# Design of Forward Collision Warning System using Relative Acceleration Estimation and Multi-Object Tracking

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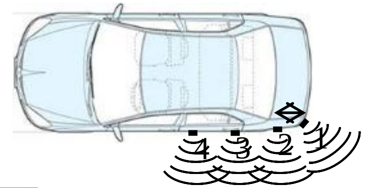
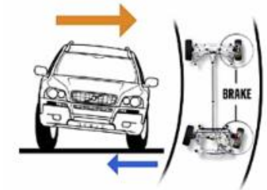
# Self Introduction

- Education
  - Ph.D., Mechanical Engineering, U. of Michigan
  - M.S., Electrical Engineering, U. Michigan
  - M.S., Mechanical Engineering, U. Michigan
  - B.S., Naval Architecture and Ocean Engineering, NTU

- Experience
  - Assistant Professor, Vehicle Eng. Dept., NTUT
  - Strategy and Software Engineer, Powertrain Control Dept., Visteon, USA
  - Research Assistant, Automotive Research Center, U. of Michigan
- Awards
  - Outstanding Young Engineer Award, SAE Taipei Section, 2008.
  - Excellent Paper Awards, National Conference on Vehicle Engineering, Taiwan, 2008, 2009, 2010.
  - Top 5 in Super Mileage Competition, SAE Taipei Section, 2004-2010.
- Research Areas
  - Active Safety, Vehicle Dynamics and Control, Hybrid Electric Vehicle, Engine Control, Optimum Control

# Research Areas

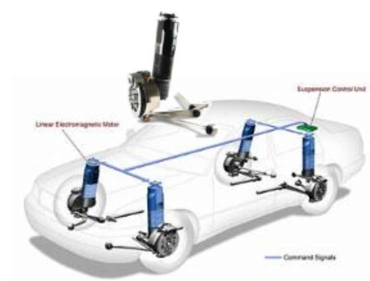
- Active Safety
  - Electronic Stability Control
  - Rollover Prevention
  - Forward Collision Warning
  - Lane Departure Warning
  - Side Collision Warning
  - Auto Parking
- Vehicle Dynamic and Control
  - Light Weight Electric Vehicle
  - Electric Differential
  - Electric Power Steering
  - ABS/TCS
  - Semi-active Suspension
- Hybrid Electric Vehicle
  - Hybrid Electric Scooter
  - Power Management System
- Engine Control
  - Idle Speed Control
  - Engine Management System








# Statistics

- In U.S., the percentage of rear end collision in all collisions was about 31.5% in 2009.




**Crashes by First Harmful Event, Manner of Collision, and Crash Severity**

| | Crash Severity | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Fatal | | Injury | | Property Damage Only | | Total | |
| First Harmful Event | Number | Percent | Number | Percent | Number | Percent | Number | Percent |
| **Collision with Motor Vehicle in Transport:** | | | | | | | | |
| Angle | 5,637 | 18.3 | 448,000 | 29.5 | 965,000 | 24.4 | **1,418,000** | **25.8** |
| Rear End | 1,674 | 5.4 | 448,000 | 29.5 | 1,283,000 | 32.4 | **1,733,000** | **31.5** |
| Sideswipe | 757 | 2.5 | 58,000 | 3.8 | 367,000 | 9.3 | **426,000** | **7.7** |
| Head On | 3,007 | 9.8 | 60,000 | 4.0 | 63,000 | 1.6 | **126,000** | **2.3** |
| Other/Unknown | 115 | 0.4 | 2,000 | 0.1 | 15,000 | 0.4 | **17,000** | **0.3** |
| *Subtotal* | *11,190* | *36.3* | *1,016,000* | *66.9* | *2,693,000* | *68.1* | ***3,720,000*** | ***67.6*** |

Source: Traffic Safety Facts 2009

# Human Error

- 80% of drivers attempted no action in rear end collisions.

Table 1. Definition and Relative Frequency of Top Five Rear-End Precrash Scenarios (Based on 1992- 1996 GES) [2]

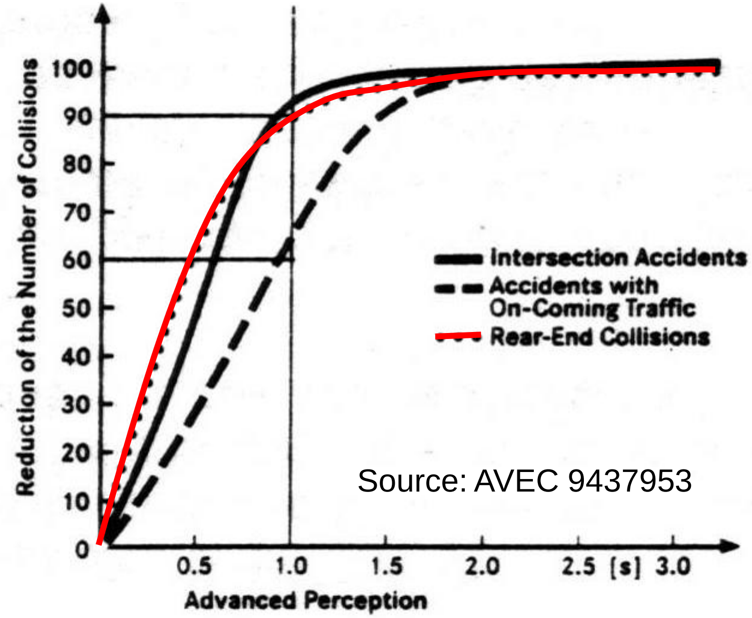
| No. | Scenario Definition | Relative* Frequency, % |
|---|---|---|
| 1 | Both following and lead vehicles are traveling at constant speed on a *straight road* and lead vehicle then decelerates. | 37.0 |
| 2 | Following vehicle is traveling at constant speed on a *straight road* and encounters a lead vehicle stopped in traffic lane ahead. | 30.2 |
| 3 | Following vehicle is traveling at constant speed on a *straight road* and encounters a lead vehicle traveling at a constant, lower speed ahead. | 14.1 |
| 4 | Both following and lead vehicles are decelerating on a *straight road* and lead vehicle then decelerates at a higher rate. | 4.5 |
| 5 | Following vehicle is traveling at constant speed on a *curved road* and encounters a lead vehicle stopped in traffic lane ahead. | 3.0 |
| | Sum | 88.8 |

*: Relative frequency represents the average value from 1992 through 1996.

Source: SAE Paper 1999-01-0817

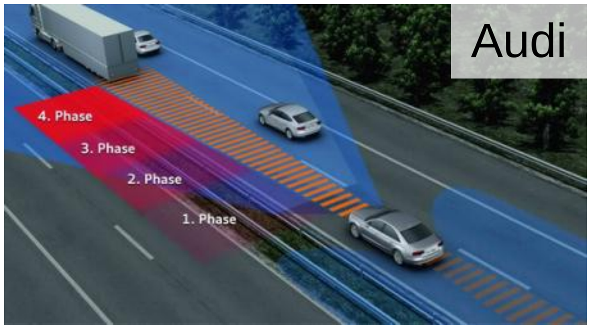
Table 2. Percent Distribution of Attempted Avoidance Maneuvers (Based on 1996 GES)

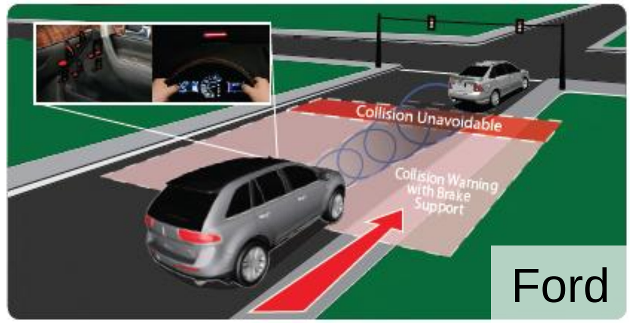
| Action Attempted | No. 1 | No. 2 | No. 3 | No. 4 | No. 5 |
|---|---|---|---|---|---|
| No Action | 81.4 | 78.4 | 83.8 | 68.6 | 86.2 |
| Braked | 12.2 | 15.5 | 8.1 | 25.7 | 11.1 |
| Steered | 1.1 | 2.2 | 1.7 | 1.4 | 0.7 |
| Braked & Steered | 0.5 | 1.0 | 0.4 | 1.4 | 0.2 |
| Accelerated | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 |
| Other/No Details | 0.3 | 0.1 | 0.4 | 0.1 | 0.0 |
| Unknown | 4.5 | 2.8 | 5.6 | 2.8 | 1.8 |
| Sum | 100.1* | 100.0 | 100.0 | 100.0 | 100.0 |

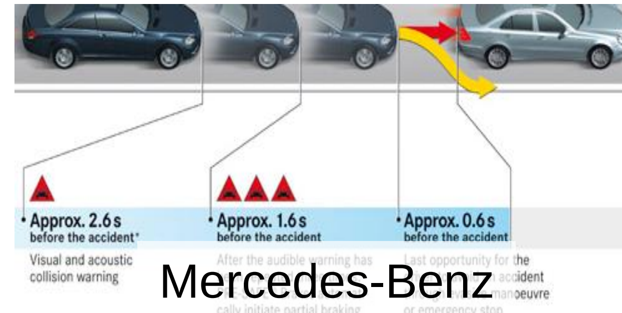



Source: AVEC 9437953

# Existing Technologies



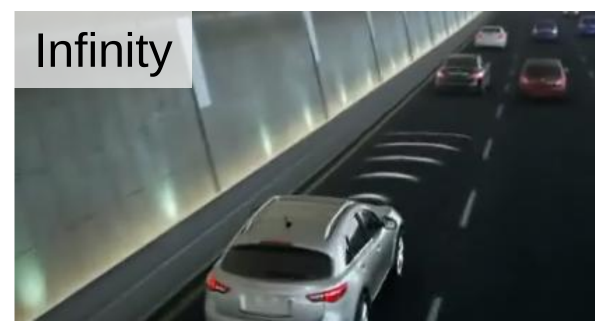











# Object Detection Systems

- Infrared Laser
  - Transmit energy in the THz range (1 THz=$10^{12}$ Hz).
  - Superior angular resolution.
  - Limited performance due to atmospheric effects, such as fog and rain.
  - Does not perform well on wet objects or targets whose surface roughness is the order of the laser wavelength (10.6 microns).
- Microwave/Millimeter wave radar
  - Transmit energy in the tens of GHz range (1 GHz = $10^9$ Hz)
  - Better adverse weather penetration than active laser systems.
- Camera
  - Usable distance accuracy for short-range detection (less than 55 m)
  - Poor accuracy for long-range detection due to the pixel resolution

# Forward Collision Warning System

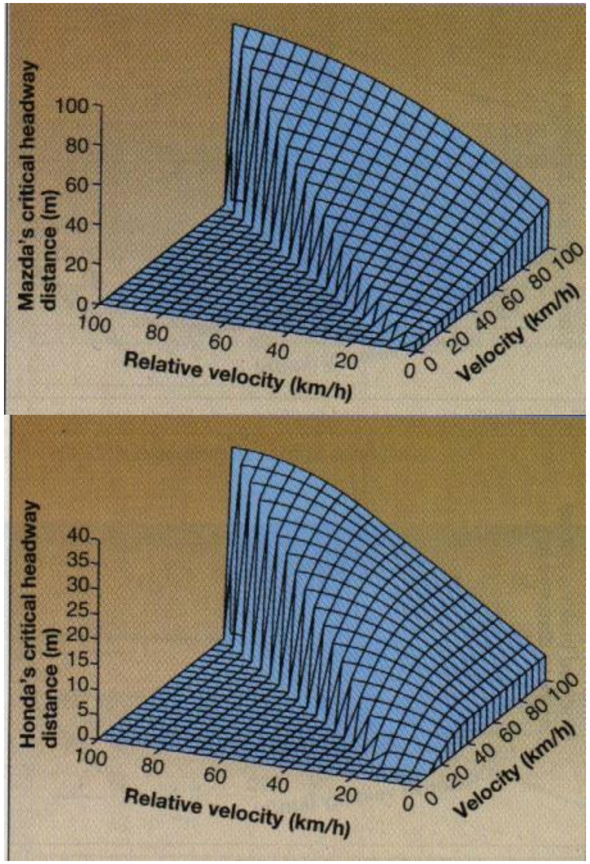
- Autonomous Solutions:
  - Identify valid target and measure range, range rate, and vehicle speed (10Hz or faster).
  - Vehicle path prediction
  - Issue warning based on
    - Time-to-Collision

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

    - Time-headway (time gap)

$$THW = \frac{R}{V_{host}}$$

    - Threshold distance
      From vehicle speed, road friction, and human delays such as "blank time" and "judgment time," a "safe following distance" $d$ can be constructed.




Source: SAE 98PC-417

# Relative Acceleration Estimation

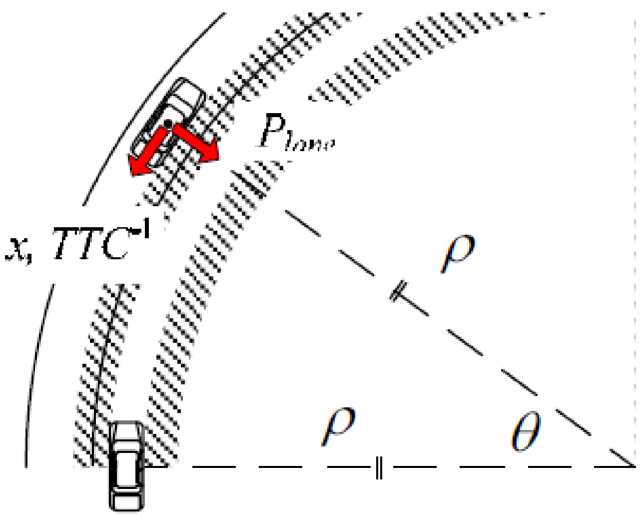
- Lee and Peng (2005) mentioned that the leading vehicle acceleration is a critical step for developing practical collision warning/avoidance systems.
- Good estimation of relative acceleration is the key to reduce the false alarm of FCWS.
  - Dagan et al. (2004) calculated TTC from the momentary TTC defined by Hayward 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.

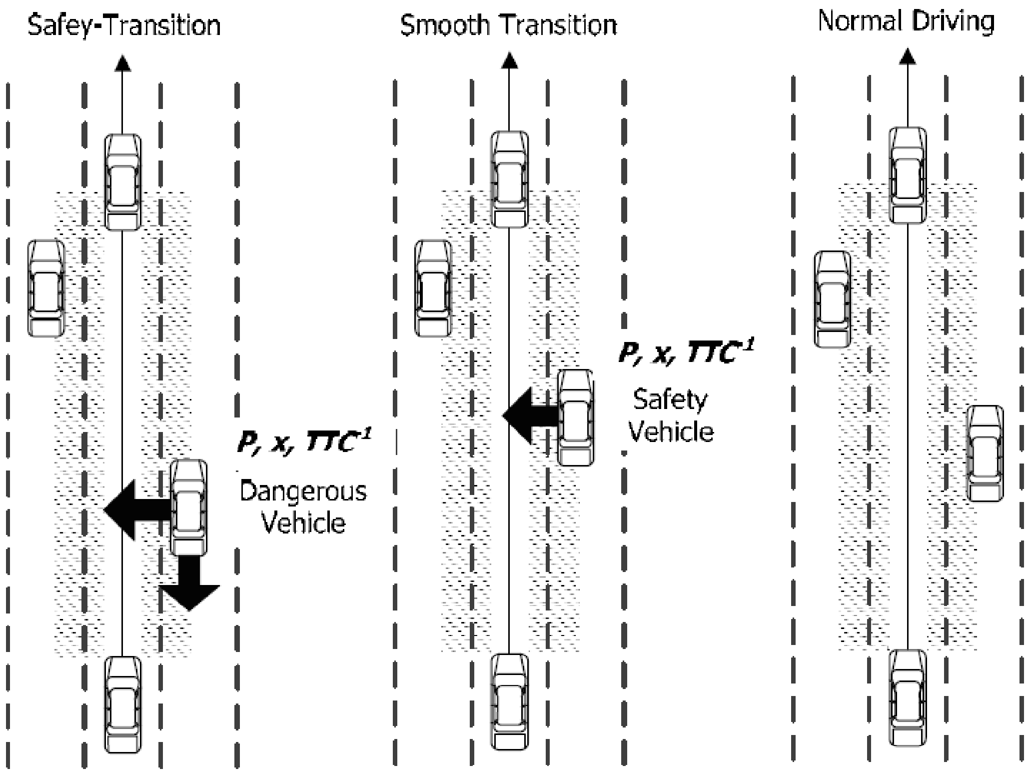
$$\hat{\mathbf{x}}(k+1) = \mathbf{A}\hat{\mathbf{x}}(k) + \mathbf{L}(y(k) - \mathbf{C}\hat{\mathbf{x}}(k)),\ \hat{\mathbf{x}}(k) = \begin{bmatrix} \hat{R} & \hat{V} & \hat{A} \end{bmatrix}^T$$

$$\mathbf{A} = \begin{bmatrix} 1 & T & 0.5T^2 \\ 0 & 1 & T \\ 0 & 0 & 1 \end{bmatrix},\ \mathbf{G} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix},\ \mathbf{C} = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}$$

# Multi-object Tracking

- Moon et al. (2009) proposed primary target selection
  - A yaw-rate based subject vehicle's lane detection, a motion based analysis, and an integration process.
  - Primary target might be changed quite often during transient yaw motion.



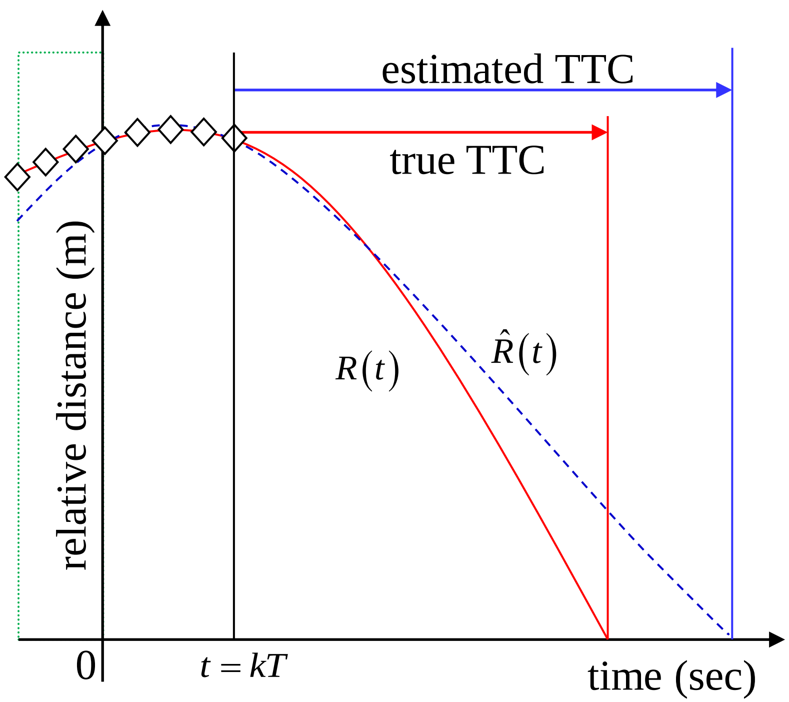



# Proposed Approach

- Recursive Least Squares

$$\hat{R}(k) = a_R(k)t^2 + b_R(k)t + c_R(k) = \boldsymbol{\varphi}^T(k)\hat{\boldsymbol{\theta}}_R(k)$$

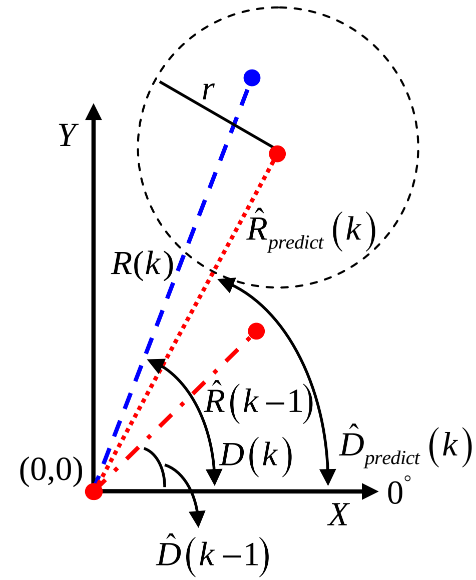
$$\hat{D}(k) = a_D(k)t^2 + b_D(k)t + c_D(k) = \boldsymbol{\varphi}^T(k)\hat{\boldsymbol{\theta}}_D(k)$$




$$\hat{\boldsymbol{\theta}}_R = \begin{bmatrix} a_R(k) & b_R(k) & c_R(k) \end{bmatrix}^T$$

$$\hat{\boldsymbol{\theta}}_D = \begin{bmatrix} a_D(k) & b_D(k) & c_D(k) \end{bmatrix}^T$$

$$\boldsymbol{\varphi}(k) = \begin{bmatrix} t^2 & t & 1 \end{bmatrix}^T, \quad t = kT$$




overflow when *t* is large

⇨ reset to zero during safe maneuvers

$$\mathbf{K}(k) = \mathbf{P}(k-1)\boldsymbol{\varphi}(k)\left(\lambda\mathbf{I} + \boldsymbol{\varphi}^T(k)\mathbf{P}(k-1)\boldsymbol{\varphi}(k)\right)^{-1}$$

$$\hat{\boldsymbol{\theta}}(k) = \hat{\boldsymbol{\theta}}(k-1) + \mathbf{K}(k)\left(y(k) - \boldsymbol{\varphi}^T(k)\hat{\boldsymbol{\theta}}(k-1)\right)$$

$$\mathbf{P}(k) = \left(\mathbf{I} - \mathbf{K}(k)\boldsymbol{\varphi}^T(k)\right)\mathbf{P}(k-1)/\lambda$$

$$\hat{\boldsymbol{\theta}}(0) = \left(\sum_{k=-3}^{0}\boldsymbol{\varphi}(k)\boldsymbol{\varphi}^T(k)\right)^{-1}\left(\sum_{k=-3}^{0}\boldsymbol{\varphi}(k)y(k)\right)$$

# Proposed Approach

- Variable forgetting factor
  - Large forgetting factor is suitable for small relative acceleration. However, the estimation performance deteriorates with large relative accelerations.
  - Small forgetting factor is suitable for large relative accelerations. However, it might produce noisier estimations for small relative acceleration.
  - Adjust the forgetting factor according to the estimated relative acceleration, i.e. variable forgetting factor, might be a good solution.

$$\lambda_R = d_R - m_R \left|\hat{A}\right| \qquad \lambda_D = d_D - m_D \left|\hat{\alpha}\right|$$

$$\hat{R}(k) = \hat{a}_R(k)t^2 + \hat{b}_R(k)t + \hat{c}_R(k)$$

$$\hat{V}(k) = 2\hat{a}_R(k)t + \hat{b}_R$$

$$\hat{A}(k) = 2\hat{a}_R(k)$$

$$\Rightarrow \quad TTC(k) = \frac{-\hat{V}(k) \pm \sqrt{\hat{V}^2(k) - 2\hat{A}(k)\hat{R}(k)}}{\hat{A}(k)}$$

# Optimization

- Kalman Smoothing
  - the forward filtered data contains undesirable time delays,

$$\dot{\mathbf{x}}_{KF}(t) = \mathbf{A}_f \mathbf{x}_{KF}(t) + \mathbf{G}\mathbf{w}(t)$$
$$\mathbf{y}(t) = \mathbf{C}\mathbf{x}_{KF}(t) + \mathbf{N}\mathbf{v}(t)$$

$$\Longrightarrow \hat{\mathbf{x}}_{KF}(k+1) = \mathbf{A}_{df} \cdot \hat{\mathbf{x}}_{KF}(k) + \mathbf{L}_s[\mathbf{y}(k) - \mathbf{C}\hat{\mathbf{x}}_{KF}(k)]$$

$$\mathbf{x}_{KF}(t) = \left[V_F(t) \quad a_F(t) \quad R(t) \quad V_L(t) \quad a_L(t)\right]^T$$

$$\mathbf{A}_f = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}, \ \mathbf{G} = \begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix}, \ \mathbf{C} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix}, \ \mathbf{N} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

  - a backward Kalman filter is constructed to cancel its effect

$$\hat{\mathbf{z}}(k+1) = \mathbf{A}_{db}\hat{\mathbf{z}}(k) + \mathbf{L}_s[\mathbf{y}(k) - \mathbf{C}\hat{\mathbf{z}}(k)], \quad \mathbf{A}_{db} = [\mathbf{A}_{df}^T \mathbf{A}_{df}]^{-1} \mathbf{A}_{df}^T$$

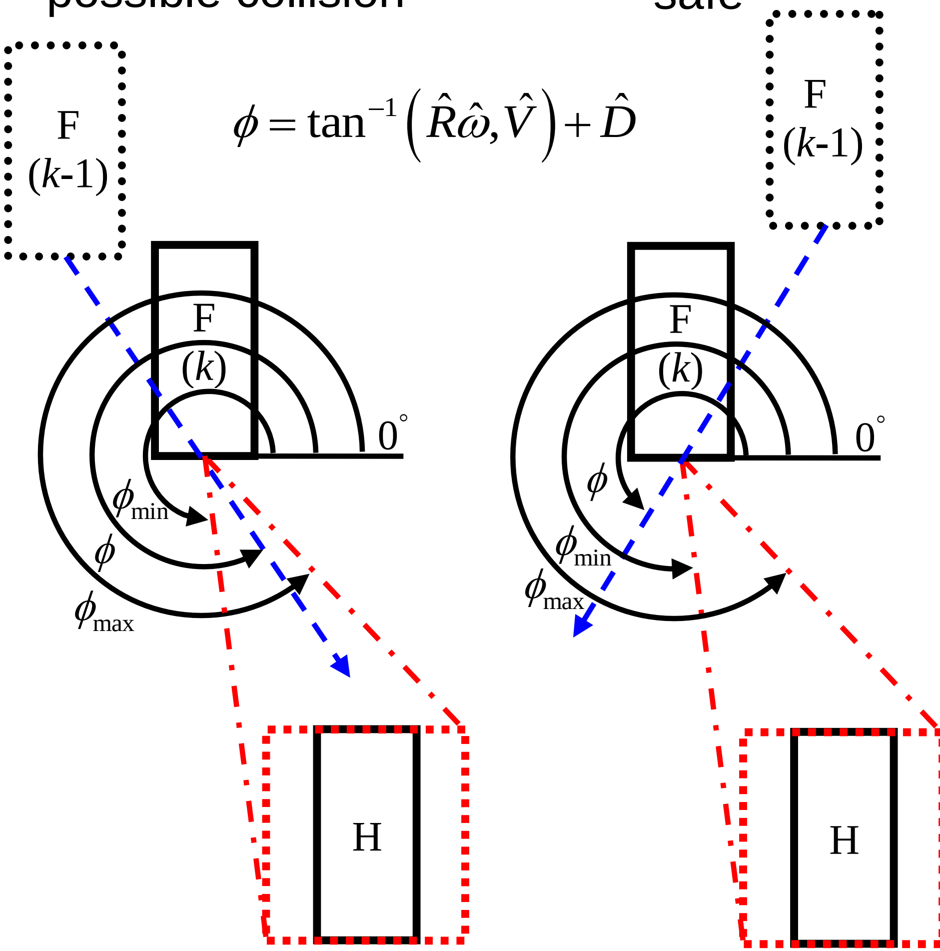
  - The averaged data is then used as the ground truth.
  - The same smoothing procedure is applied to the relative orientation.

# Proposed Approach

- Multi-object Tracking

possible collision　　　　safe

$$\phi = \tan^{-1}\left(\hat{R}\hat{\omega}, \hat{V}\right) + \hat{D}$$




if $TTC < TTC_{th}$

  if $\phi_{min} \le \phi \le \phi_{max}$ and $count \ge count_{th}$

    possible collision, warning on

  else

    safe, warning off

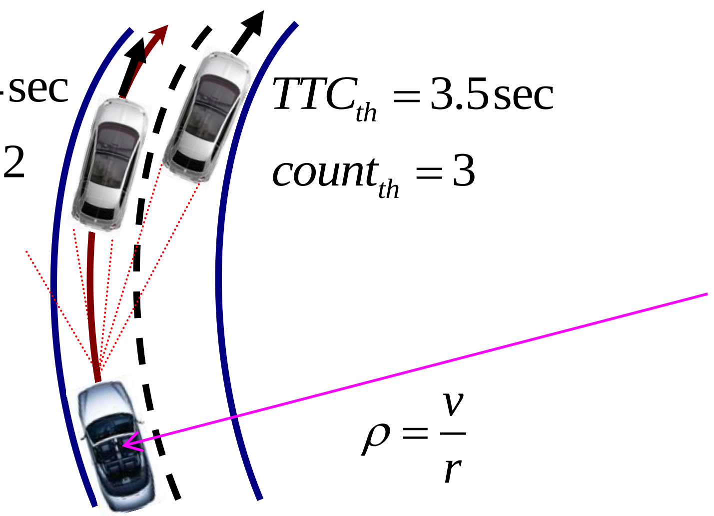
else

  safe, warning off

end

$TTC_{th} = 4\text{sec}$

$count_{th} = 2$

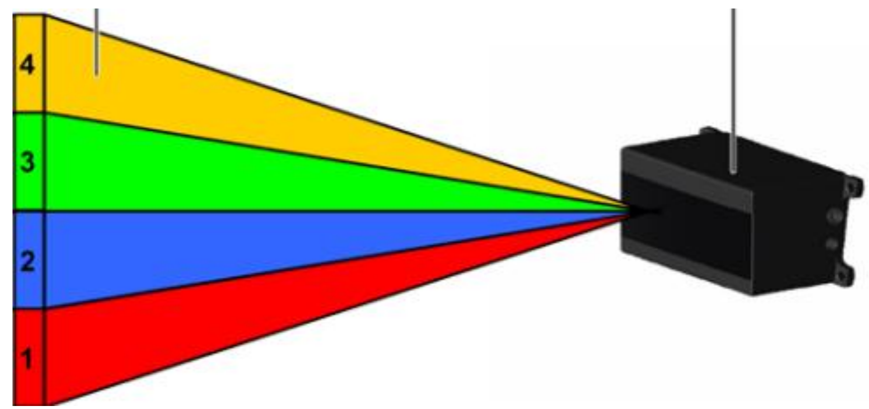


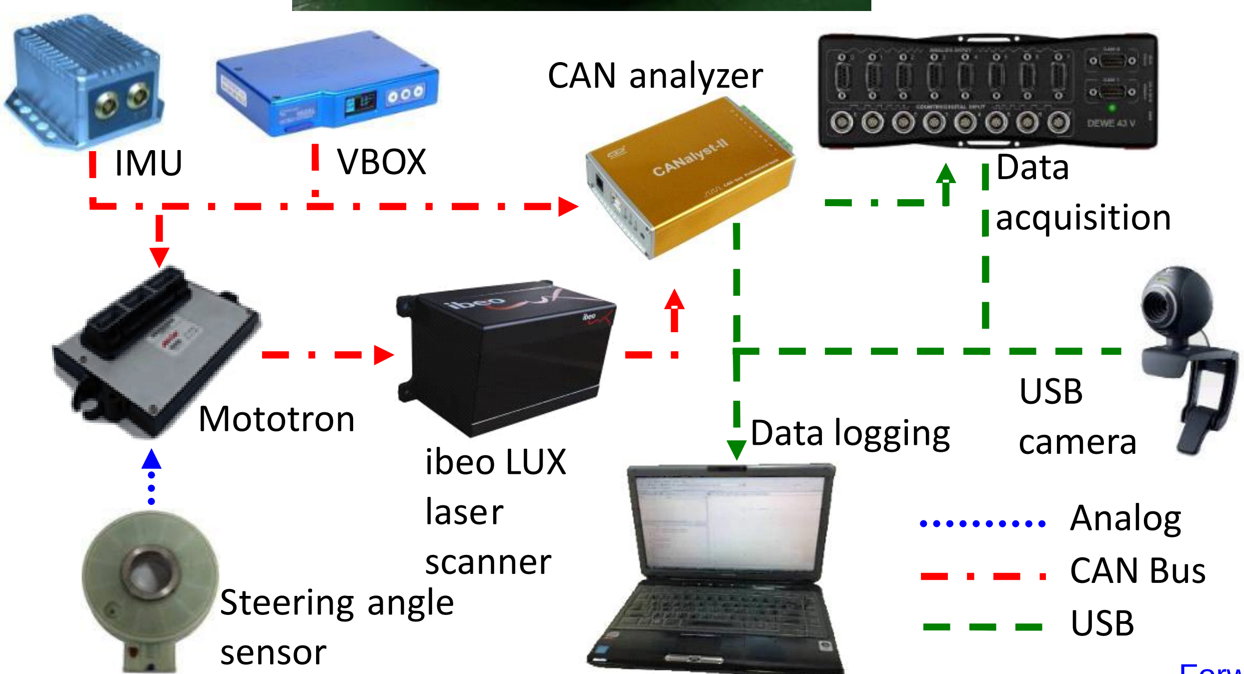
$TTC_{th} = 3.5\text{sec}$

$count_{th} = 3$

$$\rho = \frac{v}{r}$$

# Experimental Setup

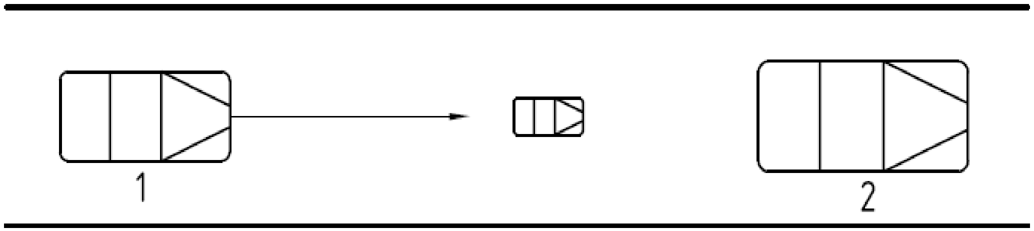


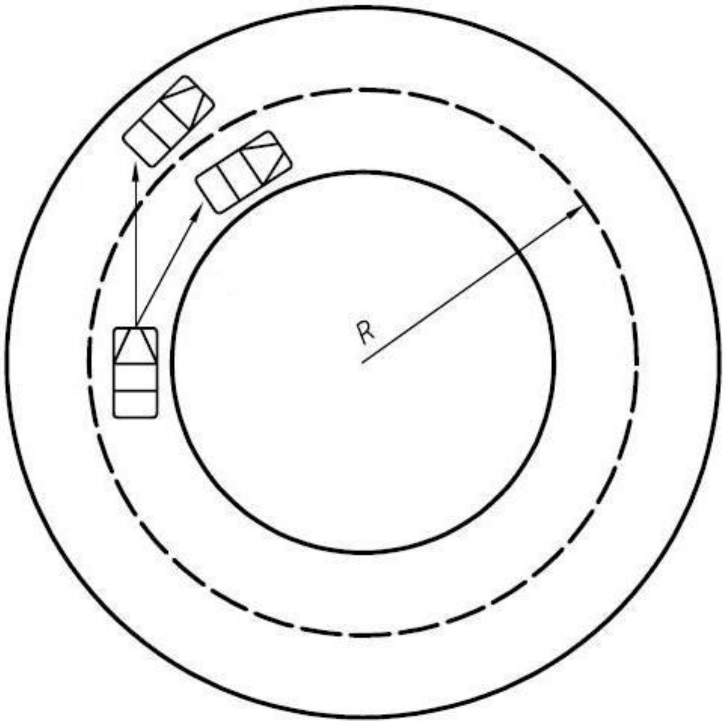

| ibeo LUX technical data | |
|---|---|
| Working area with 4 layers | 85° |
| Working area expansion with 2 layers | 100° |
| Range | 0.3 to 200m |
| Angular resolution | 0.125° to 1° |
| Vertical aperture angle | 3.2° |
| Scanning layers | 4 vertical |
| Echos per measurement | 3 |
| Scanning frequency | 12,5 Hz / ( 25 Hz ) |
| Wavelength | 905nm |
| Dimensions (HxWxD) | 85 x 128 x 93mm |
| Temperature range | -40°C to +85°C |
| Eye-safety | Laser class 1 |
| Weight | Approx. 1kg |
| Interfaces | 100MBit Ethernet / CAN 2.0 B |
| Voltage | 9-27V DC/max. 10W, average 6W |
| Distance resolution | 4cm |

# ISO 15623

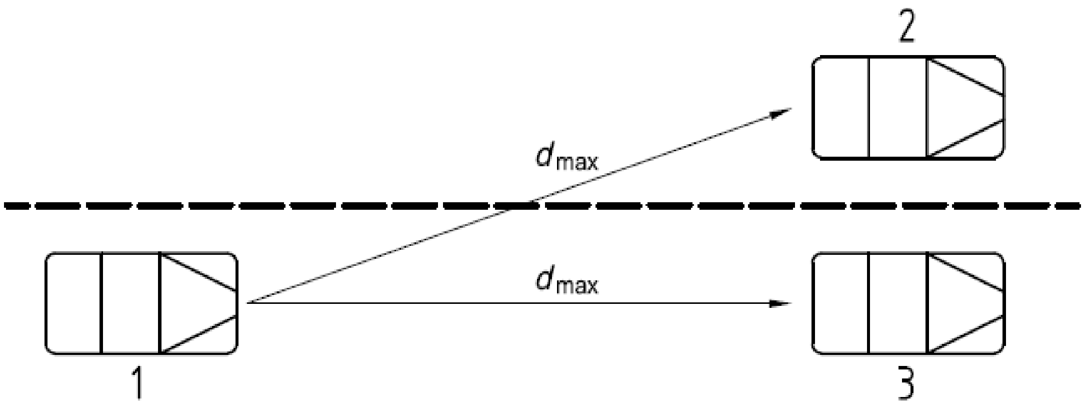
**Longitudinal target discrimination ability test**




**Curved test track and target discrimination ability test**

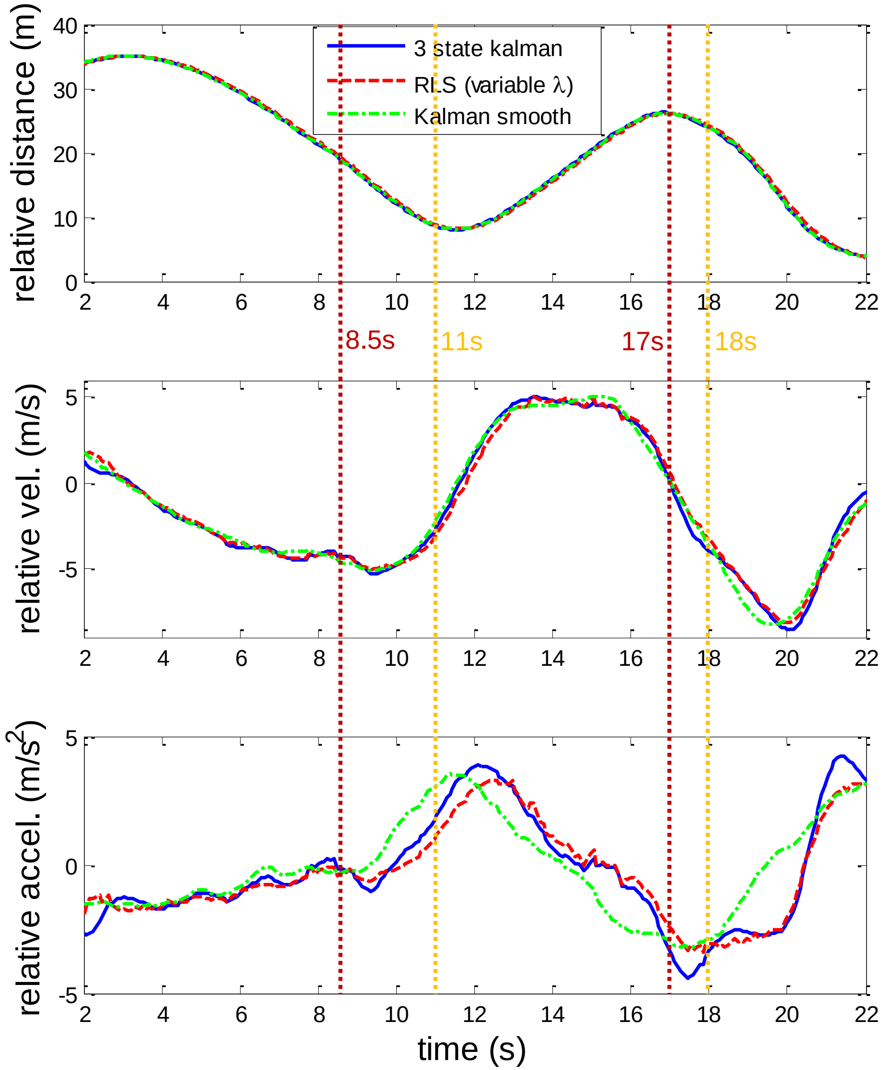



**Straight road lateral target discrimination ability test**

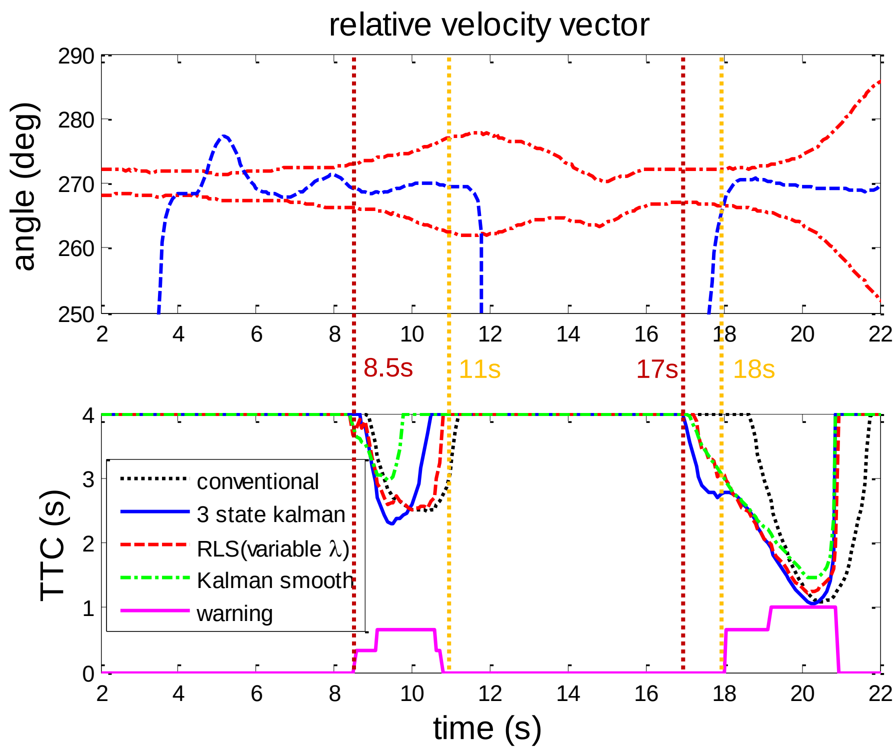


# ISO Test -1

# ISO Test -1



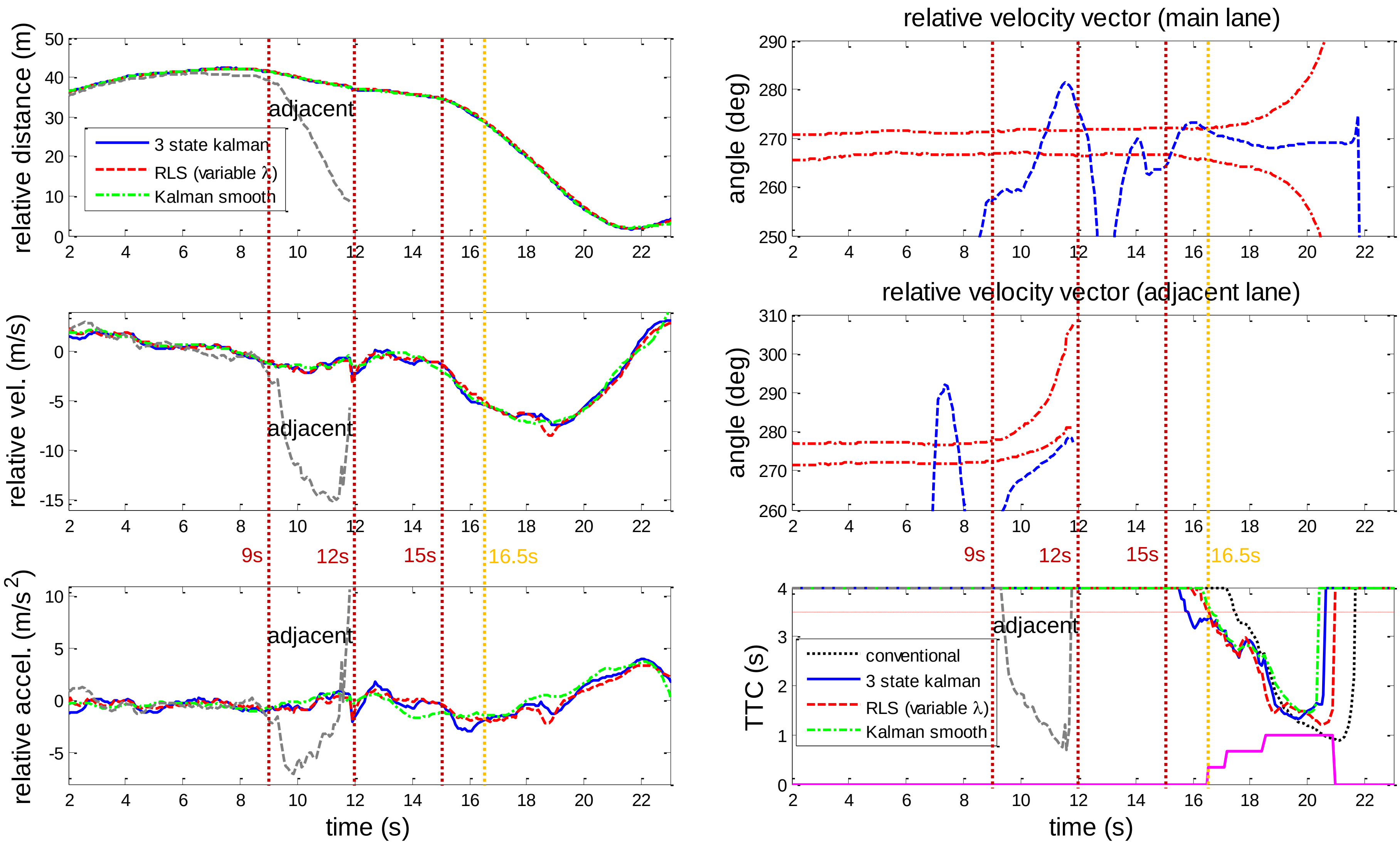
3 state kalman
RLS (variable λ)
Kalman smooth
relative distance (m)
relative vel. (m/s)
relative accel. (m/s2)
8.5s
11s
17s
18s
time (s)

relative velocity vector
angle (deg)
8.5s
11s
17s
18s
conventional
3 state kalman
RLS(variable λ)
Kalman smooth
warning
TTC (s)
time (s)

# ISO Test - 2

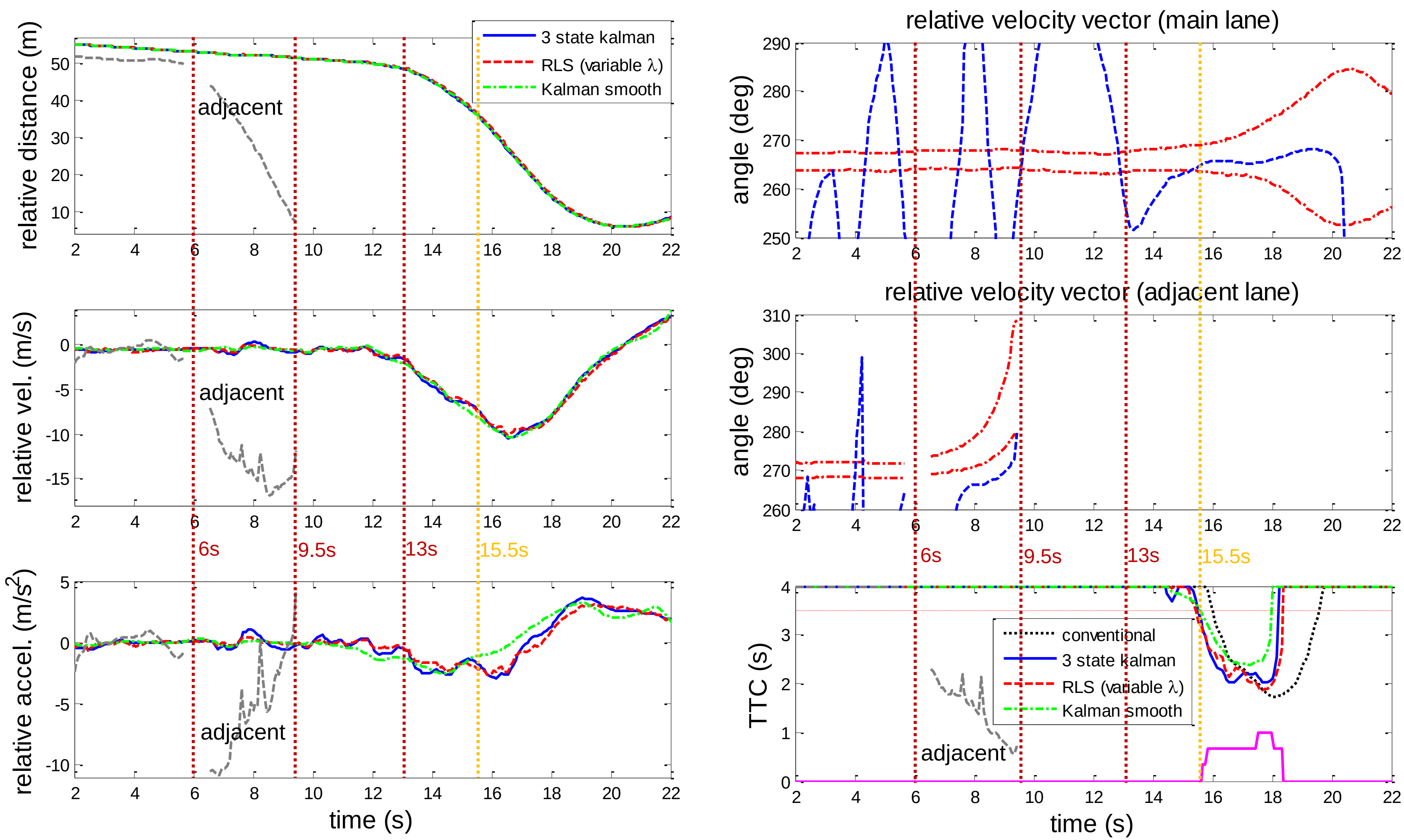
# ISO Test - 2



relative distance (m)
adjacent
3 state kalman
RLS (variable λ)
Kalman smooth
relative vel. (m/s)
adjacent
9s
12s
15s
16.5s
relative accel. (m/s^2)
adjacent
time (s)
relative velocity vector (main lane)
angle (deg)
relative velocity vector (adjacent lane)
angle (deg)
9s
12s
15s
16.5s
TTC (s)
adjacent
conventional
3 state kalman
RLS (variable λ)
Kalman smooth
time (s)

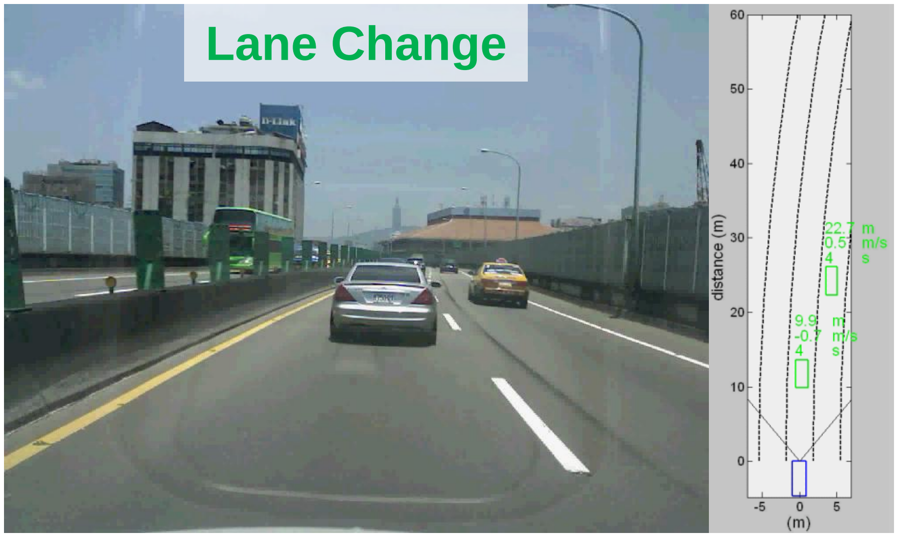
# ISO Test - 3

# ISO Test - 3




Forward Collision Warning System (FCWS)

# Expressway Tests



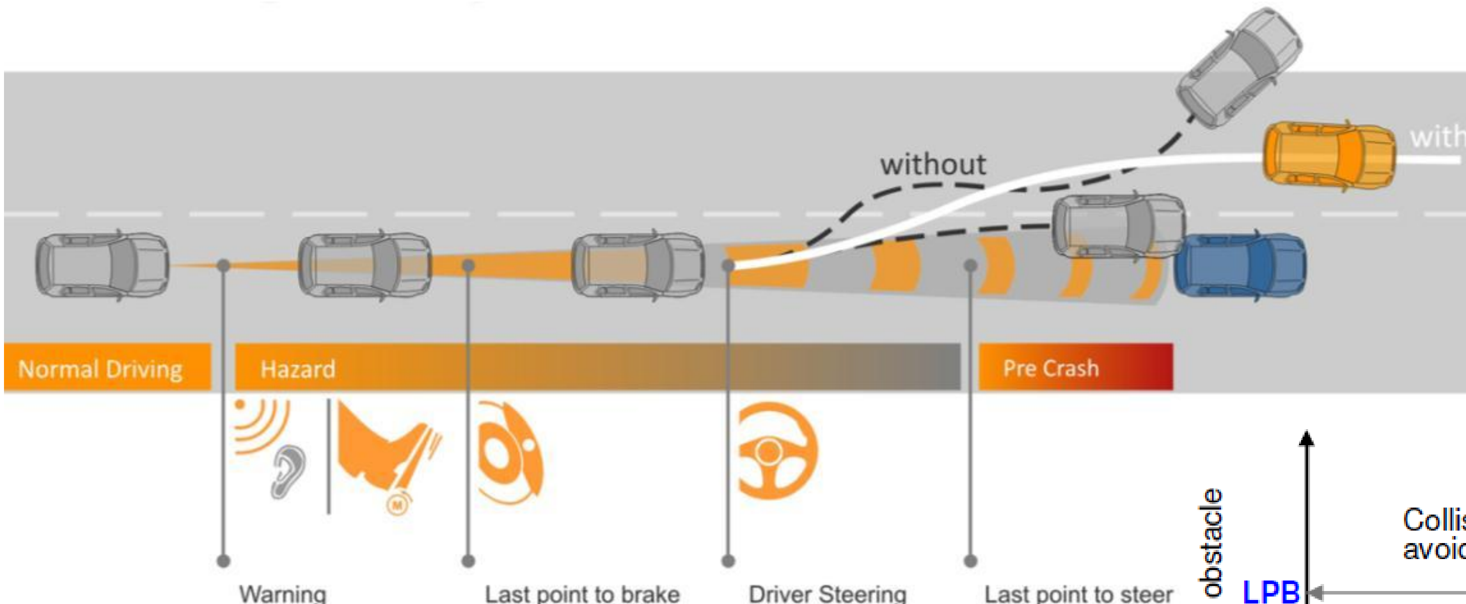


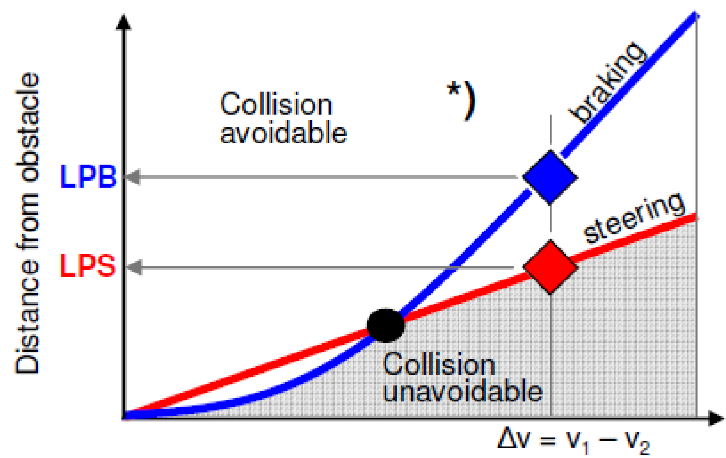

# Conclusions

- Relative acceleration is considered to improve the accuracy of TTC estimation.
  - Recursive least square technique with variable forgetting factor is used to estimate coefficients of two second order polynomials for the relative distance and relative orientation, respectively.
- The region of interest for FCWS is extended from the main lane to adjacent lanes.
  - According to the measured relative distance and relative orientation, a multi-object tracking algorithm is developed in this research.
  - When the TTC is below the threshold value, relative velocity vector is used to determine if there is an impending threat for collision.
- Experimental results show that the proposed algorithm
  - can pass all 3 tests of ISO 15623
  - and issue valid warnings to the driver without false alarms for the expressway tests.

# Future Works

- Automatic evasive maneuver for collision avoidance




Source: Continental Emergency Steer Assist 2010

# Q & A

Thank you for your attention.