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GT - CPNL (Commande Prédictive Non Linéaire)

Active Steering Assistance for Lane Keeping and Lane Departure Prevention

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Topics

- Context and motivation
- Vehicle model on the lane
- Control law design
- Experimental results for lane keeping and lane departure avoidance
- Interaction steering assistance – driver
- Experimental results steering assistance – driver interaction
- Conclusions

Context and motivation

- Driver assistance systems have a double objective:
  - to decrease driver’s workload
  - to increase the driving safety

Context and motivation

- Steering assistance can be provided
  - Convenience system:
    - to compensate for minor road perturbations helping the driver to follow the lane centerline
  - Safety system:
    - to avoid leaving the lane and road departure accidents (safety system)

(US Traffic Safety Facts 2005, 28% of fatal accidents by lane keeping failure and lane departure, Germany GDV 2006, light trucks drivers : 23% of accidents are due to micro sleeps)

Context and motivation

- Main idea
  - The same steering control law acting by means of a DC motor on the steering column shall satisfy a double objective:
    - assist the driver to the lane keeping task if the driver is attentive
    - lane departure avoidance if the driver has a lapse of attention

Context and motivation

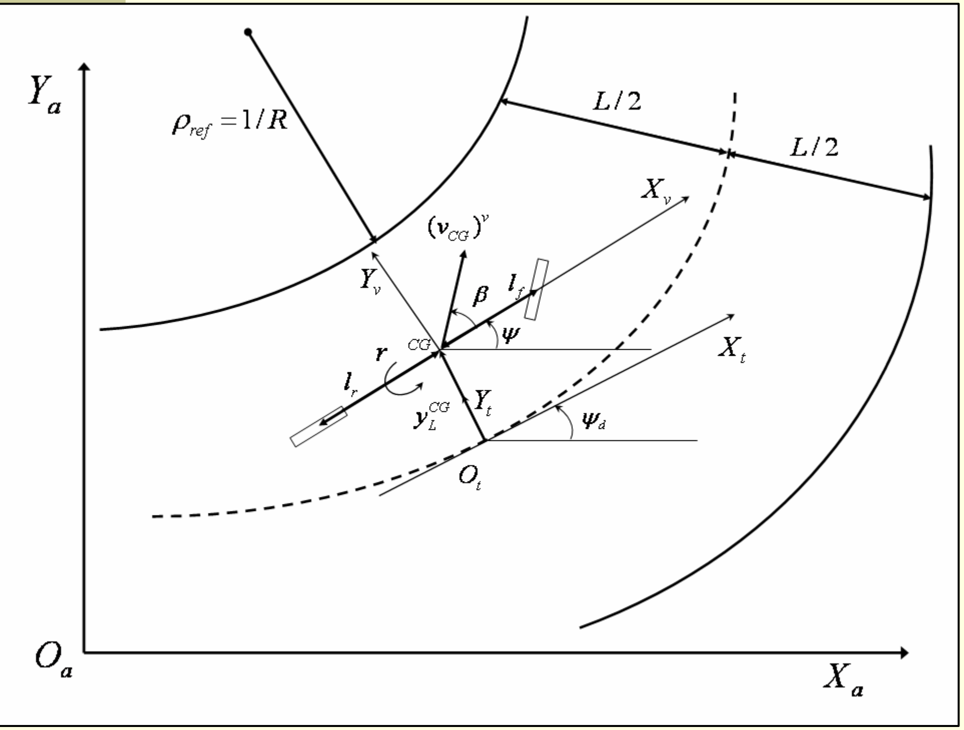
- The two objectives might have different constraints:
  - assisting to the lane keeping if the driver is attentive
    - good lane keeping performance
    - comfortable vehicle dynamics
    - good steering feel for the driver during the assistance
  - lane departure avoidance if the driver has a lapse of attention
    - reduced response time
    - minimum overshoot of the activation position to avoid lane departure
    - maintain the high vehicle dynamics below the tire-road capacity

Context and motivation

- In the work presented here
  - A vehicle control law is developed to do lane keeping and lane departure avoidance.
  - The interaction on the steering wheel between the control law and the driver is studied in order to determine the influence of the driver's action on the lane keeping performance of the control law.
  - The driver's steering feel is beyond the scope of this study.

Vehicle model on the lane

- Single track “bicycle model”



$$\dot{x} = Ax + B_u(T_a + T_d) + B_\rho \rho_{ref}$$

$$x = \left(\beta, r, \psi_L, y_L, \delta_f, \dot{\delta}_f\right)^T$$

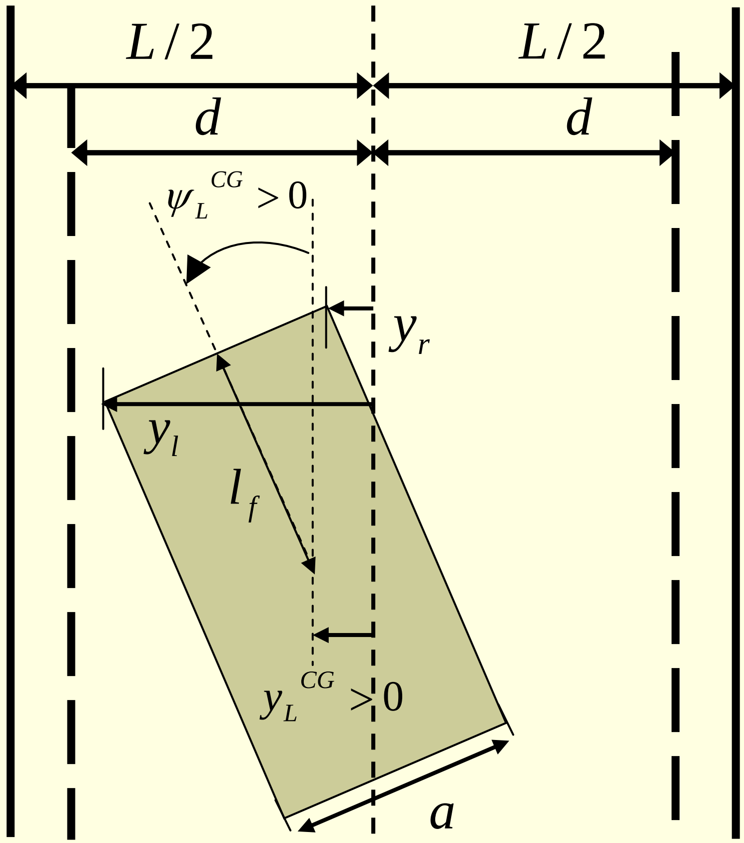
$$\left|\rho_{ref}\right| \le \rho_{ref}^{\max} \quad \rho_{ref} = w_1 \rho_{ref}^{\max} \quad \left|w_1\right| \le 1$$

$$\left|T_d\right| \le T_d^{\max} \quad T_d = w_2 T_d^{\max} \quad \left|w_2\right| \le 1$$

$$\dot{x} = Ax + B_u T_a + B_{w2} w_2 + B_{w1} w_1 \qquad B_{w1} = B_\rho \rho_{ref}^{\max} \quad B_{w2} = B_u T_d^{\max}$$

Vehicle model on the lane

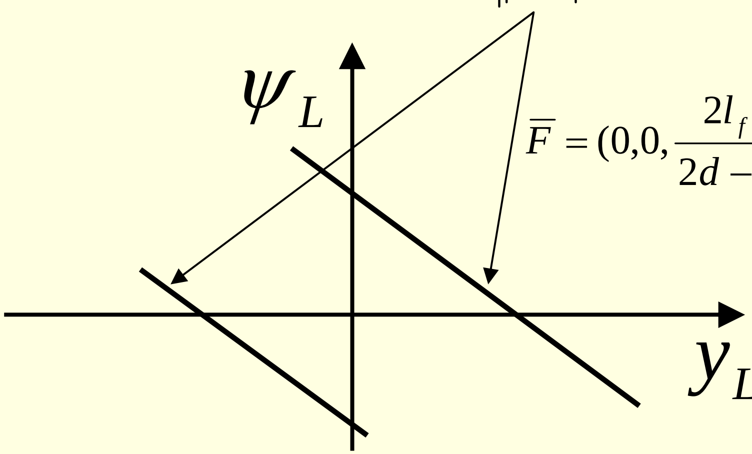
- Vehicle related to the lane borders



$$y_l = y_L^{CG} + l_f \psi_L^{CG} + \frac{a}{2} \qquad y_r = y_L^{CG} + l_f \psi_L^{CG} - \frac{a}{2}$$

$$-\frac{2d-a}{2} \le y_L^{CG} + l_f \psi_L^{CG} \le \frac{2d-a}{2} \quad \Leftrightarrow$$

$$x \in L(\overline{F}) = \left\{ x \in \Re^6 \,\middle|\, \left|\overline{F}x\right| \le 1 \right\}$$



$$\overline{F} = \left(0, 0, \frac{2l_f}{2d-a}, \frac{2}{2d-a}, 0, 0\right)$$

Control law design

- Linear system with two disturbance inputs
  - Road curvature: assumed measurable
  - Driver's input: neglected for the control design but studied afterwards

$$\dot{x} = Ax + B_u T_a + B_{w2} w_2 + B_{w1} w_1 \qquad B_{w1} = B_\rho \rho_{ref}^{\max} \quad B_{w2} = B_u T_d^{\max}$$

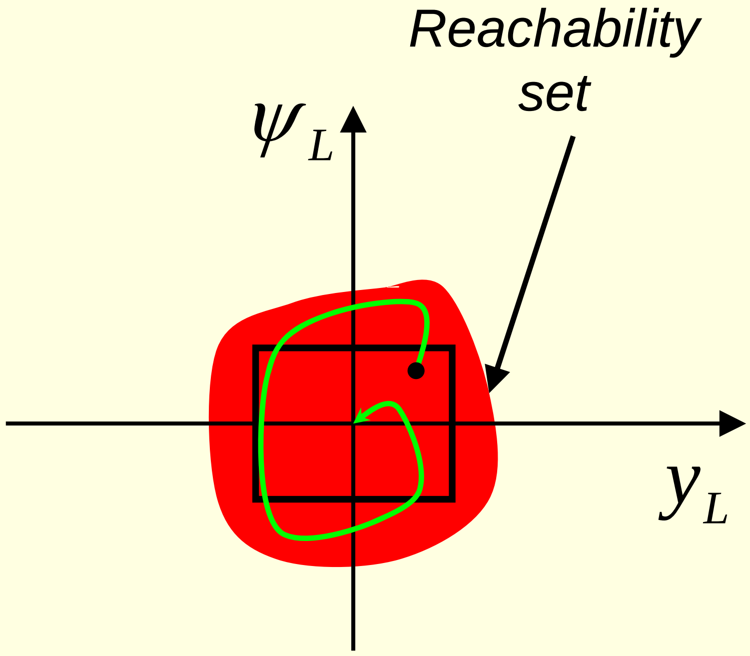
$$T_a = Kx + F_f \rho_{ref} = Kx + F_f \rho_{ref}^{\max} w_1$$

Measurable
disturbance input

$$\dot{x} = (A + B_u K)x + \bar{B}_{w1} w_1 \quad \bar{B}_{w1} = B_{w1} + F_f \rho_{ref}^{\max}$$

Control law design

- Find the control law which minimizes the excursions outside a “normal driving” set defined around the lane centerline



Control law design

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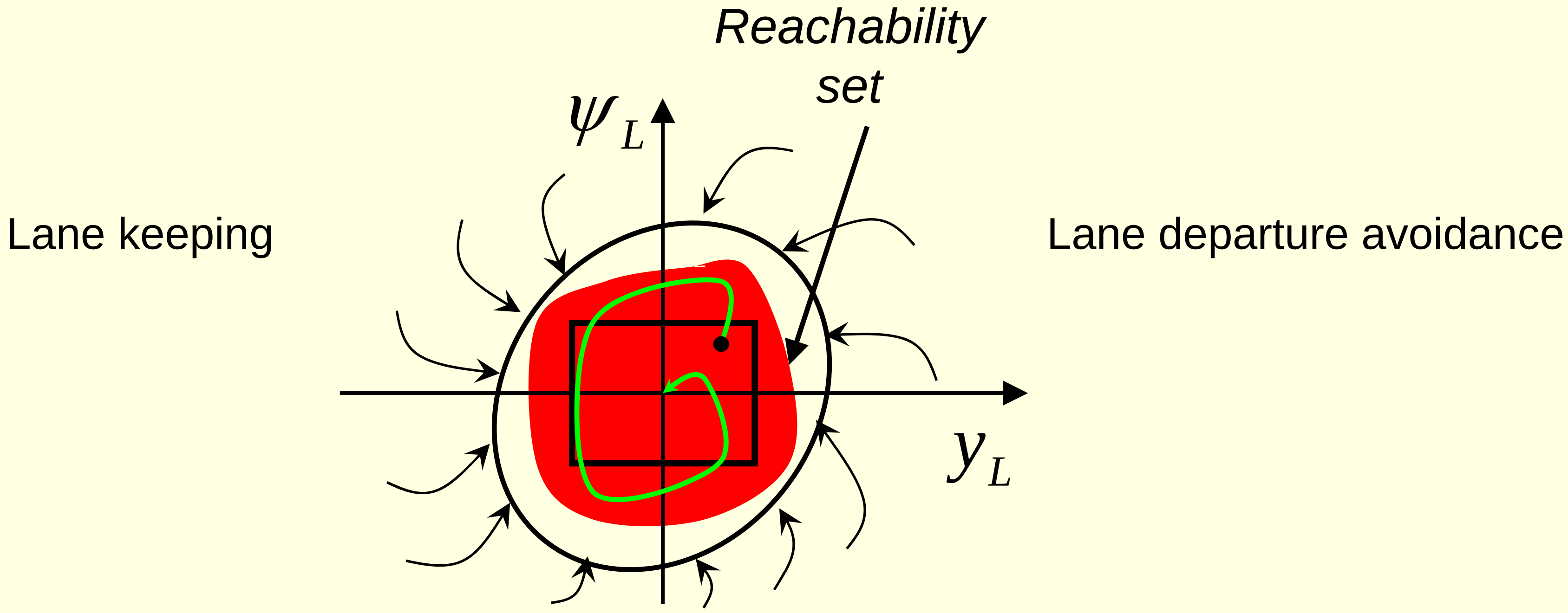


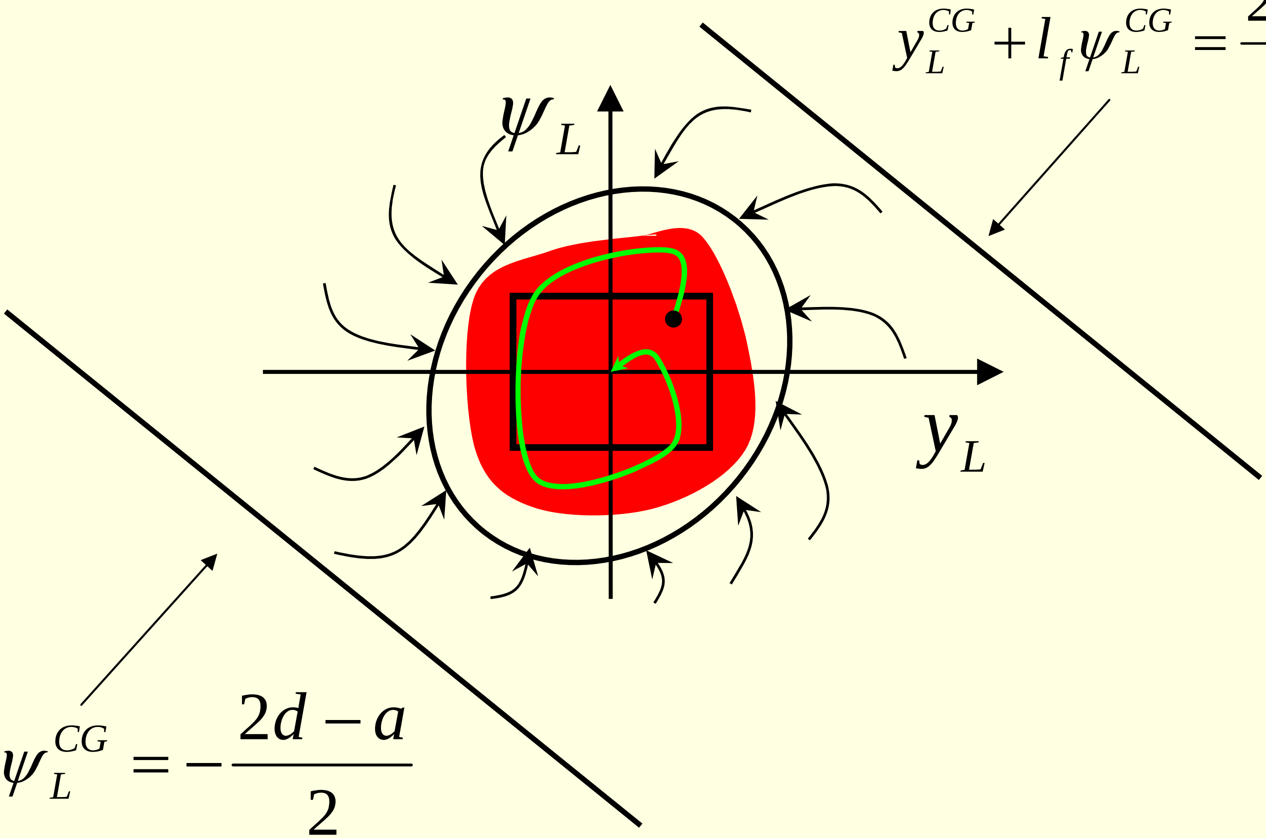
Control law design

- Lane departure avoidance
  - Invariant set → estimation of the lateral displacement

Control law design

- Lane departure avoidance
  - Invariant set ➔ estimation of the lateral displacement

$$y_L^{CG} + l_f \psi_L^{CG} = \frac{2d - a}{2}$$

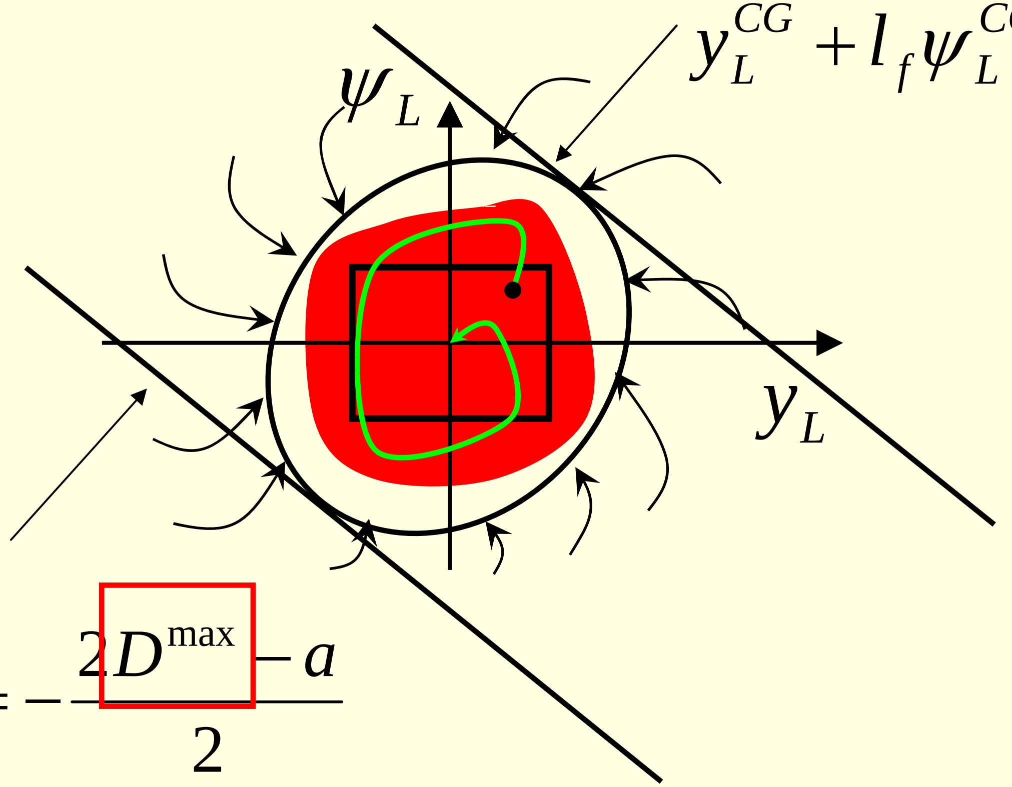


$$y_L^{CG} + l_f \psi_L^{CG} = -\frac{2d - a}{2}$$

Control law design

- Lane departure avoidance
  - Invariant set ➔ estimation of the lateral displacement

$$y_L^{CG} + l_f \psi_L^{CG} = \frac{2D^{\max} - a}{2}$$



$$y_L^{CG} + l_f \psi_L^{CG} = -\frac{2D^{\max} - a}{2}$$

Control law design

Search for quadratic function *V(x)=x^T^Px and*

for the feedback $T_a = Kx + F_f \rho_{ref}{}^{\max} w_1$

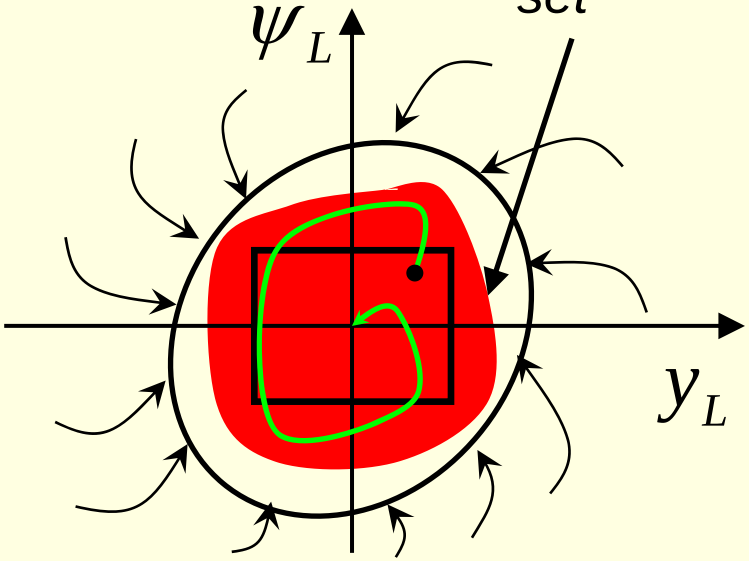
$$\frac{dV(x)}{dt} < 0$$

$$\forall x \in \Re^6 \quad such \quad that \quad x^T P x \geq 1$$

$$\forall w_1 \in \Re \quad such \quad that \quad |w_1| \leq 1$$

"Normal driving" region confined to

$$\varepsilon(P) = \{x \in \Re^6 : \; x^T P x \leq 1\}$$



$$\dot{x} = (A + B_u K)x + \overline{B}_{w1} w_1$$

Control law design

- Bounded control torque input

$$-T_{\max} \leq Kx + F_f \rho_{ref}^{\max} w_1 \leq T_{\max}$$

$$-1 \leq w_1 \leq 1$$

Control law design

BMI optimization problem

$\min \quad trace(Q)$ *Minimize the reachability set*

$$\alpha \succ 0, \qquad Q \succ 0, \qquad \tau_j \succ 0, \quad j = 1, \ldots, 4$$

Invariant set

$$\begin{pmatrix} QA^T + Y^T B_u^T + AQ + B_u Y + \alpha Q & \rho_{ref}^{\max}(B_u F_f + B_\rho) \\ \rho_{ref}^{\max}(B_u F_f + B_\rho)^T & -\alpha \end{pmatrix} \prec 0,$$

"Normal driving" set inclusion

$$\begin{pmatrix} 1 & (z_i^N)^T \\ z_i^N & Q \end{pmatrix} \succ 0, \qquad i = 1, \ldots, 32,$$

Bounded assistance torque

$$\begin{pmatrix} 0 & 0 & -\frac{1}{2}Y^T \\ 0 & 0 & -\frac{1}{2}\rho_{ref}^{\max}F_f \\ -\frac{1}{2}Y & -\frac{1}{2}\rho_{ref}^{\max}F_f & T_{\max} \end{pmatrix} \succ \tau_1 \begin{pmatrix} -Q & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \tau_2 \begin{pmatrix} 0 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\begin{pmatrix} 0 & 0 & \frac{1}{2}Y^T \\ 0 & 0 & \frac{1}{2}\rho_{ref}^{\max}F_f \\ \frac{1}{2}Y & \frac{1}{2}\rho_{ref}^{\max}F_f & T_{\max} \end{pmatrix} \succ \tau_3 \begin{pmatrix} -Q & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \tau_4 \begin{pmatrix} 0 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

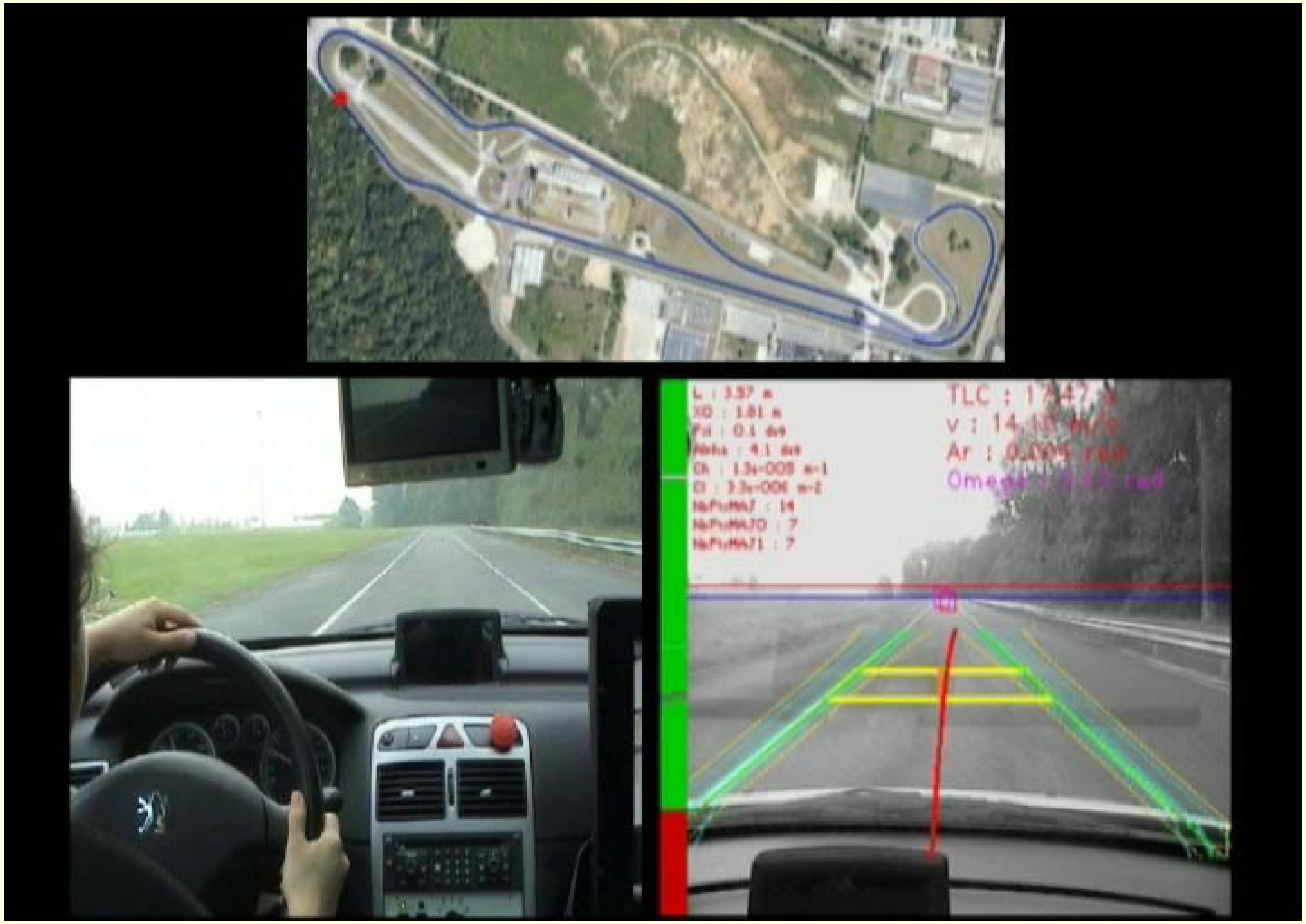
$$P = Q^{-1}$$

$$K = YQ$$

$$F_f \quad \alpha$$

Experimental results for lane keeping and lane departure avoidance

Experimental results for lane keeping and lane departure avoidance



Interaction steering assistance – driver

- Same theoretical approach as for the control law design to estimate the driver's impact on the control law performance

$$\dot{x} = Ax + B_u T_a + B_{w2} w_2 + B_{w1} w_1$$

$$T_a = Kx + F_f \rho_{ref}^{\max} w_1$$

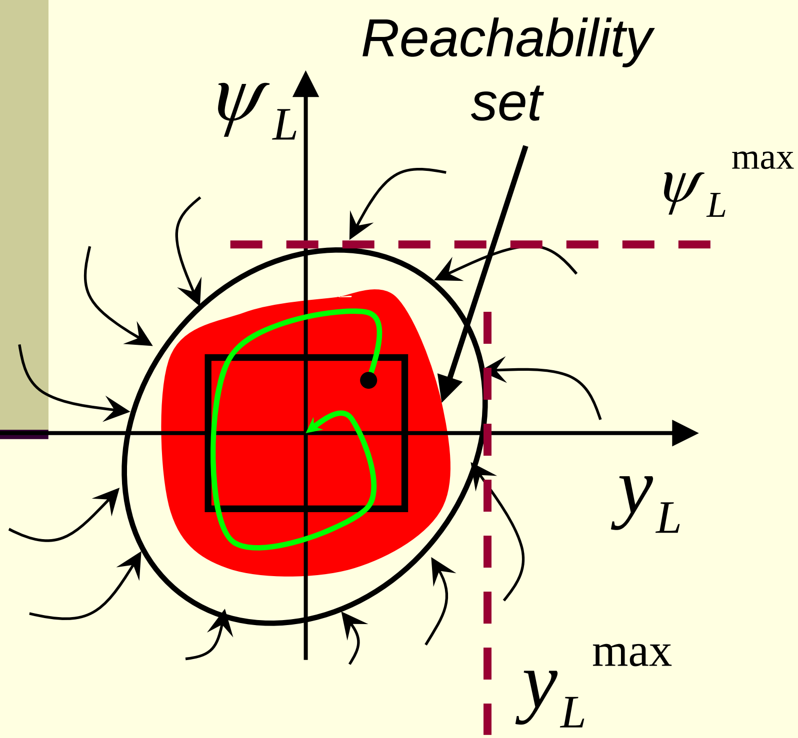
$$\dot{x} = A_{cl} x + \overline{B}_{w1} w_1 + B_{w2} w_2$$

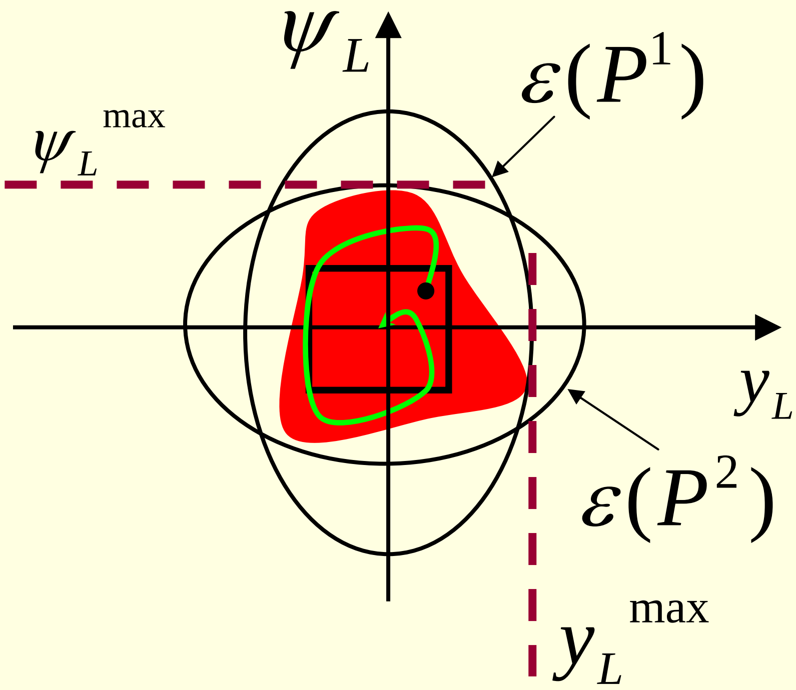
$$|w_1| \leq 1 \quad |w_2| \leq 1$$

Estimation of the vehicle reachability set going from the "normal driving" set.

Interaction steering assistance – driver

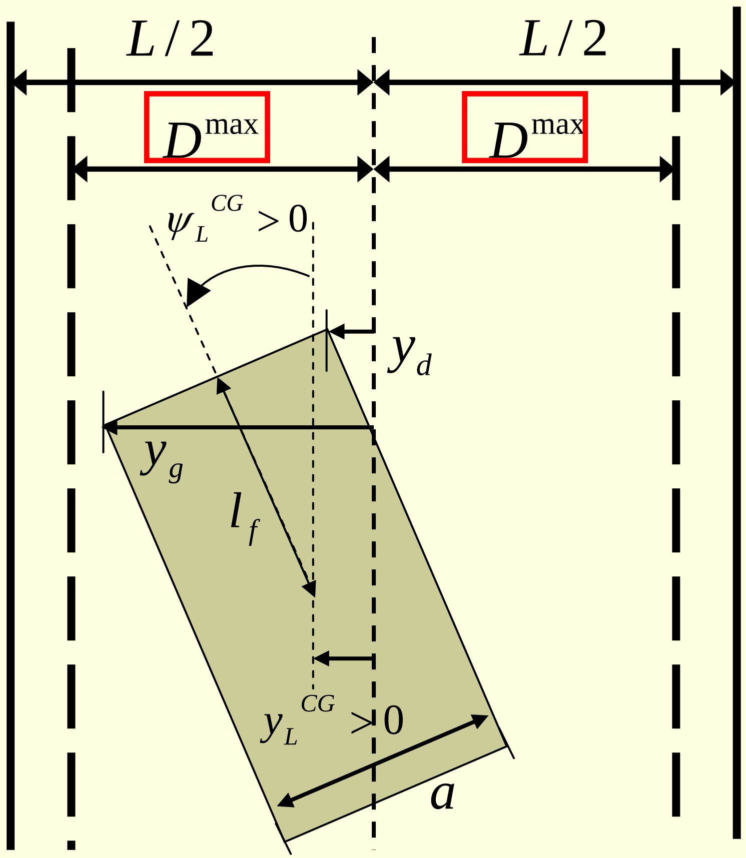
- Invariant set including vehicle reachability set
  - Upper bound for the vehicle dynamics



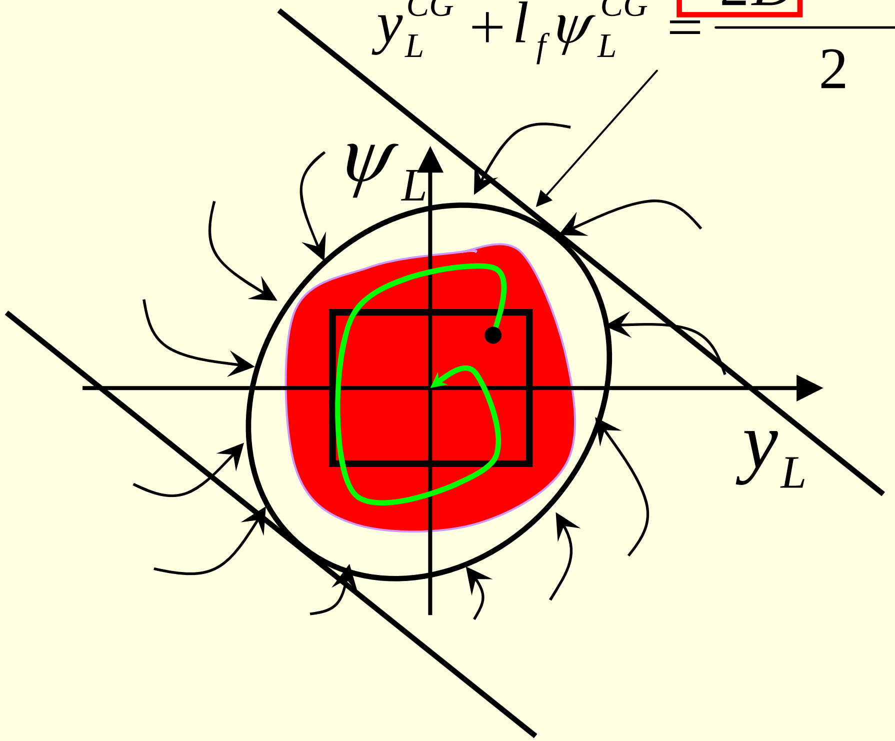


Interaction steering assistance – driver

- Invariant set including vehicle reachability set
  - Upper bound for the lateral displacement



$$y_L^{CG} + l_f \psi_L^{CG} = \frac{2D^{max} - a}{2}$$



Interaction steering assistance – driver

- Invariant set including vehicle reachability set

BMI optimization problem

$$Q = P^{-1}$$

$$\min \quad trace(Q)$$

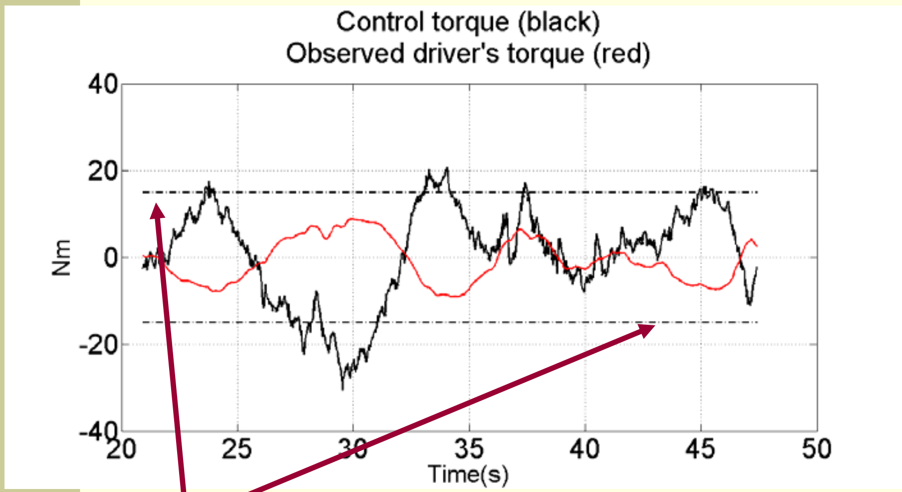
$$\alpha_j \succ 0, \qquad Q \succ 0, \quad j = 1,\ldots,3$$

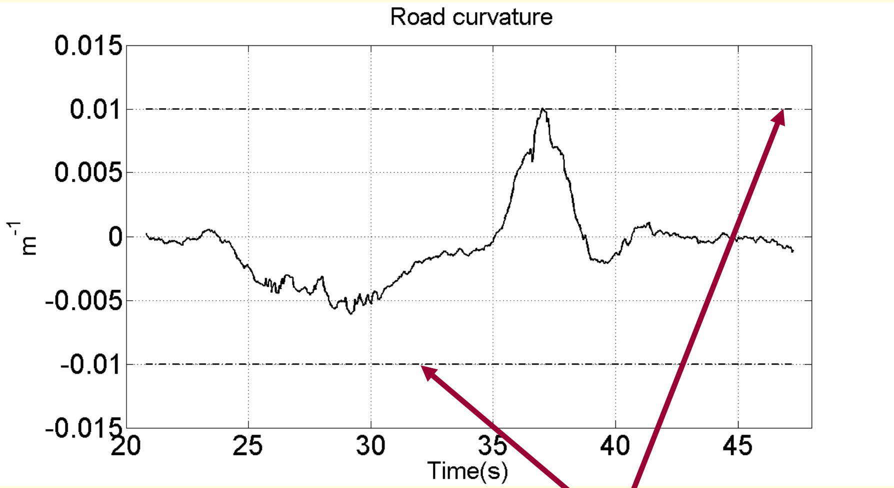
$$i = 1,\ldots,32,$$

$$\begin{pmatrix} QA_{cl}^T + A_{cl}Q + \alpha_1 Q & B_{w1} & B_{w2} & 0 \\ B_{w1}{}^T & -\alpha_2 & & \\ B_{w2}{}^T & & -\alpha_3 & \\ 0 & & & -\alpha_1 + \alpha_2 + \alpha_3 \end{pmatrix} \prec 0$$

$$\begin{pmatrix} 1 & (z_i{}^N)^T \\ z_i{}^N & Q \end{pmatrix} \succ 0$$

Experimental results steering assistance – driver interaction





$|T_d| \leq 15Nm$

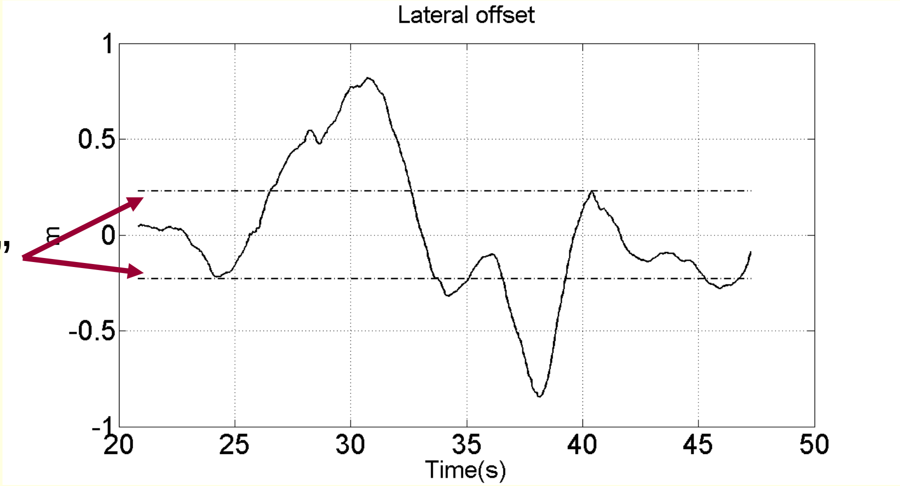
$|\rho_{ref}| \leq 0.01m^{-1}$

Computed

$D^{\max} = 2.19m$

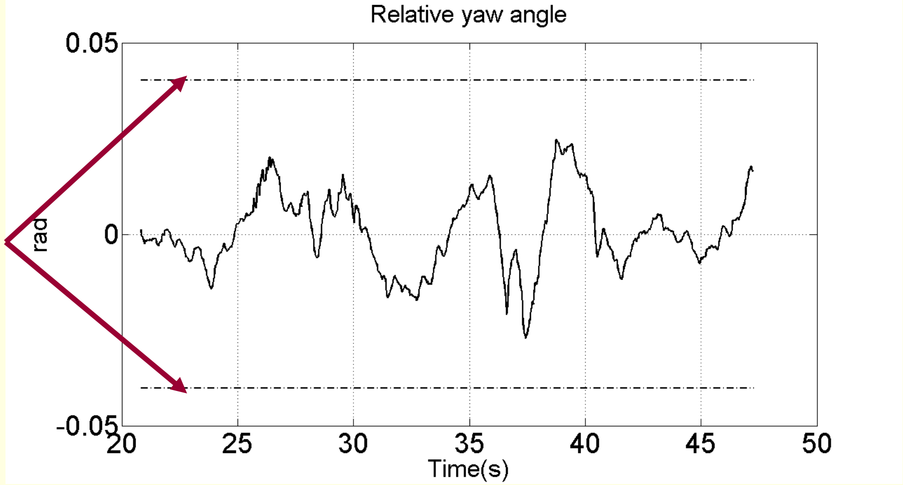
Lane border

Experimental results
steering assistance – driver interaction



Start inside “normal driving” zone

Upper bound for the lateral offset under the simultaneous action driver-steering assistance
1.59m



Start inside “normal driving” zone

Upper bound for the yaw angle under the simultaneous action driver-steering assistance
0.27rad

Conclusions

- Main function of the steering assistance
  - help the inattentive driver to correct the vehicle trajectory for drifting off cases and guiding to the center of the lane subsequently
- Features
  - activation during curve negotiation with stability proof
  - guaranteed front wheels displacement during activation
  - excellent lane keeping performances proven by experimental test even for curvatures higher than the design values
- Control design method
  - Minimize the reachability set with a linear feedback for initial states in a bounded set around the origin and under the influence of a peak-bounded disturbancy (road curvature)
  - LMI and BMI optimization

Conclusions

- Simultaneous action of the driver and of the steering assistance
  - estimation of the vehicle reachability set starting from a “normal driving” situation
  - implementation of BMI and LMI optimization methods
  - upper bounds obtained for the vehicle lateral displacement on the road and for the vehicle dynamics.
- An experimental validation of the obtained results has been conducted
  - all theoretical bounds have been confirmed
  - a the obtained bounds has been noticed in practice conservative
- Further works
  - influence of the driver’s action on the steering control law performance: better approximation of the reachability set through invariant sets with other shapes than ellipsoids
  - influence of the steering control law on the driver’s action: ergonomic study