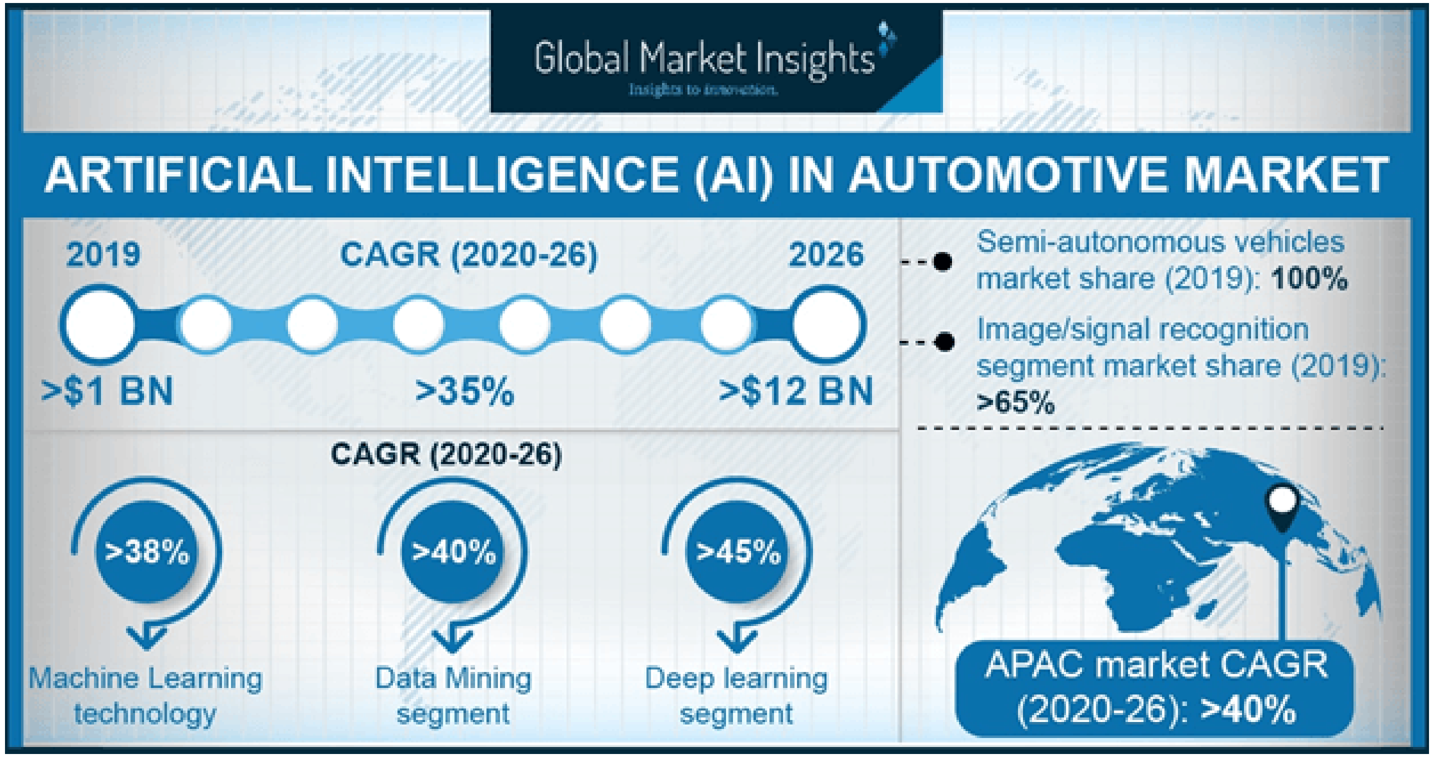
IFIP WG10.4 IVDS Workshop
January 31, 2021

http://vehical.org

Growing Use of Machine Learning/Artificial Intelligence in Safety-Critical Autonomous Systems







Source: gminsights.com

Growing Concerns about Safety:

- Numerous papers showing that *Deep Neural Networks can be easily fooled*
- *Accidents*, including some *fatal,* involving potential failure of AI/ML-based perception systems in self-driving cars

Can Formal Methods Help?

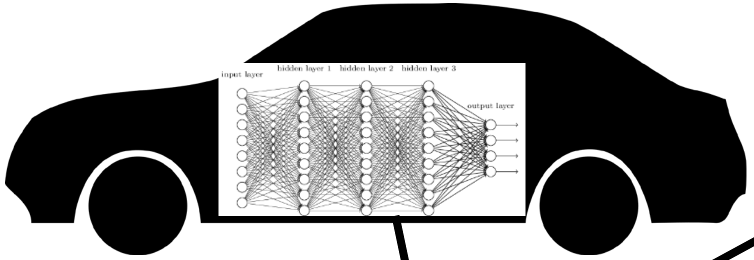
Formal methods = Mathematical, Algorithmic techniques for modeling, design, analysis

- Specification: WHAT the system must/must not do
- Verification: WHY it meets the spec. (or not)
- Synthesis: HOW it meets the spec. (correct-by-construction design)

Can we address the Design & Verification challenges of AI/ML-based Autonomy with Formal Methods?

Challenges for Verified AI

S. A. Seshia, D. Sadigh, S. S. Sastry.
Towards Verified Artificial Intelligence. July 2016. https://arxiv.org/abs/1606.08514.



System **S**

Environment **E**

Specification **φ**

Does S || E satisfy φ?

YES [+ proof]

NO [+ counterexample]

Need to Search Very High-Dimensional Input and State Spaces

Design Correct-by-Construction?

Need Principles for Verified AI

Challenges | **Principles**

1. Environment (incl. Human) Modeling →
2. Formal Specification →
3. Learning Systems Representation →
4. Scalable Training, Testing, Verification →
5. Design for Correctness →

?

S. A. Seshia, D. Sadigh, S. S. Sastry. *Towards Verified Artificial Intelligence*. July 2016. https://arxiv.org/abs/1606.08514.

http://learnverify.org/VerifiedAI

Talk Outline

- Environment Modeling
- Simulation-Based Verification
- Simulation → Road Testing
- Principles for Verified AI

Environment Modeling: Know Your Assumptions!

More Challenging

What's Unknown/ Uncertain		Approach
Parameters		**Probabilistic Programming and Reasoning** [D. Fremont et al., PLDI 2019]
Behaviors / Dynamics		**Learning Models from Data/Interaction** [D. Sadigh et al., RSS & IROS 2016; M. Vazquez-Chanlatte et al., NeurIPS 2018]
Agents / Objects		**Introspective Environment Modeling** [S. A. Seshia, RV 2019]

SCENIC: Environment Modeling and Data Generation

- *Scenic* is a probabilistic programming language defining *distributions over scenes/scenarios*
- *Use cases:* data generation, test generation, verification, debugging, design exploration, etc.

```
model scenic.domains.driving.model

ego = Car

spot = OrientedPoint on visible curb
badAngle = Uniform(1.0, -1.0) * Range(10, 20) deg
parkedCar = Car left of spot by 0.5,
                facing badAngle relative to roadDirection
```

```
model scenic.domains.driving.model

behavior PullIntoRoad():
    while (distance from self to ego) > 15:
        wait
    FollowLaneBehavior(lane=ego.lane)

ego = Car with behavior DriveAvoidingCollisions

spot = OrientedPoint on visible curb
badAngle = Uniform(1.0, -1.0) * Range(10, 20) deg
parkedCar = Car left of spot by 0.5,
                facing badAngle relative to roadDirection,
                with behavior PullIntoRoad
```

Example: Badly-parked car

Image created with GTA-V

Video created with CARLA

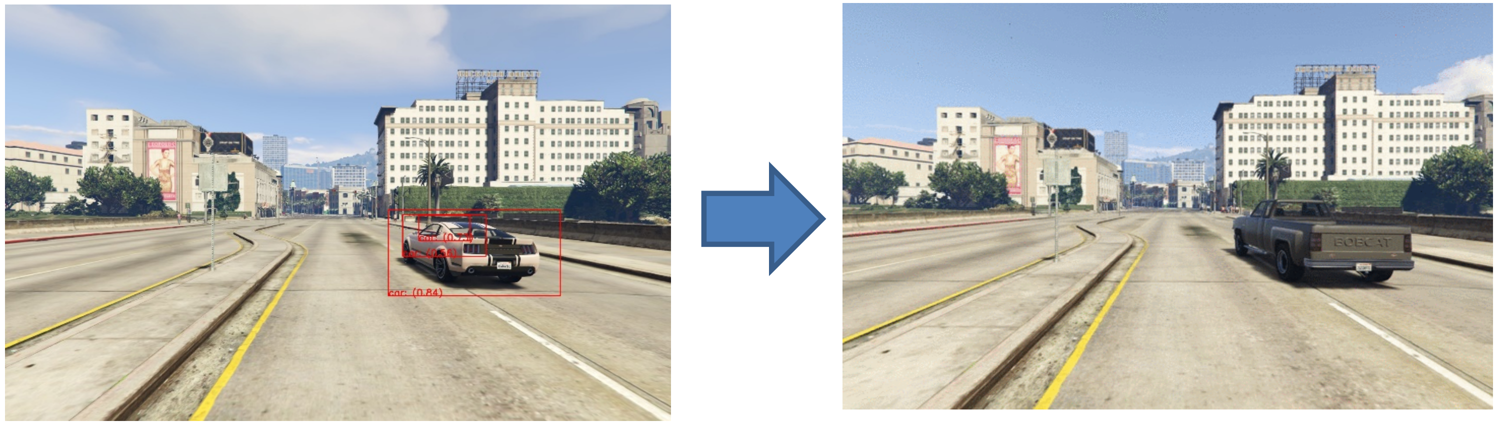
[D. Fremont et al., "Scenic: A Language for Scenario Specification and Scene Generation", TR 2018, PLDI 2019.]

Some Applications of Scenic [details in PLDI 2019 paper]

- Data Generation, (Re)-Training
  - More controllable, interpretable
  - Improves performance significantly
  - Rare scenarios, controlled distributions, etc.

Car detection with occlusions

- Debugging Failures
  - Vary scenarios systematically
  - Explain failures of ML



Test Hypothesis: does the car model lead to a mis-detection?

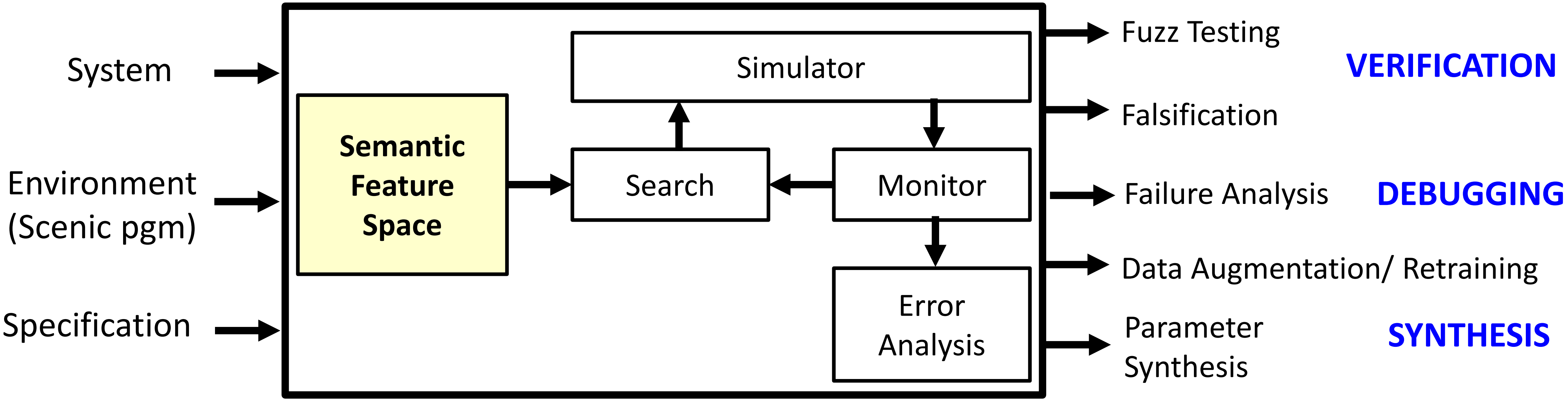
- Design Space Exploration

Simulation-Based Verification

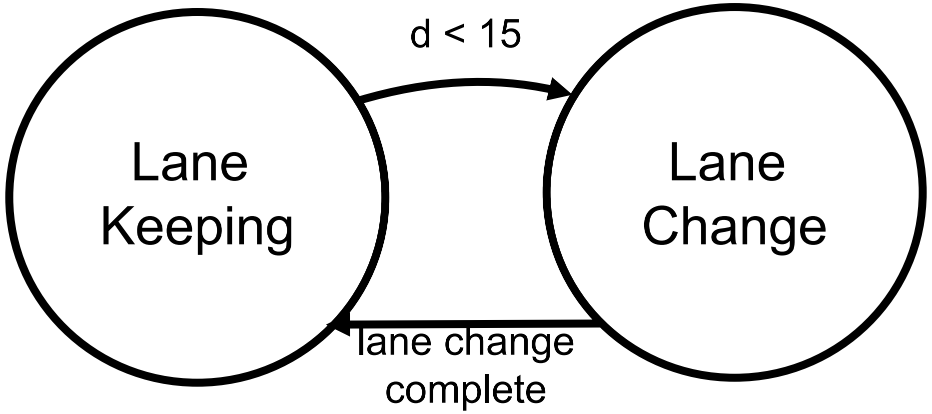
- Start with **System-Level Specification**
  - Temporal Logic/Cost Function
  - Transform Logical Spec into Cost Function
  - $\boldsymbol{G}_{[0,\tau]}(\text{dist(vehicle, obstacle)} > \delta)$ → $\inf_{[0,\tau]}$ [dist(vehicle, obstacle) - δ]
- Falsification: Verification as Optimization
  - Directed search for property violations in simulation
- Scalability requires *Compositional* Falsification
  - Abstract high-dimensional ML (DNN) models
  - Model semantic feature space (e.g. with Scenic program)
  - Semantic adversarial analysis of ML models
  - see [Dreossi, Donze, Seshia, NASA Formal Methods 2017; Dreossi, Jha, Seshia, CAV 2018]

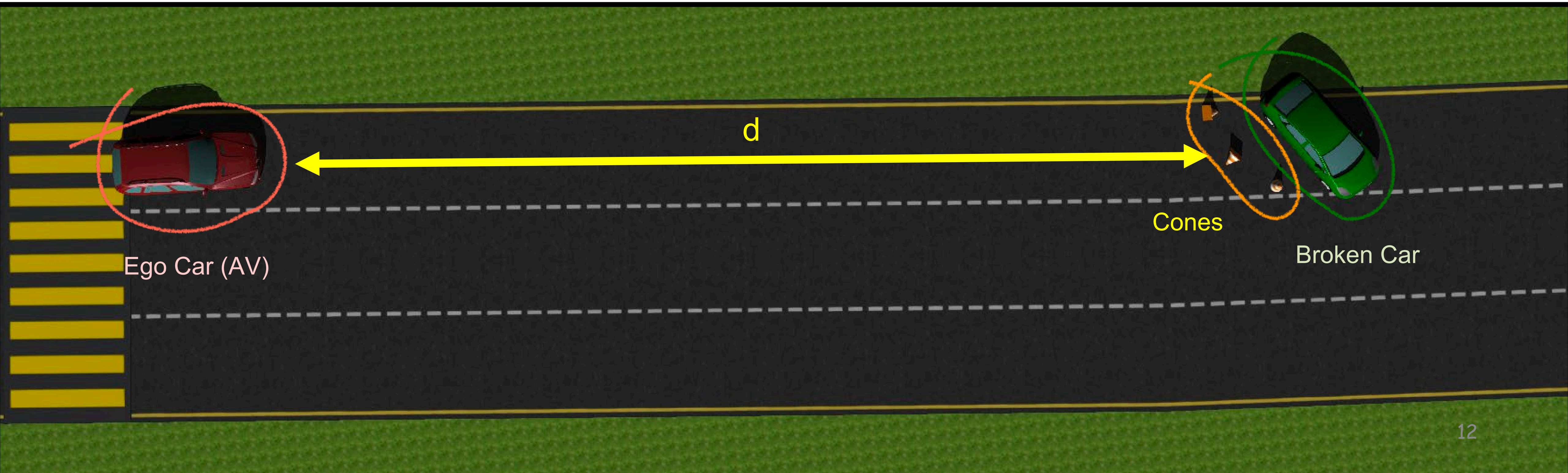
VERIFAI: A Toolkit for the Design and Analysis of AI-Based Systems [CAV 2019]

https://github.com/BerkeleyLearnVerify/VerifAI



Case Study for Temporal Logic Falsification with VerifAI: Navigation around an accident scenario



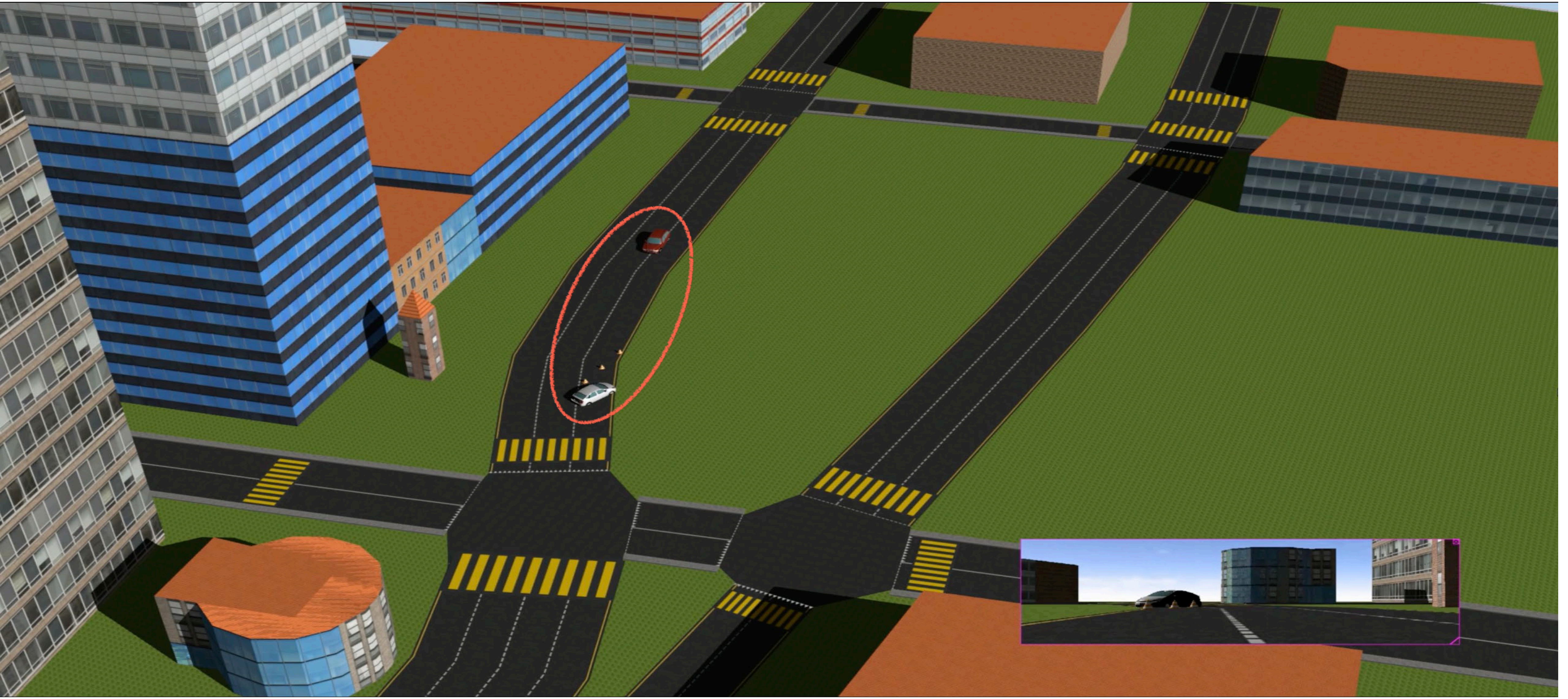


Modeling Case Study in the Scenic Language

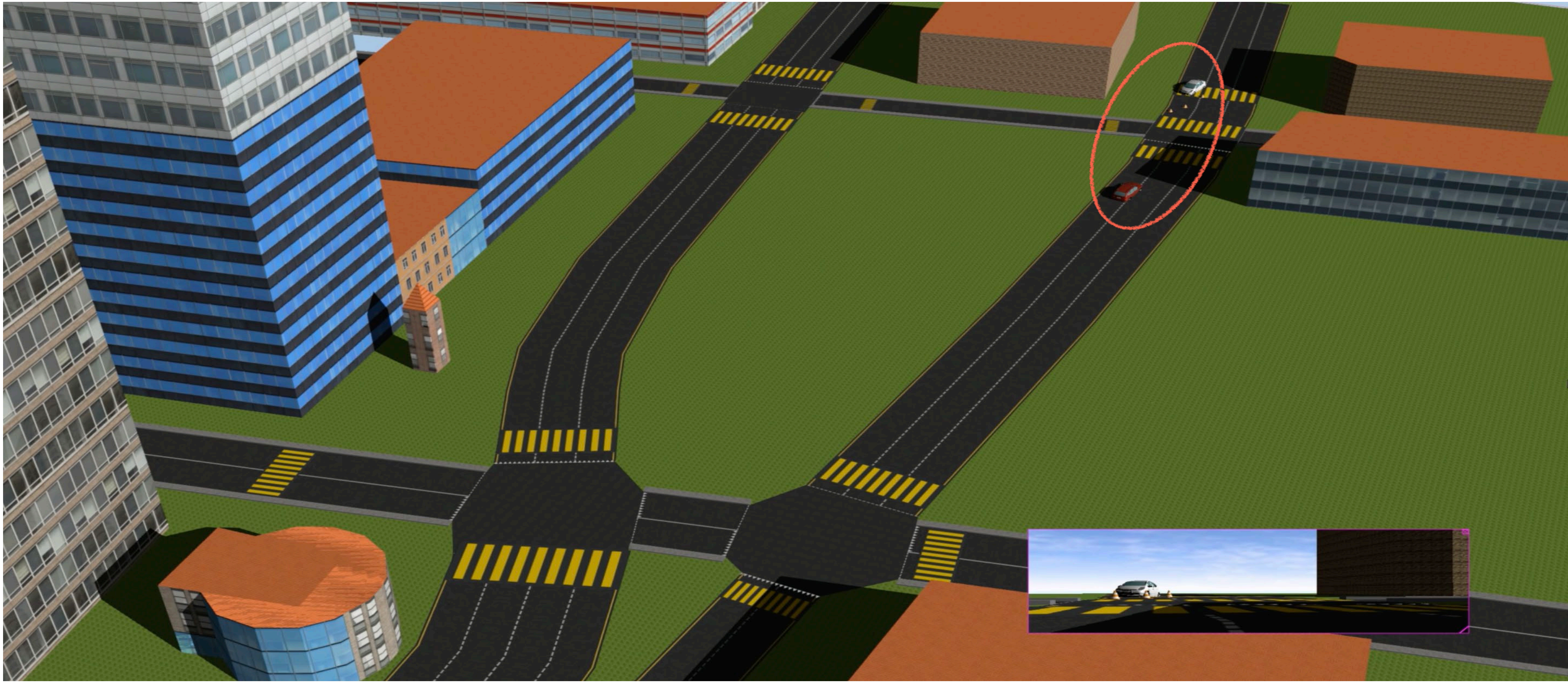
```
# Pick location for blockage randomly along curb
blockageSite = OrientedPoint on curb

# Place traffic cones
spot1 = OrientedPoint left of blockageSite by (0.3, 1)
cone1 = TrafficCone at spot1,
                    facing (0, 360) deg

...

# Place disabled car ahead of cones
SmallCar ahead of spot2 by (-1, 0.5) @ (4, 10),
         facing (0, 360) deg
```

Fremont et al., *Scenic: A Language for Scenario Specification and Scene Generation*, PLDI 2019.

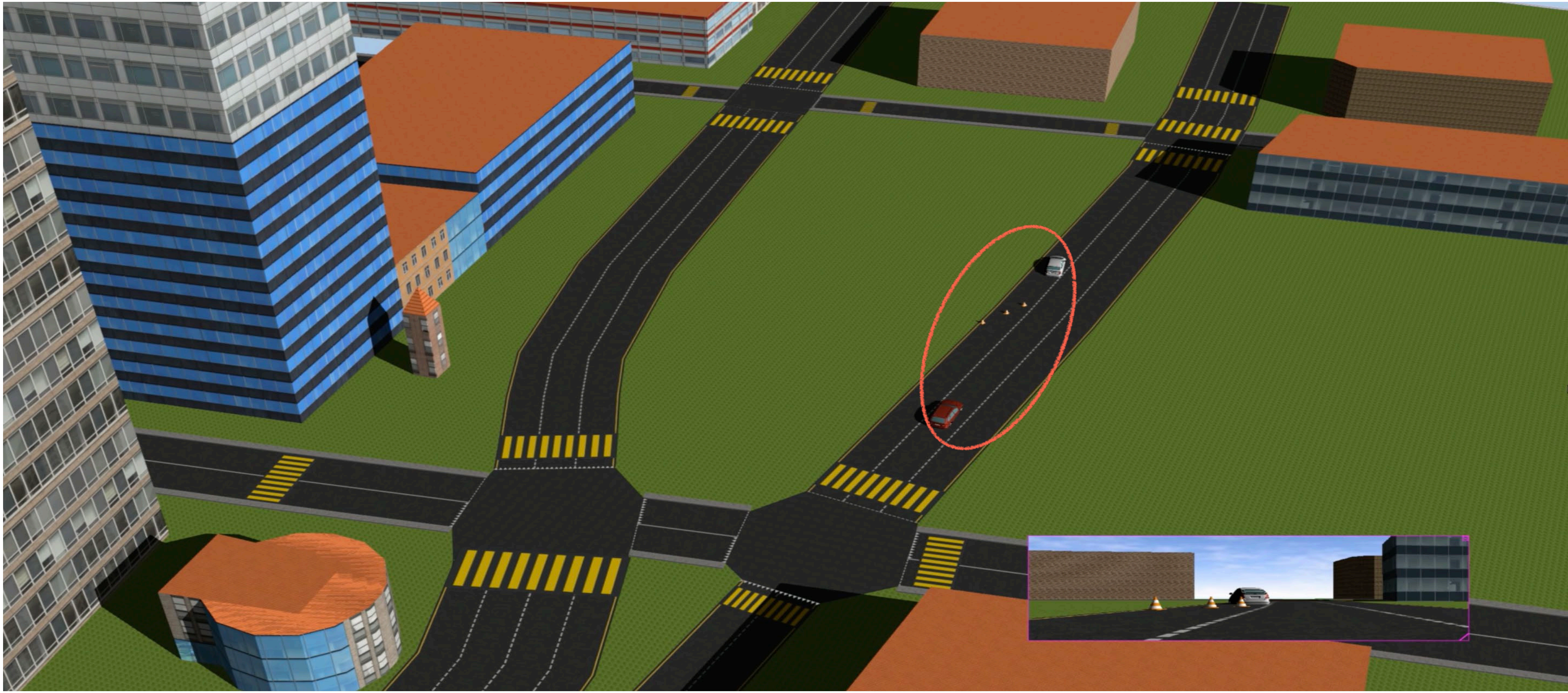
Using Scenic to Generate Initial Scenes



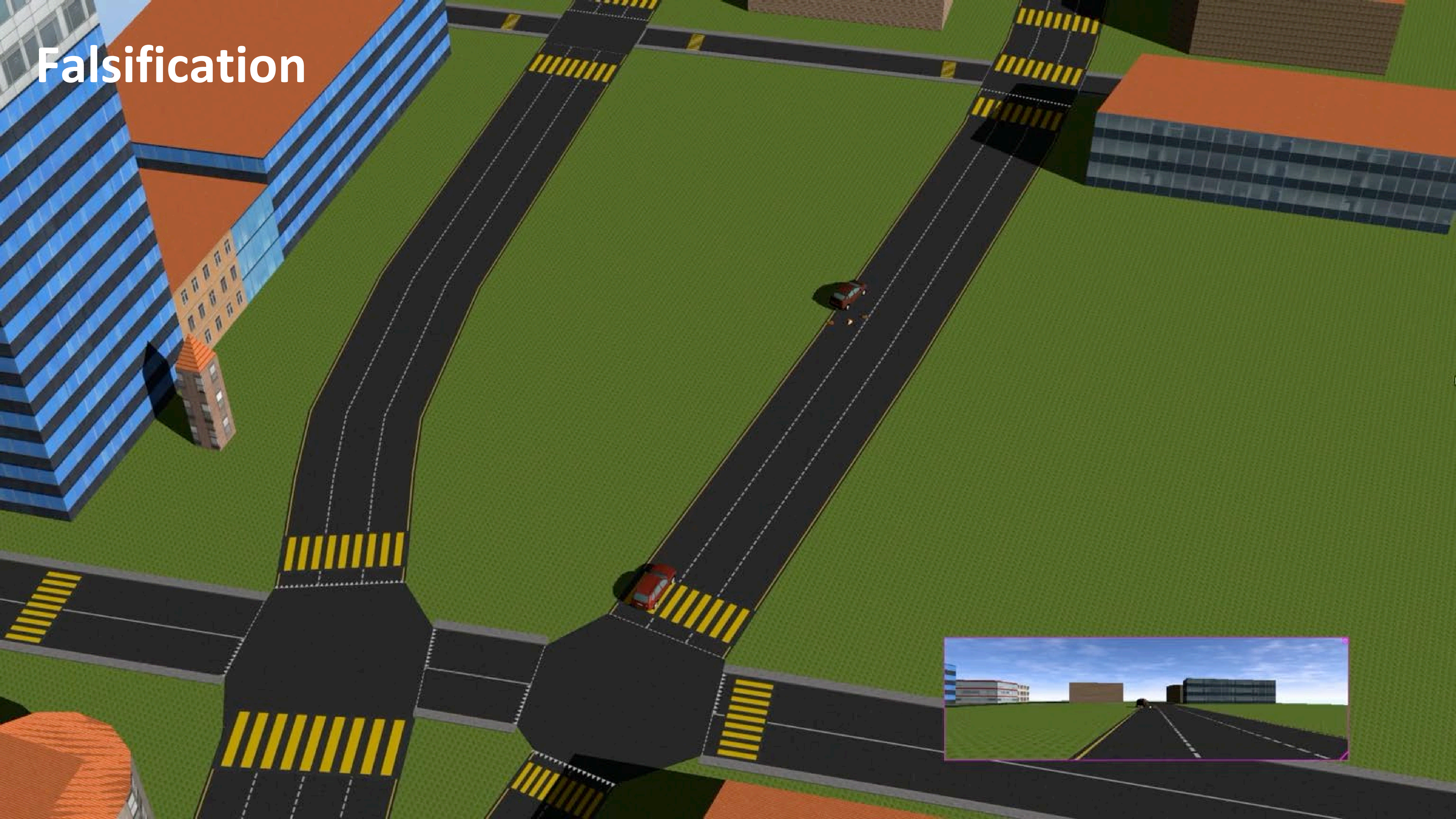
Using Scenic to Generate Initial Scenes



Using Scenic to Generate Initial Scenes



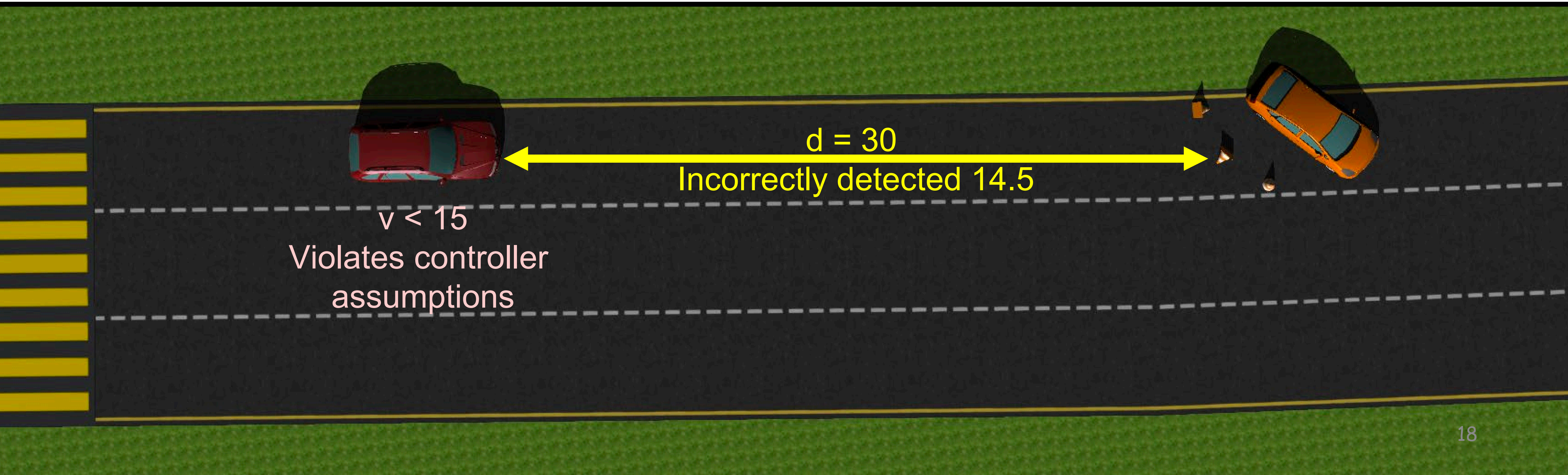
Falsification



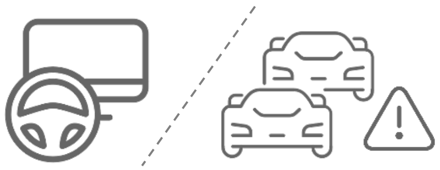
Analyzing the failure

Fix the controller:
Update model assumptions
and re-design controller

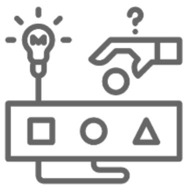
Retrain the perception module:
Collect the counter-example images and
retrain the network [IJCAI’18]



From Simulation to Real-World Testing: Key Questions



#1 **Safety violations in simulation**: Do they transfer to the **real world**? How well?



#2 **Scenario testability**: Can we use **formally guided simulation** to effectively design **real-world tests**?

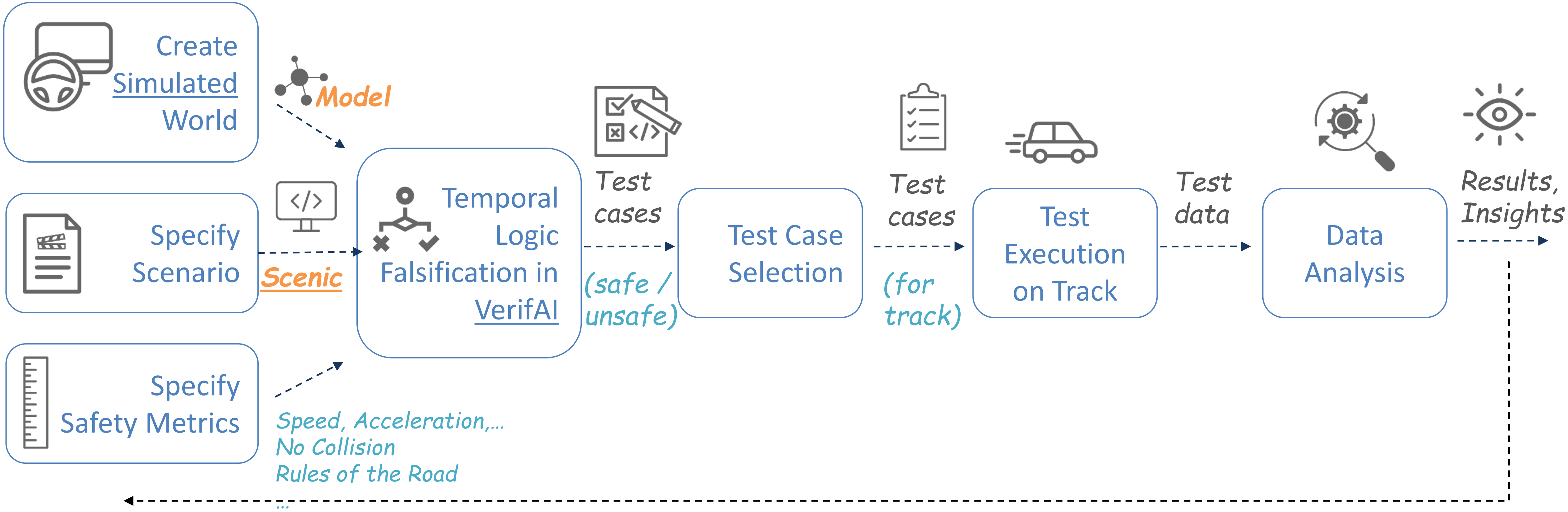
First use of formal methods for scenario-based testing of AI-based autonomy in both simulation and real world

GOMENTUM STATION

Owned and Operated by AAA NCNU

Fremont, Kim, Pant, Seshia, Acharya, Bruso, Wells, Lemke, Lu, Mehta, ***"Formal Scenario-Based Testing of Autonomous Vehicles: From Simulation to the Real World"***, Arxiv e-prints, https://arxiv.org/abs/2003.07739 *[ITSC 2020]*

Formal Scenario-Based Testing (with Scenic and VerifAI)



Source: Fremont et al., *"Formal Scenario-Based Testing of Autonomous Vehicles: From Simulation to the Real World"*, Intelligent Transportation Systems Conference (ITSC), September 2020. https://arxiv.org/abs/2003.07739

Scenario Overview: Focus on Vulnerable Road Users (VRUs)

+53%

Pedestrian fatalities: 53% increase in the last decade (2009-2019)
2019: ~6500 (estimated)

17%

Of all traffic fatalities, 17% are **Pedestrians**

67%

Fatalities at **night** (low-light, limited vision environment)

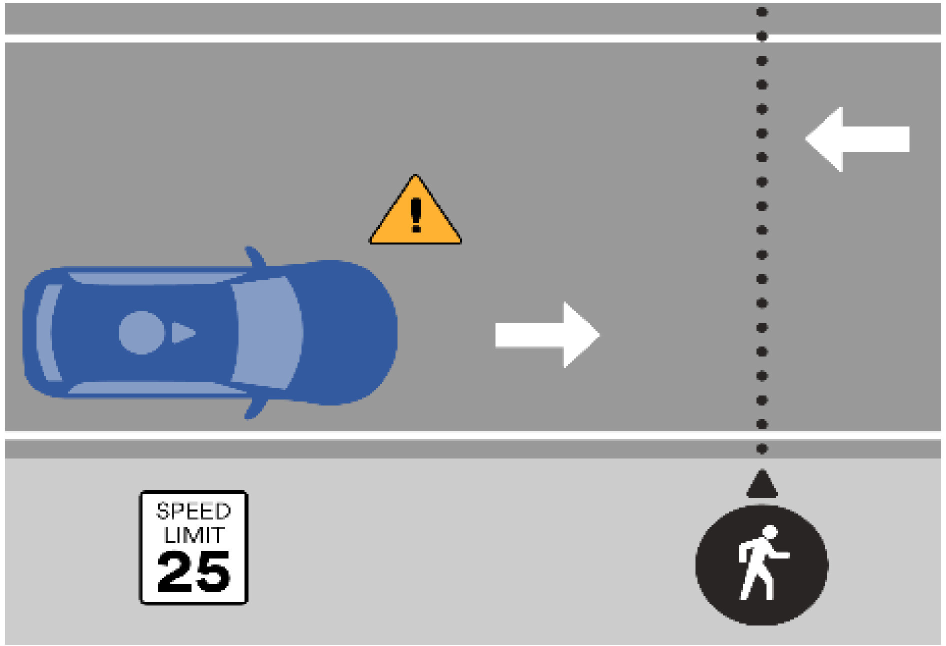
Source:
GHSA: https://www.thecarconnection.com/news/1127308_pedestrian-deaths-reach-30-year-high-in-2019
IIHS: https://www.iihs.org/topics/pedestrians-and-bicyclists

Test Equipment and Use at AAA GoMentum Testing Grounds

Robotic platform for Test Targets

Scenario Execution

[Shows EuroNCAP VRU AEB]



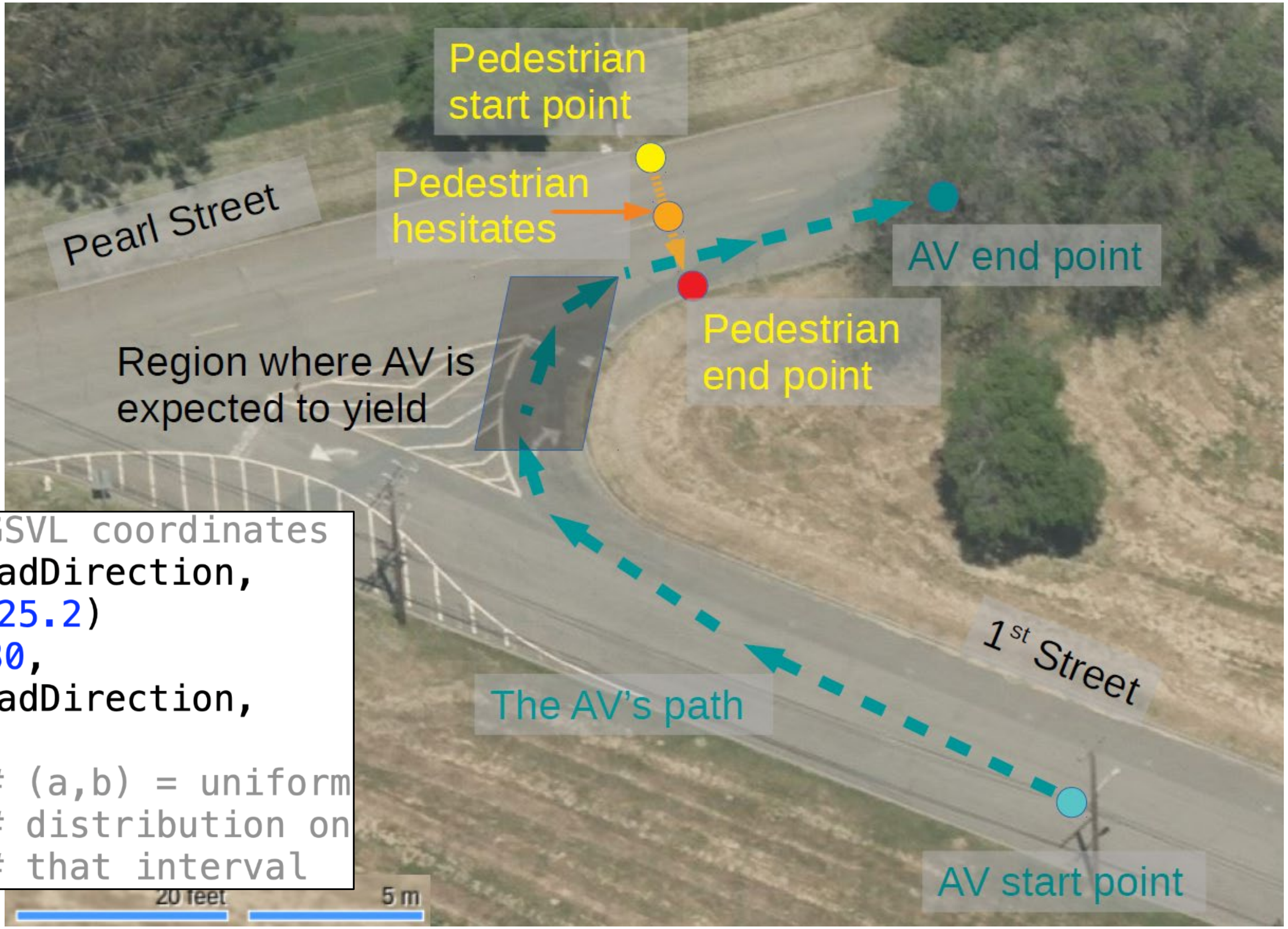
Scenario Evaluation

Object & Event Detection/Response: Metrics & Evaluation

- Object detection
- Time to collision
- Separation distance
- Deceleration profile
- Autonomy Disengagement

Example Scenario: AV making right turn, pedestrian crossing

Lincoln MKZ running Apollo 3.5



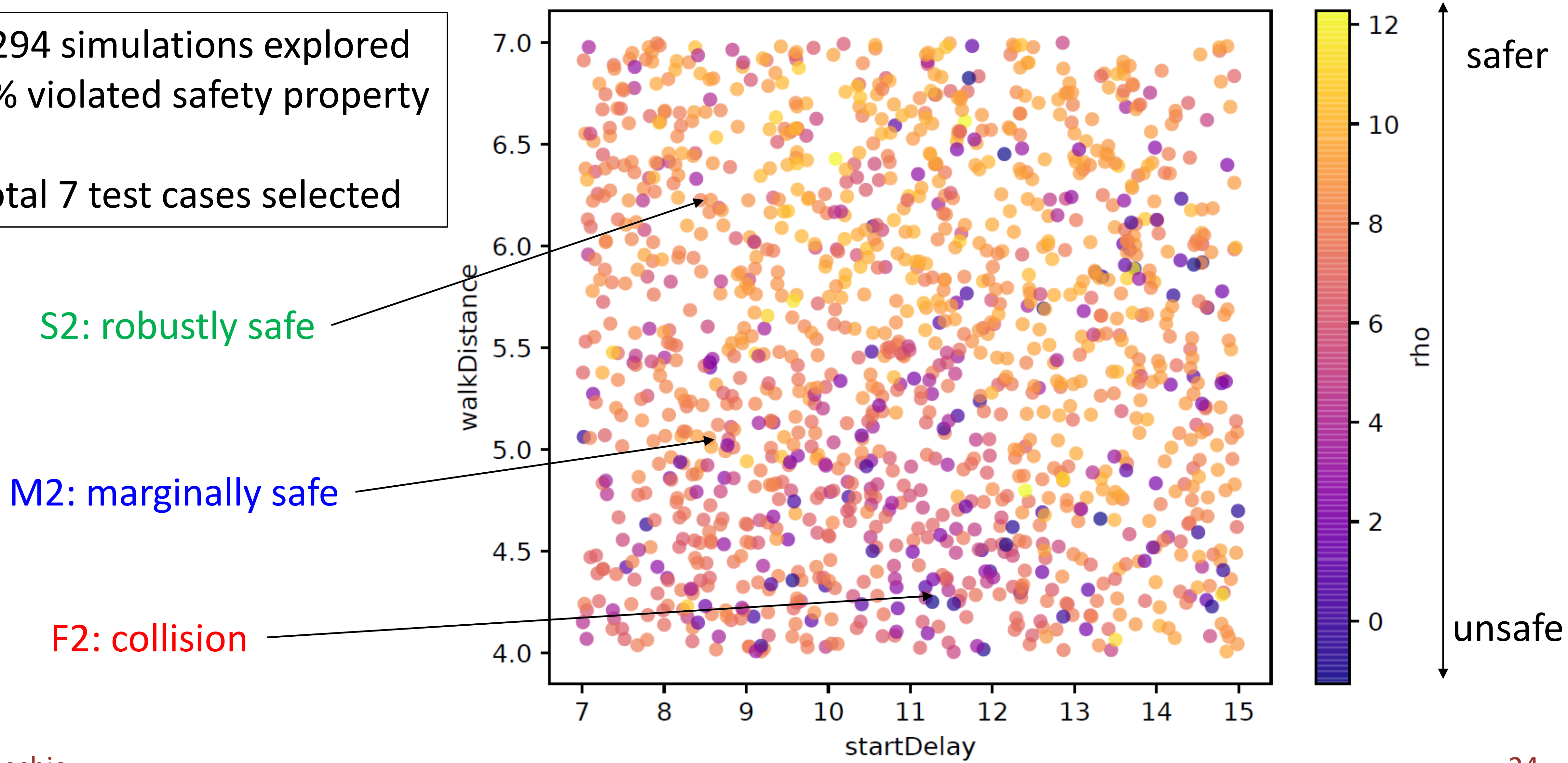

```
ego = EgoCar at 38.6 @ 183.9,   # LGSVL coordinates
       facing 10 deg relative to roadDirection,
       with behavior DriveTo(40 @ 225.2)
ped = Pedestrian at 19.782 @ 225.680,
       facing 90 deg relative to roadDirection,
       with behavior Hesitate,
       with startDelay (7, 15),    # (a,b) = uniform
       with walkDistance (4, 7),   # distribution on
       with hesitateTime (1, 3)    # that interval
```

Snippet of Scenic program

Results: Falsification and Test Selection

1294 simulations explored
2% violated safety property

Total 7 test cases selected



Fundamental Research - Contract FA8750-18-C-0101

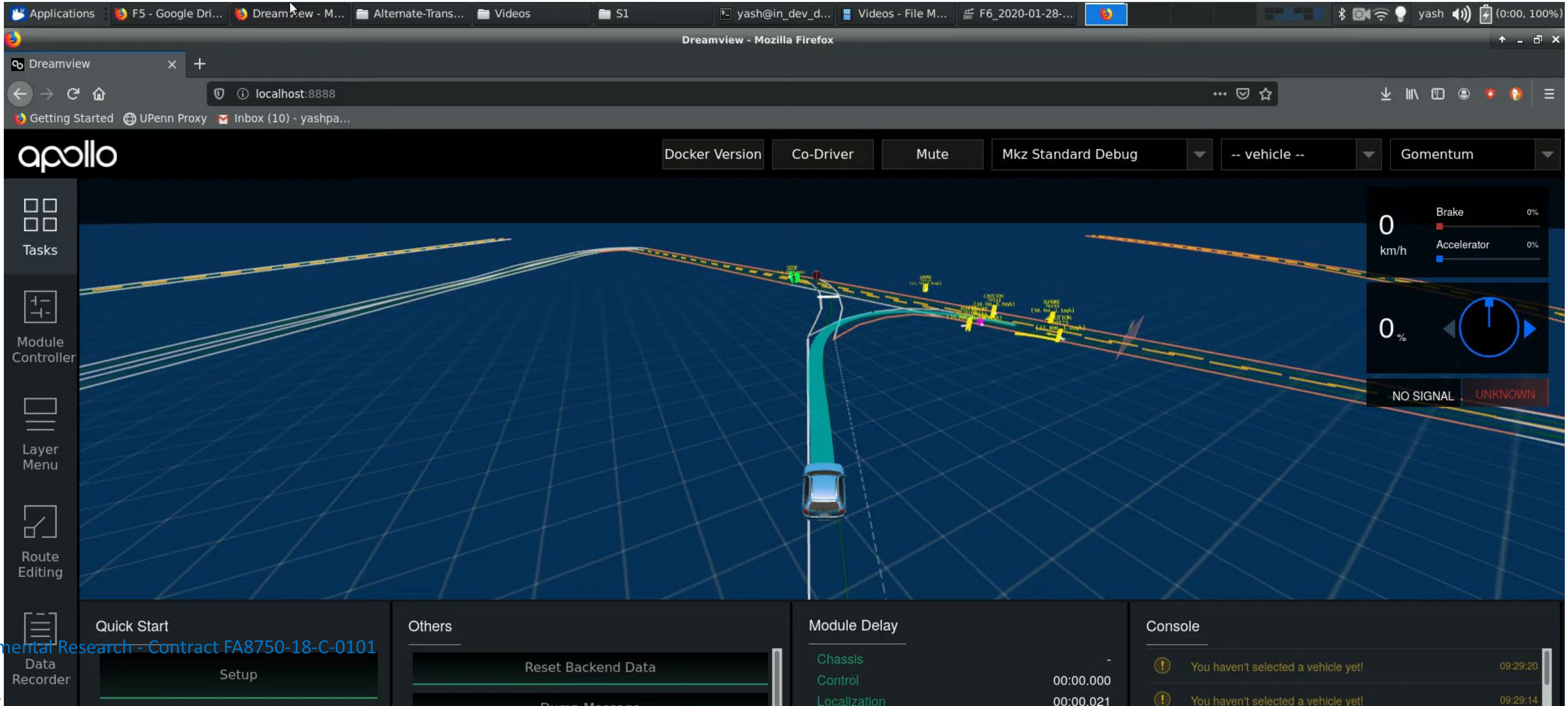
Results: Does Safety in Simulation → Safety on the Road?

Unsafe in simulation → unsafe on the road: **62.5% (incl. collision)**

Safe in simulation → safe on the road: **93.5% (no collision)**

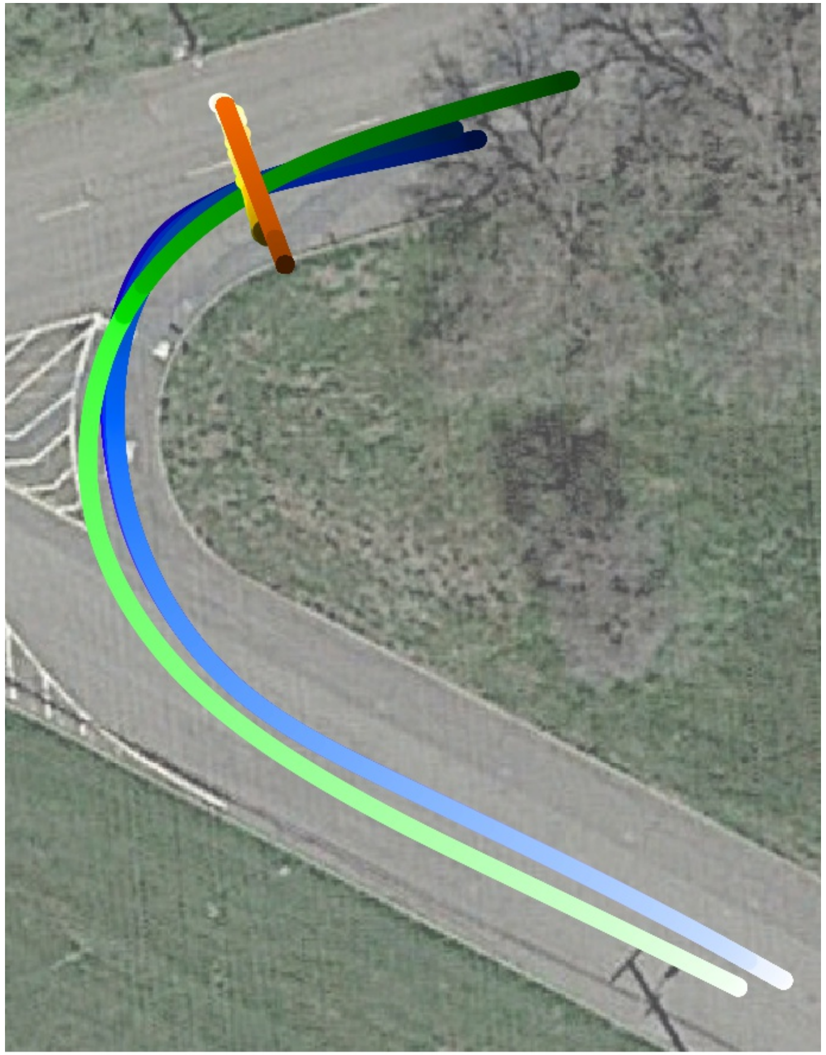
Results: Why did the AV Fail?

Perception Failure: Apollo 3.5 lost track of the pedestrian several times

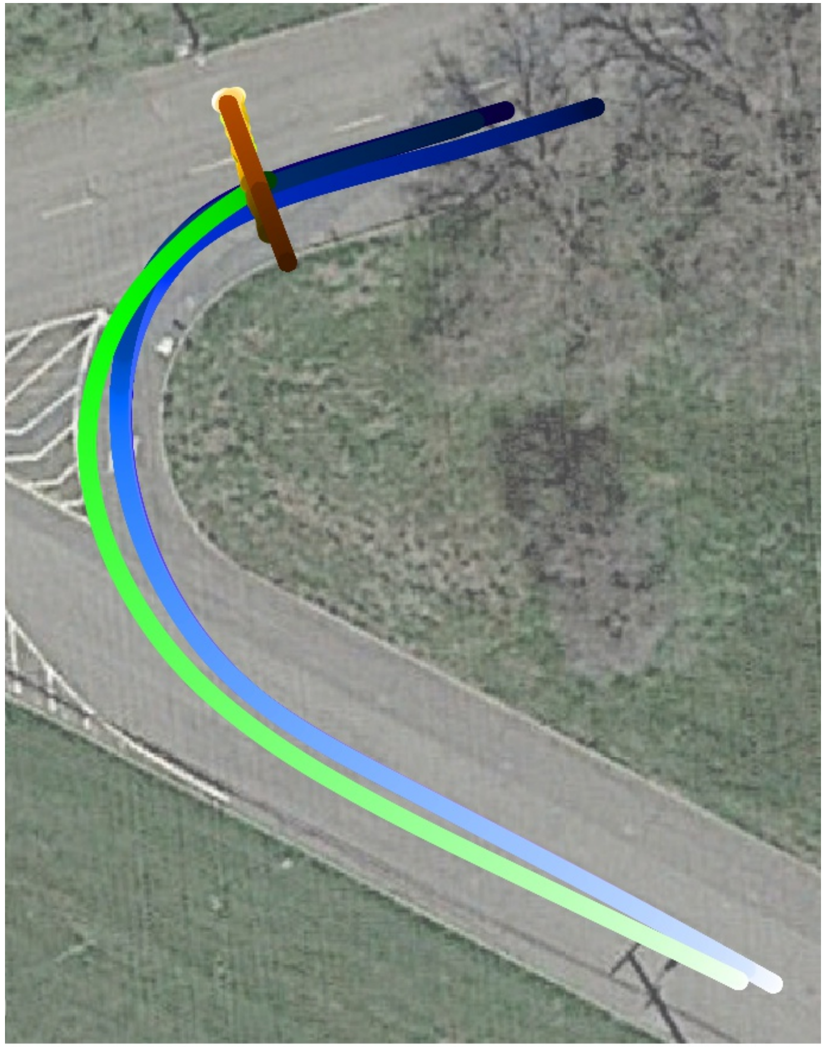


Fundamental Research - Contract FA8750-18-C-0101

Results: How well do the trajectories match?



S1 Run 2



F1 Run 1

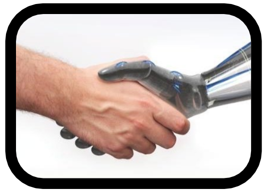
Green – AV real
Blue – AV sim

Orange – Ped real
Yellow – Ped sim

Fundamental Research - Contract FA8750-18-C-0101

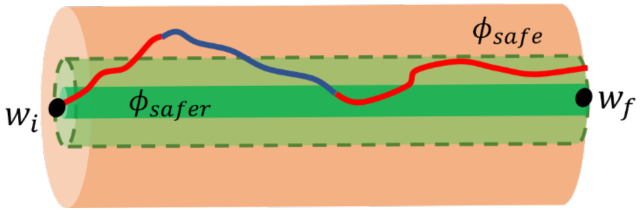
Other Contributions

Open-Source Verified AI Toolkit
(VerifAI & Scenic, on github)



Verified Human-Robot Collaboration
Learning Specifications from Demonstrations, Interaction-Aware Control, etc. [IROS 2016, NeurIPS 2018, CAV 2020]

Run-Time Assurance
SOTER framework based on Simplex architecture [DSN 2019]



Counterexample-Guided Retraining
Boeing research automated taxiing system
Used Scenic and VerifAI to find failures and retrain to eliminate [CAV 2020]

Conclusion: Towards Verified AI/ML based Autonomy

Challenges		Core Principles
1. Environment (incl. Human) Modeling	→	Data-Driven, Introspective, Probabilistic Modeling
2. Specification	→	Start with System-Level Specification, then Component Spec (robustness, …)
3. Learning Systems Complexity	→	Abstraction, Semantic Representation, and Explanations
4. Efficient Training, Testing, Verification	→	Compositional Analysis and Semantics-directed Search/Training
5. Design for Correctness	→	Oracle-Guided Inductive Synthesis; Run-Time Assurance

Thank you!

S. A. Seshia, D. Sadigh, S. S. Sastry. *Towards Verified Artificial Intelligence*. July 2016. https://arxiv.org/abs/1606.08514.