
Accelerated Evaluation Methods

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The Building Blocks of Autonomy

Prepared by  VISION SYSTEMS INTELLIGENCE

AUTONOMOUS SOLUTIONS



Level of Integration ↑

PROCESSING



SENSORS



CONNECTIVITY



MAPPING



ALGORITHMS



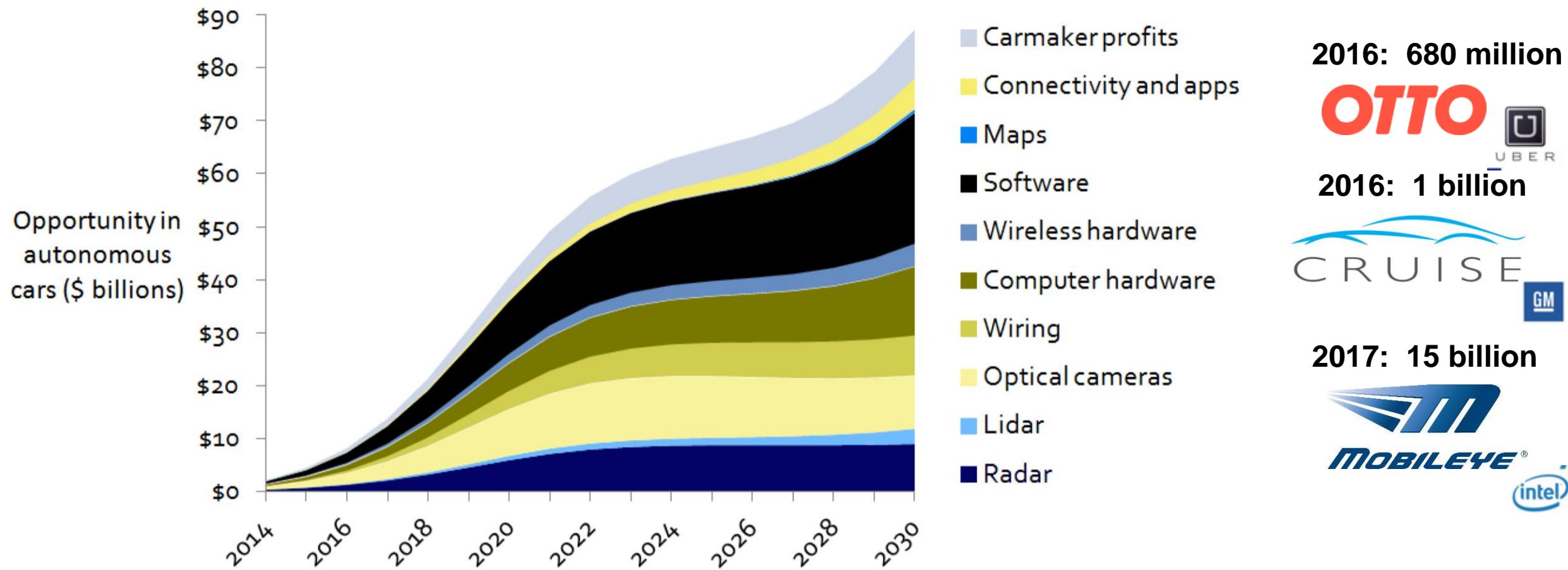
SECURITY/SAFETY



DEVELOPMENT TOOLS



Estimated Market of AVs in 2030



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 as
reliable as running
water

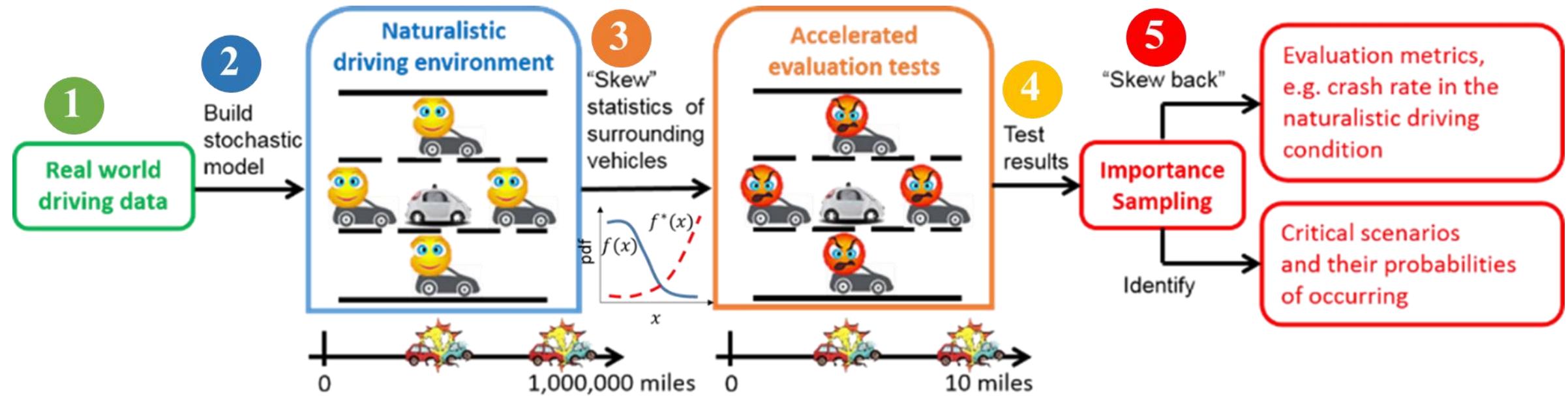
My Research are Trying to Answer

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



and other companies ...

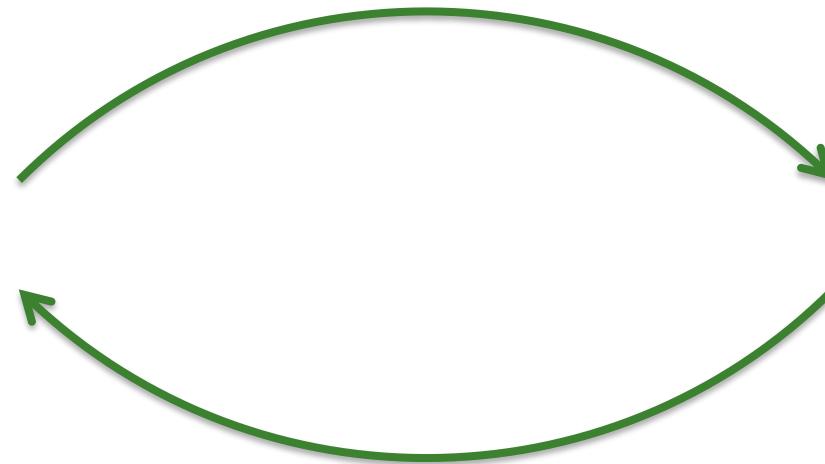
Accelerated Evaluation



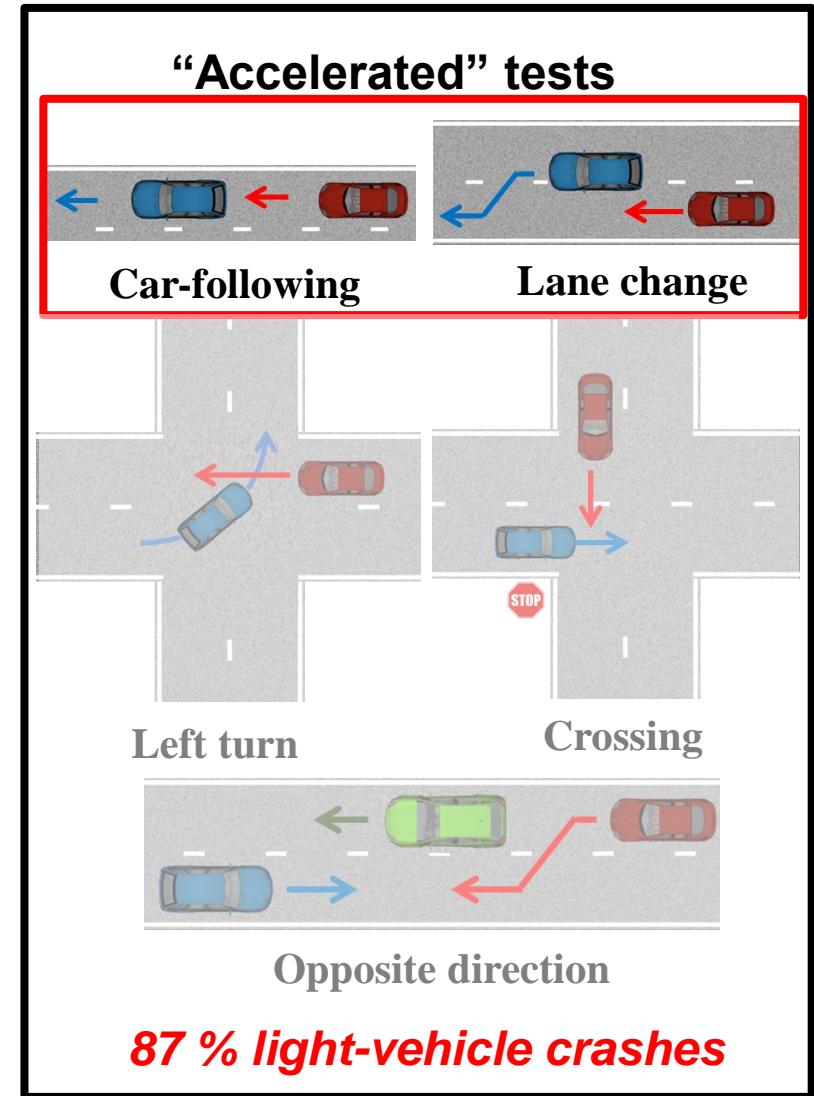
Five Steps of the Accelerated Evaluation

- 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

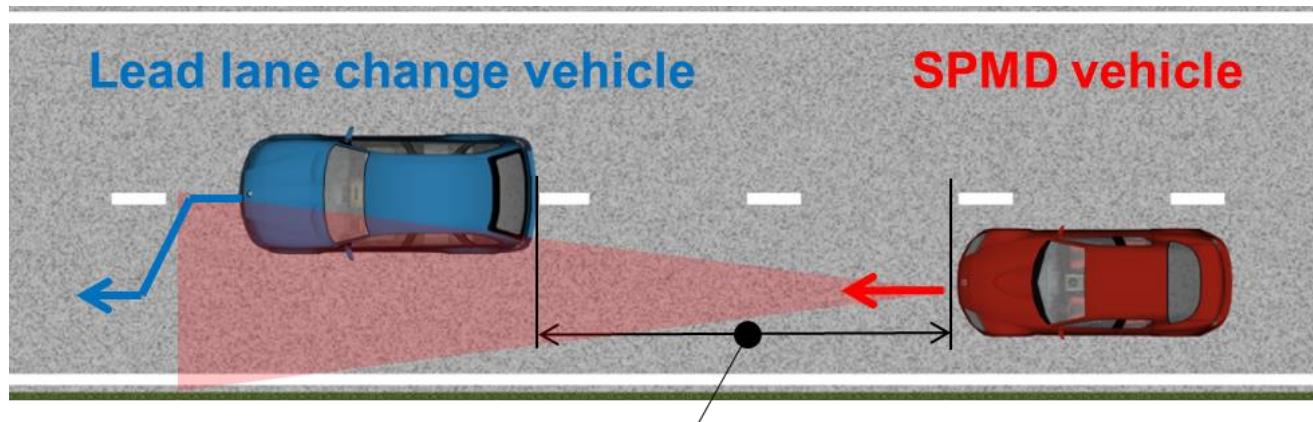
Naturalistic driving



- ④ Simulate (at accelerated pace)
- ⑤ “Skew back” to understand real-world safety benefits



Case 1: Lane Change Scenarios



Acceleration $a_L(t)$

Velocity $v_L(t)$

Position $D_L(t)$

Range

$$R_L(t) = D_L(t) - D(t)$$

Range rate

$$\dot{R}_L(t) = \frac{d}{dt} R_L(t)$$

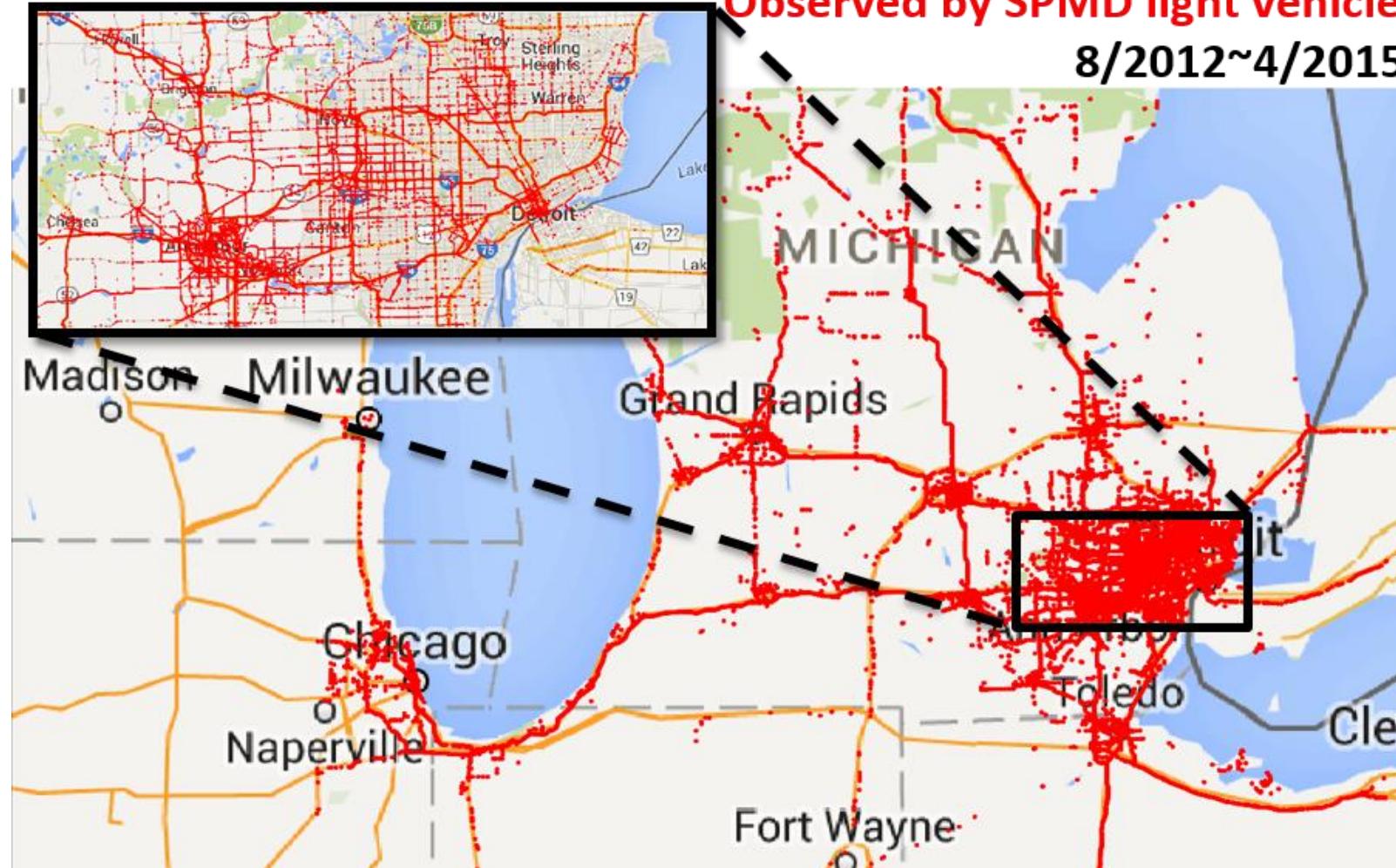
Acceleration $a(t)$

Velocity $v(t)$

Position $D(t)$

Lane Change Events in Safety Pilot Database

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



Criteria:

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

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

94 drivers
1.3 million miles

Importance Sampling Techniques



Motivation

Gap acceptance

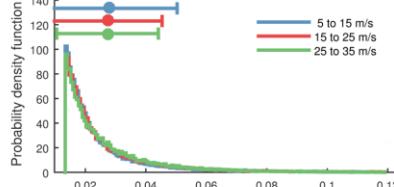
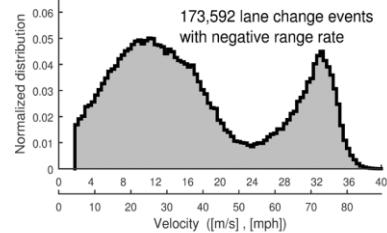
$[v_L, R_L, TTC_L]$

Execution

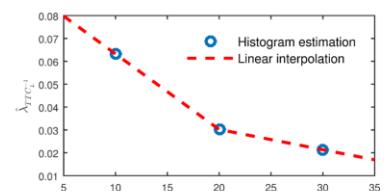
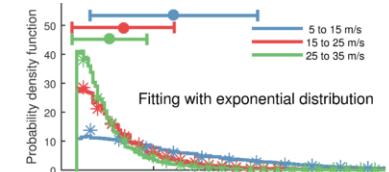
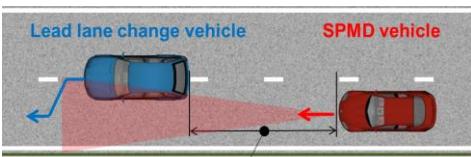
③ Skew the statistics

Importance Sampling

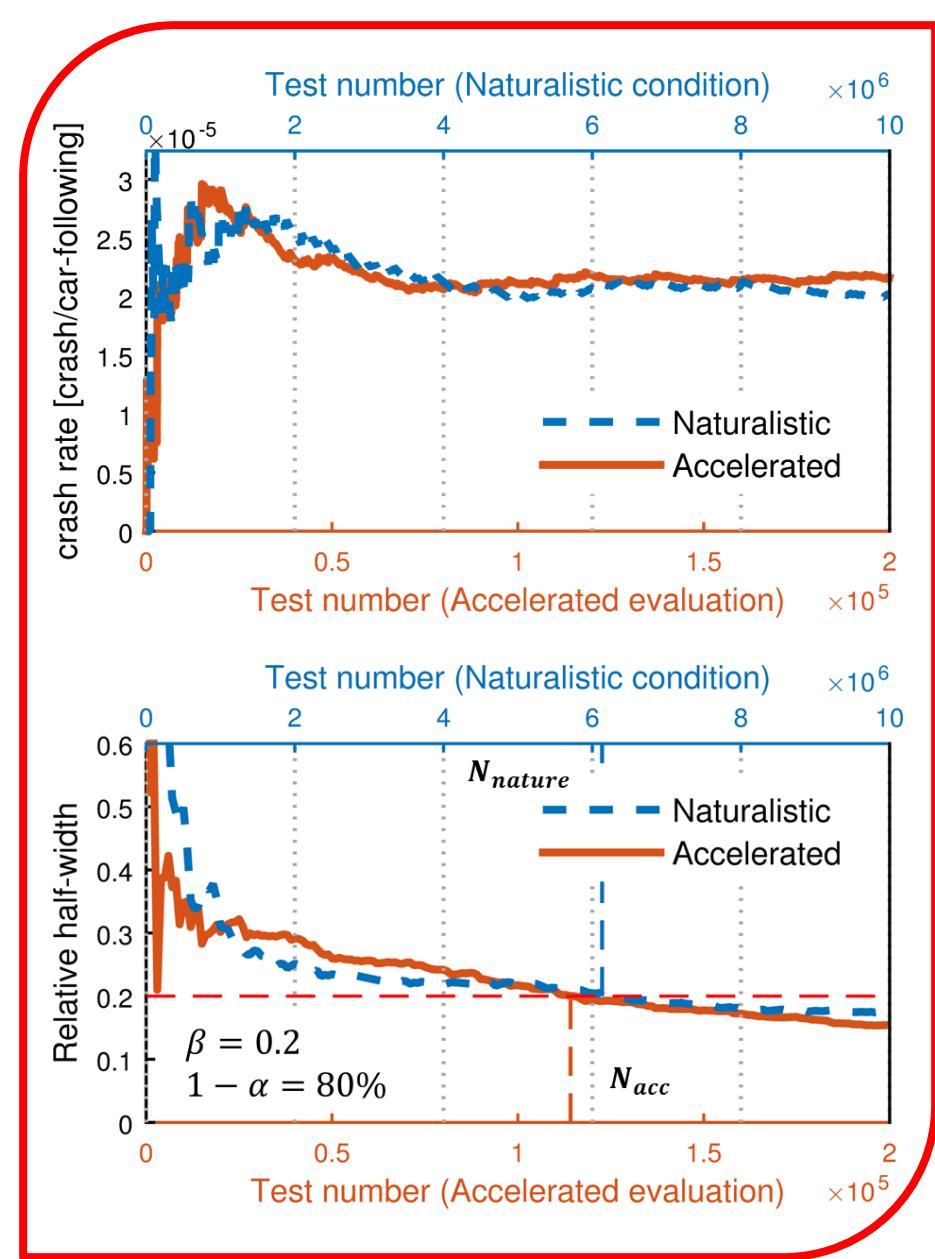
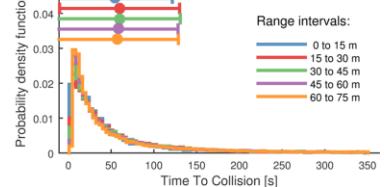
⑤ "Skew back"



$$f_{v_L} \rightarrow v_L \rightarrow f_{R_L^{-1}} \rightarrow R_L$$

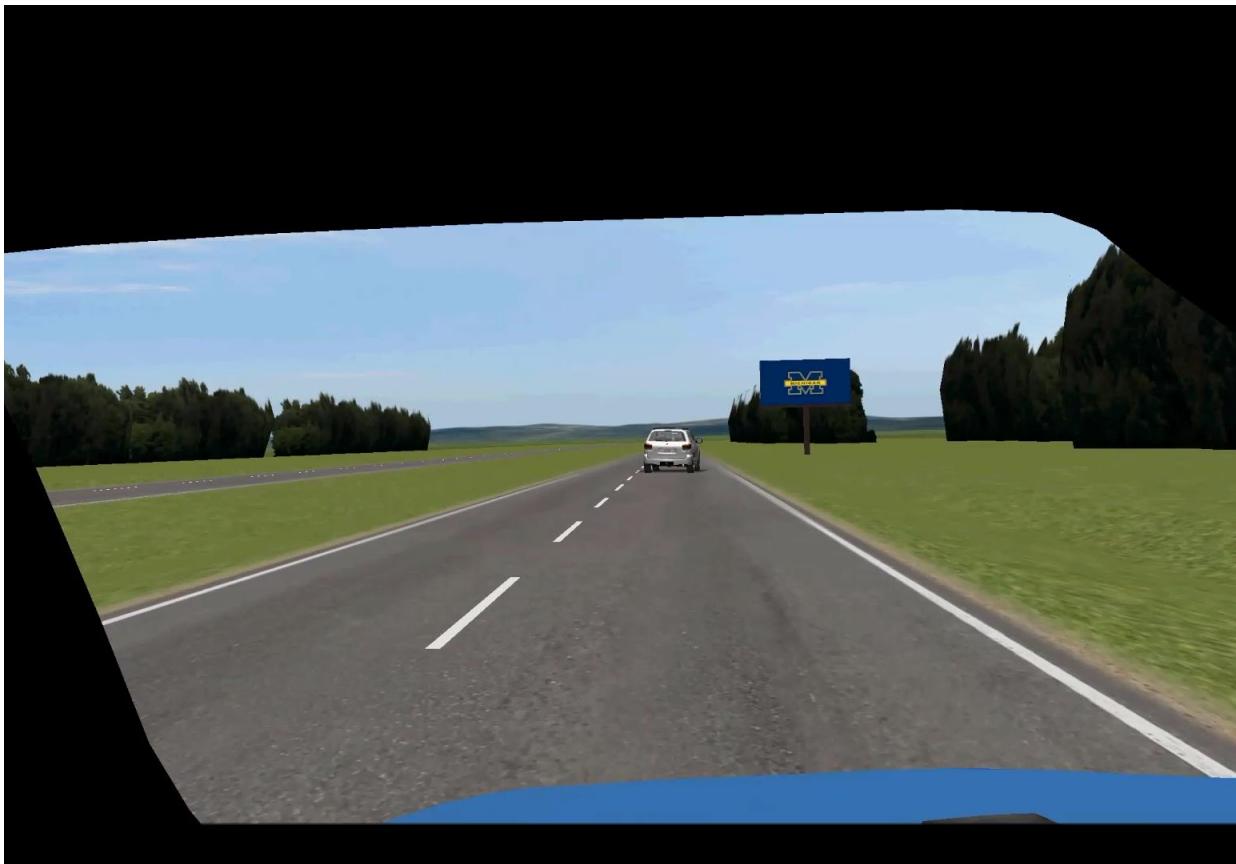


$$f_{v_L} \rightarrow v_L \rightarrow f_{R_L^{-1}} \rightarrow R_L \rightarrow f_{TTC_L^{-1}} \rightarrow TTC_L$$



Naturalistic Driving vs Accelerated Tests

Naturalistic driving conditions



Accelerated tests

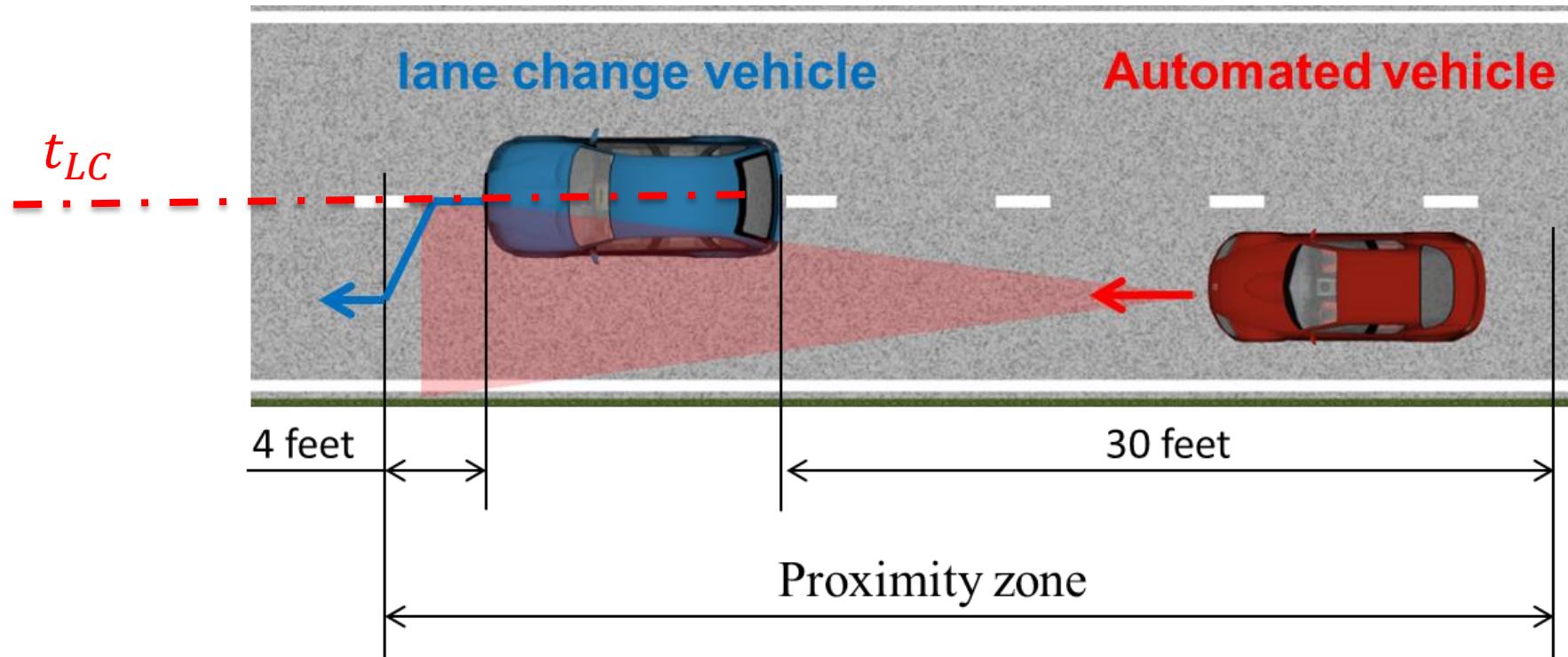


Accelerate Rate

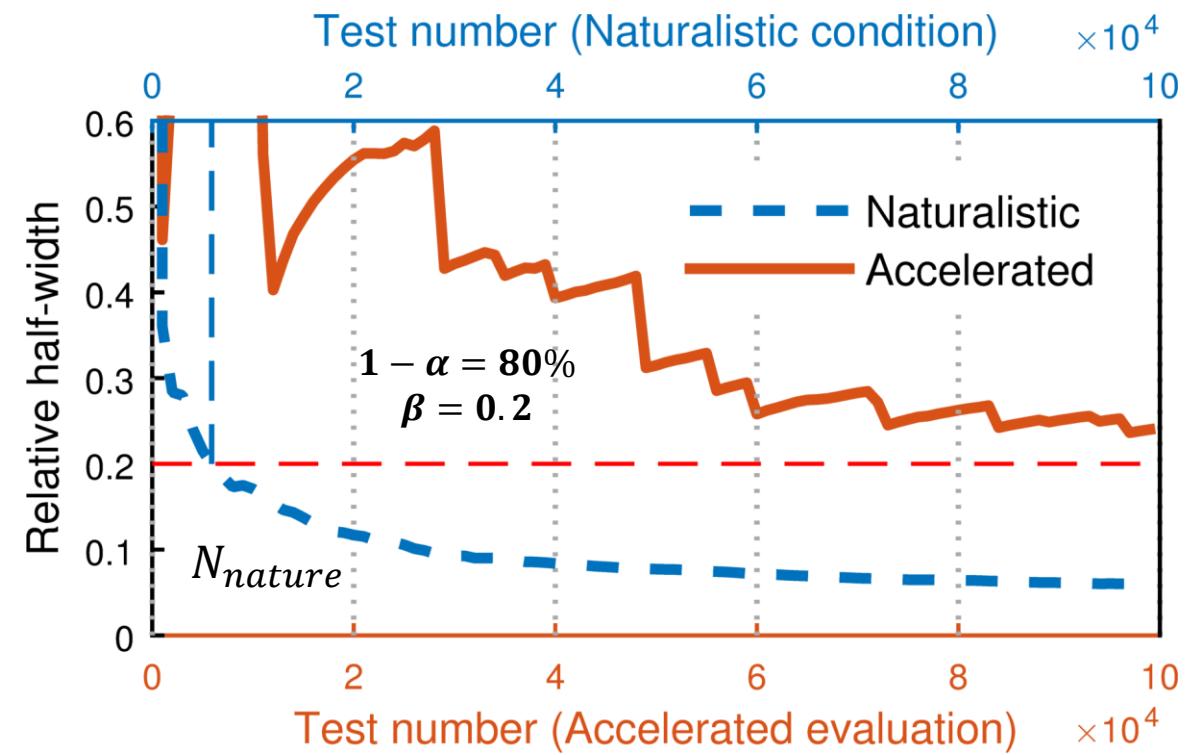
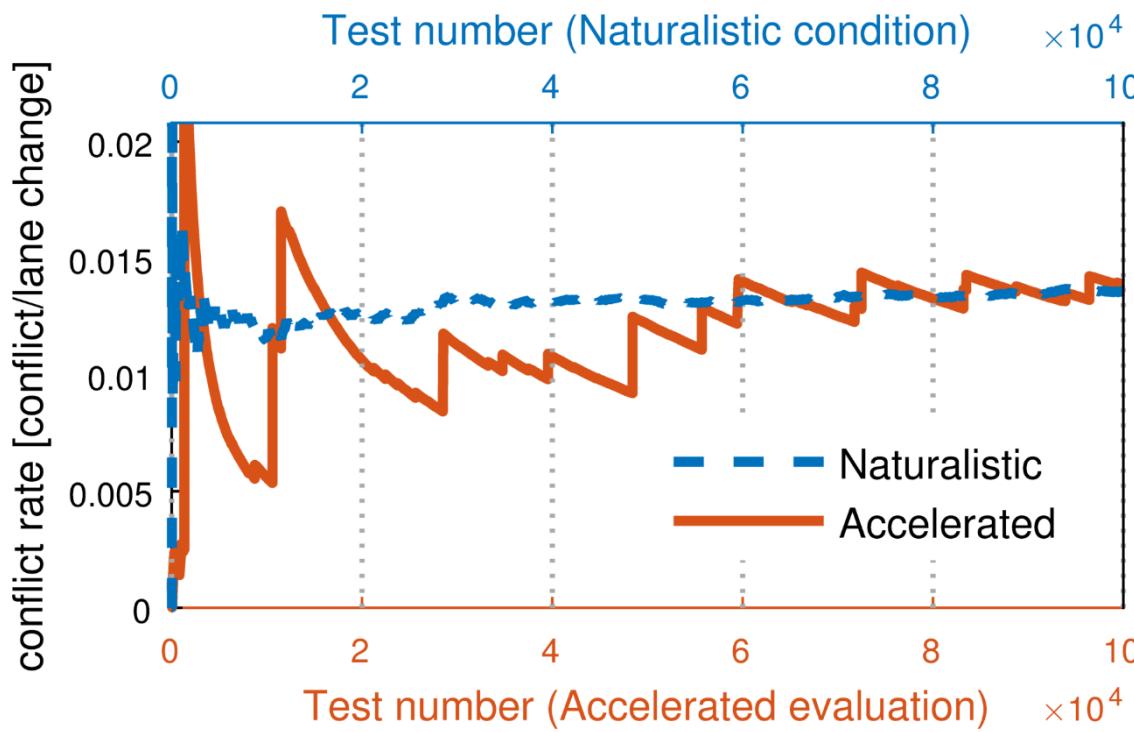
	D_{nature}	D_{acc}	r_{acc}
	mile	mile	-
Crash	4.71e7	7.48e3	6.30e3
Injury (belted)	4.70e7	4.85e3	9.70e3

“Accelerated” Test with the Non-optimized AE Distribution

- Apply the previous AE distributions (f^*) on a new metric
 - Previous: crash, injury
 - New: conflict

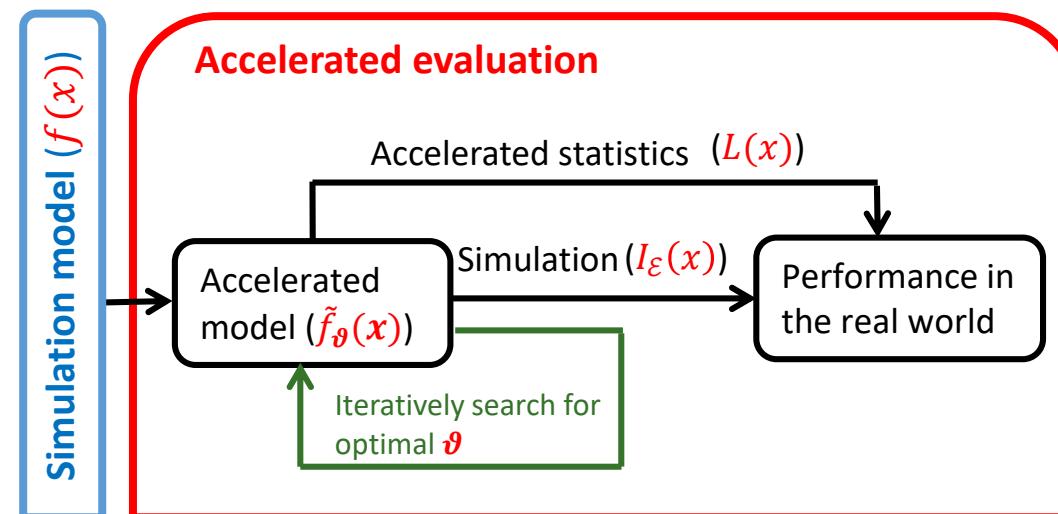


Simulation Results



Adaptive Accelerated Evaluation

- The core idea
 - Identify a family of distribution $\tilde{f}_\vartheta(x)$
 - Find a ϑ that can effectively accelerate the evaluation in a small amount of pre-test



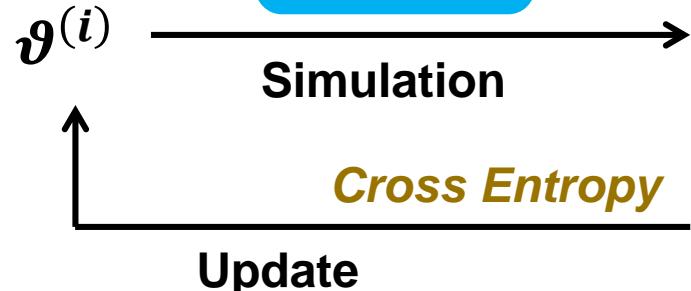
Find Optimal $f^*(\cdot)$ Iteratively

Exponential twisting

$$\tilde{f}_\vartheta(x) = \exp(\vartheta x - \Psi(\vartheta)) f(x)$$

$$\Psi(\vartheta) = \log E(\exp(\vartheta^T x))$$

$$\tilde{f}_{\vartheta^{(i)}}(x)$$



Theoretically optimal $f^*(\cdot)$

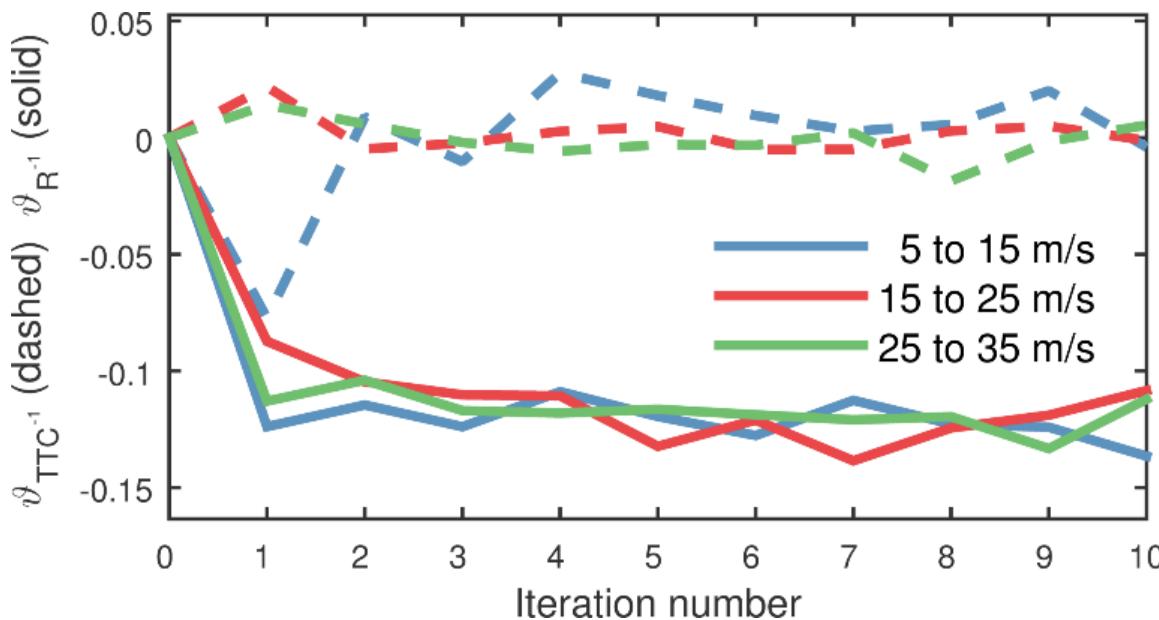
$$f_{zv}^*(x) = \begin{cases} \frac{f(x)}{\gamma}, & I_{\mathcal{E}}(x) = 1 \\ 0, & I_{\mathcal{E}}(x) = 0 \end{cases}$$

$\vartheta^{(i+1)} = \underset{\vartheta}{\operatorname{argmin}}$ difference $(f_{zv}^*(x), \tilde{f}_\vartheta(x))$
based on the simulation results using $\tilde{f}_{\vartheta^{(i)}}(x)$

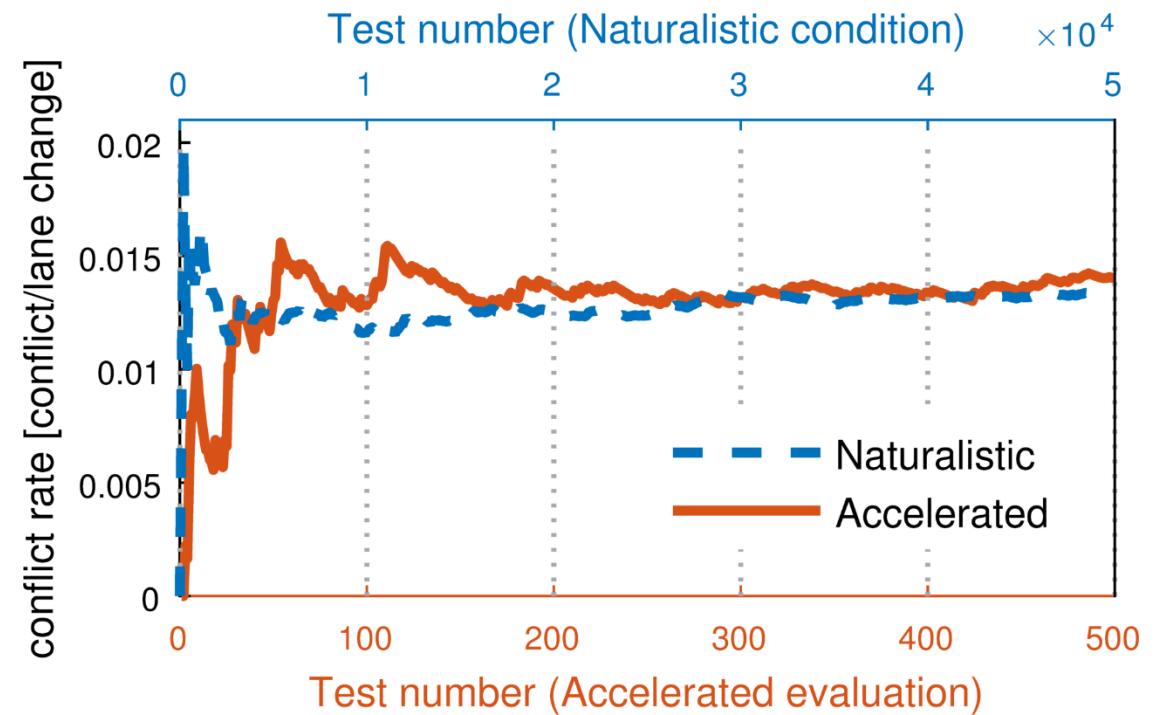
Kullback–Leibler divergence

$$f_{KL}(f_1(x), f_2(x)) = \int \log \left[\frac{f_{zv}^*(x)}{\tilde{f}_\vartheta(x)} \right] f_{zv}^*(x) dx$$

Conflict Analysis



Find the optimal $f^*(\cdot)$
using the Cross Entropy method

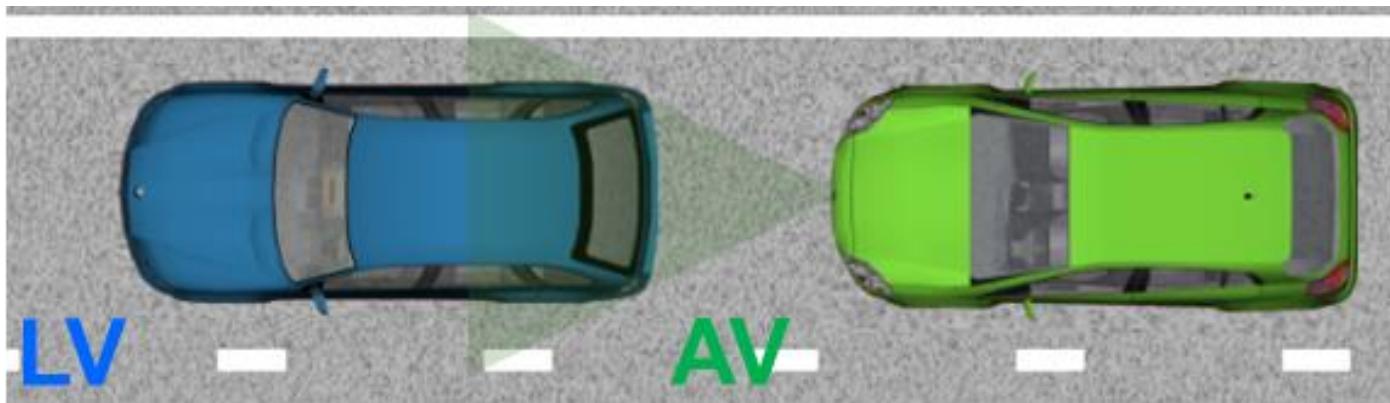


Estimate the probability of conflict

Summary

	D_{nature}	D_{acc}	r_{acc}	r_{acc}
	mile	mile		Non-optimal AE distribution
Conflict	4.53e4	16.4	2.77e3	<1
Crash	4.71e7	4.02e3	1.17e4	6.30e3
Injury	4.70e7	2.53e3	1.86e4	9.70e3

Case 2: Car-following Scenarios



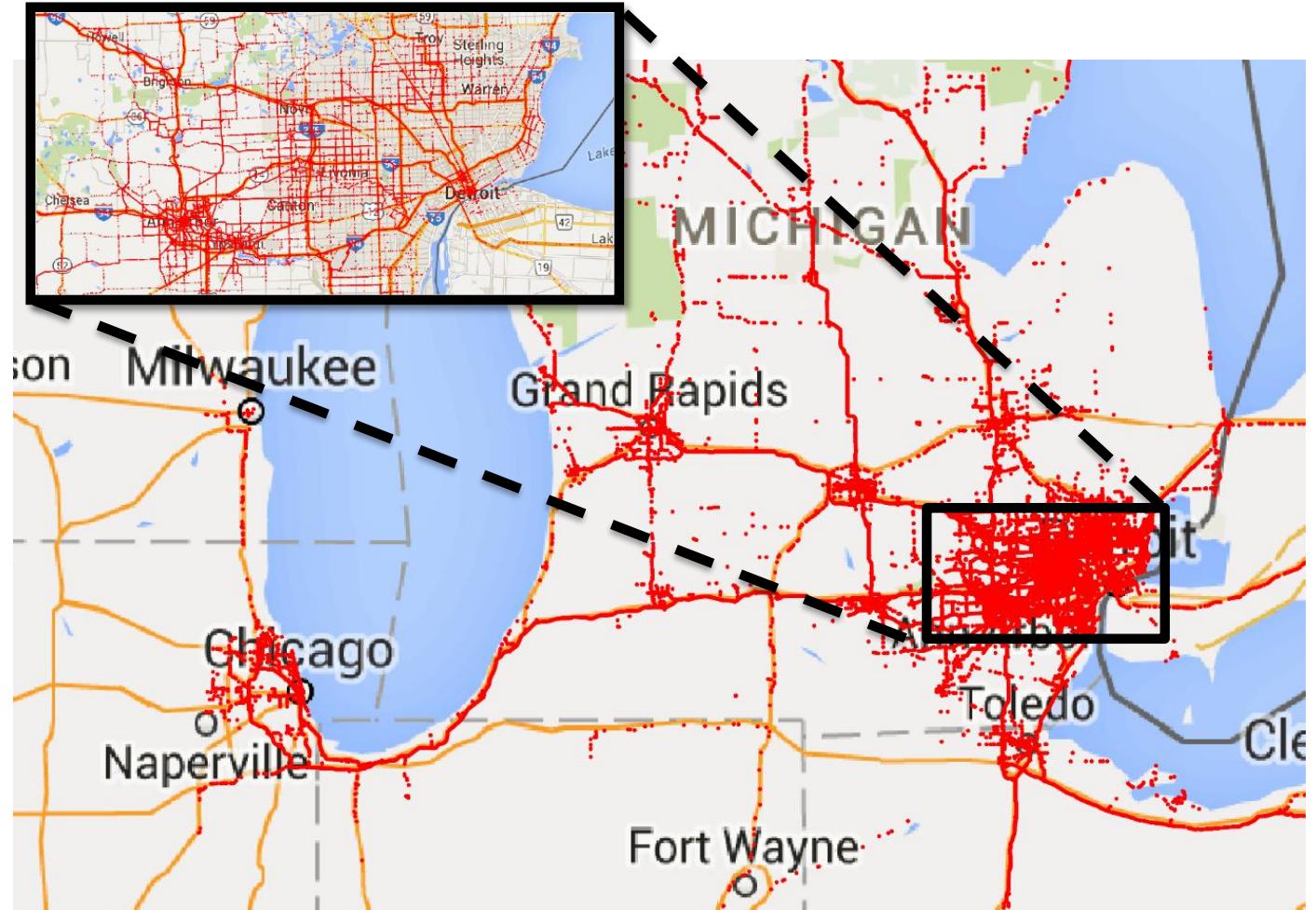
D. Zhao, X. Huang, H. Peng, H. Lam, D. LeBlanc, Accelerated Evaluation of Automated Vehicles in Car-Following Maneuvers. *IEEE Transactions on Intelligent Transportation Systems*, 2017

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.

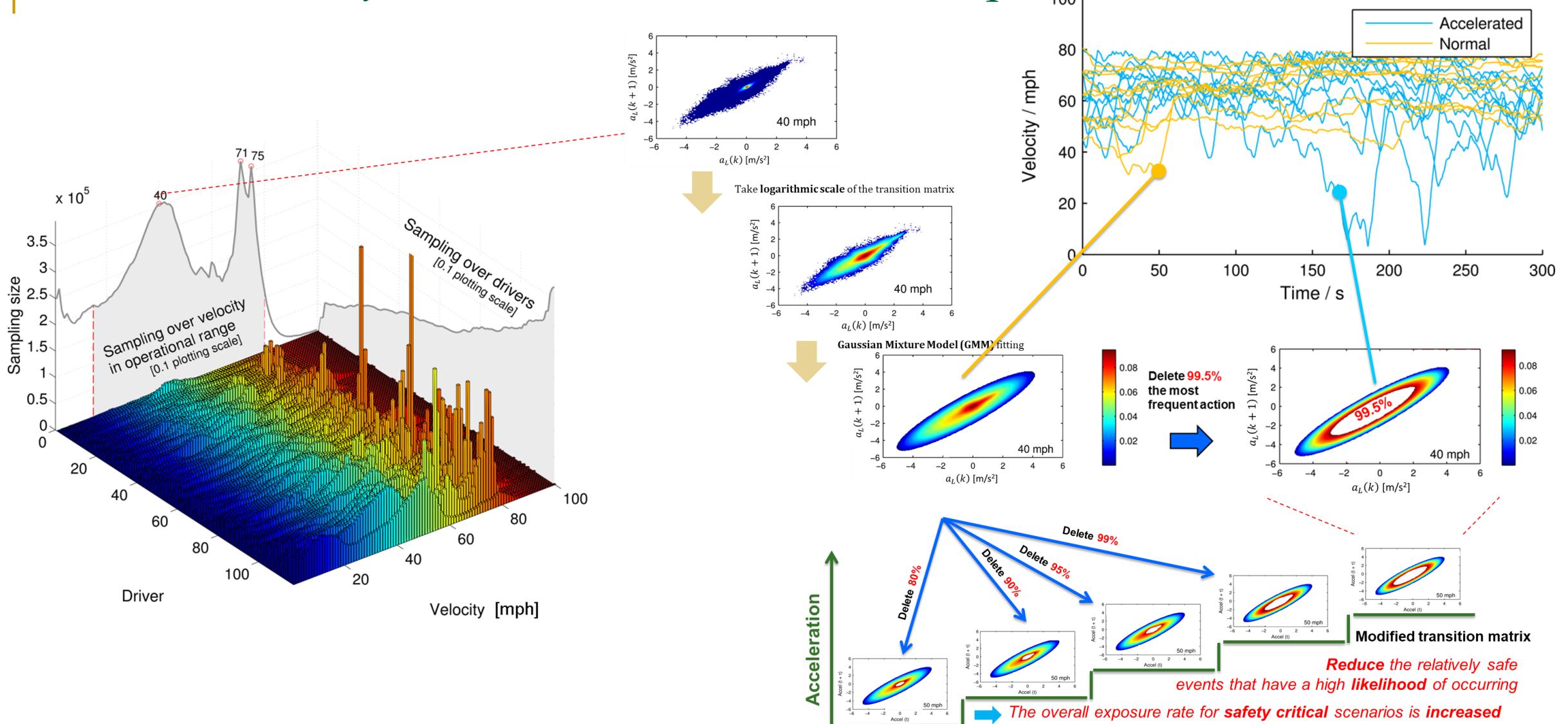
Query Car-following Events

163,332 car following events

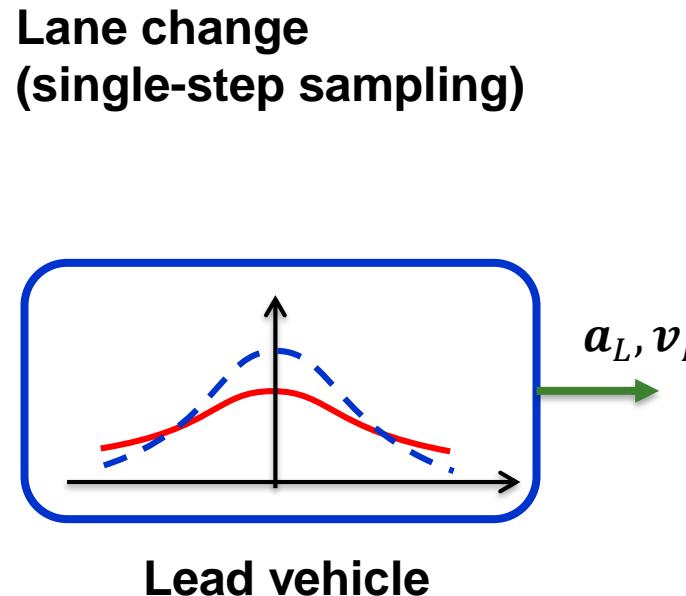
- Criteria
 - $R_L(t) \in (0.1 \text{ m}, 90 \text{ m})$
 - Longitude $\in (-88.2^\circ, -82.0^\circ)$
 - Latitude $\in (41.0^\circ, 44.5^\circ)$
 - No cut-in vehicles between HV and SPMD vehicle
 - No lane changes of HV and SPMD vehicle
 - Duration of car-following $> 50 \text{ s}$



A “Naïve” Way to Accelerate: “Cut the Frequent Parts”

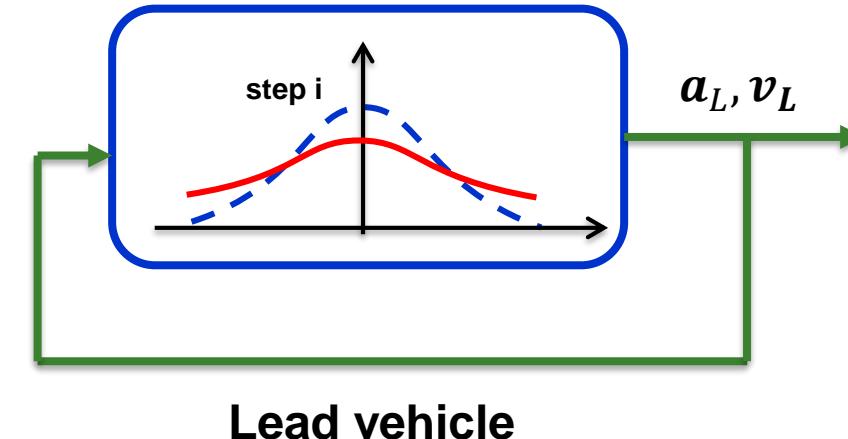


Single-step Sampling vs Multi-step Sampling



Naturalistic distribution
AE distribution

**Car-following
Multi-step stochastic sampling
(Dynamic sampling)**



- Fold N-step dynamic sampling together to a N-dimensional distribution and solve the new problem with stochastic method.

Accelerated Evaluation of the Dynamic Interaction

The optimal $\boldsymbol{\ell}(k)$ is calculated to achieve two goals

i) To make a crash happen at a specific time

$$k_T^* = 1, \dots, K$$

ii) To maximize the likelihood of the occurring of the events of interest

Run the Accelerated Tests

$$\boldsymbol{\ell}_{k_T^*}(1:K)$$

$$a_L(1:k_T)$$

$$I_{\varepsilon}(n)$$

Optimal change of HV statistics (off-line)

Likelihood ratio

$$L(n)$$

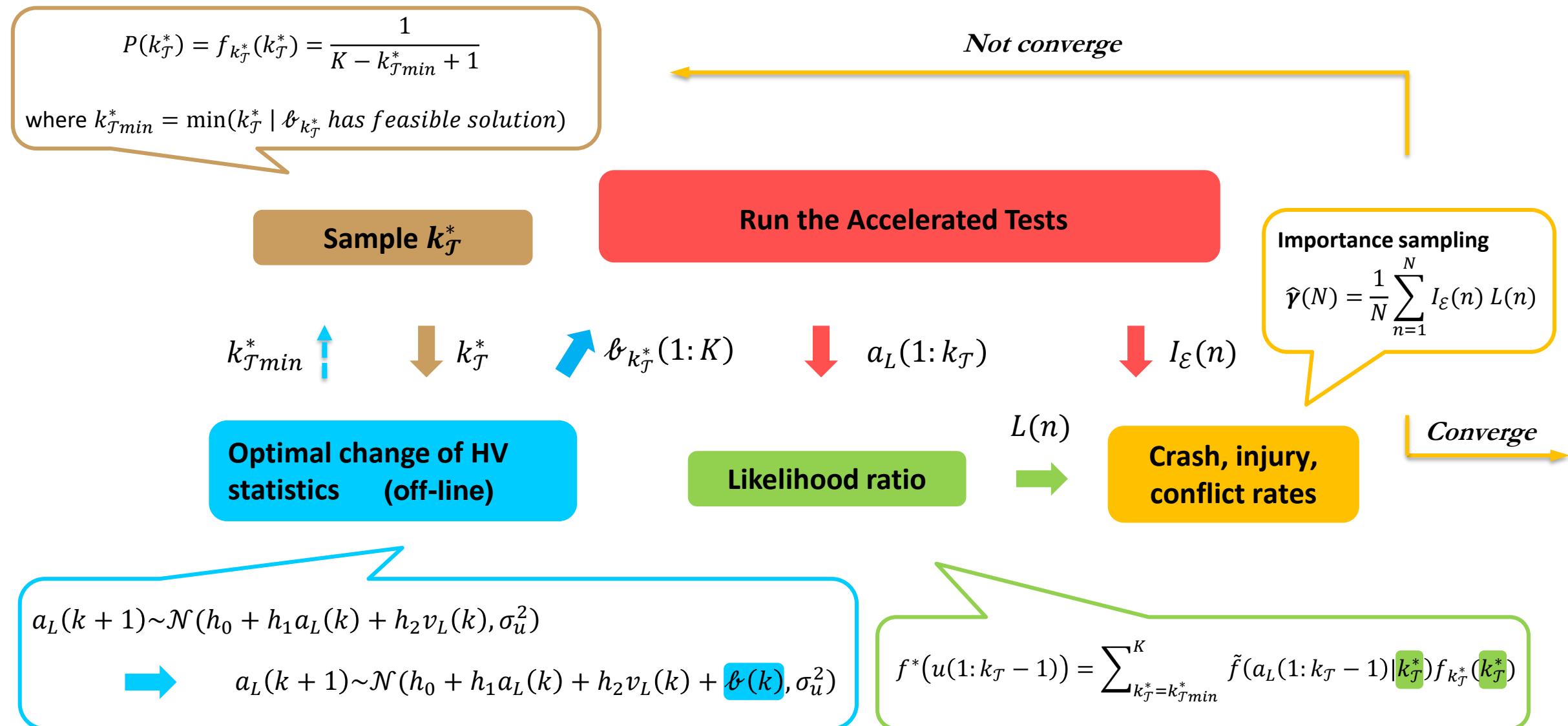
Crash, injury, conflict rates

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



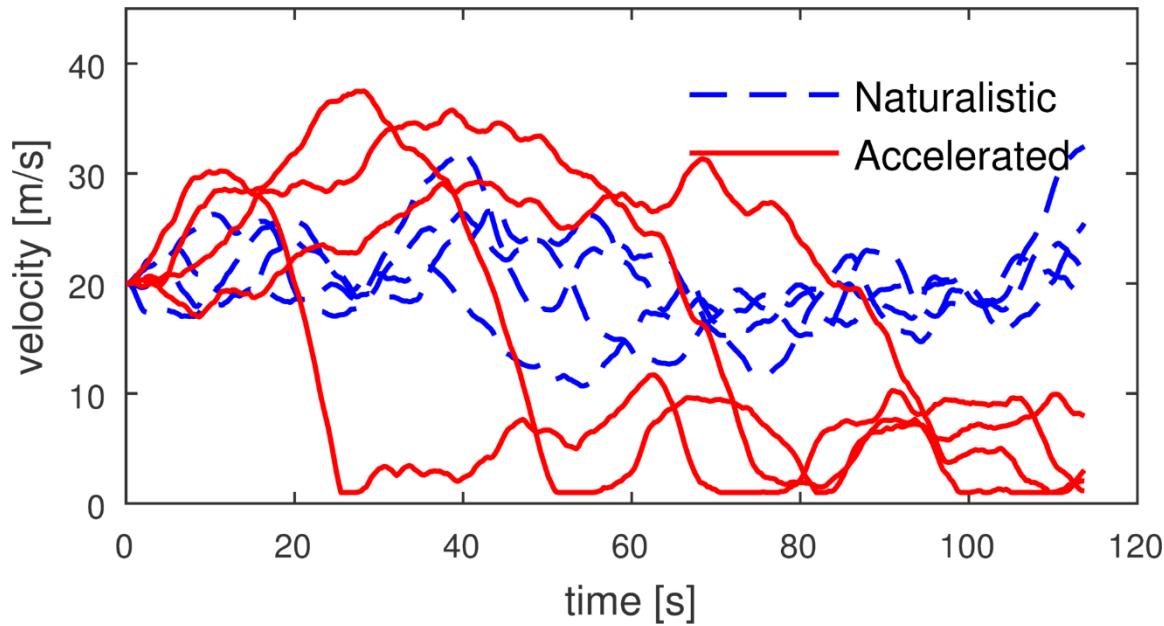
$$a_L(k+1) \sim \mathcal{N}(h_0 + h_1 a_L(k) + h_2 v_L(k) + \boldsymbol{\ell}(k), \sigma_u^2)$$

Accelerated Evaluation of the Dynamic Interaction

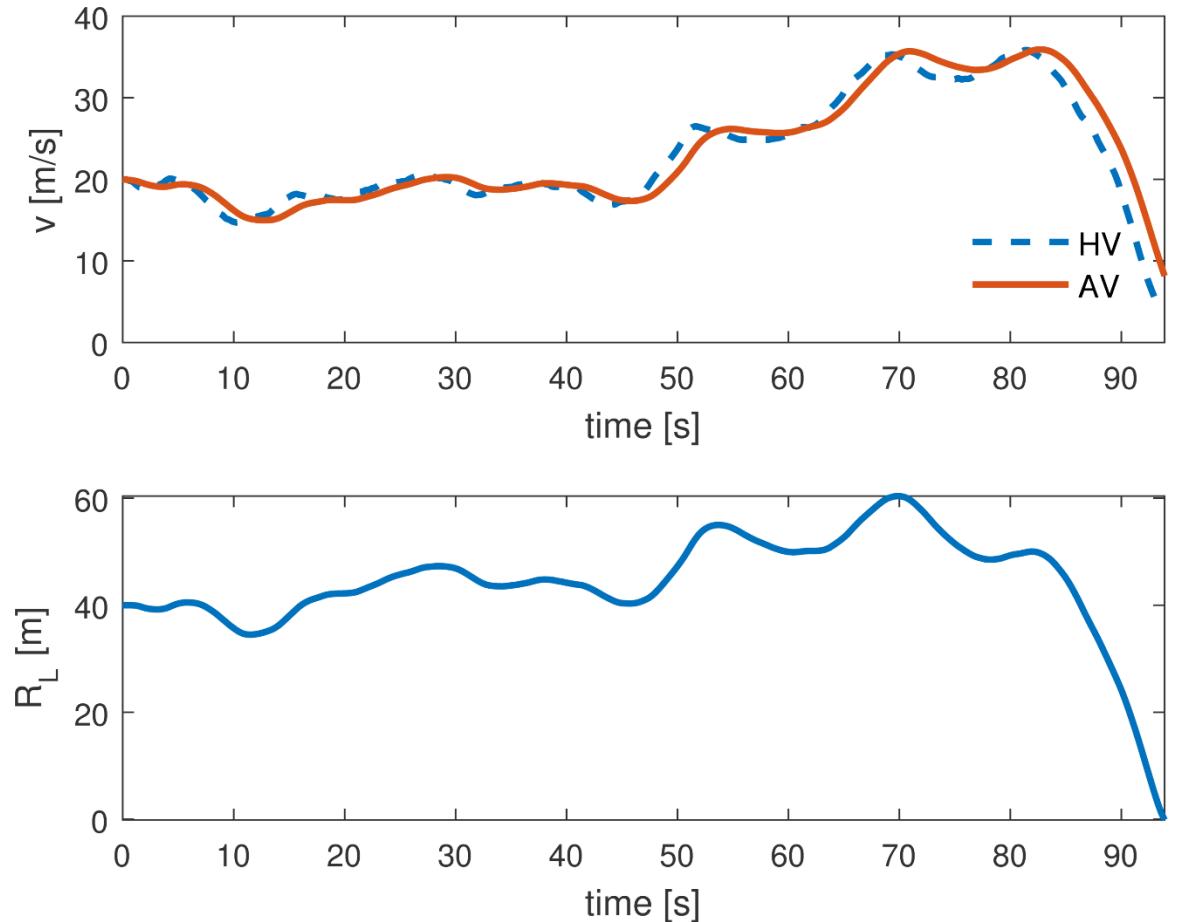


Examples of Accelerated Evaluation

Examples of velocity profiles of the lead vehicle

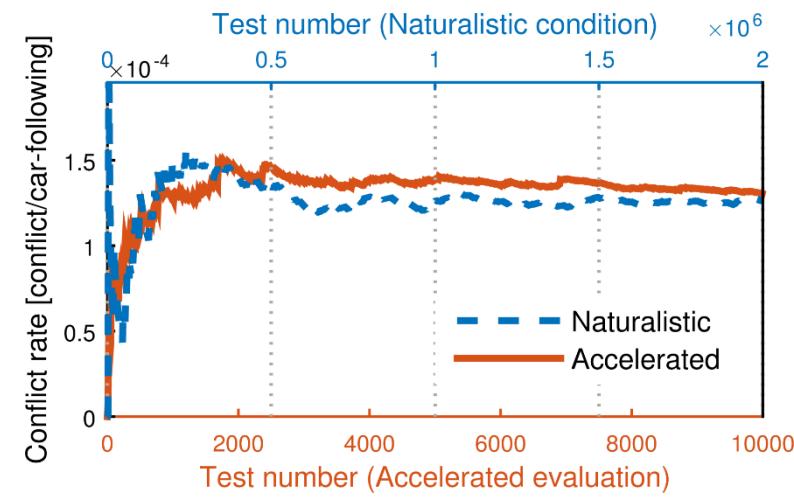
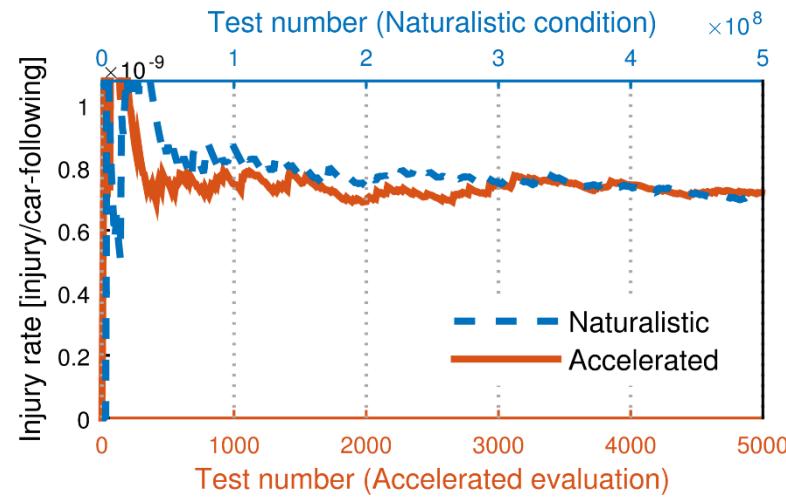
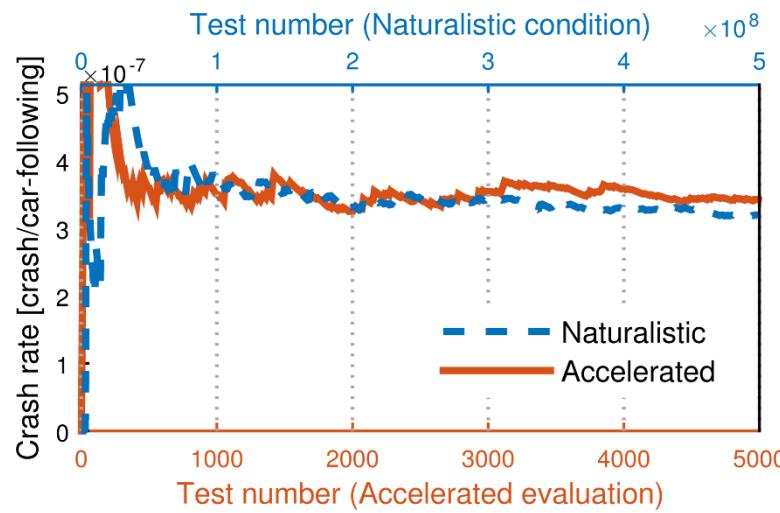


An example of the crash event



Estimation of Crash, Injury, and Conflict Rate

Estimation



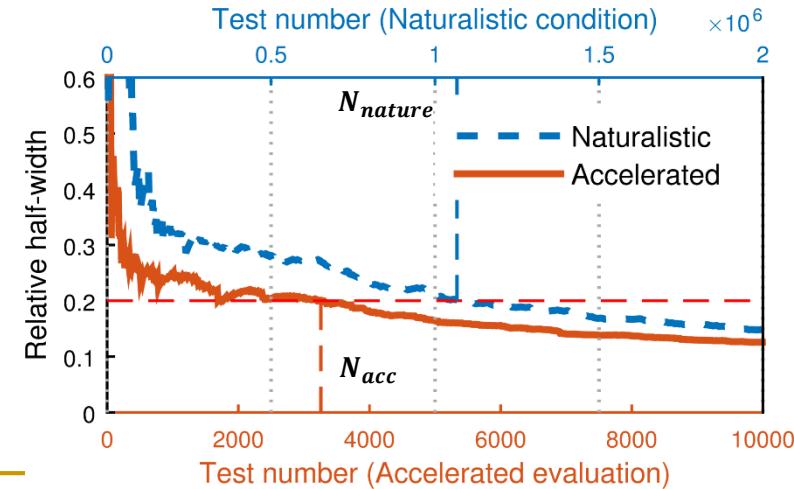
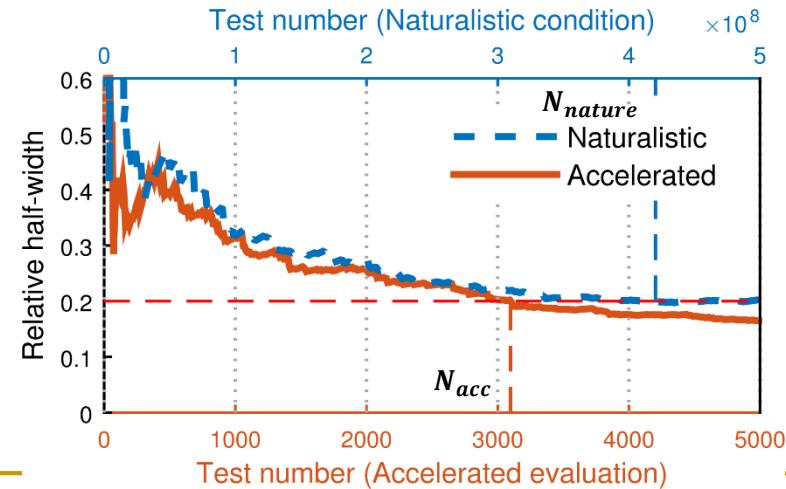
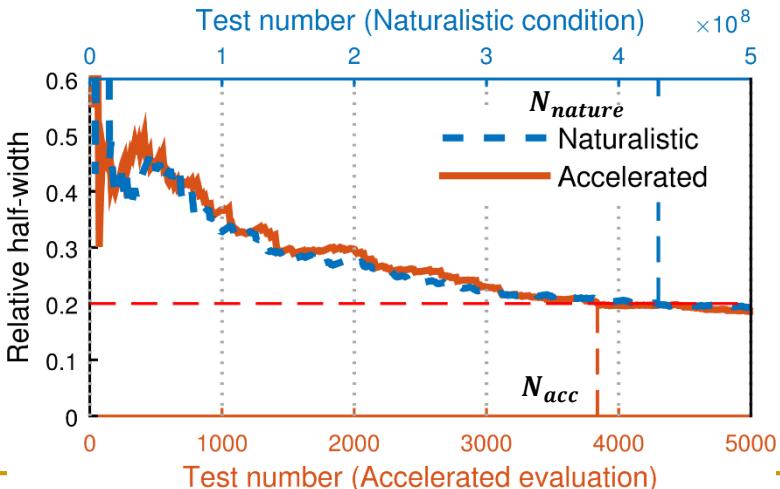
N_{nature}/N_{acc} :

Crash (1.12e5)

Injury(1.35e5)

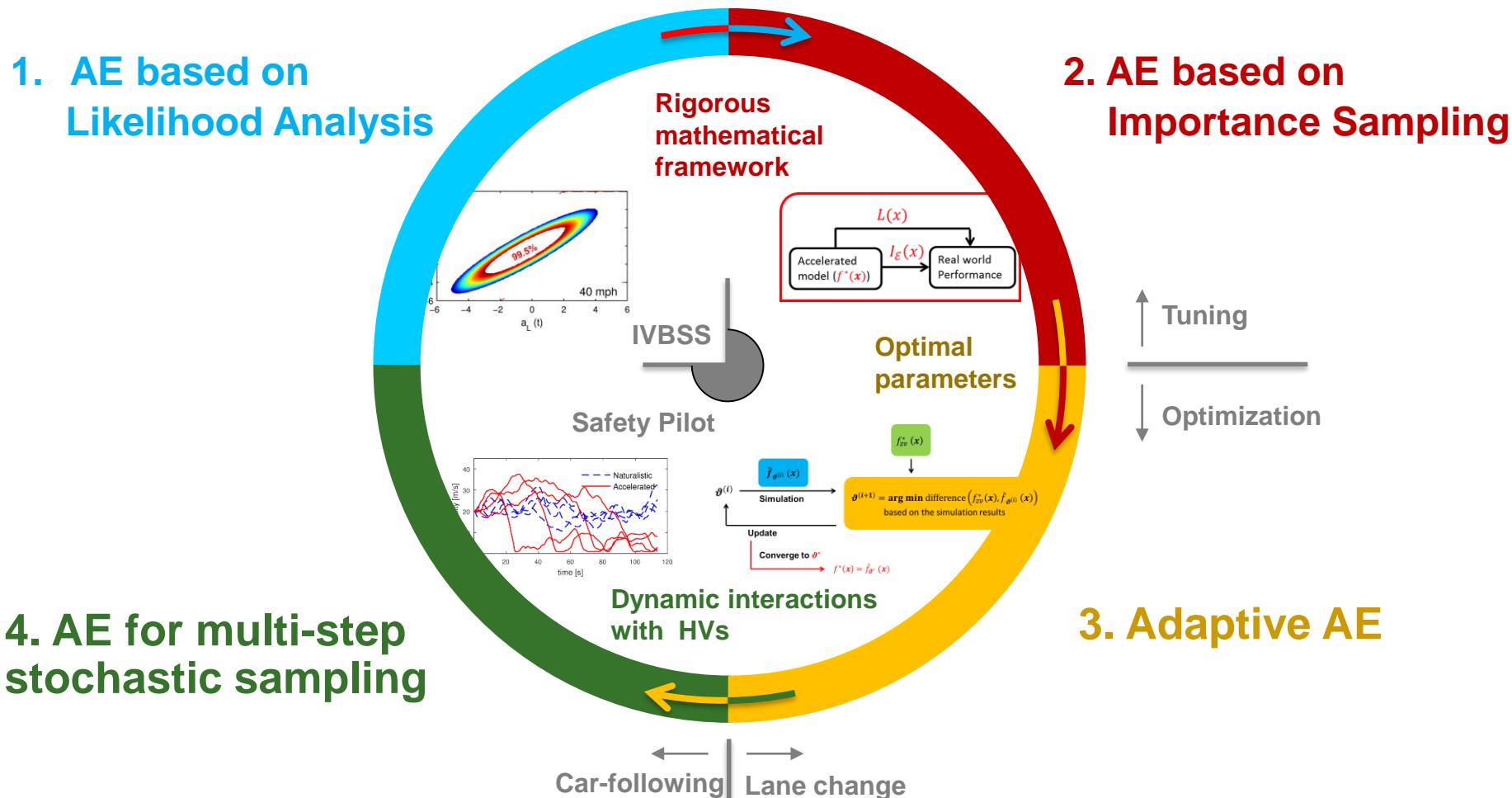
Conflict (3.28e2)

Convergence

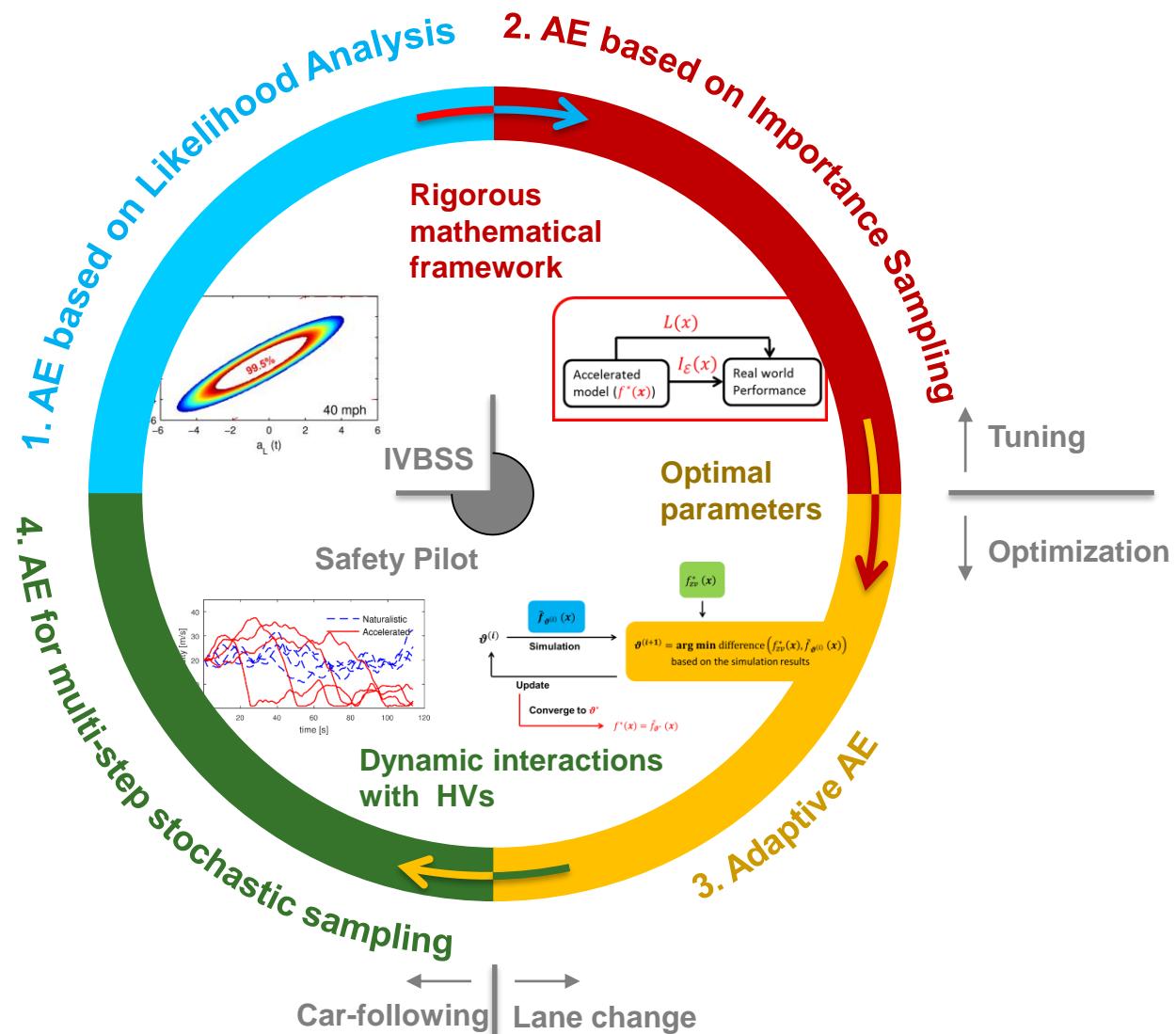


Summary: Four Methodologies of the Accelerated Evaluation (AE)

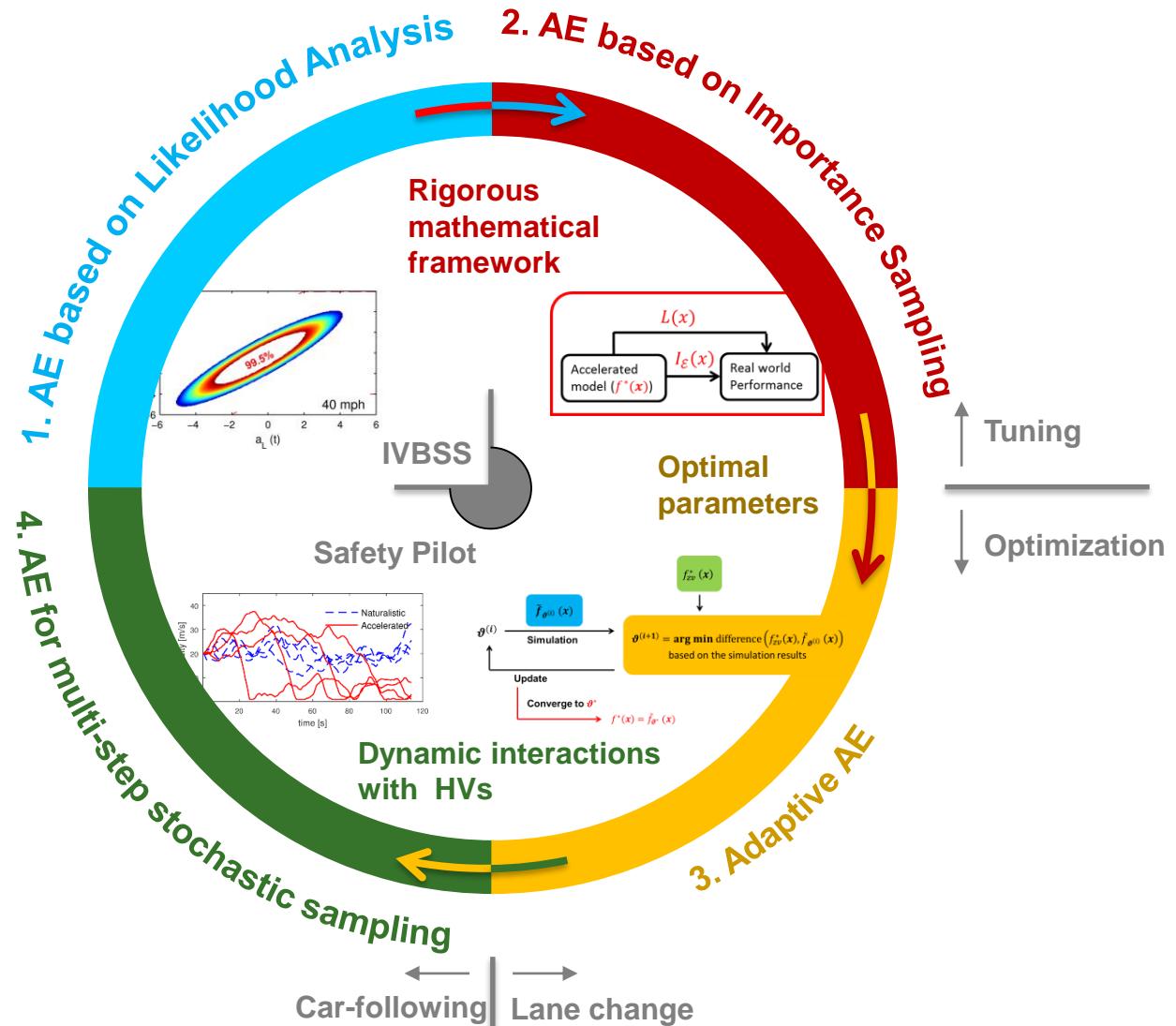
- The “Accelerated Evaluation” concept is new in the field of AV testing and evaluation.
- Four Accelerated Evaluation methods.



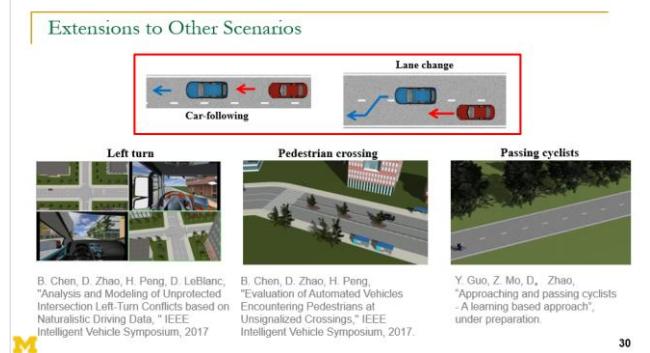
Extensions to the Accelerated Evaluation



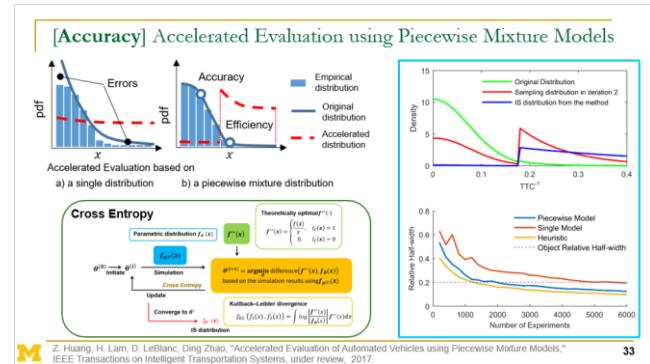
Extensions to the Accelerated Evaluation



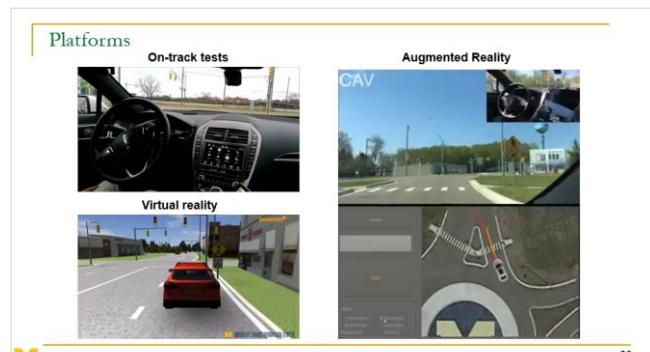
Variations



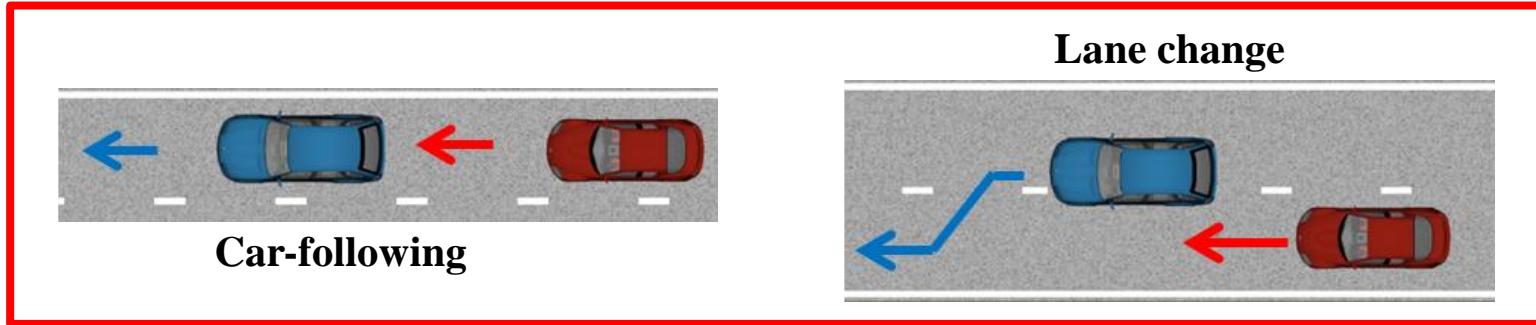
Theories



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



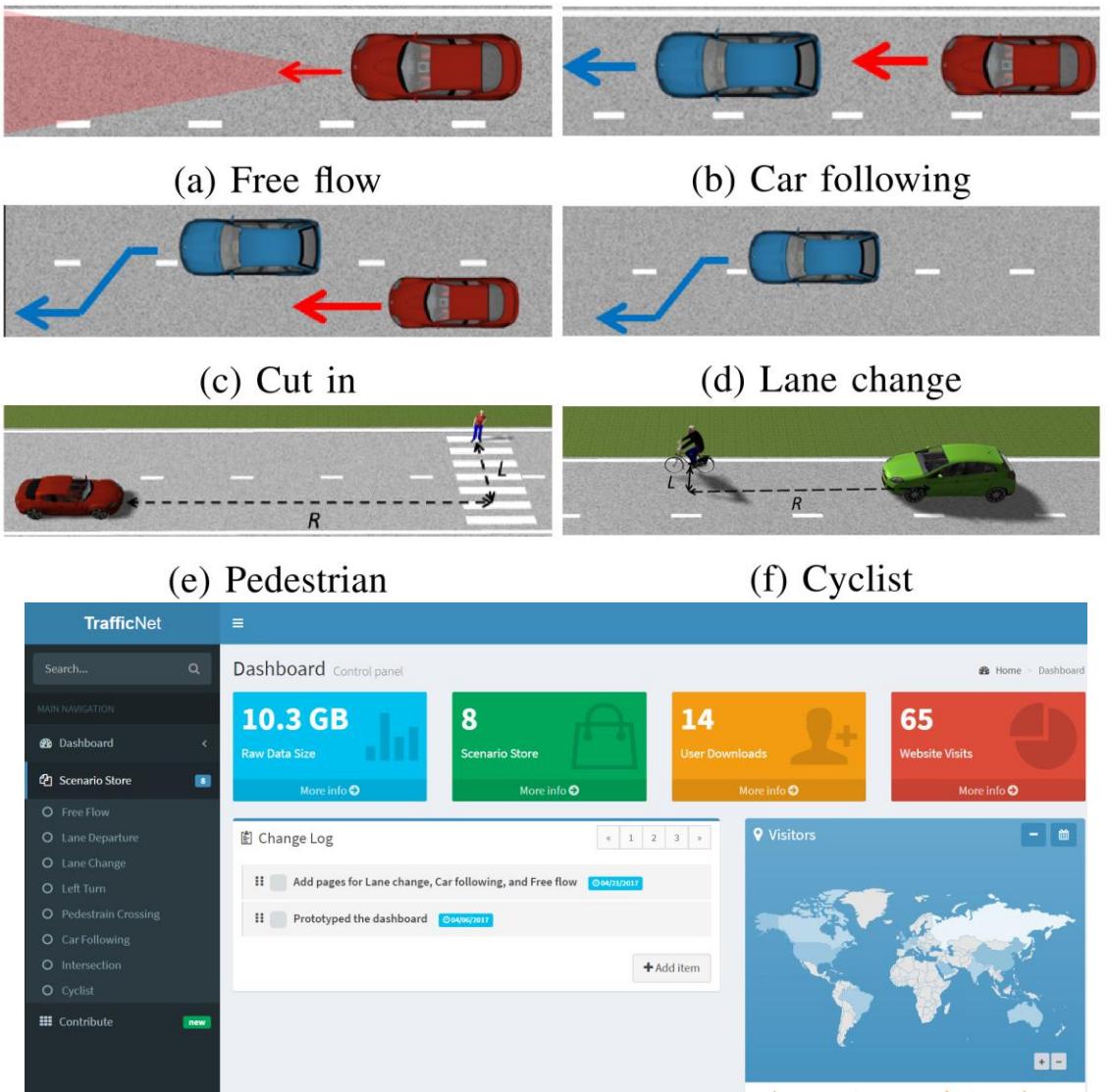
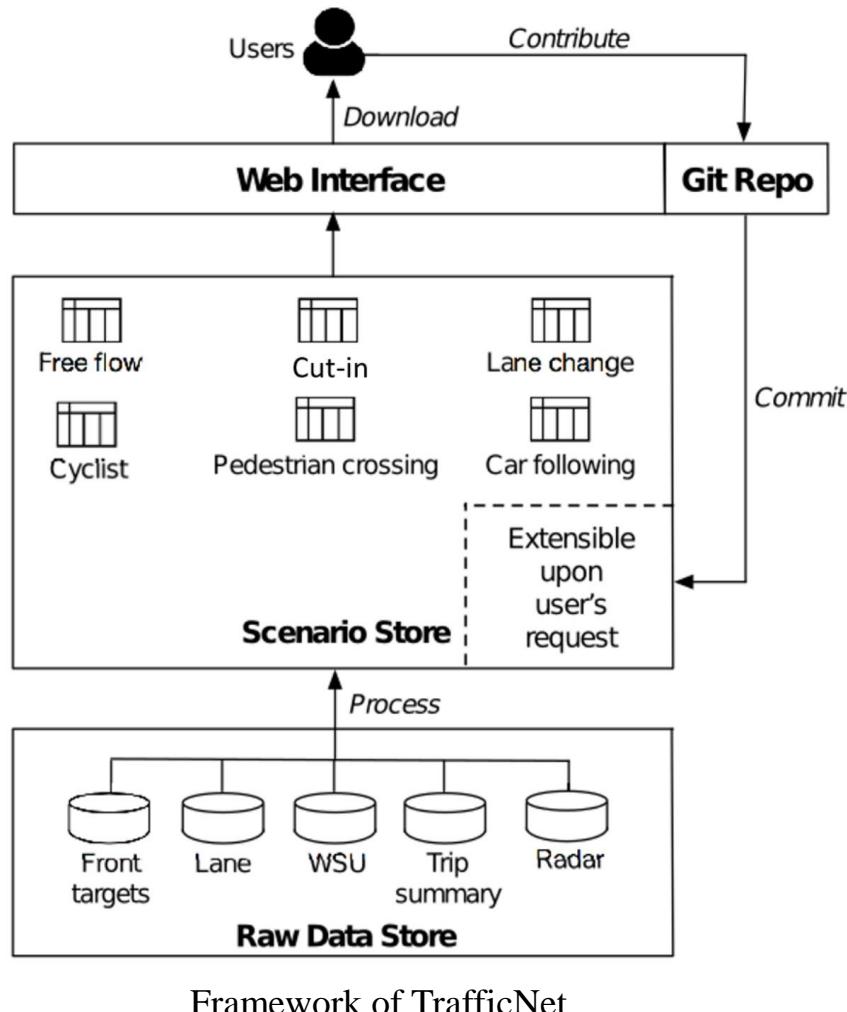
B. Chen, D. Zhao, H. Peng,
"Evaluation of Automated Vehicles
Encountering Pedestrians at
Unsignalized Crossings," IEEE
Intelligent Vehicle Symposium, 2017.

Passing cyclists

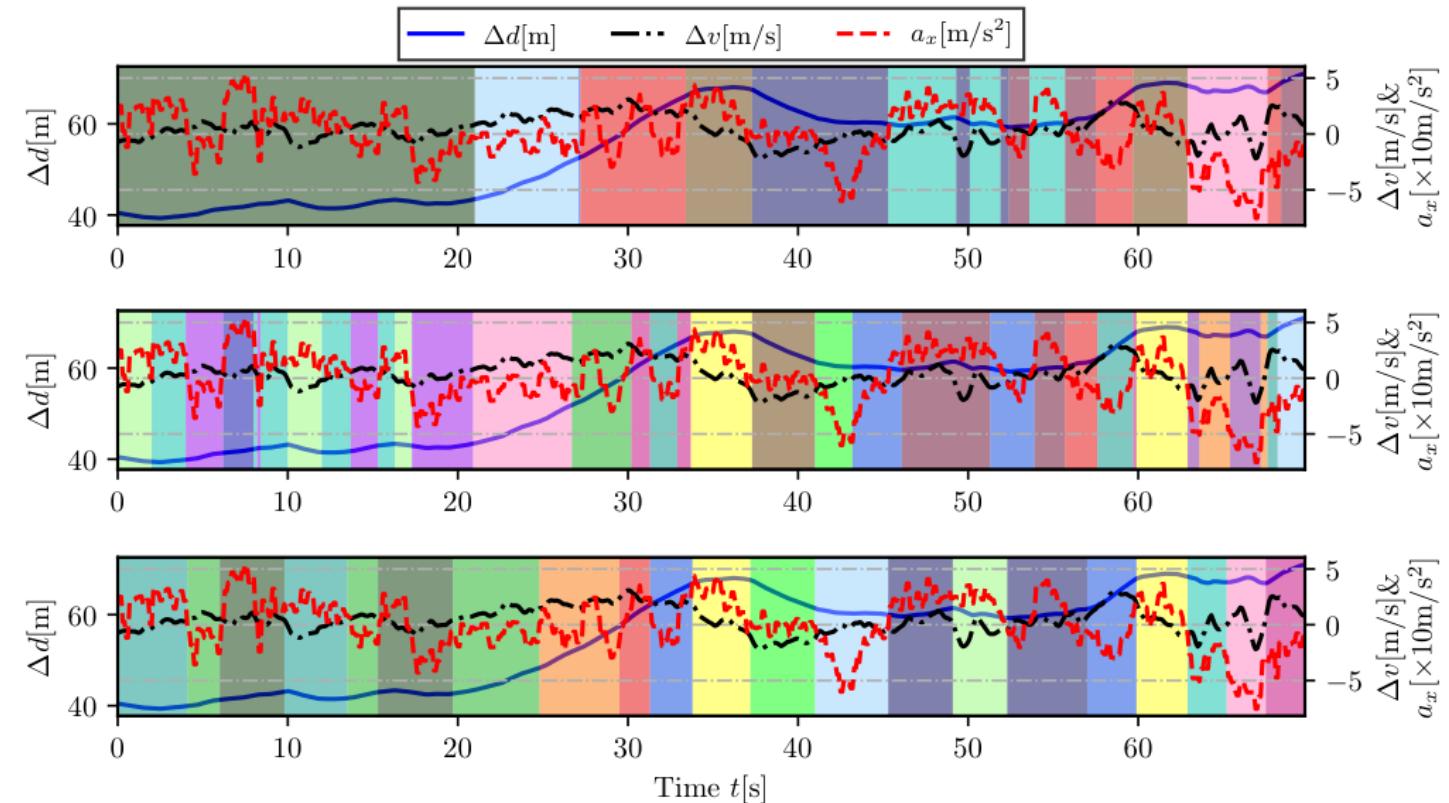
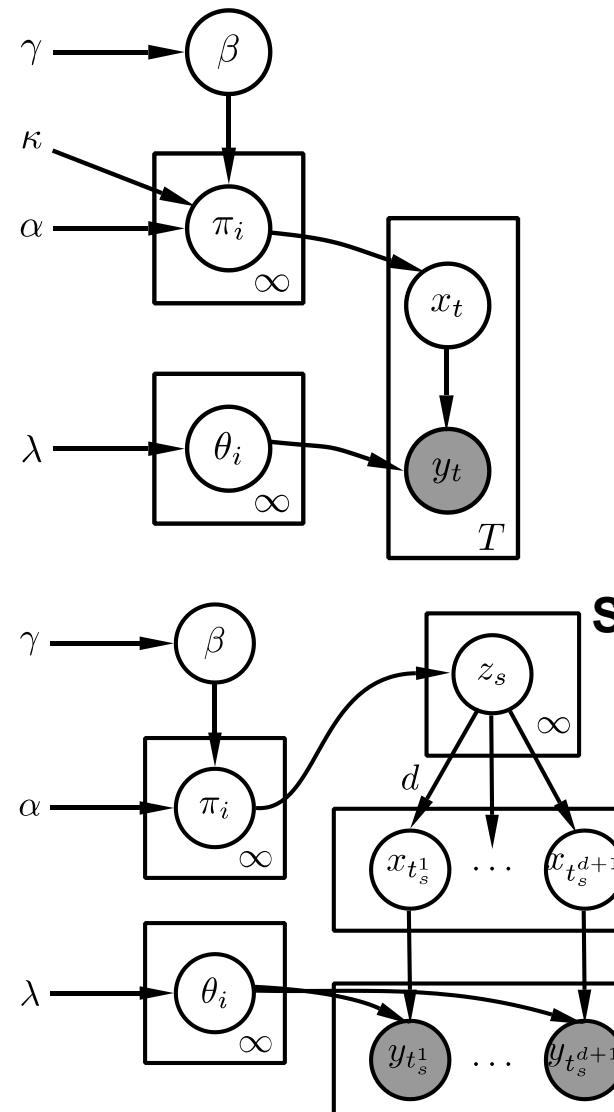


Y. Guo, Z. Mo, D. Zhao,
"Approaching and passing cyclists
- A learning based approach",
under preparation.

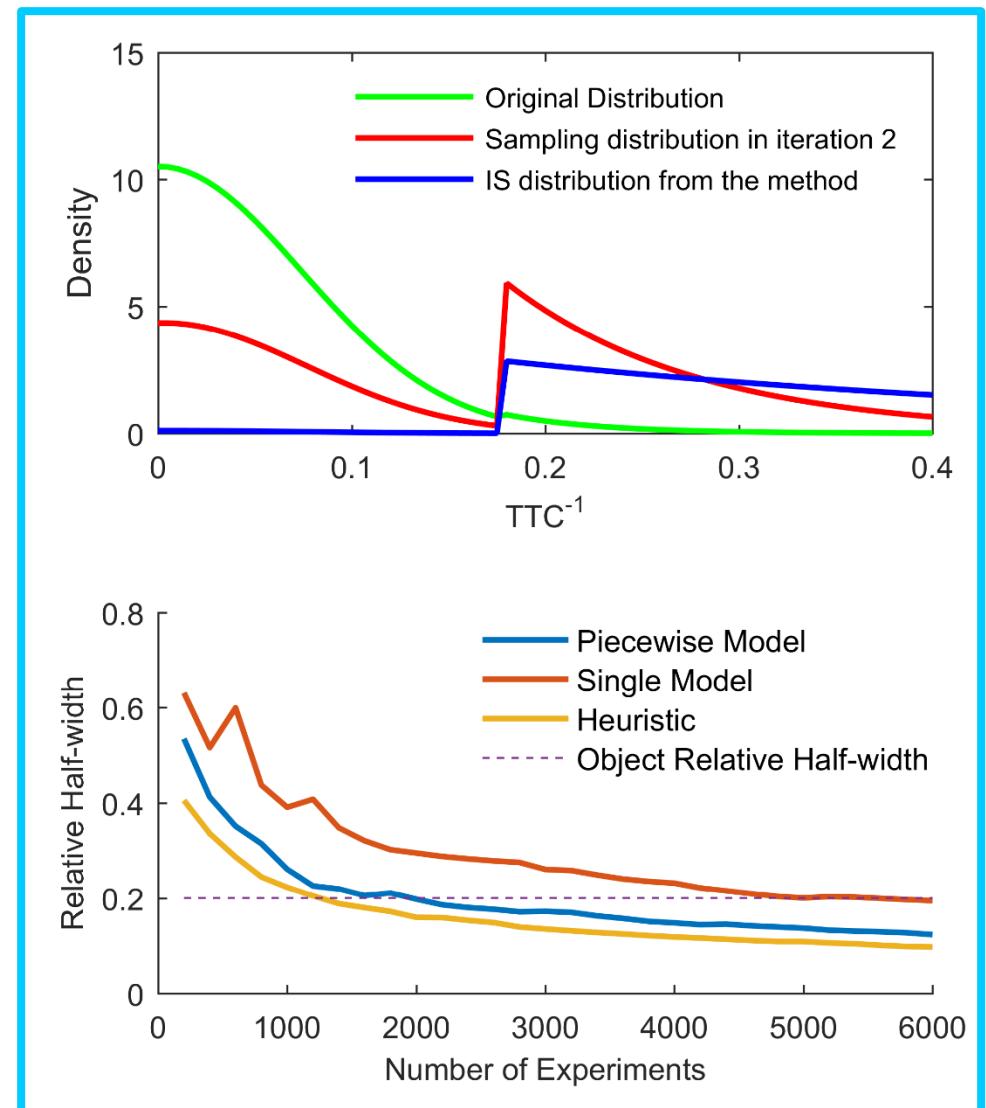
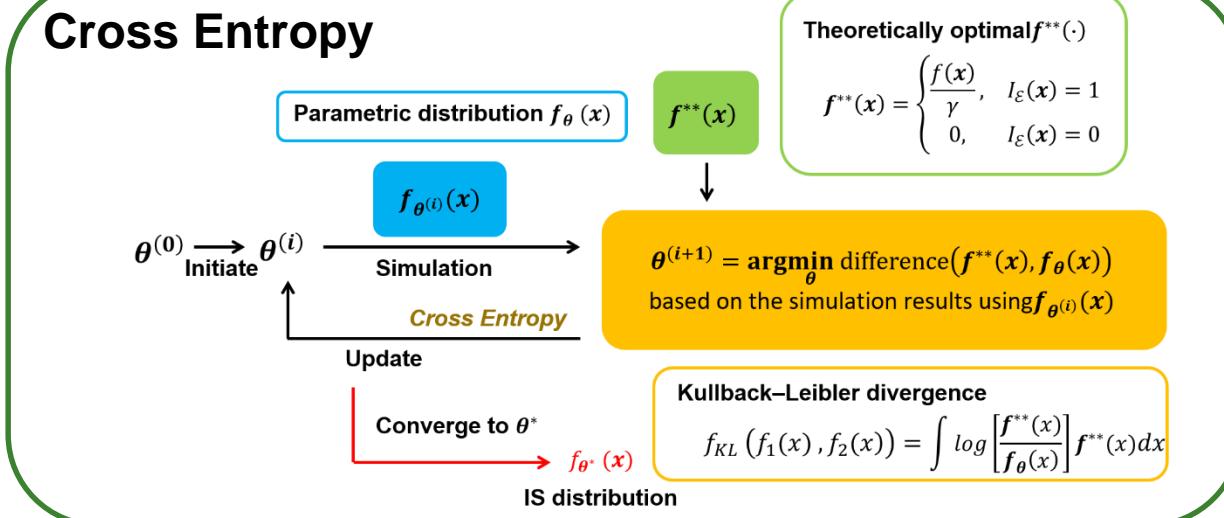
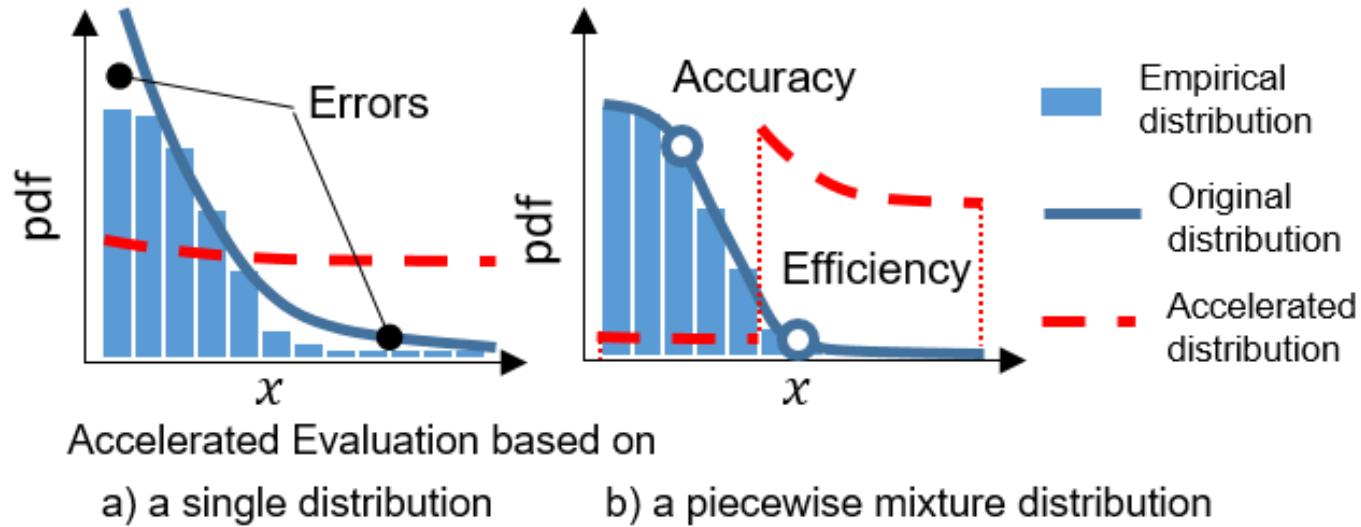
TrafficNet: An Open Naturalistic Driving Scenario Library



SceneCarp: Extract/Segment Scene Automatically from Raw Data

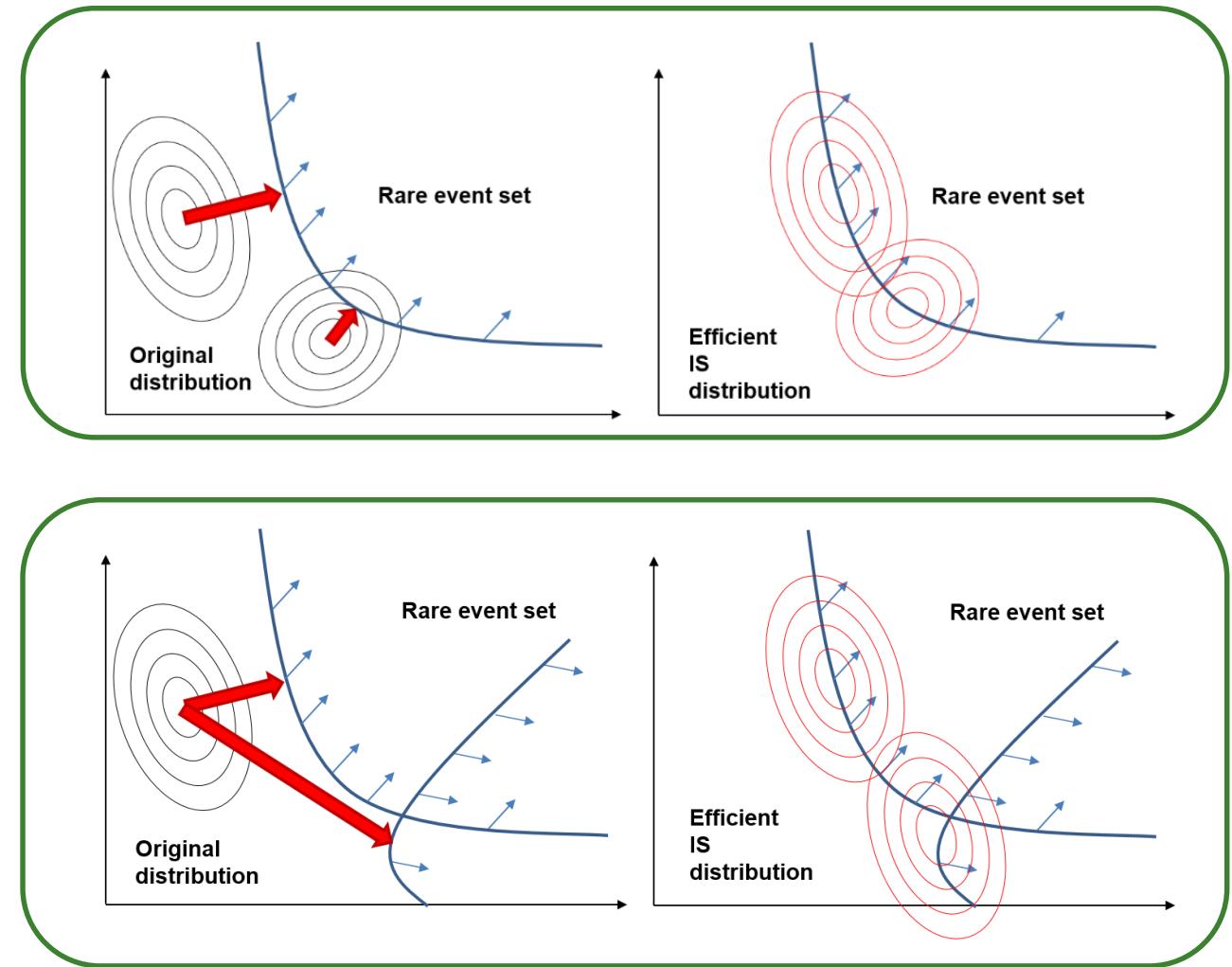
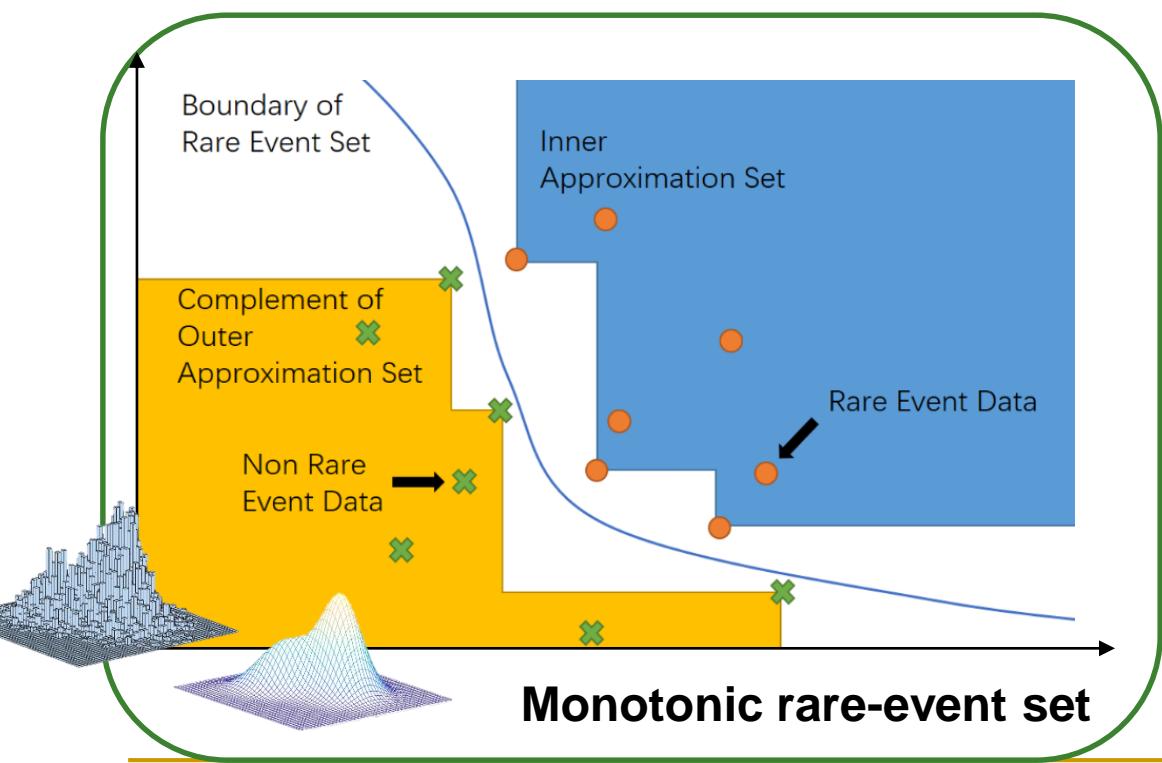


[Accuracy] Accelerated Evaluation using Piecewise Mixture Models

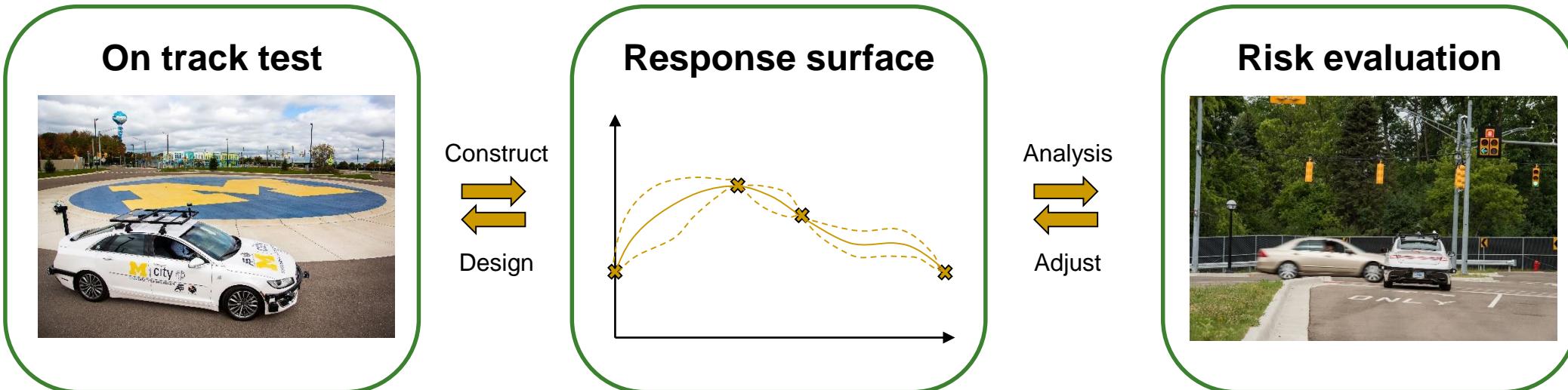


[Versatility] Accelerated Evaluation using Joint Distribution

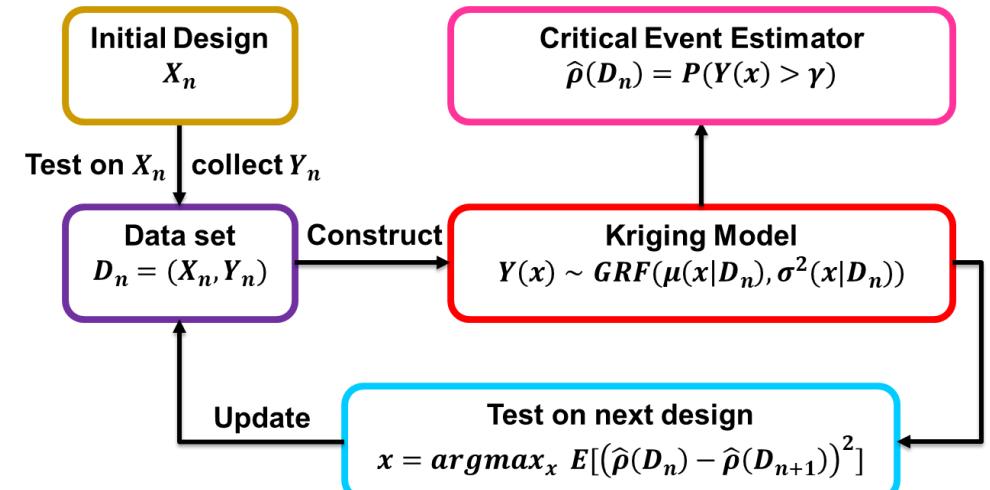
- Motivation
 - Capture the dependency between variables
 - A robust approach to all types of distribution
- Challenges: Construct accelerated distribution



[Efficiency] Kriging-based 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



Platforms

On-track tests



Augmented Reality



Virtual reality

