Vehicle Dynamics Control of Automated Driving

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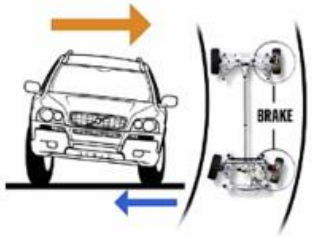
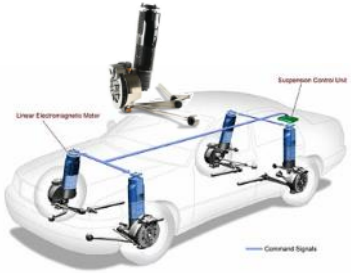
Self Introduction

- Education
  - Ph.D., Mechanical Engineering, U. of Michigan
  - Dual M.S., EE & ME, U. of Michigan
  - B.S., Naval Architecture and Ocean Engineering, NTU
- Experience
  - Technical Specialist, ARTC, TAIWAN
  - Committee Member, MIH, TAIWAN
  - Research Fellow, NARLabs, TAIWAN
  - Strategy and Software Engineer, Powertrain Control Dept., Visteon, USA
- Honors
  - International Scientific Committee, AVEC, 2016-2022.
  - Best paper award, National Conference on Vehicle Engineering, SAE Taipei, 2019, 2020.
  - Invited Speech for the 5th Automotive Engineers Forum in Bangkok, 2019.
  - Invited Speech for Taiwan-Germany-U.S. International Advanced Vehicle Tech. Forum, 2018.
  - IJAT Most Cited Article Award, Springer, 2017.
  - Best paper award, the 2014-2015 JSAE KANTO International Conference of Automotive Technology for Young Engineers (ICATYE), Kanto, Japan, 2015.
  - Invited Speech for International Forum on Eco-friendly Vehicle System, Seoul, Korea, 2014.
  - Invited Speech for Asia Intelligent Vehicle Summer Workshop, National Seoul University, 2013.
  - SETC2013 Taiwanese Special Awards, 2013.
  - Hiwin Thesis Award – Special Award for U. of Technology, Hiwin, 2012.
  - Educational Achievement Award, SAE Taipei Section, 2011.
  - Outstanding Young Engineer Award, SAE Taipei Section, 2008.

Research Areas

- Active Safety/ADAS/Automated Driving
  - Forward Collision Warning
  - Adaptive Cruise Control
  - Lane Keeping/Following Control
  - Traffic Jam Assist
  - Automatic Lane Change System
  - Automatic Emergency Braking
  - Automatic Emergency Steering
  - Autonomous Valet Parking
- Vehicle Dynamics and Control
  - ABS/TCS
  - Electric Differential
  - Electronic Stability Control
  - Rollover Prevention
  - Electric Power Steering
  - Semi-active Suspension
- Electric Vehicle/HEV
  - Battery Management System
  - Power Management System



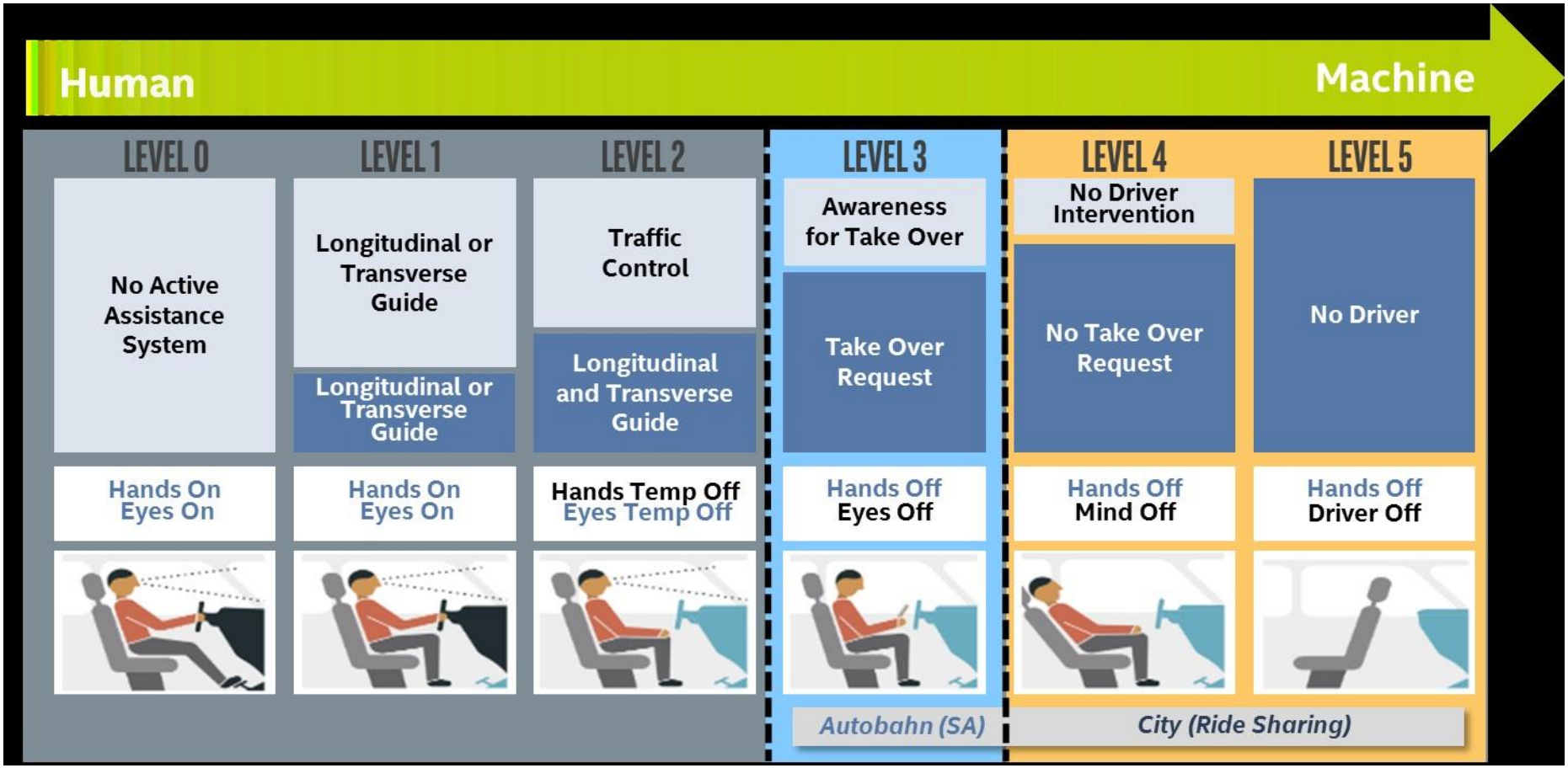


Outline

- Introduction
- Longitudinal Dynamics Control
  - Adaptive Cruise Control with Stop-and-Go
  - Throttle-by-wire
  - Brake-by-wire
- Lateral Dynamics Control
  - Lane Following Control
  - Steer-by-wire
  - Differential Braking
- Fault-Tolerant Control
- Conclusion

Automation Levels

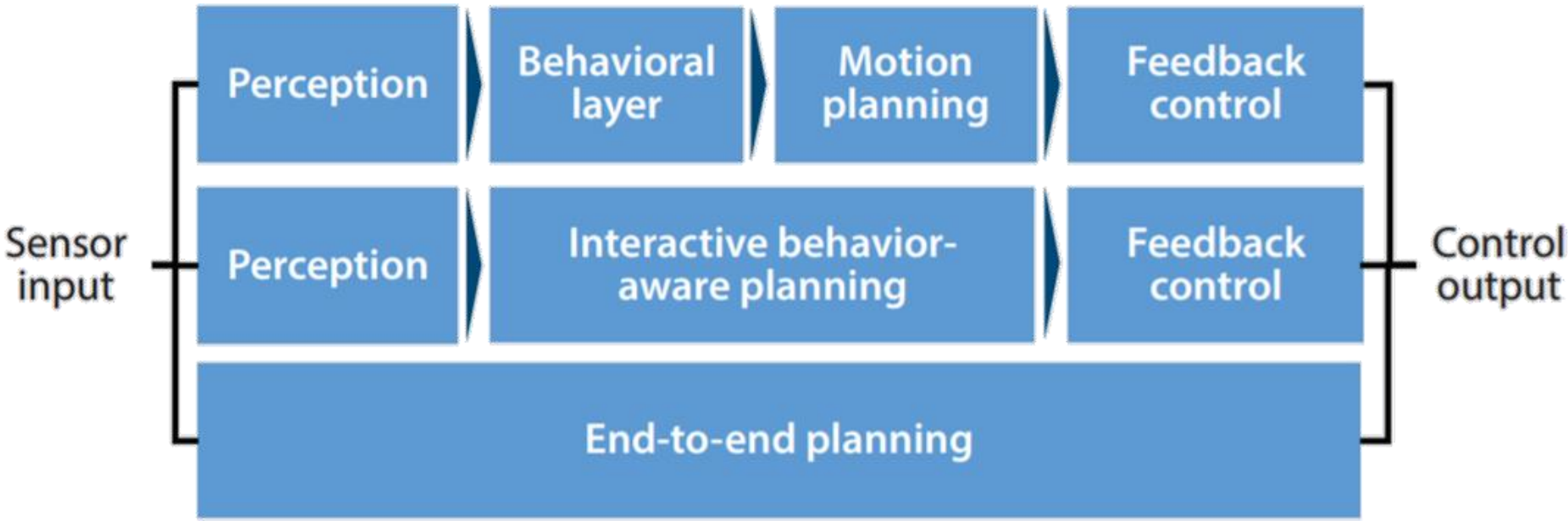
- SAE International classifies vehicle automation using five levels.



https://iq.intel.com/autonomous-cars-road-ahead/

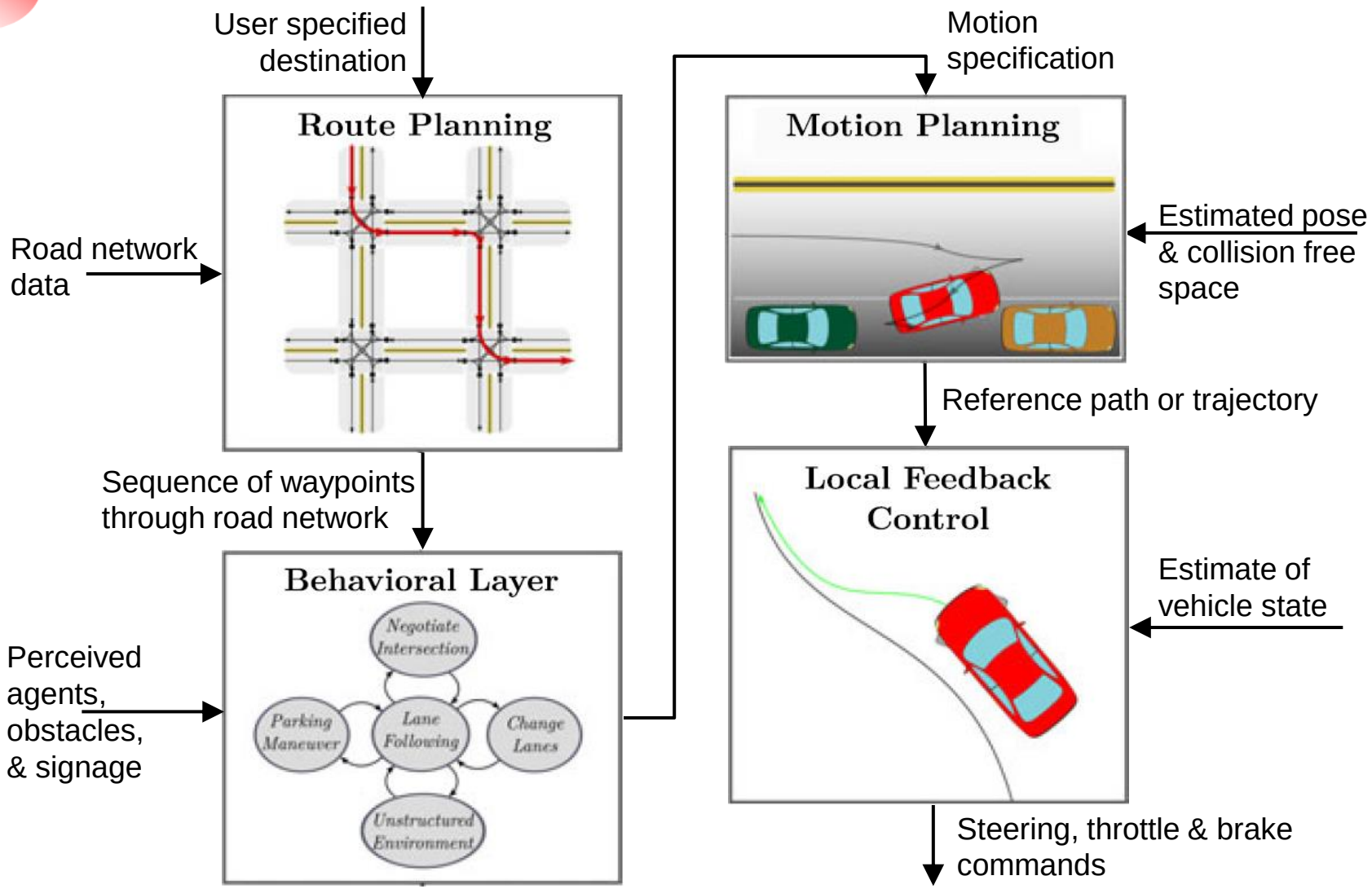
Planning and Decision Making

- Classification



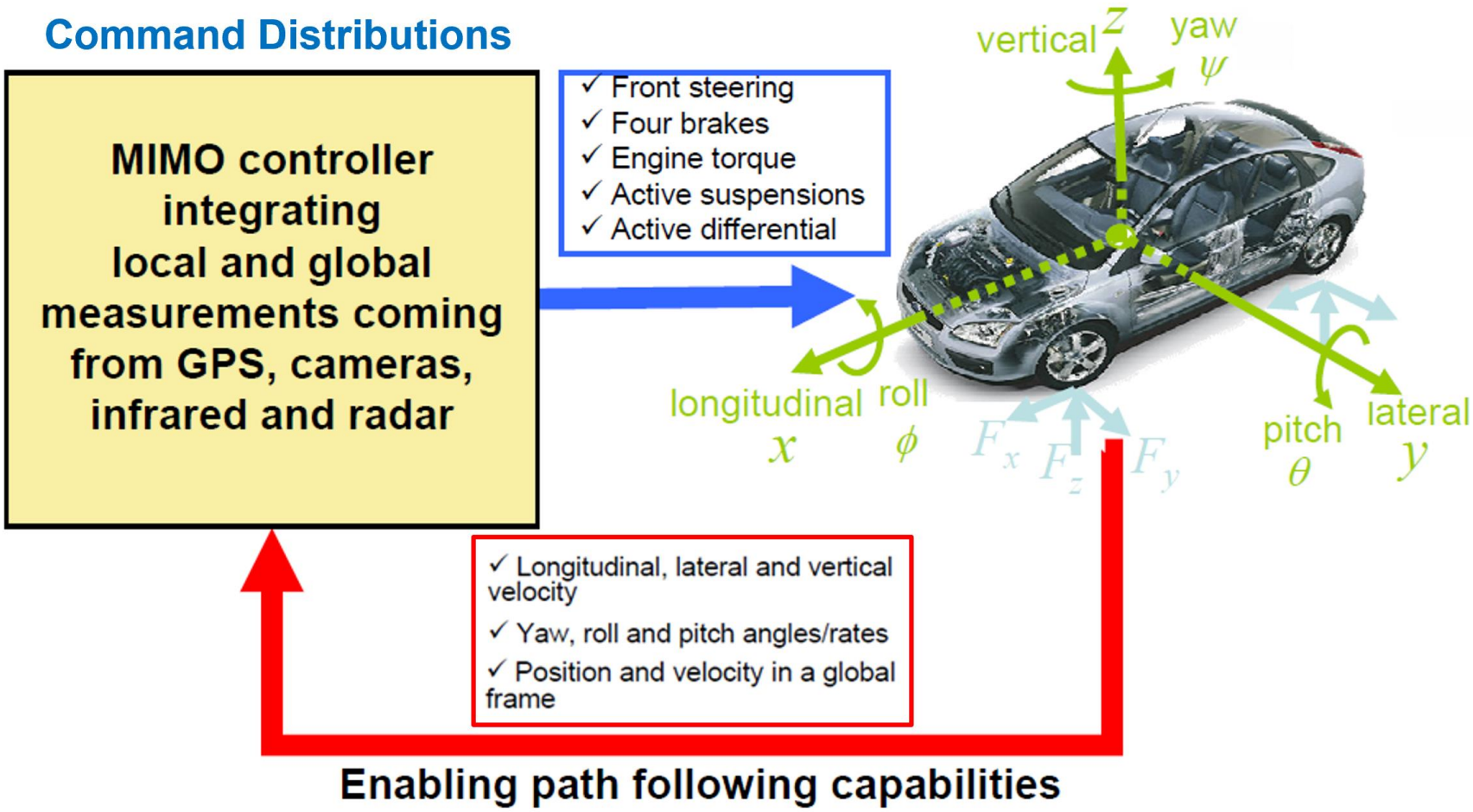
Planning and Decision-Making for Autonomous Vehicles, 2018

Typical Approach



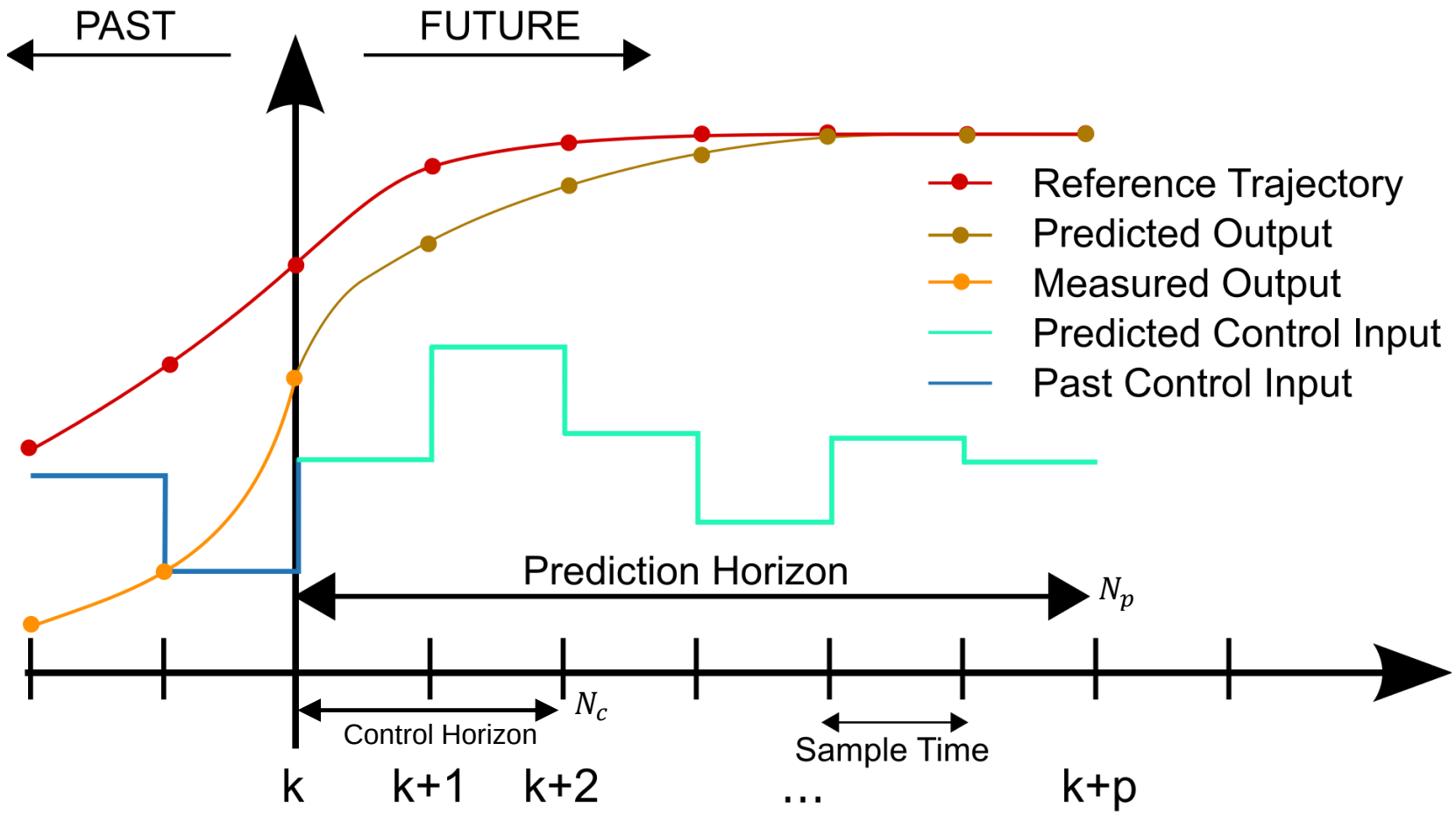
A Survey of Motion Planning and Control Techniques for Self-Driving Urban Vehicles, 2016

Integrated VDC



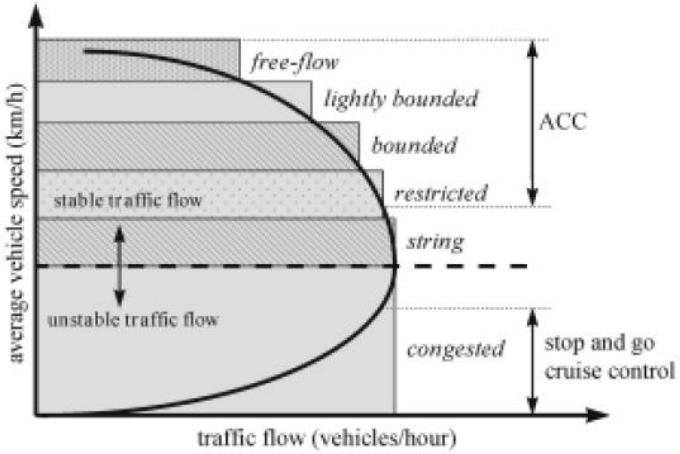
Integrated Vehicle Dynamics Control in Autonomous Vehicles: A Real-Time MPC Approach, 2007

Model Predictive Control



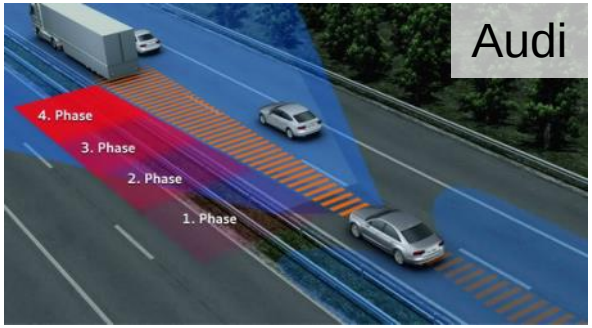
Adaptive Cruise Control with Stop & Go

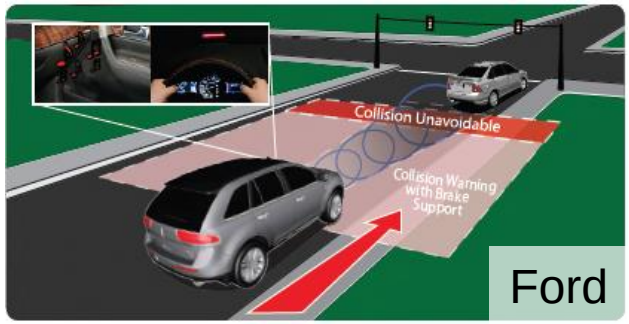
- ACC Functions
  - To maintain a proper distance from a slower leading vehicle when one is present.
  - Otherwise, function like a conventional cruise control system.
- Measurements
  - Range, range rate, and vehicle speed.
- Control Commands
  - Throttle, brake, gear-shift, desired speed, or desired acceleration.

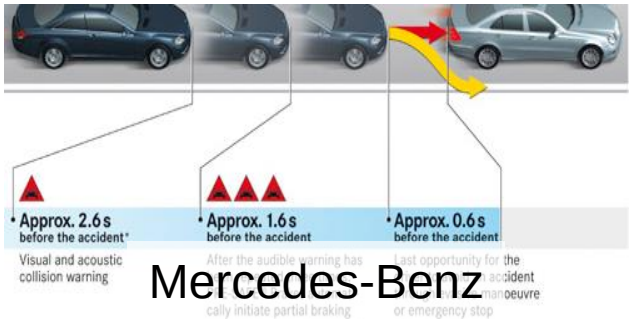


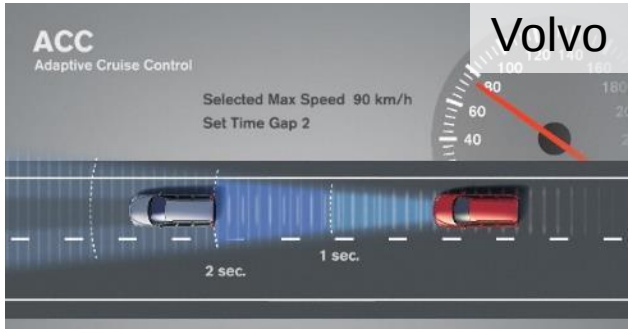
Kellar, 1987

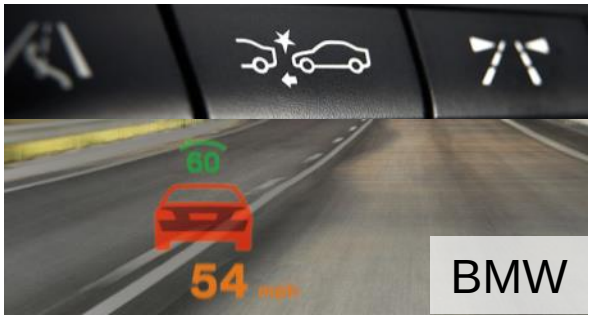
Existing Technologies



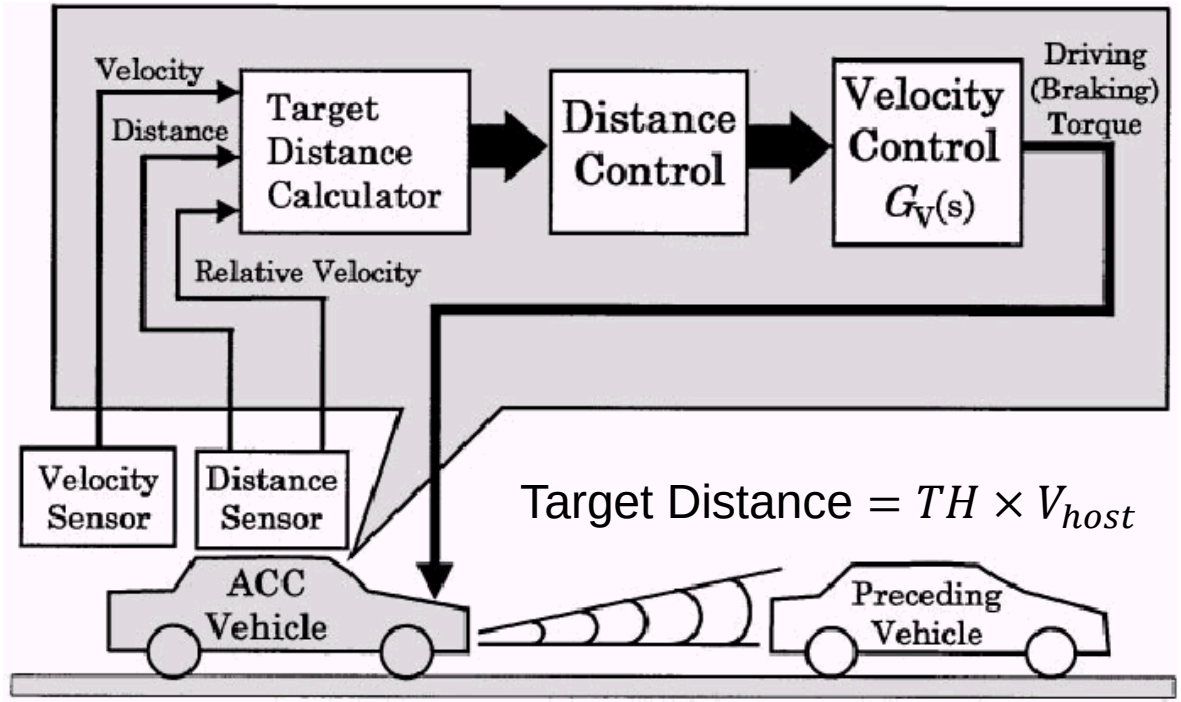


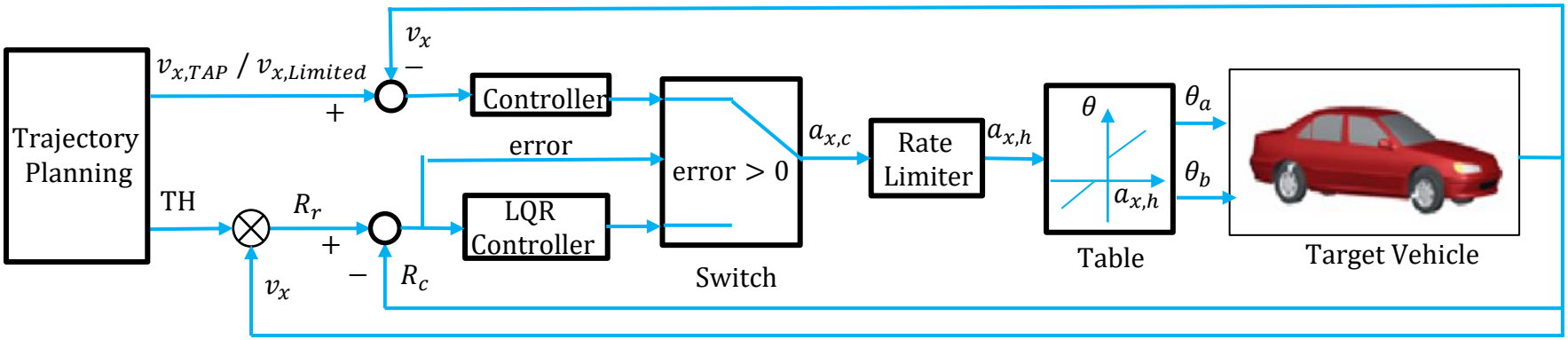






Integrated Distance & Velocity Control





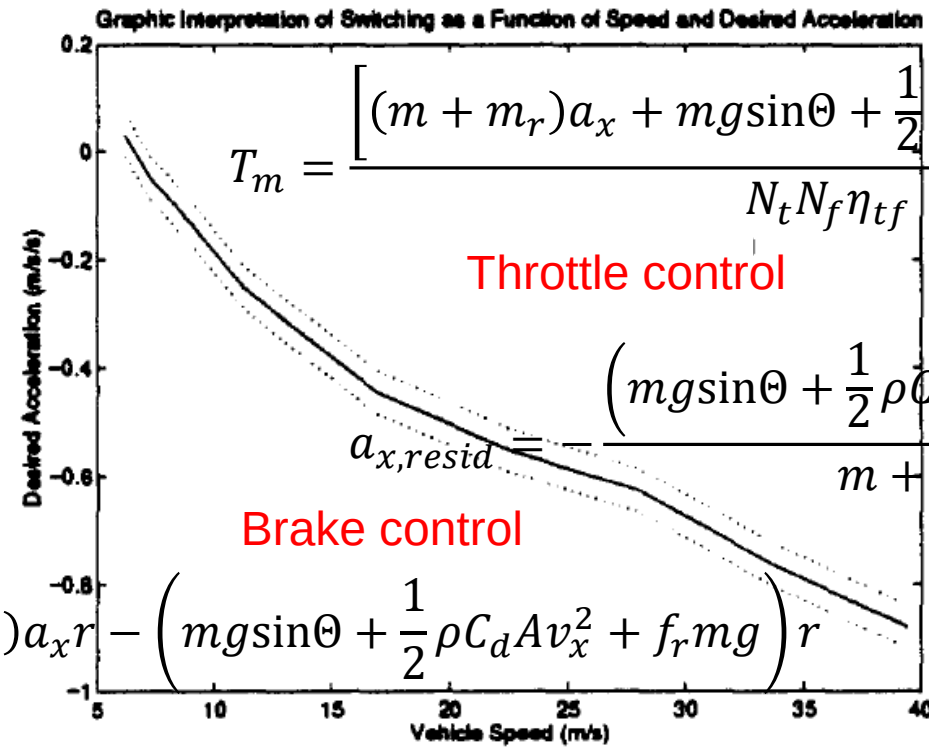
Higashimata et al., "Design of a headway distance control system for ACC," JSAE Review 22 (2001)

Low Level Torque Control

- Longitudinal Vehicle Dynamics

$$(m+m_r)a_x = \frac{T_m N_t N_f \eta_{tf} - T_b}{r} - mg\sin\Theta - \frac{1}{2}\rho C_d A v_x^2 - f_r mg$$

gravity force | aerodynamic drag | rolling resistance



$$T_m = \frac{\left[(m+m_r)a_x + mg\sin\Theta + \frac{1}{2}\rho C_d A v_x^2 + f_r mg\right] r}{N_t N_f \eta_{tf}}$$

Throttle control

$$a_{x,resid} = -\frac{\left(mg\sin\Theta + \frac{1}{2}\rho C_d A v_x^2 + f_r mg\right)}{m+m_r}$$

Brake control

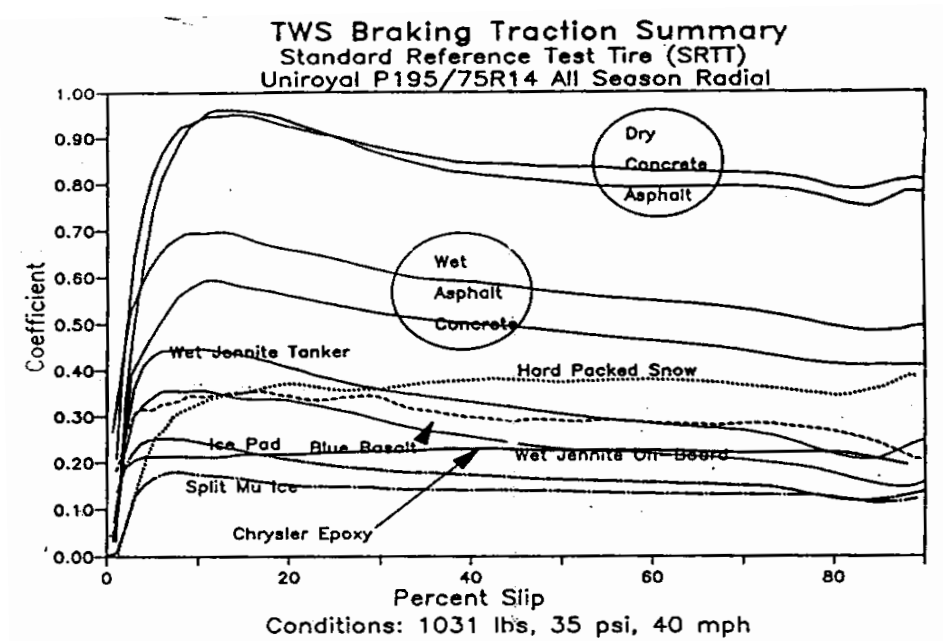
$$T_b = -(m+m_r)a_x r - \left(mg\sin\Theta + \frac{1}{2}\rho C_d A v_x^2 + f_r mg\right) r$$

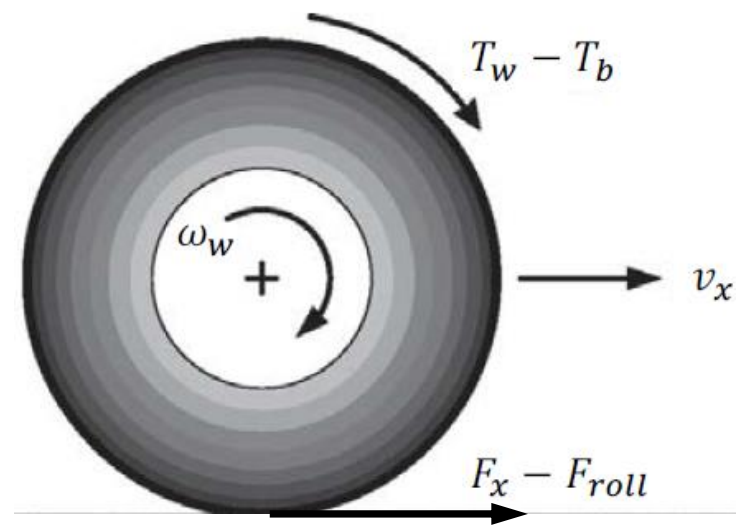
Vehicle speed and spacing control via coordinated throttle and brake actuation, 1997

Slip Ratio Control

- Maintain the slip ratio in the stable region
  - Anti-lock braking system
  - Traction control system
- Generate the desired longitudinal tire force

$$F_x = \mu(\lambda) F_z$$



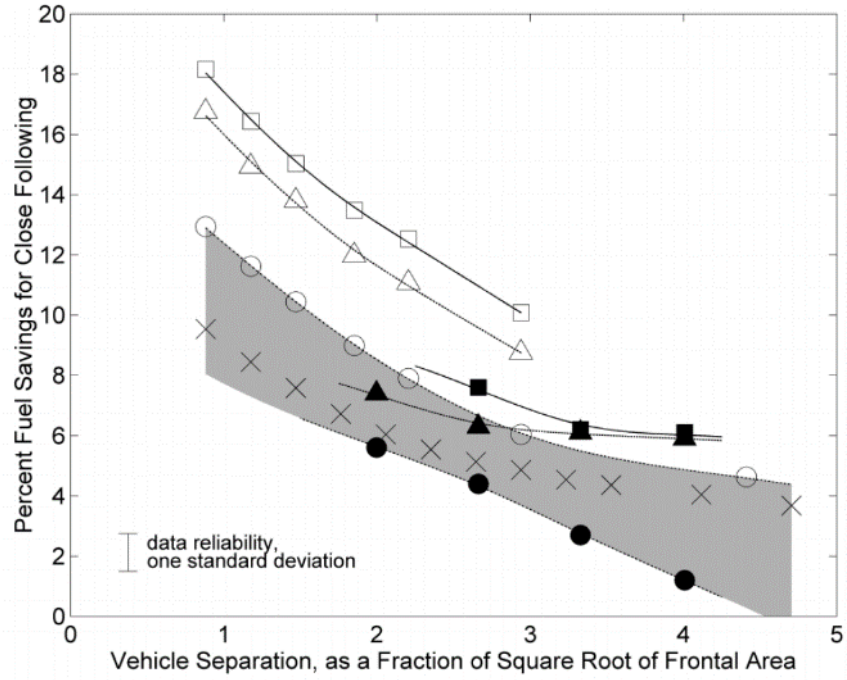


Stop & Go Demo

Platoon (Cooperative ACC)

- Truck platoon demo reveals 15% bump in fuel economy
  - Lower aerodynamic drag resistance results as the rear vehicles
  - the lead truck can benefit from less drag at its rear as the pressure wave ahead of the tailing vehicle in effect “pushes” the lead truck forward.

Source: http://articles.sae.org/11937/



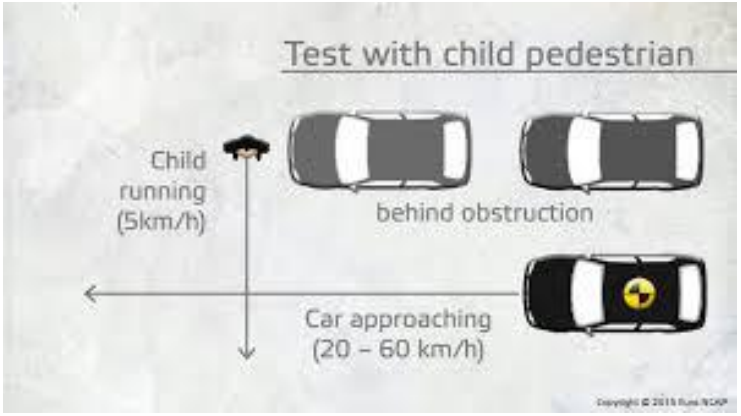
Source: UCB-ITS-PRR-2000-14

Autonomous Emergency Braking

- From 2014 onward, Euro NCAP will include AEB in its assessment, which will make it impossible for any model without the tech to achieve a five-star safety rating.
  - Autonomous: the system acts independently of the driver to avoid or mitigate the accident.
  - Emergency: the system will intervene only in a critical situation.
  - Braking: the system tries to avoid the accident by applying the brakes.
- Activate full braking when time-to-collision (TTC) is less than a certain critical value.

$$TTC = \frac{R}{\dot{R}}$$

$$TTC = \frac{-\hat{V} \pm \sqrt{\hat{V}^2 - 2\hat{A}\hat{R}}}{\hat{A}}$$



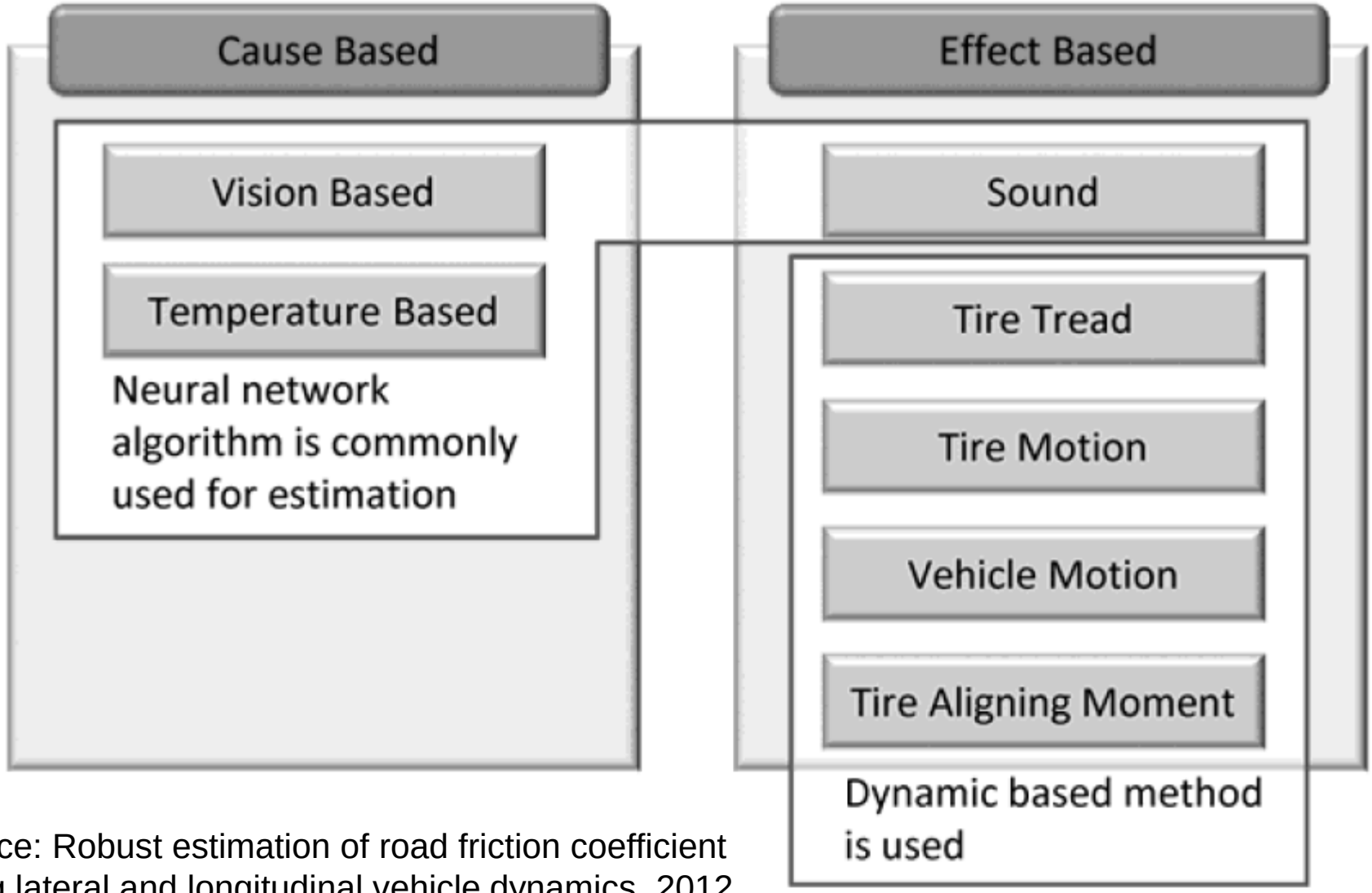
Relative Acceleration Estimation

- Lee and Peng (2005) mentioned that the leading vehicle acceleration is a critical step for developing practical collision warning/avoidance systems.

$$TTC = \frac{-\hat{V} \pm \sqrt{\hat{V}^2 - 2\hat{A}\hat{R}}}{\hat{A}}$$

- Good estimation of relative acceleration is the key to reduce the false alarm of FCWS.
  - Dagan et al. (2004) calculated TTC from the momentary TTC and its derivative, which is closely related to relative acceleration and can be computed by the scale change in the image.
  - Araki et al. (1996) applied a 3-state Kalman filter to estimate relative velocity and acceleration.
  - Chen (2000) proposed a forward collision warning system using relative acceleration estimation and multi-object tracking.
  - Chen et al. (2014) proposed a forward collision warning system using estimated relative acceleration and velocity vector

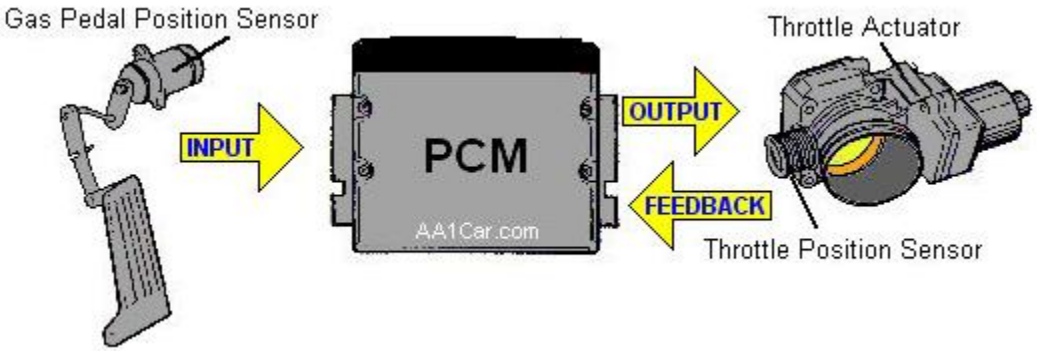
Road Friction Estimation



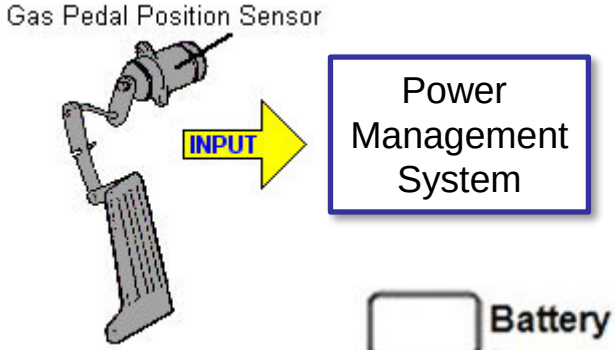
Source: Robust estimation of road friction coefficient using lateral and longitudinal vehicle dynamics, 2012.

Throttle-by-wire

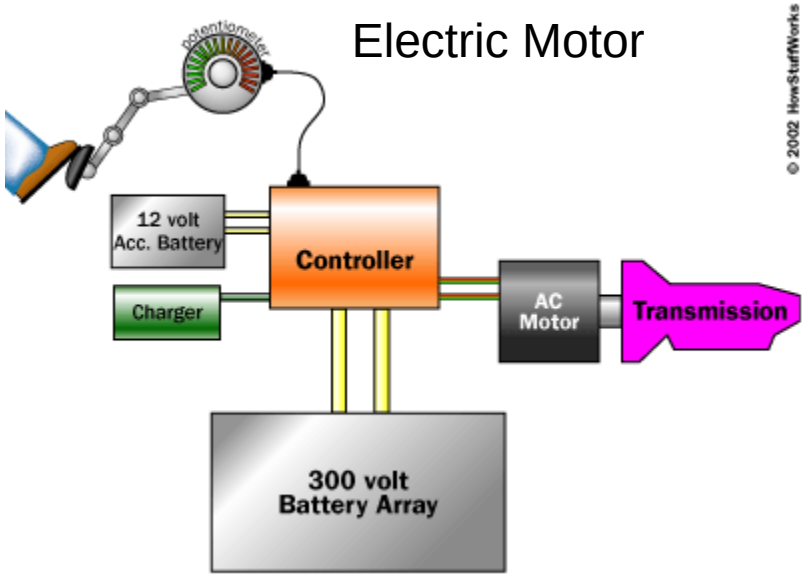
Internal Combustion Engine

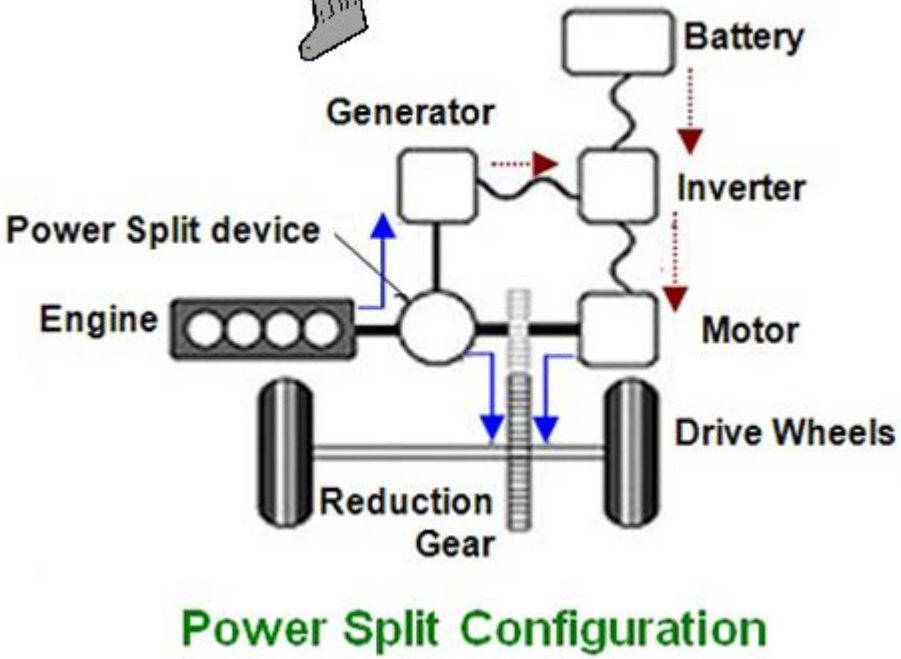


Hybrid Electric Vehicle



Electric Motor

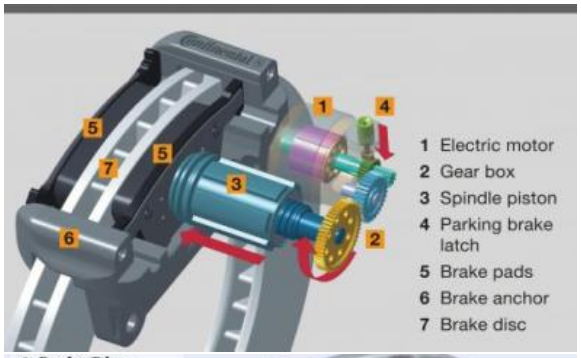




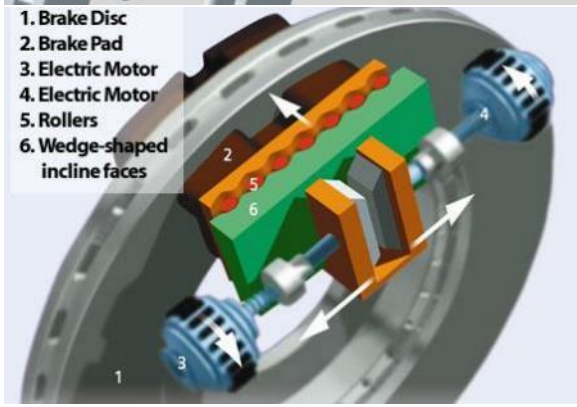
Brake-by-wire Actuators

iBooster

EHB

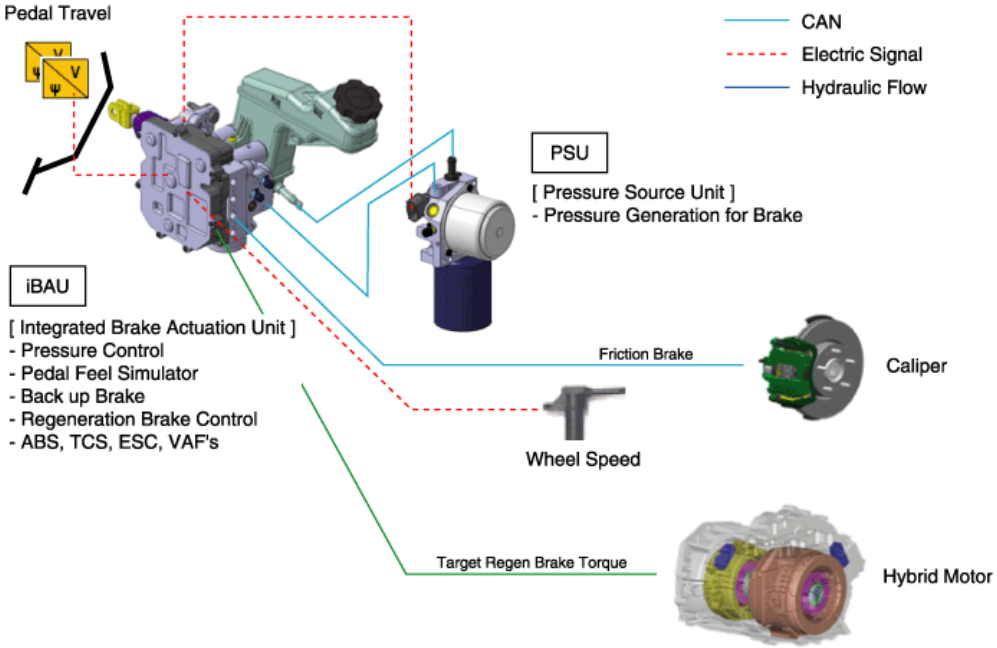


EMB

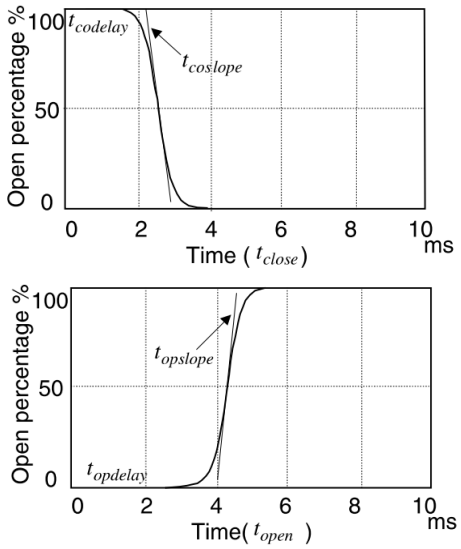


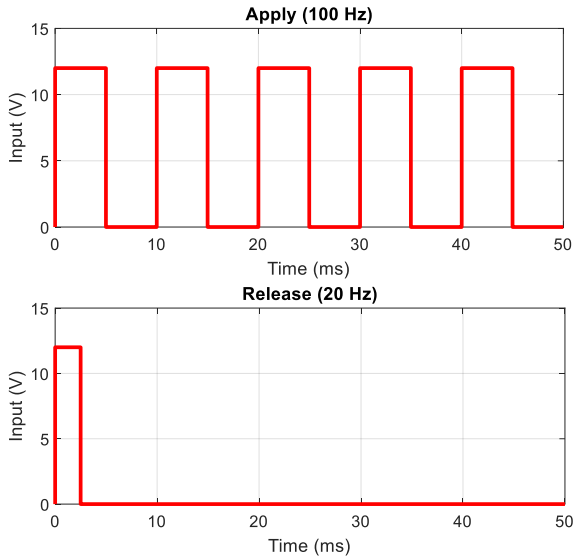
EWB

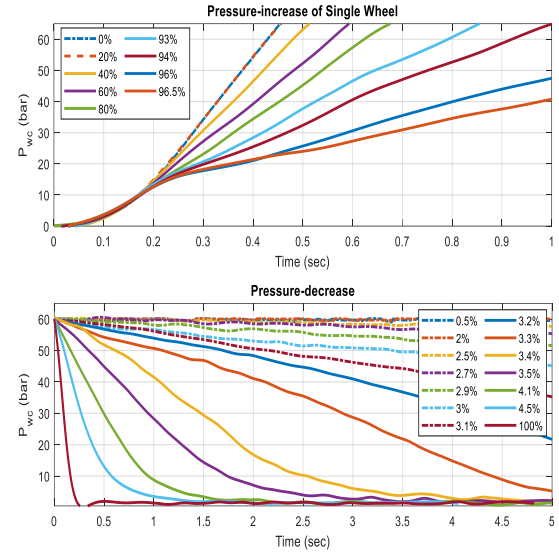
Active Hydraulic Boost

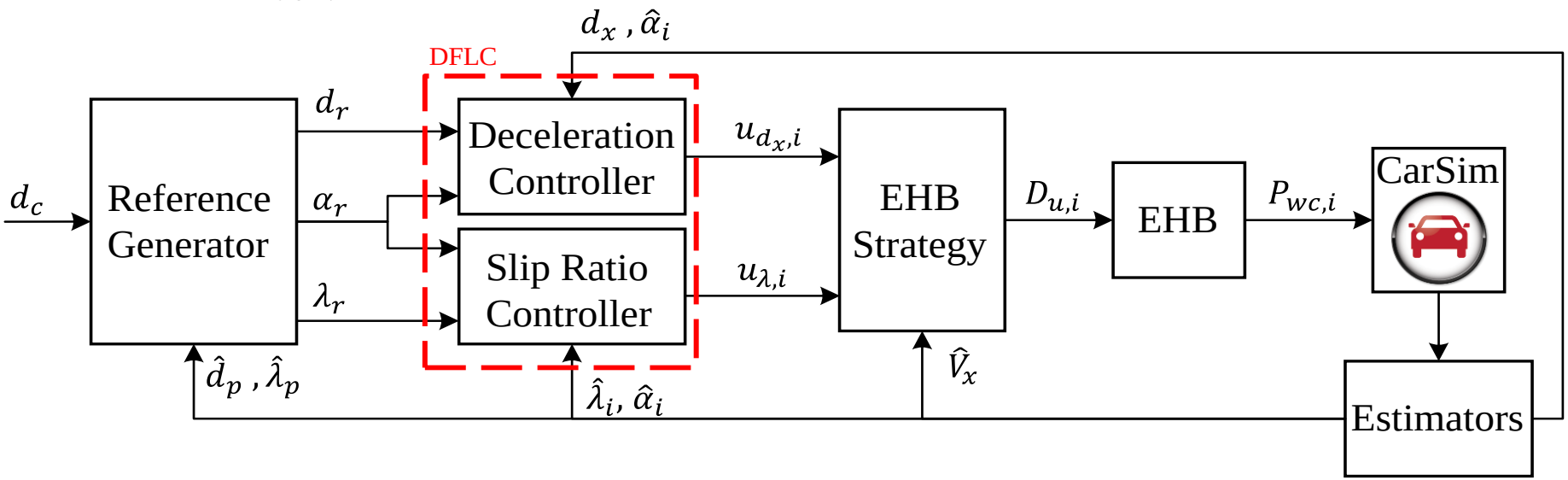


Step Pressure Increase/Decrease

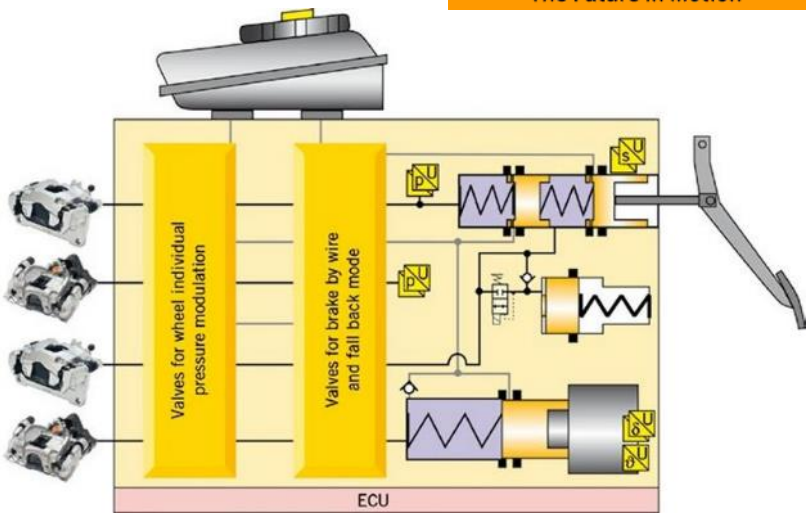


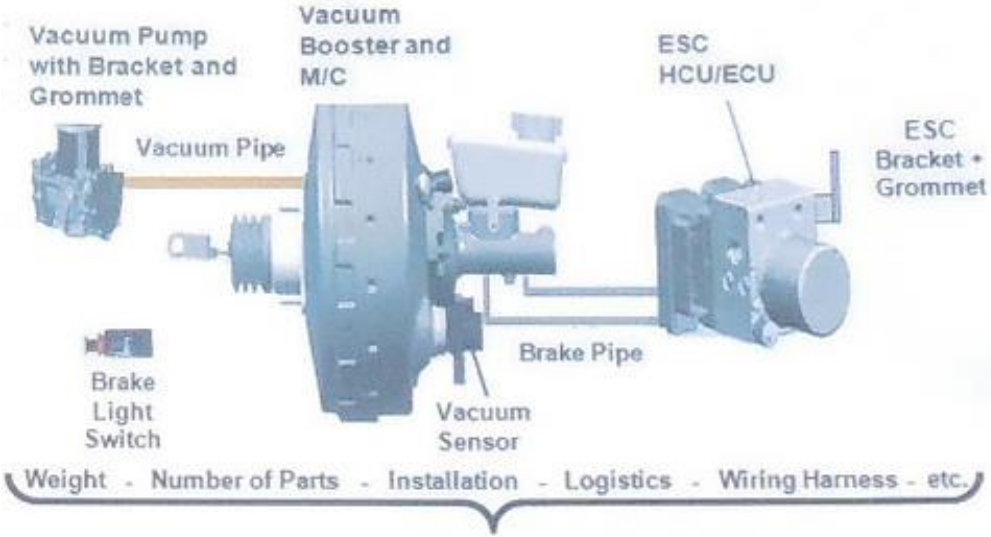


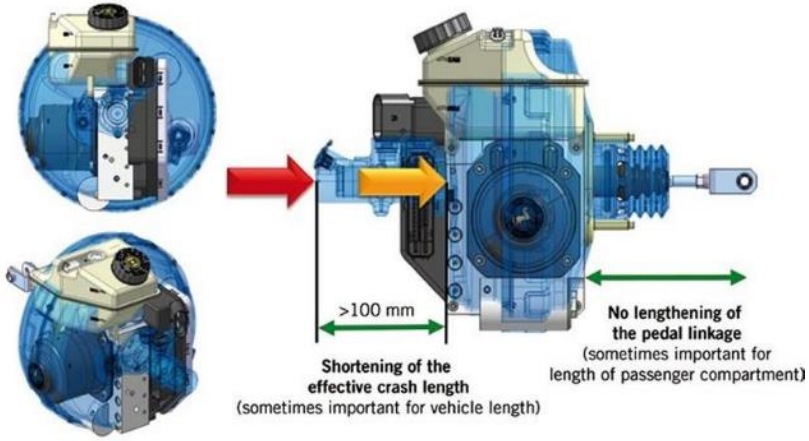


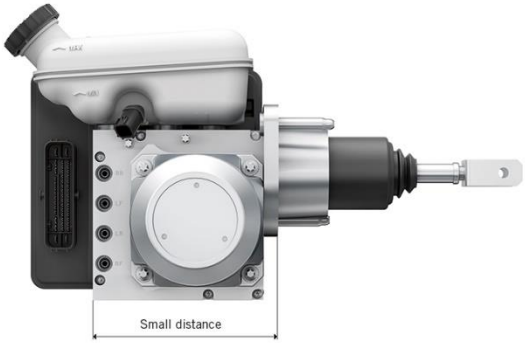


Integrated Braking



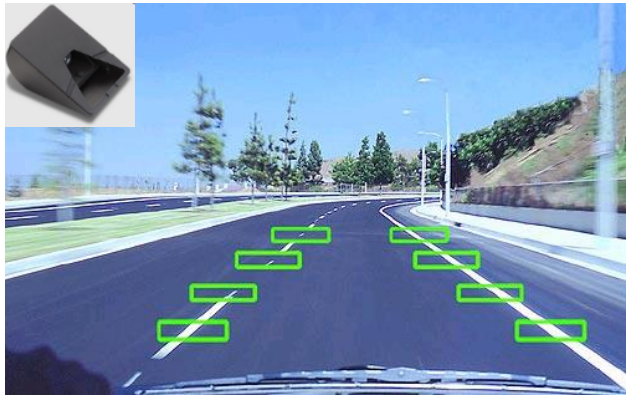


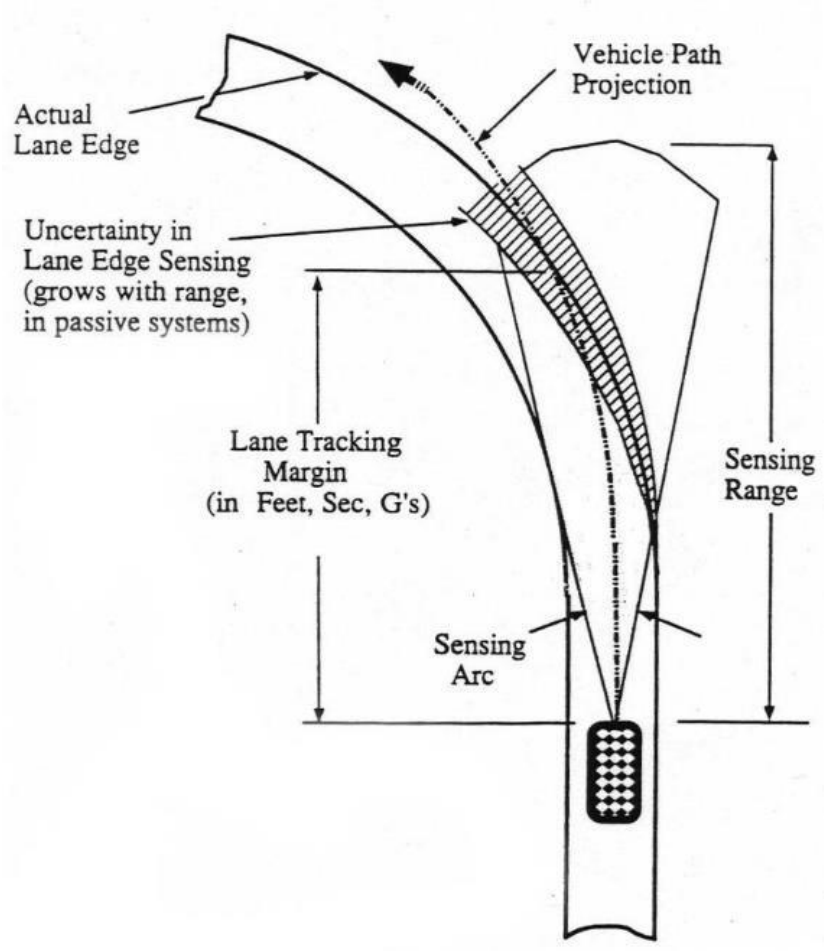




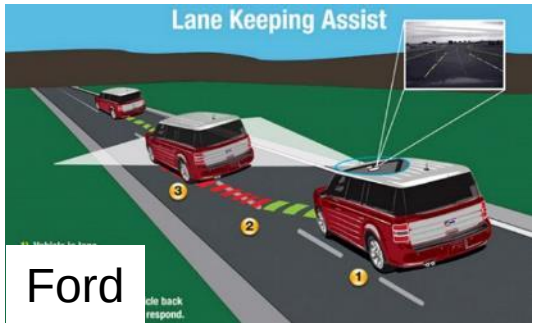
Lane Following Control

- LFC Function
  - To follow the reference line located in the middle of the lane.
- Measurements
  - Lane equations expressed in the body coordinate system.
  - Steering, yaw rate, vehicle speed, and lateral acceleration.
- Control Commands
  - Steering angle or yaw moment.

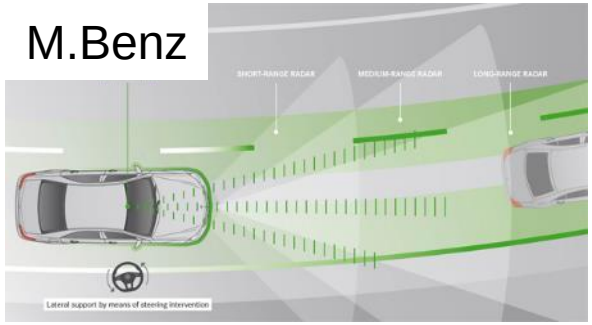




Existing Technologies

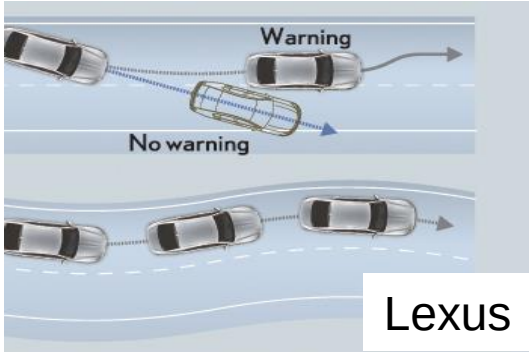


Ford

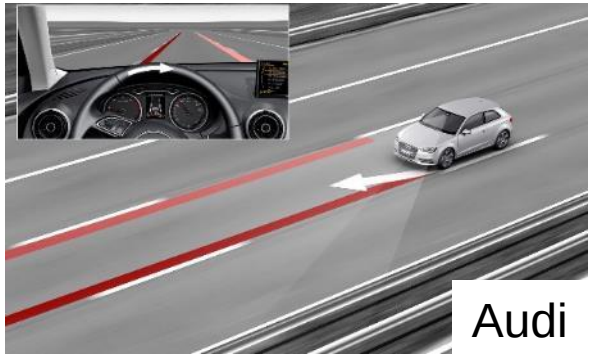


M.Benz

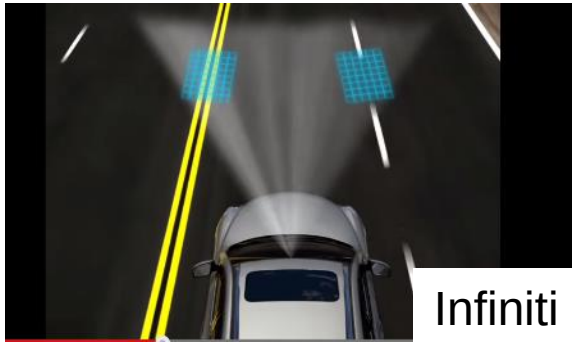
Toyota



Lexus

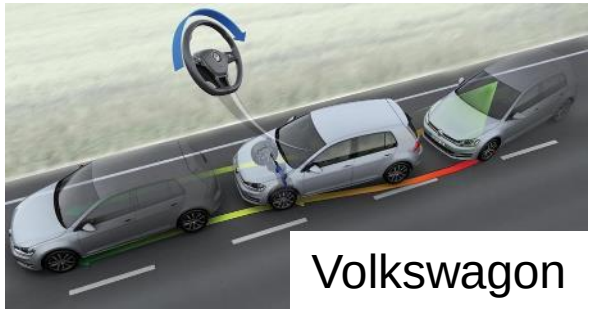


Audi



Infiniti

Hyundai

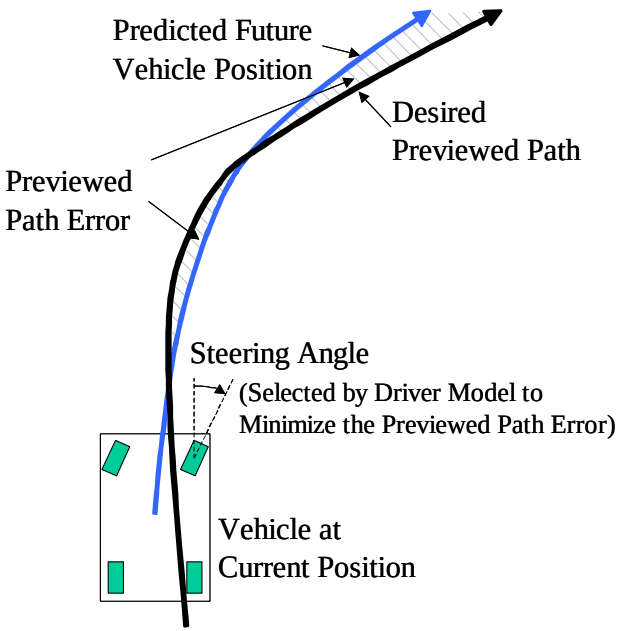


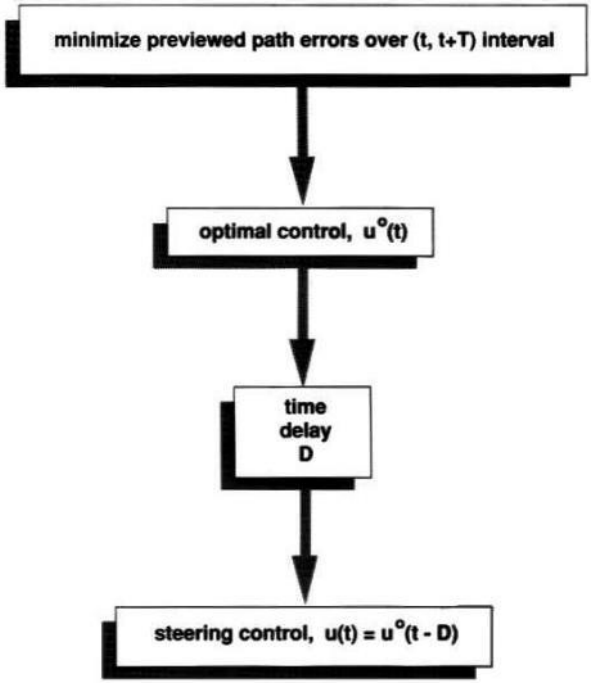
Volkswagon

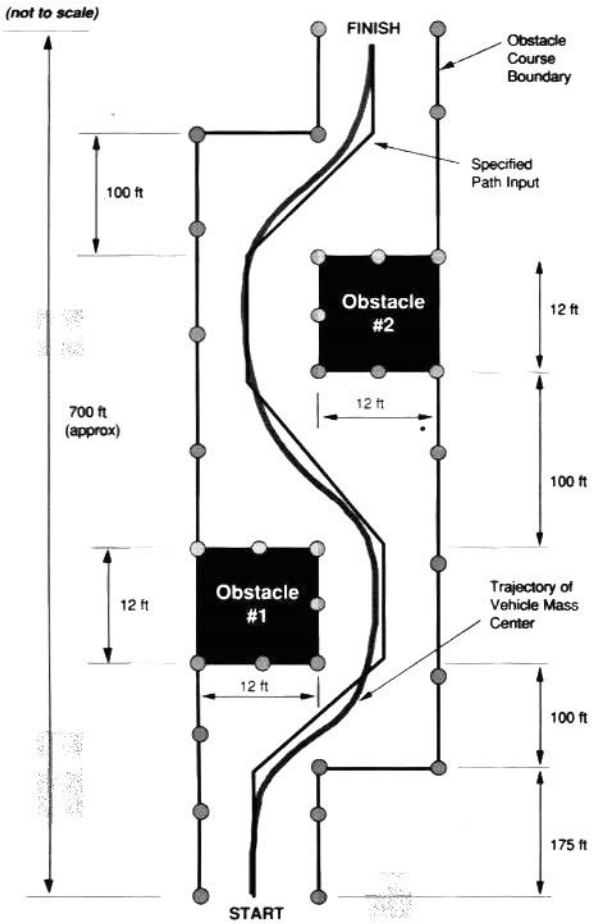
Acura

Preview/Predictive Control

- Use future road curvature (preview) and possibly future vehicle trajectory (predictive) to determine proper steering actions.



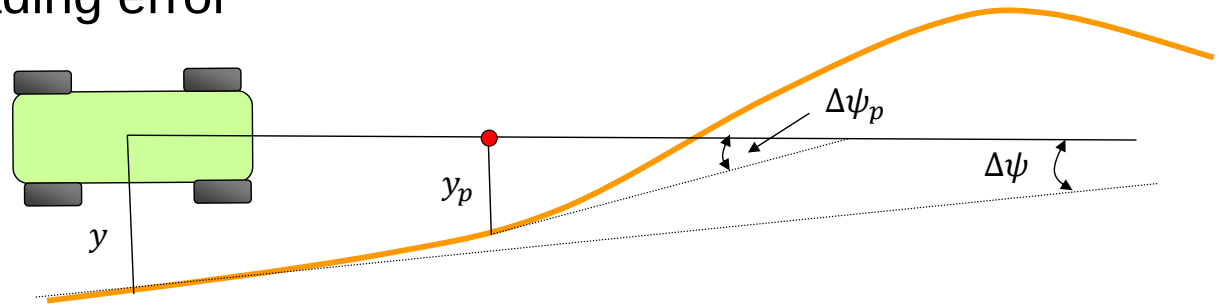




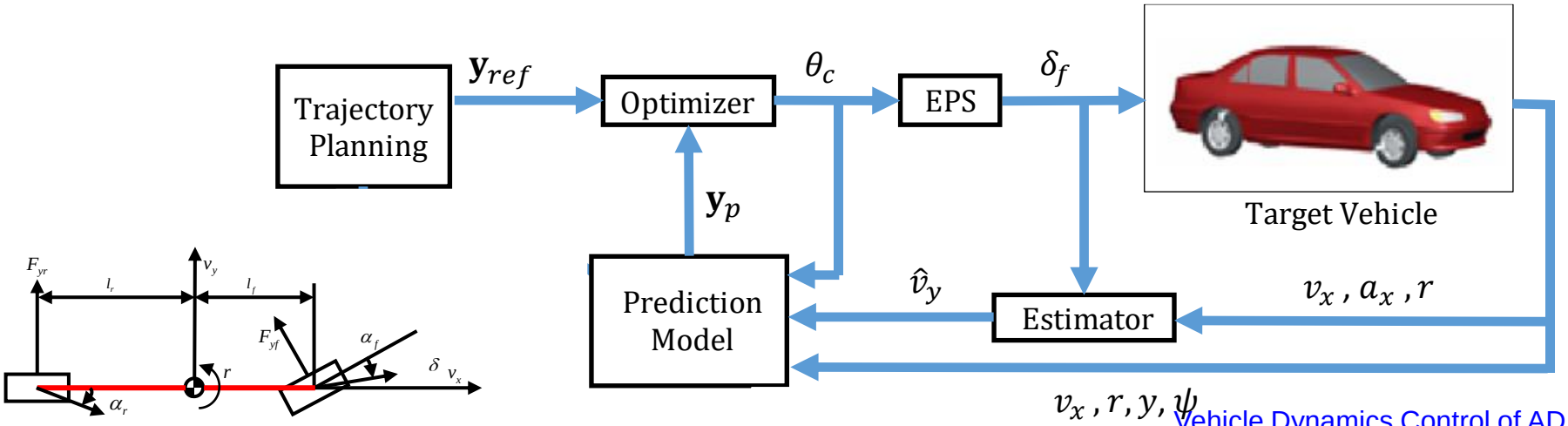
MacAdam, C. C. "Development of Driver/Vehicle Steering Interaction Models for Dynamic Analysis." Final Technical Report, UMTRI-88-53. TACOM Contract DAAE07-85-C-R069. 1988.

Control Approaches

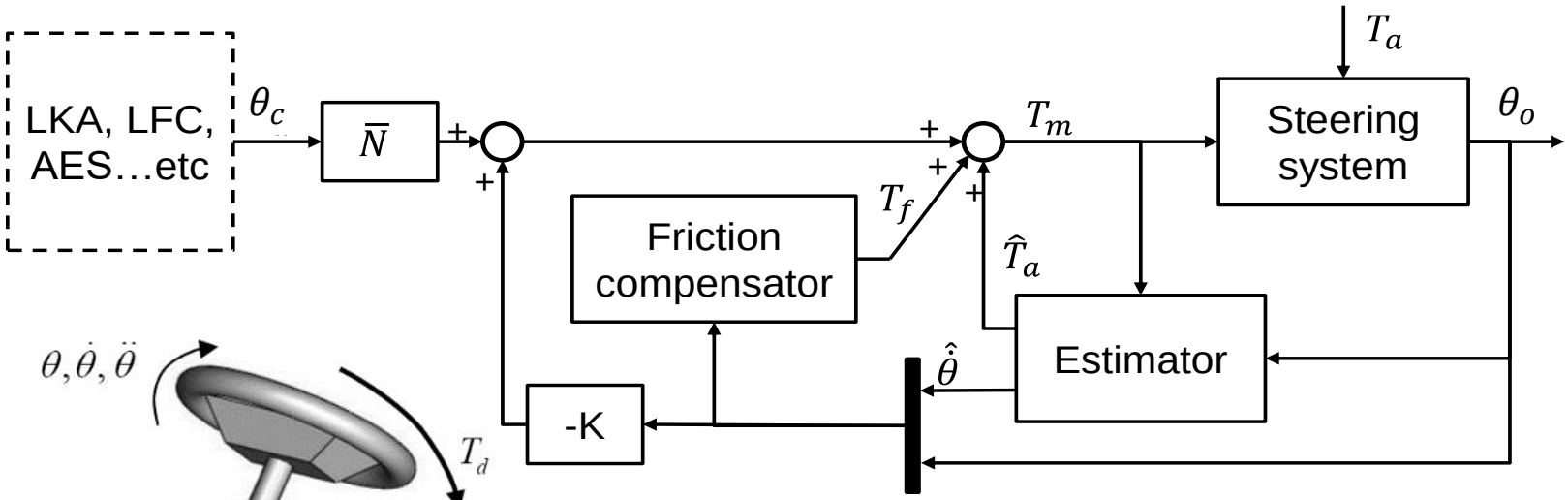
- Model Free
  - Steering control based on previewed lateral displacement and heading error

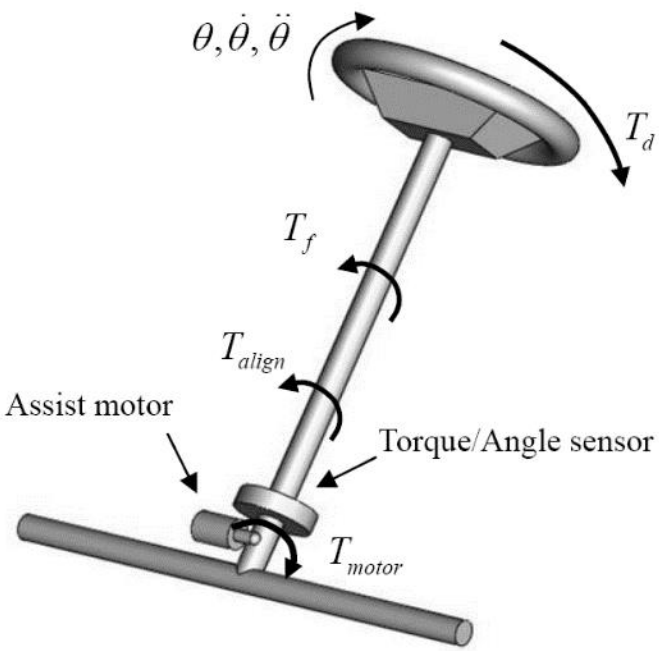


- Model Based
  - Model predictive control (MPC) based on a 4-state bicycle model



Steering Actuator Dynamics





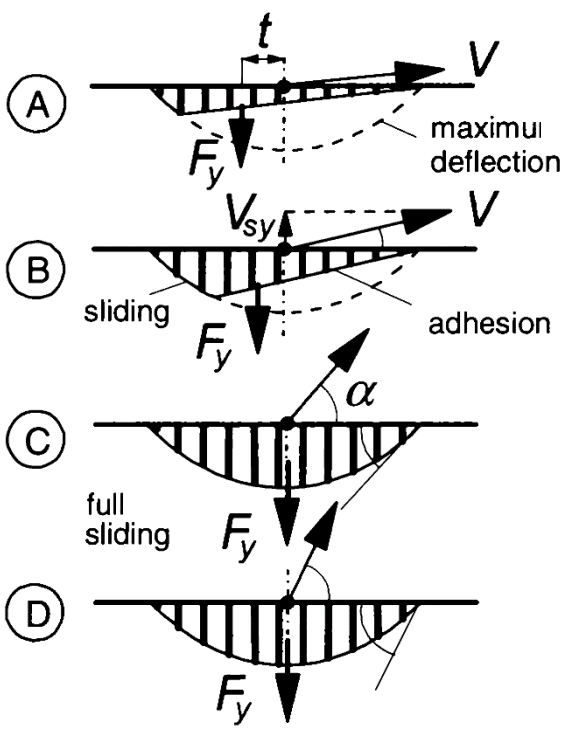
Electric Power Steering

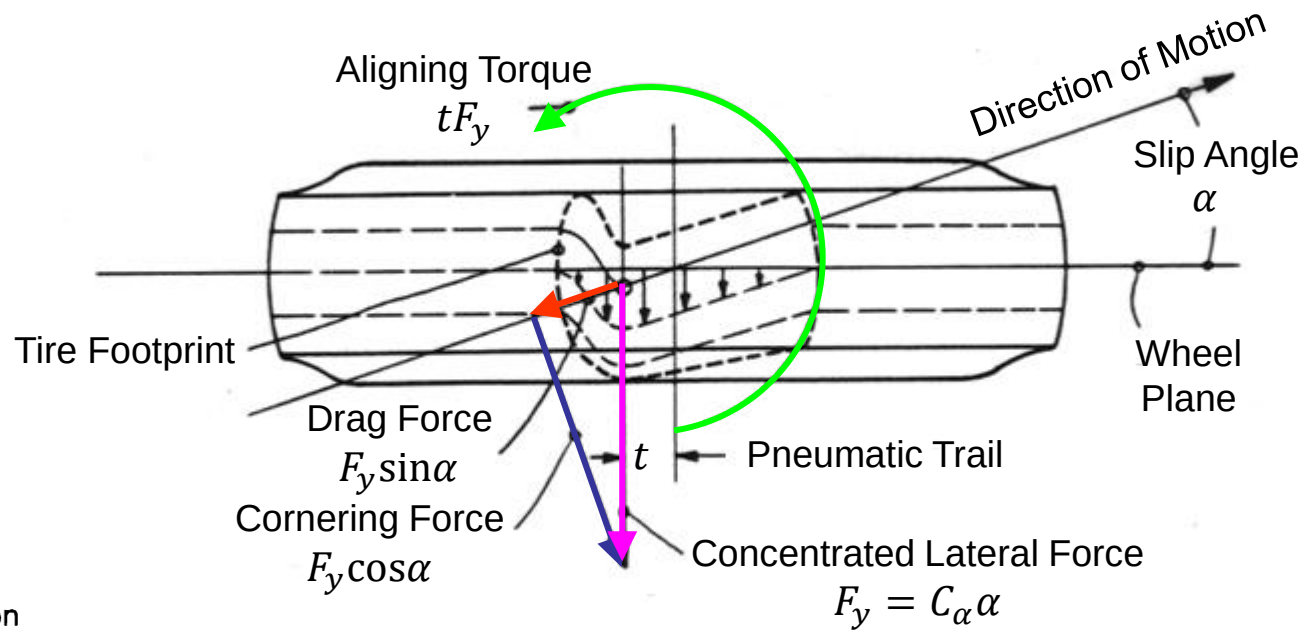
Simplification

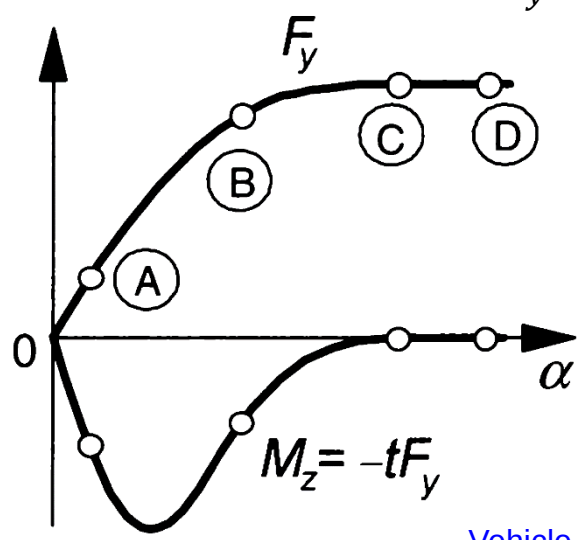
First-order dynamics

$$\theta_c \longrightarrow \boxed{\frac{1}{\tau s + 1}} \longrightarrow \theta_o$$

Lateral Slip Angle

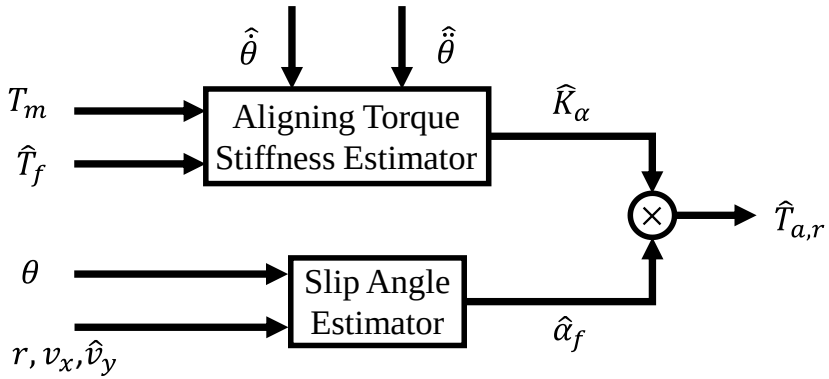


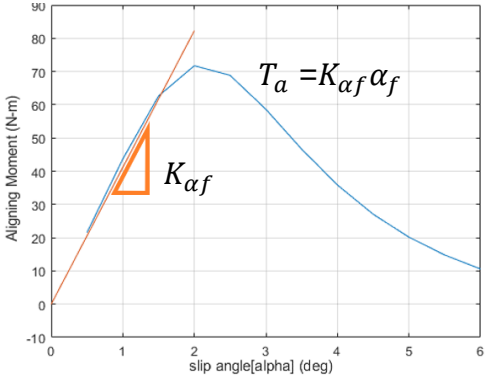




Aligning Torque Estimation

- Recursive least square with Adaptive Forgetting Factor

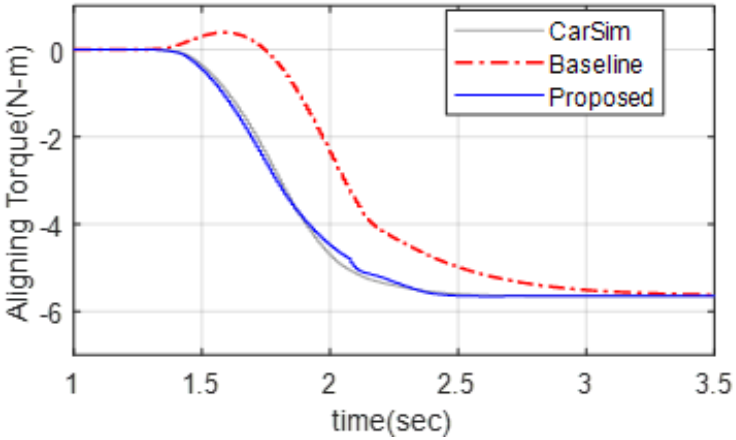




- Tire slip angle estimator

$$\hat{\alpha}_f = \delta_f - \frac{\hat{v}_y + ar}{v_x}$$

- Frozen/unfrozen rule
  - sign change of the estimated friction torque
  - angular velocity > threshold



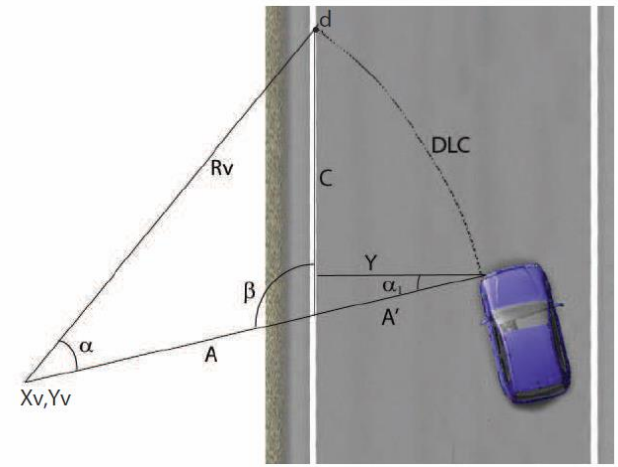
Lane Keeping Assistance Systems

- ISO 11270:2014 Intelligent transport systems -- Lane keeping assistance systems (LKAS) -- Performance requirements and test procedures
  - basic control strategy
  - minimum functionality requirements
  - basic driver interface elements
  - minimum requirements for diagnostics and reaction to failure
  - performance test procedures
- Lateral acceleration shall not exceed $3m/s^2$, and lateral jerk shall not exceed $5m/s^3$.
- The lane keeping action shall not cause a longitudinal deceleration larger than $3m/s^2$.
- As the one of examples, the system shall be tested on a curved road which has the radius 800m.

Time-to-lane Crossing for LKAS

- Look sideways

$$TLC = \frac{d}{v_y}$$



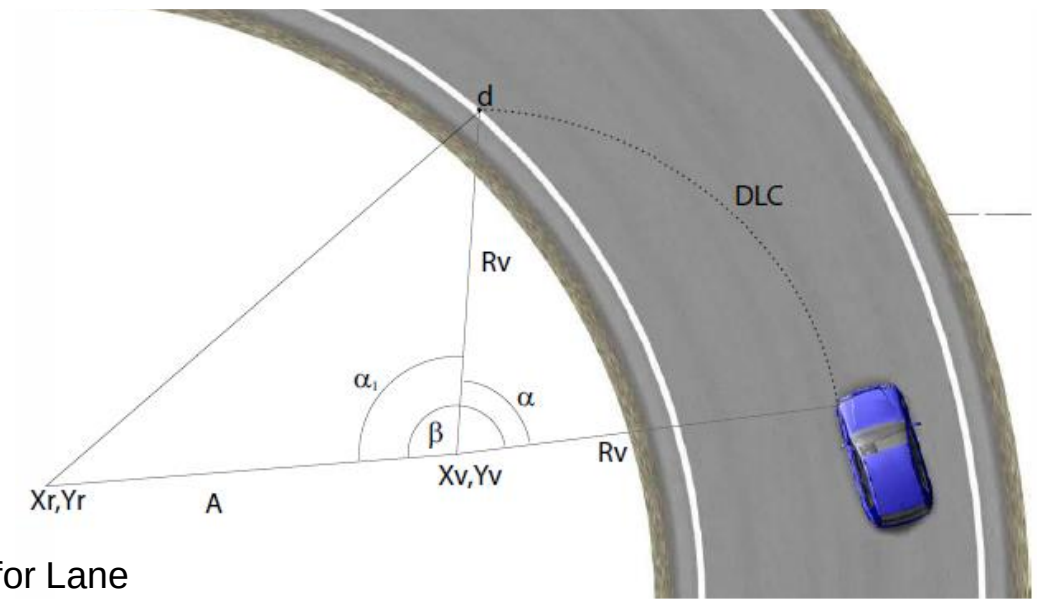
- Constant acceleration

$$d = v_x \tan\theta \cdot TLC + \frac{1}{2} a_y \cdot TLC^2,\ a_y = r v_x$$

- Distance to lane crossing

$$TLC = \frac{DLC}{v_x}$$

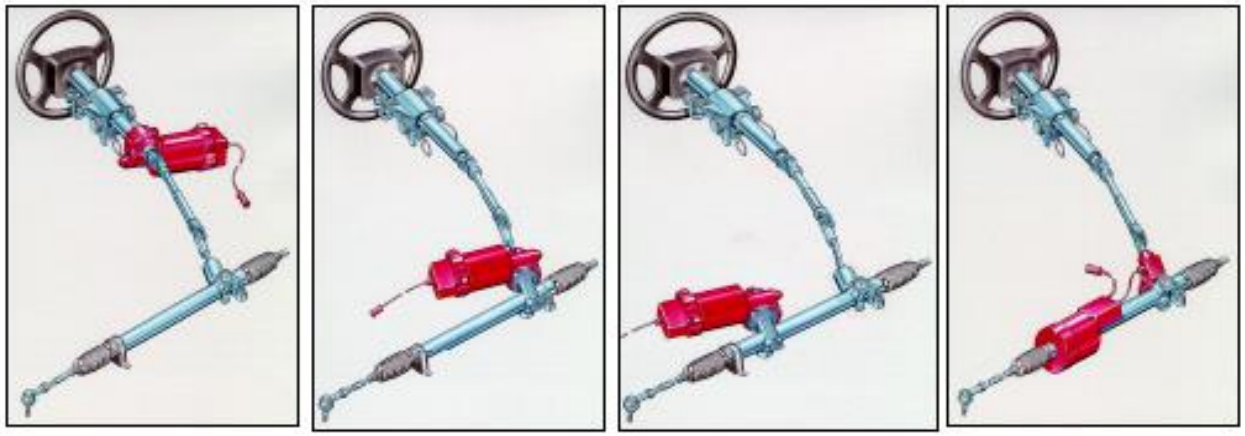
- Model-based prediction



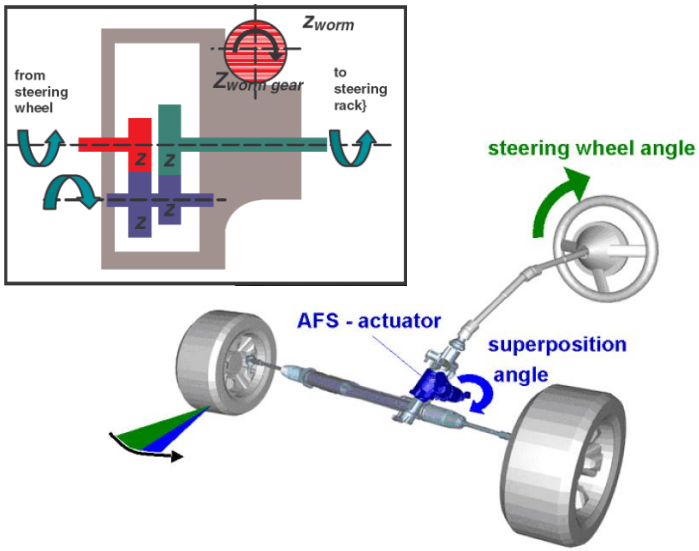
Predictive Time-to-lane-crossing Estimation for Lane Departure Warning Systems, 2009.

Steer-by-wire Actuators

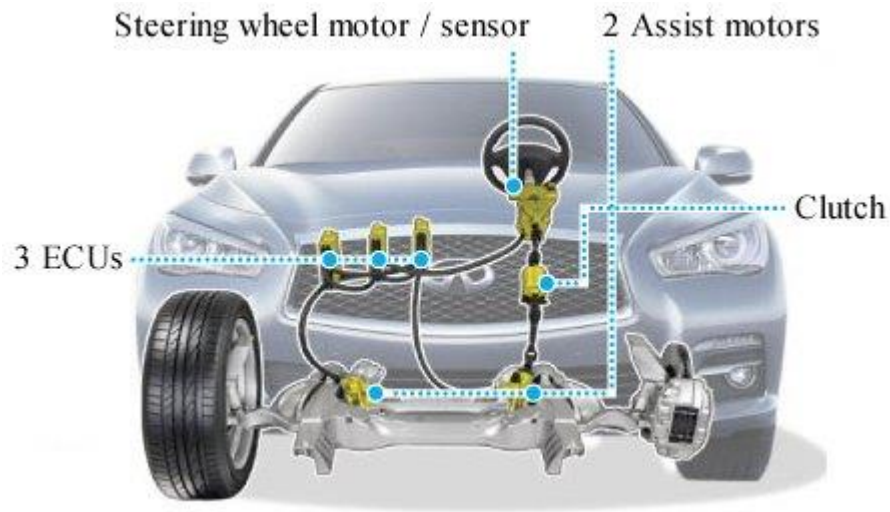
Electric power steering (EPS)



Active steering

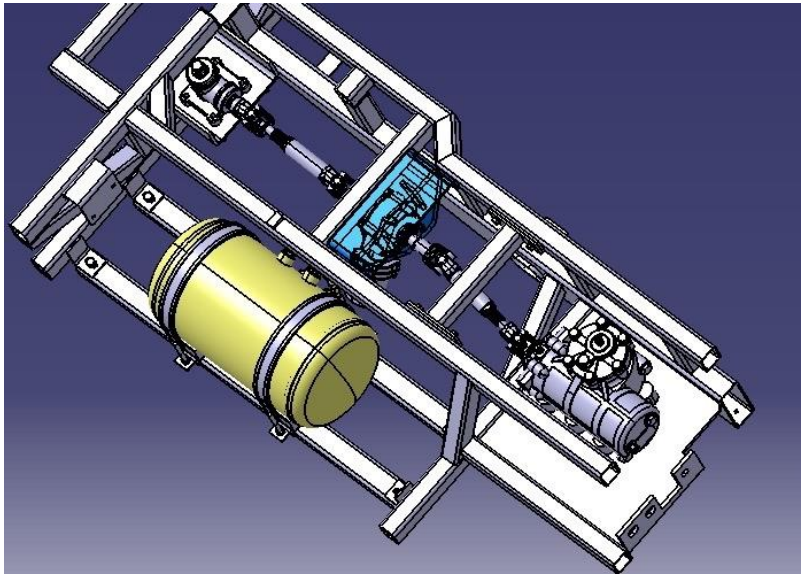


Steer-by-wire



Hardware-in-the-loop Experiment

LKA for Electric Bus

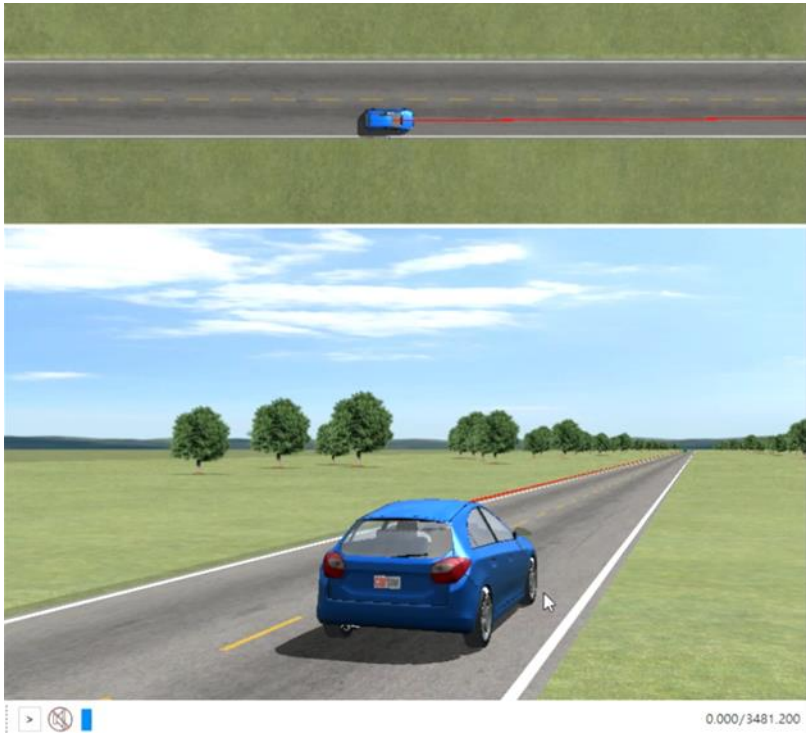


Level 2 ADAS Demo

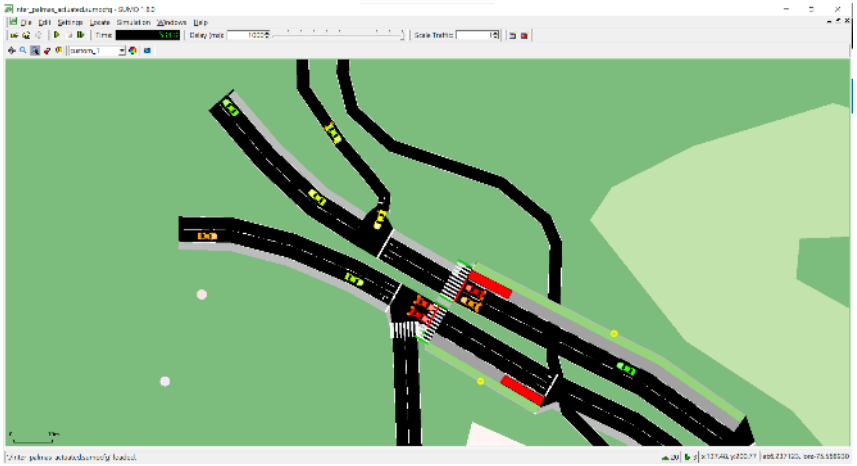
- Lane Following Control + ACC

Level 2+ Automatic Lane Change

- CarSim
  - Front leading vehicles with different slower speeds (v_{FV}=0~30km/hr)
  - On-coming vehicle with a constant cruising speed (v_{OV}=50km/hr)
- SUMO is used to provide traffic flow dynamics



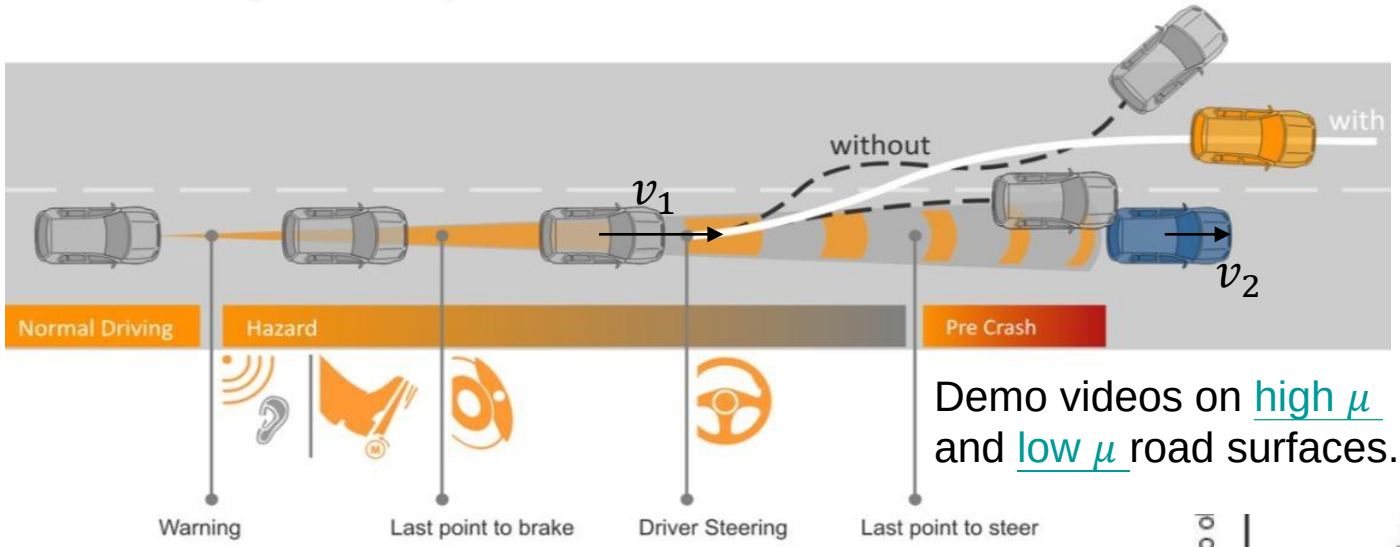
CarSim verifications (8x play speed)



SUMO traffic flow

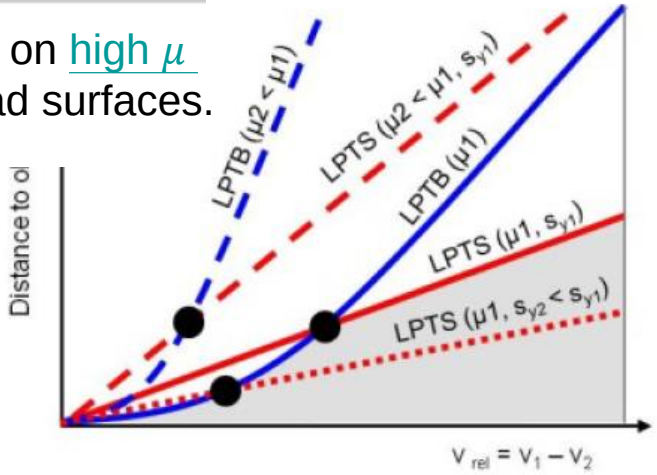
Autonomous Emergency Steering

- Automatic evasive maneuver for collision avoidance



s_y necessary lateral offset

Demo videos on high μ and low μ road surfaces.



μ: tyre/road friction
s_y: necessary lateral offset

Last point to brake (LPTB):

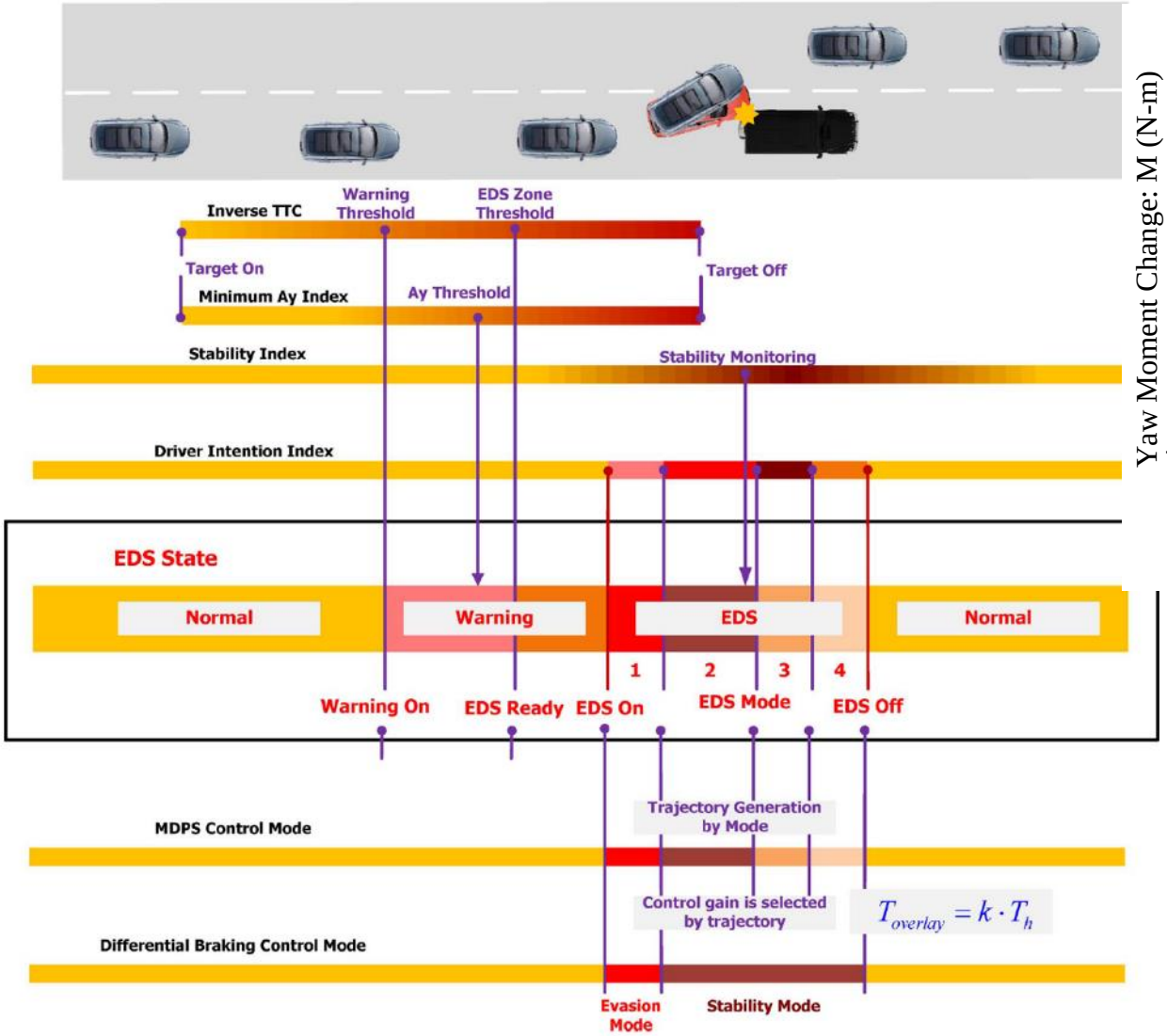
$$d_b = -\frac{1}{2a_x} * v^2_{rel}$$

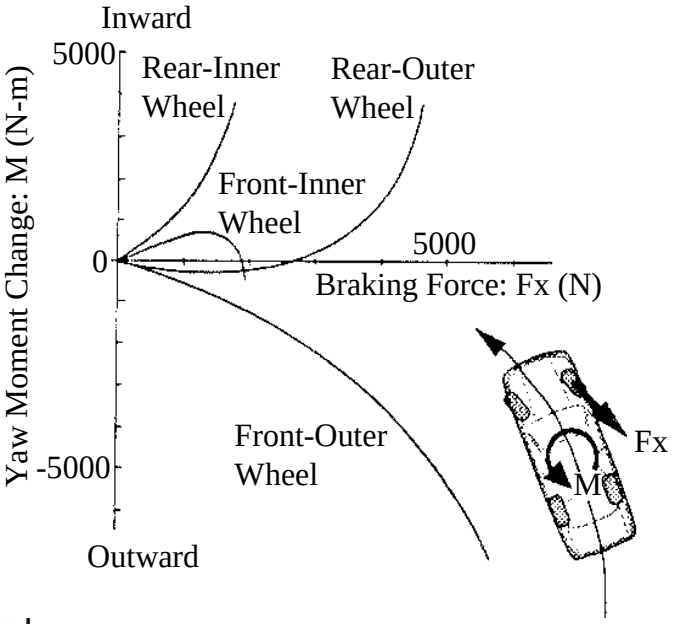
Last point to steer (LPTS):

$$d_e = \sqrt{\frac{2s_y}{a_y}} * v_{rel}$$

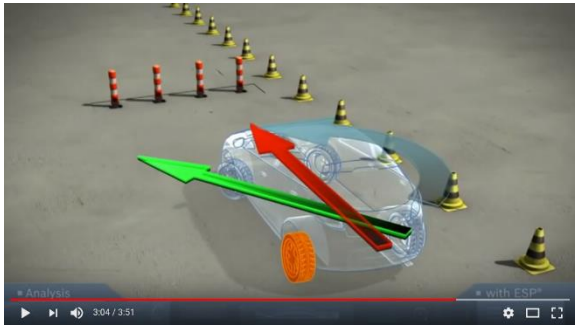
Source: Continental, Emergency Steer and Brake Assist, ESV 22, 2011

AES + ESC





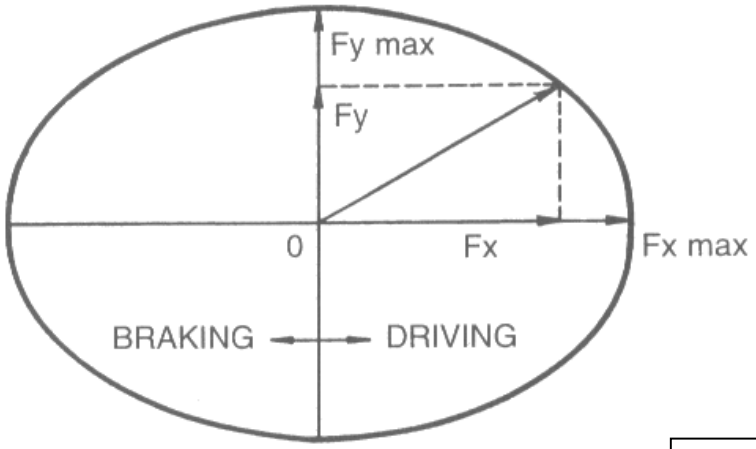
Source: SAE 960487



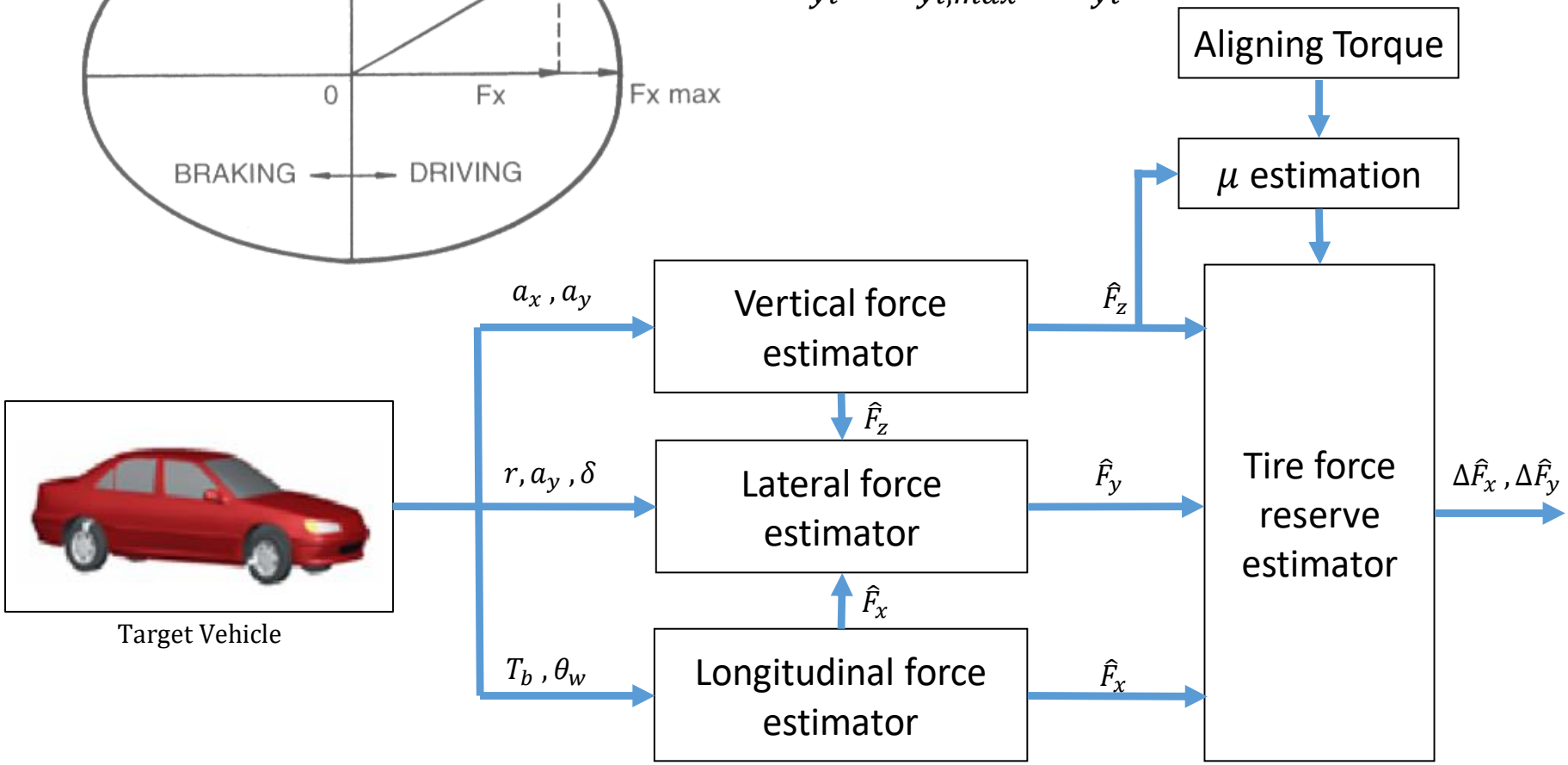
Source: Coordinated Control of Motor-Driven Power Steering Torque Overlay and Differential Braking for Emergency Driving Support, 2014.

Tire Force Reserve Estimator

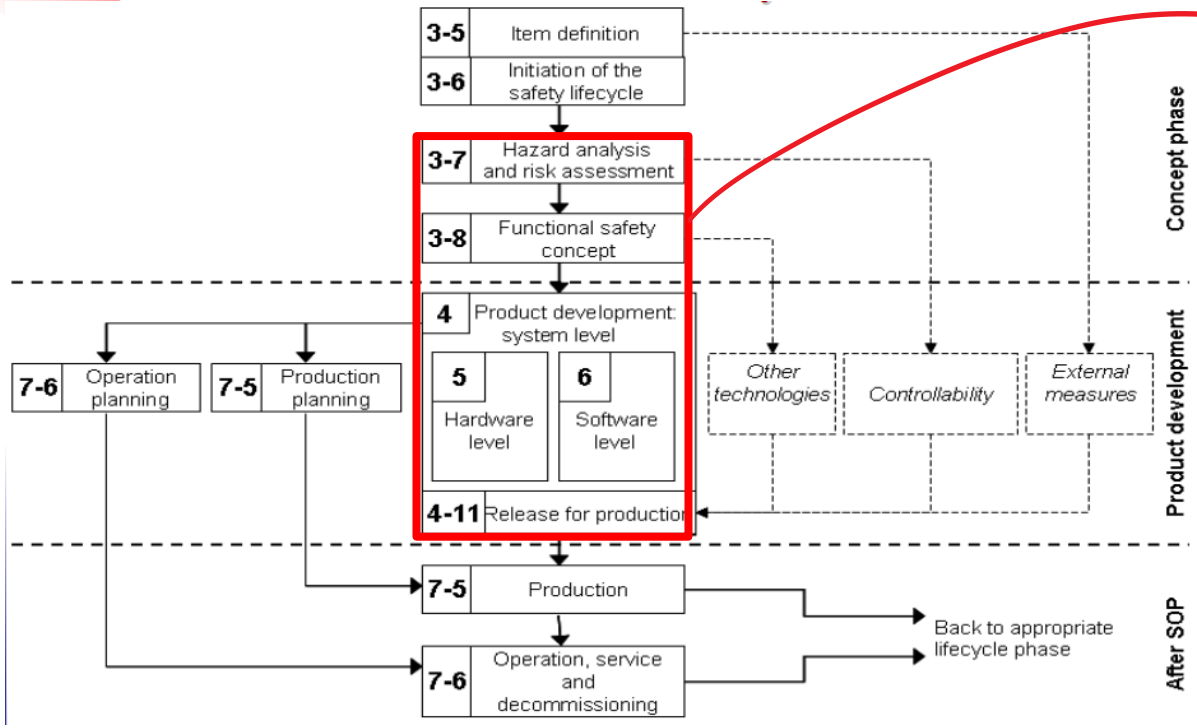
- Model-based approach

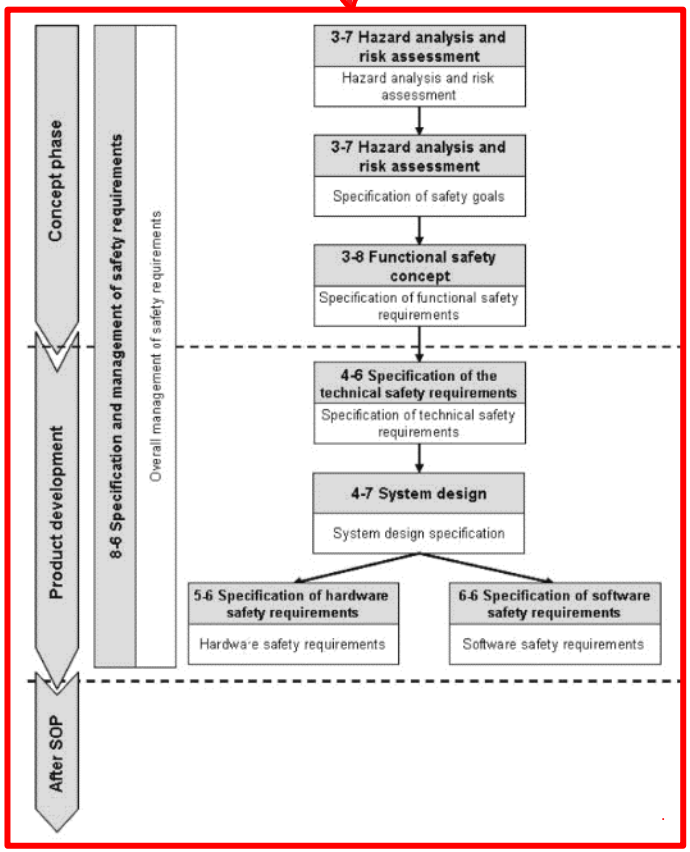


$$\Delta\hat{F}_{xi} = \hat{F}_{xi,max} - \hat{F}_{xi}$$
$$\Delta\hat{F}_{yi} = \hat{F}_{yi,max} - \hat{F}_{yi}$$



ISO 26262 Functional Safety





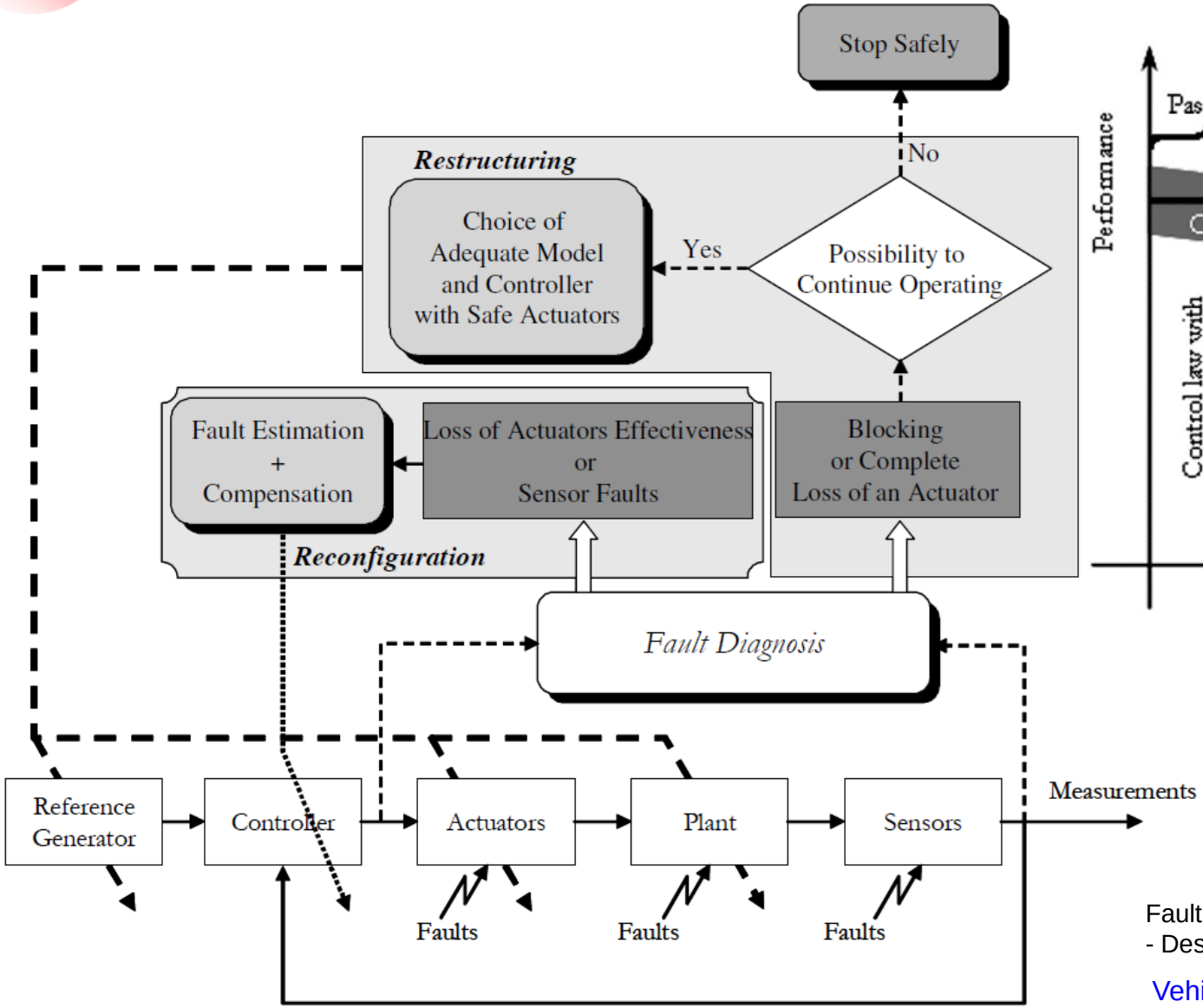
Safety analysis both deductive (**FTA**) and inductive (**FMEA**) are highly recommended methods for ASIL C/D

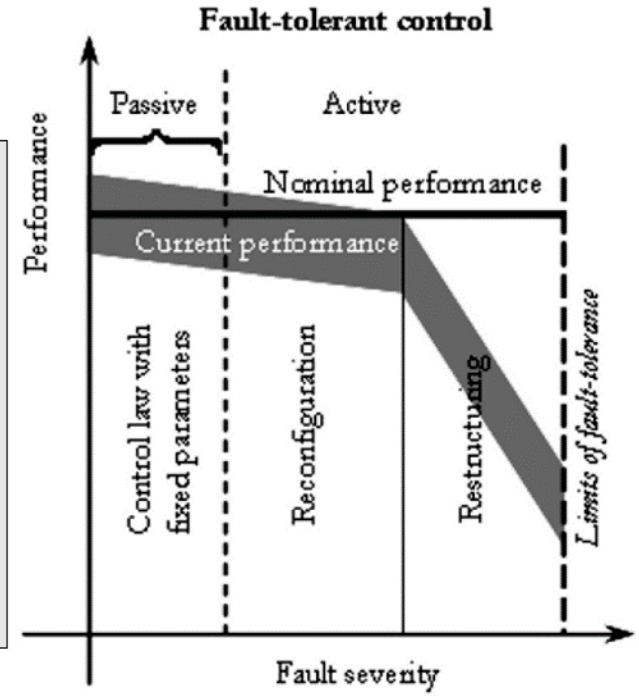
Simulation and prototyping are highly recommended methods for system, HW and SW design verification, specially as a **fault-injection technique**

Integrate and test at **hardware/software, system and vehicle levels** using different methods:

- Requirement-based testing
- **Fault-injection testing**
- Performance testing
- Etc.

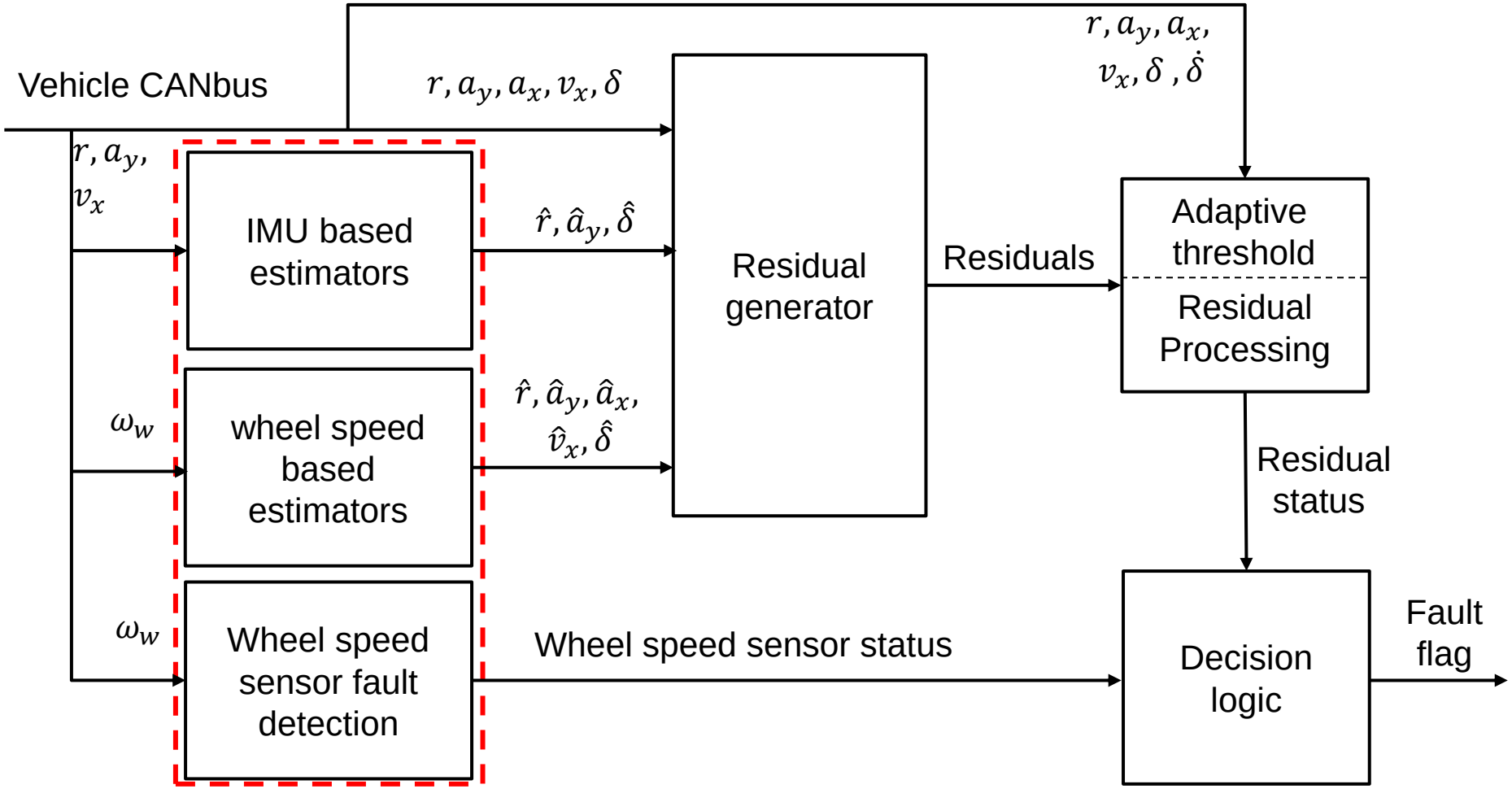
Fault-tolerant Control





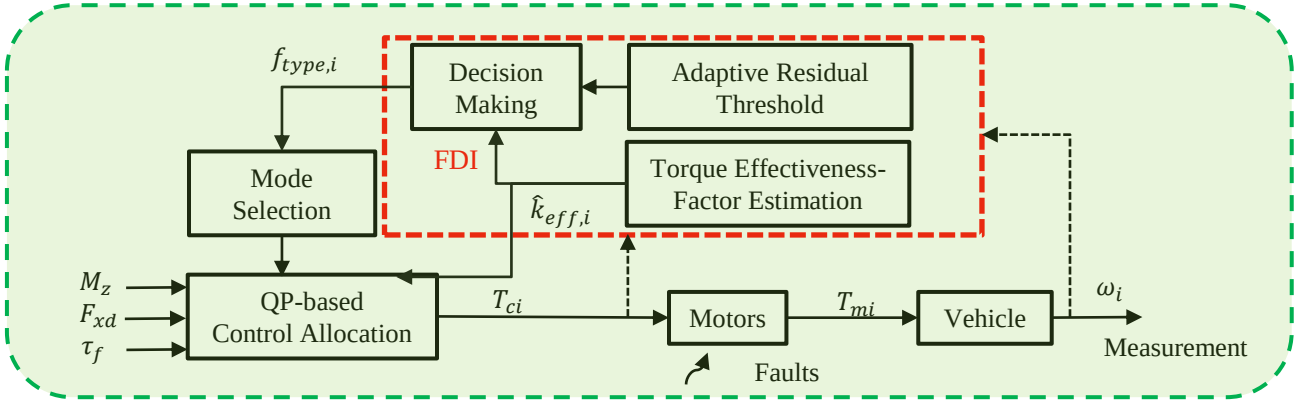
Fault-tolerant Control Systems
- Design and Practical Applications, 2009

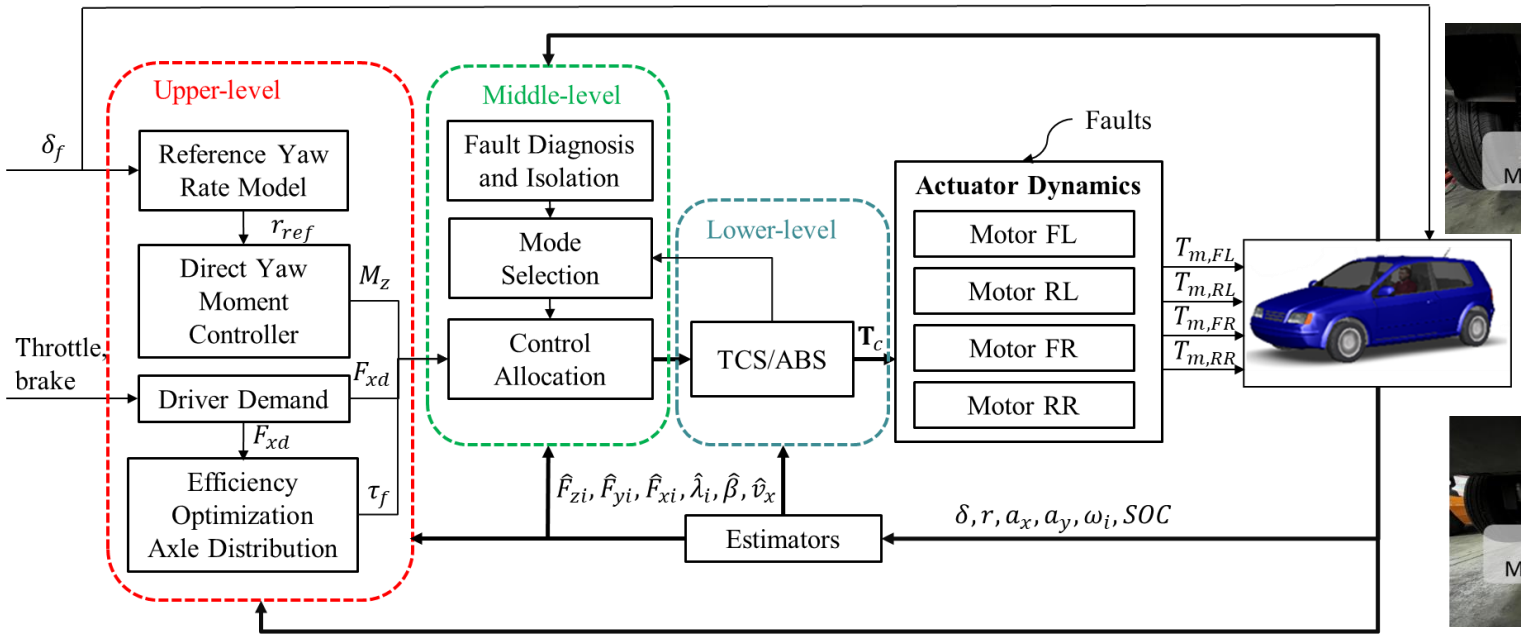
Sensor Fault Detection

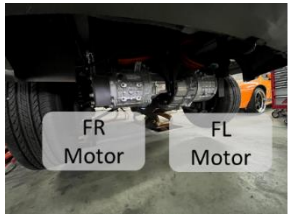


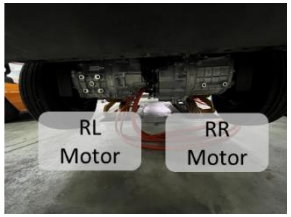
Actuator Fault Detection

- Active Fault Tolerant Control



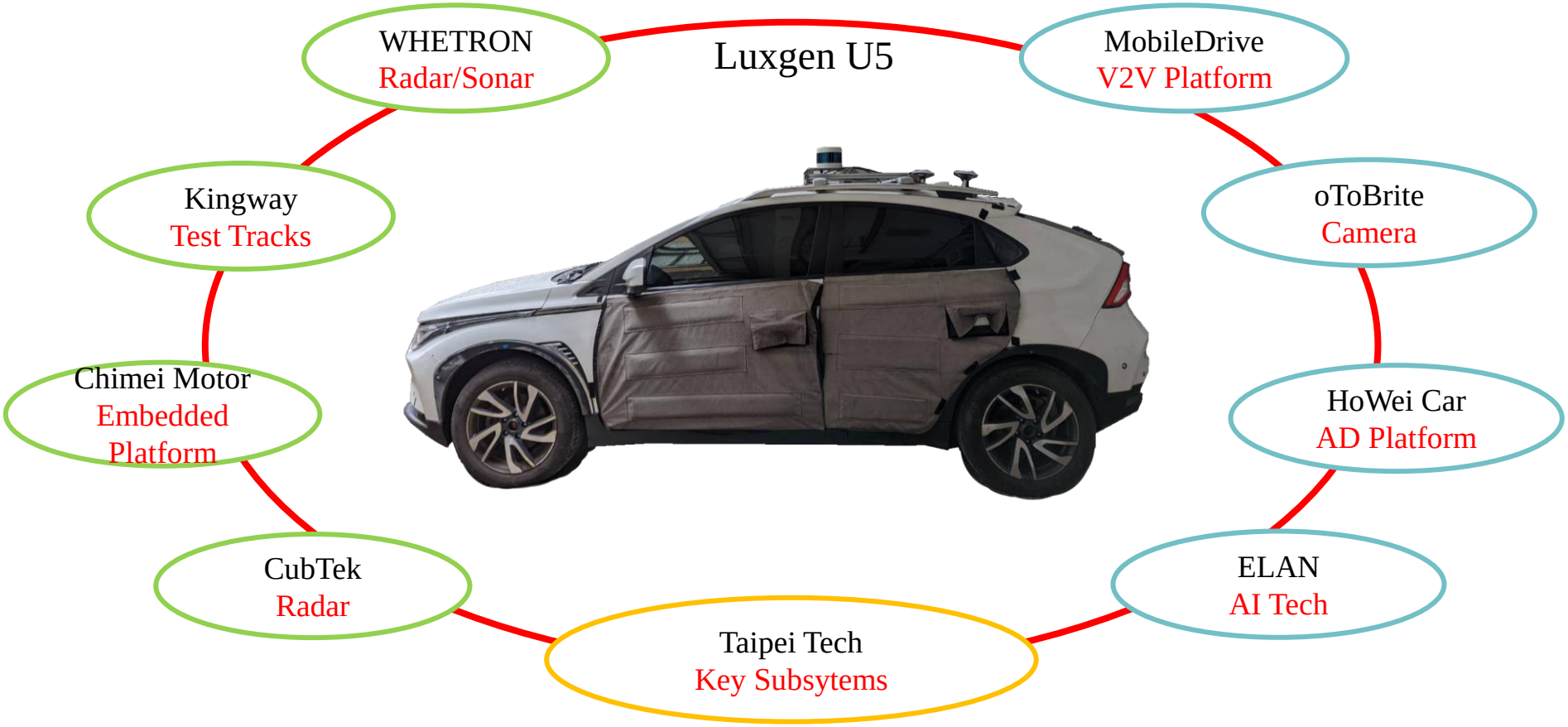






On-going Projects at Taipei Tech

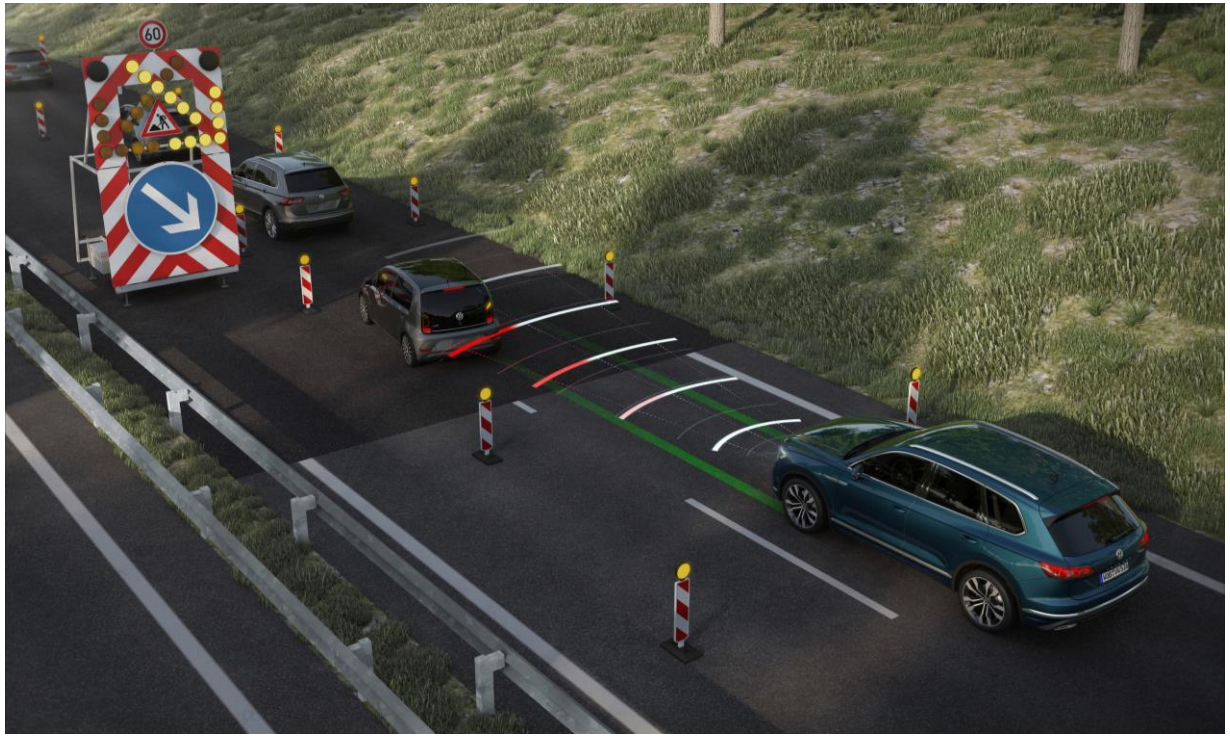
- Subsystems of Autonomous Driving



Demo of Automated Driving

Traffic Jam Assist

- The system makes driving in traffic jams or stop and go conditions considerably more convenient.
  - many surrounding vehicles at speeds below 60 km/h
  - the car automatically follows the vehicle in front
  - steers automatically to stay in the lane

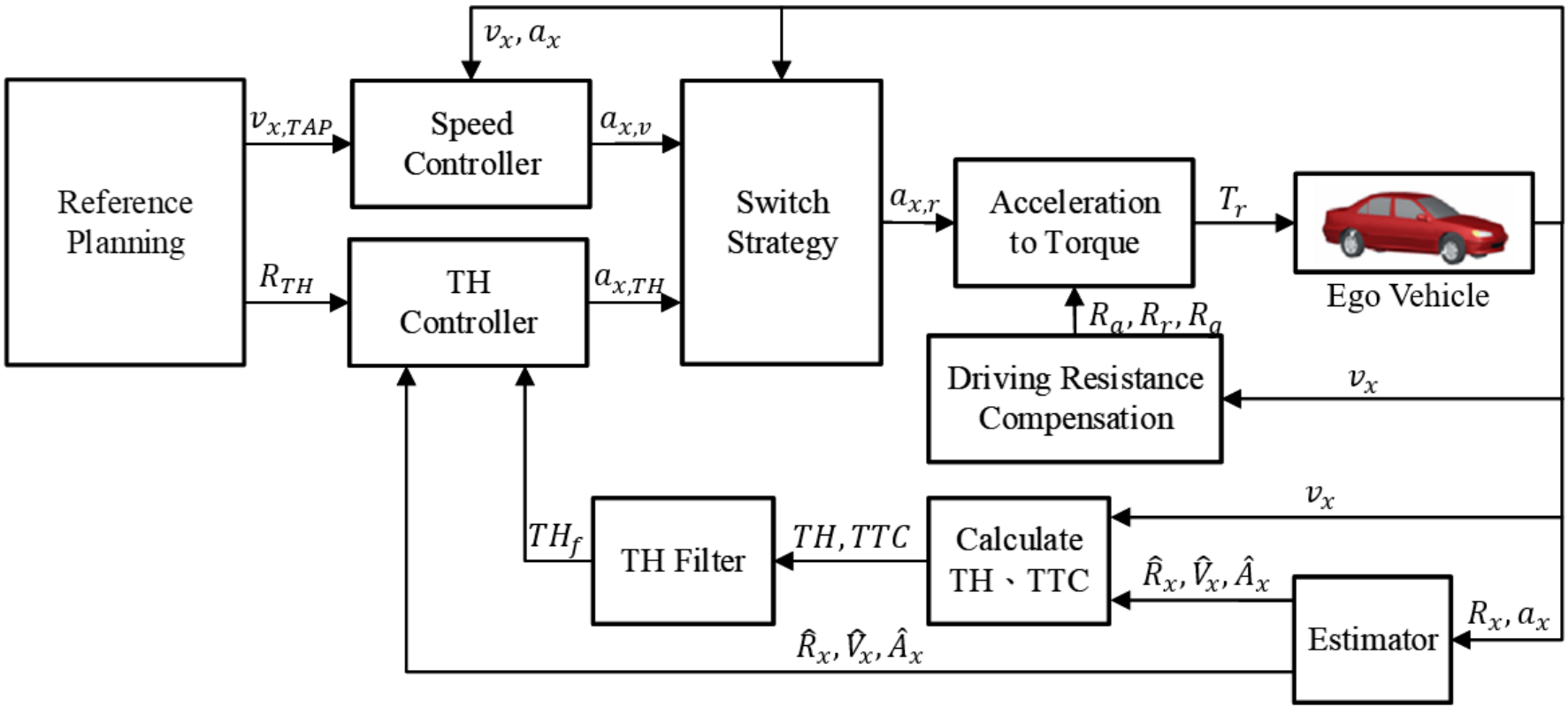


TJA Demo

Corolla Cross
Luxgen U5
North Dis.(m)
East Dis.(m)
60
50
40
30
20
10
0
-30
-20
-10
0
10
20
30

ACC for Cut-in Vehicles

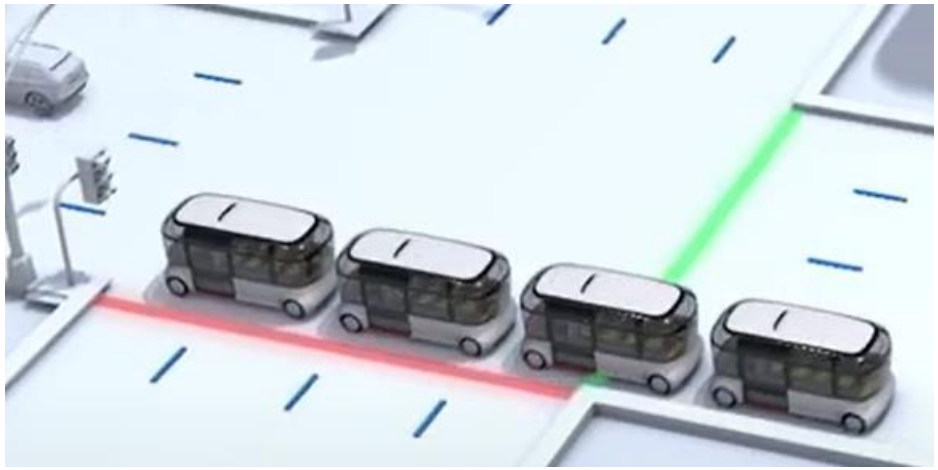
- The time constant of the TH filter is designed using TTC.
- Sudden brake can effectively reduced for cut-in vehicles with faster vehicle speeds.



V2V enhanced TJA

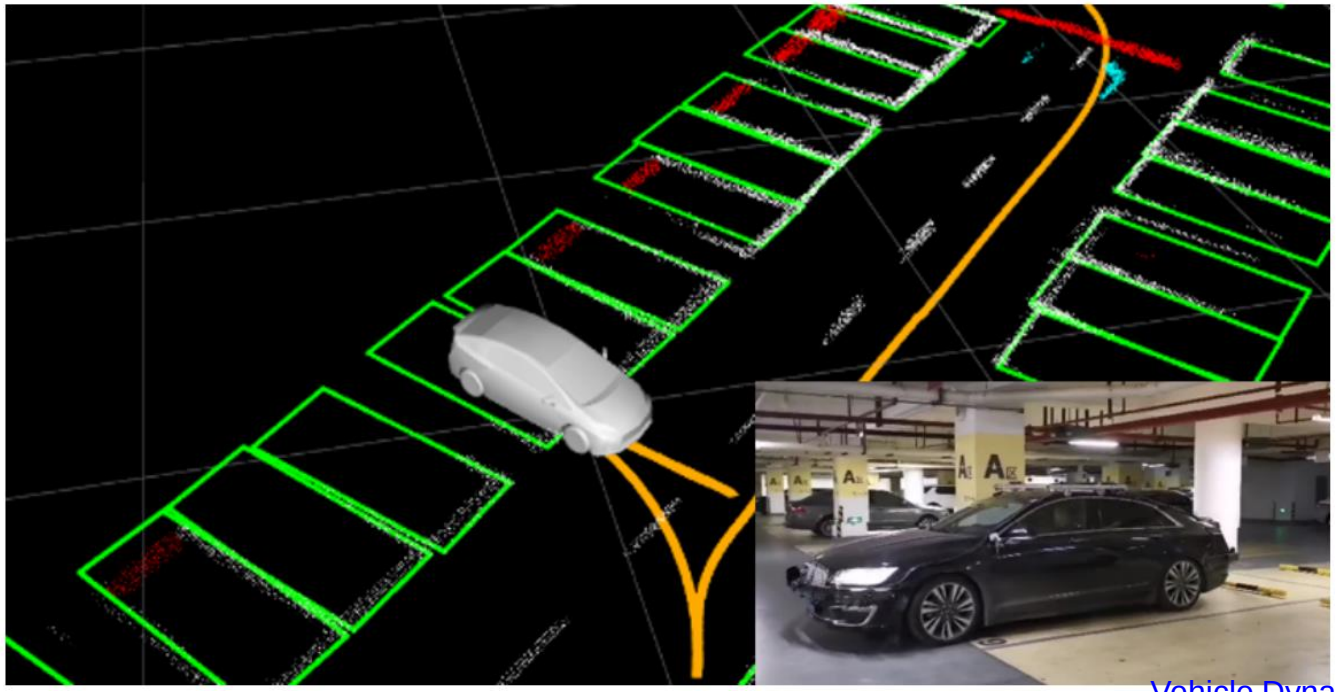
- Platoon

- Autonomous Rail Rapid Transmit



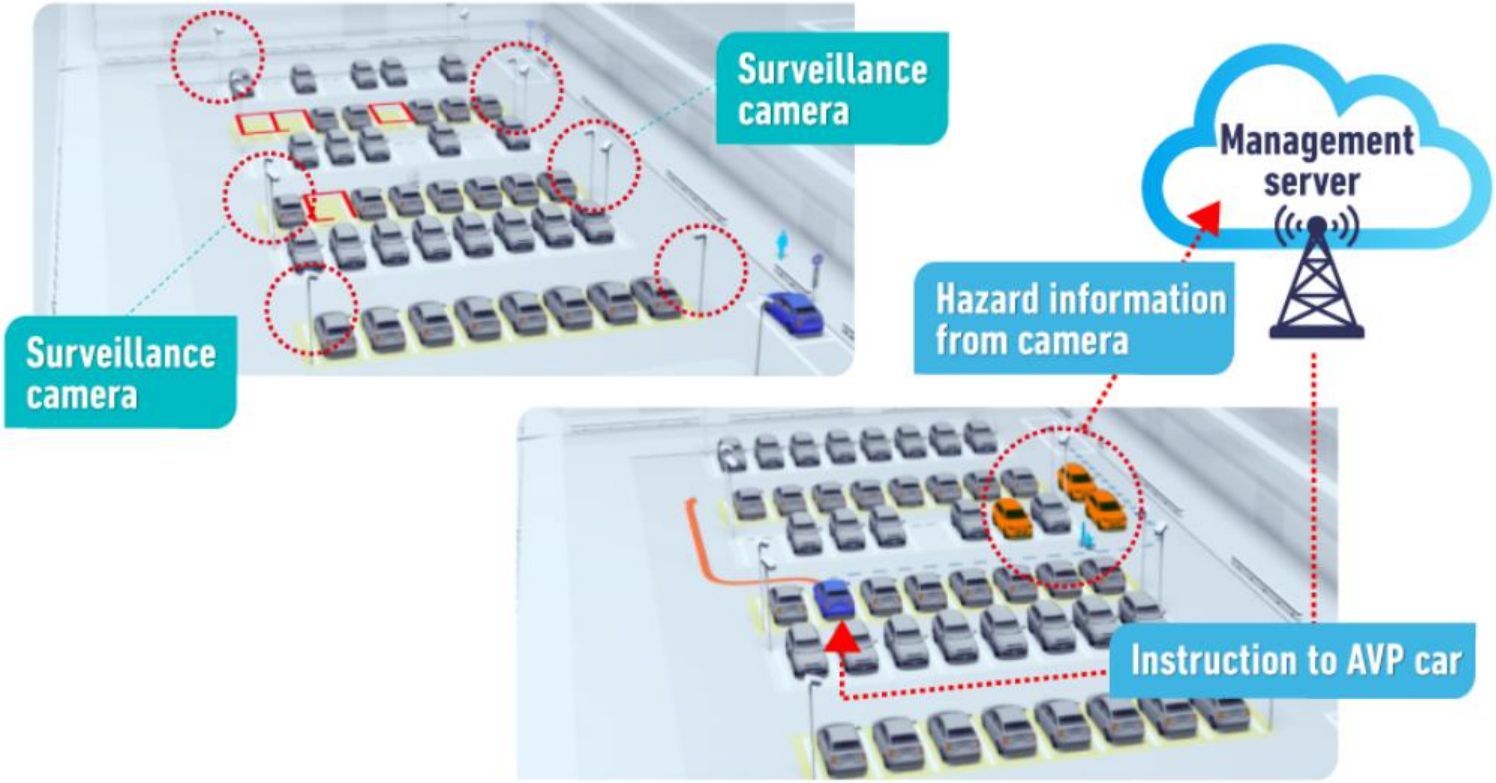
Automated Valet Parking

- Allows the vehicle to be left at the drop-off area of the parking garage
  - Activate the smartphone app to establish digital contact with the parking garage
  - and the route to a free or memorized parking spot is computed.
  - Visual SLAM is required. (can be enhanced by RSU)



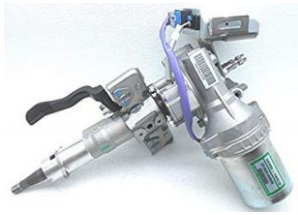
RSU enhanced AVP

- Surveillance cameras monitor the parking
- Management server links to surveillance Information
- High accuracy localization without GPS



Conclusion

- To enable the path following capability requires
  - Fast and reliable X-by-wire actuators
  - Control allocation
  - Numerous requests of retrofit and vehicle dynamics control



- Fault tolerant control
  - Model-based fault detection
  - Control reconfiguration/restructuring
- Vehicle dynamics control is the essential piece to the puzzle of the automated driving.

Q & A

Thank you for your attention.