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Safety Evaluation for Self-Driving Cars (and Other Intelligent Systems)

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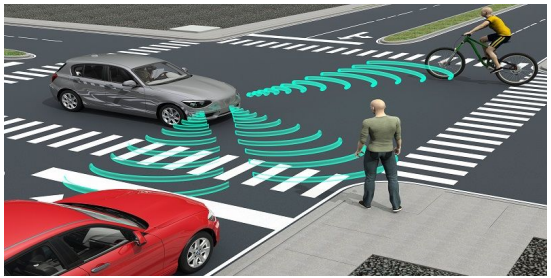
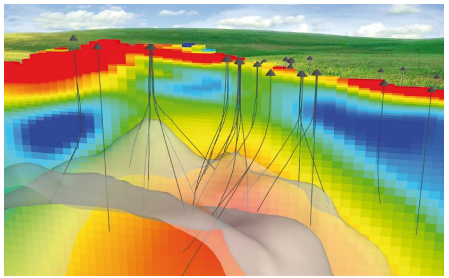
High-stake decisions are clouded with uncertainty



Autonomy stack

Mineral exploration



Renewable energy

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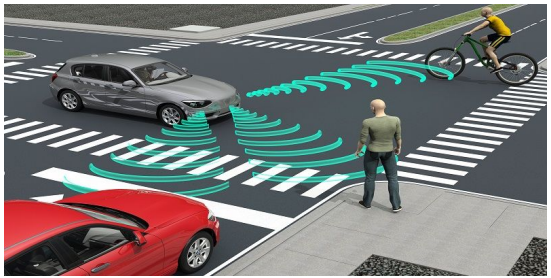
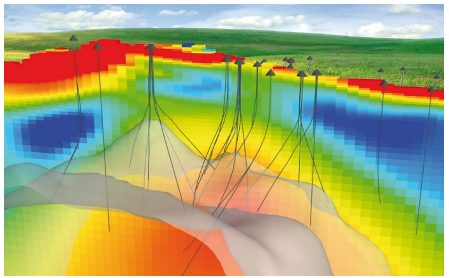
Effective support systems plays a crucial role





Preventing accidents

Most-efficient operations

Sustainable operations

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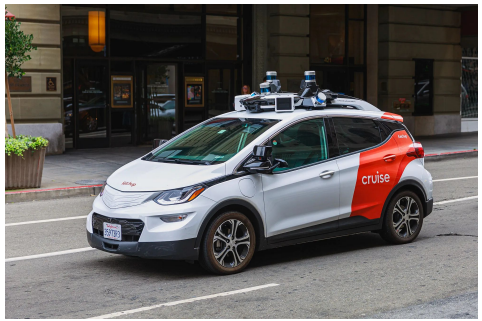
AI autonomy is here…



WIRED BACKCHANNEL BUSINESS CULTURE GEAR IDEAS SCIENCE SECURITY MERCH SIGN IN SUBSCRIBE

Robotaxis Can Now Work the Streets of San Francisco 24/7

Robotaxis can offer paid rides in San Francisco around the clock after Alphabet's Waymo and GM's Cruise got approval from the California Public Utilities Commission.

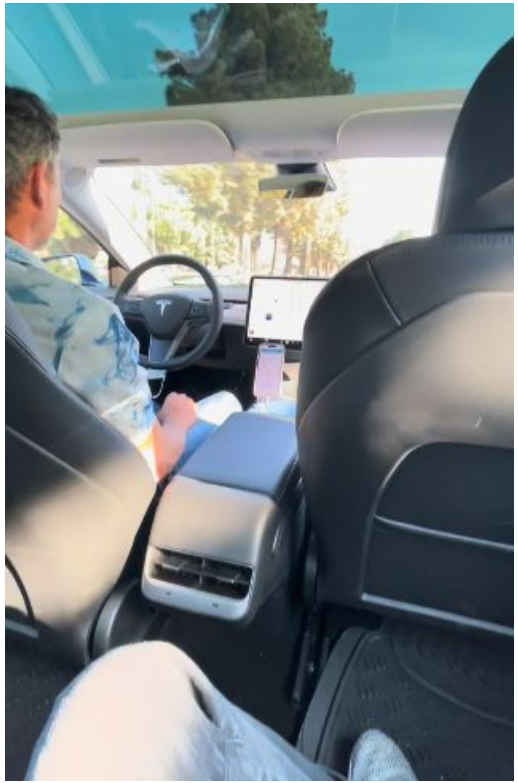


Photo I took two weeks ago, in an Uber ride

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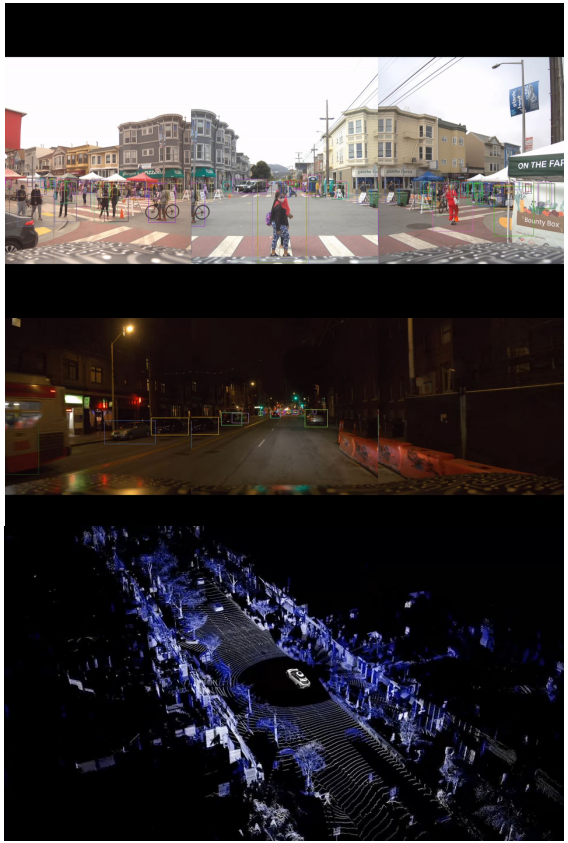
AI autonomy is here…

How self-driving cars “see” their environments



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AI autonomy is here…

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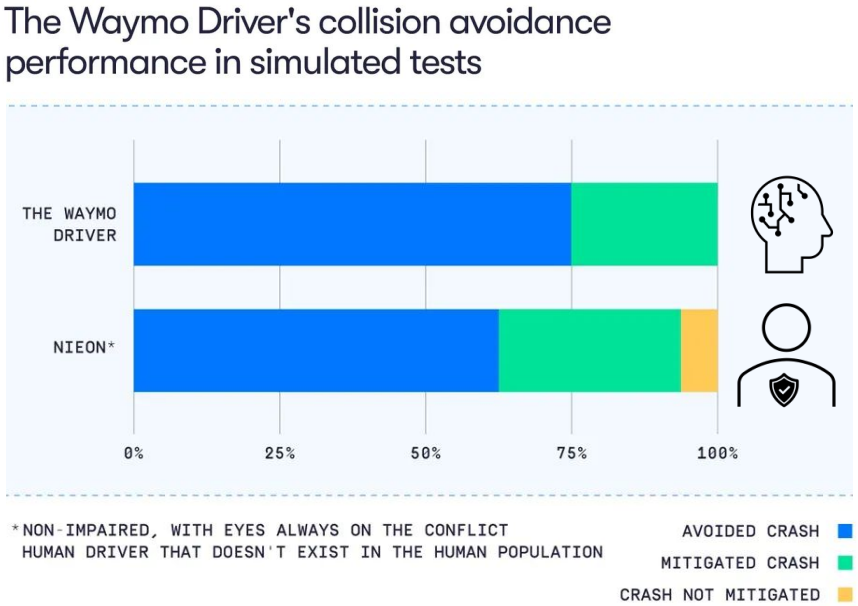
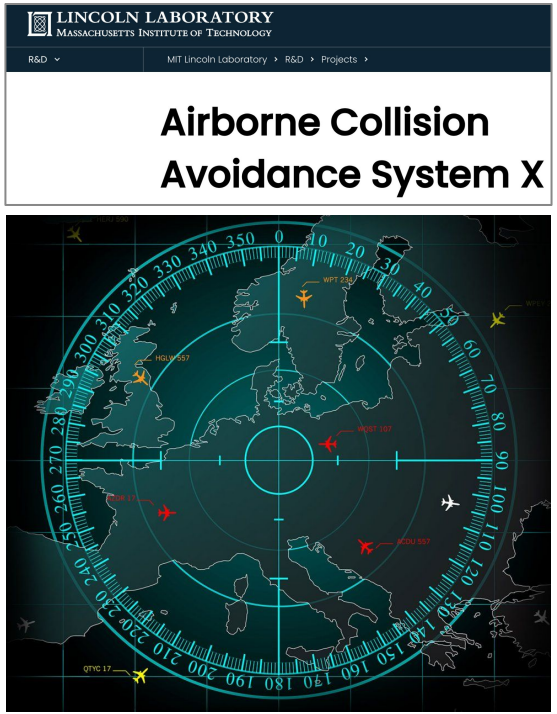
AI autonomy is here… and becomes safer everyday



Source: https://www.theverge.com/2022/9/29/23377219/waymo-av-safety-study-response-time-crash-avoidance, https://waymo.com/waymo-one-san-francisco/



A next-generation collision avoidance system will help pilots and unmanned aircraft safely navigate the airspace.

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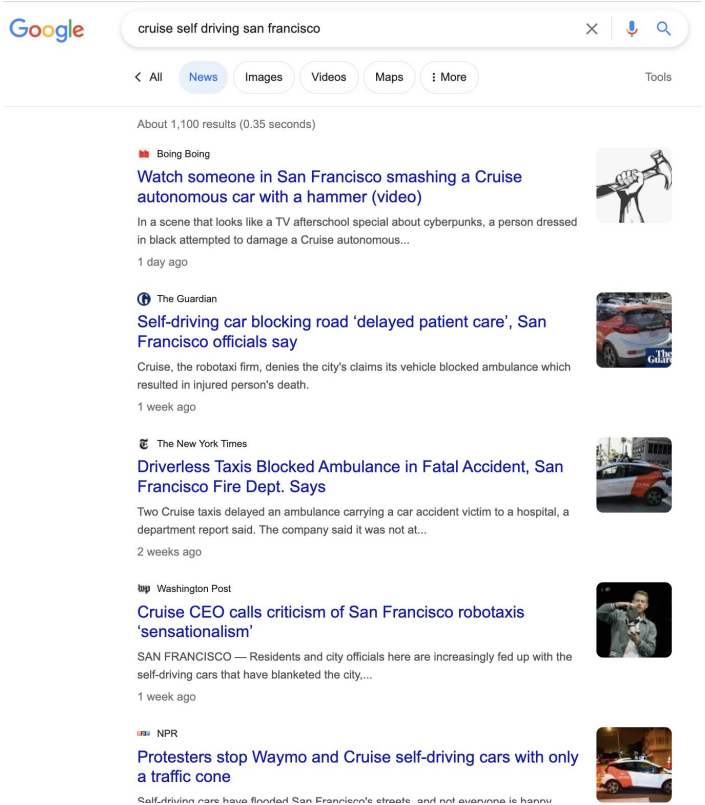
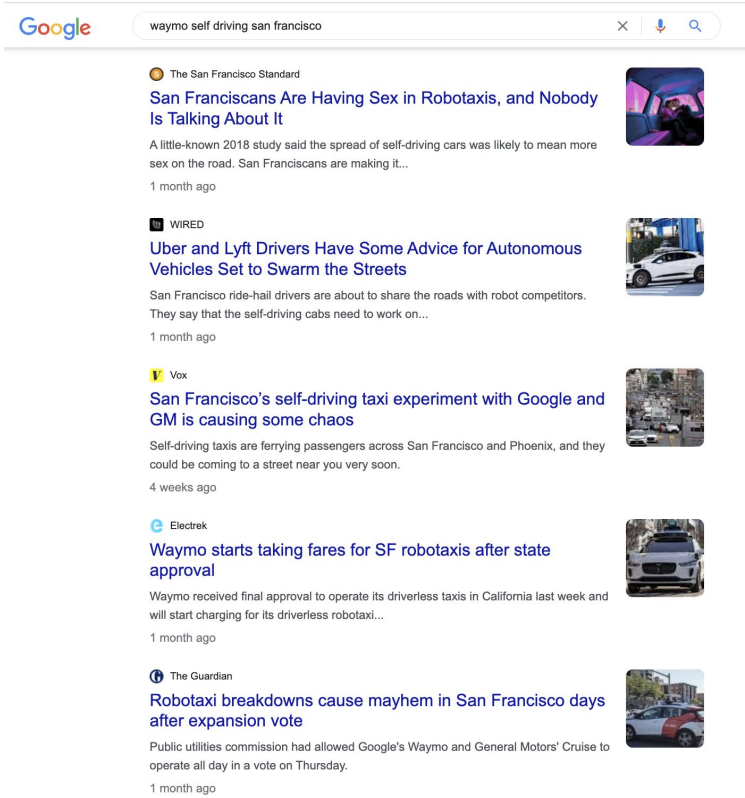
Is it safe enough?





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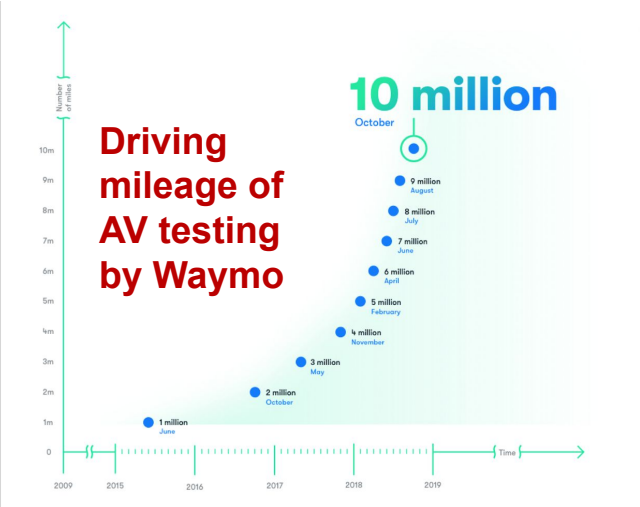
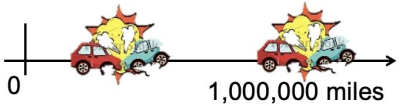
Safe AI is hard to evaluate

- If the **failure rate is μ**, then on average we need **$1/\mu$ samples** to observe the first failure (geometric distribution).
- Hence, **smaller μ** requires **larger sample size**.



Source: Waymo

Main reason:



Crashes happen extremely **rarely** (NHTSA, 2019).

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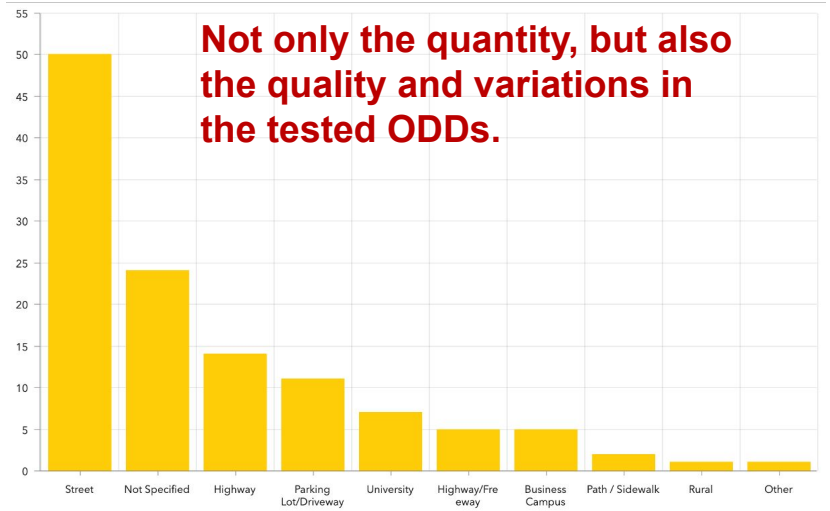

Source: https://www.nhtsa.gov/automated-vehicle-test-tracking-tool

- The huge testing burden results in **costly, lengthy, and risky** on-road deployments.[1]

[1] *Arief, Mansur, Glynn, P., & Zhao, D. An accelerated approach to safely and efficiently test pre-production autonomous vehicles on public streets. In 2018 21st International Conference on Intelligent Transportation Systems (ITSC) (pp. 2006-2011). IEEE, 2018.*

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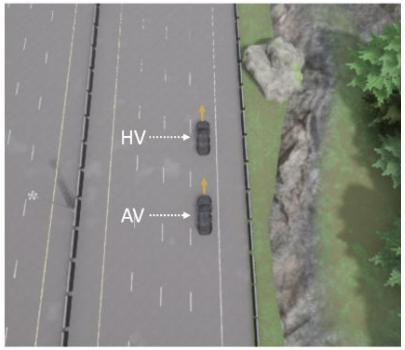
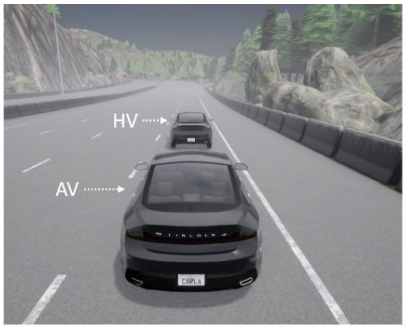
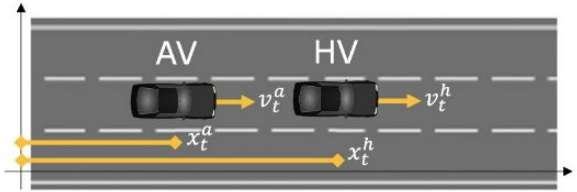
Inefficiency remains an issue in simulations





AV Simple PI Controller (SAE Level 2):



$$a_t^a = a_{t-1}^a + K_p(e_t^{thw} - e_{t-1}^{thw}) + K_i(e_t^{thw} + e_{t-1}^{thw})T_s/2$$

where a_t^a : AV acceleration at time t

e_t^{thw} : target and realization time headway error at time t

K_p, K_i : P and I gain, respectively

T_s : simulation frequency

- Naturalistic simulation takes up to **a month of runtime** to estimate $\mu = 2\times10^{-5}$

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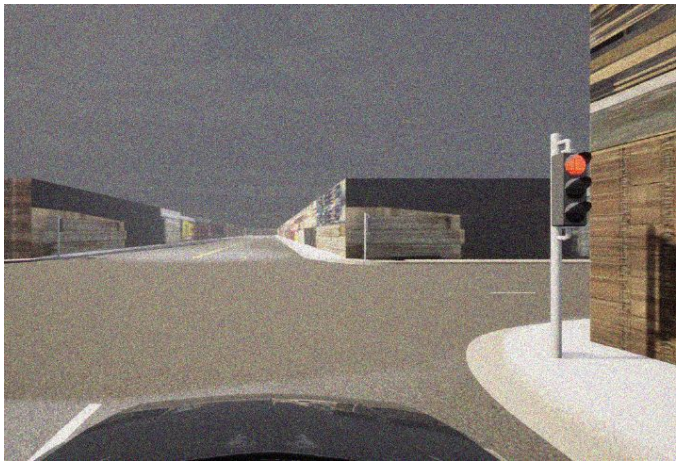
Inefficiency remains an issue in simulations

AV Perception Algorithm (YOLOv5)



Normal cases **Extremely rare (1 in 1 million simulation)**

- May take **3 months (estimated) runtime** to estimate smaller $\mu = 1 \times 10^{-6}$

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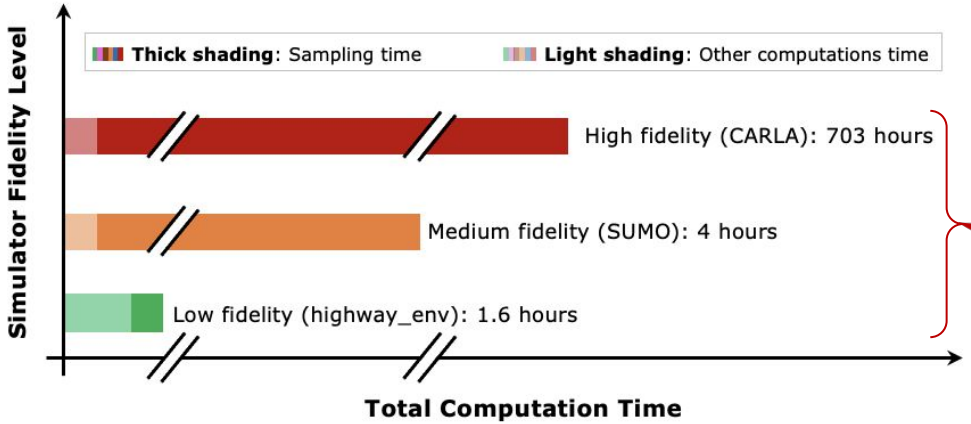
Inefficiency remains an issue in simulations



Increases as $\mu \to 0$

Simply lowering the fidelity is NOT a scalable solution!

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Why must we care?

Because Safety is Urgent™

Autonomous Driving Technology Can Save Lives and Improve Mobility

1.36M
deaths due to vehicle crashes each year

42,915
deaths in the U.S. in 2021 and 2.5 million injuries

$836B
in harm from loss of life and injury each year

50M
Injuries worldwide due to vehicle crashes each year

79%
of seniors age 65 and older live in car-dependent communities.

12M
people 40 years and over in the United States have vision impairment.

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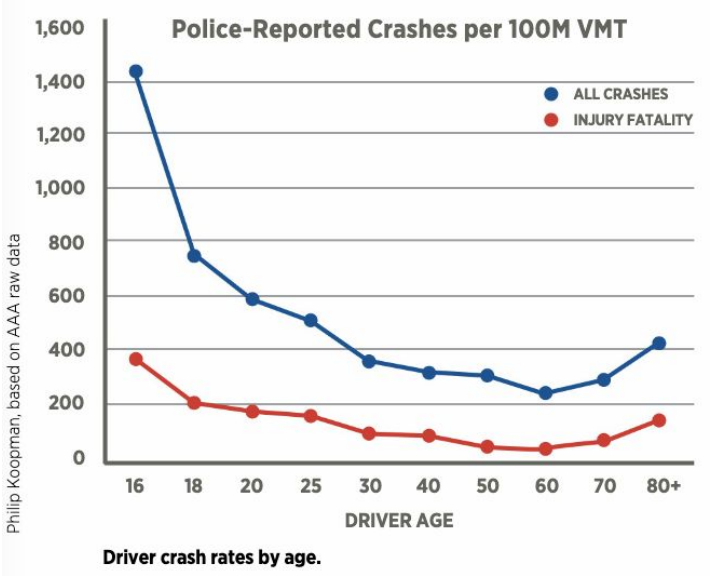
How to certify safety?

- **Main focus**: probabilistic evaluation
  - compares to **baseline** and standards
  - allows **risk mitigation** strategies
  - more **practical** and aligns with engineering continuous improvement
    - ISO 26262, ISO 21448
    - UL4600, SAE J3018



Driver crash rates by age.

Source: SAE Update p. 31

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Can we just list all test cases? (EuroNCAP)

- No, because AI is “smart” and trainable
- We recently published a paper on generating safety-critical test cases

Mansur Maturidi Arief

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Stanford University
Verified email at stanford.edu - Homepage

Rare-event simulation importance sampling autonomous vehicle safety analysis sustainability

TITLE	CITED BY	YEAR
A survey on safety-critical driving scenario generation—A methodological perspective W Ding, C Xu, M Arief, H Lin, B Li, D Zhao IEEE Transactions on Intelligent Transportation Systems	50	2023

but it’s not enough. We want to get “unbiased” safety estimate

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Scalable and certifiable evaluation algorithms

- **Objective**: Develop algorithms that can deal with
  - extreme rarity and high-dimensional inputs
- **Requirements**:
  - efficiency guarantee and efficient computation
- **Proposed algorithms**:
  - **Deep IS**: Deep Importance Sampling[1]
  - **Deep-PrAE**: Deep Probabilistic Accelerated Evaluation[2]
  - **CERTIFY**: Computationally Efficient and Robust Evaluation of Safety[3]

[1]Arief, Mansur, Zhepeng Cen, Zhenyuan Liu, Zhiyuan Huang, Bo Li, Henry Lam, and Ding Zhao. "Certifiable Evaluation for Autonomous Vehicle Perception Systems Using Deep Importance Sampling (Deep IS)." In *Proceedings of* the *2022 25th International Conference on Intelligent Transportation Systems (ITSC)*. IEEE, 2022. [Link]

[2]Arief, Mansur, Zhiyuan Huang, Guru Koushik Senthil Kumar, Yuanlu Bai, Shengyi He, Wenhao Ding, Henry Lam, and Ding Zhao. "Deep Probabilistic Accelerated Evaluation: A Certifiable Rare-Event Simulation Methodology for Black-Box Autonomy." In *Proceedings of the 24th International Conference on Artificial Intelligence and Statistics (AISTATS)*. PMLR, 2021. [Link]

[3]Arief, Mansur, Zhepeng Cen, Huan Zhang, Henry Lam, and Ding Zhao. "CERTIFY: Computationally Efficient Rare-failure Certification of Autonomous Vehicles." *Under review for IEEE T-IV.* [Link]

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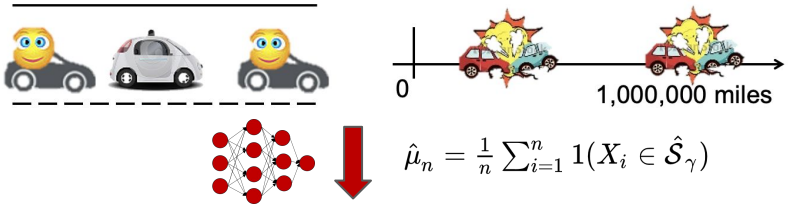
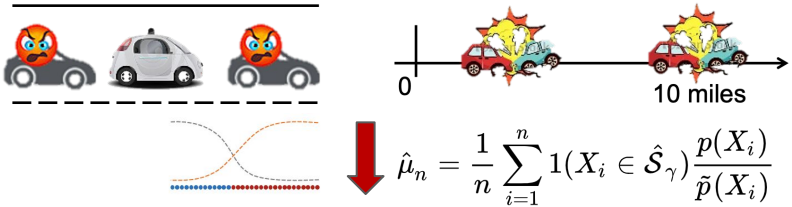
Statistical Workhorse: Importance Sampling

- **High-level idea**

Naturalistic driving conditions:



Aggressive driving conditions:



Unbiased result

Key steps:

1. Start with normal driving
2. Learn the statistical model
3. Bias the statistics toward more aggressive driving
4. Use importance weights to obtain unbiased result
5. Return unbiased statistics

[1]Arief, Mansur, Zhepeng Cen, Zhenyuan Liu, Zhiyuan Huang, Bo Li, Henry Lam, and Ding Zhao. "Certifiable Evaluation for Autonomous Vehicle Perception Systems Using Deep Importance Sampling (Deep IS)." In *Proceedings of* the *2022 25th International Conference on Intelligent Transportation Systems (ITSC)*. IEEE, 2022. [Link]

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Deep IS: Unbiased, given an accurate approximation

- Suppose NN gives a set approximation $\hat{\mathcal{S}}_\gamma \approx \mathcal{S}_\gamma$ (the true failure rate) after training with n_1 samples. We have, with $n_2 = n - n_1$ samples,

$$
\begin{aligned}
\mathbb{E}_{X\sim\tilde{p}}[\hat{\mu}_n] &= \mathbb{E}\left[\frac{1}{n_2}\sum_{i=1}^{n_2}\mathbb{1}\left(X_i \in \hat{\mathcal{S}}_\gamma\right) L(X_i)\right] \\
&= \frac{1}{n_2}\sum_{i=1}^{n_2}\mathbb{E}\left[\mathbb{1}\left(X_i \in \hat{\mathcal{S}}_\gamma\right)\frac{\phi(\tilde{X}_i;\lambda,\Sigma)}{\sum_{a\in\hat{A}_\gamma} w_a\phi(\tilde{X}_i;a,\Sigma)}\right] \\
&= \frac{1}{n_2}\sum_{i=1}^{n_2}\int_{\mathbb{R}^d}\mathbb{1}\left(X_i \in \hat{\mathcal{S}}_\gamma\right)\frac{\phi(\tilde{X}_i;\lambda,\Sigma)}{\sum_{a\in\hat{A}_\gamma} w_a\phi(\tilde{X}_i;a,\Sigma)}\sum_{a\in\hat{A}_\gamma} w_a\phi(\tilde{X}_i;a,\Sigma)dX_i \\
&= \frac{1}{n_2}\sum_{i=1}^{n_2}\int_{\mathbb{R}^d}\mathbb{1}\left(X_i \in \hat{\mathcal{S}}_\gamma\right)\phi(\tilde{X}_i;\lambda,\Sigma)dX_i \\
&= \frac{1}{n_2}\sum_{i=1}^{n_2}\mathbb{E}_{X\sim p}\mathbb{1}\left(X_i \in \hat{\mathcal{S}}_\gamma\right) \\
&\approx \frac{1}{n_2}\sum_{i=1}^{n_2}\mathbb{E}_{X\sim p}\mathbb{1}\left(X_i \in \mathcal{S}_\gamma\right) \\
&= \mu.
\end{aligned}
$$

If we have accurate deep learning classifier, we have provable unbiased results!

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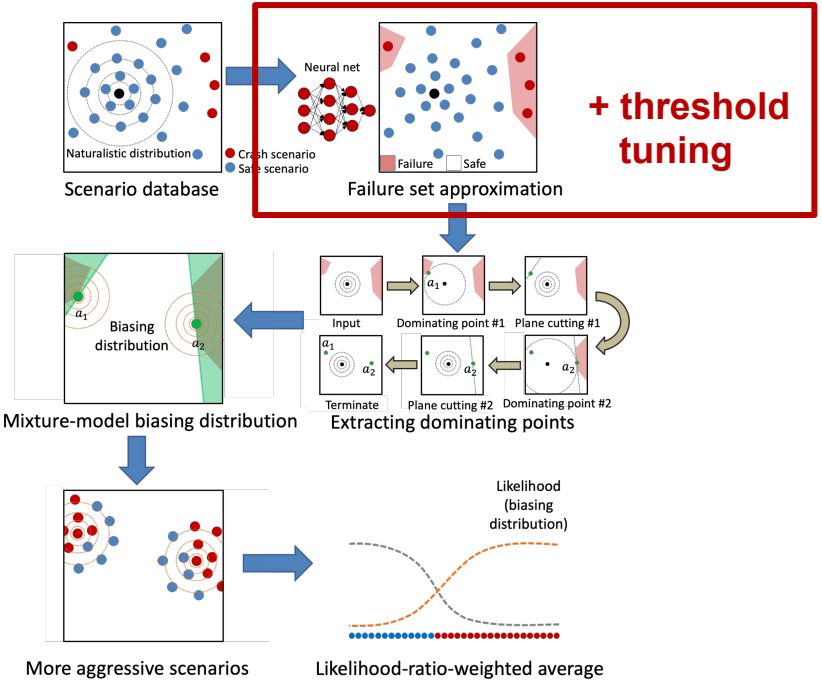
Deep-PrAE: Deep Probabilistic Accelerated Evaluation

- **What if we have an error, can we prove efficiency? Yes, a conservative one!**



[2]Arief, Mansur, Zhiyuan Huang, Guru Koushik Senthil Kumar, Yuanlu Bai, Shengyi He, Wenhao Ding, Henry Lam, and Ding Zhao. "Deep Probabilistic Accelerated Evaluation: A Certifiable Rare-Event Simulation Methodology for Black-Box Autonomy." In *Proceedings of the 24th International Conference on Artificial Intelligence and Statistics (AISTATS)*. PMLR, 2021. [Link]

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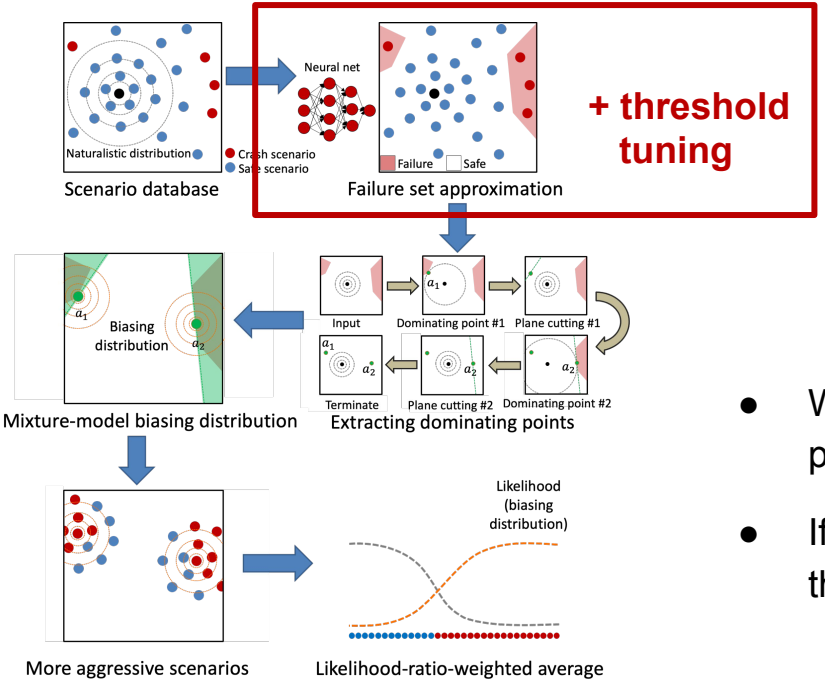

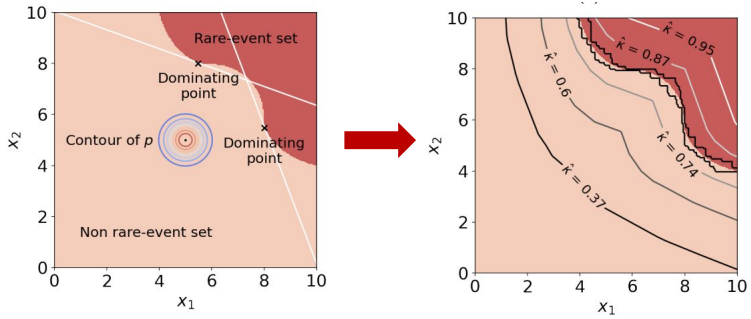

- With this, we have an upper-bound for the failure probability, but it is still useful for safety evaluation
- If an upper bound for something is below some value, then its true value must be below it too

[2]Arief, Mansur, Zhiyuan Huang, Guru Koushik Senthil Kumar, Yuanlu Bai, Shengyi He, Wenhao Ding, Henry Lam, and Ding Zhao. "Deep Probabilistic Accelerated Evaluation: A Certifiable Rare-Event Simulation Methodology for Black-Box Autonomy." In *Proceedings of the 24th International Conference on Artificial Intelligence and Statistics (AISTATS)*. PMLR, 2021. [Link]

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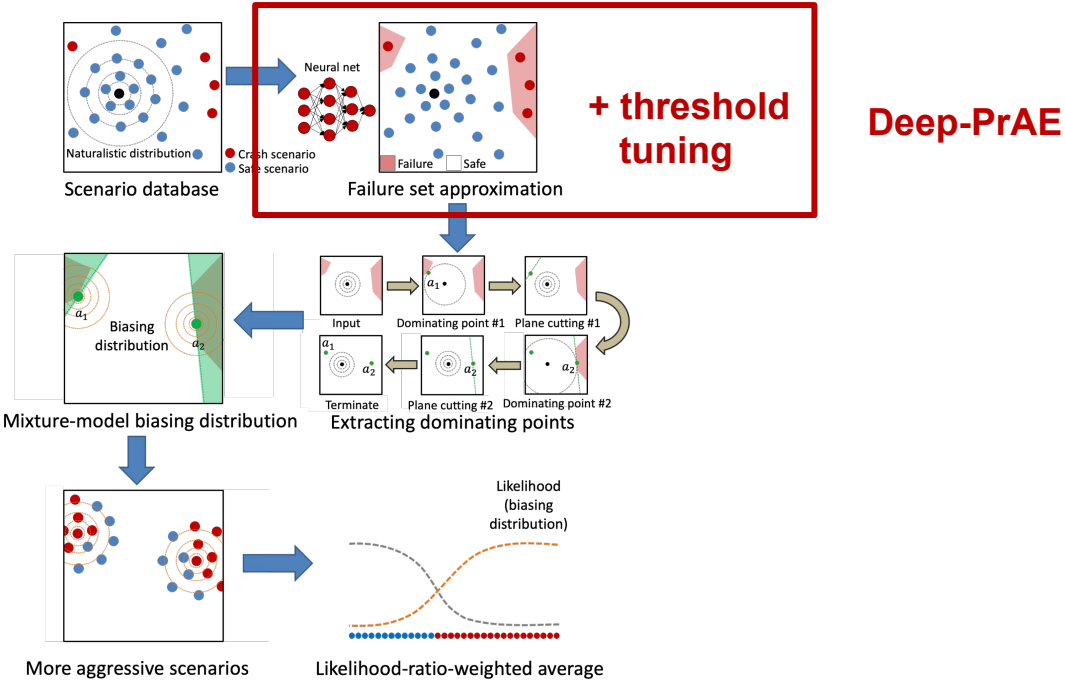
CERTIFY: Computationally Efficient and Robust Evaluation of Safety

- **Main idea: Can we speed up? Yes, by simplifying neural network constraints!**



[3]Arief, Mansur, Zhepeng Cen, Huan Zhang, Henry Lam, and Ding Zhao. "CERTIFY: Computationally Efficient Rare-failure Certification of Autonomous Vehicles." *Under review.*

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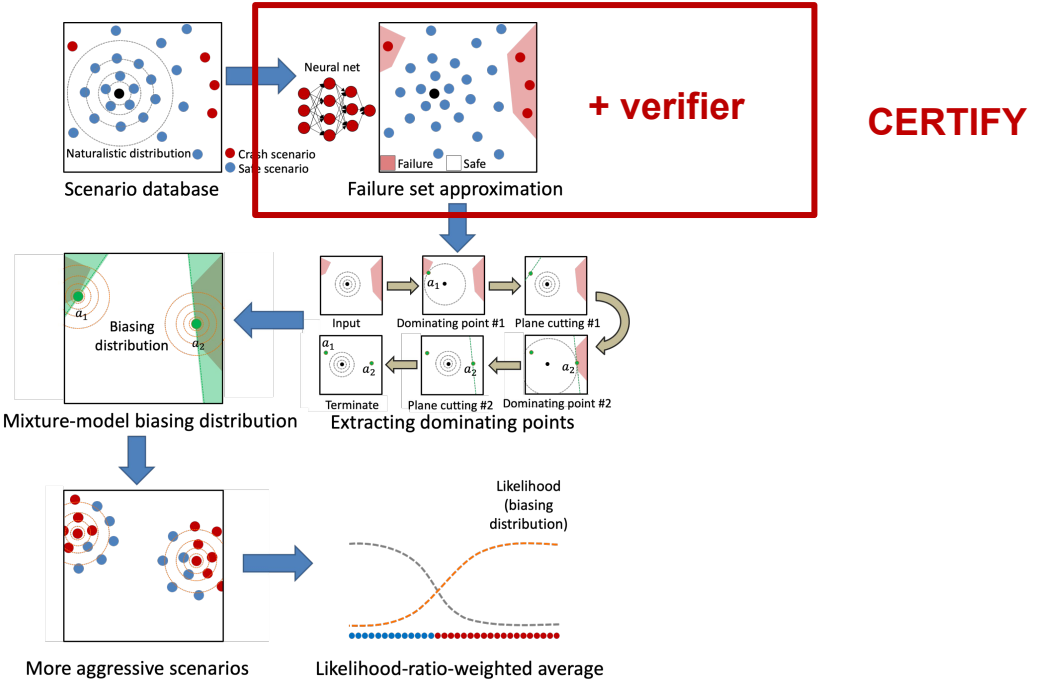

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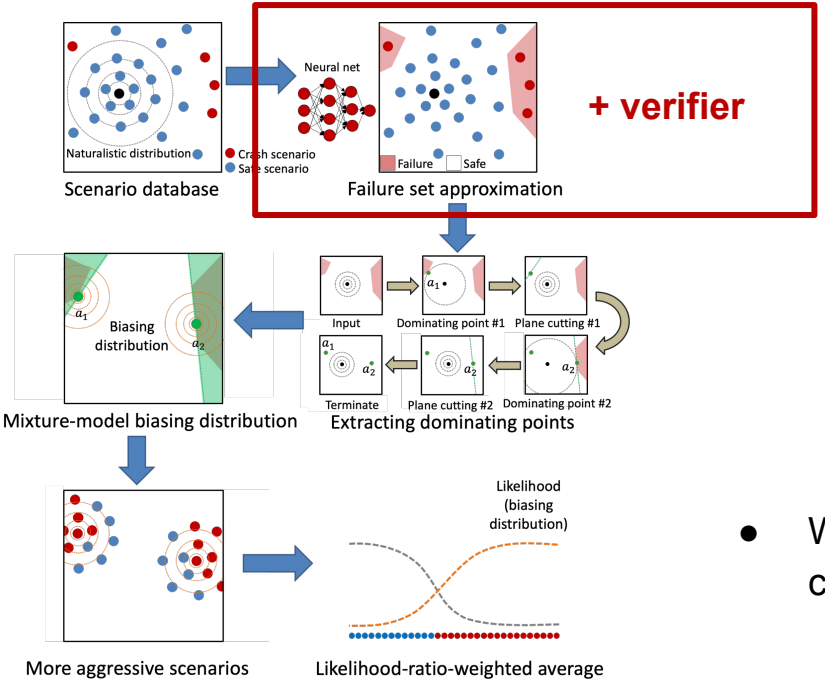

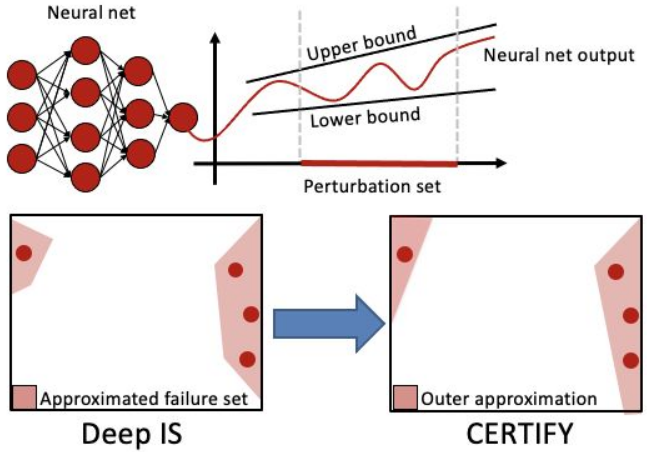

- With this, we have a valid upper-bound that is fast to compute, but might be more conservative

[3] Arief, Mansur, Zhepeng Cen, Huan Zhang, Henry Lam, and Ding Zhao. "CERTIFY: Computationally Efficient Rare-failure Certification of Autonomous Vehicles." *Under review.*

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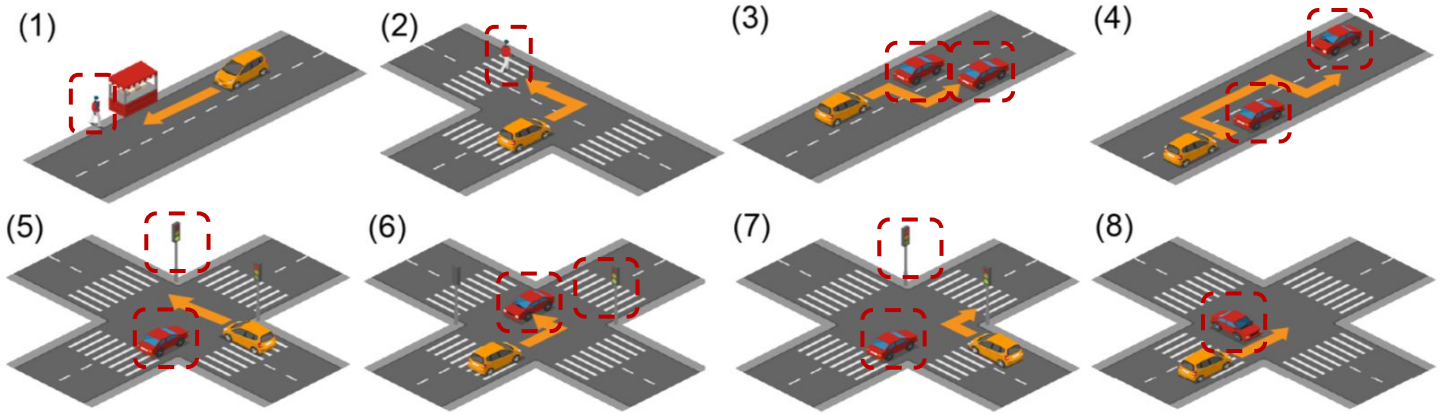
Benchmarking settings

- **Driving scenarios**: Eight driving scenarios as defined in SafeBench [1].



(1) Straight Obstacle, (2) Turning Obstacle, (3) Lane Changing, (4) Vehicle Passing,
(5) Red-light Running, (6) Unprotected Left-turn, (7) Right-turn, and (8) Crossing Negotiation.

[1]Xu, Chejian, et al. "SafeBench: A Benchmarking Platform for Safety Evaluation of Autonomous Vehicles." arXiv preprint arXiv:2206.09682 (2022).

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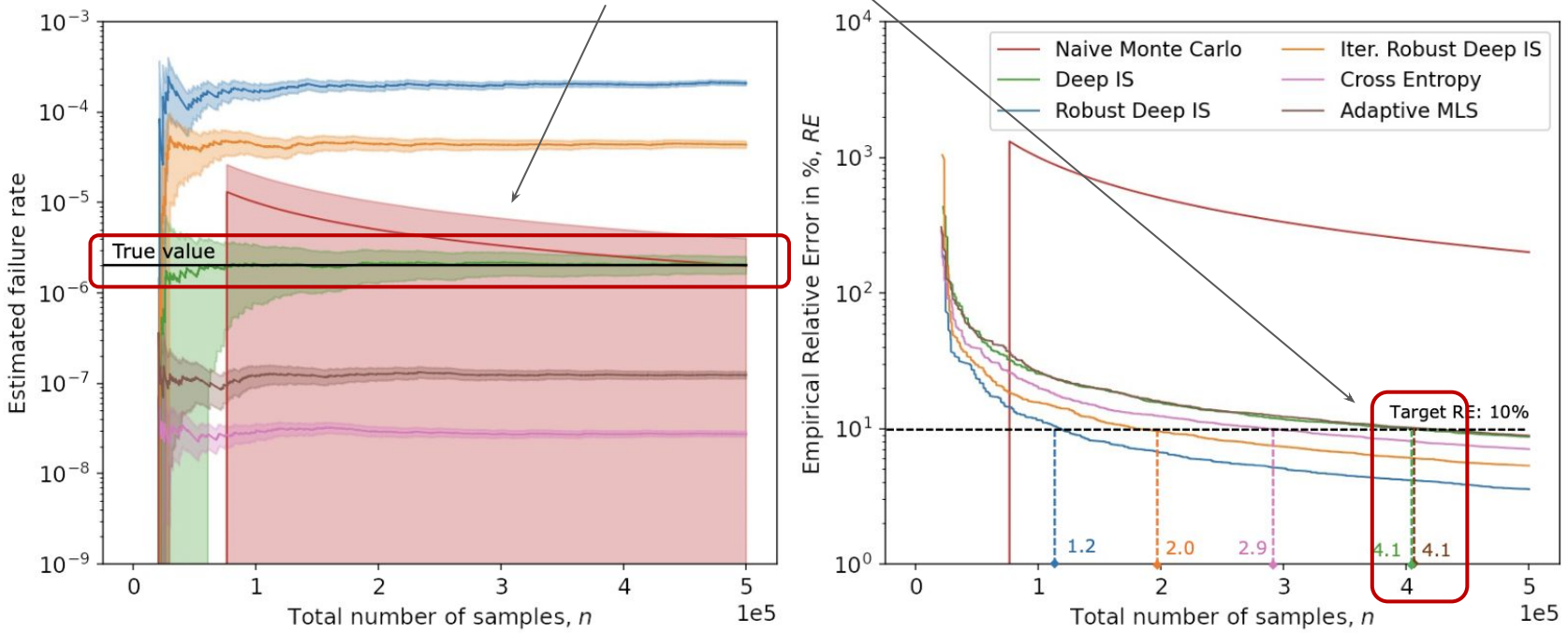
Deep IS numerical experiments

- **Main result: Deep IS is unbiased and sample-efficient**



[1]Arief, Mansur, Zhepeng Cen, Zhenyuan Liu, Zhiyuan Huang, Bo Li, Henry Lam, and Ding Zhao. "Certifiable Evaluation for Autonomous Vehicle Perception Systems Using Deep Importance Sampling (Deep IS)." In *Proceedings of* the *2022 25th International Conference on Intelligent Transportation Systems (ITSC)*. IEEE, 2022. [Link]

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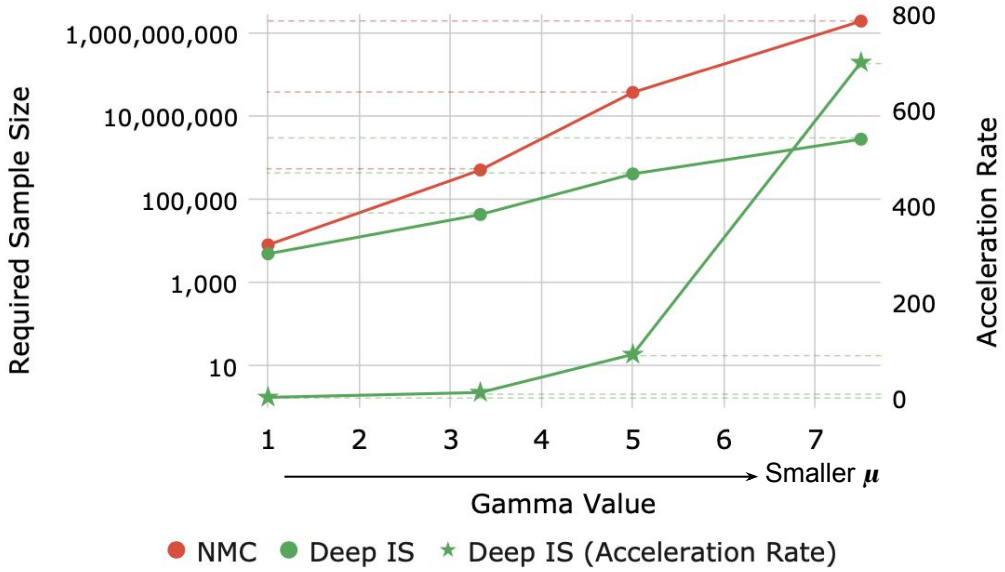
Deep IS numerical experiments

- **Main result: (Empirically) Handles rarity well with efficiency boost!**



[1]Arief, Mansur, Zhepeng Cen, Zhenyuan Liu, Zhiyuan Huang, Bo Li, Henry Lam, and Ding Zhao. "Certifiable Evaluation for Autonomous Vehicle Perception Systems Using Deep Importance Sampling (Deep IS)." In *Proceedings of* the *2022 25th International Conference on Intelligent Transportation Systems (ITSC)*. IEEE, 2022. [Link]

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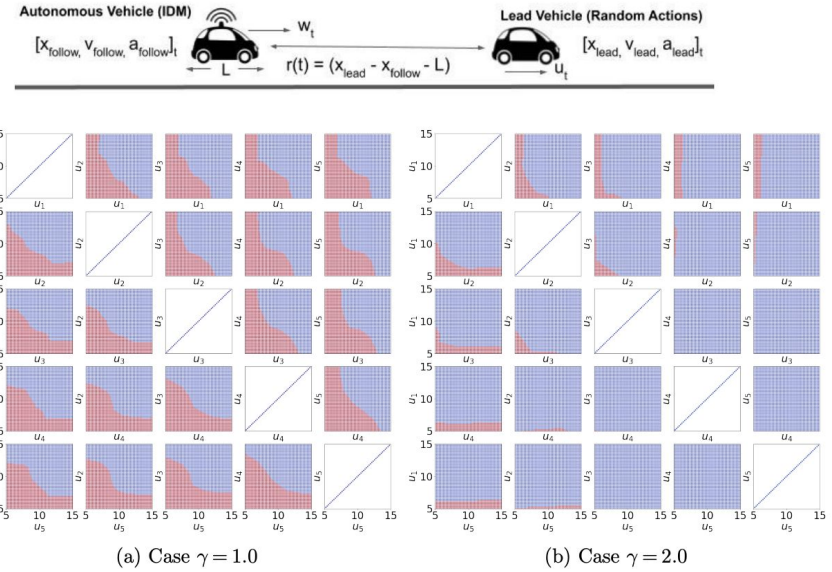
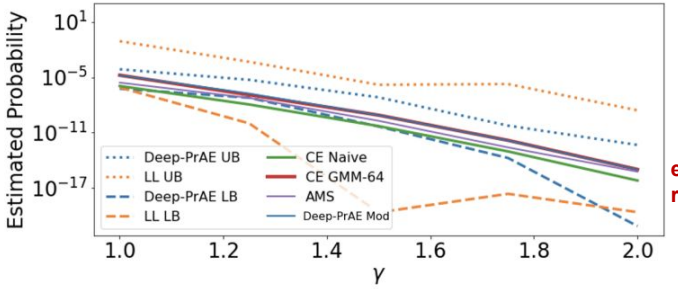
Deep-PrAE numerical experiments

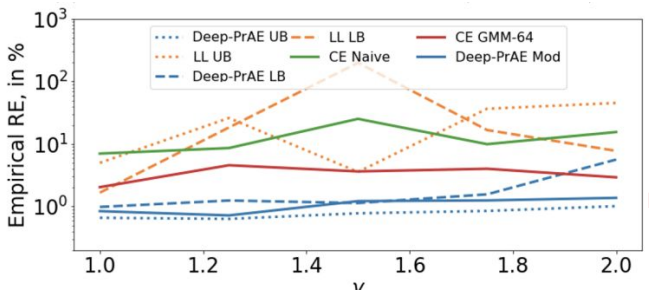
- **Autonomy evaluation example: Deep-PrAE efficiency dominates.**



(a) Case $\gamma = 1.0$ (b) Case $\gamma = 2.0$



extreme rarity



lowest erro

[2]Arief, Mansur, Zhiyuan Huang, Guru Koushik Senthil Kumar, Yuanlu Bai, Shengyi He, Wenhao Ding, Henry Lam, and Ding Zhao. "Deep Probabilistic Accelerated Evaluation: A Certifiable Rare-Event Simulation Methodology for Black-Box Autonomy." In *Proceedings of the 24th International Conference on Artificial Intelligence and Statistics (AISTATS)*. PMLR, 2021. [Link]

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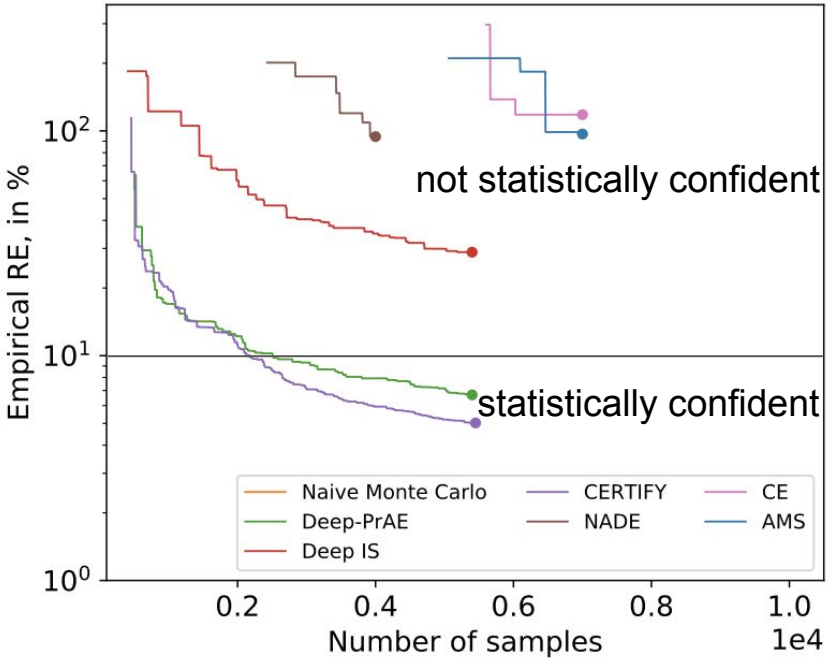
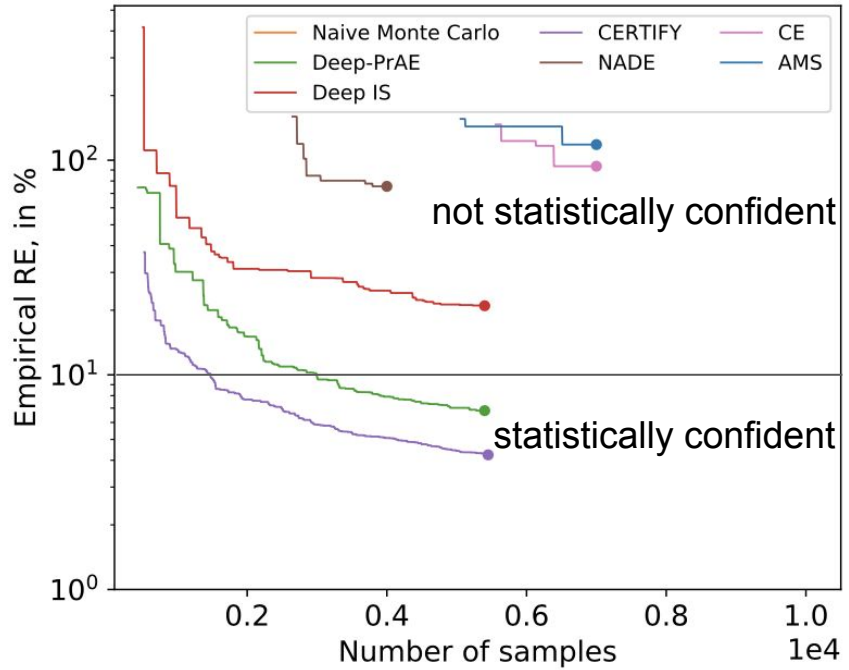
CERTIFY numerical experiments

Alg. #1 TPH-YOLOv5



Alg. #2 FocalNets



- **Only Deep-PrAE and CERTIFY achieve high confidence (<10% RE).**

[2]J. Yang, C. Li, X. Dai, and J. Gao, "Focal modulation networks," Advances in Neural Infor- mation Processing Systems, vol. 35, pp. 4203–4217, 2022.

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Summary

- Testing complex (blackbox) AI with rare failure cases is challenging
- The “intelligence” notion of AI makes conventional testing approaches ineffective
- Other domains with rare but critical failure events can be evaluation similarly
- In the context of safety, the notion of statistical confidence should be emphasized (which makes safety evaluation more challenging)

[1]Arief, Mansur, Zhepeng Cen, Zhenyuan Liu, Zhiyuan Huang, Bo Li, Henry Lam, and Ding Zhao. "Certifiable Evaluation for Autonomous Vehicle Perception Systems Using Deep Importance Sampling (Deep IS)." In *Proceedings of* the *2022 25th International Conference on Intelligent Transportation Systems (ITSC)*. IEEE, 2022. [Link]

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Collaborations with Institutions in Indonesia

- **DSA-POMDP**
  - How can we optimize stroke patient treatment as a sequential decision-making framework, determining when to perform surgery, MRA, DSA, etc. with limited prior information?
  - With 2 MD graduates, from UI and UIN Syarif Hidayatullah
- **Robust Design of EV Charging Stations in Indonesia**
  - We are using variance reduction technique into simulation-based optimization to determine infrastructure for EVs under outage uncertainty
  - With ITS and Carnegie Mellon
- **Intelligent Decision Support System for Agro-Products and Sustainable Mining**
  - How to best integrate IoT, smart devices, and deep learning to reduce food loss and maximize total values - with IPB and Carnegie Mellon
  - How to design proactive community development enterprise and ensure sustainable ecosystems during and post-mining operations - with MineralX and Unhas

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Collaboration with Interdisciplinary Scholars

- **IndoSTEELERS:** Indonesian Scholars Thriving in Excellence in Education, Learning, and Research
- Scholars (professors, practitioners, postdocs, graduate students) in
  - law
  - music and society
  - education
  - health informatics
  - public policy
  - intelligent systems, including AD, LLM, and robotics
- Open to collaborate for relevant researches in Indonesian context

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Research Areas

VERIFICATION & VALIDATION

Development of efficient verification and validation algorithms for autonomous systems.

1. Ding, Wenhao, Chejian Xu, Mansur Arief, Haohong Lin, Bo Li, Ding Zhao. "A Survey on Safety-Critical Driving Scenario Generation—A Methodological Perspective." *T-ITS, 2023.*
   https://ieeexplore.ieee.org/abstract/document/10089194
2. Arief, Mansur. "Certifiable Evaluation for Safe Intelligent Autonomy." *Carnegie Mellon University, 2023.*
   https://www.proquest.com/openview/45f55565d4810a203cc28fc50dd878a6
3. Arief, Mansur, Zhepeng Cen, Zhenyuan Liu, Zhiyuan Huang, Bo Li, Henry Lam, and Ding Zhao. "Certifiable Evaluation for Autonomous Vehicle Perception Systems Using Deep Importance Sampling (Deep IS)." *ITSC, 2022.*
   https://ieeexplore.ieee.org/abstract/document/9922202
4. Arief, Mansur, Yuanlu Bai, Wenhao Ding, Shengyi He, Zhiyuan Huang, Henry Lam, and Ding Zhao. "Certifiable Deep Importance Sampling for Rare-Event Simulation of Black-Box Systems." *Under Review.*
   https://arxiv.org/abs/2111.02204
5. Arief, Mansur, Zhiyuan Huang, Guru Koushik Senthil Kumar, Yuanlu Bai, Shengyi He, Wenhao Ding, Henry Lam, and Ding Zhao. "Deep Probabilistic Accelerated Evaluation: A Certifiable Rare-Event Simulation Methodology for Black-Box Autonomy. "*AISTATS, 2021.*
   https://proceedings.mlr.press/v130/arief21a/arief21a.pdf
6. Chen, Rui, Mansur Arief, Weiyang Zhang, and Ding Zhao. "How to Evaluate Proving Grounds for Self-Driving? A Quantitative Approach." *T-ITS, 2020.*
   https://ieeexplore.ieee.org/document/9094370
7. Huang, Zhiyuan, Mansur Arief, Henry Lam, and Ding Zhao. "Evaluation Uncertainty in Data-Driven Self-Driving Testing." *ITSC, 2019.*
   https://ieeexplore.ieee.org/abstract/document/8917406
8. Arief, Mansur, Peter Glynn, and Ding Zhao. "An Accelerated Approach to Safely and Efficiently Test Pre-production Autonomous Vehicles on Public Streets." *ITSC, 2018.*
   https://ieeexplore.ieee.org/document/9094370

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Research Areas

AUTONOMOUS DRIVING PERCEPTION

Works that design robust perception systems for autonomous driving applications.

1. Abdussyukur, Hafizh, Mahmud Dwi Sulistiyo, Ema Rachmawati, Mansur Arief, Gamma Kosala. "Semantic Segmentation for Identifying Road Surface Damages Using Lightweight Encoder-Decoder Network." *ICACNIS, 2022.* https://ieeexplore.ieee.org/abstract/document/10056030
2. Arief, Hasan Asy'ari, Mansur Arief, Guilin Zhang, Zuxin Liu, Manoj Bhat, Ulf Geir Indahl, Håvard Tveite, and Ding Zhao. "SAnE: Smart Annotation and Evaluation Tools for Point Cloud Data." *IEEE Access, 2020.* https://ieeexplore.ieee.org/iel7/6287639/8948470/09143095.pdf
3. Liu, Zuxin, Mansur Arief, and Ding Zhao. "Where Should We Place LiDARs on the Autonomous Vehicle? An Optimal Design Approach." *ICRA, 2019.* https://ieeexplore.ieee.org/document/8793619
4. Arief, Hasan Asy`ari, Mansur Arief, Manoj Bhat, Ulf Geir Indahl, Håvard Tveite, and Ding Zhao. "Density-Adaptive Sampling for Heterogeneous Point Cloud Object Segmentation in Autonomous Vehicle Applications." *CVPR Workshops, 2019.* https://openaccess.thecvf.com/content_CVPRW_2019/papers/UG2+%20Prize%20Challenge/Arief_Density-Adaptive_Sampling_for_Heterogeneous_Point_Cloud_Object_Segmentation_in_Autonomous_CVPRW_2019_paper.pdf

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Research Areas

EV & INFRASTRUCTURE

Studies focused on vehicle electrification and infrastructure designs.

1. Arief, Mansur, Yan Akhra, Iwan Vanany. "A Robust and Efficient Optimization Model for Electric Vehicle Charging Stations in Developing Countries under Electricity Uncertainty." *Under Review.*
   https://arxiv.org/abs/2307.05470
2. Amilia, Nissa, Zulkifli Palinrungi, Iwan Vanany, Mansur Arief. "Designing an Optimized Electric Vehicle Charging Station Infrastructure for Urban Area: A Case Study from Indonesia." *ITSC, 2022.*
   https://ieeexplore.ieee.org/abstract/document/9922278

OPTIMIZATION UNDER UNCERTAINTY

Exploration of optimization and simulation techniques for in the context of decision-making under uncertainty.

1. Ziyad, Muhammad, Kenrick Tjandra, Mushonnifun Faiz Sugihartanto, Mansur Arief. "An Optimized and Safety-aware Maintenance Framework: A Case Study on Aircraft Engine." *ITSC, 2022.*
   https://ieeexplore.ieee.org/abstract/document/9922187
2. Oktavian, Muhammad Rizki, Diana Febrita, Mansur Arief. "Cogeneration Power-Desalination in Small Modular Reactors (SMRs) for Load Following in Indonesia." *ICST, 2018.*
   https://ieeexplore.ieee.org/abstract/document/8528706
3. Pujawan, Nyoman, Mansur Arief, Benny Tjahjono, and Duangpun Kritchanchai. "An Integrated Shipment Planning and Storage Capacity Decision under Uncertainty." *International Journal of Physical Distribution & Logistics Management (IJPDLM), 2015.*
   https://www.emerald.com/insight/content/doi/10.1108/IJPDLM-08-2014-0198/full/html

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