5th Annual RCCADS Workshop

AI-Guided Integrative Vehicle Safety through Pre-crash and Crash Simulations

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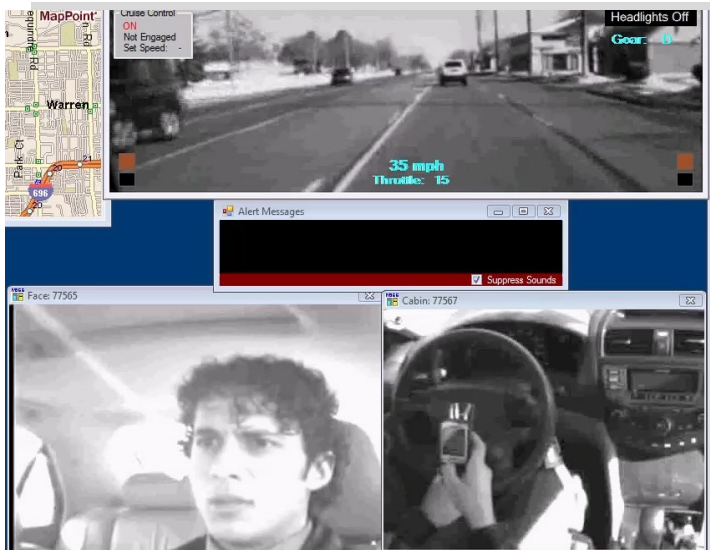
Background

Active Safety | t_0 | Passive Safety

Normal Driving | **Pre-Crash** | **Crash**

- Driving
- Talking
- Singing
- Eating
- Calling
- Texting?
- Gaming?
- Sleeping?



>> 3 s

~ 3 s

100 ~ 150 ms

Time

Danger

Crash

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Motivation – Why Integrated Safety?

- **Problem #1:** About 90% of crashes involve human error, yet most crash tests and models ignore pre-crash behavior.
- **Problem #2:** Current pre-crash safety algorithms focus on crash avoidance, but do not consider potential injury outcomes if a crash is inevitable.

- **Research Gap:** Traditional approaches treat **pre-crash** and **crash** as separate silos

- **Research Need:** Holistic decision making considering both pre-crash and crash conditions and outcomes simultaneously.

The Approach

Naturalistic Driving Data

Pre-crash Simulations:
- Sensing signals (camera, radar, lidar, etc.)
- Vehicle kinematics (speed, direction, etc.)
- ADAS/ADS algorithms and controls
- Impact scenarios (DeltaV, PDOF, etc.)

Injury Outcomes
- Head
- Chest
- Lower extremities
- etc.

AI

Create **surrogate models**
Generate **rare-edge-cases**
Optimize **system parameters**

Crash condition

Occupant condition

Design Tuning
- ADAS/ADS
- Seat belt
- Airbag
- etc.

Crash Simulations:
- Occupant stature, weight, age, sex, etc.
- Occupant posture and movement
- Vehicle safety designs (belt, airbag, etc.)
- Occupant injury outcome

Crash/Injury Data

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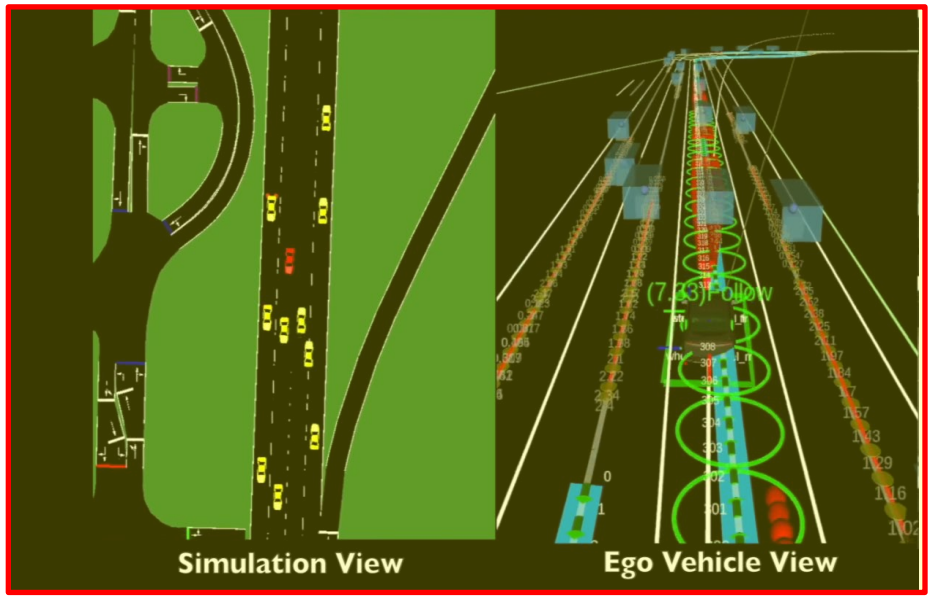
Pre-Crash Simulation Examples



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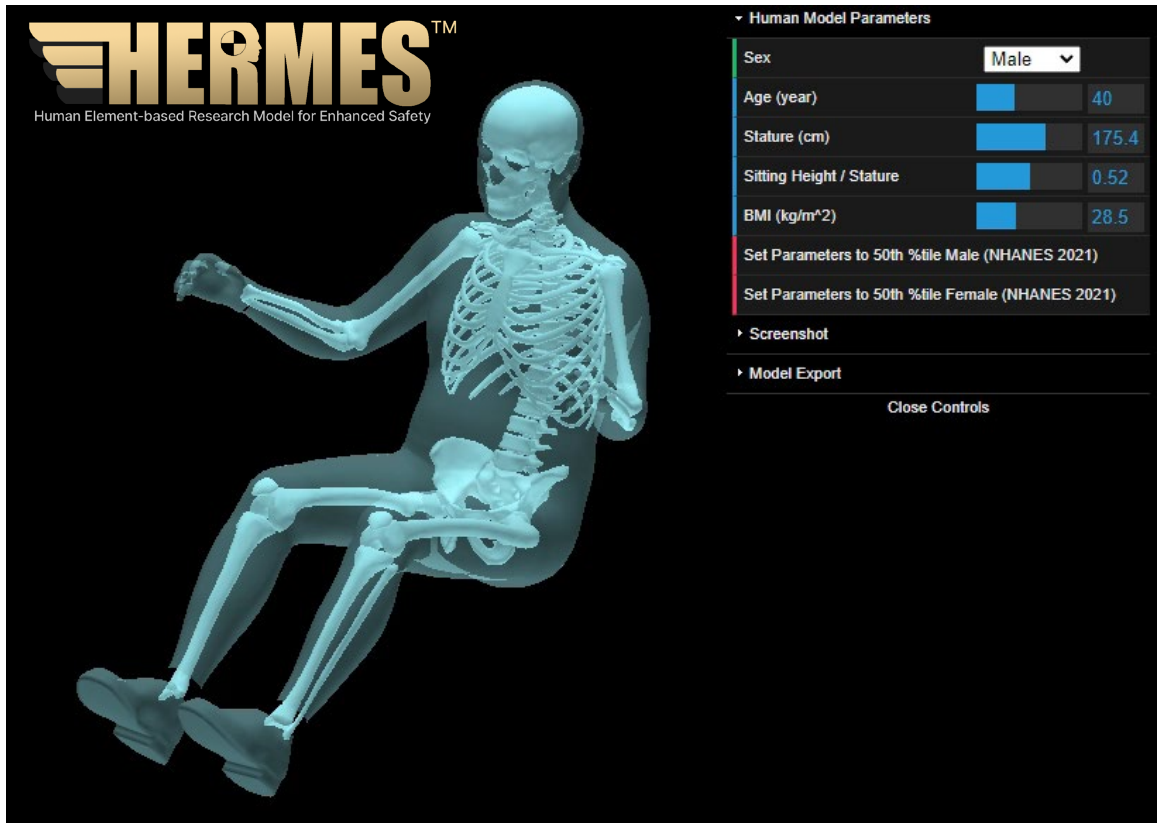
Parametric Human Body Models

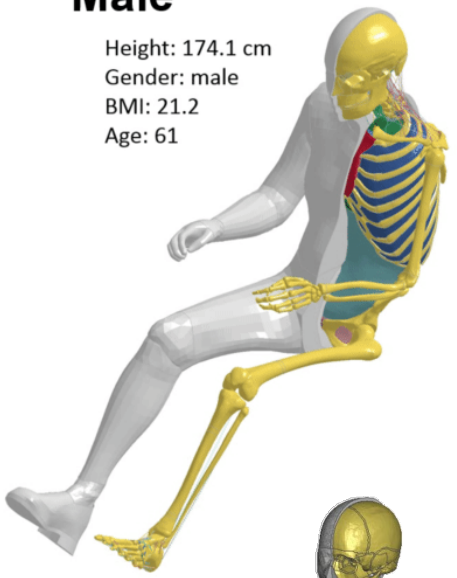


Mesh Morphing

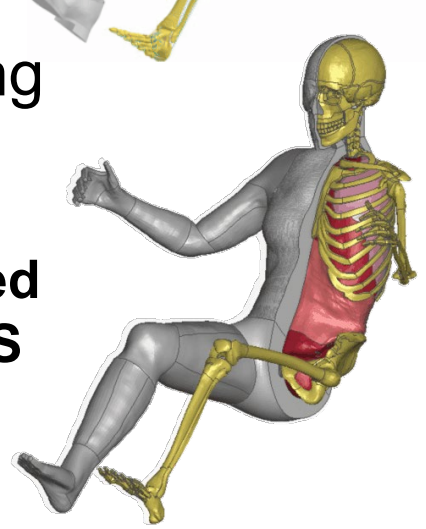
Female

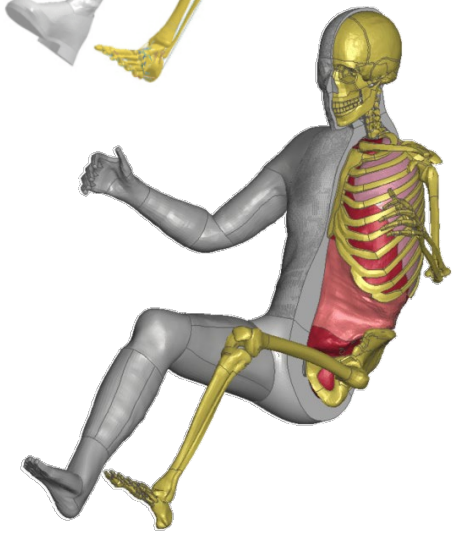
Male

Morphed GHBMC



Morphed THUMS





http://humanshape.org/HERMES/MDP_web_public/#home

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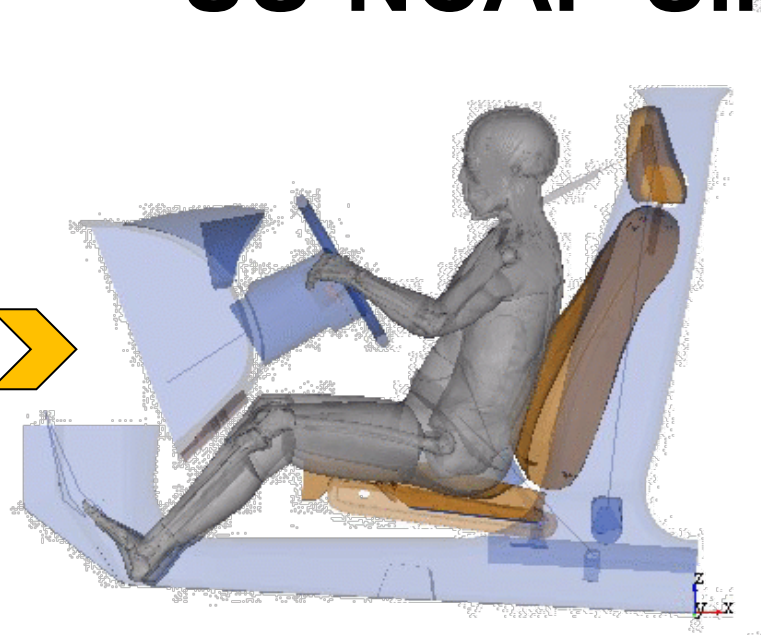
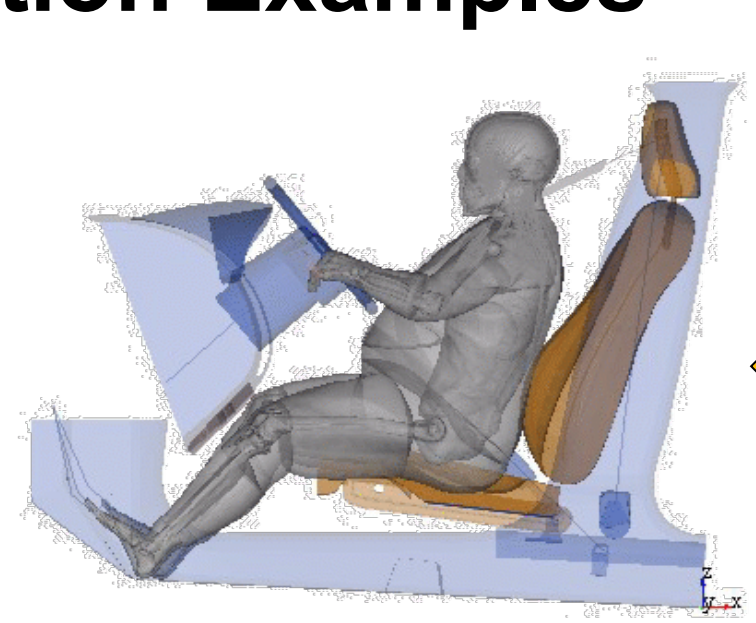
US-NCAP Simulation Examples

Mid-Stature Lean Female

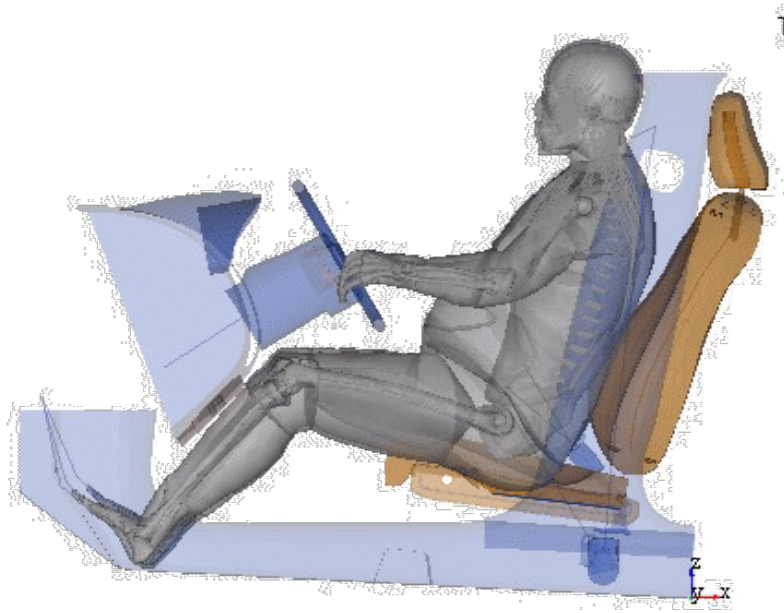


Short Obese Female



Midsize Male

Tall Obese Male



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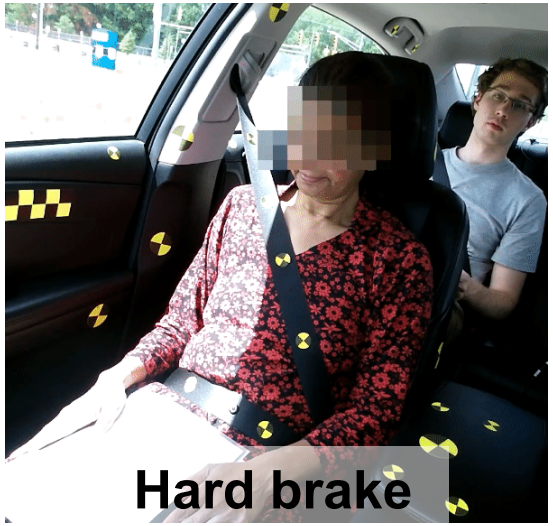
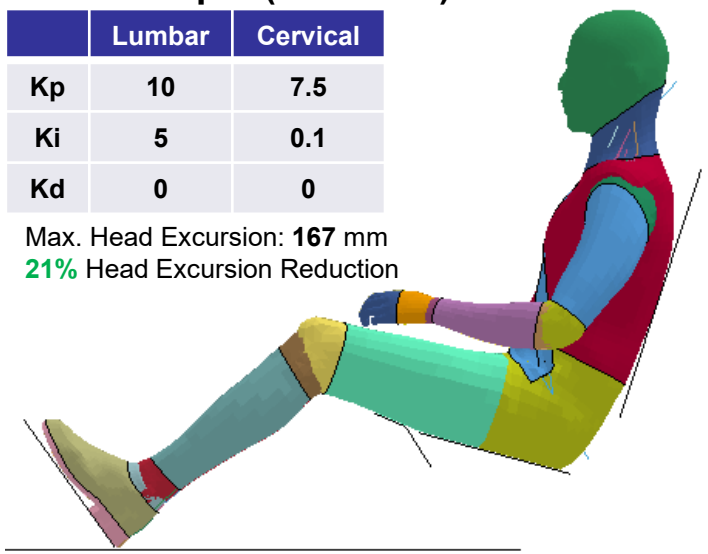
Active Human Body Model



GHBMCsi-pre (Active 5x)

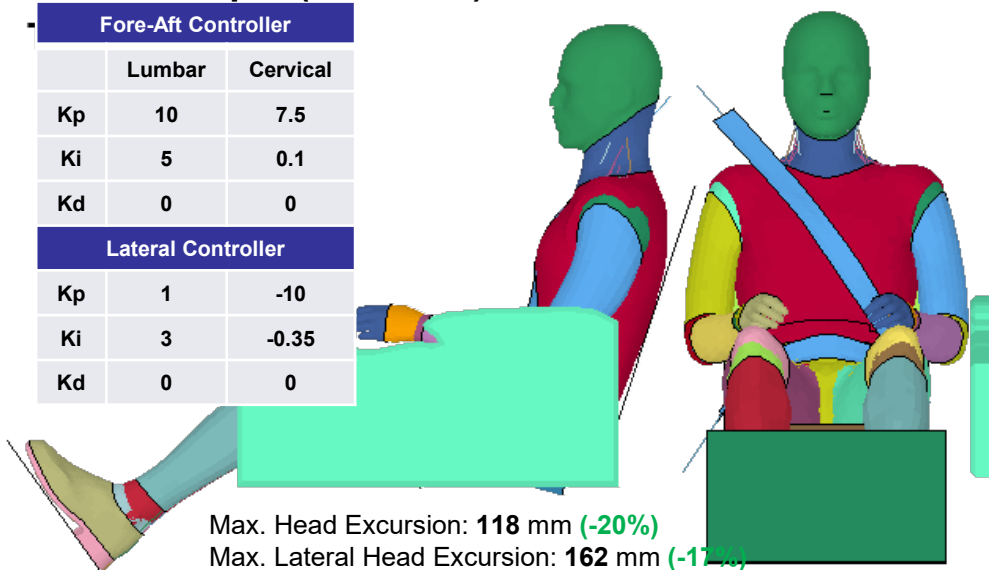
	Lumbar	Cervical
Kp	10	7.5
Ki	5	0.1
Kd	0	0

Max. Head Excursion: **167** mm
21% Head Excursion Reduction

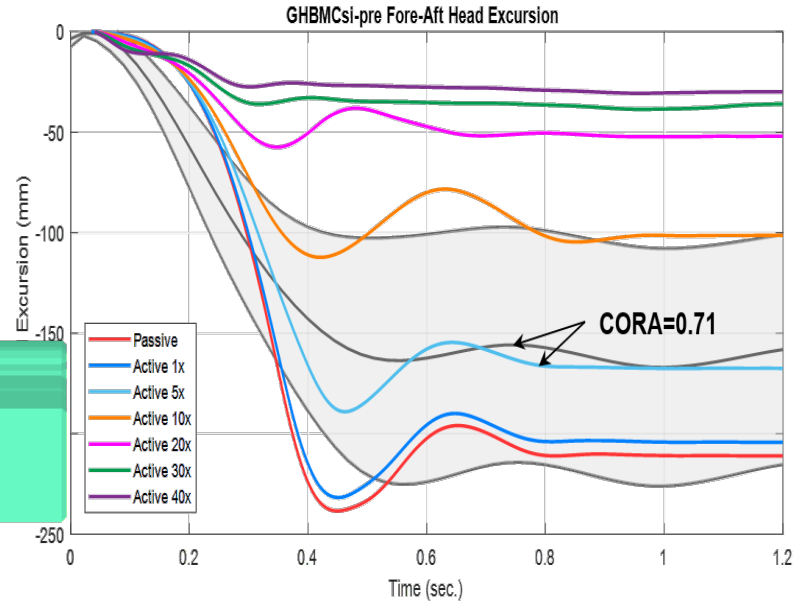


GHBMCsi-pre (Active 5x)

Fore-Aft Controller		
	Lumbar	Cervical
Kp	10	7.5
Ki	5	0.1
Kd	0	0
Lateral Controller		
Kp	1	-10
Ki	3	-0.35
Kd	0	0



Max. Head Excursion: **118** mm **(-20%)**
Max. Lateral Head Excursion: **162** mm **(-17%)**



What Affects Crash Outcomes?

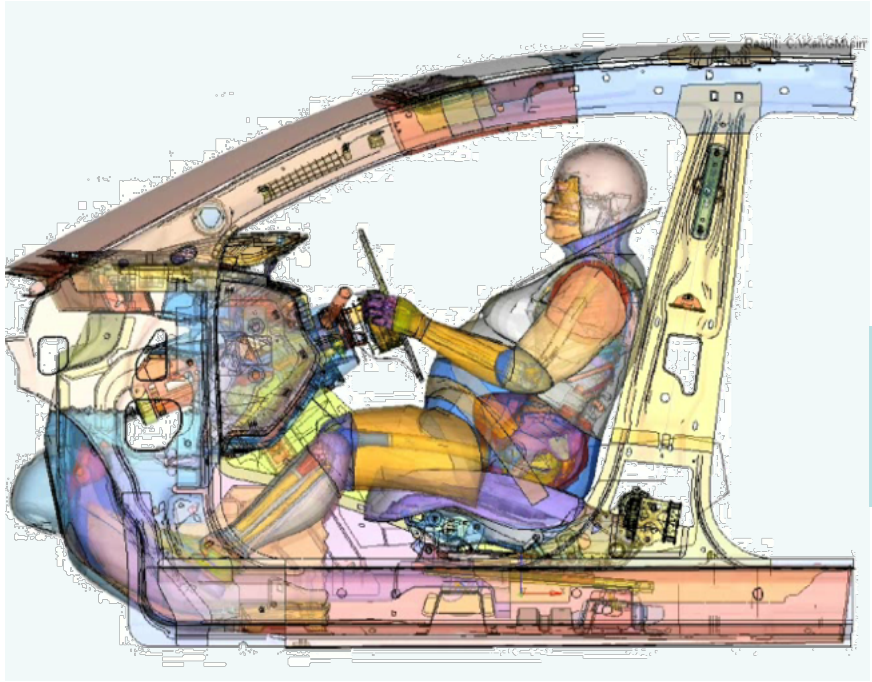
Occupant Factors

Vehicle Factors

Occupant Characteristics
Sex, BMI, body shape, bone strength, …

Restraint Parameters
Pre-tensioning, load limit, inflation pressure…

Posture
Torso recline & flexion, LX position, rotation, …



Restraint Geometry
Belt anchorage & knee bolster locations, airbag size & shape…

Seat Position
Fore-aft/vertical/cushion angle

Vehicle Interior Geometry
Steering wheel & dash locations, pillars, header, …

Belt Fit
Shoulder & lap

Crash Pulse
Direction, magnitude, phases

Pre-Crash Maneuver
AEB, FCW, lane change, …

Crash Factors

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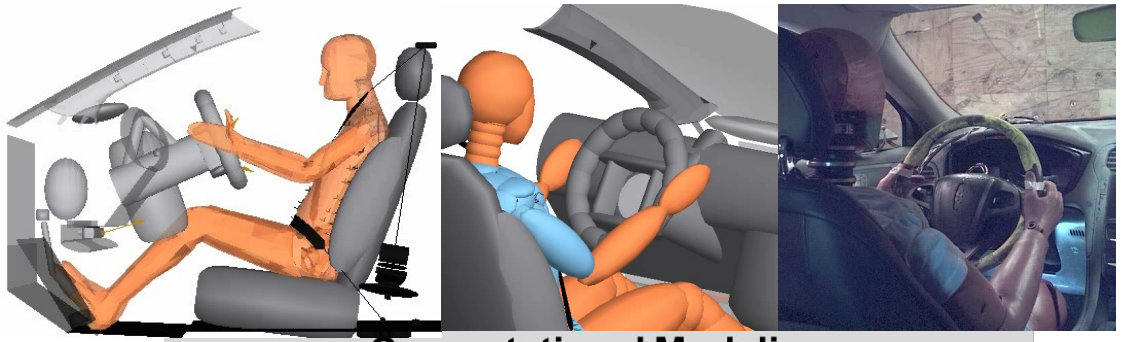
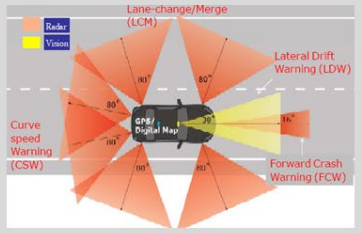
Early Work: Field Capability



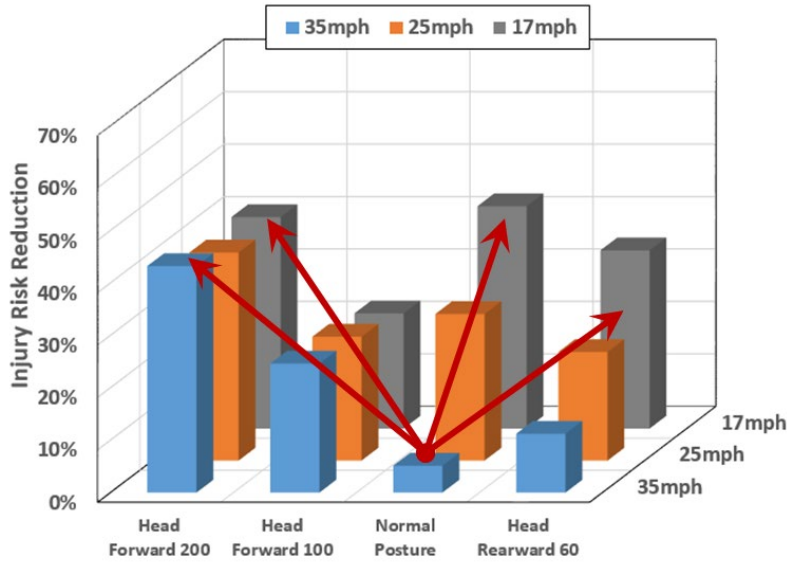
Computational Modeling

Field Data Analysis

Integration of Active and Passive Safety



Naturalistic Driving Data Analysis



Head location	Injury Risk Reduction	
	ATD Model	Human Model
Head forward	43%	58%
Head neutral	14%	47%
Head rearward	13%	44%
Weighted average	**17%**	**48%**

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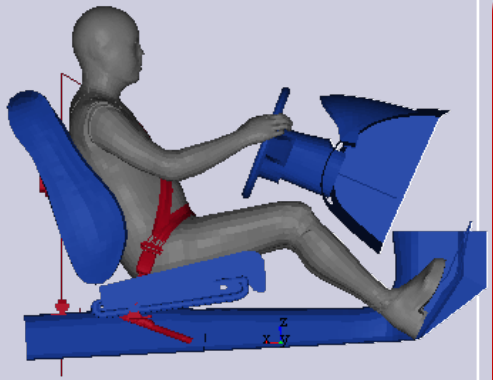
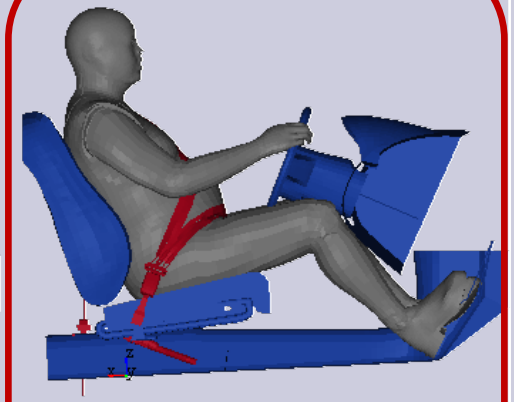
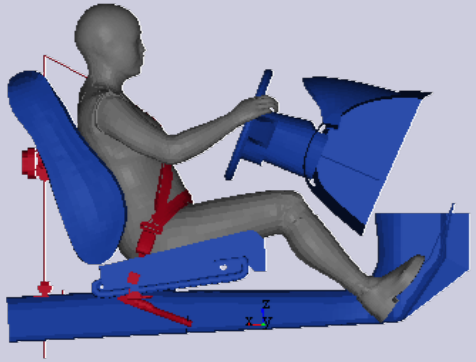
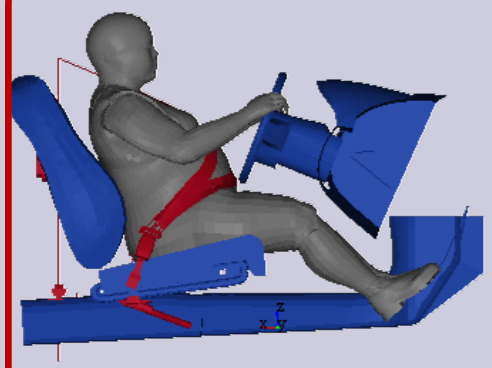
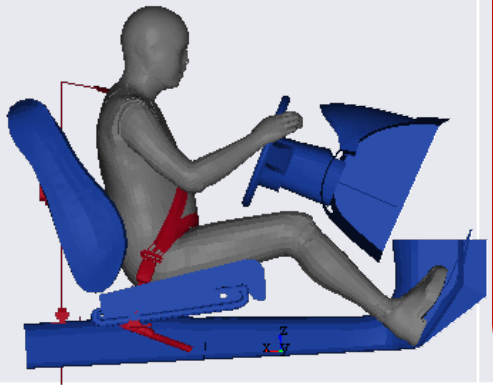
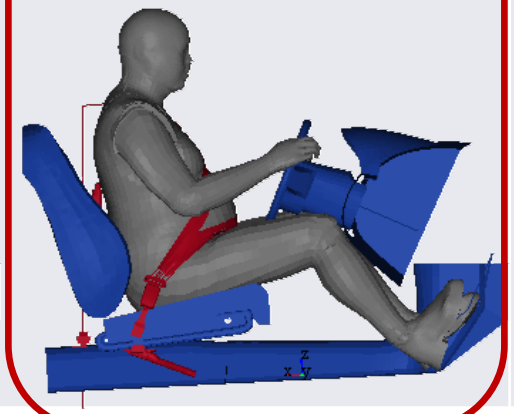
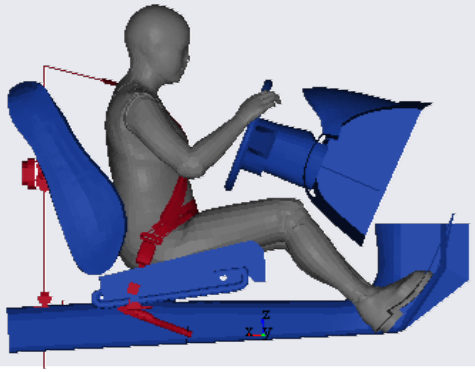
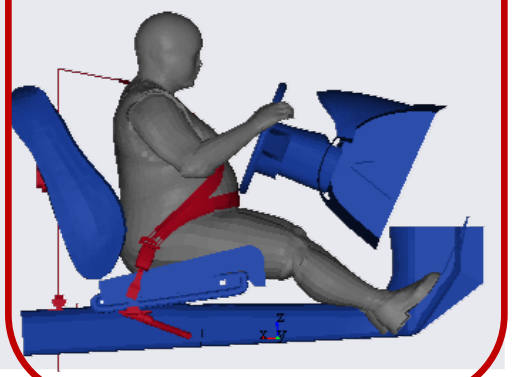
Hu et al. 2015 Stapp

Pre-Crash Posture and Occupant Size Effects

	Midsize Male	Large Obese Male	Midsize Female	Short Obese Female
Normal posture				
Pre-crash braking induced posture				

Head to IP contact

LX concerns

Boyle et al. 2020 TIP

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Design Optimizations Addressing Different Needs

$$a^* = \arg\min_{a \in \mathcal{A}} \mathbb{E}_s \left[f\left(s, a(s)\right) \right]$$

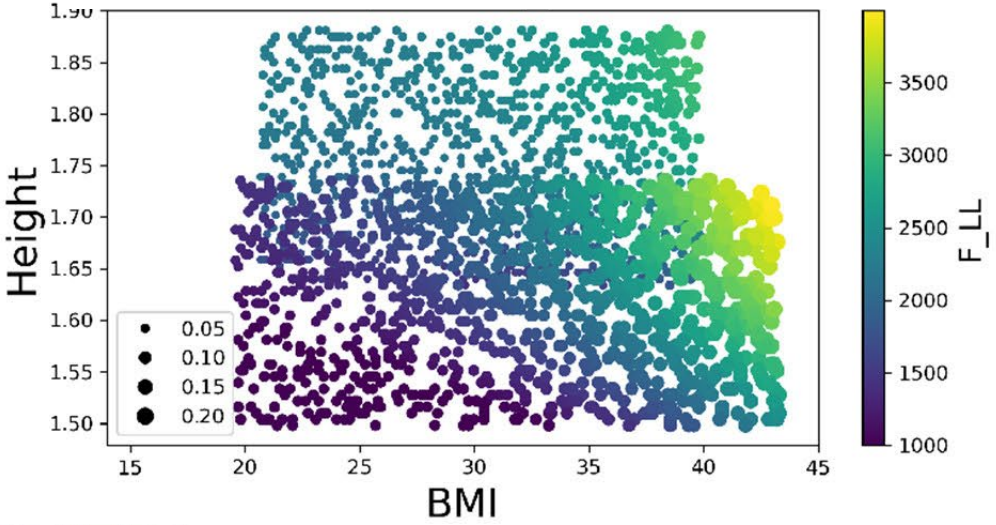
$$= \arg\min_{a \in \mathcal{A}} \int_{s \in \mathcal{S}} f\left(s, a(s)\right) p\left(s\right) ds,$$

$d = a(s)$ Design policy

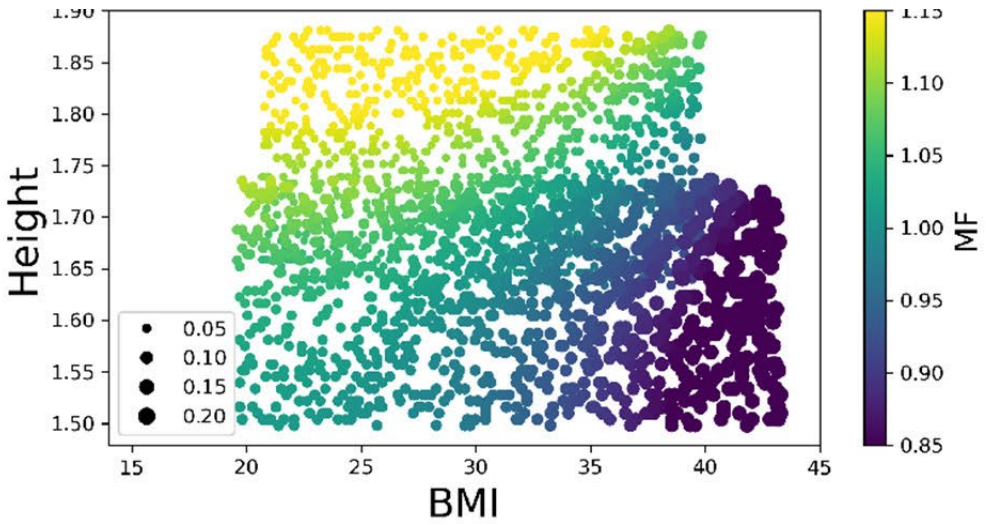
s: Occupant and crash covariates

$p(S)$: Occupant weighting function

Optimal belt load limit (F_LL)



Optimal airbag mass flow (MF)



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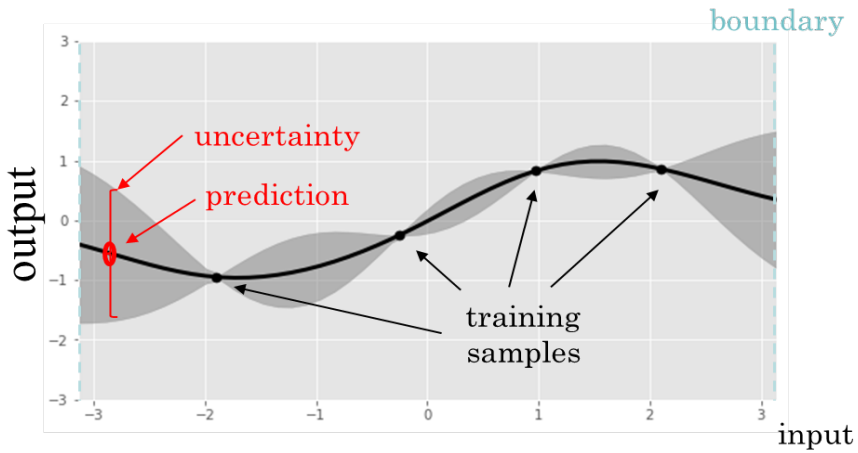
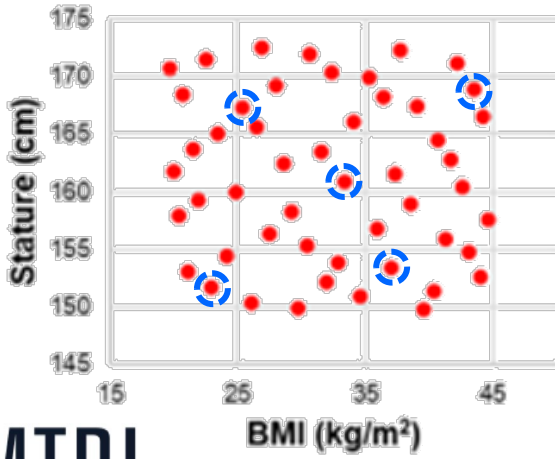
Sun et al. 2023 Frontiers

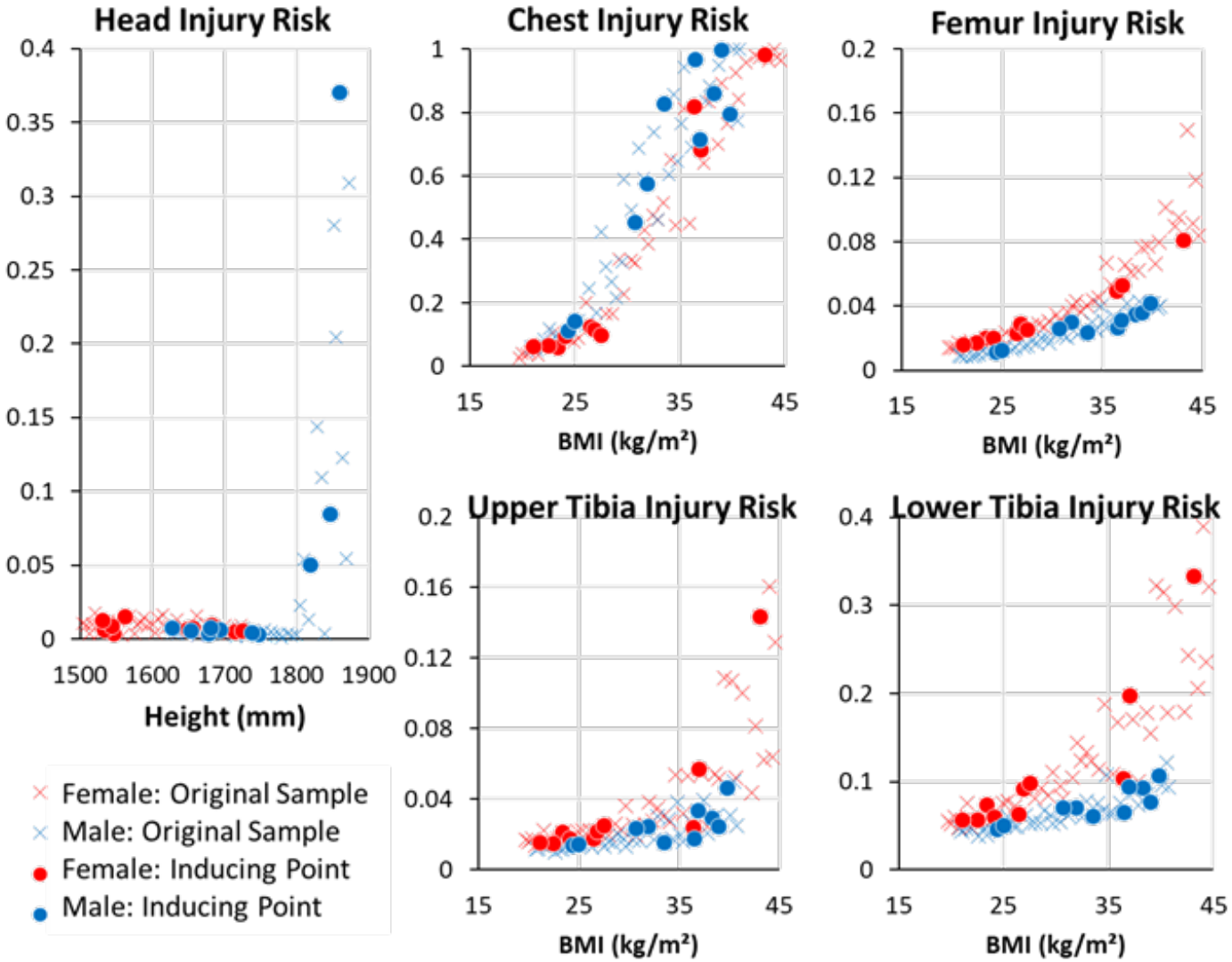
Gaussian Process (GP) Model & Inducing Points

Inducing points: representative subjects that accounts for population variation



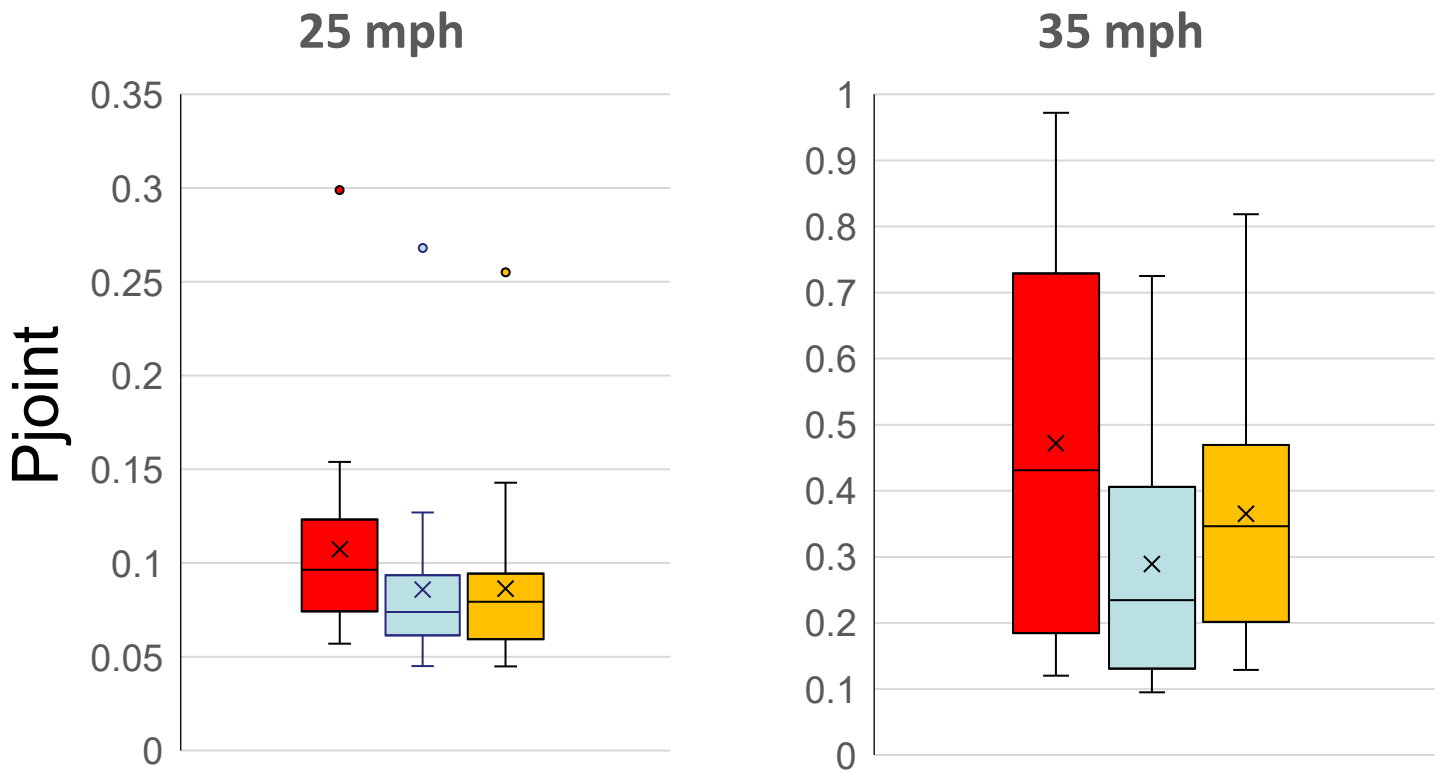
Gaussian Process Surrogate Model





Sun et al. 2024 AAAM

Adaptive Design Optimization Results



Injury Risk Mitigation (Pjoint)

	25 mph	35 mph
Male	-17%	-13%
Female	-47%	-27%

The adaptive designs are associated with lower means and standard deviations of injury risks compared to the baseline design.

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Sun et al. 2024 AAAM

Pedestrian Pre-Crash Simulation Example #1

Test Setting: Walking Pedestrian

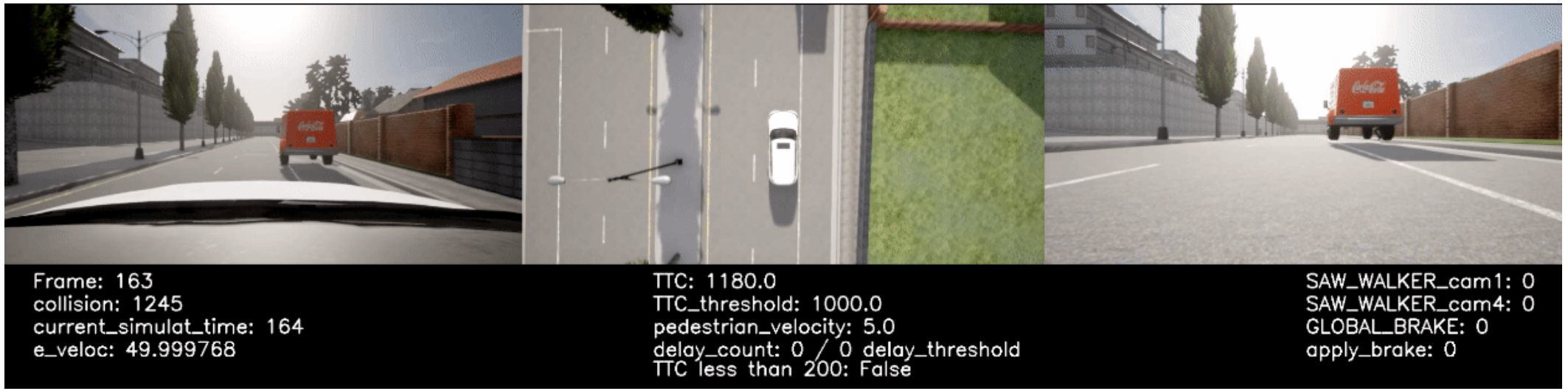
AEB Setting: TTC threshold: 1000 ms; AEB braking g-force: 0.5; Pedestrian Speed: 5km/h.

Vehicle stats: SUV, initial speed: 50 km/h; *hitting speed: 39.97 km/h*.

Subject info: Female, 1.65m, Age 30, BMI 22.

Injury Risks [head, chest, femur, tibia] (%): [11.01, 38.50, 79.77, 27.45]

Pjoint: 91.97%



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Pedestrian Pre-Crash Simulation Example #2

Test Setting: Walking Pedestrian

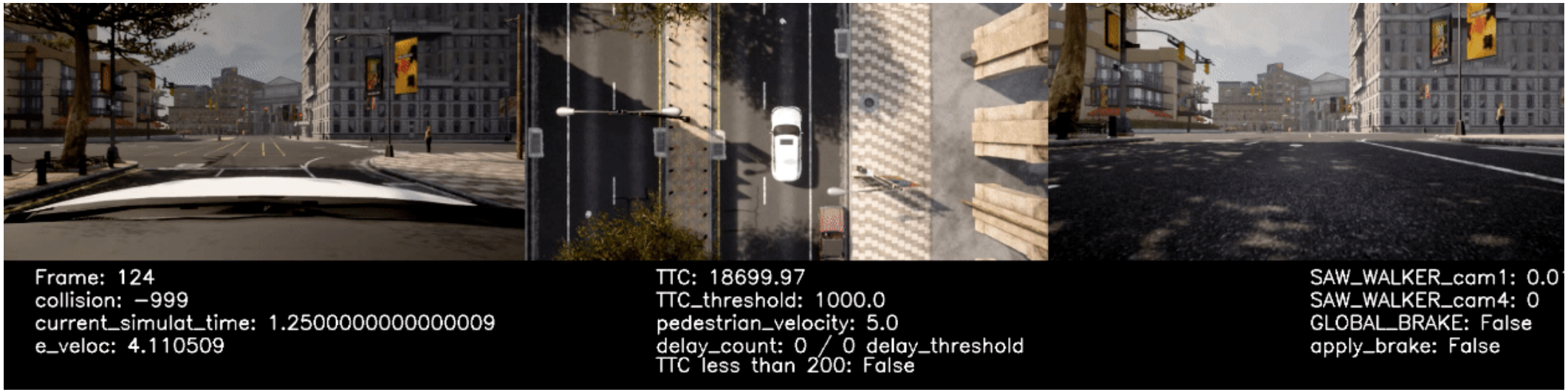
AEB Setting: TTC threshold: 1000 ms; AEB braking g-force: 0.3; Pedestrian Speed: 5km/h.

Vehicle stats: SUV, initial speed: 40 km/h; *hitting speed: 26.17 km/h.*

Subject info: Female, 1.65m, Age 30, BMI 22.

Injury Risks [head, chest, femur, tibia] (%): [0.01, 17.54, 1.05, 11.96]

Pjoint: 27.78%



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Integrative Pedestrian Safety Device Triggering Algorithm

Sensing uncertainty of vehicle speed

Sensing uncertainty of pedestrian speed

Injury threshold

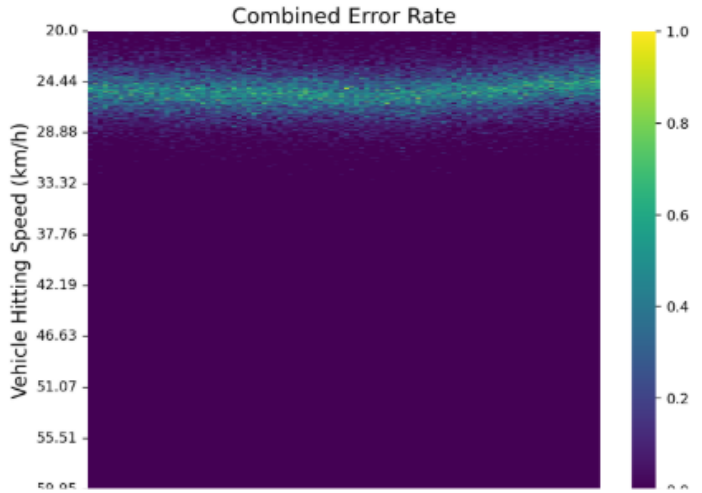
Bootstrap sample size

Setup I

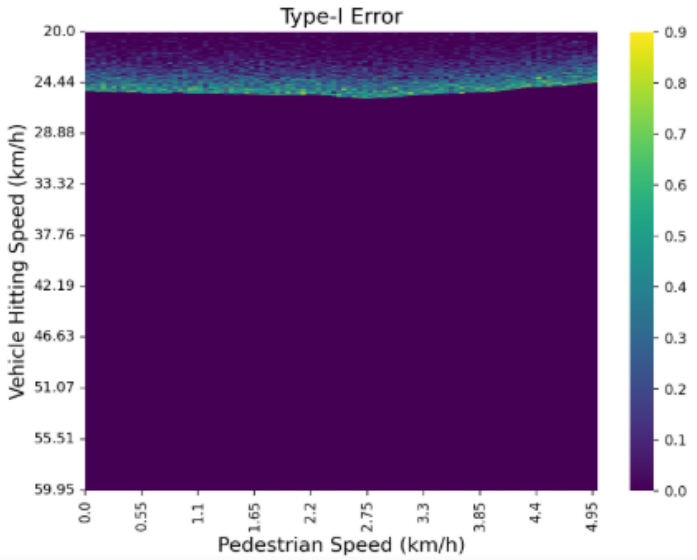
σ_v=1, σ_p=0.1, T=0.1, n=25.

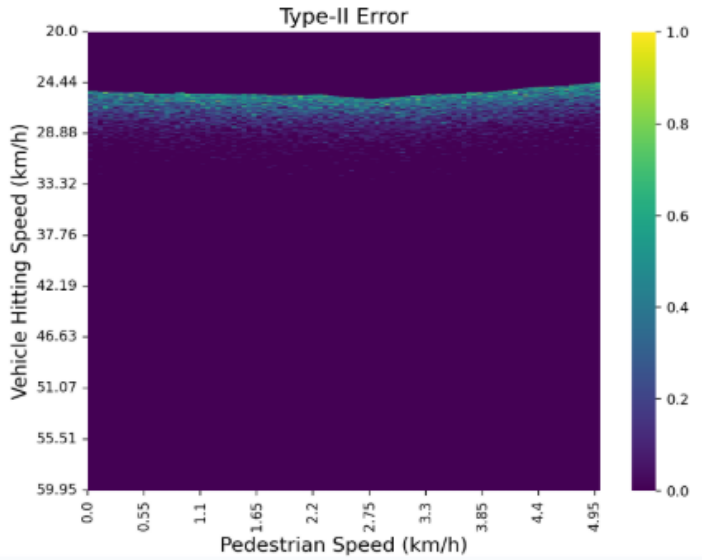
Range: v_vehicle: 20 - 60 km/h

Note: not much errors when v_vehicle is large.



Correct integrative safety decisions





Trigger the airbag for minor crashes

Fail to trigger the airbag for severe crashes

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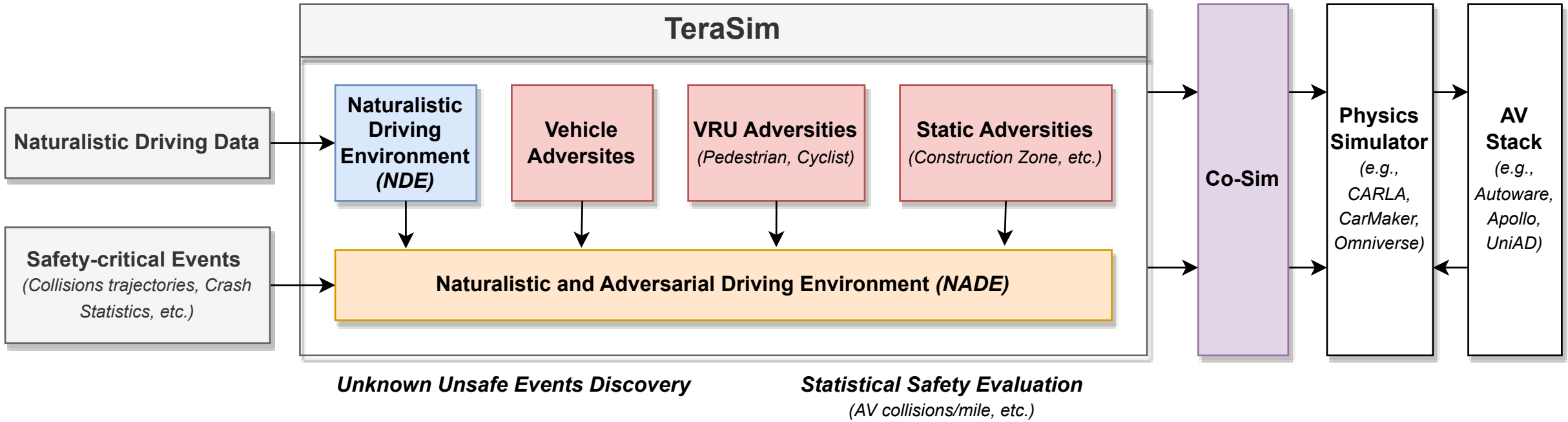
TeraSim Architecture



TeraSim is a traffic environment simulator that provides:

- **NDE:** Interactive naturalistic traffic environment learned from real world
- **Adversities:** Diverse stochastic challenging events
- **NADE:** Adversity orchestrator to intelligently challenge the AV
- **Integration:** API for seamless integration with existing simulators

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Courtesy to Henry Liu, UMTRI Director

Challenges

- Improve realism of AI-generated behavior
- Validation against real crash data
- Consider sensing accuracy and robustness

Ultimately, integrated safety is not about a single simulation or a single algorithm, It's about creating a continuous feedback loop that connects how we avoid crashes, how we survive them, and how we learn from every outcome. By combining AI, computational models, and design optimizations, we pave the way for smarter and more adaptive safety designs.

Acknowledgements

Sponsors

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Collaborators

Tsinghua University, Hunan University, Beijing Forestry University, Wayne State University, Chalmers University of Technology, Wake Forest University, University of Virginia

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