Evaluation and Testing of Automated Vehicles

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The Building Blocks of Autonomy

Prepared by VISION SYSTEMS INTELLIGENCE

Level of Integration

AUTONOMOUS SOLUTIONS

TOYOTA, TESLA, Ford, GM, VOLVO, HYUNDAI, KIA MOTORS, GEELY, Google, UBER, NVIDIA, Continental, nauya, ZMP Robot of Everything, Audi, BMW, CHANGAN, HONDA, PSA PEUGEOT CITROËN, NISSAN, BAIC, Mercedes-Benz, SAIC, CHERY, Apple, DELPHI, BOSCH, Baidu 百度, VisLab.it Extend Your Vision, RENESAS, OTTO, nuTonomy, drive.ai, ZOOX

PROCESSING

RENESAS, NVIDIA, MOBILEYE, NXP, TOSHIBA Leading Innovation, CEVA, cadence, Imagination, ARM, ANALOG DEVICES, intel, XILINX, videantis passion for video, ALTERA, TEXAS INSTRUMENTS, MARVELL, QUALCOMM, Movidius, ST

SENSORS

BOSCH, DELPHI, MITSUBISHI ELECTRIC, NXP, Continental, ibeo, Valeo, ZF, TRW, HITACHI, OmniVision, Pioneer, Autoliv, TOSHIBA Leading Innovation, HYUNDAI MOBIS, POINT GREY Innovation in Imaging, KOSTAL, DENSO, LG Innotek, Panasonic, MAGNA, HARMAN, FUJITSU TEN, Visteon, QUANERGY, Melexis Microelectronic Integrated Systems, Mando Corporation, applanix A Trimble Company, FLIR SYSTEMS, OSRAM, ON Semiconductor, LeddarTech, Neusoft, Infineon, SONY, PEPPERL+FUCHS, TriLumina, Phantom Intelligence, u-blox, Velodyne LiDAR

CONNECTIVITY

HITACHI, RENESAS, Peloton, Continental, NXP, BOSCH, DELPHI, intel, Cohda Wireless Mobile Broadband, QNX, TTTech, DENSO, HARMAN, Infineon, Mentor Graphics

MAPPING

TomTom, here, Google, NAVINFO, mapscape, HARMAN, NVIDIA, GeoDigital, Increment P Feel the Space, EXONAV Mapping Automation, ZENRIN, applanix A Trimble Company, sanborn, Civil Maps, AND

ALGORITHMS

MOBILEYE, NVIDIA, MITSUBISHI ELECTRIC, Elektrobit, dSPACE, AdasWorks, Neusoft, ETAS, LUXOFT, KPIT, VECTOR

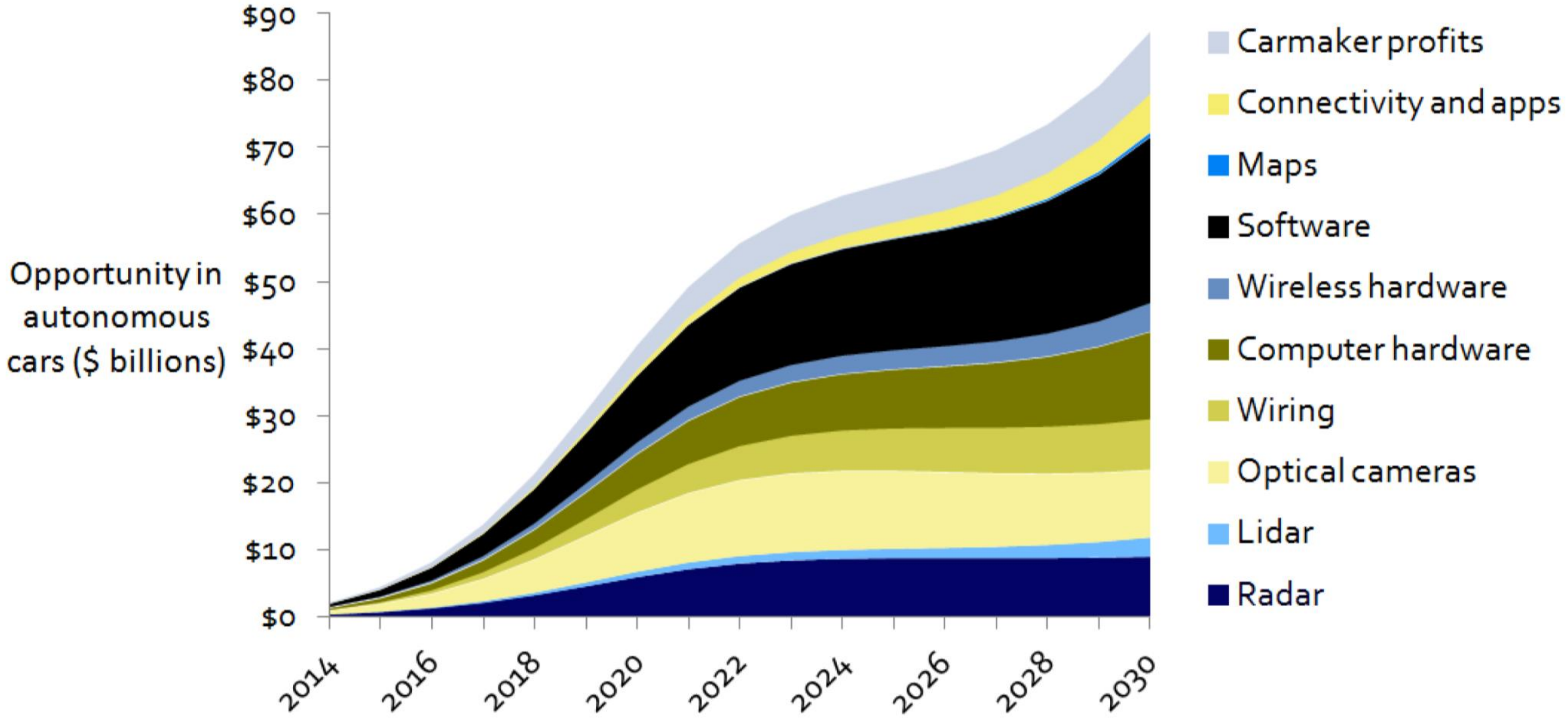
SECURITY/SAFETY

HITACHI, RENESAS, Mentor Graphics, BOSCH, Continental, DELPHI, NXP, WIND, ARGUS Cyber Security, Elektrobit, intel, QNX, DENSO, ETAS, Green Hills Software, HARMAN, Infineon, KPIT, VECTOR

DEVELOPMENT TOOLS

BASELABS, IAR SYSTEMS, LDRA, MathWorks, SYNOPSYS, VECTOR software, automotive engineering iav, Elektrobit, KPIT, LUXOFT, Mentor Graphics, HARBRICK, KISHONTI INFORMATICS, INTEMPORA Multisensor Software Solutions, tass international, TTTech, dSPACE, ETAS, VECTOR, QNX

Estimated Market of AVs in 2030



2016: 680 million

OTTO / UBER

2016: 1 billion

CRUISE / GM

2017: 15 billion

MOBILEYE / intel

But Things Can Go Wrong … Even for the Leaders

Tesla Autopilot Fatal Crash, May, 2016

Google Car Accident, Sep, 2016

Uber Self-driving Rollover, March, 2017

How to prove the technology is safe

My Research are Trying to Answer

- Are CAVs safer?
  - Better than a human driver on average
- How safe?
  - Crash rate, injury rate, …
- Possible failure modes and their probabilities of occurring

U.S. Department of Transportation

and other companies …

Existing AV Evaluation Methods

Test matrix

Pro: easy to execute, fast
Con: Pre-announced

EURO NCAP AEB

Scenario	$v_L(t_0)$ [km/h]	a_L [m/s²]	R_L [m]	$v(t_0)$ [km/h]
1	0	0	100	30:5:80
2	20	0	100	30:5:70
3	50	-2 & -6	12 & 40	50

Static

Moving

Braking

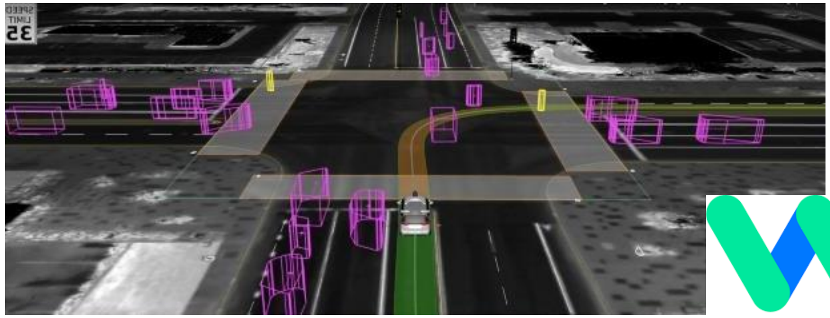
Naturalistic Field Operational Tests

Pro:
The real-world!

Con:
Slow, expensive
Low exposure to safety critical cases

❖ 100 million mi / fatal crash (NHTSA 2013)

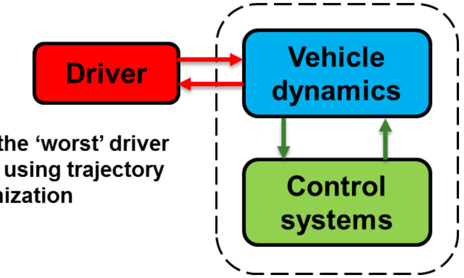
Monte Carlo Simulation



WAYMO

Pro: Stochastic
Con: Does not “accelerate” (cut the boring parts)

Worst-case Scenario Evaluation



Find the ‘worst’ driver input using trajectory optimization

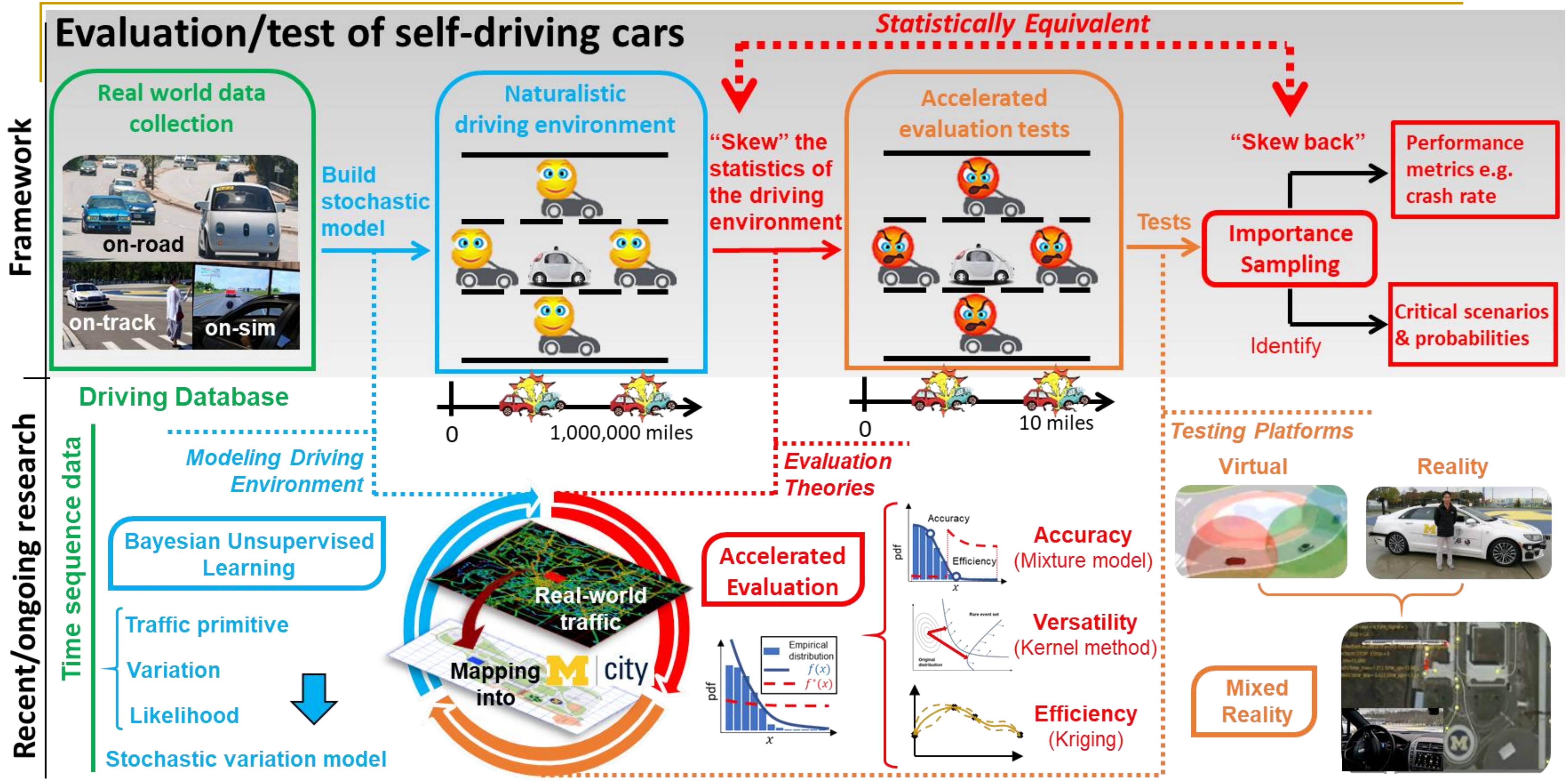
Roll-over analysis

Pro: Worst cases
Con: No probability information

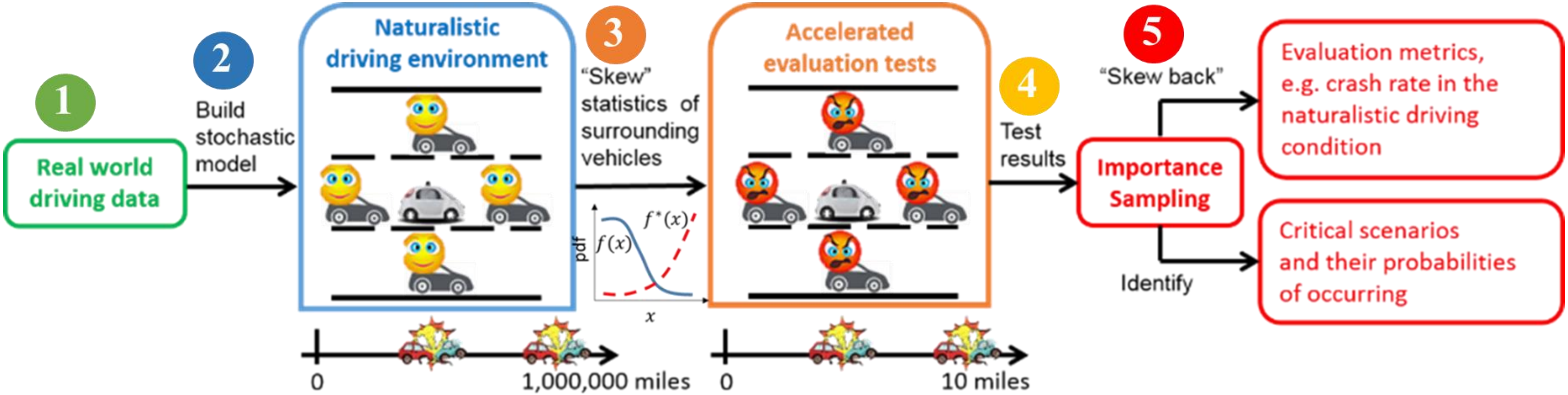
NCAP: New Car Assessment Programme
AEB: Autonomous Emergency Braking

Earth from Sun: 93 million mi

Evaluation/test of self-driving cars



Accelerated Evaluation



Zhao, Ding. "Accelerated Evaluation of Automated Vehicles." *PhD dissertation, The University of Michigan*, 2016.

Five Steps of the Accelerated Evaluation

④ **Simulate (at accelerated pace)**

① **Collect naturalistic driving data**

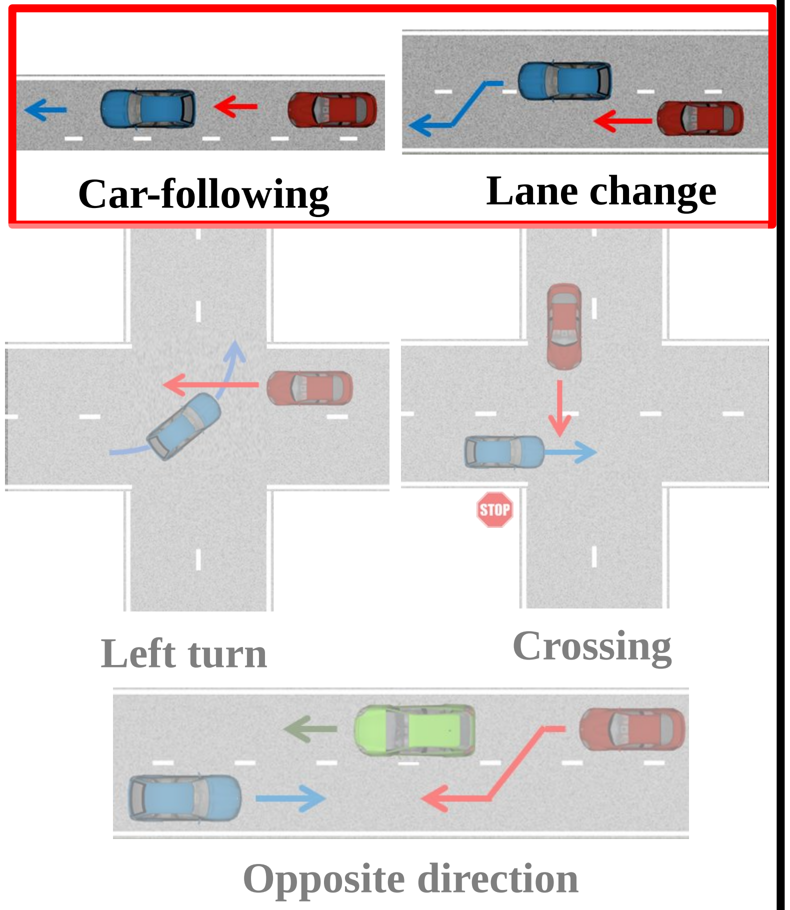
② **Model behaviors of "other vehicles" as disturbance**

③ **Skew the disturbance statistics to reduce the boring part of daily driving**

Naturalistic driving

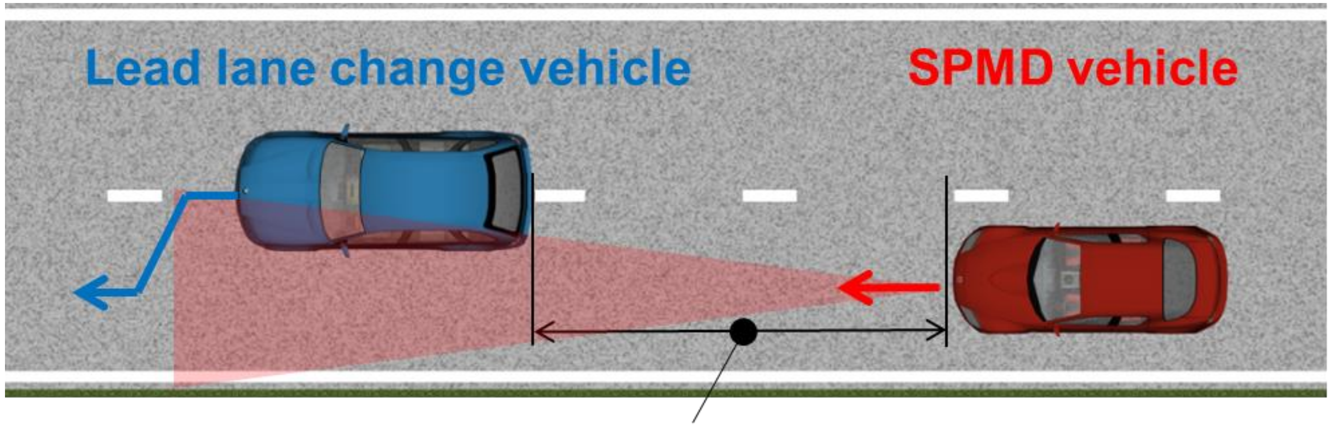
⑤ "Skew back" to understand real-world safety benefits

"Accelerated" tests



87 % light-vehicle crashes

Case 1: Lane Change Scenarios



Acceleration $\boldsymbol{a_L(t)}$
Velocity $\boldsymbol{v_L(t)}$
Position $\boldsymbol{D_L(t)}$

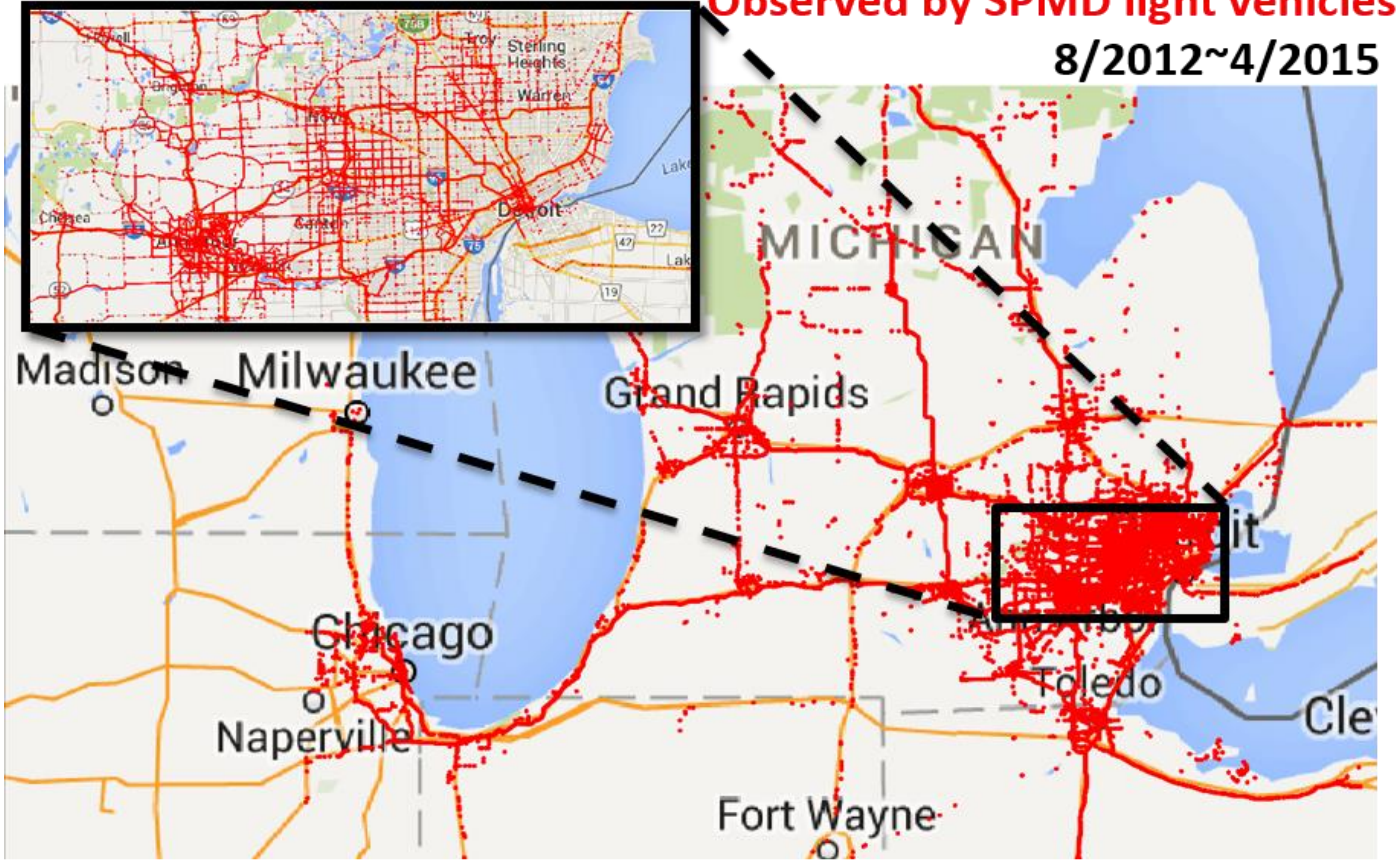
Range
$R_L(t) = \boldsymbol{D_L(t) - D(t)}$
Range rate
$$\dot{\boldsymbol{R}}_L(t) = \frac{d}{dt}\boldsymbol{R_L(t)}$$

Acceleration $\boldsymbol{a(t)}$
Velocity $\boldsymbol{v(t)}$
Position $\boldsymbol{D(t)}$

D. Zhao, H. Lam, H. Peng, S. Bao, D. LeBlanc, K. Nobukawa, C. Pan, "Accelerated evaluation of automated vehicles safety in lane-change scenarios based on importance sampling techniques," *IEEE transactions on intelligent transportation systems*, *18*(3), 595-607, 2017

Lane Change Events in Safety Pilot Database

403,581 lane change events
Observed by SPMD light vehicles
8/2012~4/2015



Criteria:

Longitude $\in (-88.2°, -82.0°)$
Latitude $\in (41.0°, 44.5°)$

$v(t_{LC}) \in (2\ \text{m/s}, 40\ \text{m/s})$
$v_L(t_{LC}) \in (2\ \text{m/s}, 40\ \text{m/s})$
$R_L(t_{LC}) \in (0.1\ \text{m}, 75\ \text{m})$

94 drivers
1.3 million miles

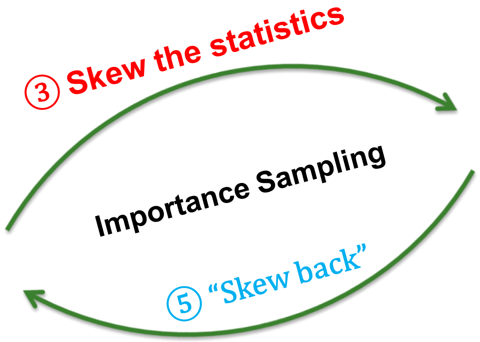
SPMD: Safety Pilot Model Deployment

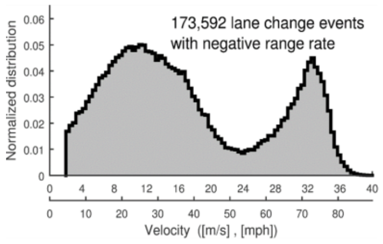
Importance Sampling Techniques

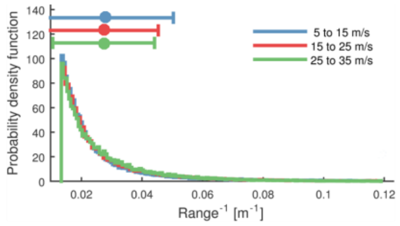
Motivation

Gap acceptance → $[v_L, R_L, TTC_L]$

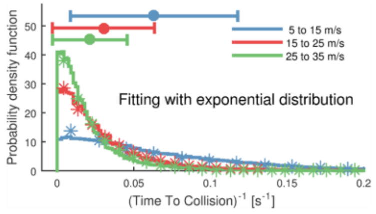
Execution

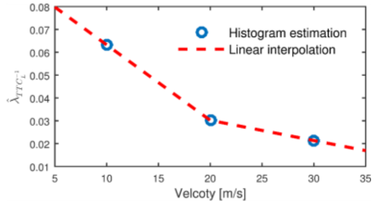


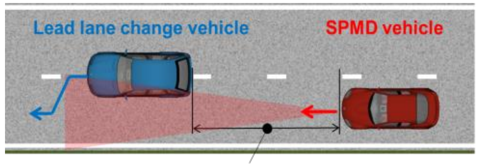




$f_{v_L} \longrightarrow v_L \dashrightarrow f_{R_L^{-1}} \longrightarrow R_L$

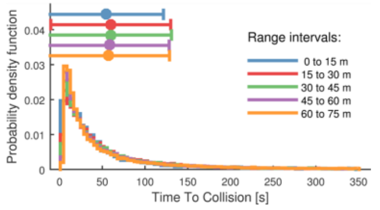


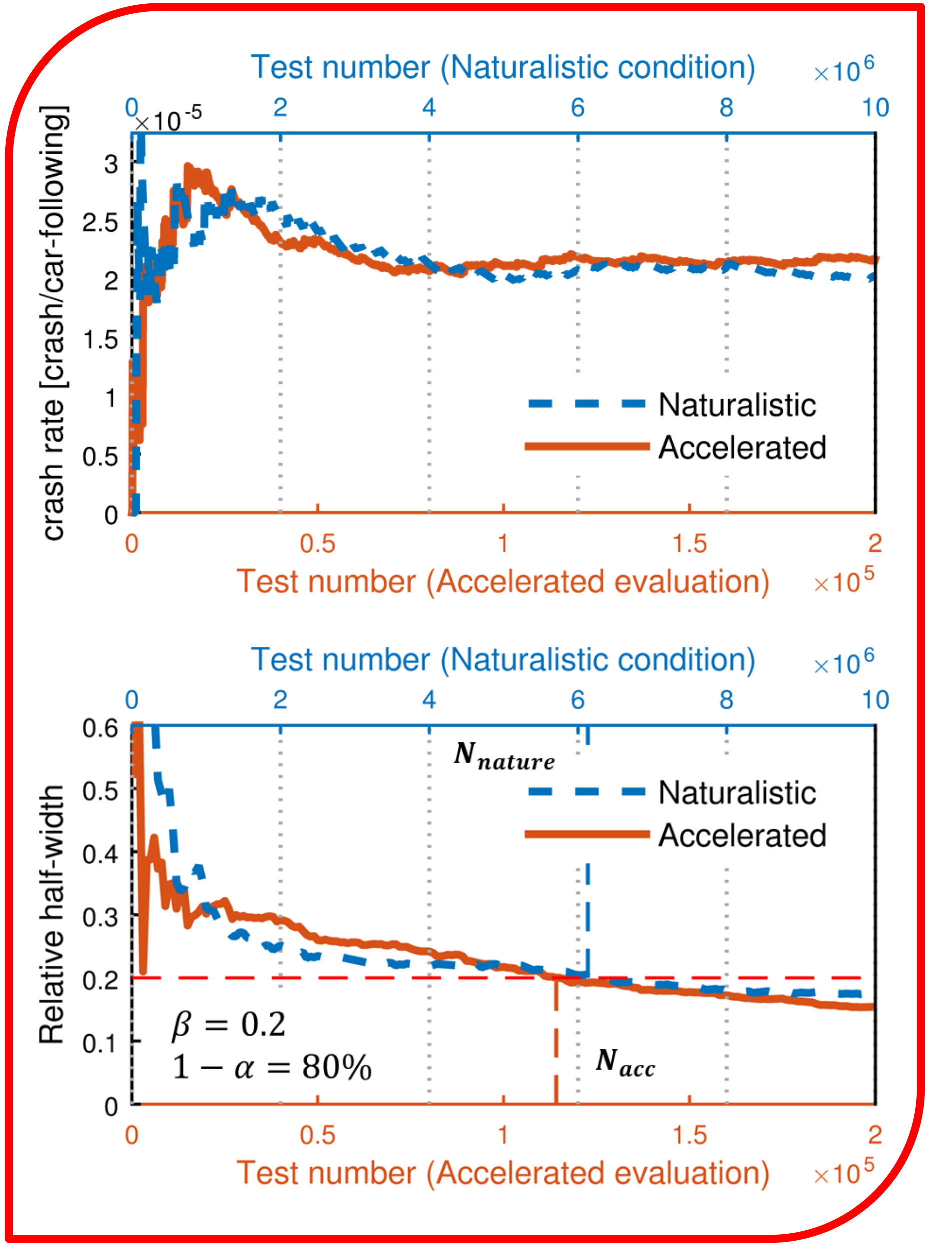




$f_{v_L} \longrightarrow v_L \dashrightarrow f_{R_L^{-1}} \longrightarrow R_L$

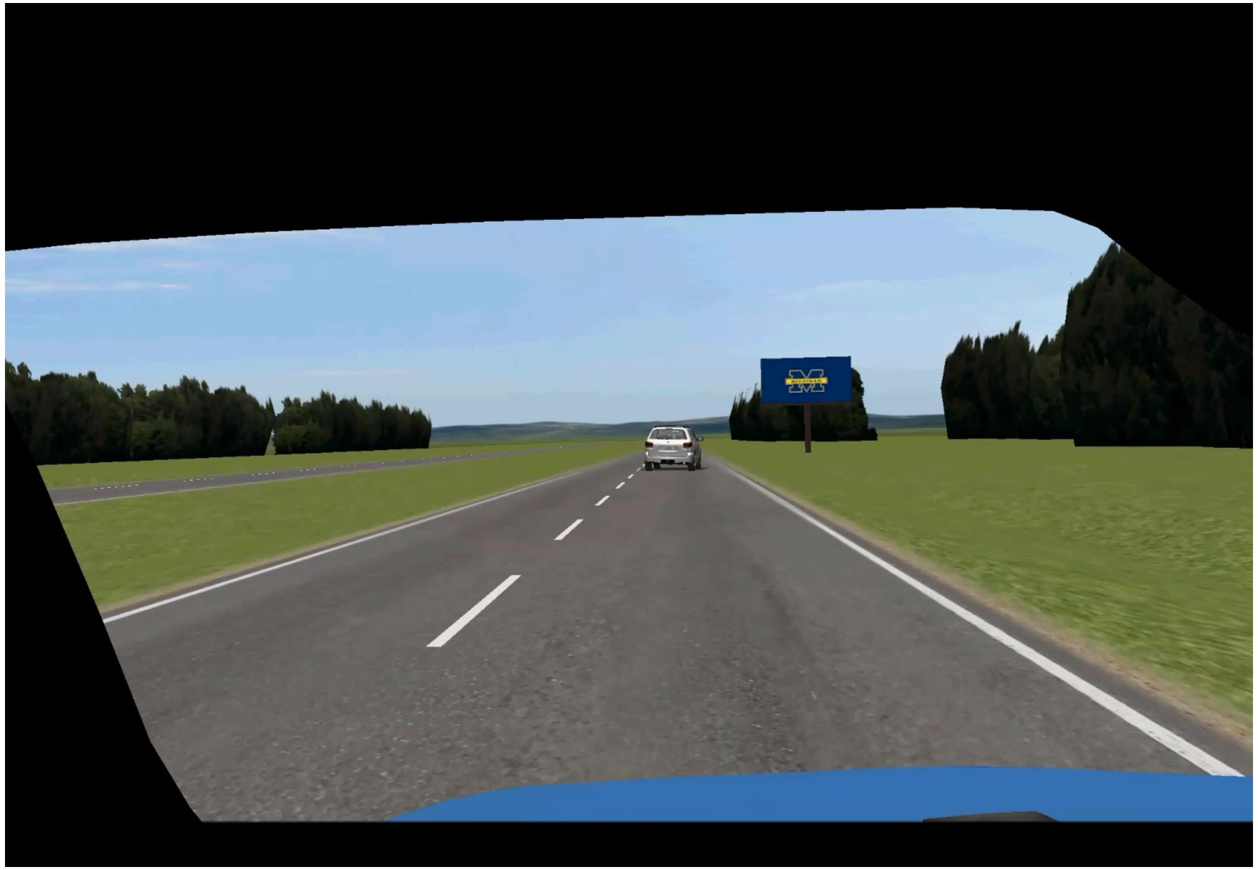
$f_{TTC_L^{-1}} \longrightarrow TTC_L$





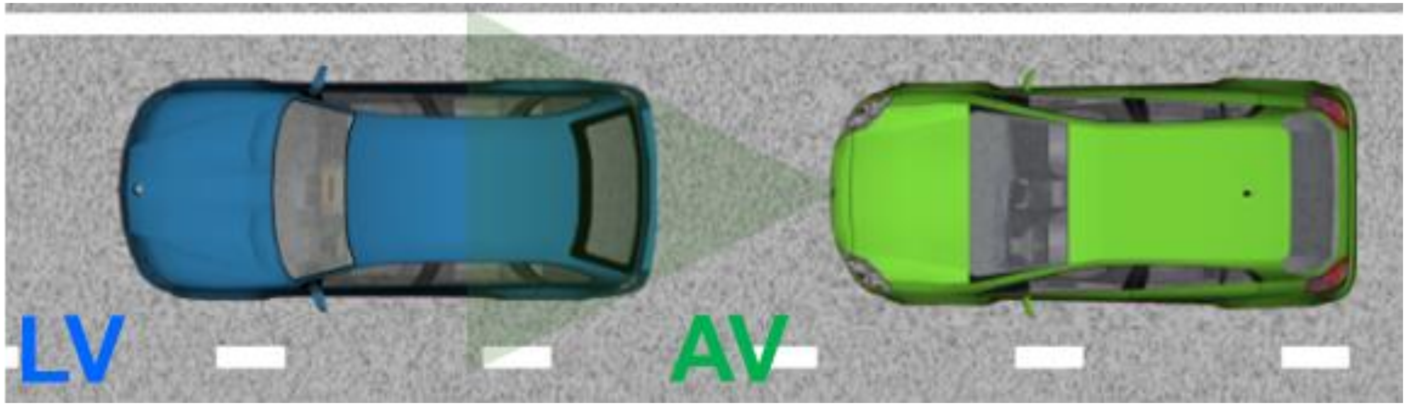
Naturalistic Driving vs Accelerated Tests

Naturalistic driving conditions



Accelerated tests

Case 2: Car-following Scenarios



D. Zhao, X. Huang, H. Peng, H. Lam, D. LeBlanc, Accelerated Evaluation of Automated Vehicles in Car-Following Maneuvers. *IEEE Transactions on Intelligent Transportation Systems,* 2017
D. Zhao, H. Lam, H. Peng, S. Bao, D. LeBlanc, K. Nobukawa, C. Pan,"Accelerated Evaluation of Automated Vehicles using Extracted Naturalistic Driving Data," *Proceedings of the 24th Symposium of the International Association for Vehicle System Dynamics*, Graz, Austria, August 17-21, 2015.

Accelerated Evaluation of the Dynamic Interaction

$$P(k_{\mathcal{T}}^*) = f_{k_{\mathcal{T}}^*}(k_{\mathcal{T}}^*) = \frac{1}{K - k_{\mathcal{T}min}^* + 1}$$

where $k_{\mathcal{T}min}^* = \min(k_{\mathcal{T}}^* \mid \mathcal{b}_{k_{\mathcal{T}}^*} \text{ has feasible solution})$

Not converge

Sample $k_{\mathcal{T}}^*$

Run the Accelerated Tests

Importance sampling

$$\hat{\gamma}(N) = \frac{1}{N}\sum_{n=1}^{N} I_{\mathcal{E}}(n)\, L(n)$$

$k_{\mathcal{T}min}^*$ $k_{\mathcal{T}}^*$ $\mathcal{b}_{k_{\mathcal{T}}^*}(1{:}K)$ $a_L(1{:}k_{\mathcal{T}})$ $I_{\mathcal{E}}(n)$

$L(n)$

Converge

Optimal change of HV statistics (off-line)

Likelihood ratio

Crash, injury, conflict rates

$$a_L(k+1) \sim \mathcal{N}(h_0 + h_1 a_L(k) + h_2 v_L(k), \sigma_u^2)$$

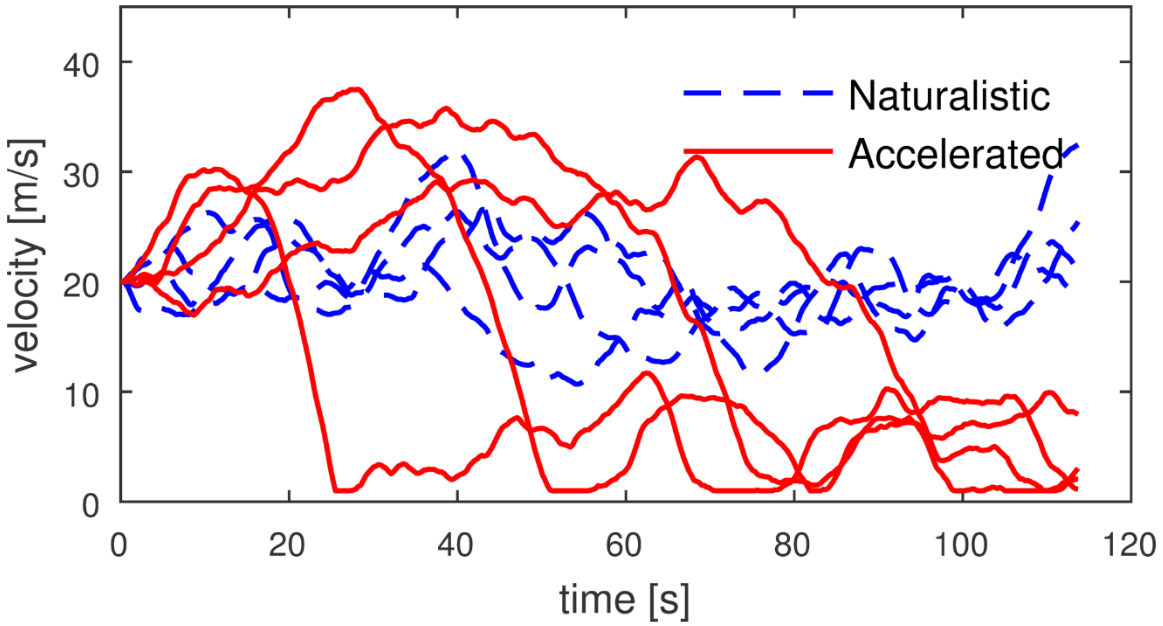
$$\Rightarrow \quad a_L(k+1) \sim \mathcal{N}(h_0 + h_1 a_L(k) + h_2 v_L(k) + \mathcal{b}(k), \sigma_u^2)$$

$$f^*(u(1{:}k_{\mathcal{T}}-1)) = \sum_{k_{\mathcal{T}}^* = k_{\mathcal{T}min}^*}^{K} \tilde{f}(a_L(1{:}k_{\mathcal{T}}-1) \mid k_{\mathcal{T}}^*) f_{k_{\mathcal{T}}^*}(k_{\mathcal{T}}^*)$$

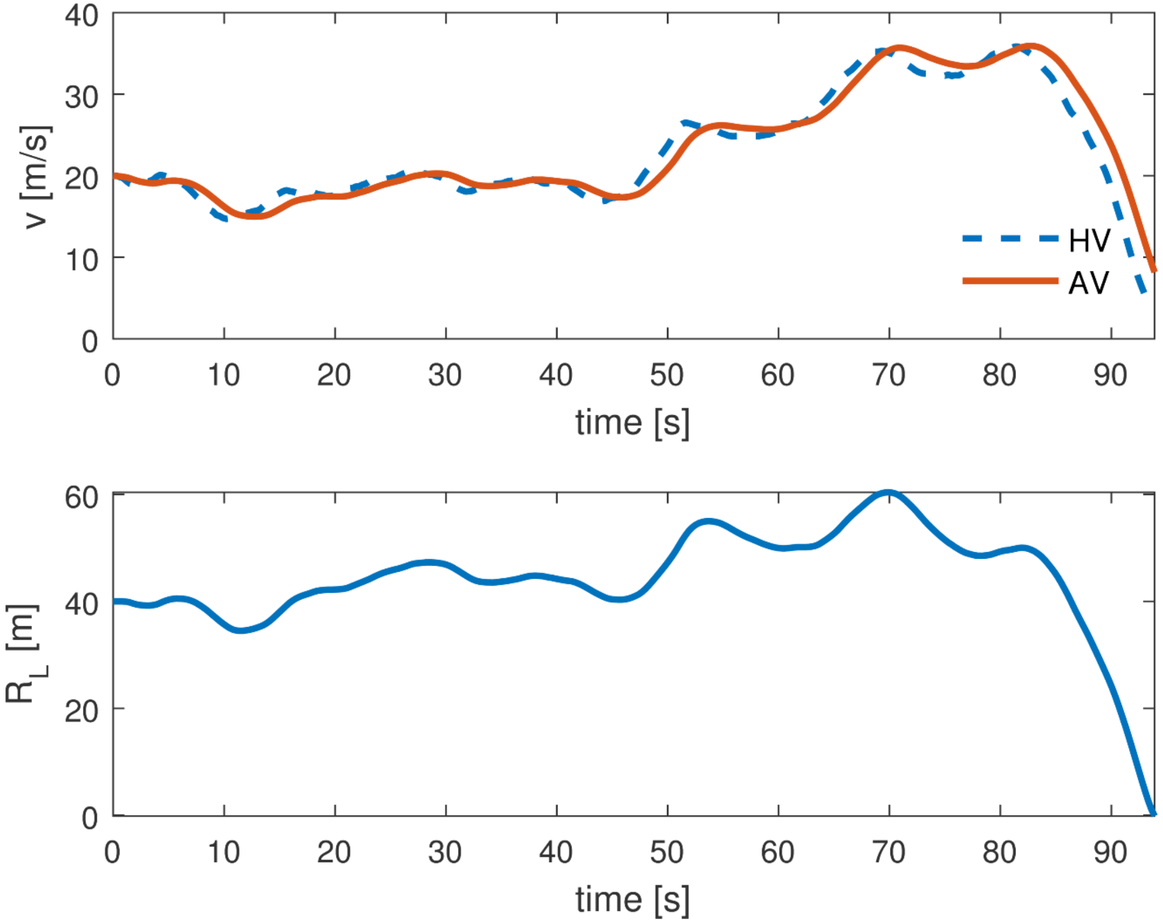
D. Zhao, X. Huang, H. Peng, H. Lam, D. LeBlanc, Accelerated Evaluation of Automated Vehicles in Car-Following Maneuvers. IEEE Transactions on Intelligent Transportation Systems, 2017

Examples of Accelerated Evaluation

Examples of velocity profiles of the lead vehicle

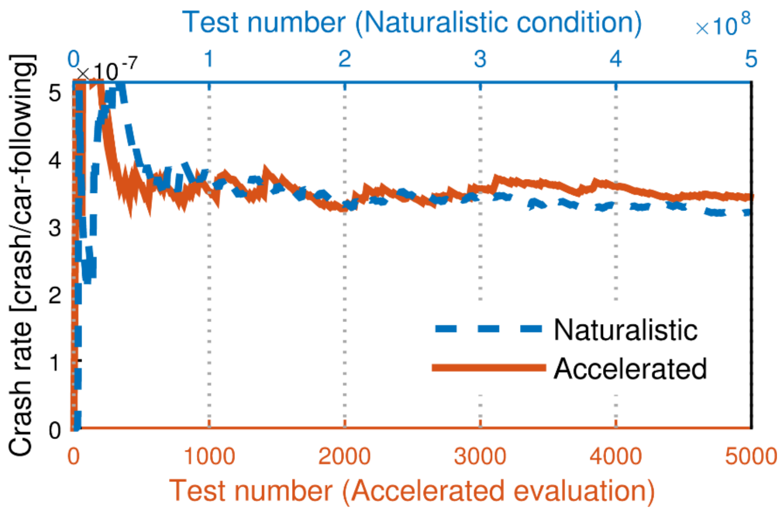


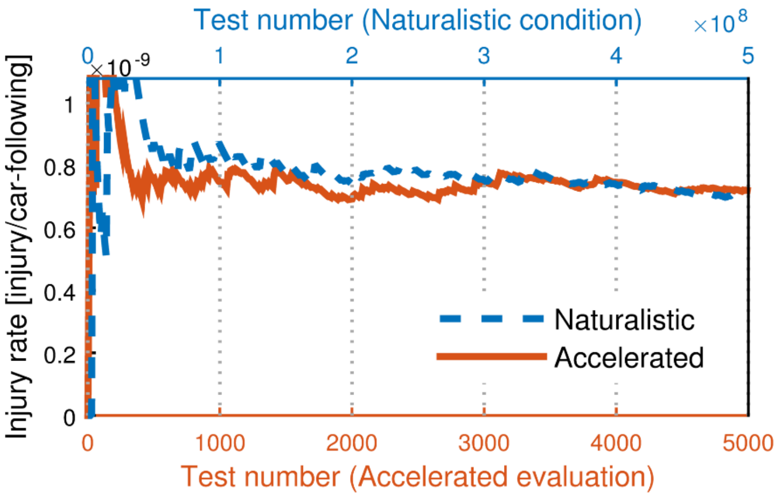
An example of the crash event

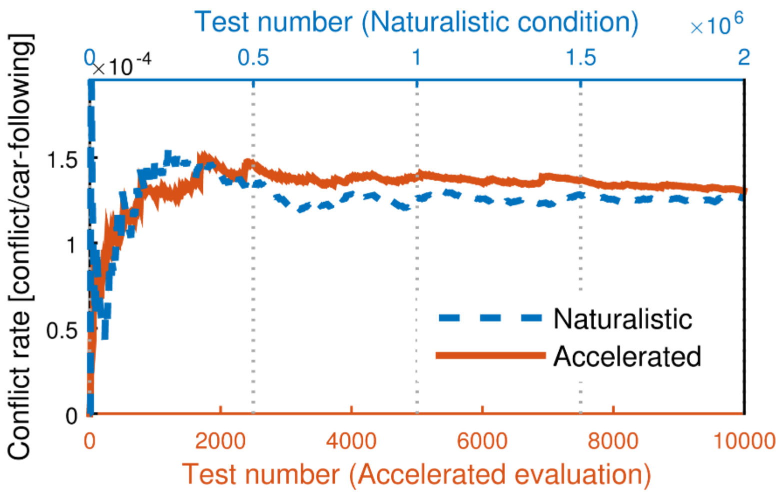


Estimation of Crash, Injury, and Conflict Rate

Estimation

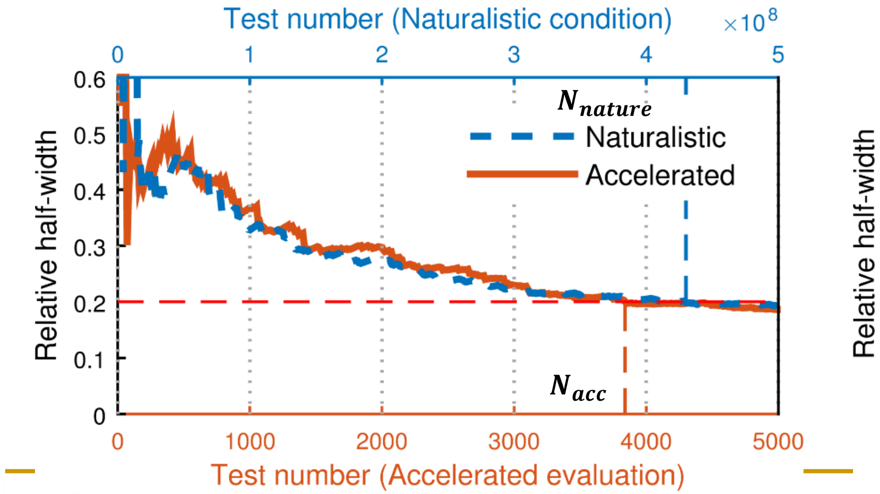


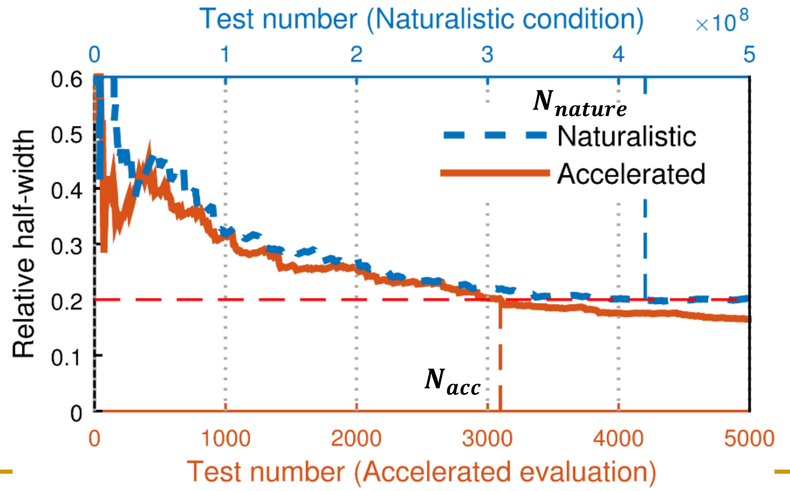


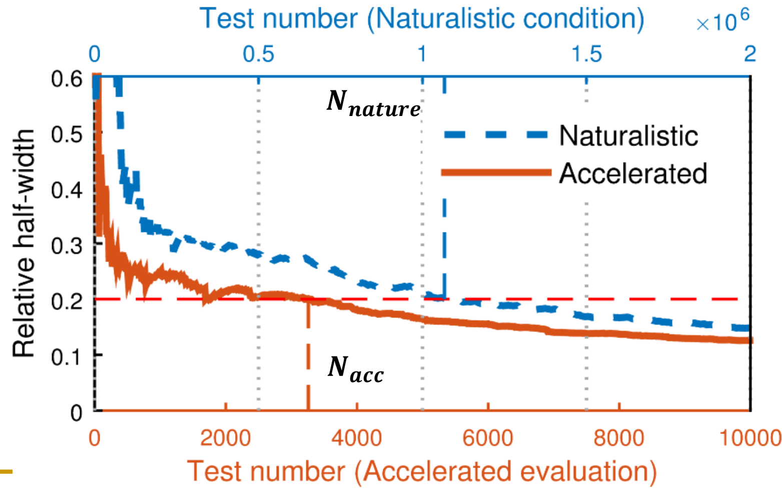


N_{nature}/N_{acc}: **Crash (1.12e5)** **Injury(1.35e5)** **Conflict (3.28e2)**

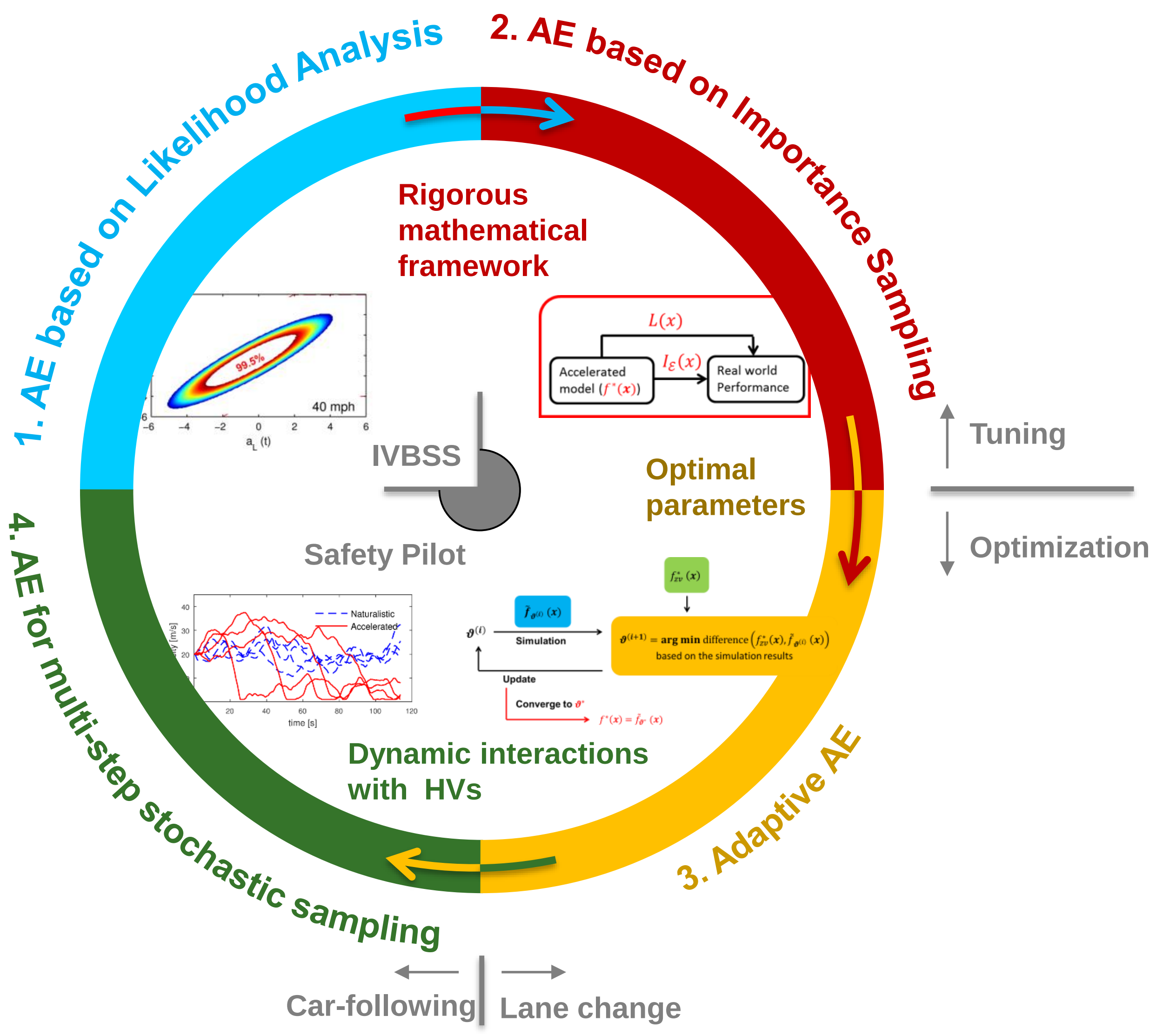
Convergence



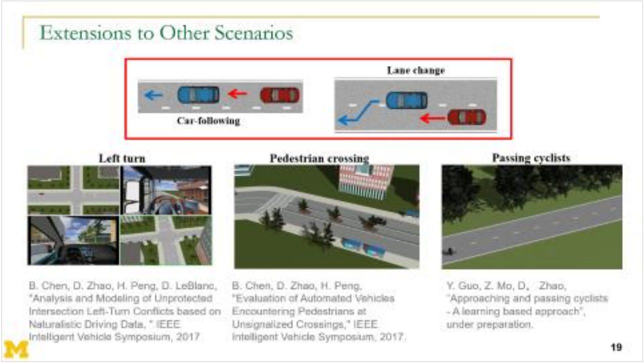




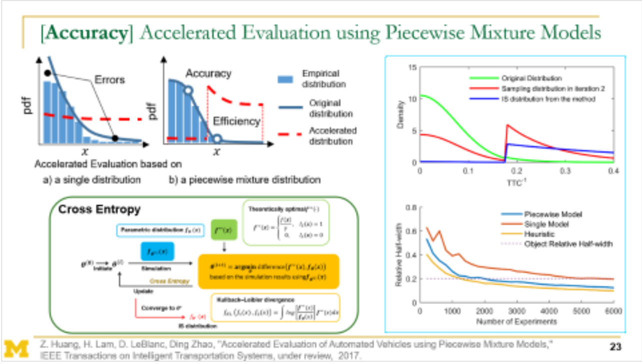
Extensions to the Accelerated Evaluation



Variations

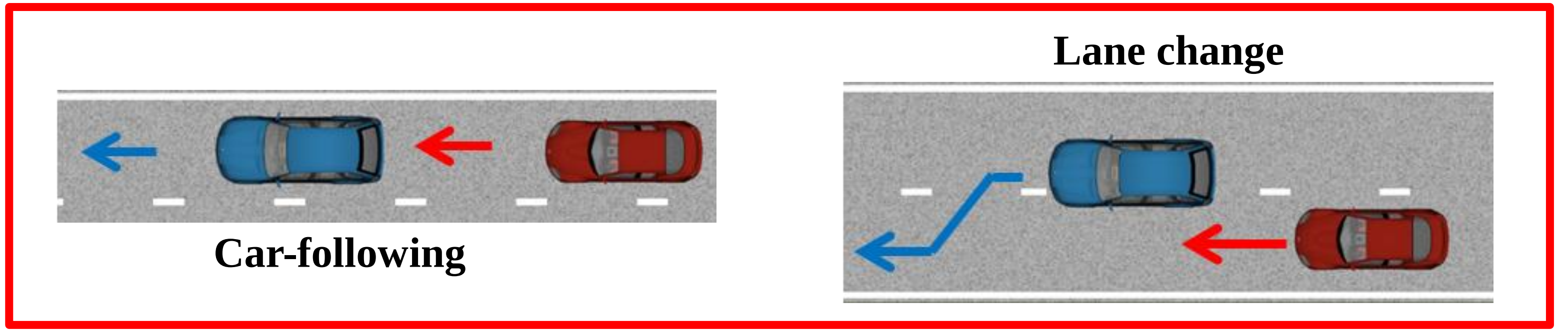


Theories



Platforms

Extensions to Other Scenarios



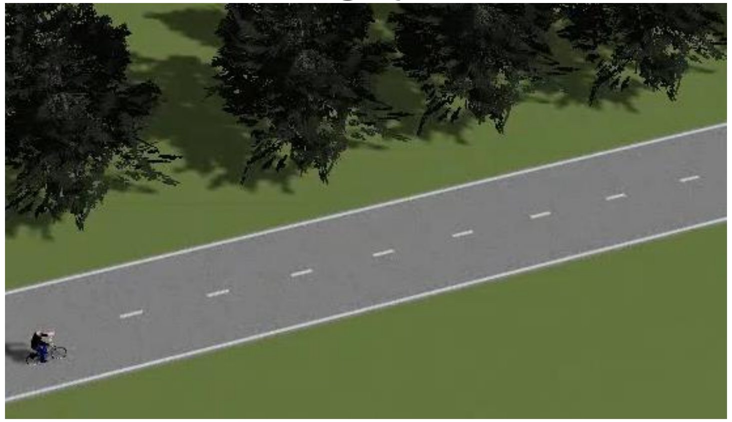
Left turn

B. Chen, D. Zhao, H. Peng, D. LeBlanc, "Analysis and Modeling of Unprotected Intersection Left-Turn Conflicts based on Naturalistic Driving Data, " IEEE Intelligent Vehicle Symposium, 2017

Pedestrian crossing

B. Chen, D. Zhao, H. Peng, "Evaluation of Automated Vehicles Encountering Pedestrians at Unsignalized Crossings," IEEE Intelligent Vehicle Symposium, 2017.

Passing cyclists



Y. Guo, Z. Mo, D。 Zhao, "Approaching and passing cyclists - A learning based approach", under preparation.

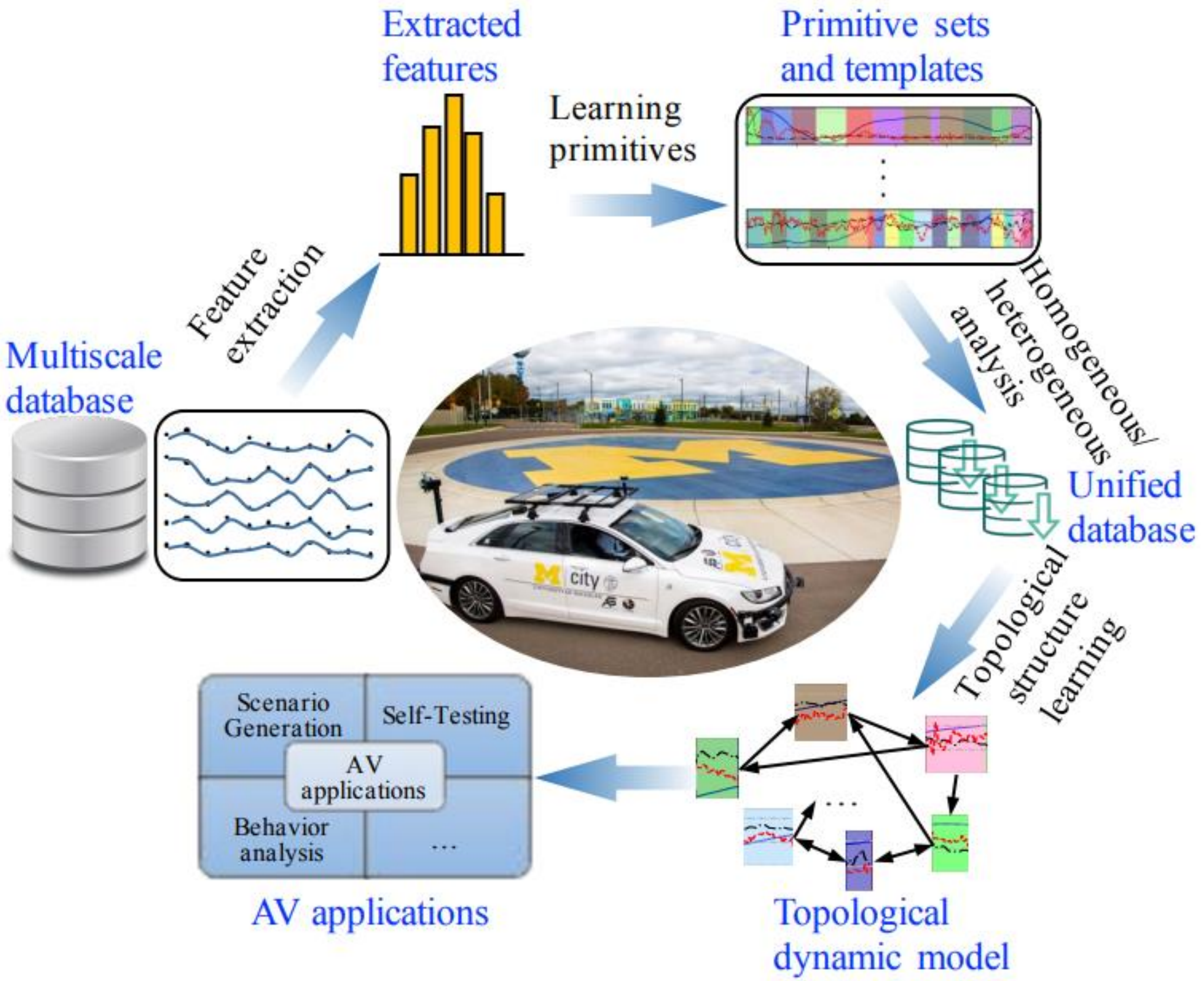
Recent Progress: Extract Scenarios Automatically from Raw Data

Previous method:
- Define scenario
- Create query condition manually
- Update query with trial and error

- Subjectively-selected scenarios/variations

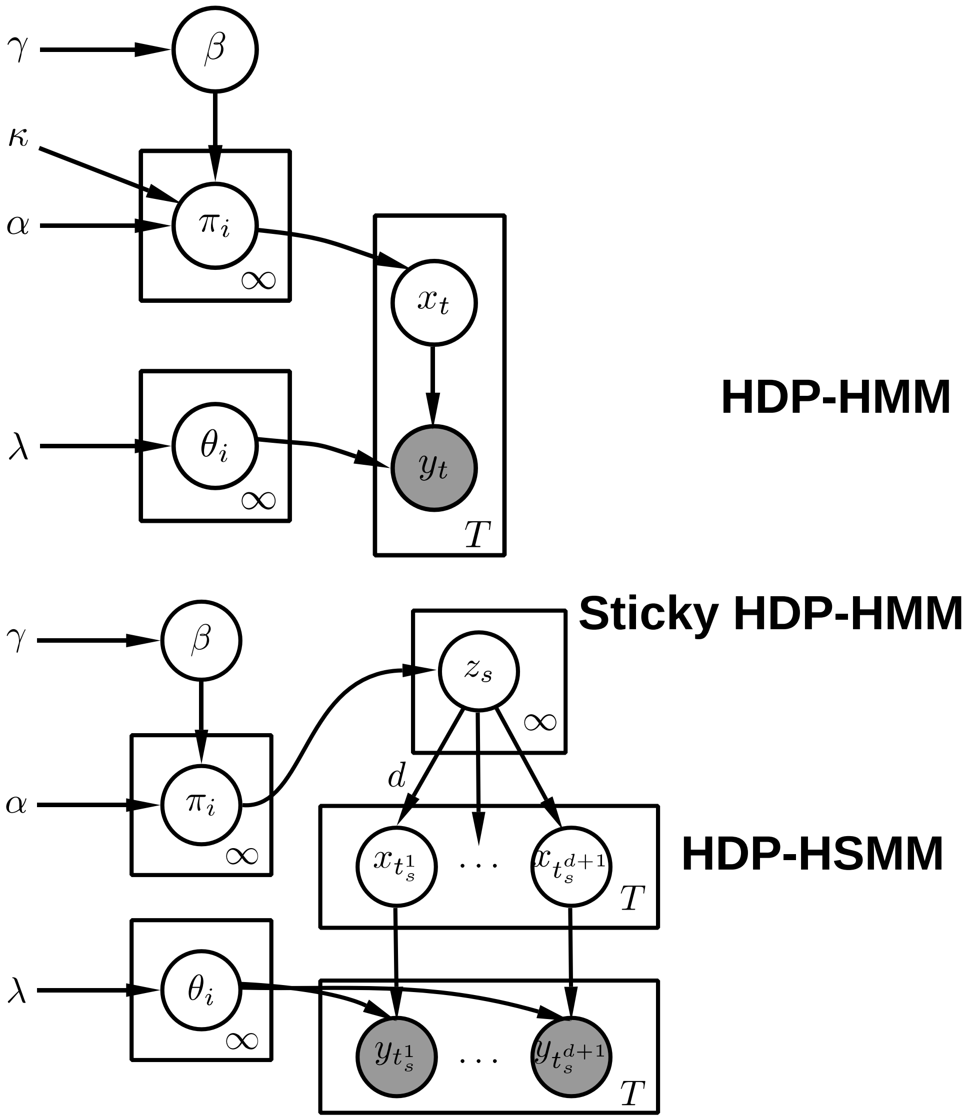
Traffic Primitive:
- Segment/cluster similar traffic scenes automatically using Bayesian nonparameter inference

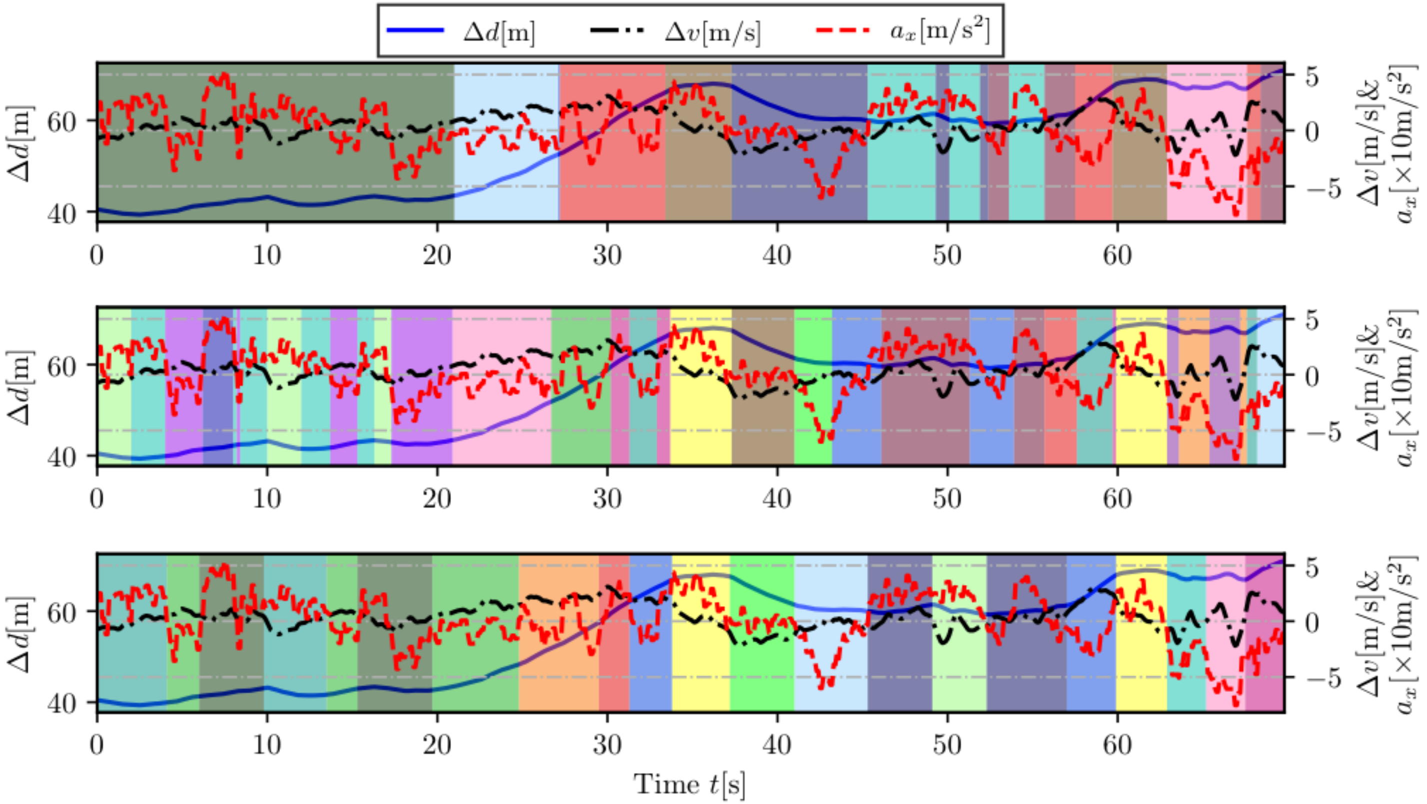
- Objectively-selected scenarios/variations



W. Wang, D. Zhao, "Extracting Traffic Primitives Directly from Naturalistically Logged Data for Self-Driving Applications *IEEE Robotics and Automation Letters (under review)*, arXiv 1709.03553, 2017.

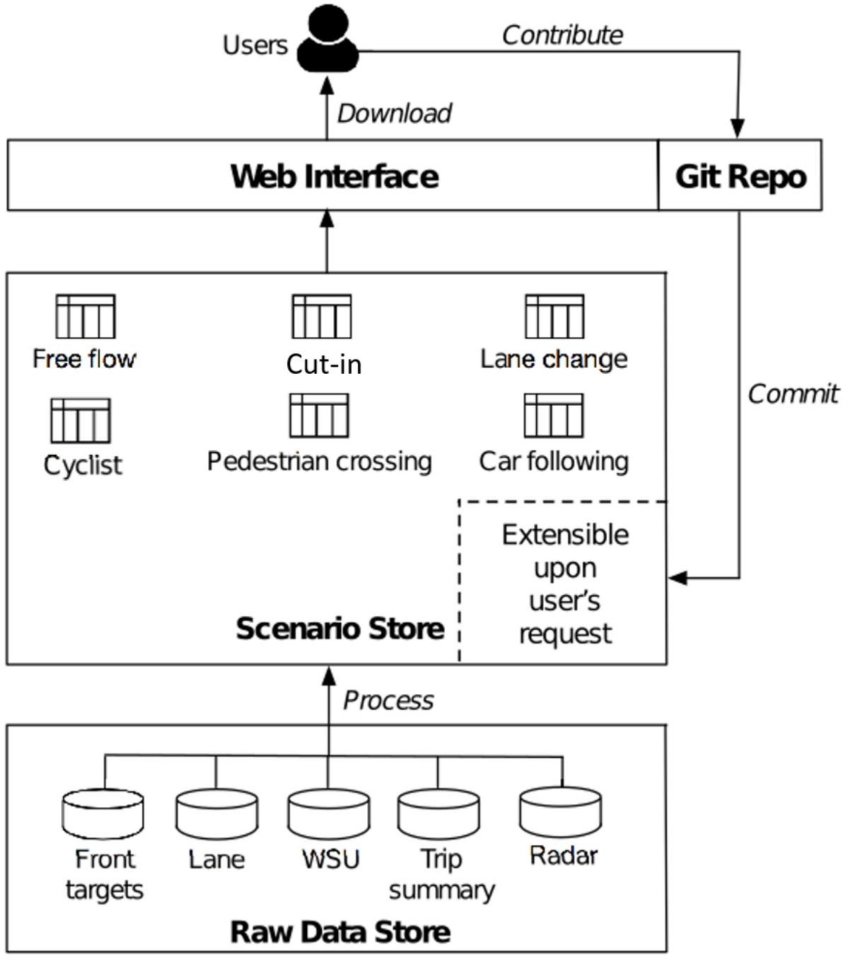
Traffic Primitive: Extract Scenarios Automatically from Raw Data



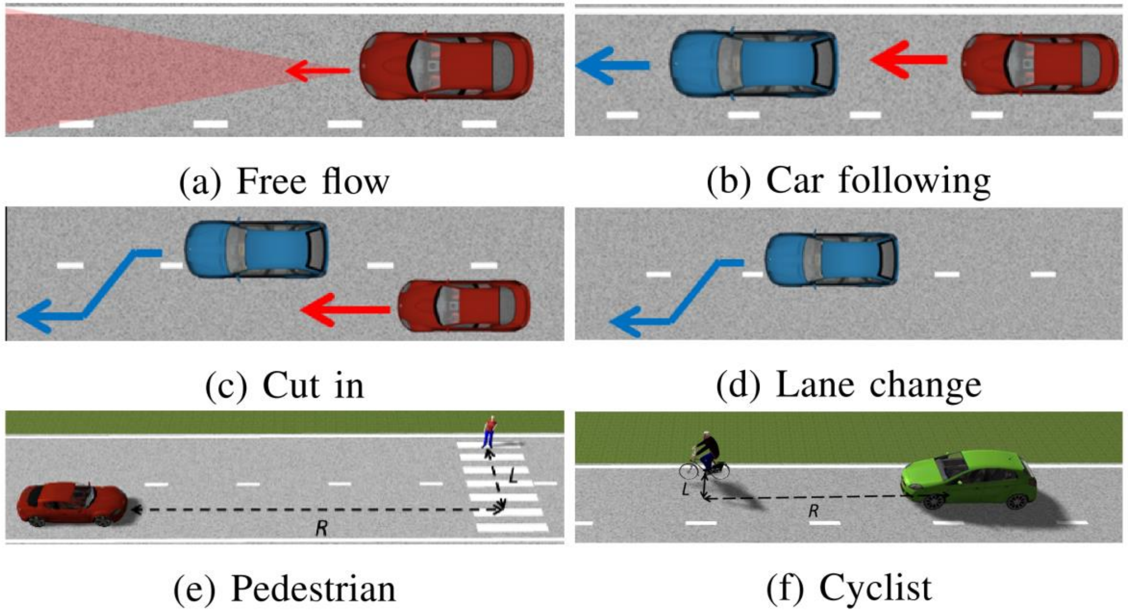


W. Wang, J. Xi, D. Zhao, " Driving Style Analysis Using Primitive Driving Patterns With Bayesian Nonparametric Approaches," under review.

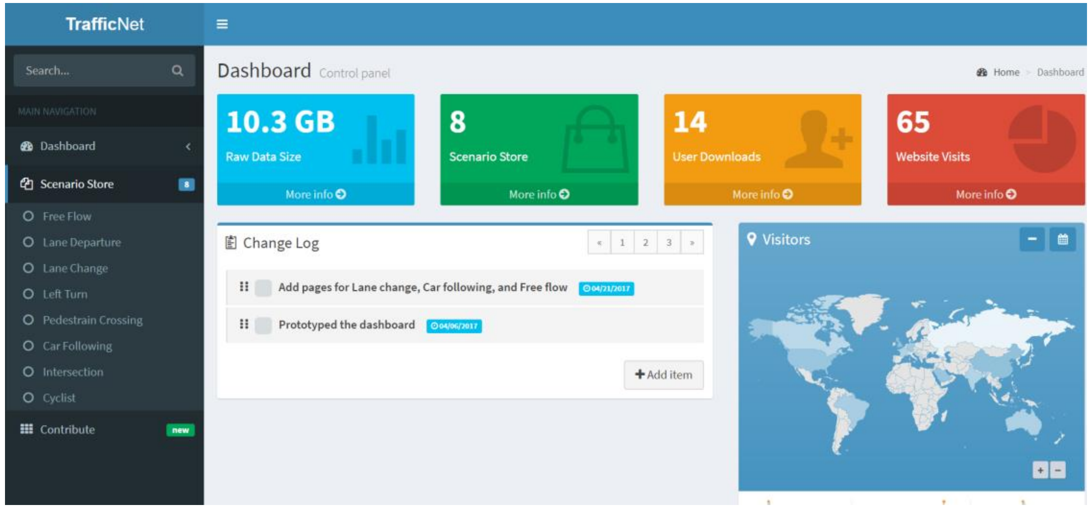
TrafficNet: An Open Naturalistic Driving Scenario Library



Framework of TrafficNet

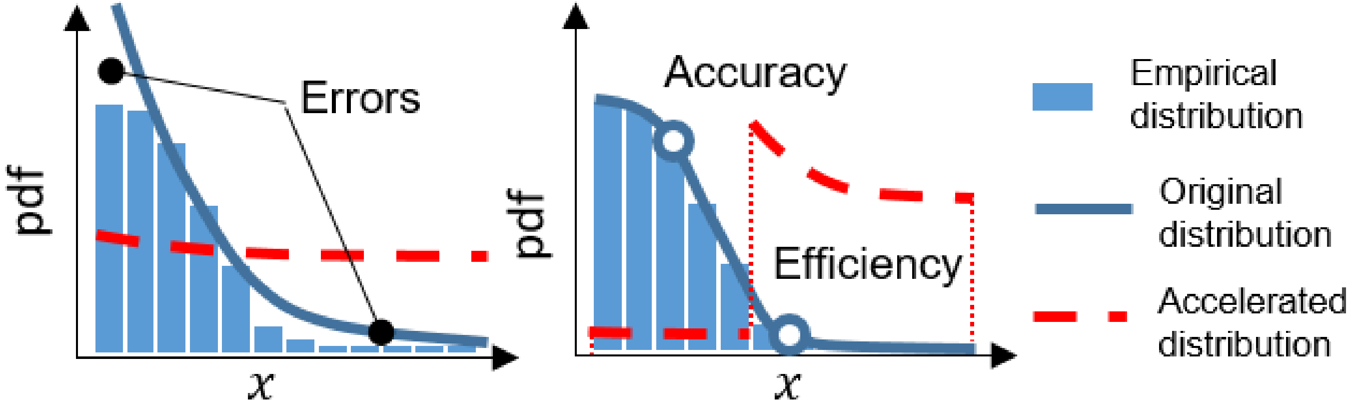


(a) Free flow (b) Car following (c) Cut in (d) Lane change (e) Pedestrian (f) Cyclist



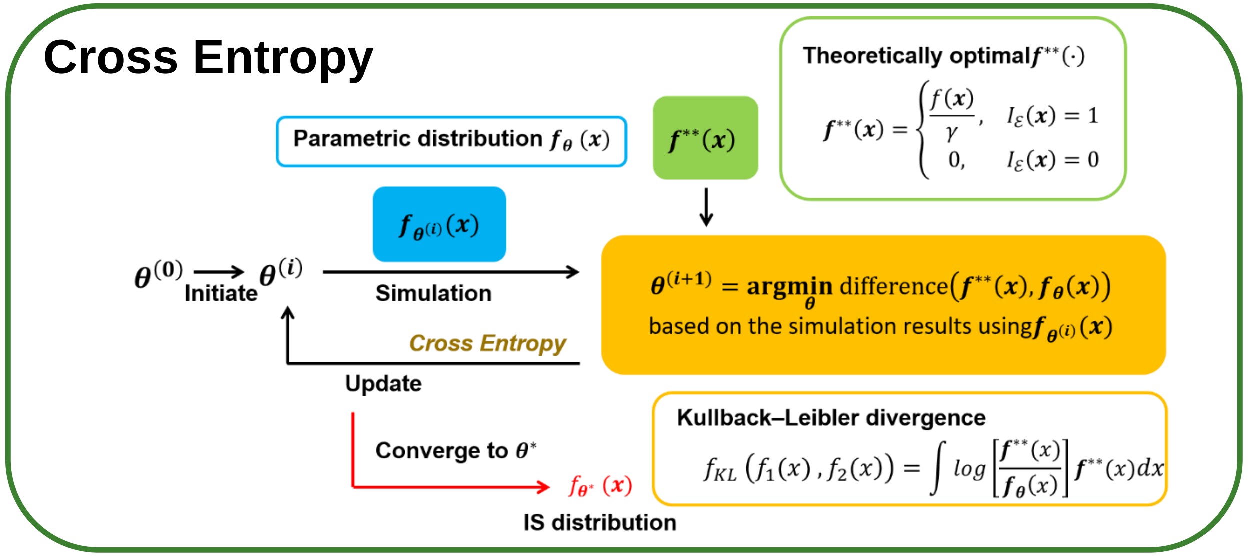
D. Zhao, Y. Guo, Y. J. Jia, "TrafficNet: An Open Naturalistic Driving Scenario Library," Proceedings of the IEEE 20th International Intelligent Transportation Systems Conference (ITSC), Yokohama, Japan, October 16-19, 2017.

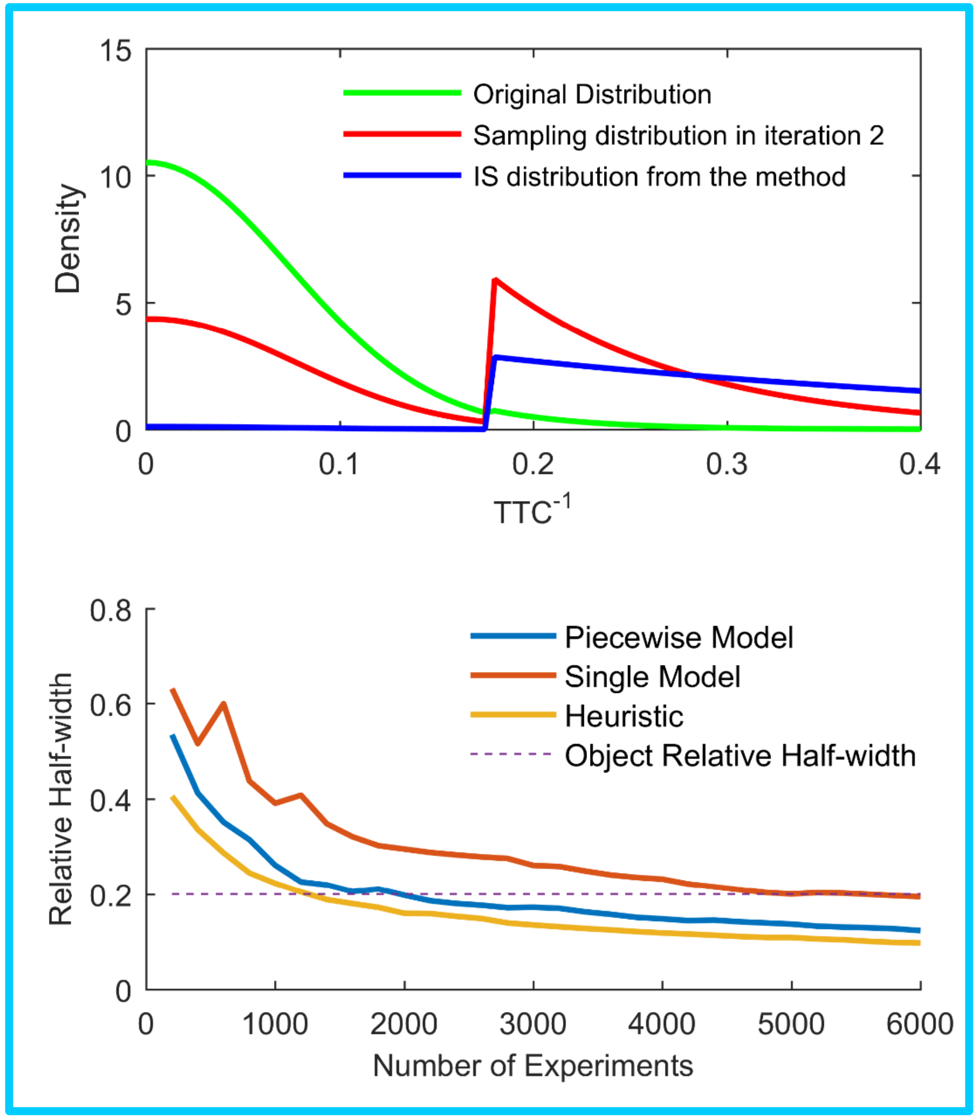
[**Accuracy**] Accelerated Evaluation using Piecewise Mixture Models



Accelerated Evaluation based on

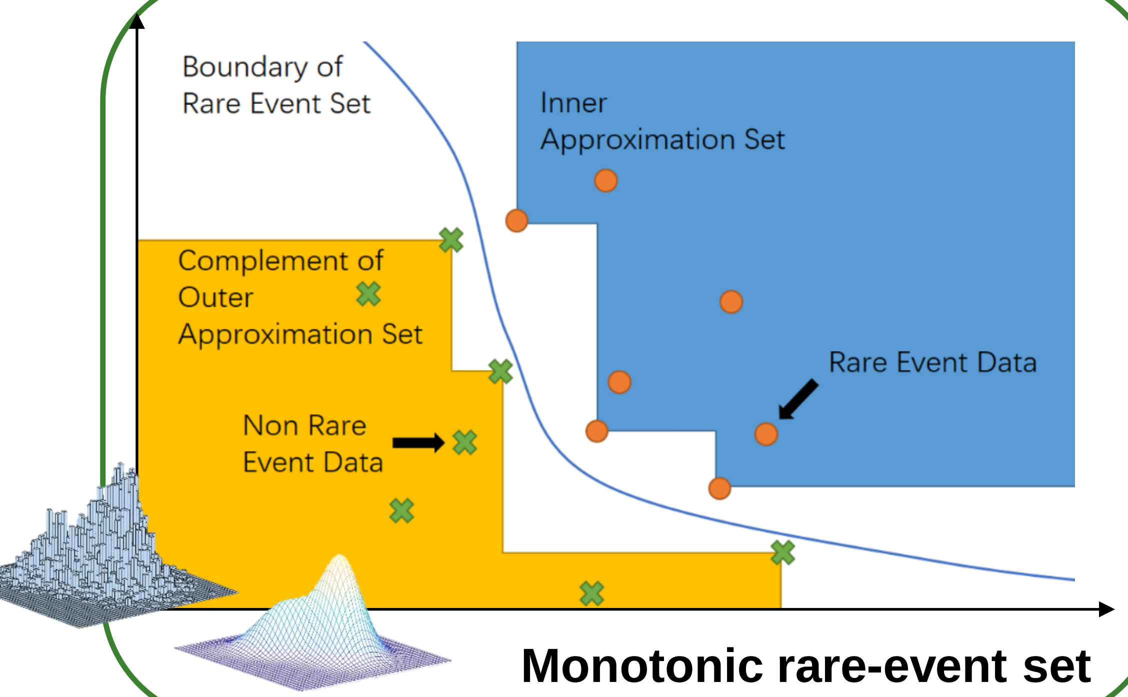
a) a single distribution b) a piecewise mixture distribution



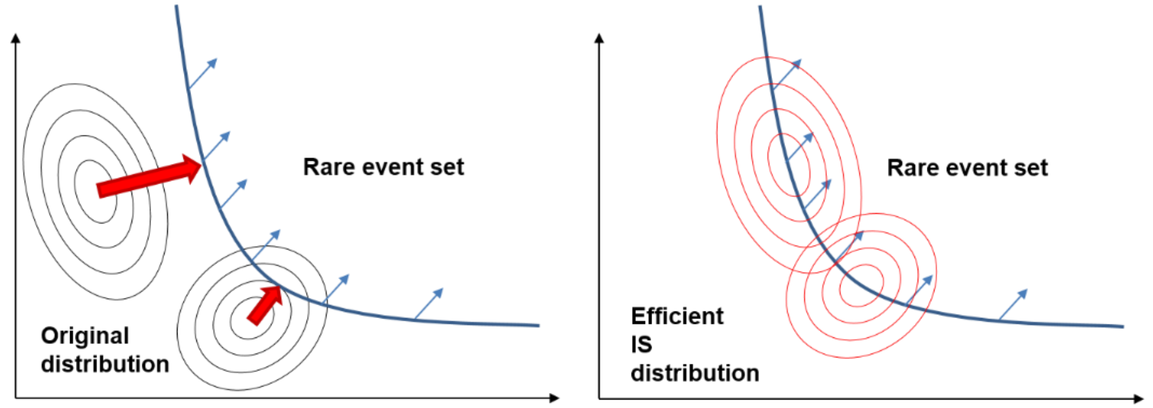


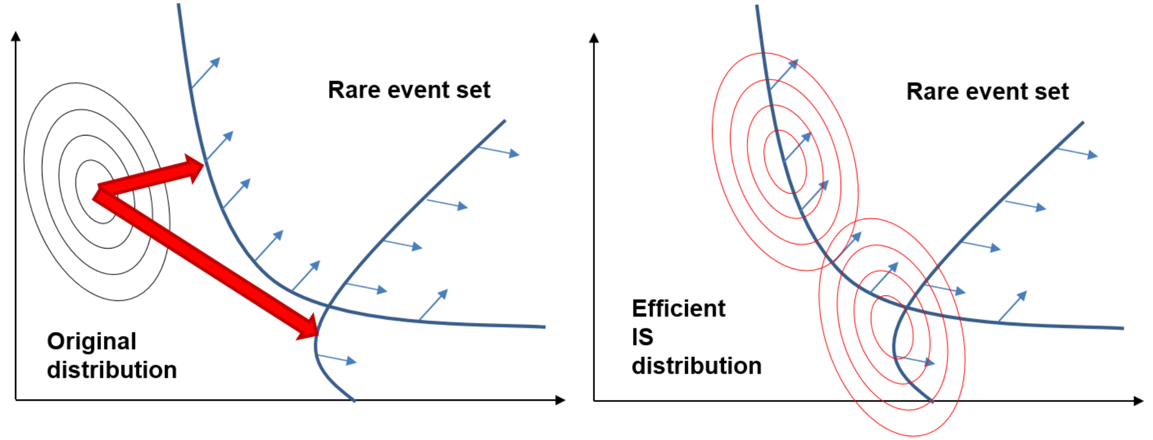
[Versatility] Accelerated Evaluation using Joint Distribution

- Motivation
  - Capture the dependency between variables
  - A robust approach to all types of distribution
- **Challenges: Construct accelerated distribution**



Monotonic rare-event set





Z. Huang, H. Lam, Ding Zhao, "An Accelerated Testing Approach for Automated Vehicles with Background Traffic Described by Joint Distributions, " Proceedings of the IEEE 20th International Intelligent Transportation Systems Conference (ITSC), 2017.

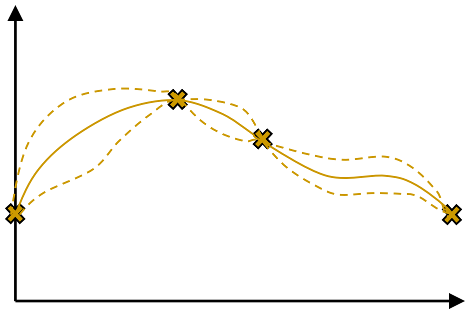
[Efficiency] Kriging-based Evaluation

On track test

Construct

Design

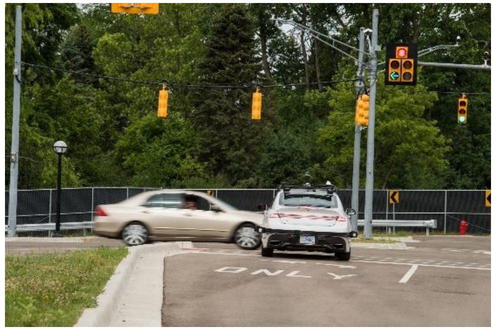
Response surface



Analysis

Adjust

Risk evaluation



- On track tests are expensive and time-consuming
- Previous accelerated rate is high, but not enough
- **Objective**
  - **Introduce reasonable assumptions s.t. on-track test is affordable**

Initial Design
X_n

Test on X_n | collect Y_n

Data set
$D_n = (X_n, Y_n)$

Construct

Kriging Model
$Y(x) \sim GRF(\mu(x|D_n), \sigma^2(x|D_n))$

Critical Event Estimator
$\hat{\rho}(D_n) = P(Y(x) > \gamma)$

Test on next design
$x = argmax_x \ E[(\hat{\rho}(D_n) - \hat{\rho}(D_{n+1}))^2]$

Update

Z. Huang, H. Lam, Ding Zhao, "Towards Affordable On-track Testing for Autonomous Vehicle - A Kriging-based Statistical Approach, " Proceedings of the IEEE 20th International Intelligent Transportation Systems Conference (ITSC), Yokohama, Japan, 2017.

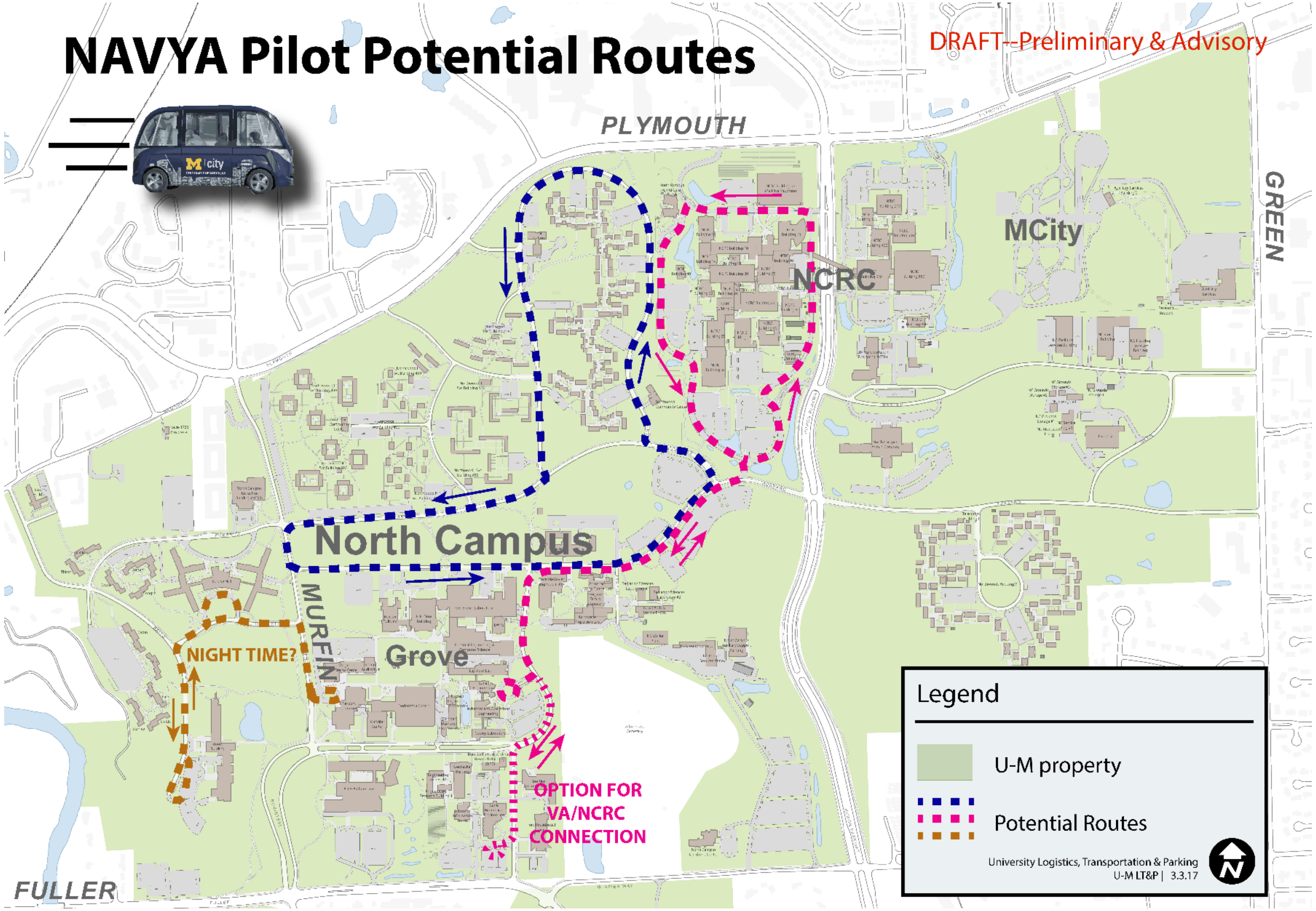
Platforms

On-track tests

Virtual reality

Augmented Reality

Deployment of Testing Vehicles



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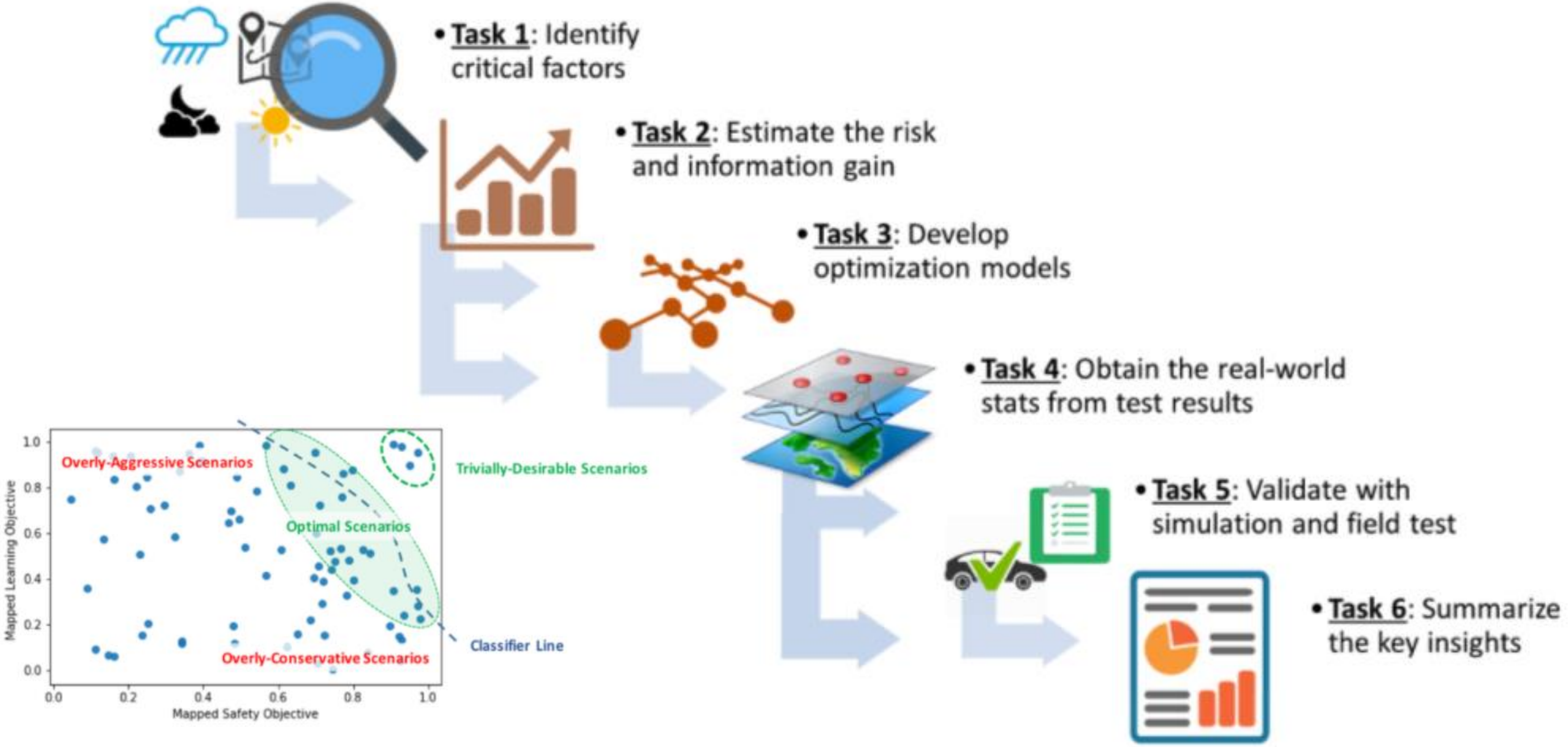
Design Deployment Policy



Dynamic Scenario Optimization

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Thanks for your attention

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