# *Active Safety Control in Automotive Cyber-Physical Systems*


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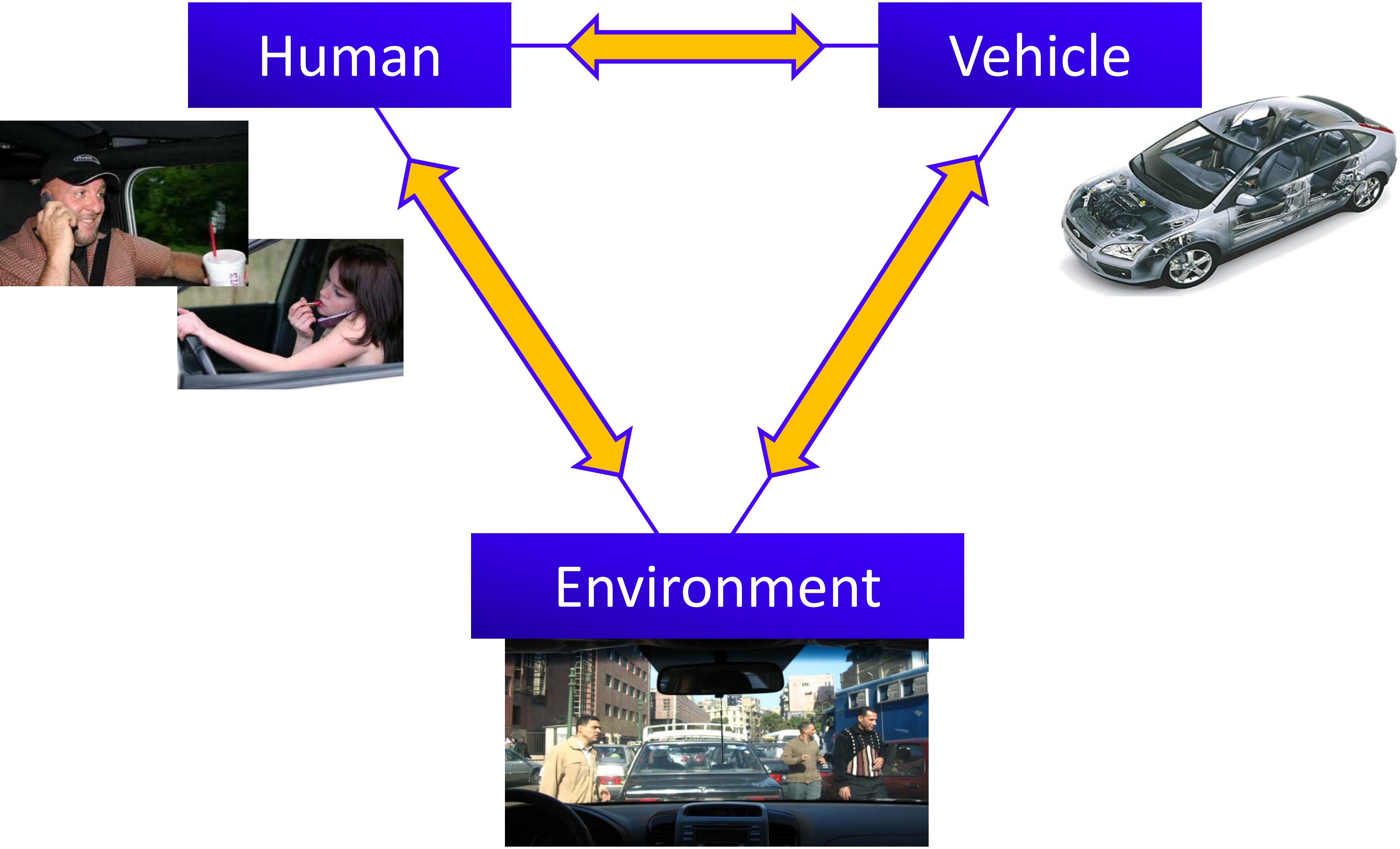
## Karl Hedrick, Ruzena Bajcsy

## Edgar Lobaton, Ed Vul

# Cars Can Be Unsafe
# ~32k killed in 2012
# ~2.5M injured

# Driving Cars: Synoptic Scheme



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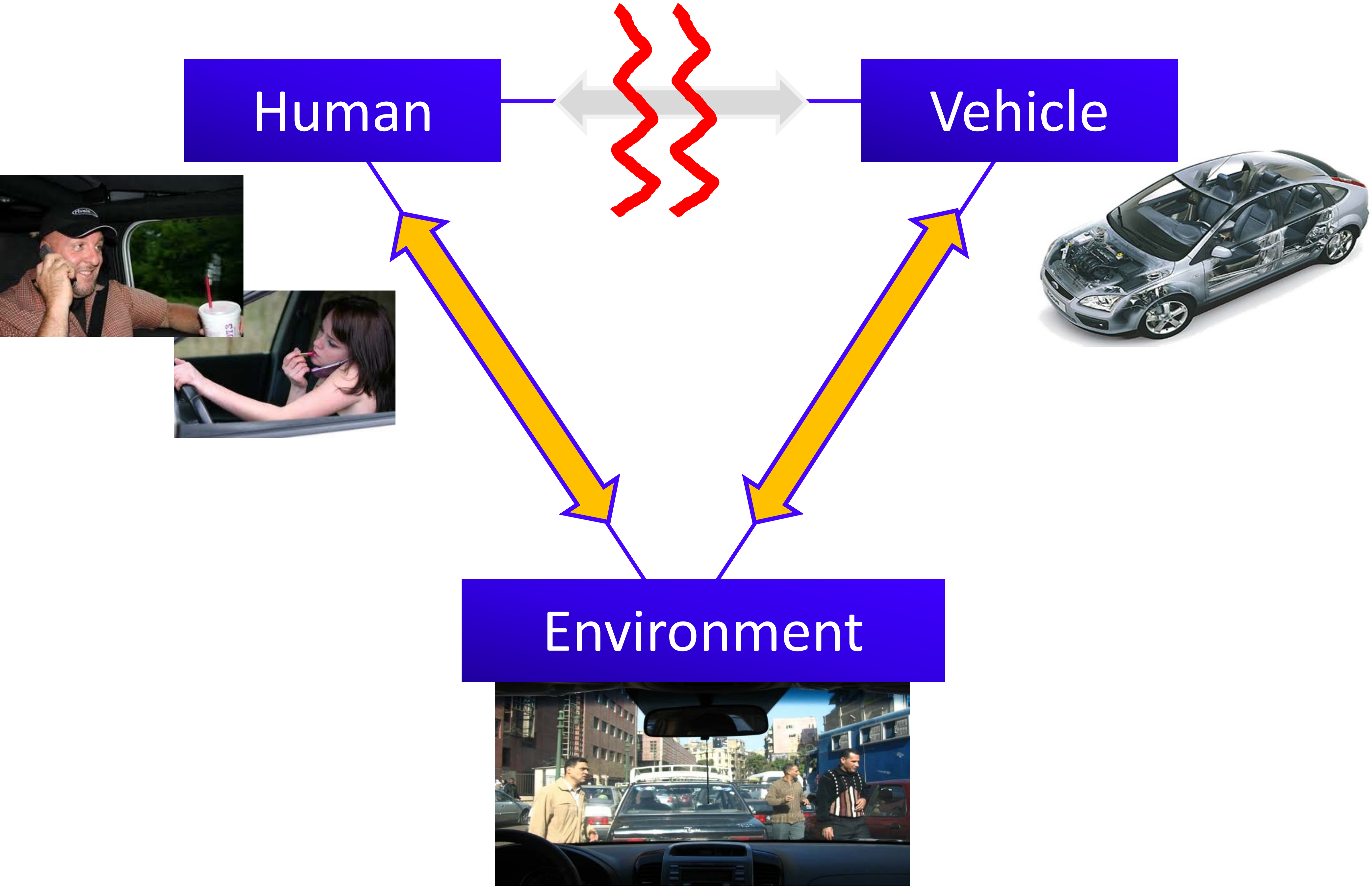
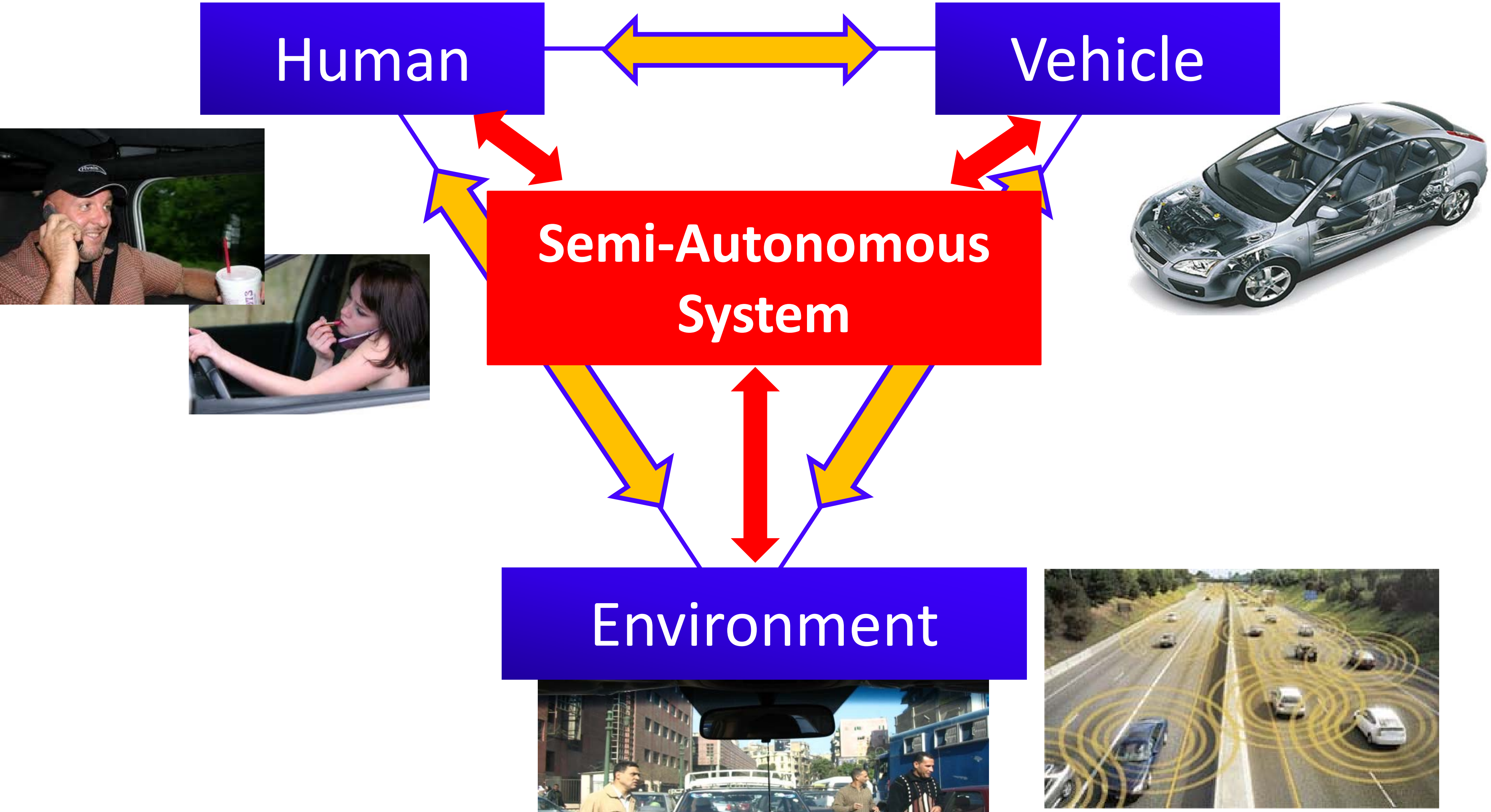



Fresno, CA
CAR ON ROOF
STUDIO B

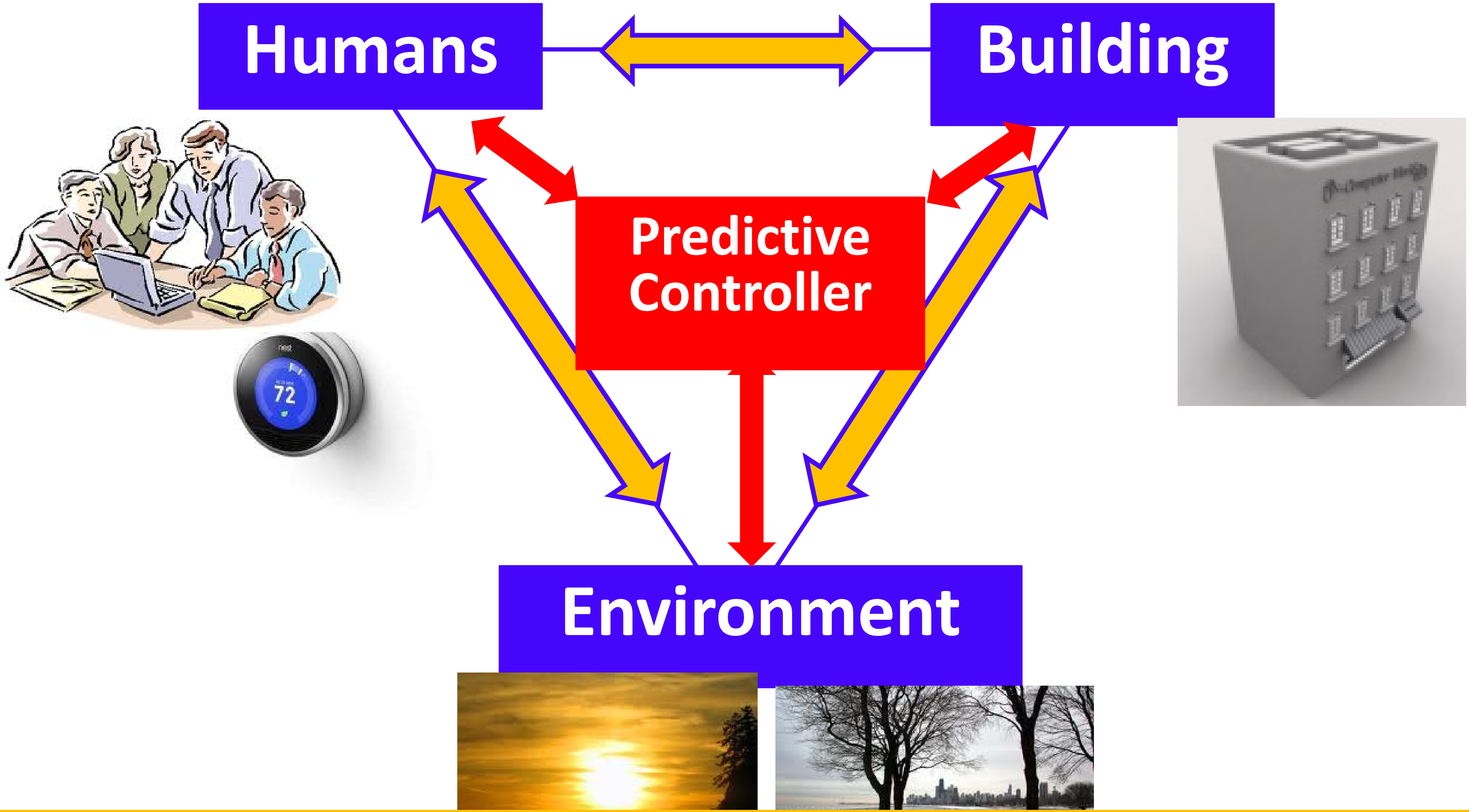
# Can We Make Vehicles Safer?




**Predictions on**

System Dynamics, Friction, Obstacles, Driver Behavior

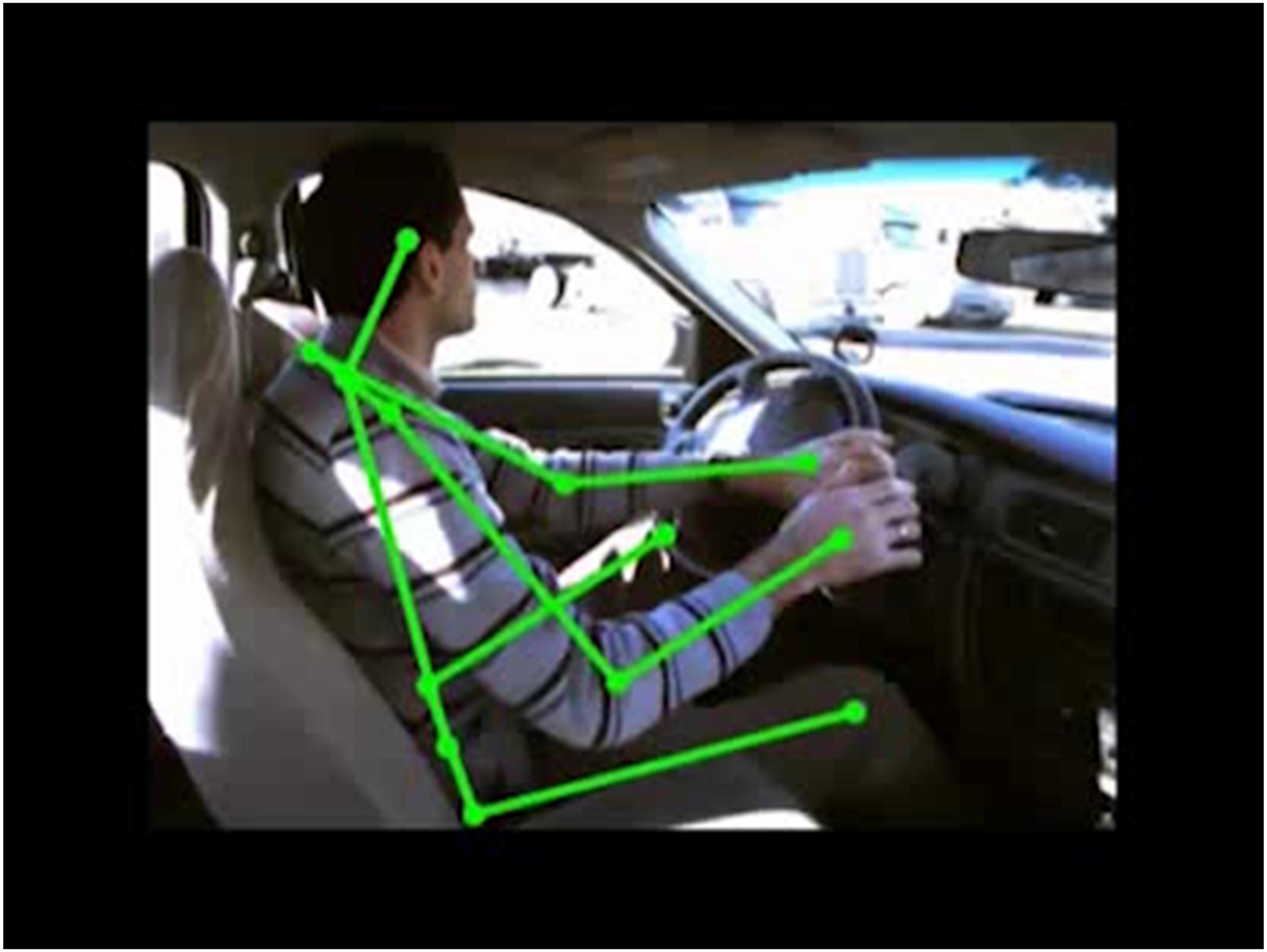
# Can We Make Buildings Greener?



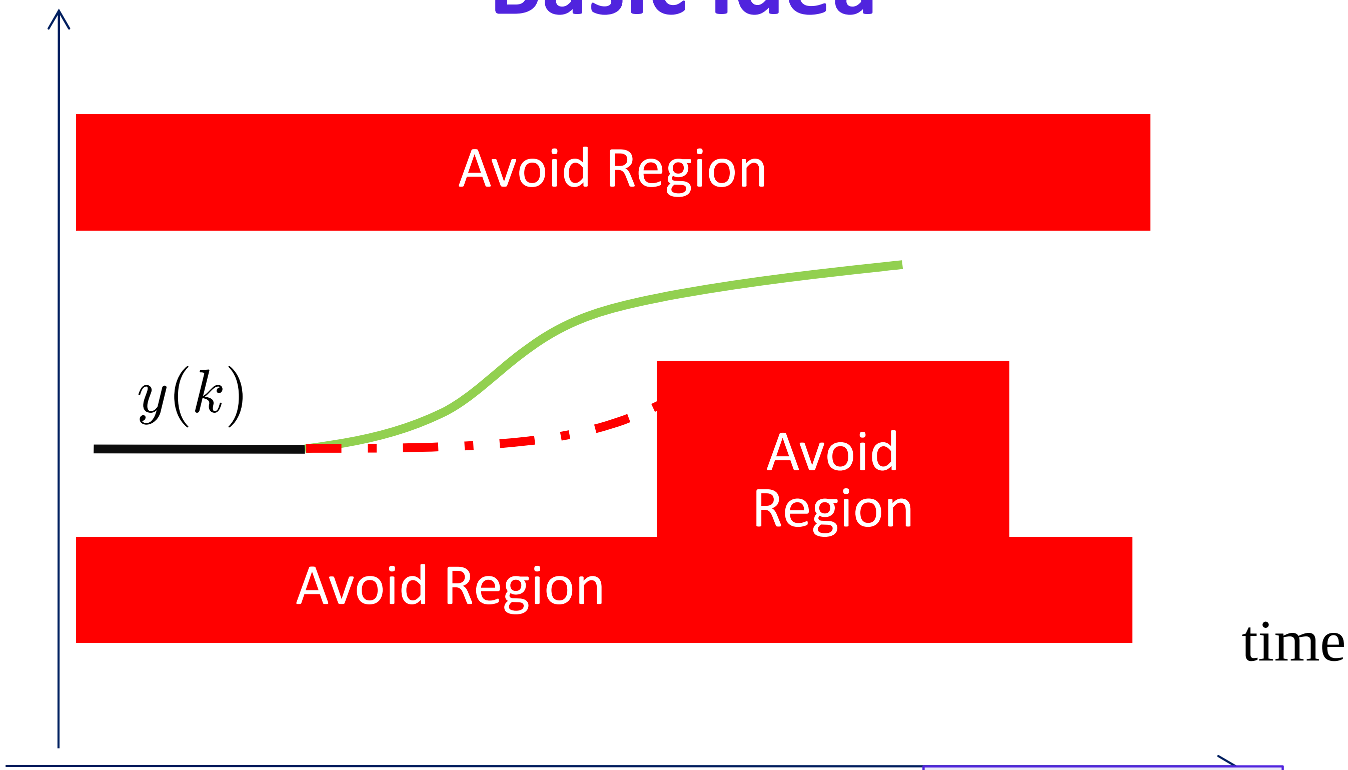

**Predictions on**

Building Dynamics, Weather, Occupancy, Comfort

# Advanced Active Safety System



# Basic Idea




human, environment

control action

constraints

$$y(k+1) = y(k) + b_w w(k) + b_u u(k), \quad y(k) \in \mathcal{Y}(k)$$

At step t decide on ***u(t)*** based on prediction on ***w(t),…, w(t+N)***, $\mathcal{Y}$***(t),…,***$\mathcal{Y}$***(t+N)***

Two Combined Effects : Anticipation and Coordination

# Steps Towards Success

human, environment

control action

constraints

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- "Good" Model Abstraction
- Quantifying Uncertain Predictions

$$w(t+1|t) \in \mathcal{W}(t+1|t), \ldots, w(t+N|t) \in \mathcal{W}(t+N|t)$$

- Safe Control Design and Architecture

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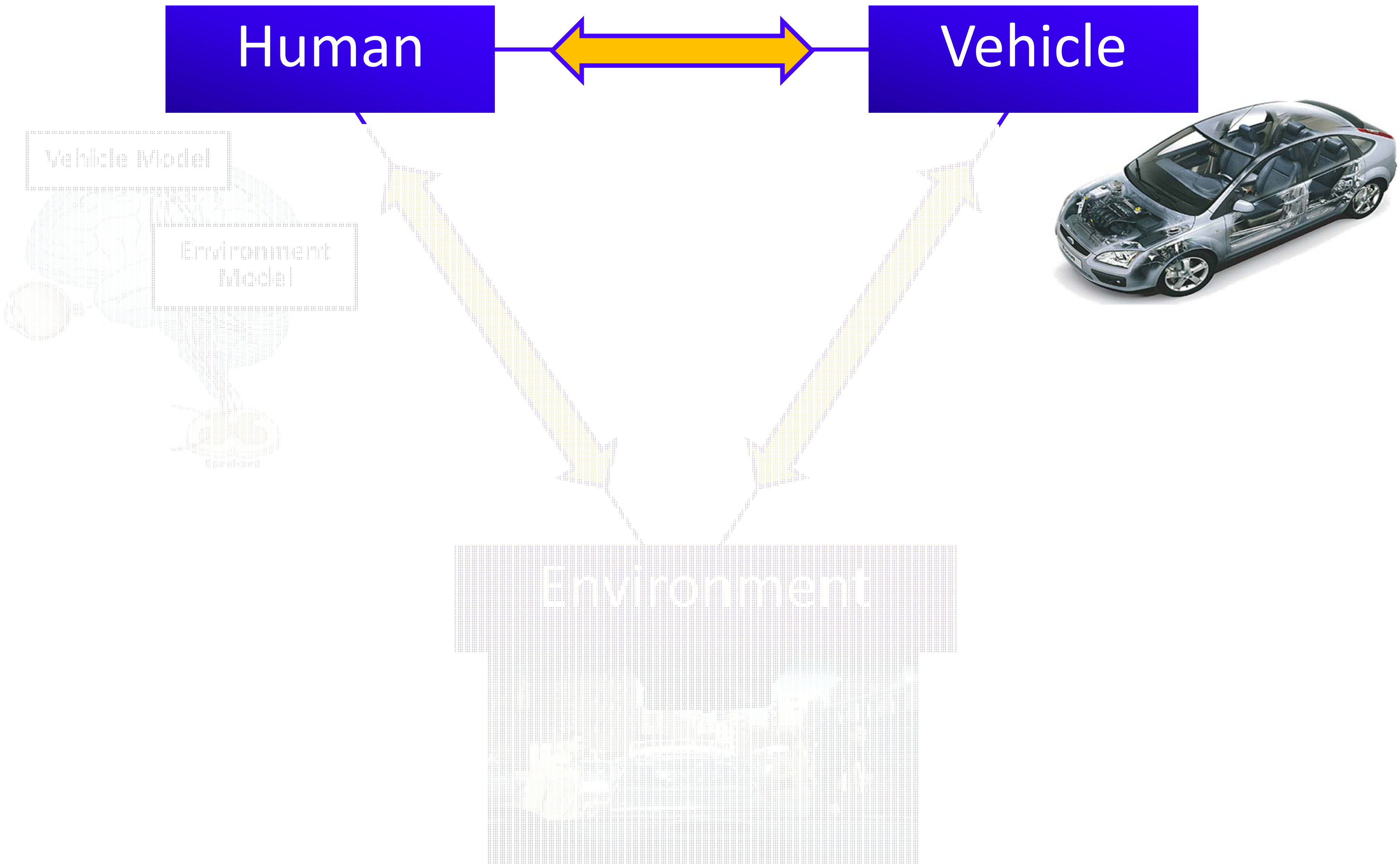
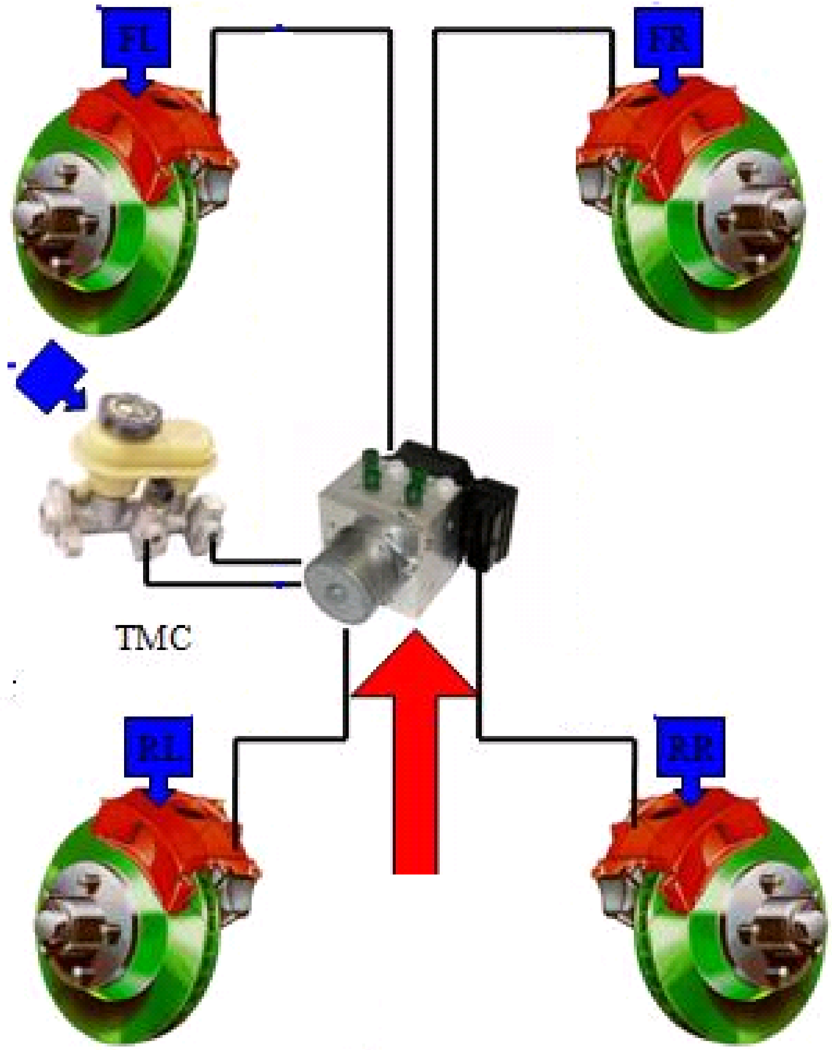


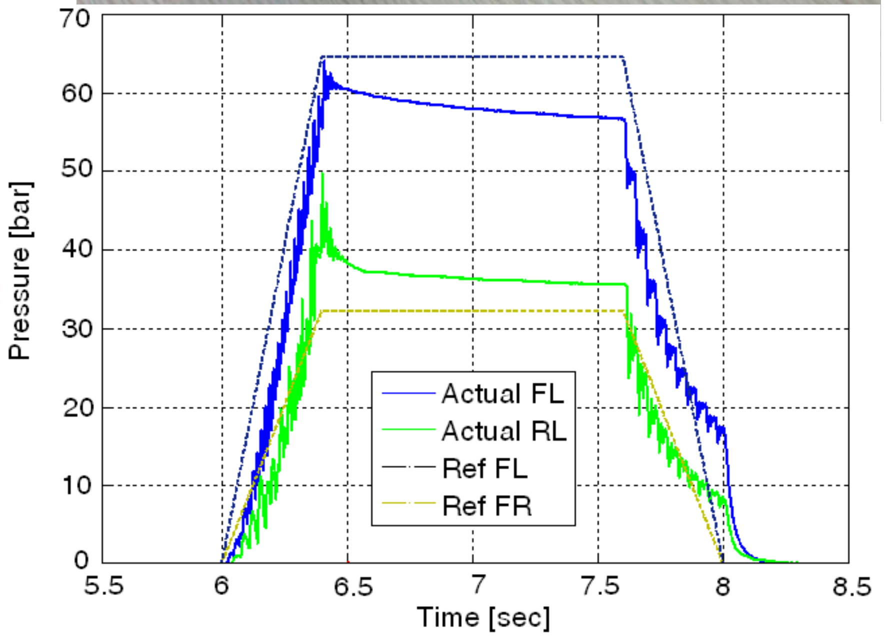
# Human-Vehicle Interface

**Actuation System**

- Steering Angle
- Wheels Traction Torque
- Wheels  Braking Torques
- ........

# Hydraulic Brake Unit

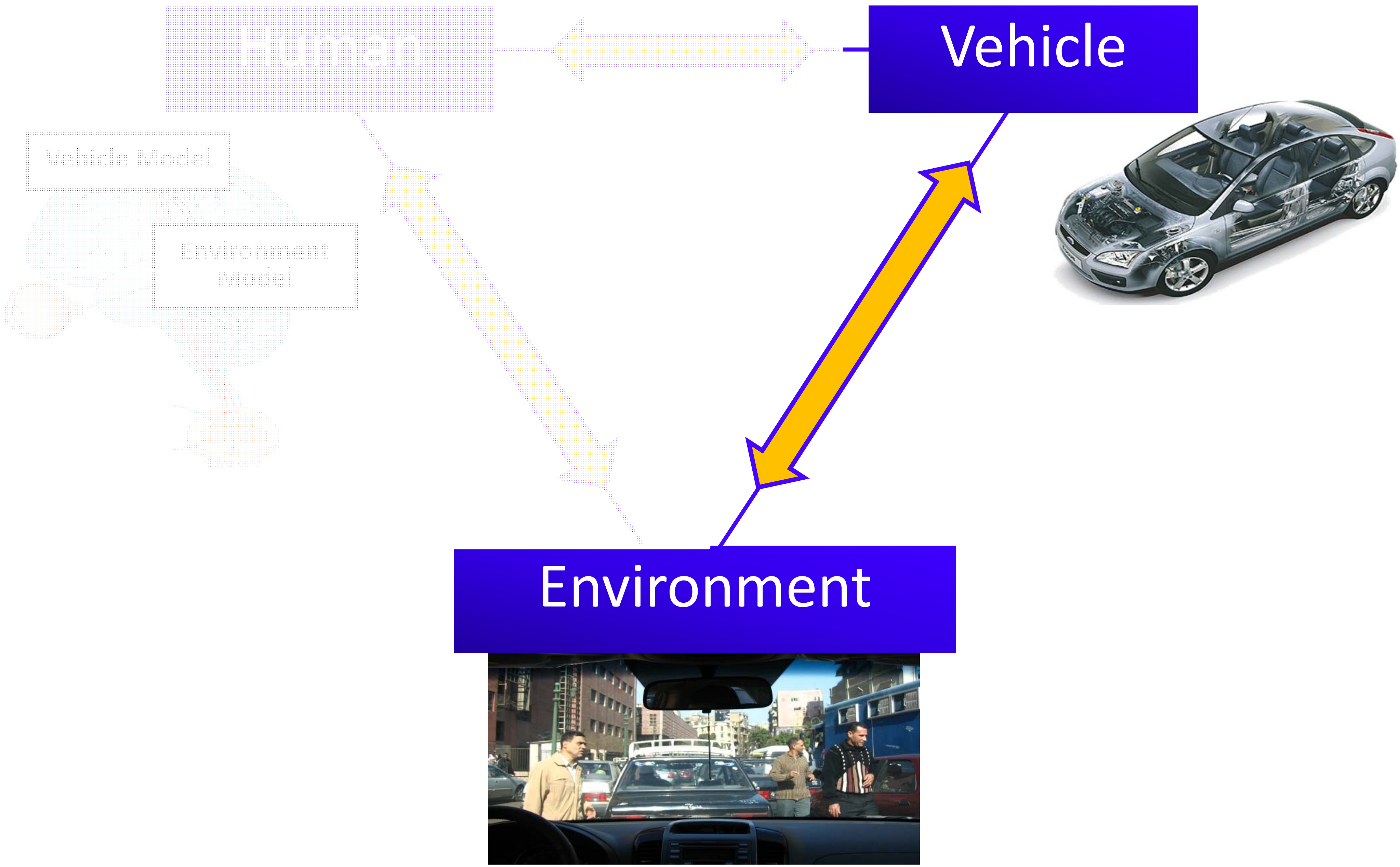


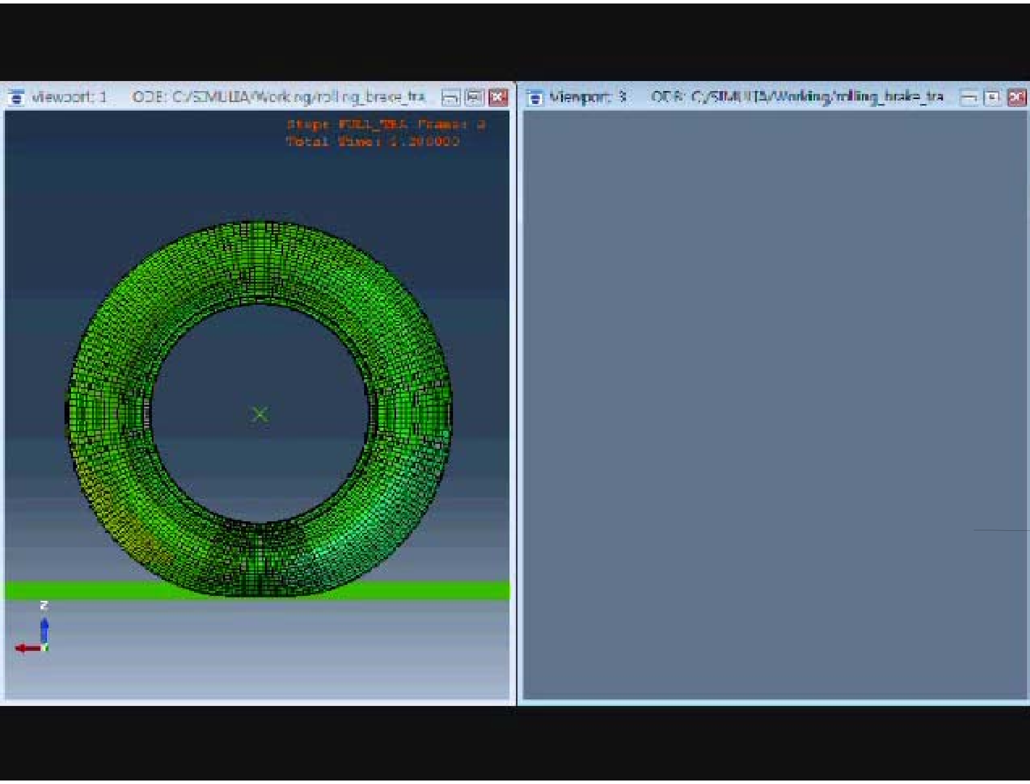

Tests carried by

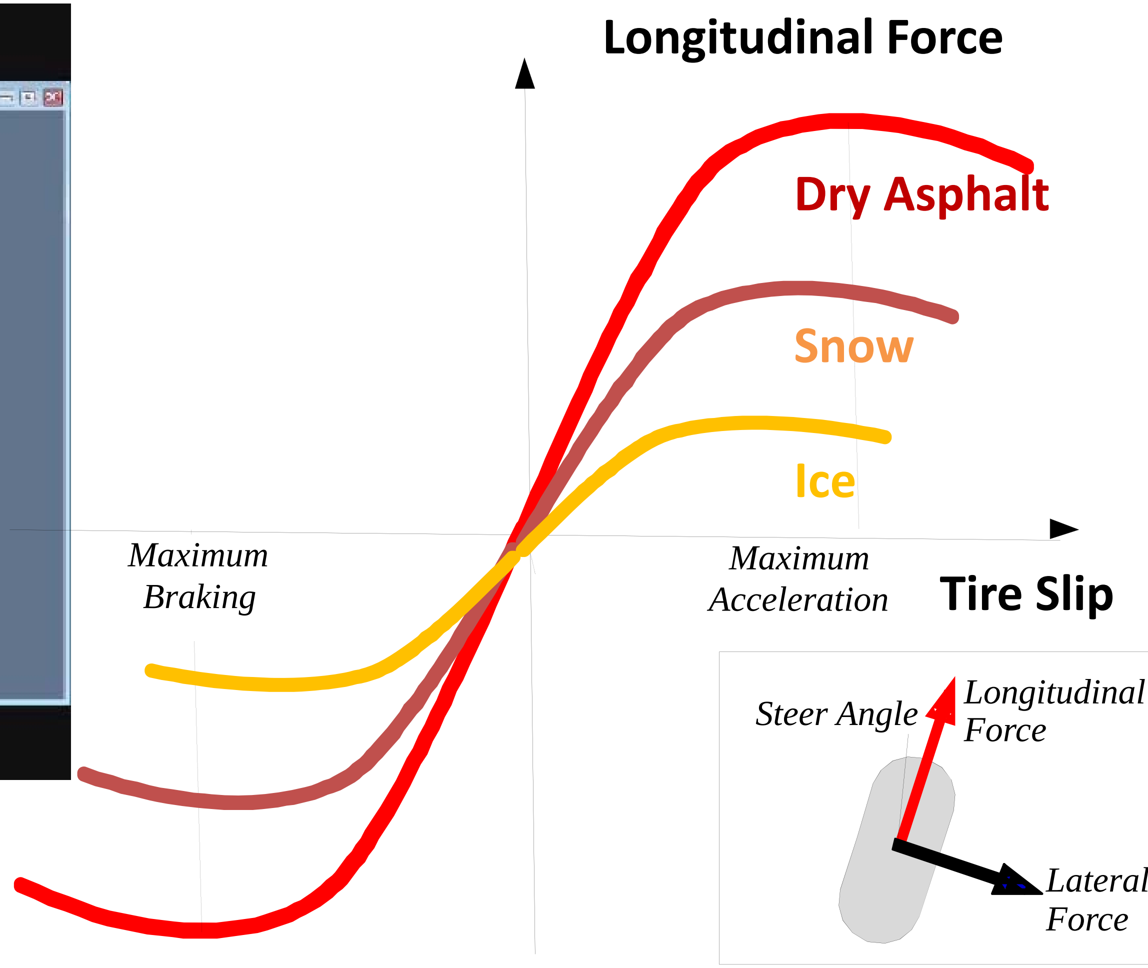
Velardocchia's Lab University of Torino

# Driving Cars: Synoptic Scheme



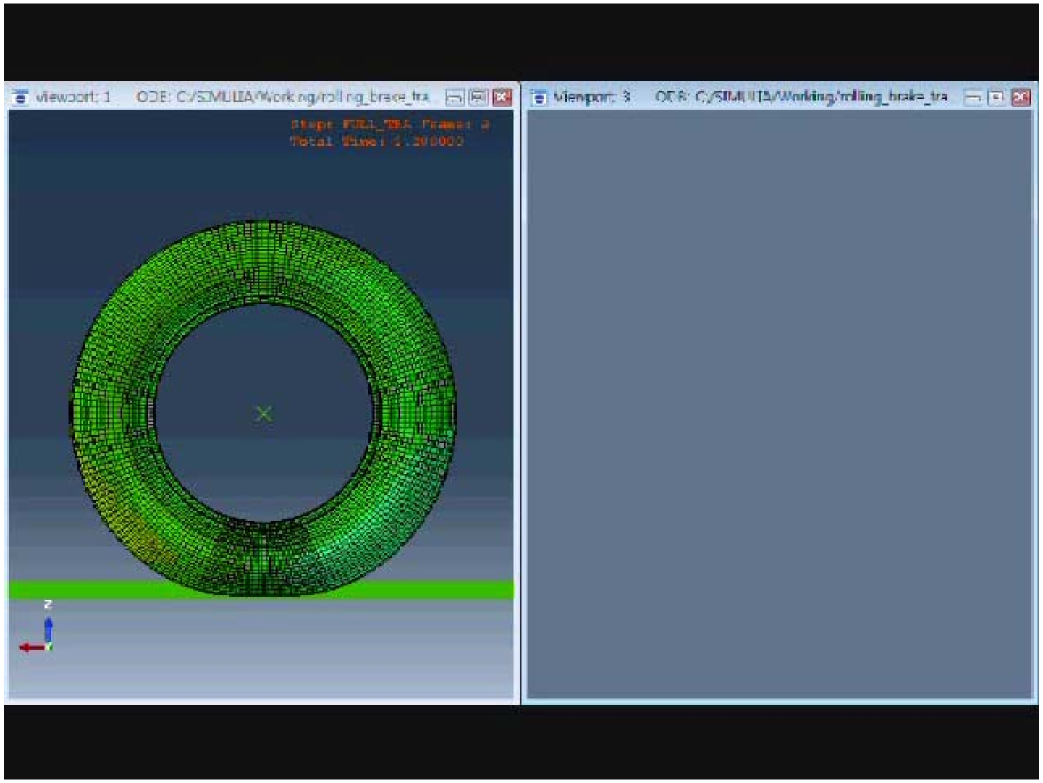
# Vehicle-Road Interaction
# FEM Simulation and Simplified Nonlinear Model





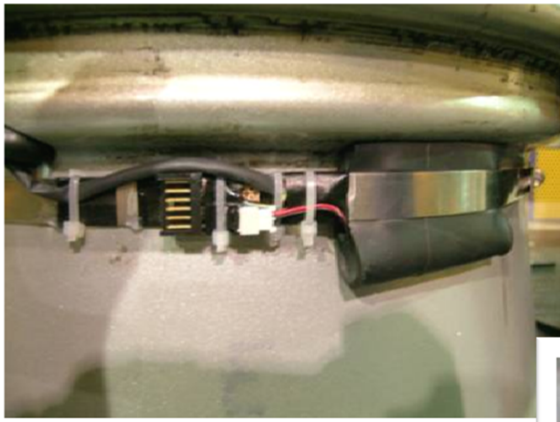
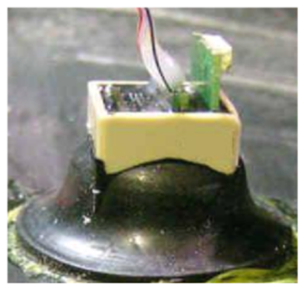
# Friction Coefficient Estimation Through Embedded Tire Sensors

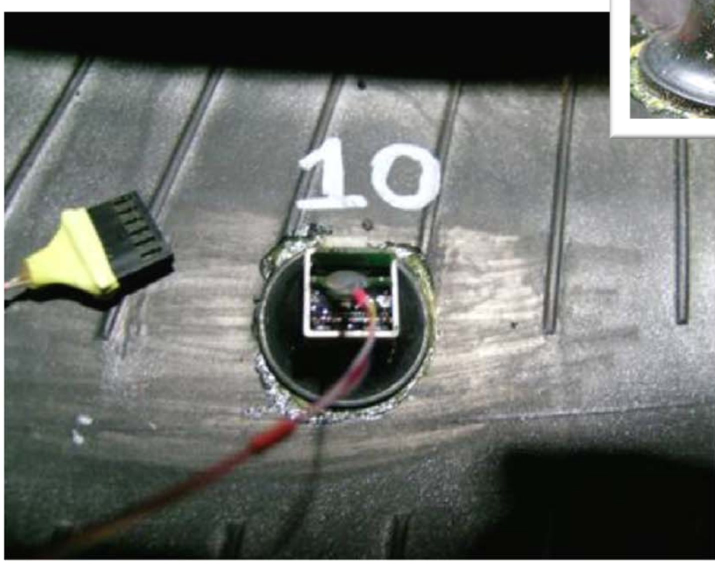

Selec-Terrain®



# Smart Tire Sensor

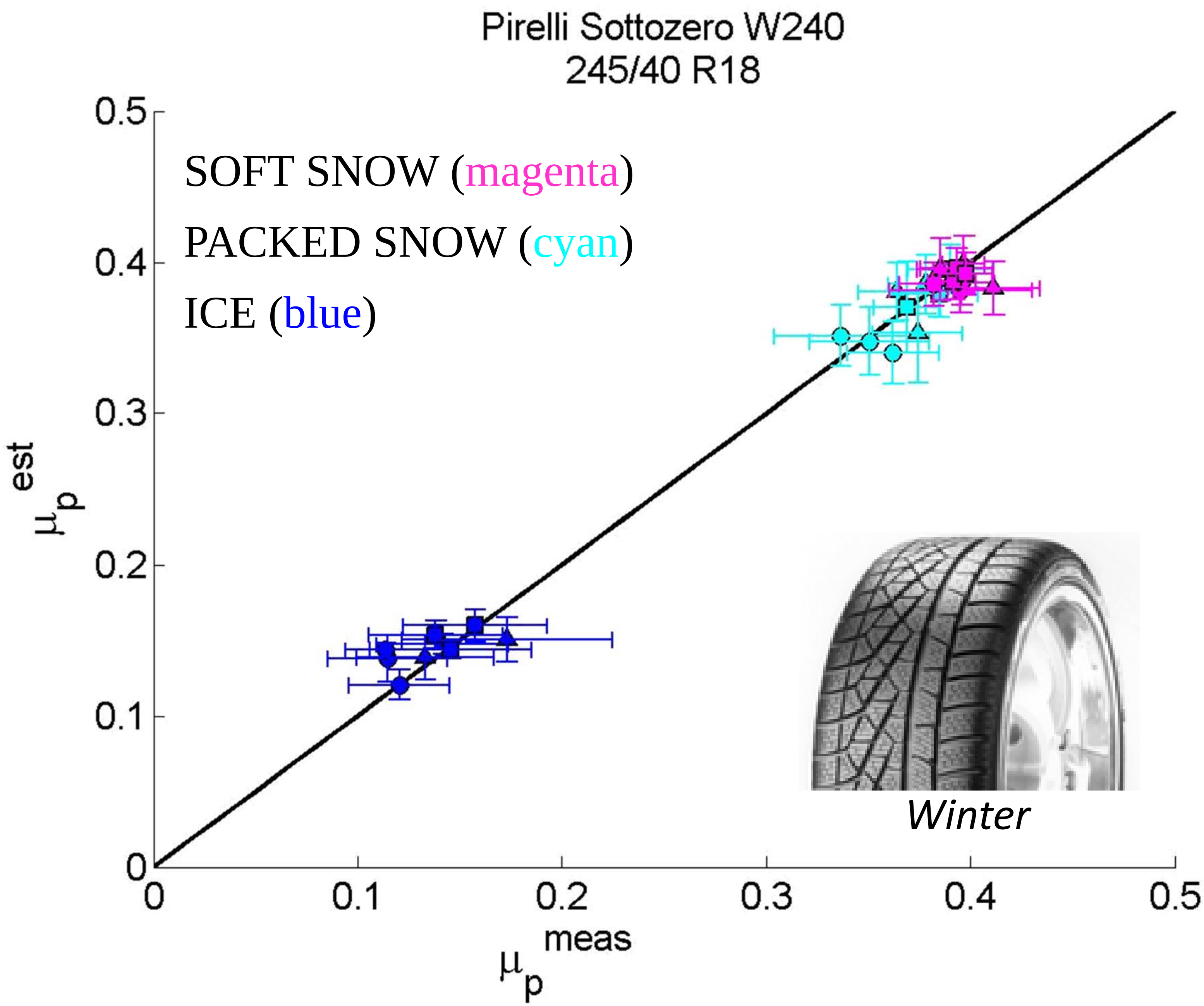




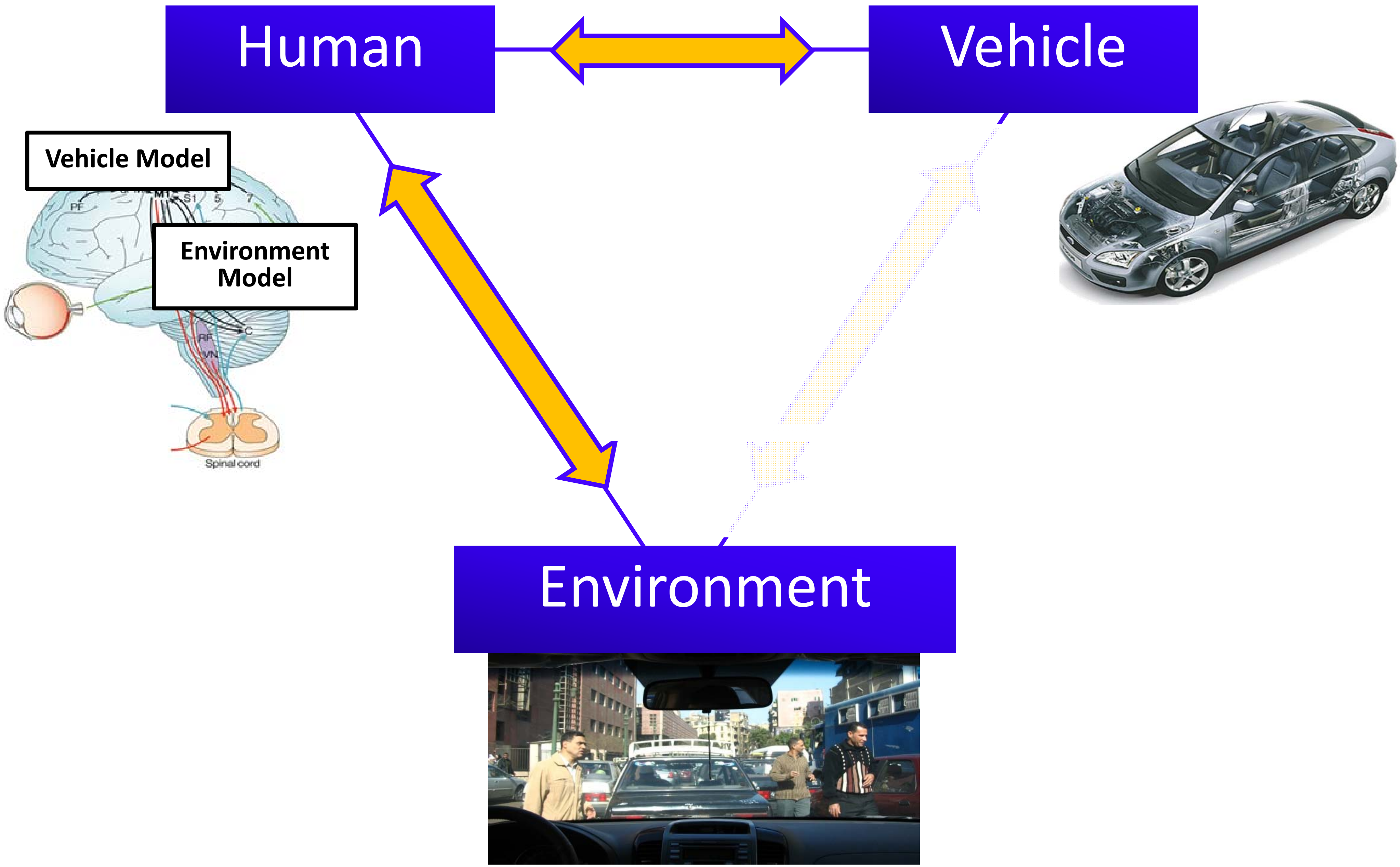
5 wheel turns av

Free rolling




*Winter*

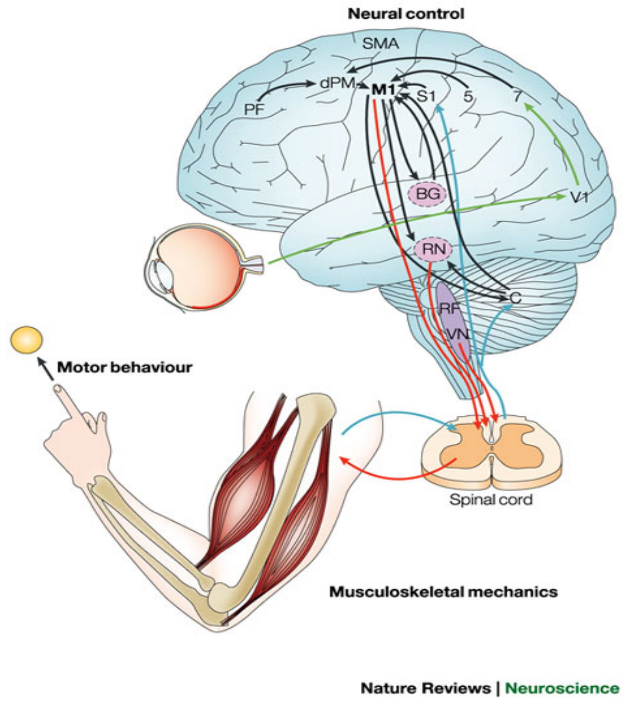
# Driving Cars: Synoptic Scheme

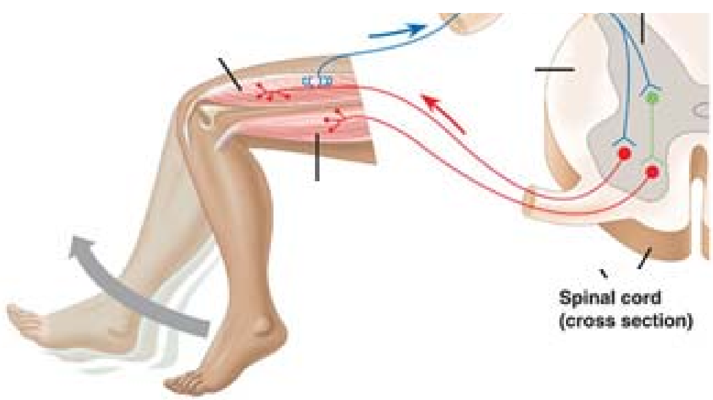


# Human/Environment-Vehicle Interaction

Vehicle Model

Environment Model




Sensory Inputs

Brain

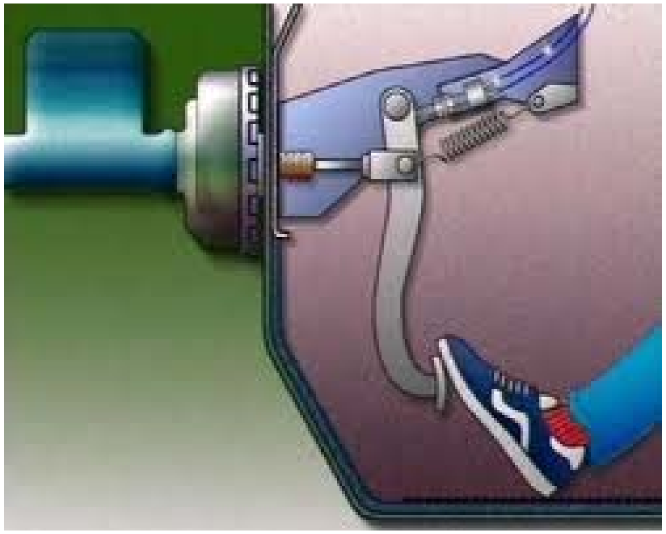
Spinal Cord

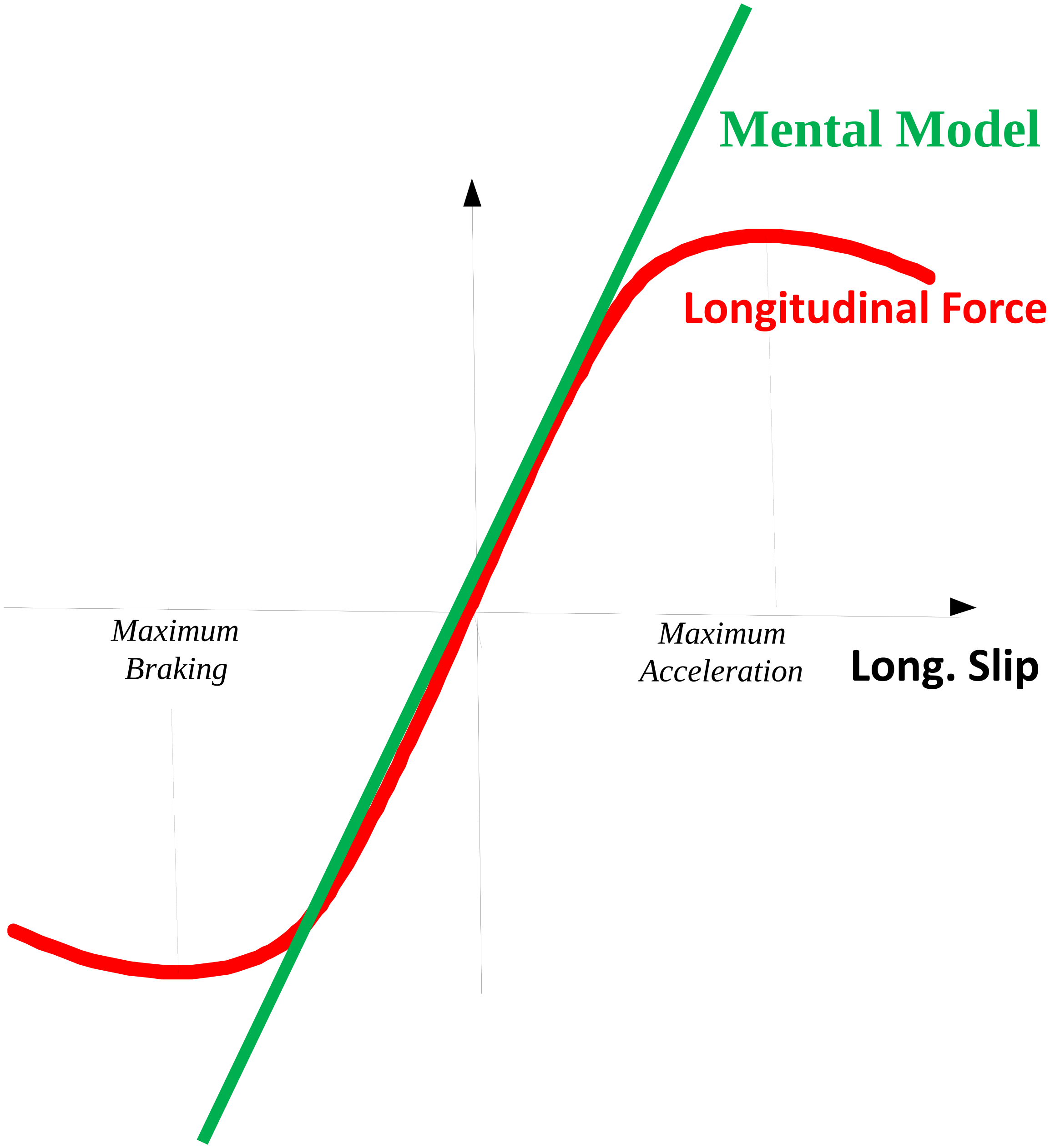
Muscles

**``We know that a lot of the brain has an internal neural simulator"… "to anticipate or predict the future for a given a input"**

**Eric Kandel (Charlie Rose interview, 2008)**

# Anti-Lock Braking and Traction Control Systems

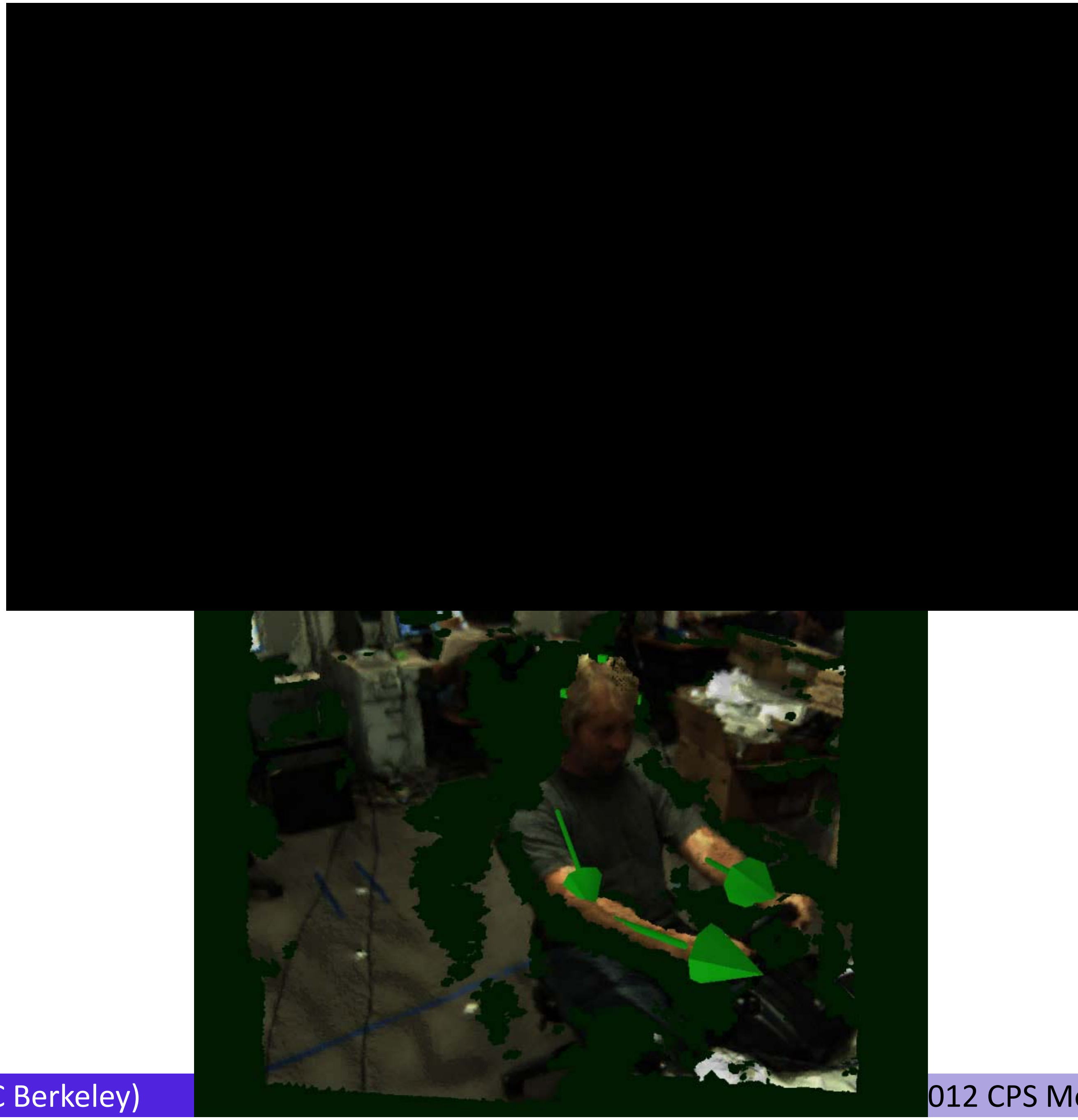


# Counter-Steering and Over-Steering


No driver model exists in this regime….

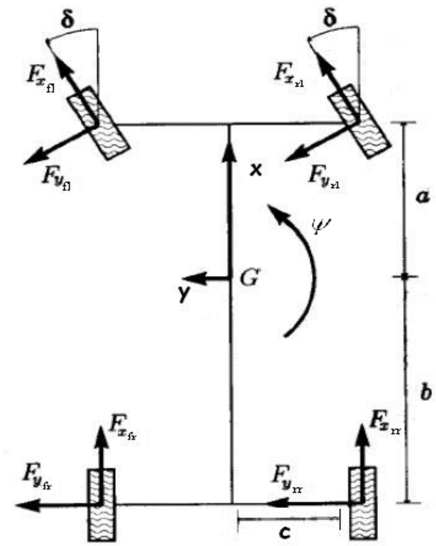
# Driver Modeling & In-Vehicle Sensors for Detecting Distraction



# Useful Model Abstraction

- **Nonlinear Dynamical System**

$$
\begin{aligned}
m\ddot{y} &= -m\dot{x}\dot{\psi} + F_{y_{f,l}} + F_{y_{f,r}} + F_{y_{r,l}} + F_{y_{r,r}} \\
m\ddot{x} &= m\dot{y}\dot{\psi} + F_{x_{f,l}} + F_{x_{f,r}} + F_{x_{r,l}} + F_{x_{r,r}} \\
I\ddot{\psi} &= a(F_{y_{f,l}} + F_{y_{f,r}}) - b(F_{y_{r,l}} + F_{y_{r,r}}) \\
&\quad + c(-F_{x_{f,l}} + F_{x_{f,r}} - F_{x_{r,l}} + F_{x_{r,r}}) \\
\dot{Y} &= \dot{x}\sin\psi + \dot{y}\cos\psi \\
\dot{X} &= \dot{x}\cos\psi - \dot{y}\sin\psi
\end{aligned}
$$




- **Static Nonlinearities**
  - Tires
- **Uncertain Predictions**
  - Drivers Behavior and Environment
- **Inequality Constraints**
  - Safety region

# Steps Towards Success

human, environment | control action | constraints

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# Can We Make Vehicles Safer?

Human

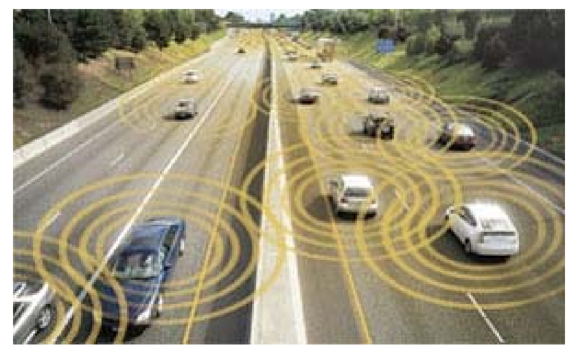
Vehicle

Forecast ??

Semi-Autonomous System

Forecast ??

Environment

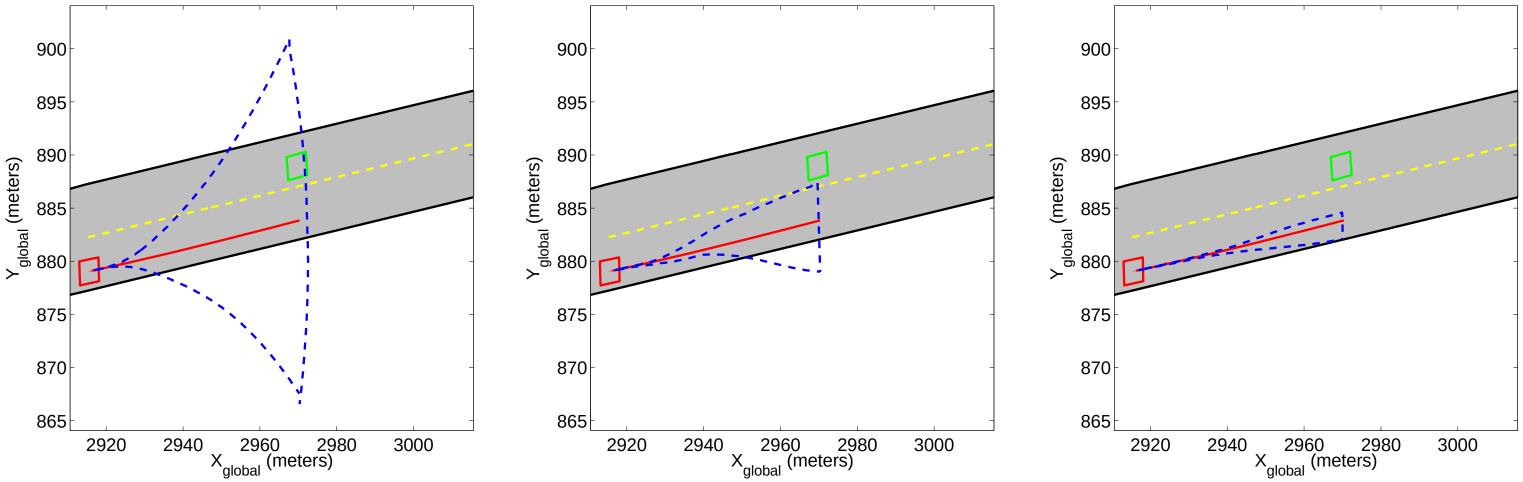


**Predictions on**

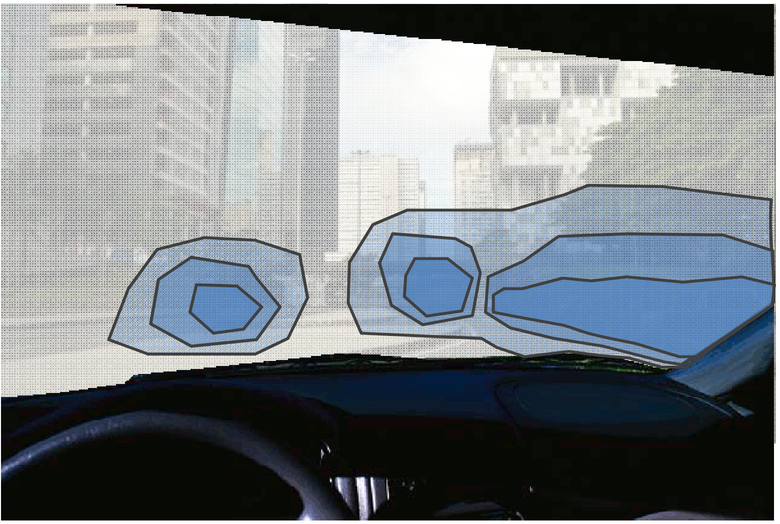
System Dynamics, Friction, Obstacles, Driver Behavior

# Big Challenges

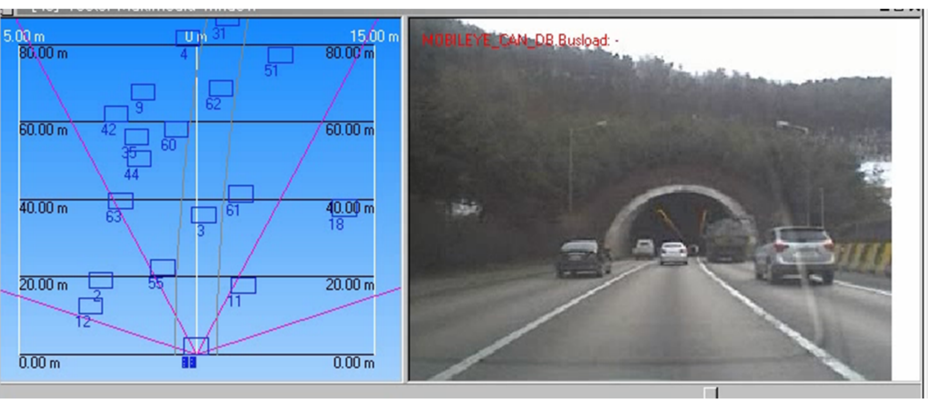
- Cost Effective and Evidence-Based Uncertain Quantification
- Assessing the Value of Uncertainty in Closed-Loop
- Real-time Use of Uncertain Prediction Maps



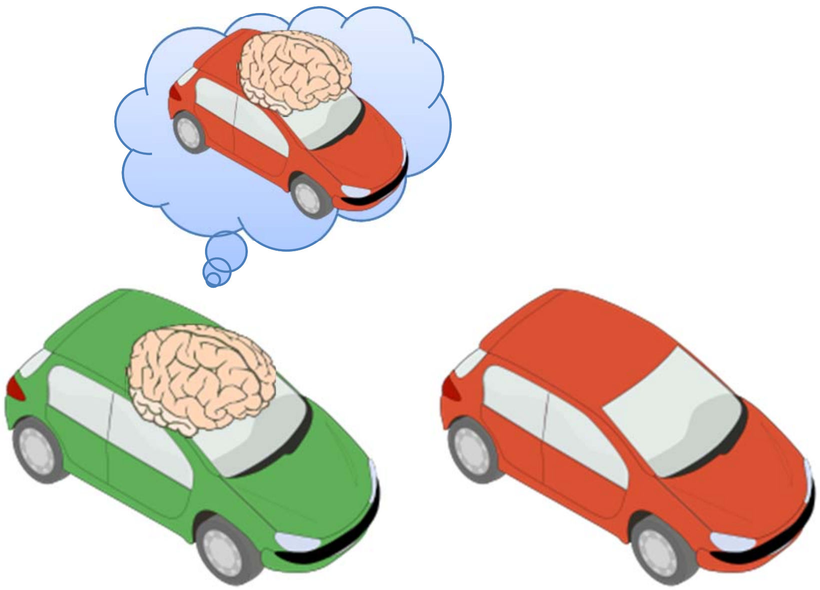
# Understanding the Environment (foundation)



- Robust reconstruction of a scene in order to identify objects with guarantees.
- Hierarchical approaches that provide a trade-off between computational power and precision.



# Understanding the Human Drivers (foundation)



- **How will the driver act/react? How will other drivers act/react?**
- **Needs to be fast, and with accuracy guarantees**

1. **Develop detailed cognitive model**
2. **Use model to inform approximations**
   - with abstraction, precision, and speed as needed
   - boundaries on precision/computational cost tradeoff
   - parametric formulation to capture driver variability
   - parameters ascertained empirically using real-world driving behavior and new data from the driving simulator at UC Berkeley and the Virtex Simulator

# Drive Modeling in Complex manouvers

Driver performs 180° turn by drifting

Snow test track

Record:

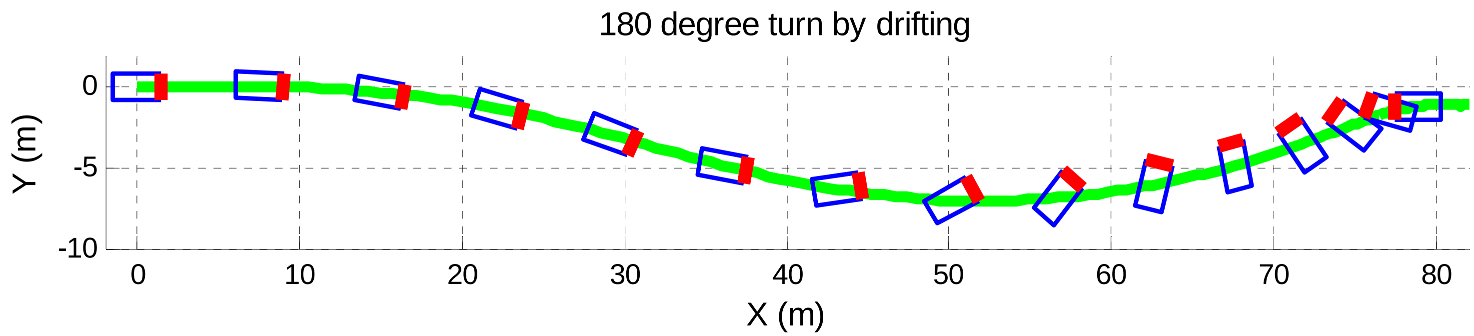
$$u = \delta$$
$$\xi = [\dot{y}, \dot{x}, \psi, \dot{\psi}, Y, X]'$$

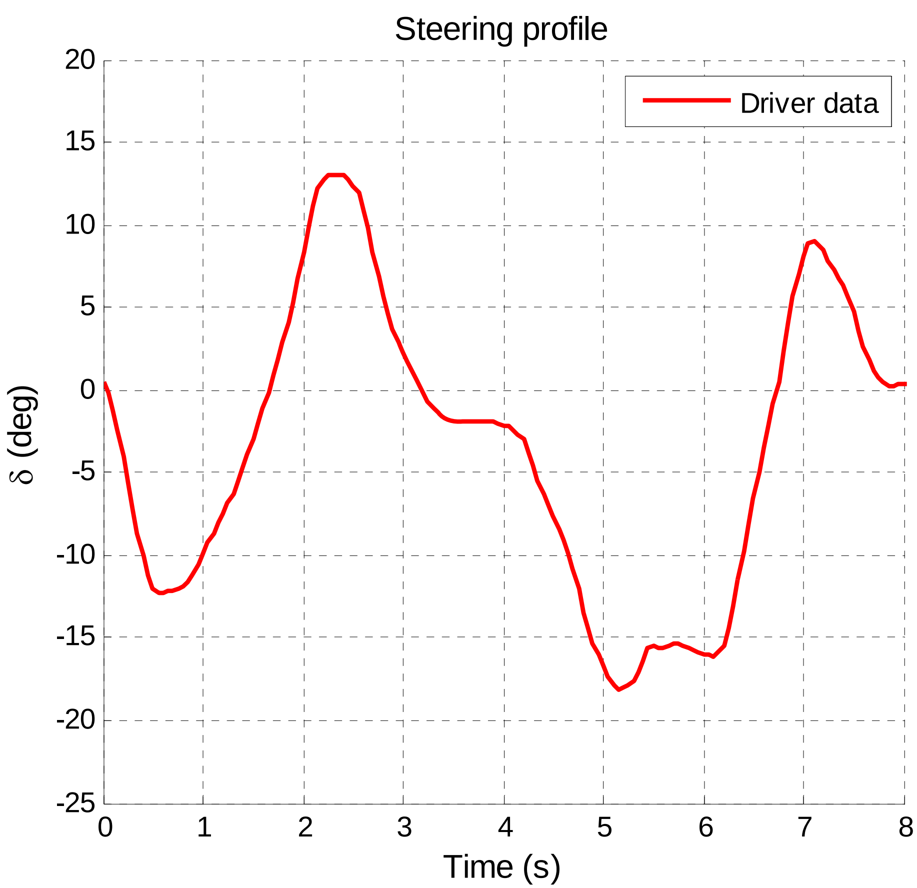
Car equipped with GPS, IMU

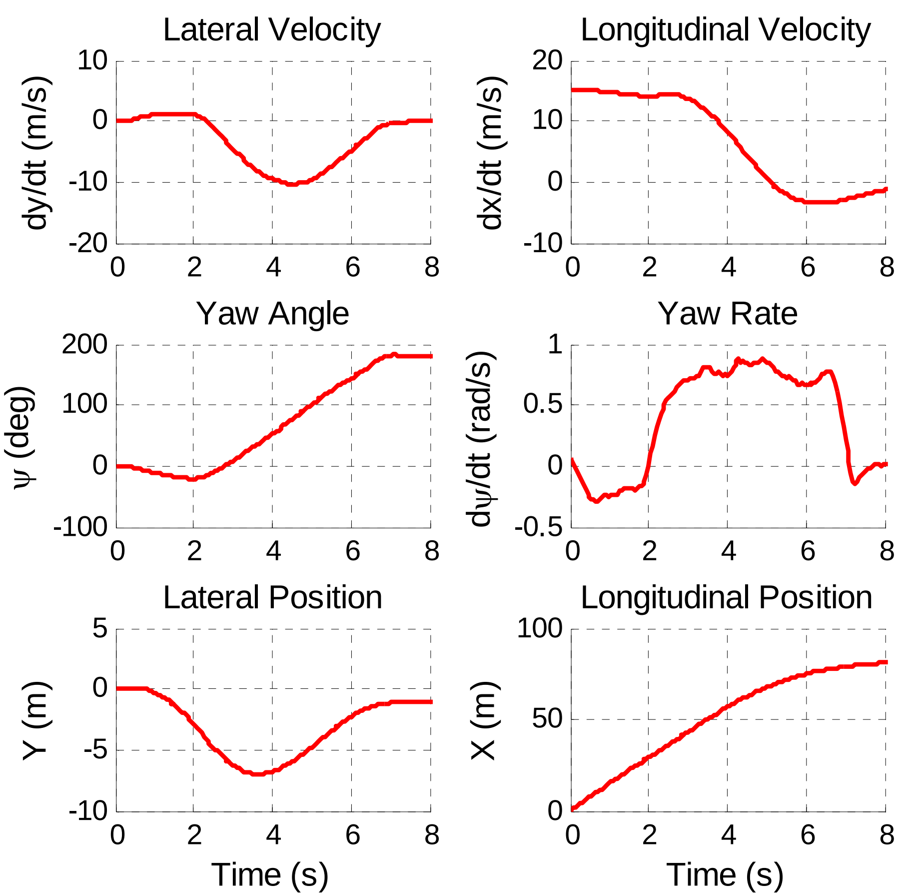
Drifting in ground vehicle

- Vehicle operating in the saturated regions of tires
- Hard to control, near unstable equilibrium points

# Input and State Trajectories



# Switched Differential Equation Model

Vehicle states:

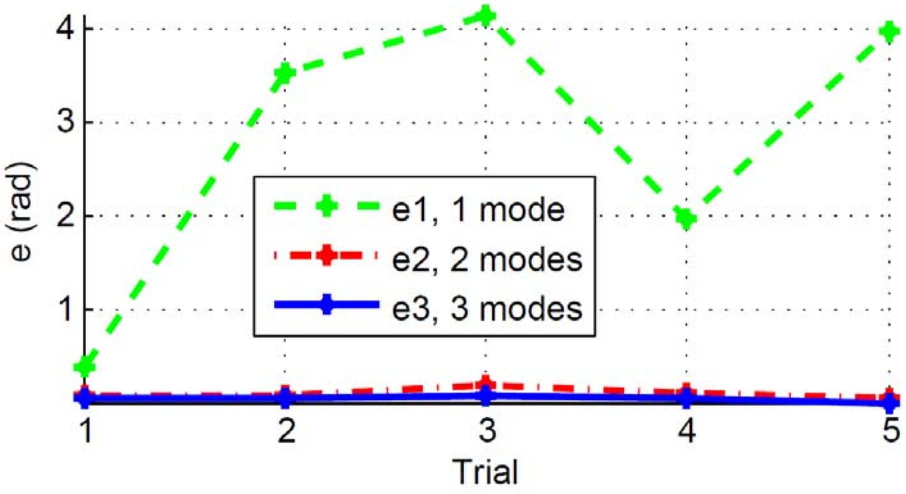
(Inputs to LS fit)

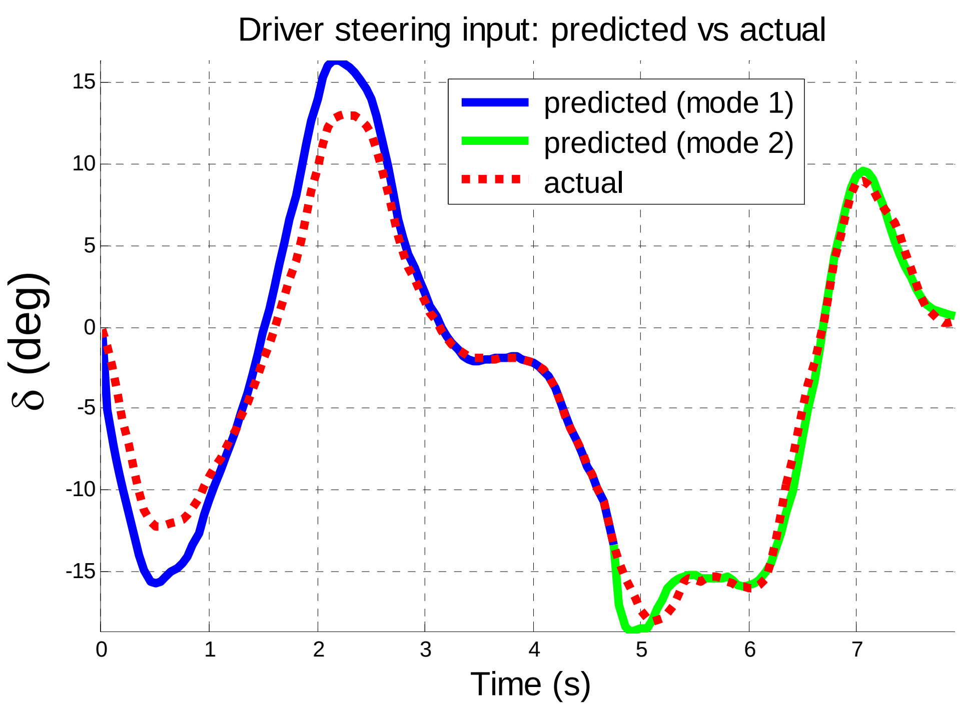
$$e_k = \begin{bmatrix} \dot{y}_k \\ \dot{x}_k \\ \psi_k - \pi \\ \dot{\psi}_k \end{bmatrix}$$

Driver steering:

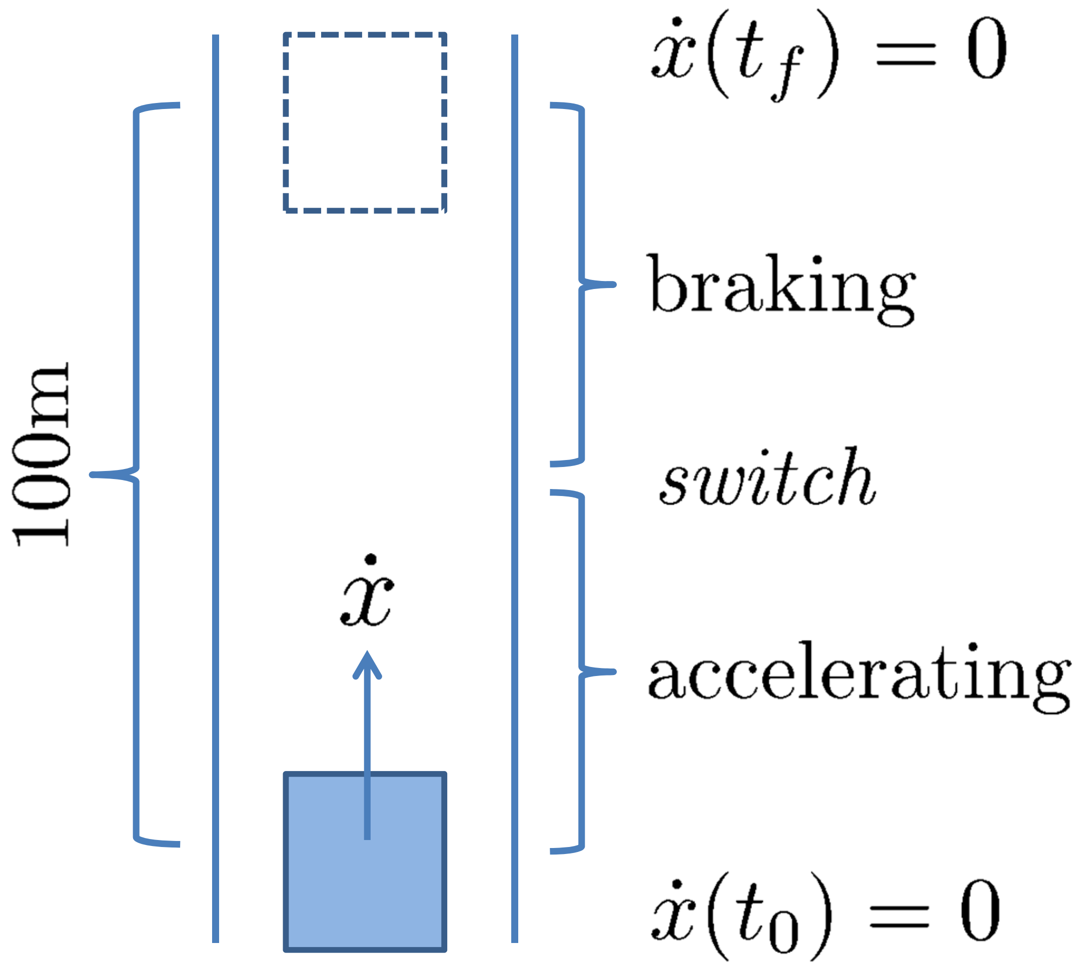
(Output of LS fit)

$$\delta_k$$



# Example 2: Test maneuver

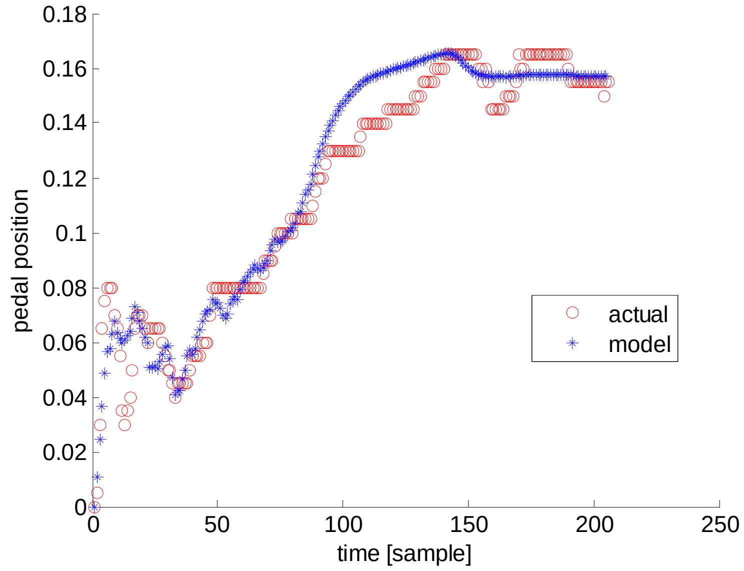


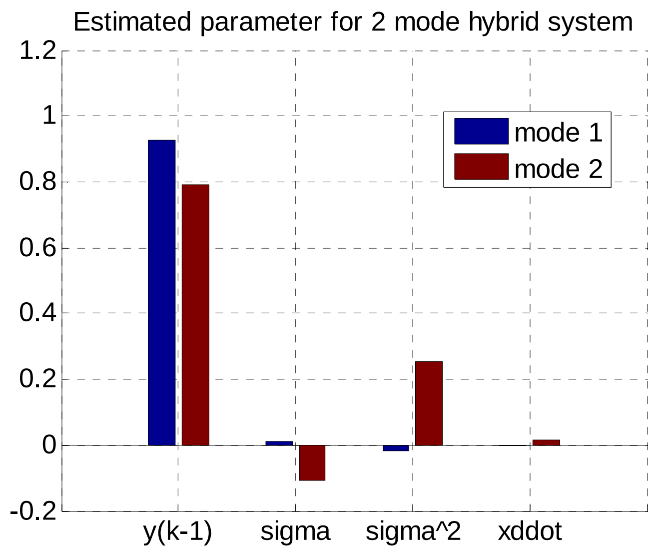

- Identify driver, $y_k$
  - throttle action
  - switching condition

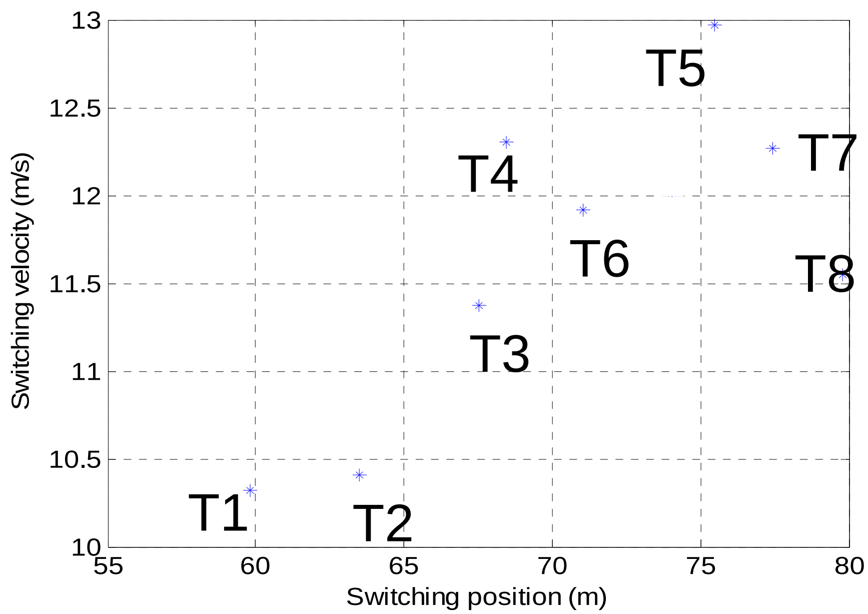
- Regressor:

$$y_{k-1},\ \sigma,\ \sigma^2,\ \ddot{x}$$

# Modeling Human Braking Behavior



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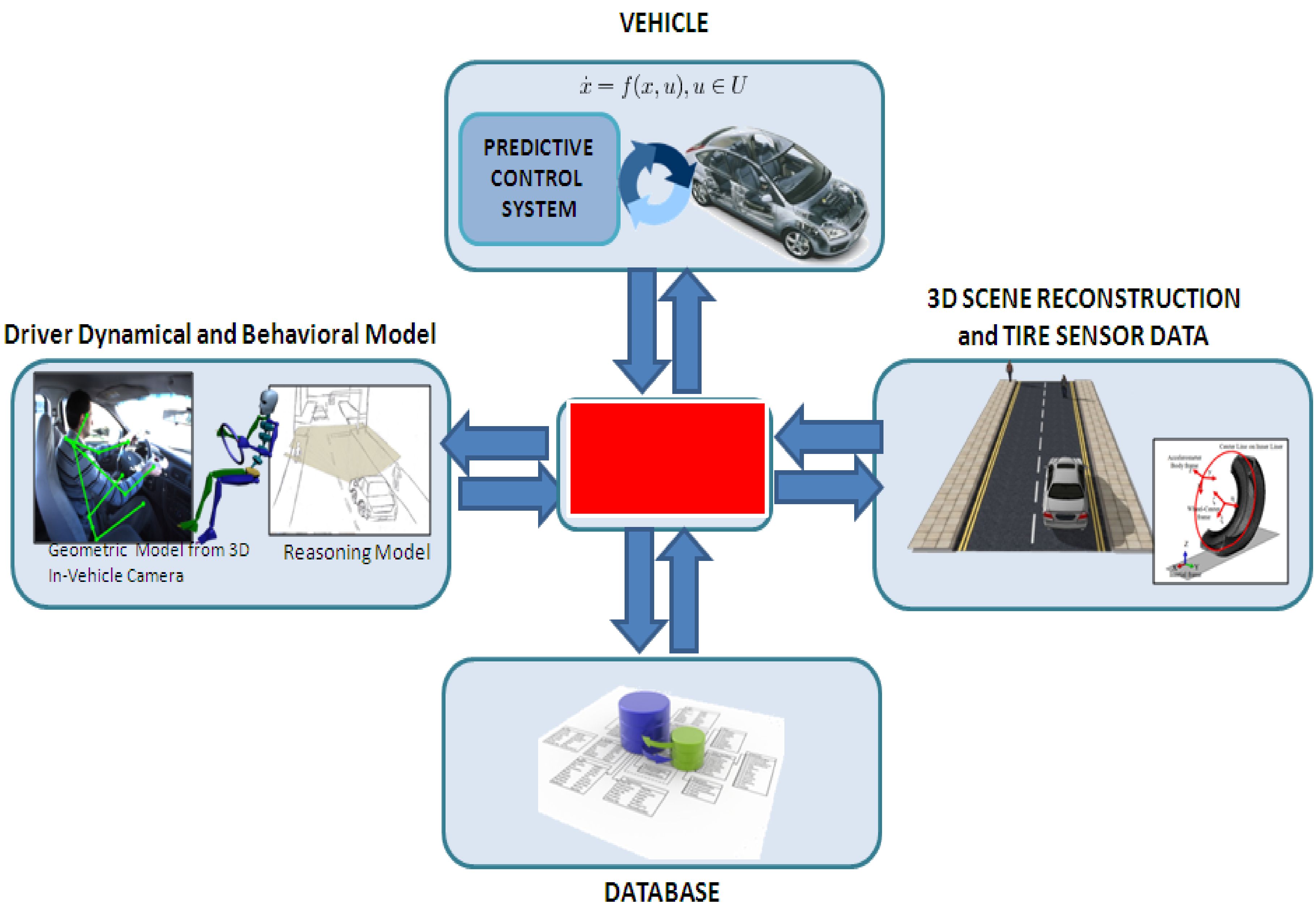
- **Safe Control Design & Architecture**

# Control Design and Architecture

## Moving from deterministic optimization to evidence-based and stochastic



# The Basic Setup – Finite Time Optimal Control

$$\min_{\pi_0(\cdot),\pi_1(\cdot),\ldots,\pi_{N-1}(\cdot)} J_{0\to N}(x_0,\Pi)$$

$$\begin{array}{c}\text{subj. to}\\ k=0,\ldots,N-1\end{array} \left\{\begin{array}{l} x_{k+1}=f(x_k,u_k,w_k)\\ u_k=\pi_k(x_k)\\ u_k\in\mathcal{U}, x_k\in\mathcal{X}, \quad \forall w_k\in\mathcal{W}\end{array}\right.$$

$\pi_k(\cdot)$ Feedback Control Policies: $\pi_k:\ x_k\in\mathcal{X}\mapsto u_k\in\mathcal{U}$

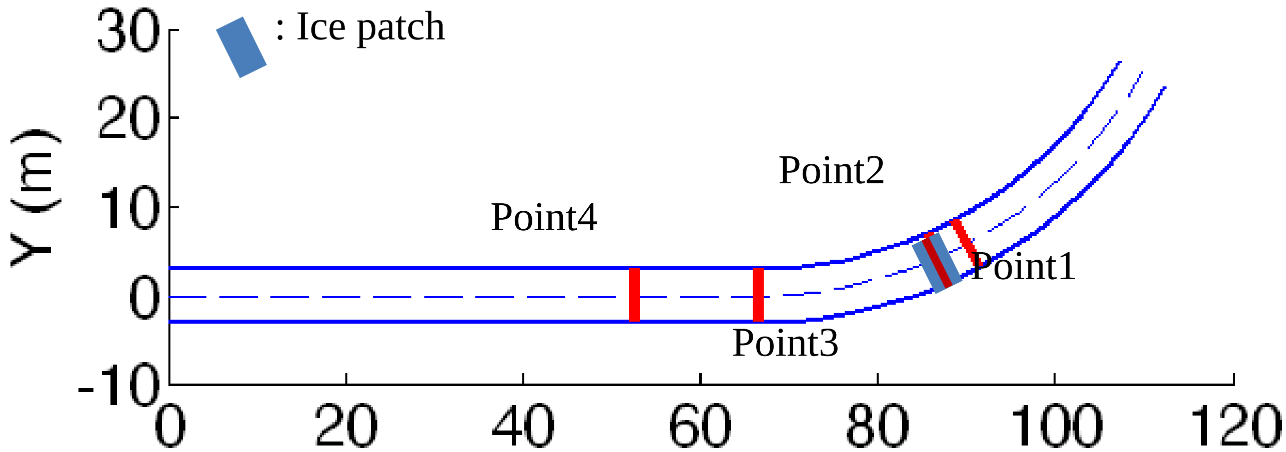
## Problem Class

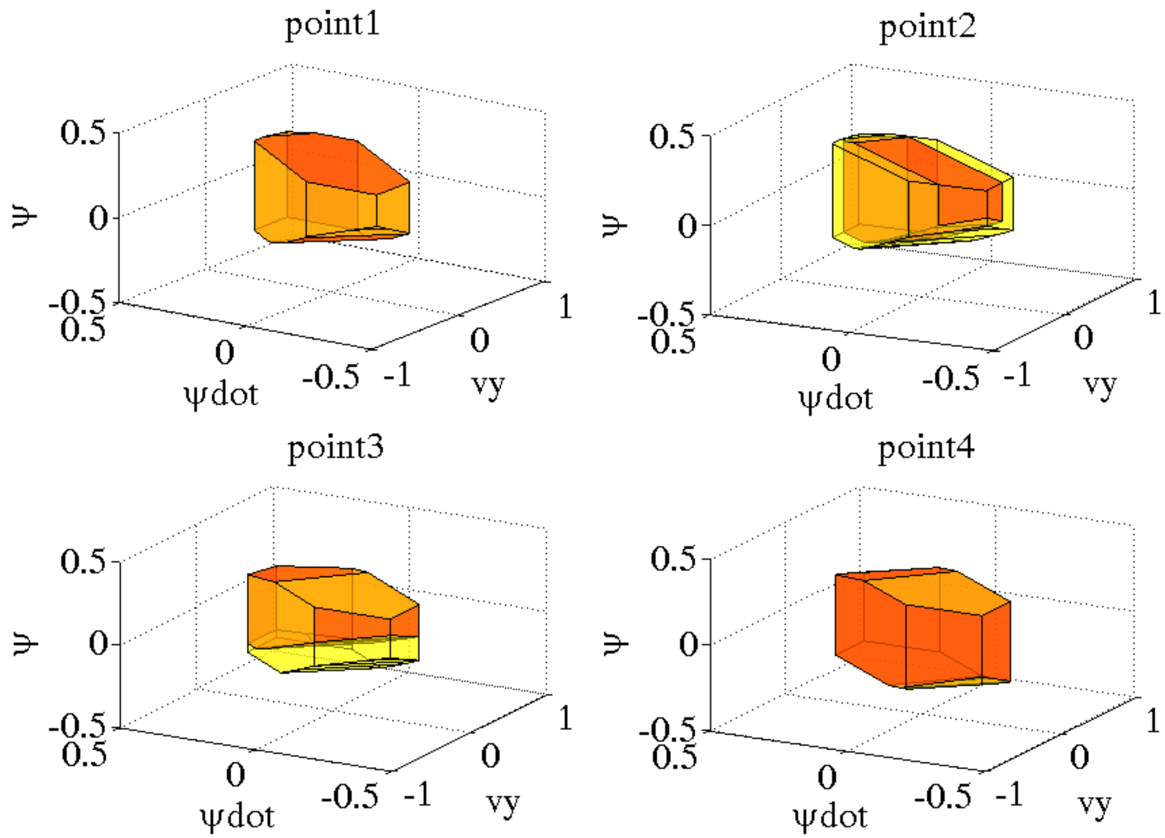
- $x_{k+1}=A^i x_k+B^i u_k+D^i w_k+c^i \quad \text{if } [x_k,u_k]\in\mathcal{X}^i$
- $\mathcal{X},\ \mathcal{U},\ \mathcal{W}$ polyhedra
- Piecewise Linear or Quadratic Costs

$$J_{0\to N}(x(0),\Pi)=\max_{w_0,\ldots,w_{N-1}}\left[p(x_N)+\sum_{k=0}^{N-1}q(x_k,\pi(x_k))\right]$$

$$J_{0\to N}(x(0),\Pi)=E_{w_0,\ldots,w_{N-1}}\left[p(x_N)+\sum_{k=0}^{N-1}q(x_k,\pi(x_k))\right]$$

# Curve with and without ice patch
# Vx=10m/s, uncertain mu, steering only



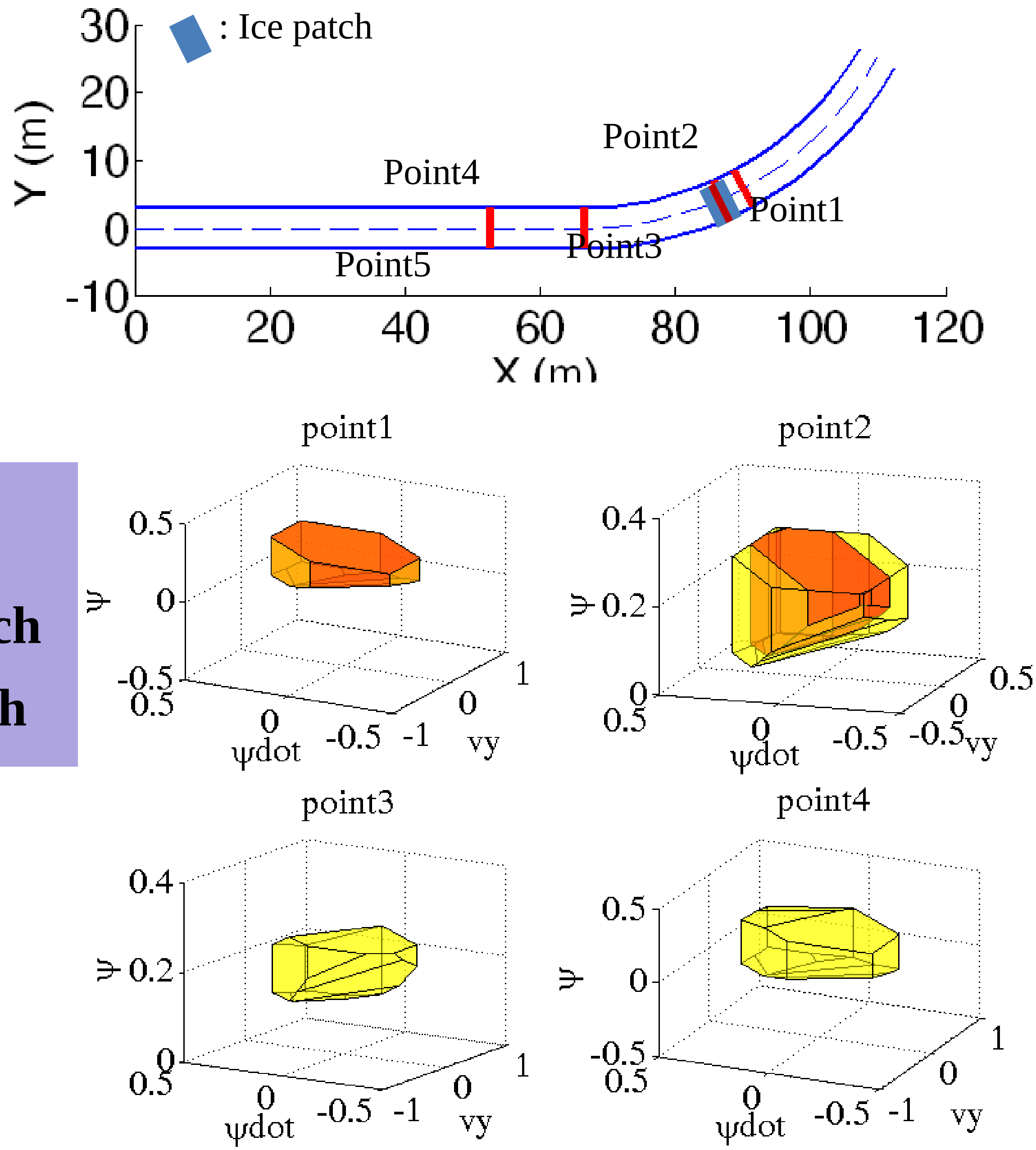




**Projection of safe sets:**

**-Yellow: no ice patch**

**-Red: with ice patch**

# Curve with and without ice patch
# Vx=14m/s, uncertain mu, steering only




**Projection of safe sets:**

**-Yellow: no ice patch**

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DELL

# Semi-Autonomous Driving – Volvo Experiments 2012

# Cars Can Be Unsafe
# ~32k killed in 2012
# ~2.5M injured

| Table 1: Fatalities and Fatality Rate in 2010 | | |
|---|---|---|
| **Fatalities** | Vehicle Miles of Travel | Fatality Rate per 100 Million Vehicle Miles of Travel |
| **32788** | 37050 Millions | **1.13** |

# Experimental Validation

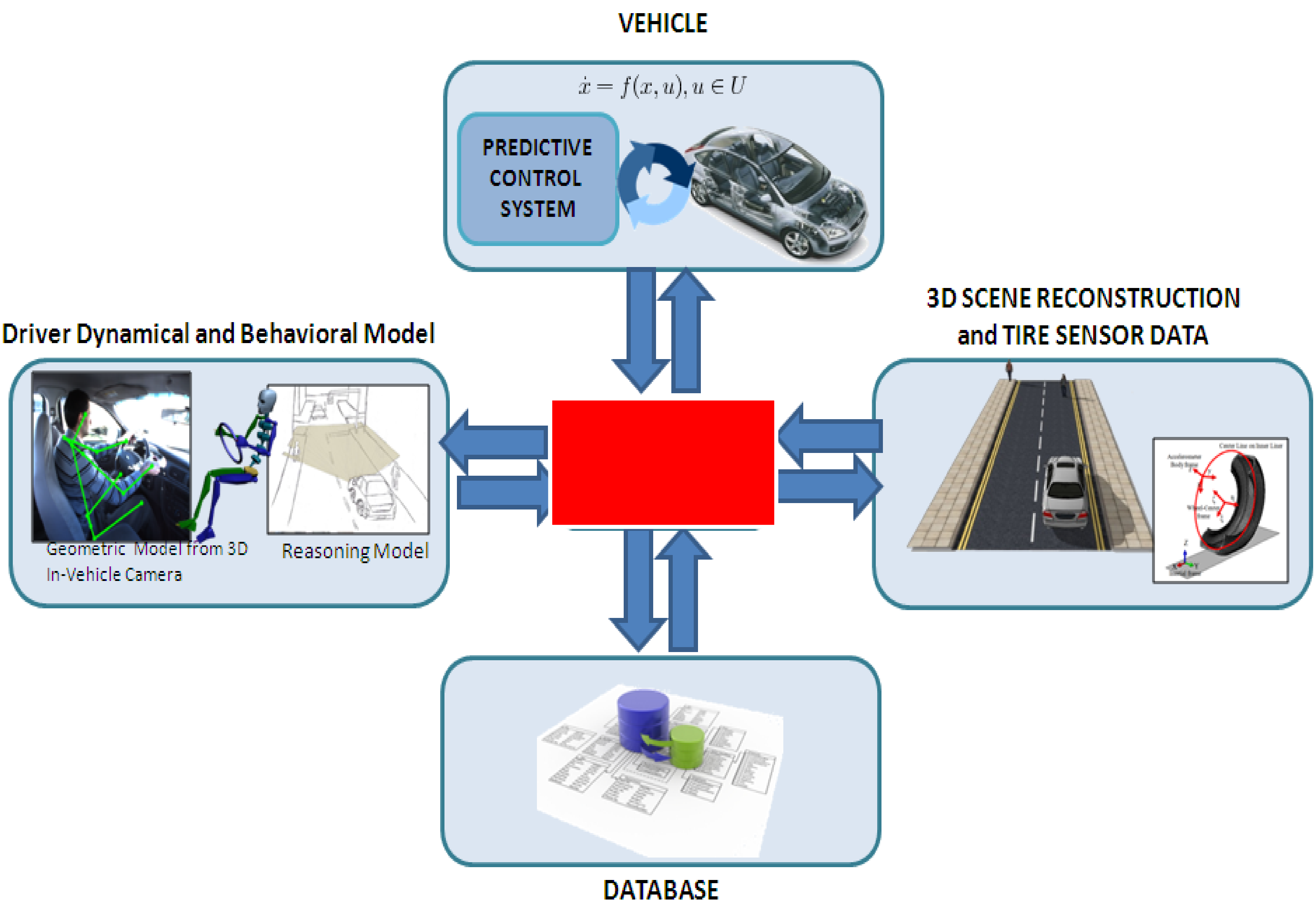
*Platform 1*. The Jaguar in Figure 5 is equipped with active steering, braking and throttling. GPS, accelerometers, gyros and 3D stereo vision. The controllers are run on a dSPACEAutobox system.

*Platform 2*. The VIRtual Test Track Experiment (VIRTTEX) simulator, pictured on the left, is a spherical dome (with a actual car inside) on top of a hydraulic system to mimic vehicle movement. In addition, it has image rendering technologies to provide a high-resolution, digitally projected 360-degree horizontal field-of-view to test and measure driver acceleration, braking and steering performance as well as overall driver reactions in varying conditions.

*Platform 3*.The *vehicular test bed* is a car equipped with outward looking and inward looking cameras observing the interior and exterior of the vehicle, illustrated on the left. Drivers will employ the test bed during daylong experiments (in real driving) while the driver's input, the vehicle's state, observations of the driver, and observations of the environment will be recorded for post-


prescan
ACC_Stop_GO_002
Motorway slow traffic (Stop&Go) (2)
Host car travels at 20 km/h in slow moving traffic column.
Target car drives in front on the same line. It goes and stops within 0-10 km/h
(due to traffic jam).

# Semi-Autonomous Driving CPS



# Acknowledgements


**UC Berkeley Graduate Students**

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**Former Collaborators**

Miroslav Baric, Gurkan Erdogan, Ricardo Cervera Navarro, Mark Godwin

## Industrial Partners

**Ford Research Labs (USA)**
- Eric Tseng, Davor Hrovat

**Volvo Cars (Sweden)**
- Mohammad Ali, Erik Coegling

**Hyundai Research Labs (Korea)**
- Chan Kyu Lee

**Pirelli Research Labs (Italy)**
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