Robust Constrained Control for Driver-Automation Shared Driving of Intelligent Vehicles

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Outline

❶ Context and challenges

❷ Human-in-the-loop control design

- System modeling
- Description of the proposed method
- Control design

❸ Illustrative experimental results

❹ Concluding Remarks

Context

- Human drivers are responsible 90% road accidents[1]

- Automation can help to reduce the workload and the human errors

- Full automation of vehicle could be possible!

Google Driverless Car

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[1] ONISR, 2010

Context

- Why not full automation of the driving task?
  - Unpredictable environments (outside the operating range of the automation)

Absence of markings on the ground

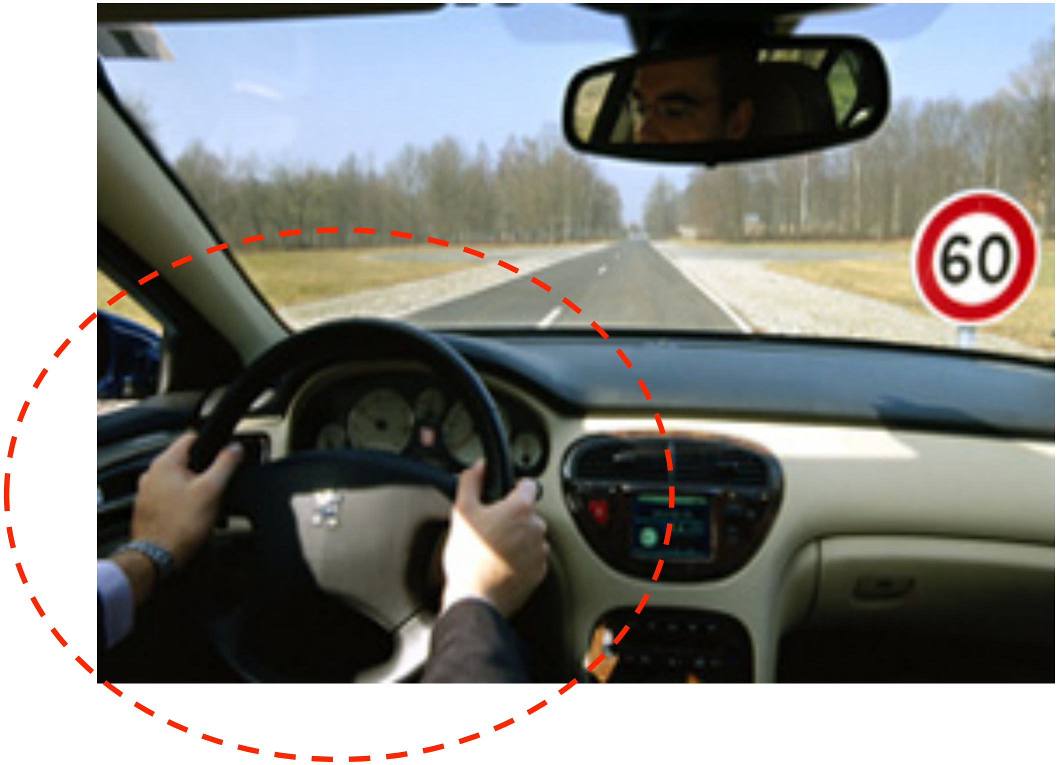
Loss of GPS signal

Presence of undetected obstacle

Human capacities (creativity and insight) are still needed!

Challenging Issue

- Human-machine system



Question: “How could we combine the best of the human and machine?”

Principe of cooperative control[1]

[1] Abbink and al., 2012

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Vehicle Modeling for Control Design

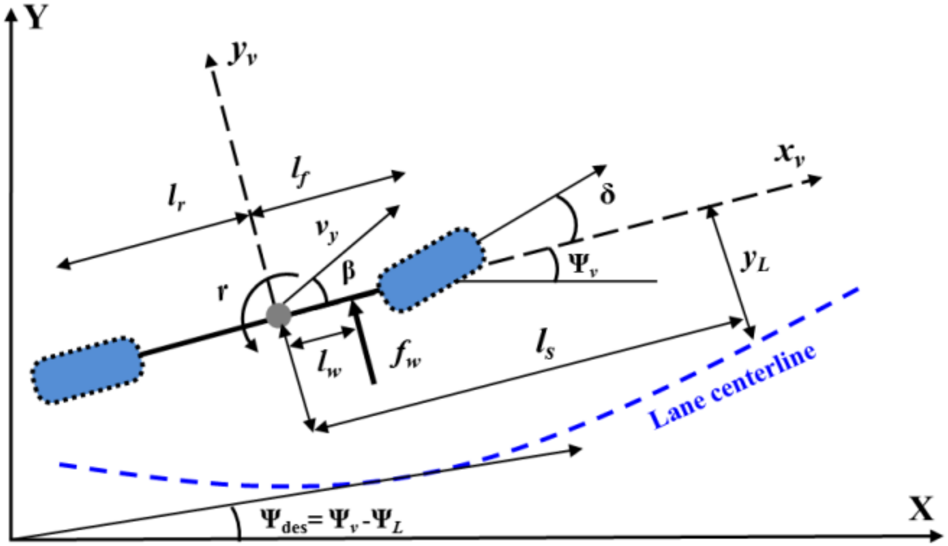
Three types of system dynamics[1]

- Vehicle dynamics (or linear bicycle model)

$$\begin{bmatrix} \dot{\beta} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} \beta \\ r \end{bmatrix} + \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} \delta + \begin{bmatrix} e_1 \\ e_2 \end{bmatrix} f_w$$

- Road-vehicle positioning

$$\begin{cases} \dot{y}_L = v_x \beta + l_s r + v_x \psi_L \\ \dot{\psi}_L = r - v_x \rho_r \end{cases}$$



- Steering system

$$\ddot{\delta}_d = \frac{T_{s\beta}}{I_s}\beta + \frac{T_{sr}}{I_s} r - \frac{T_{s\beta}}{R_s I_s}\delta_d - \frac{B_s}{I_s}\dot{\delta}_d + \frac{1}{I_s}(T_c + T_d)$$

[1] Rajamani, 2012

Vehicle Modeling for Control Design

Road-vehicle control-based model

① Lateral vehicle dynamics

② Lane keeping dynamics

③ Steering system model

$$x = A_v(v_x)x + B_u(T_c + T_d) + B_w(v_x)w$$

- System state

$$x = [v_y \quad r \quad \psi_L \quad y_L \quad \delta \quad \delta]^{\top}$$

- Control input

$$v = T_c + T_d$$

- System disturbance

$$w = \begin{bmatrix} f_w & \rho_r \end{bmatrix}$$

v_y	lateral speed
r	yaw rate
y_L	lateral offset
ψ_L	heading error
δ	steering angle
δ	*steering speed*

Vehicle Modeling for Control Design

Road-vehicle model

$$x = A_v(v_x)x + B_u(T_c + T_d) + B_w(v_x)w$$

⇨ Conflict issue

Simplified driver model[1]

$$T_d = K_{d1}\theta_{near} + K_{d2}\theta_{far}$$

- Driver tracking performance

$$\theta_{near} = y_L / v_x T_p + \psi_L$$

- Driver anticipatory behaviors

$$\theta_{far} = \theta_1 v_y + \theta_2 r + \theta_3 \delta$$

⇨ Driver torque = linear combination of system states

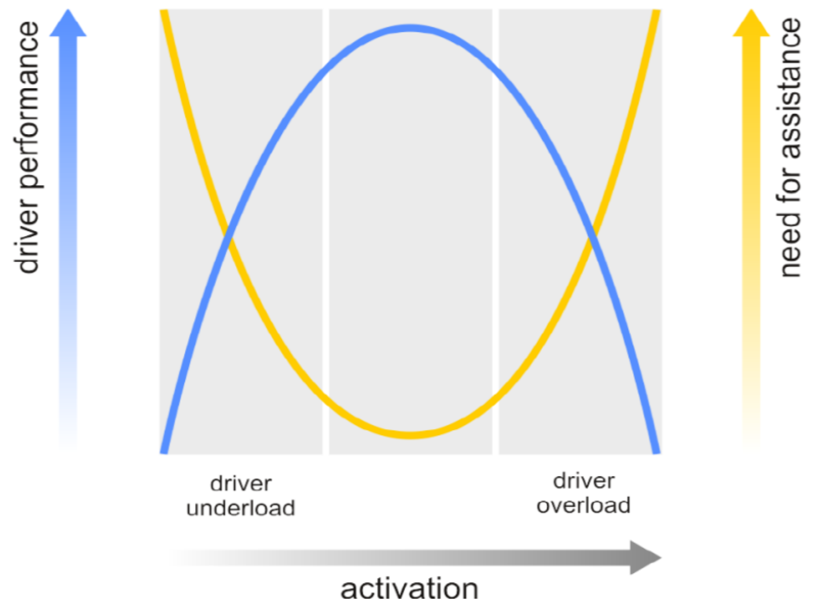
Driver-in-the-loop-vehicle model

$$x = A_v x + B_u(T_c + T_d) + B_w w \xrightarrow[\text{Driver model}]{} x = Ax + B_u T_c + B_w w$$

[1] Sentouh et al., 2009

Shared Driving Control Strategy

⦿ Need for assistance w.r.t. driver load and performance



U-shape function[2]

Principe of cooperative control[1]

- ⇨ The assistance should relieve the driver in underload and overload conditions.
- ⇨ The driver is always in the control loop.
- ⇨ There should have a continuous feedback between the automation system and the driver

⦿ Proposed solution

$$T_c = \mu(\theta_d) u$$

θ_d : driver activity variable

u: fictive torque to be designed

[1] Abbink and al., 2012 [2] Flemish and al., 2010

Shared Driving Control Strategy

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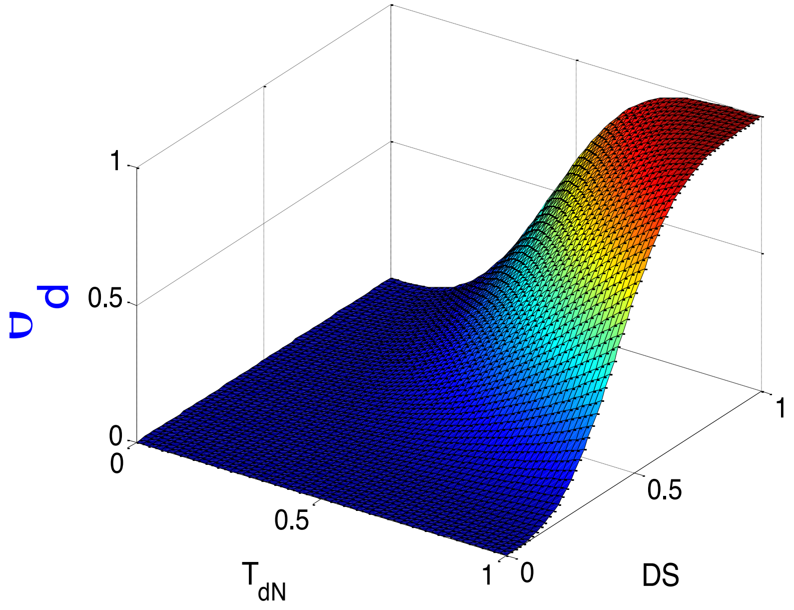

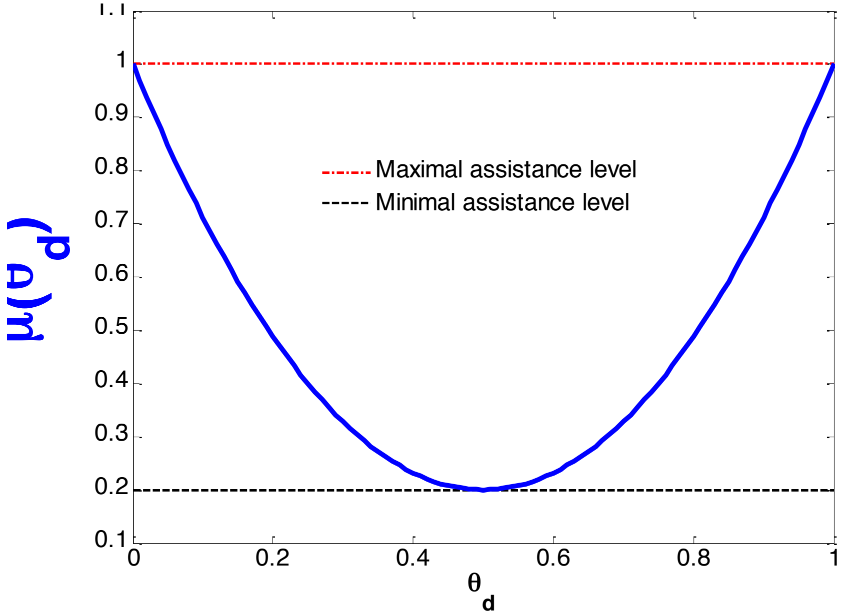

⦿ Control-based model

$$x = Ax + B_u T_c + B_w w$$

$$\Big\downarrow \; T_c = \mu(\theta_d) u$$

$$x = A(\mu(\theta_d), v_x) x + B_u(\mu(\theta_d)) u + B_w(v_x) w$$

Takagi-Sugeno model-based control technique

Takagi-Sugeno Model-Based Control Design

⦿ Takagi-Sugeno modeling[1] for quasi-LPV systems

$\dot{x} = A(\theta)x + B_u(\theta)\mathrm{sat}(u) + B_w(\theta)w \quad z = \; (\theta)x$

$\dot{x} = \sum_{i=1}^{r} \eta_i(\theta)(A_i x + B_{ui}(\theta)\mathrm{sat}($

- r: number of linear models
- Membership functions $\eta_i(\theta) \geq 0, \quad \sum_{i=1}^{r} \eta_i(\theta) = 1$
- Takagi-Sugeno fuzzy system = convex combination of linear subsystems

[1] Tanaka and Wang, 2001

Constrained Takagi-Sugeno Control Design

⦿ PDC (Parallel Distributed Compensation) control law[1]

$$u=\sum_{i=1}^{r}\eta_i(\theta)K_i x$$

⇨ Same membership functions as T-S model

⦿ System constraints $u_{min}\le u\le u_{max},\ \ Cx\le d$

- Unavoidable in almost real-world applications

☹ Degrade the system performance

☹ May make the system unstable

- How to deal with it? ⇨ Concept of robust invariant sets[2]

[1] Tanaka et al., 2001 [2] Blanchini and Miani, 2008

Constrained Takagi-Sugeno Control Design

⦿ Control task: Design an input-unsaturated PDC controller

- **Property 1: State constraints**

  Closed-loop system states remains in the polyhedral region

  $$x \in \mathfrak{D}_x = \{x \in \mathbb{R}^{n_x} : \ M_{(k)} x \le 1, \ k \in \{1,\dots,q\}\}$$

- **Property 2: Regional quadratic $\boldsymbol{\alpha}$–stability**

  When $w=0$, exponential convergence to the origin with a decay rate α

  $$\mathbb{V}(x) < -2\alpha\mathbb{V}(x), \ \mathbb{V}(x) = x^\top Px, \ P>0$$

- **Property 3: $\boldsymbol{\mathcal{L}_\infty}$ performance**

  When $w\neq 0$, the trajectories remain in the estimate domain of attraction and

  $$z(t)^\top z(t) \le \gamma, \ \forall w \in \mathcal{W}_\rho$$

Constrained Takagi-Sugeno Control Design

⦿ Sector condition for control input saturation[1]

Consider $K_i \in \mathbb{R}^{n_u \times n_x}$ and $G_i \in \mathbb{R}^{n_u \times n_x}$, $i \in \Omega_r$. Define $\psi(u) = u - sat(u)$

and

$\mathfrak{D}_u = \{x \in \mathbb{R}^{n_x} : |\sum_{i=1}^{r} \eta_i(\theta)(K_{i(l)} - G_{i(l)})x| \leq u_{\max(l)},\ l \in \Omega_{n_u}\}$

If $x \in \mathfrak{D}_u$, then

$\psi(u)^{\top} (\sum_{i=1}^{r} \eta_i(\theta) S_i)^{-1} [\psi(u) - \sum_{i=1}^{r} \eta_i(\theta) G_i x] \leq 0$

⬇

Incorporated into Lyapunov stability condition

⦿ And some other results on inclusion conditions $x \in \mathfrak{D}_x$, $x \in \mathfrak{D}_u$

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[1] Nguyen et al., 2016

Constrained Takagi-Sugeno Control Design

⦿ How to design such a controller?

Theorem: If there exist 𝑋, 𝑆↓𝑖 , 𝑉↓𝑖 , 𝑋↓21↑𝑖 , ..., and positive scalars 𝜏↓1 , 𝜏↓2 ,𝛾 such tha

1. [■𝑋&∗@𝑉↓𝑖(ℓ) −𝑊↓𝑖(ℓ) &𝑢↓max(ℓ)↑2]≥0
2. [■𝑋&∗@𝑀↓(𝑘)↑⊤ 𝑋&𝑢↓max(ℓ)↑2]≥0
3. [■𝑋&∗@𝐶↓𝑖 𝑋&𝛾𝐼]≥0
4. {■Ψ↓𝑖𝑖 <0, 𝑖∈{1,…,𝑟} @
5. 𝜏↓1 −𝜏↓2 𝜌>0

$$\Psi_{ij} = \mathrm{He}\begin{bmatrix} \Psi_{ij(1,1)} & B_i^u X_{32}^j & B_i^u X_{33}^j & -B_i^u S_j & B_i^w \\ \Psi_{ij(2,1)} & -X_{22}^j & -X_{23}^j & 0 & 0 \\ \Psi_{ij(3,1)} & -X_{32}^j & -X_{33}^j & 0 & 0 \\ W_i & 0 & 0 & -S_j & -S_j \\ 0 & 0 & 0 & 0 & -\tau_2 I/2 \end{bmatrix},$$

$$\Psi_{ij(1,1)} = A_i X + B_i^u X_{31}^j + \tau_1 X/2$$

$$\Psi_{ij(2,1)} = C_i X - X_{21}^j$$

$$\Psi_{ij(3,1)} = V_i - X_{31}^j$$

⦿ Feedback control gains

𝐾↓𝑖 =𝑉↓𝑖 𝑋↑−1 , 𝑖∈{1,…,𝑟}

☺

LMI formulation

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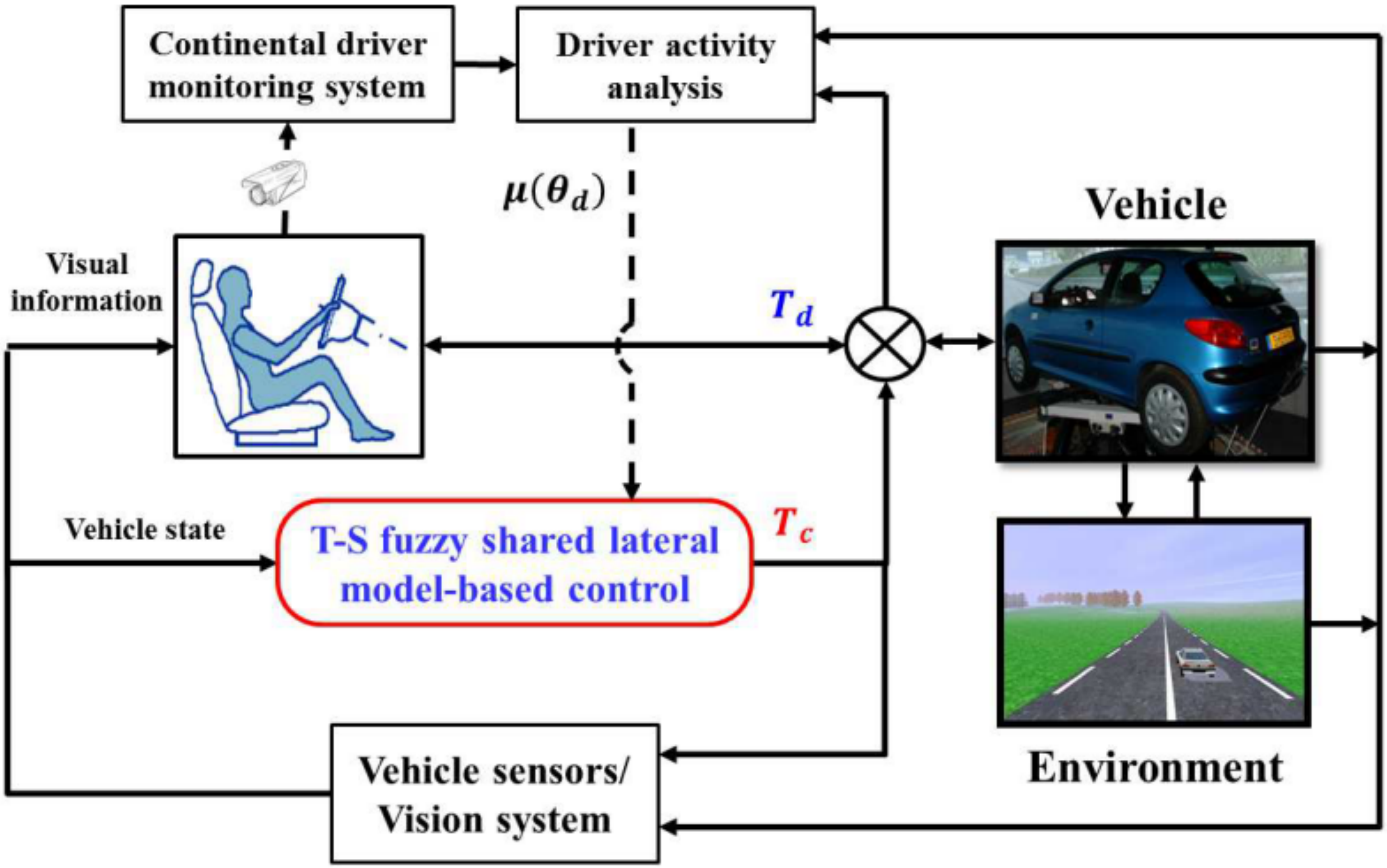
Hardware Experiments

Experimental setup: LAMIH-SHERPA interactive driving simulator

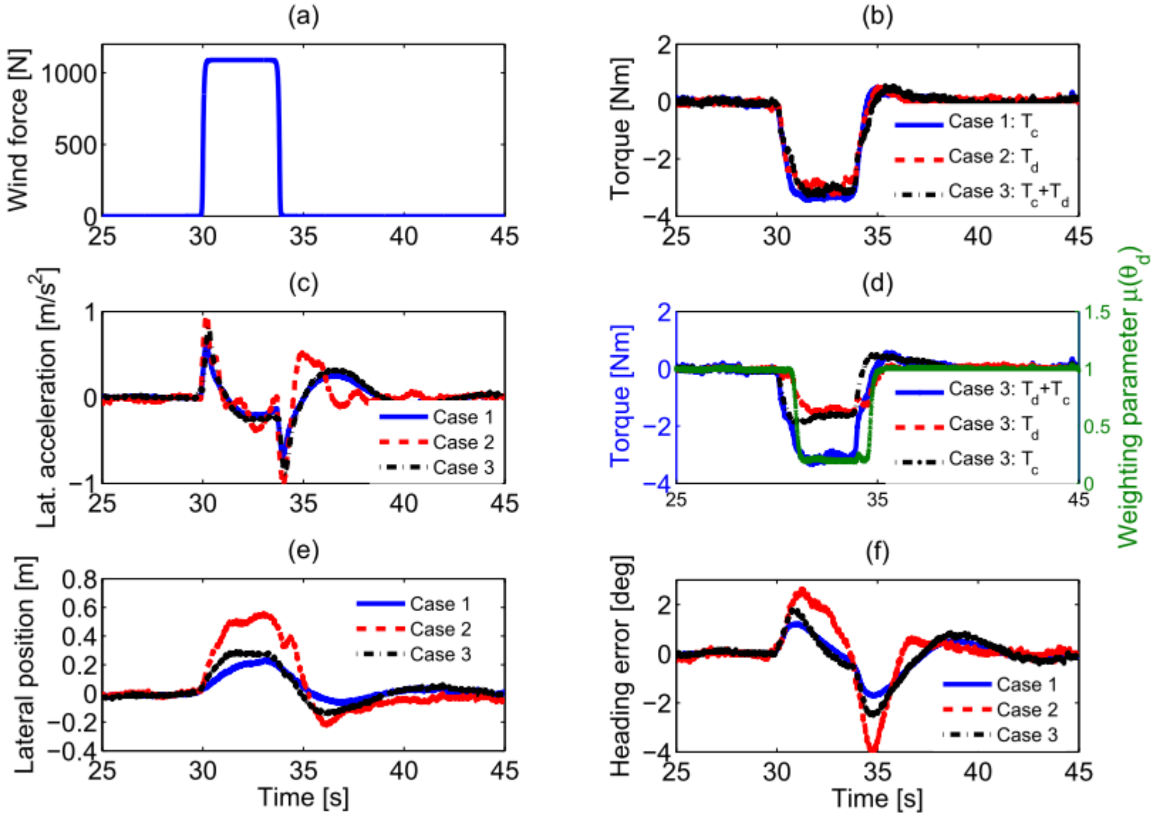


Hardware Experiments

Test 1: Disturbance rejection (straight road, $v_x=15m/s$, $f_w=1100N$)

Case 1: Automatic ($T_d=0$), Case 2: Manual ($T_c=0$), Case 3: Shared control

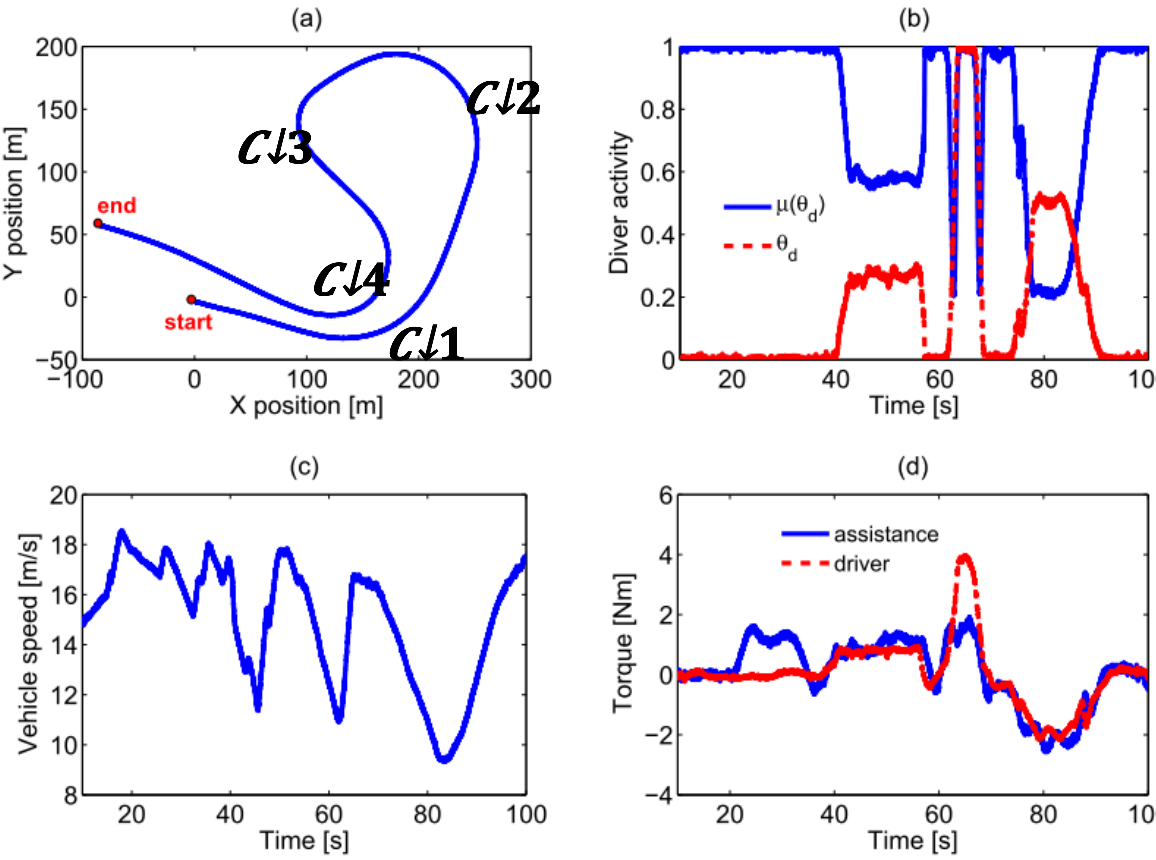
- Similar steering torques
- Small tracking errors
- Only 50% driver's effort for Case 3
- Shared control without conflict



Hardware Experiments

Test 2: Driving task with an adaptive level of assistance

- Phase 1 (10s to 40s): automatic $C\downarrow$
- Phase 2 (40s to 60s): shared $C\downarrow 2$
- Phase 3 (60s to 70s): shared $C\downarrow 3$
- Phase 4 (70s to 100s): shared $C\downarrow 4$



Lane-keeping without driver-automation conflict

Hardware Experiments

Many other tests and performance evaluation can be found here:

Anh-Tu Nguyen, Chouki Sentouh, Jean-Christophe Popieul, "Driver-Automation Cooperative Approach for Shared Steering Control under Multiple System Constraints: Design and Experiments", *IEEE Transactions on Industrial Electronics*, vol. 64, issue 5, pp. 3819-3830, 2017 [IF=7.168].

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Concluding Remarks

- **Conclusion:** Novel approach for vehicle shared driving control
  - Online adaptation of the control authority according to driver’s activity
  - Takagi-Sugeno approach ⇨ driver’s activity variable and vehicle speed variation
  - Consideration of system constraints to improve the control performance
  - Experimental validation with the SHERPA driving simulator and a human driver
- **Current investigations**
  - Sensor reduction for shared control under system constraints
  - Combined longitudinal-lateral shared control

THANK YOU FOR YOUR ATTENTION !

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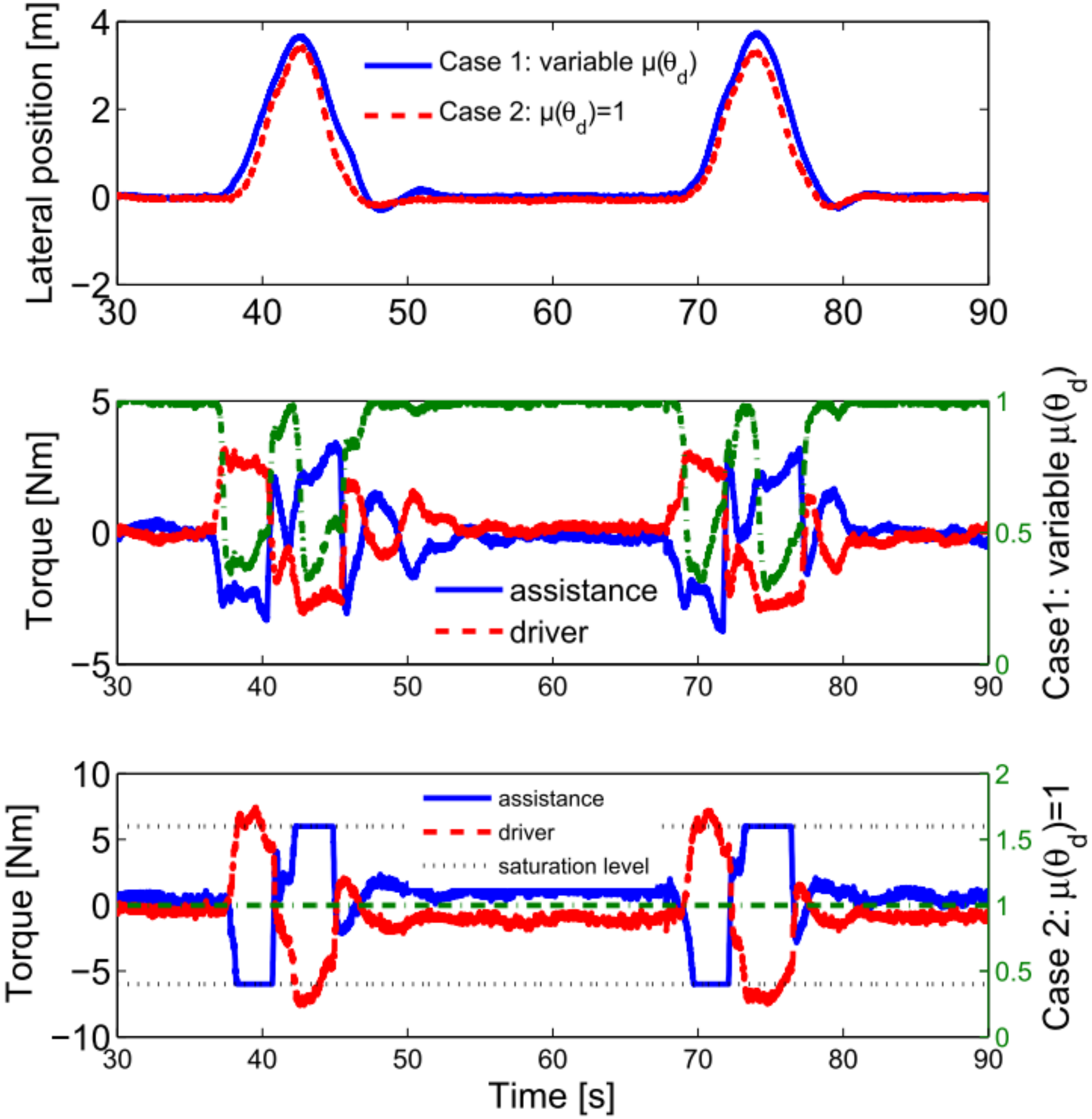
Hardware Experiments

Test 3: Emergency double lane change maneuver



- Case 1: *adaptive* authority allocation
- Case 2: *constant* authority allocation
- Small driver's effort with Case 1
- Control input saturation in Case 2