Scenic and VerifAI: Tools for Assured AI-Based Autonomy

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UC Berkeley UC Santa Cruz AAA NCNU

Webinar
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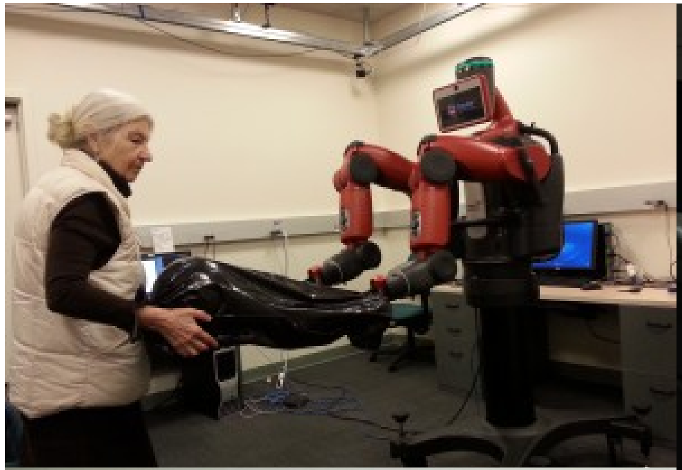
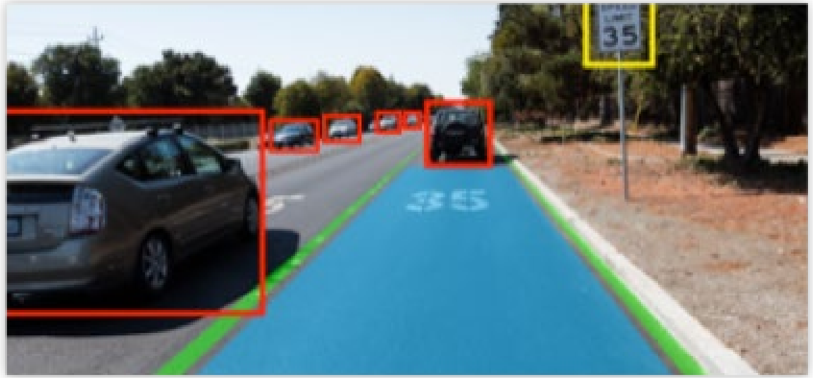
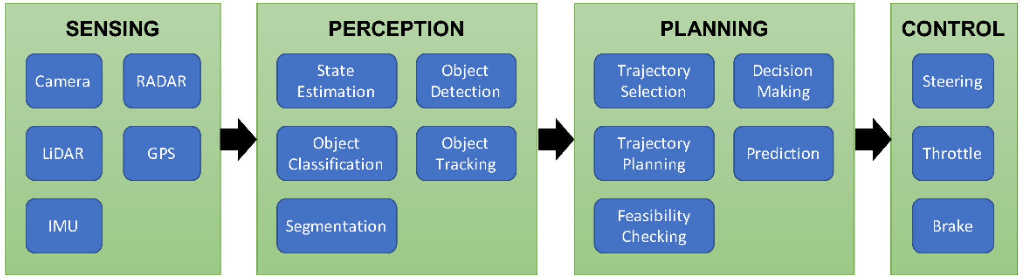
Artificial Intelligence (AI) and Autonomy

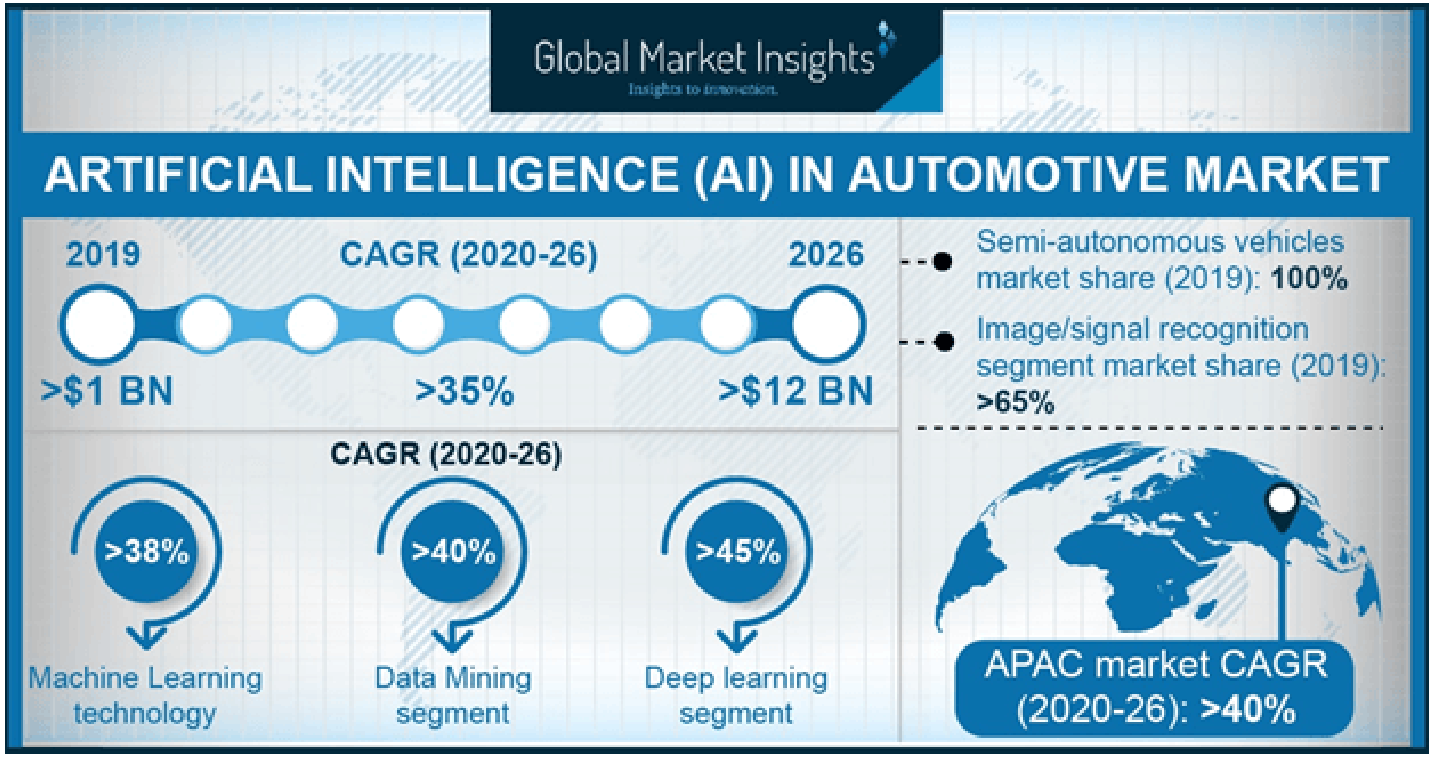
Computational Systems that attempt to mimic aspects of human intelligence, including especially the ability to learn from experience.



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 we address the Design & Verification Challenges of AI/ML-Based Autonomy with Formal Methods?

Precise, Programmatic **Environment/Scenario Modeling**



φ Mathematical **Specification of Requirements and Metrics**

Scalable Algorithms for **Verification and Testing**

Methodologies for **Provably-Robust System Design**

Berkeley DeepDrive DARPA iCyPhy NSF VeHiCaL

http://vehical.org

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

Scenic

High-Level, Probabilistic Programming Language for Modeling Environment Scenarios

VerifAI

Requirements Specification + Algorithms for Design, Verification, Testing, Debugging

GitHub **Open-Source Tools**

https://github.com/BerkeleyLearnVerify/Scenic
https://github.com/BerkeleyLearnVerify/VerifAI

for

Industry

Improve assurance of the systems you build

Academia

Use these tools in your research

Government/ Regulators

Evaluate the safety of AI-based autonomous systems

Share Scenarios and Metrics

Community

Develop Corpus of Tools and Data

Outline for this Webinar

Part I: Overview

- Challenges for Assurance of Autonomous Driving Systems
- Overview of VerifAI and Scenic
- Case Study on Formal Scenario-Based Testing in Simulation and on the Road

Part II: Tutorial

- Spatial modeling, data generation, and debugging ML-based perception with Scenic
- Spatio-temporal scenario modeling, testing, falsification, debugging, retraining with Scenic and VerifAI

Conclusion & Outlook

Challenges for Assuring Safety of ADS

What We Mean By Safety in Autonomous Driving

Safety → "absence of unreasonable risk"

SAFETY	RISK

ISO 26262

Functional Safety (FuSa)
- *Hazards due to E/E system*

ISO/PAS 21448

(**SOTIF**) **Safety of the Intended Functionality**
- *Hazards due to nominal system operation*

Risk = f (Severity, Exposure, Controllability)
[ASIL, ISO 26262]

→ Severity
- types of injuries

→ Exposure
- frequency of hazards

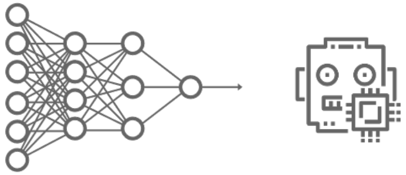
→ Controllability
- how much driver can prevent injury

No system has absolutely zero risk

Improving Safety in Automated Driving Systems: Needs

Challenges for safety-critical systems

SENSE → PERCEIVE → PREDICT → PLAN → ACT



Handle **complex neural-network** based **perception** and **prediction** tasks, including planning and control

Toolchain that integrates **design** and **verification** with **data generation** and training/testing of ML components

Simulation is important for complex, **real-world scenarios** for which **real world data is difficult/dangerous**

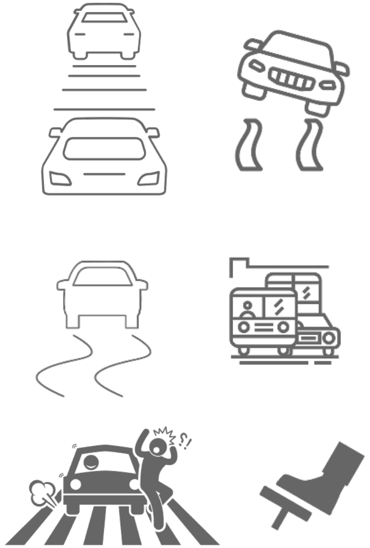
Why Testing ADS is Complex

Verification & Validation: Assurance of "*positive risk balance*"
Scenario-based testing is one standard approach for V&V

Wide variety of functions and scenarios…

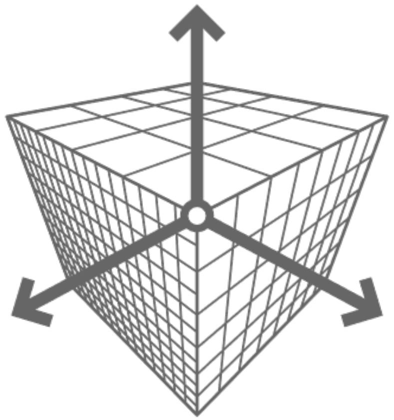
ADAS

ACC
FCW
CAS
AEB
P-AEB
LKA
LDW
BSM
ISA
…



NHTSA, EuroNCAP, JNCAP

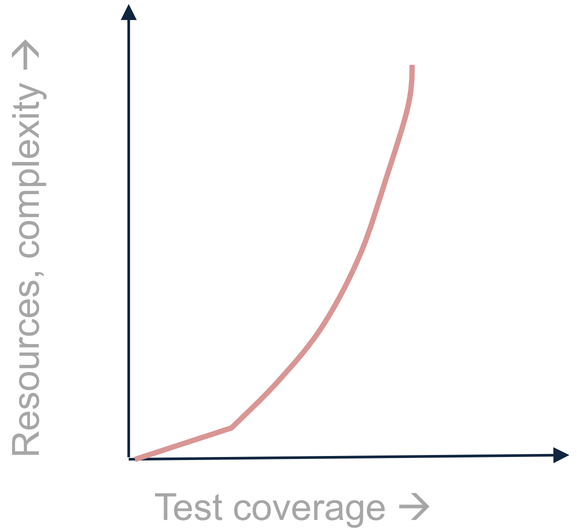
…lead to high-dimensionality of parameter search



f(speed, objects, agents, …)

Test matrix

…resulting in high complexity



Operational Design Domain: What and Why

Operating environment within which an ADS can **safely** perform its dynamic driving task (**DDT**)

Formulation

Category / sub-category / attributes
Static and dynamic elements
Additive / subtractive elements

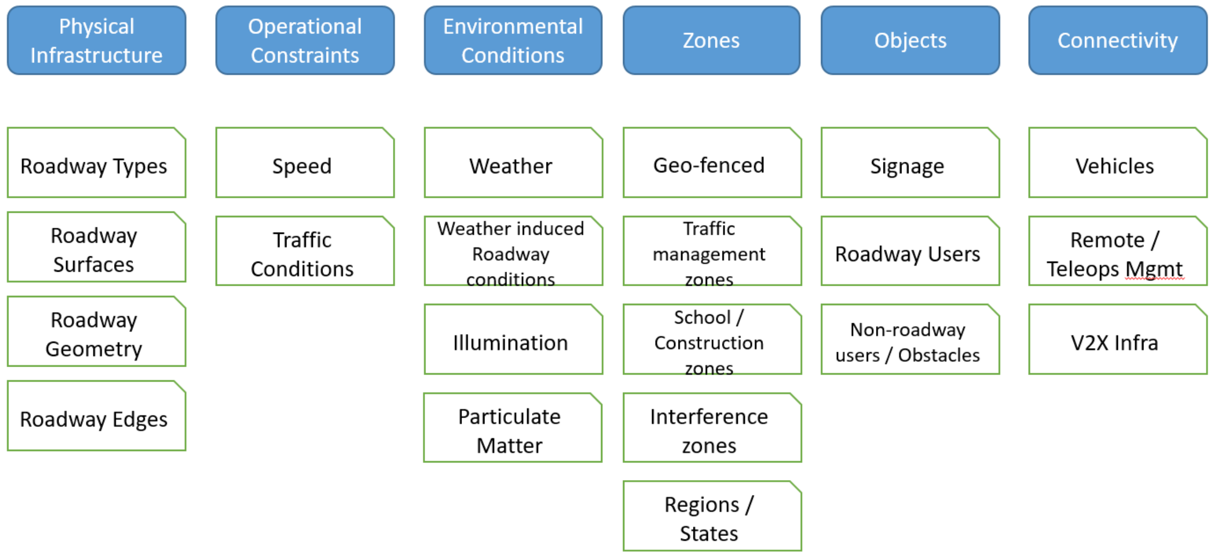
Requirements

Precisely definable
Comprehensible (human / machine)
Measurable
Monitorable (by ADS / operator)

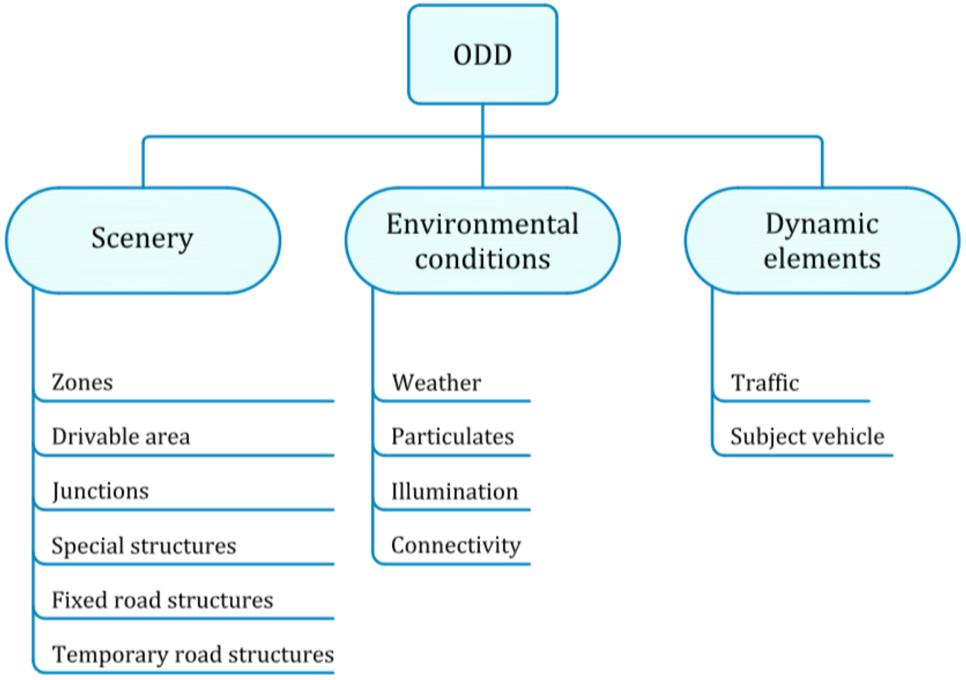
Boundary conditions

ODD detection / departure
Min Risk Condition (MRC)
Min Risk Maneuver (MRM)
Fail Safe / Fail Operational

ODD Classification



Source: NHTSA 13882 ADS Scenario Framework



Source: BSI PAS 1883

Safety Metrics: How is Success / Failure Measured

System performance is context-dependent (mission/scenario/test-case/etc.)

“Disengagement” is not a safety metric

Standards / Proposals…

ANSI / UL 4600 – “Safety Performance Indicators (SPIs)”

IEEE P2846 – “motion control based metrics”

Intel’s Responsibility-Sensitive Safety (**RSS**)

NVIDIA’s Safety Force-Field (**SFF**)

…Convergence

Vehicle Dynamics Based
Min Safe Distance Violation
Proper Response Action
Min Safe Distance Factor
Min Safe Distance Calc Error
Collision Incident
Rules-of-road violation
ADS Active
Human Traffic Control Detection Error Rate
Time to Collision (TTC)
Post-Encroachment Time
Aggressive Driving
Collision Avoidance Capability (CAC)

SPIs
Incident rates
Violation rates
- By human exposure
- By item exposure

Hazard occurrence rates
Unmitigated hazard rates
Psychological comfort rates
ODD departure rates
…
Post-deployment defect rates
Field failure rates
Misclassification rates
…

Sources:
1. “Driving Safety Performance Assessment Metrics for ADS-equipped Vehicles”, Wishart, et al (SAE WCX 2020)
2. “Collision Avoidance Capability Metric”, Silberling, et al (SAE WCX 2020)

Bridging Simulation and Real World

Testing on road/track is expensive but important, hence

- Need to carefully design road/track tests (e.g. NHTSA, NCAP, IIHS, …)
- Customize test plans based on ODD, autonomy functions, infra, …

- Ensure that models in sim are fit for their test purpose
- Ensure match between simulation scenarios and road testing scenarios

- Need fallback options (e.g. MRC) in case safety cannot be assured
- Test boundary conditions very well

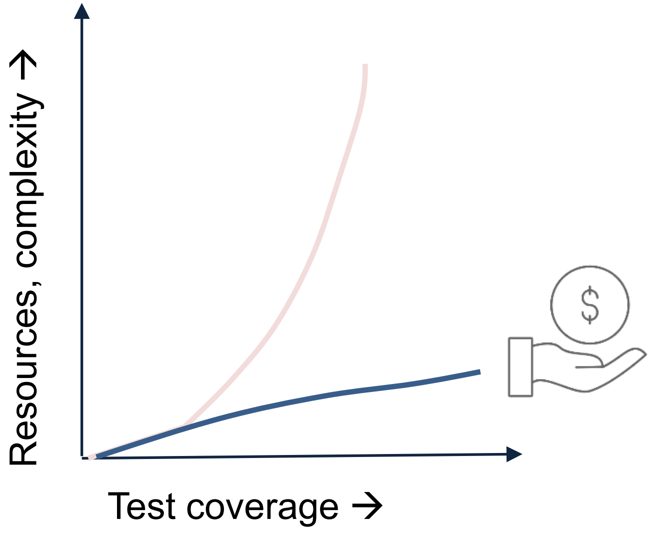
Simulation and Formal Methods can Make ADS Testing Efficient and Bridge the Gap with Road Testing

Simulation

- Efficiently search large space
- Create complex interactions safely

Formal methods

- Temporal logic
- Falsification
- Counterexample-guided retraining
- Parameter synthesis



> *"All models are wrong… but some are useful"* – George P. Box

Overview of Scenic and VerifAI

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

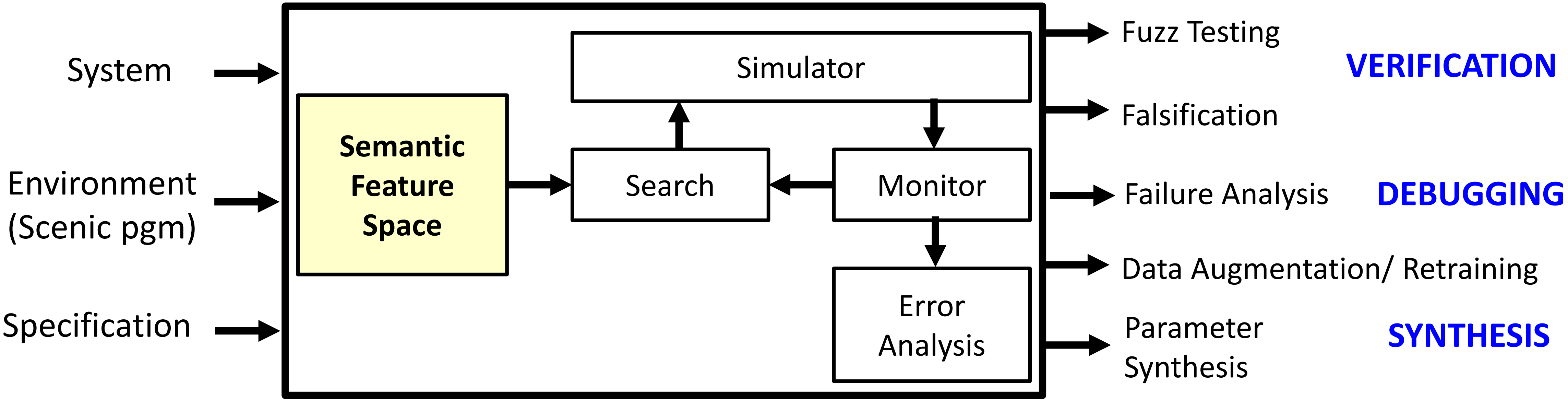
Image created with GTA-V

Video created with CARLA

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

VERIFAI: A Toolkit for the Design and Analysis of AI-Based Systems

[Dreossi et al. CAV 2019, https://github.com/BerkeleyLearnVerify/VerifAI]



Relevant Use Cases for Scenic and VerifAI

- Scenic Programs can specify ODDs and Test Scenarios
- Can specify Safety Properties/Metrics in VerifAI
- Scenic+VerifAI can
  - Automatically generate tests in simulation
  - Automatically find edge cases to safety
  - Generate data for training and testing ML models and perception
  - Automatically synthesize parameters for ML, planning, control
  - Debug and explain the behavior of perception, planning, control systems
  - Bridge the gap between simulation-based assessment and real-world/road testing
  - …

Industrial Case Study:

Formal Scenario-Based Testing in Simulation and the Real World

3-Way Project Collaboration

A. Acharya, P. Wells, X. Bruso

GoMentum Station proving ground
4Active pulley equipment, pedestrian dummy, OxTS IMU, dGPS, etc.

http://vehical.org

S. A. Seshia, D. Fremont, E. Kim, Y. V. Pant, H. Ravanbakhsh

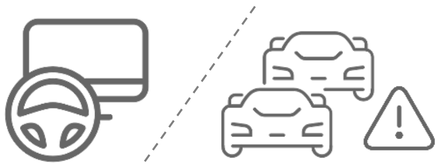
SCENIC scenario description language,
VerifAI toolkit for design and verification of AI based systems

LG Electronics R&D

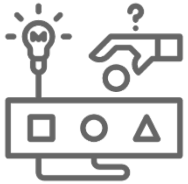
S. Lemke, Q. Lu, S. Mehta

LGSVL Simulator (open source)
LG's research AV with Baidu's Apollo autonomy stack

Key Research Questions



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

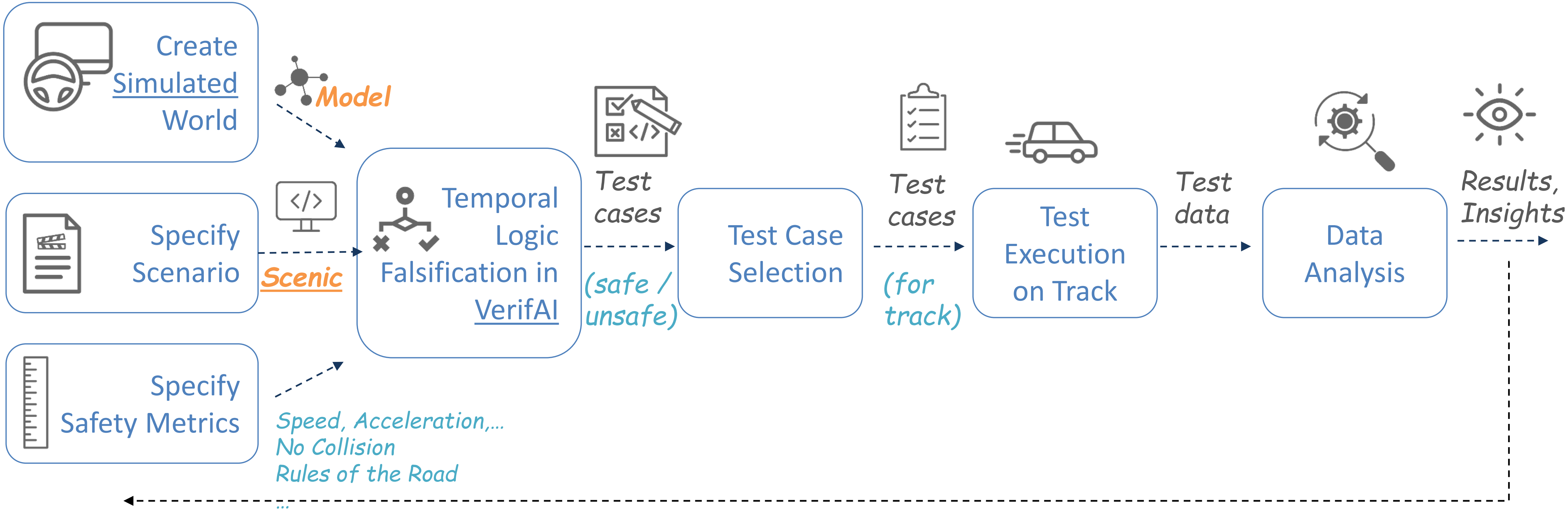


#2 Effective real-world testing: Can we use **formally guided simulation** to design effective **real-world tests**?

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

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 *[appearing **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) 2020, to appear. 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)

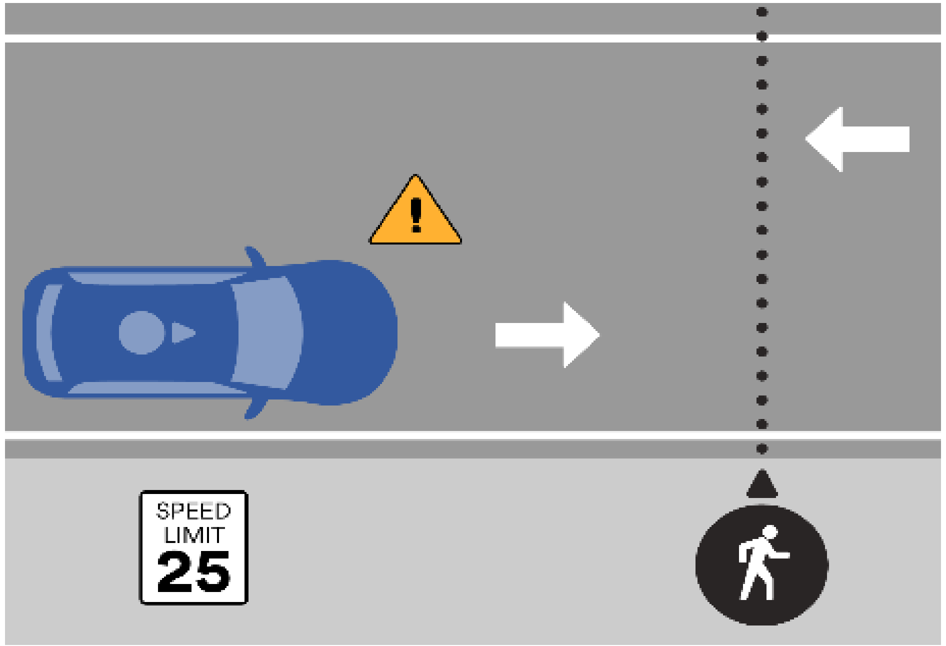
Source:
GHSA: https://www.thecarconnection.com/news/1127308_pedestrian-deaths-reach-30-year-high-in-2019
IIHS: https://www.iihs.org/topics/pedestrians-and-bicyclists

Test Equipment and Use at AAA GoMentum Testing Grounds

Robotic platform for Test Targets

Scenario Execution

[Shows EuroNCAP VRU AEB]



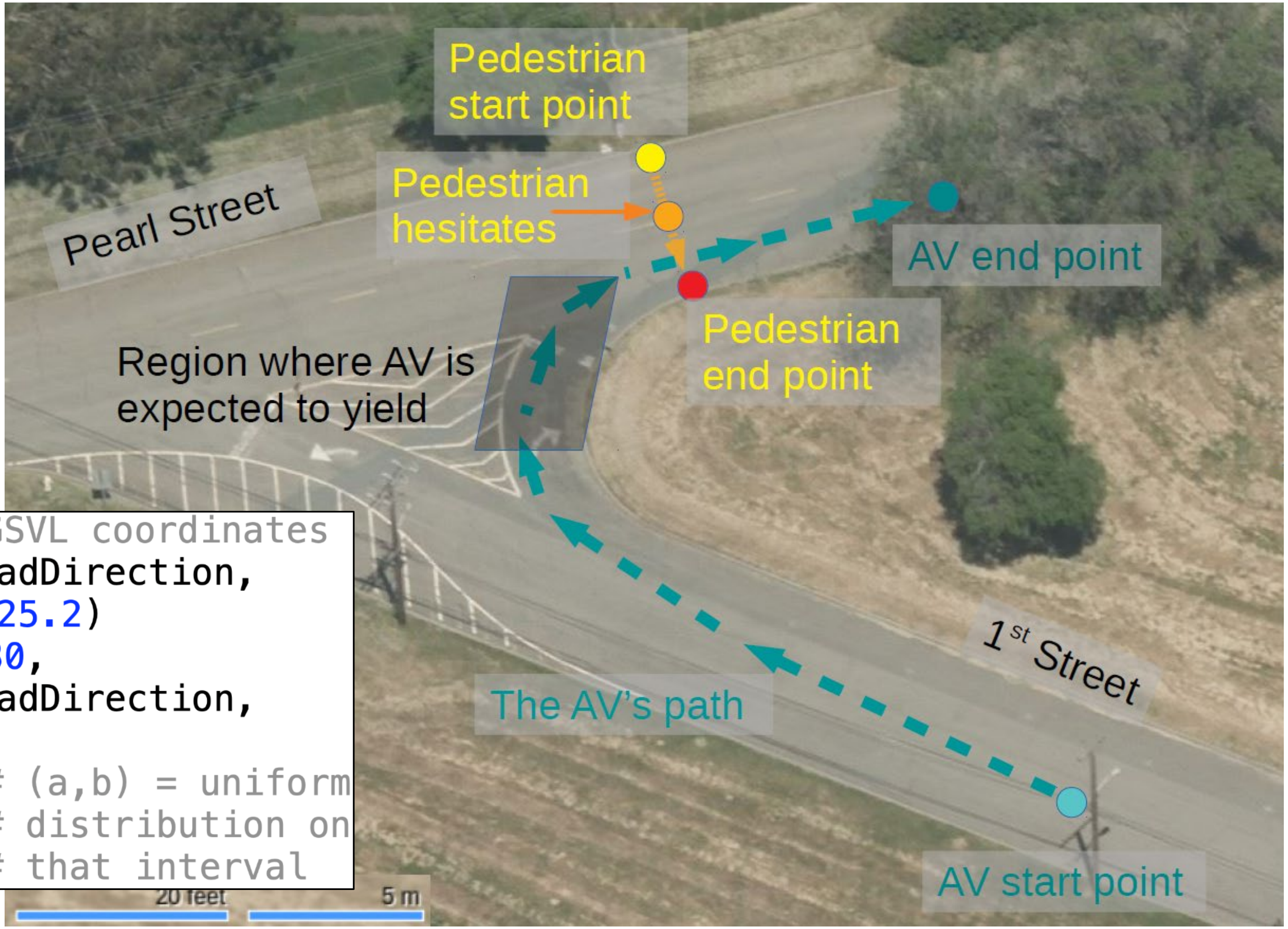
Scenario Evaluation

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



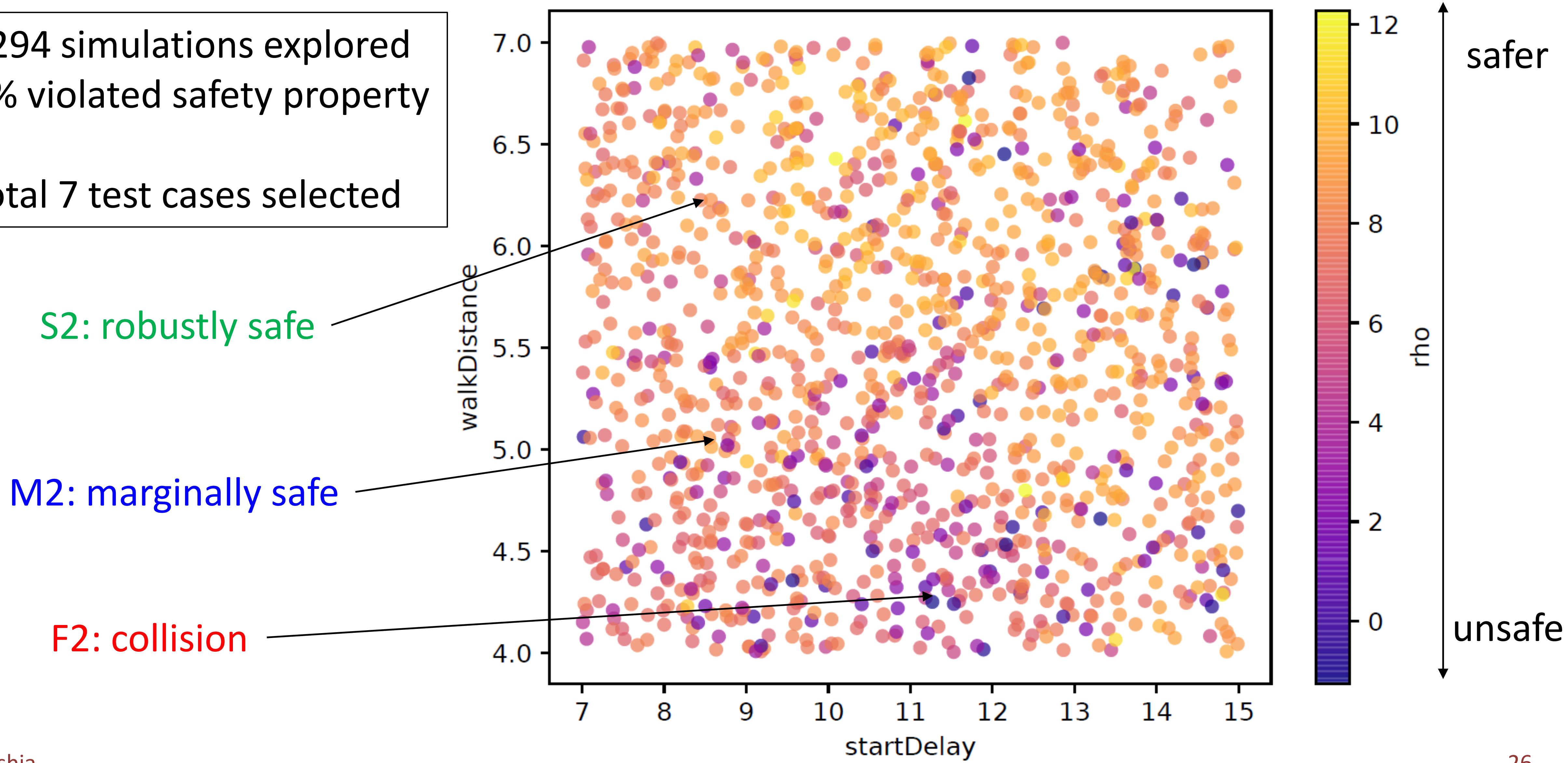

```
ego = EgoCar at 38.6 @ 183.9,  # LGSVL coordinates
       facing 10 deg relative to roadDirection,
       with behavior DriveTo(40 @ 225.2)
ped = Pedestrian at 19.782 @ 225.680,
       facing 90 deg relative to roadDirection,
       with behavior Hesitate,
       with startDelay (7, 15),    # (a,b) = 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



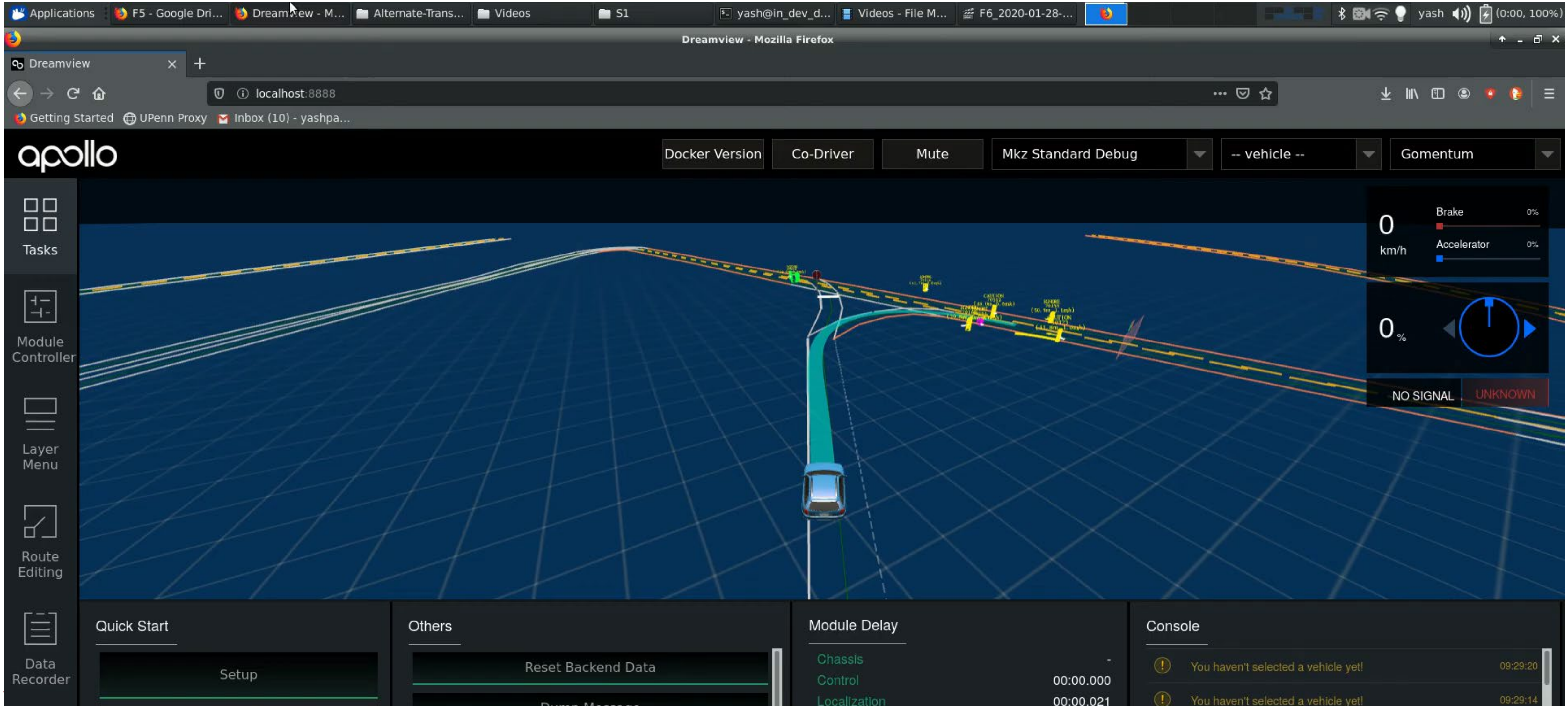
Results: Does Safety in Simulation → Safety on the Road?

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

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

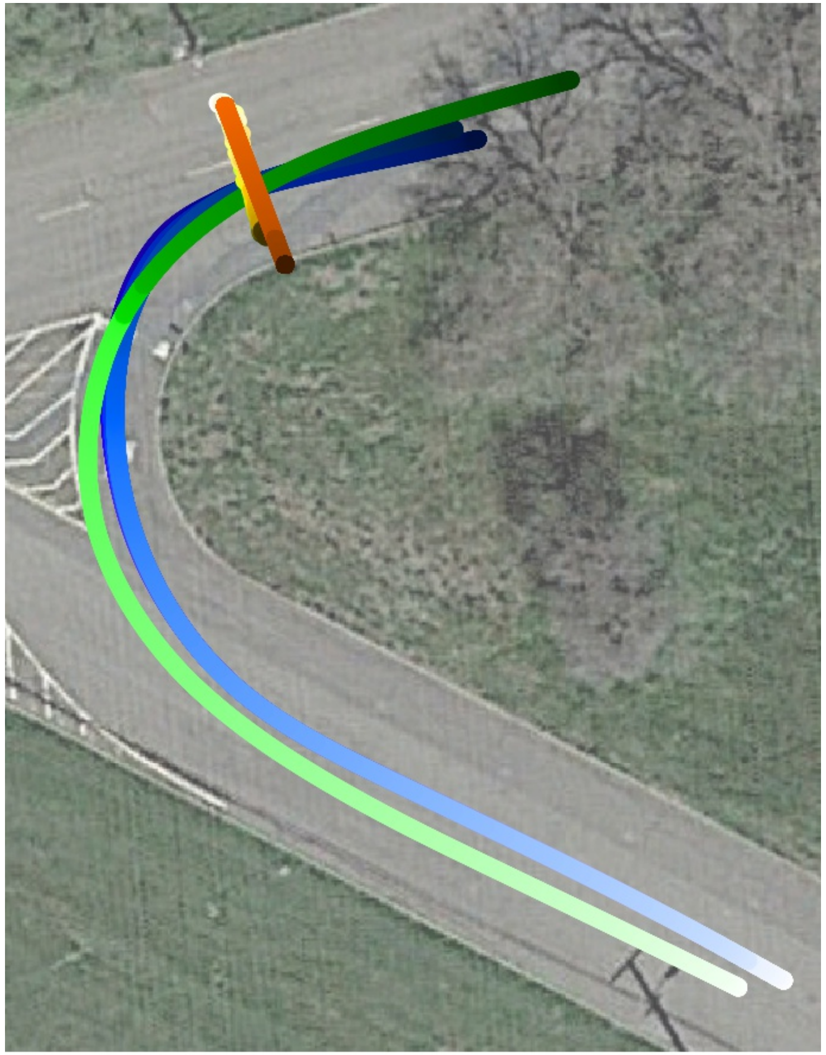
Results: Why did the AV Fail?

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

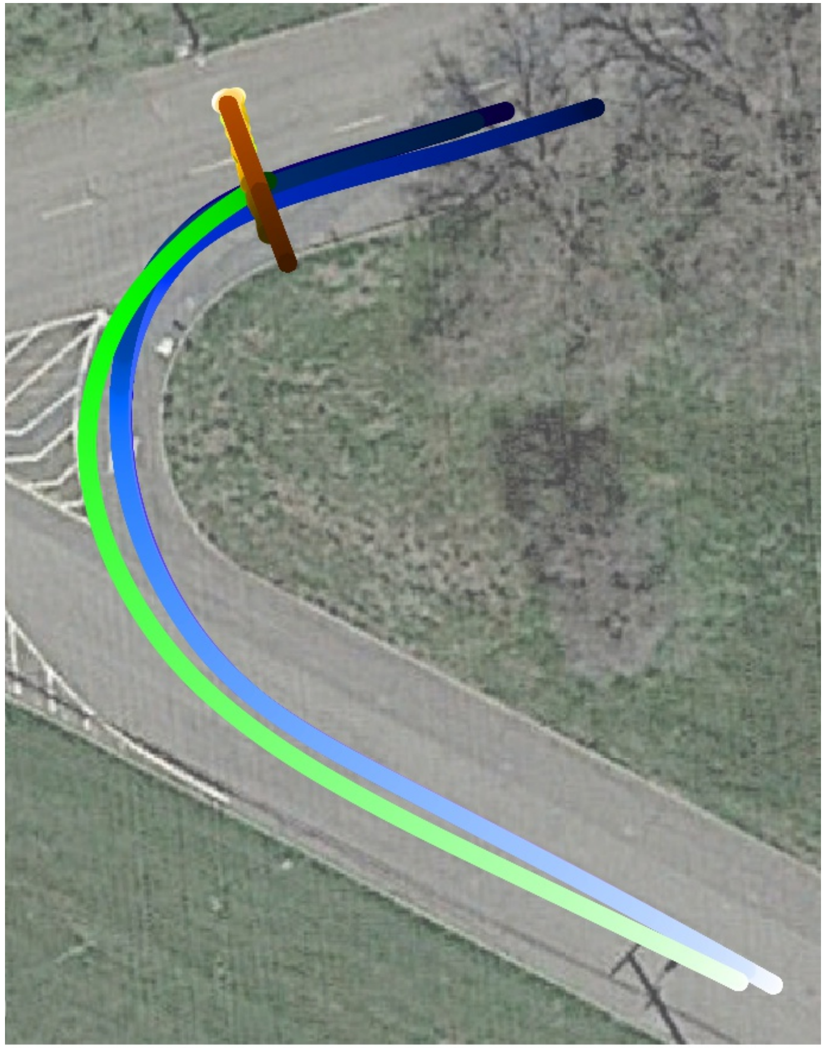


S. A.

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

Conclusion

- Scenic allows easy modeling of complex scenarios for AI-based autonomy + associated data generation
- VerifAI covers range of design, verification, and debugging tasks for AI-based autonomy
- ITSC 2020 Case Study: Scenic+VerifAI can be used to bridge the simulation-to-real world testing gap
  - Effectively evaluate safety via formally-guided simulation
  - Reduce expense of real-world testing by orders of magnitude
- Up next: 1 hour tutorial will give further details on Scenic and VerifAI and use cases for both tools

Ongoing Work and Directions

- Compiling a library of scenarios in Scenic
- Evaluation on more complex, higher-dimensional scenarios
- New algorithms for formal verification and synthesis
- Tools for automated analysis/triage of failure cases
- Improvements in track testing equipment and their connection to simulation

and more…

We welcome participation from the community!

https://github.com/BerkeleyLearnVerify/VerifAI
https://github.com/BerkeleyLearnVerify/Scenic/

Acknowledgments: Contributors, Co-authors, Collaborators

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Thank you!