A Comparison of Two Guidance Strategies for Autonomous Vehicles

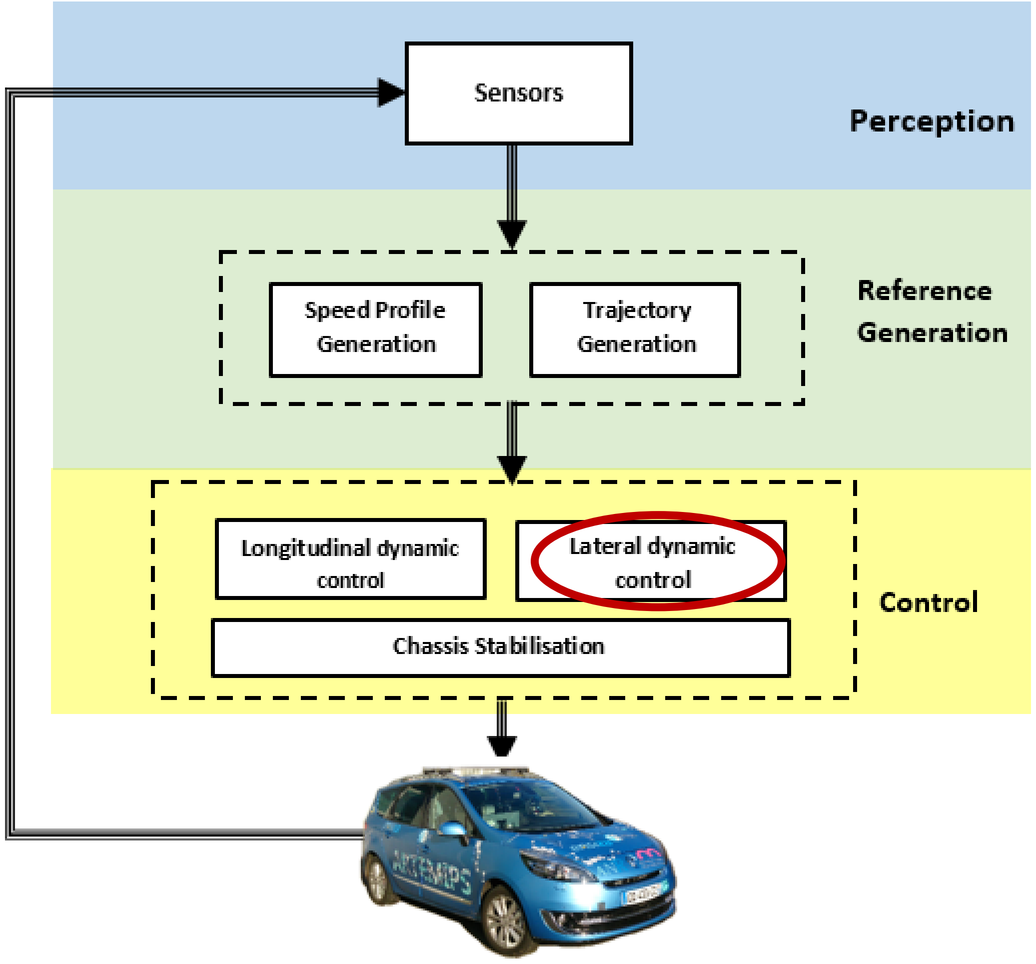
M. Boudali, R. Orjuela, M. Basset

Modeling, Intelligence, Process and Systems Laboratory (MIPS)
Mulhouse - France

Journées Automatique et Automobile du GDR MACS - Amiens, 18-19 Octobre 2017

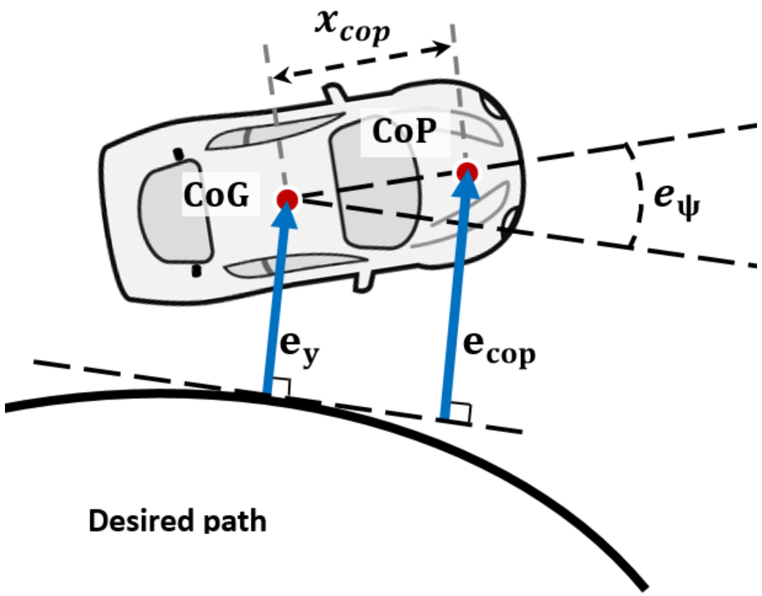
MOTIVATION

- **90%** of the road accidents are due to the **human errors.**
- **Road safety** should be improved.
- **Autonomous vehicles** are considered as promising way for the Intelligent transportation systems.
- **Lateral dynamic control** should be improved.



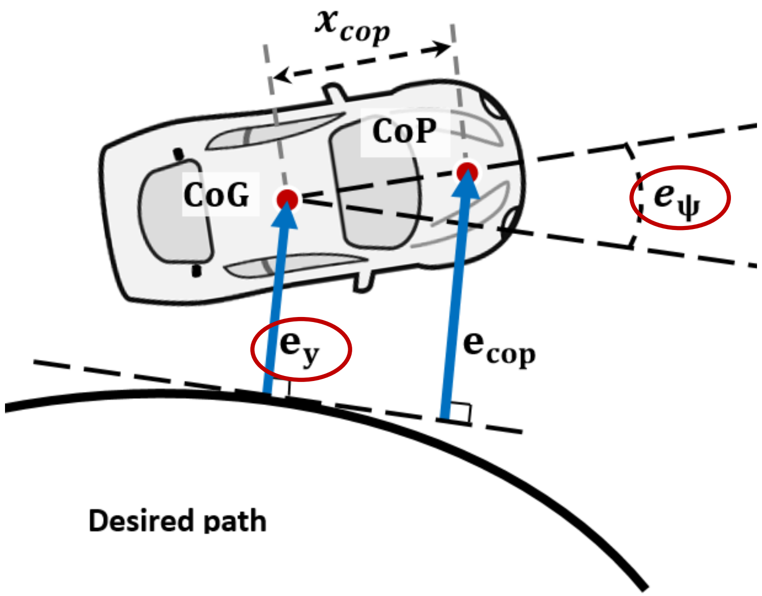
PROBLEM STATEMENT

- **Path tracking**



PROBLEM STATEMENT

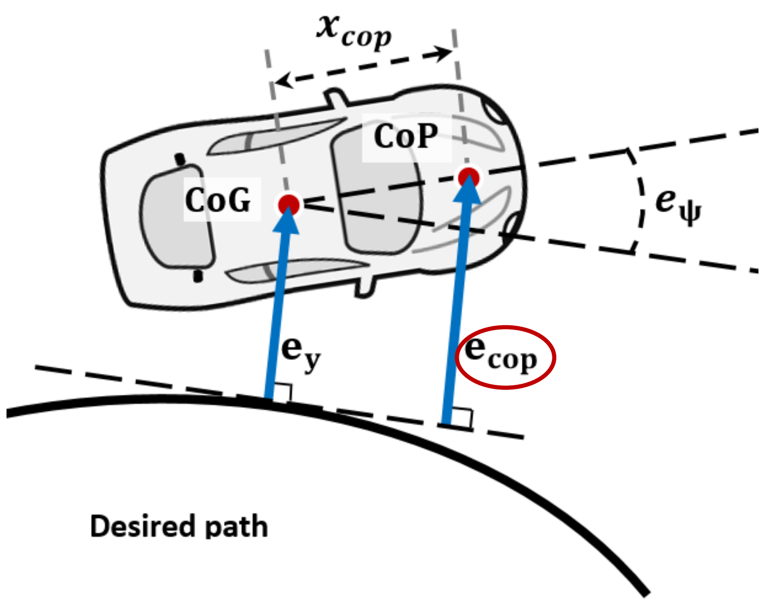
- **Path tracking**



	Center of Gravity (Classic)	Center of Percussion (Recent)
Driving situation	Normal situation	Limit of the handling

PROBLEM STATEMENT

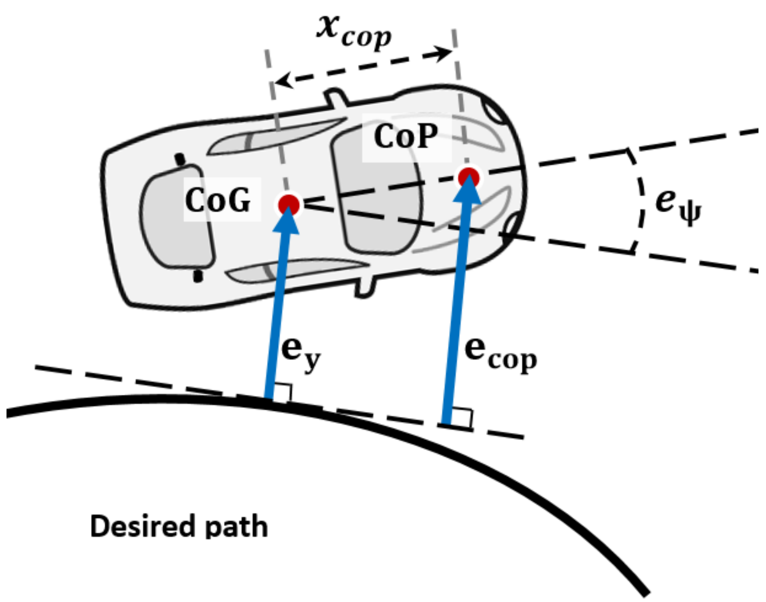
- **Path tracking**



	Center of Gravity (Classic)	Center of Percussion (Recent)
Driving situation	Normal situation	Limit of the handling

PROBLEM STATEMENT

- **Path tracking**



	Center of Gravity (Classic)	Center of Percussion (Recent)
Driving situation	Normal situation	Limit of the handling

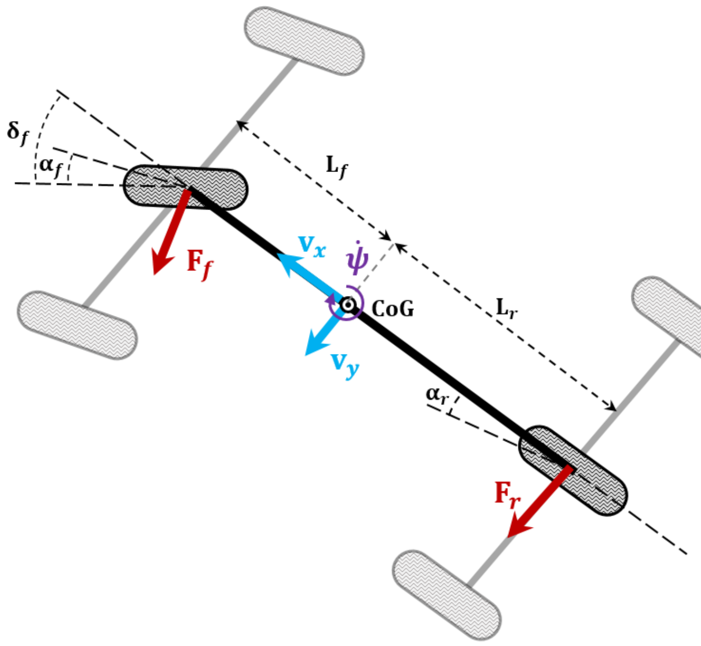
- **Main objective**
  A comparison of two lateral guidance strategies based on the CoG and on the CoP is proposed.

OUTLINE

1. Dynamic vehicle modeling
2. Errors model
3. Control design
4. Simulation tests
5. Conclusion & Outlooks

DYNAMIC VEHICLE MODELING

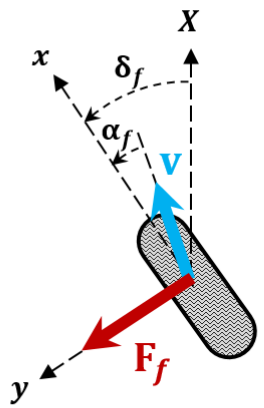
Linear bicycle model is used for the controller synthesis.



- **Lateral tire force**

$$F_y = C_y \alpha_f$$

$$\alpha_f = \frac{v_y}{v_x} - \delta_f$$



- **Lateral vehicle dynamics**

$$\sum M = L_f F_f - L_r F_r$$

$$\sum F = F_f + F_r$$

DYNAMIC VEHICLE MODELING

- **Bicycle model**

$$\begin{bmatrix} \dot{v}_y \\ \ddot{\psi} \end{bmatrix} = \begin{bmatrix} -\frac{2C_f+2C_r}{mv_x} & -v_x - \frac{2C_fL_f-2C_rL_r}{mv_x} \\ -\frac{2C_fL_f-2C_rL_r}{I_zv_x} & -\frac{2C_fL_f^2+2C_rL_r^2}{I_zv_x} \end{bmatrix} \begin{bmatrix} v_y \\ \dot{\psi} \end{bmatrix} + \begin{bmatrix} \frac{2C_f}{m} \\ \frac{2C_fL_f}{I_z} \end{bmatrix} \delta_f$$

- **Input control**
  δ_f Front steering wheel-angle.

- **Output vector**
  v_y Lateral velocity.
  $\dot{\psi}$ Yaw rate.

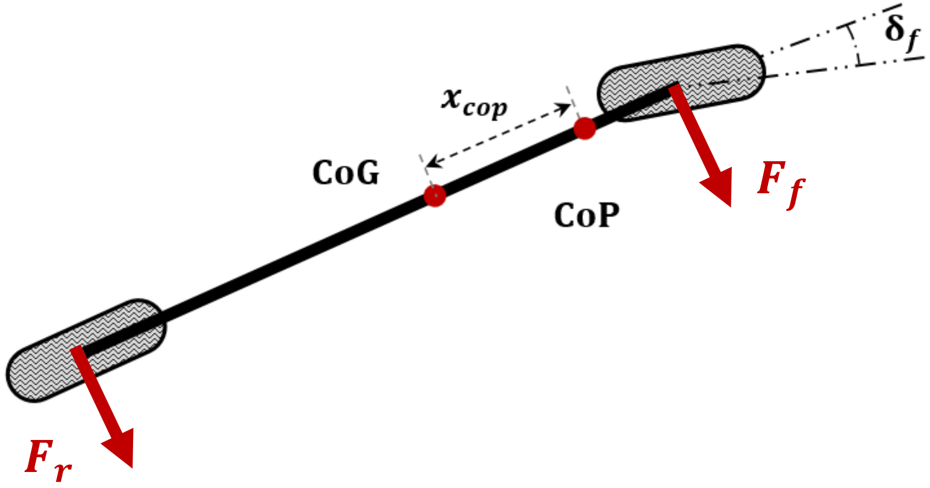
- **Remark**
  v_x Longitudinal velocity is constant.

CENTER OF PERCUSSION

CoP position

- Its position depends on the vehicle parameters

$$x_{cop} = \frac{I_z}{L_f m}$$



CENTER OF PERCUSSION

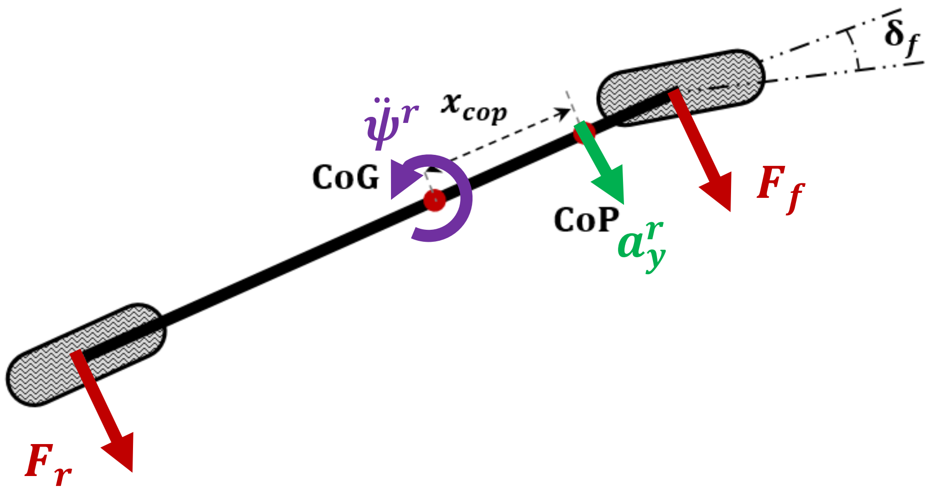
CoP position

- Its position depends on the vehicle parameters

$$x_{cop} = \frac{I_z}{L_f m}$$

The rear tire lateral force has two effects on the system dynamics

- a_y lateral acceleration along the body of the vehicle.
- $\ddot{\psi}$ angular acceleration around the vehicle's CoG.



CENTER OF PERCUSSION

CoP position

- Its position depends on the vehicle parameters

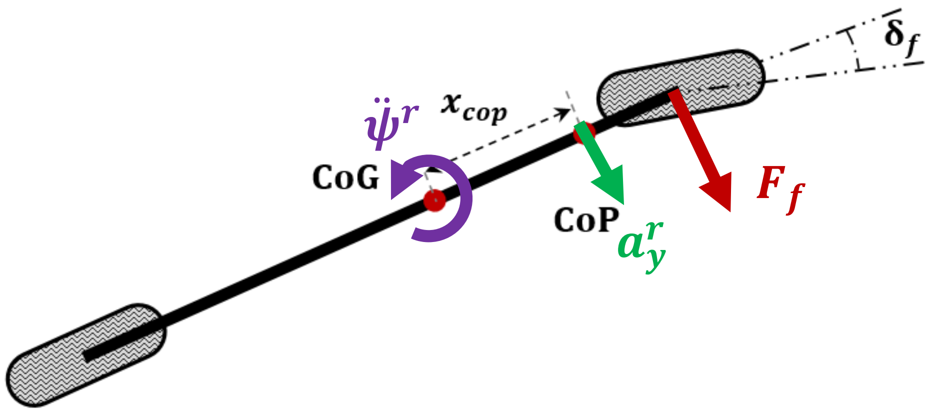
$$x_{cop} = \frac{I_z}{L_f m}$$

The rear tire lateral force has two effects on the system dynamics

- a_y lateral acceleration along the body of the vehicle.
- $\ddot{\psi}$ angular acceleration around the vehicle's CoG.

At the CoP, these two effects cancel each other out.

$$a_y^r - x_{cop}\ddot{\psi}^r = 0$$



CENTER OF PERCUSSION

CoP position

- Its position depends on the vehicle parameters

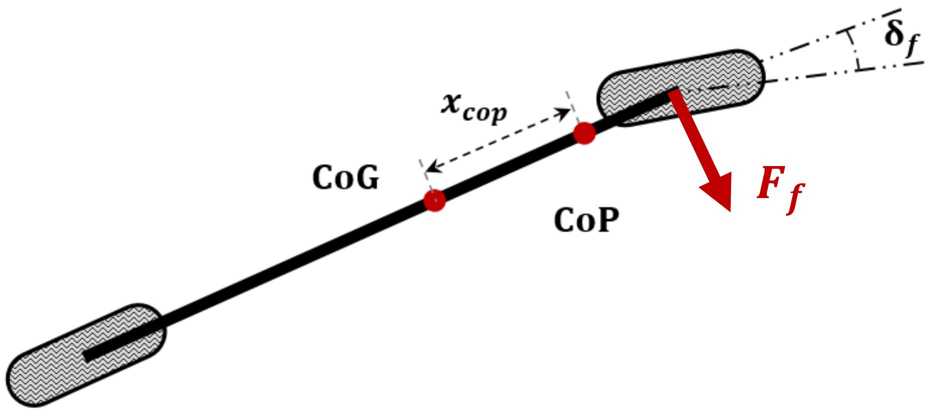
$$x_{cop} = \frac{I_z}{L_f m}$$

The rear tire lateral force has two effects on the system dynamics

- a_y lateral acceleration along the body of the vehicle.
- $\ddot{\psi}$ angular acceleration around the vehicle's CoG.

At the CoP, these two effects cancel each other out.

$$a_y^r - x_{cop}\ddot{\psi}^r = 0$$



Benefits

- Using the CoP allows to preview the lateral error (look ahead) .
- Using the CoP does not require the knowledge of the rear tire lateral force.

ERRORS MODEL

- **References**

  ψ_{ref} desired yaw angle.

  $\dot{\psi}_{ref}$ desired yaw rate.

- **Orientation error**

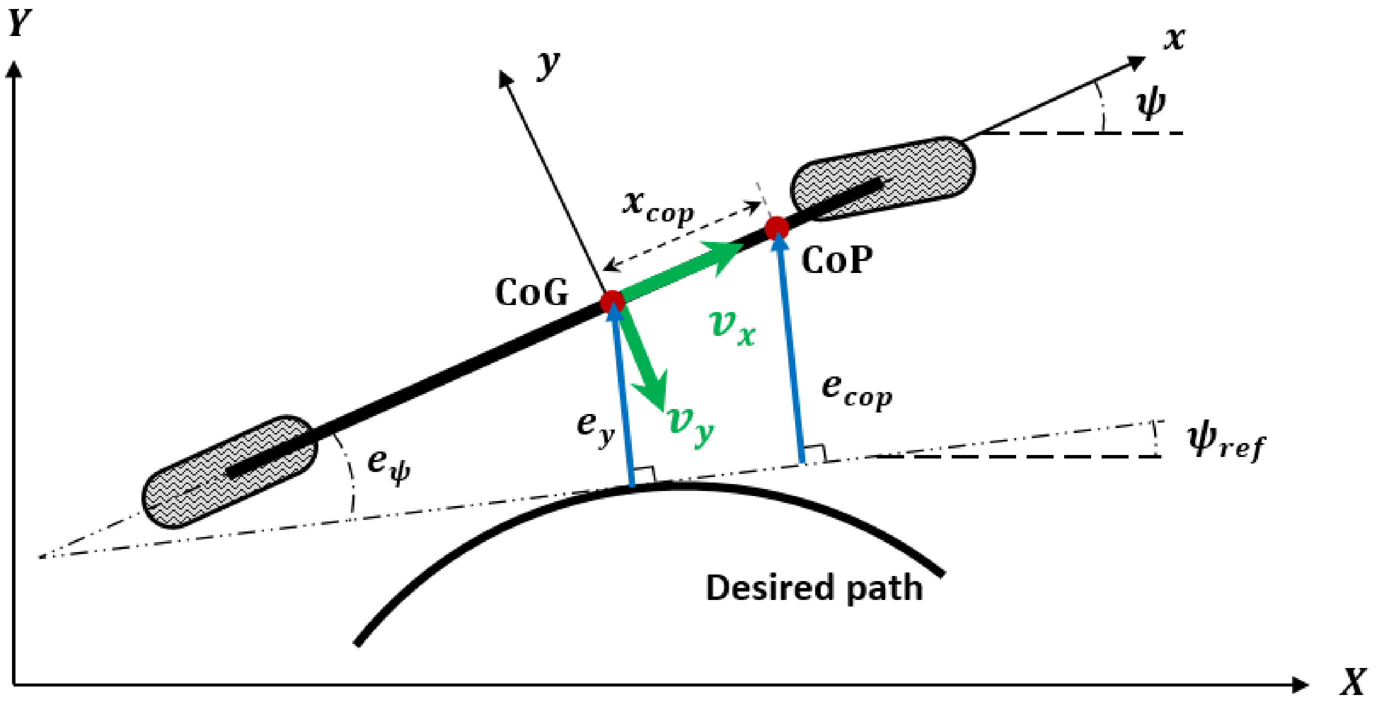
  $e_\psi = \psi - \psi_{ref}$

- **CoG lateral error dynamic**

  $\dot{e}_y = v_y + v_x e_\psi$

- **CoP lateral error dynamic**

  $\dot{e}_{cop} = \dot{e}_y + x_{cop}\dot{e}_\psi$



ERRORS MODEL

- **CoG model**

$$\frac{d}{dt}\begin{bmatrix} e_y \\ \dot{e}_y \\ e_\psi \\ \dot{e}_\psi \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -\frac{C_f+C_r}{mv_x} & \frac{C_f+C_r}{m} & -\frac{C_fL_f-C_rL_r}{mv_x} \\ 0 & 0 & 0 & 1 \\ 0 & -\frac{C_fL_f-C_rL_r}{I_zv_x} & \frac{C_fL_f-C_rL_r}{I_z} & -\frac{C_fL_f^2+C_rL_r^2}{I_zv_x} \end{bmatrix} \begin{bmatrix} e_y \\ \dot{e}_y \\ e_\psi \\ \dot{e}_\psi \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{C_f}{m} \\ 0 \\ \frac{C_fL_f}{I_z} \end{bmatrix} \delta_f + \begin{bmatrix} 0 \\ -\frac{C_fL_f-C_rL_r}{mv_x} - v_x \\ 0 \\ -\frac{C_fL_f^2+C_rL_r^2}{Izv_x} \end{bmatrix} \dot{\psi}_{ref}$$

- **CoP model**

$$\frac{d}{dt}\begin{bmatrix} e_{cop} \\ \dot{e}_{cop} \\ e_\psi \\ \dot{e}_\psi \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -R_l\frac{C_f}{mv_x} & R_l\frac{C_f}{m} & -\frac{R_lC_f(L_f-x_{cop})}{mv_x} \\ 0 & 0 & 0 & 1 \\ 0 & -\frac{C_fL_f-C_rL_r}{I_zv_x} & \frac{C_fL_f-C_rL_r}{I_z} & -\frac{C_fL_f(L_f-x_{cop})+C_rL_r^2}{I_zv_x} \end{bmatrix} \begin{bmatrix} e_{cop} \\ \dot{e}_{cop} \\ e_\psi \\ \dot{e}_\psi \end{bmatrix} + \begin{bmatrix} 0 \\ R_l\frac{C_f}{m} \\ 0 \\ \frac{C_fL_f}{I_z} \end{bmatrix} \delta_f + \begin{bmatrix} 0 \\ -R_l\frac{C_fL_f}{mv_x} - v_x \\ 0 \\ -\frac{C_fL_f^2+C_rL_r^2}{Izv_x} \end{bmatrix} \dot{\psi}_{ref}$$

ERRORS MODEL

- **CoG model**

$$\frac{d}{dt}\begin{bmatrix} e_y \\ \dot{e}_y \\ e_\psi \\ \dot{e}_\psi \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -\frac{C_f+C_r}{mv_x} & \frac{C_f+C_r}{m} & -\frac{C_fL_f-C_rL_r}{mv_x} \\ 0 & 0 & 0 & 1 \\ 0 & -\frac{C_fL_f-C_rL_r}{I_zv_x} & \frac{C_fL_f-C_rL_r}{I_z} & -\frac{C_fL_f^2+C_rL_r^2}{I_zv_x} \end{bmatrix} \begin{bmatrix} e_y \\ \dot{e}_y \\ e_\psi \\ \dot{e}_\psi \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{C_f}{m} \\ 0 \\ \frac{C_fL_f}{I_z} \end{bmatrix} \delta_f + \begin{bmatrix} 0 \\ -\frac{C_fL_f-C_rL_r}{mv_x} - v_x \\ 0 \\ -\frac{C_fL_f^2+C_rL_r^2}{Izv_x} \end{bmatrix} \dot{\psi}_{ref}$$

- **CoP model**

$$\frac{d}{dt}\begin{bmatrix} e_{cop} \\ \dot{e}_{cop} \\ e_\psi \\ \dot{e}_\psi \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -R_l\frac{C_f}{mv_x} & R_l\frac{C_f}{m} & -\frac{R_lC_f(L_f-x_{cop})}{mv_x} \\ 0 & 0 & 0 & 1 \\ 0 & -\frac{C_fL_f-C_rL_r}{I_zv_x} & \frac{C_fL_f-C_rL_r}{I_z} & -\frac{C_fL_f(L_f-x_{cop})+C_rL_r^2}{I_zv_x} \end{bmatrix} \begin{bmatrix} e_{cop} \\ \dot{e}_{cop} \\ e_\psi \\ \dot{e}_\psi \end{bmatrix} + \begin{bmatrix} 0 \\ R_l\frac{C_f}{m} \\ 0 \\ \frac{C_fL_f}{I_z} \end{bmatrix} \delta_f + \begin{bmatrix} 0 \\ -R_l\frac{C_fL_f}{mv_x} - v_x \\ 0 \\ -\frac{C_fL_f^2+C_rL_r^2}{Izv_x} \end{bmatrix} \dot{\psi}_{ref}$$

ERRORS MODEL

- **CoG model**

$$\frac{d}{dt}\begin{bmatrix} e_y \\ \dot{e}_y \\ e_\psi \\ \dot{e}_\psi \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -\frac{C_f+C_r}{mv_x} & \frac{C_f+C_r}{m} & -\frac{C_fL_f-C_rL_r}{mv_x} \\ 0 & 0 & 0 & 1 \\ 0 & -\frac{C_fL_f-C_rL_r}{I_zv_x} & \frac{C_fL_f-C_rL_r}{I_z} & -\frac{C_fL_f^2+C_rL_r^2}{I_zv_x} \end{bmatrix} \begin{bmatrix} e_y \\ \dot{e}_y \\ e_\psi \\ \dot{e}_\psi \end{bmatrix} + \begin{bmatrix} 0 \\ \boxed{\frac{C_f}{m}} \\ 0 \\ \frac{C_fL_f}{I_z} \end{bmatrix} \delta_f + \begin{bmatrix} 0 \\ -\frac{C_fL_f-C_rL_r}{mv_x} - v_x \\ 0 \\ -\frac{C_fL_f^2+C_rL_r^2}{Izv_x} \end{bmatrix} \dot{\psi}_{ref}$$

- **CoP model**

$$\frac{d}{dt}\begin{bmatrix} e_{cop} \\ \dot{e}_{cop} \\ e_\psi \\ \dot{e}_\psi \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -R_l\frac{C_f}{mv_x} & R_l\frac{C_f}{m} & -\frac{R_lC_f(L_f-x_{cop})}{mv_x} \\ 0 & 0 & 0 & 1 \\ 0 & -\frac{C_fL_f-C_rL_r}{I_zv_x} & \frac{C_fL_f-C_rL_r}{I_z} & -\frac{C_fL_f(L_f-x_{cop})+C_rL_r^2}{I_zv_x} \end{bmatrix} \begin{bmatrix} e_{cop} \\ \dot{e}_{cop} \\ e_\psi \\ \dot{e}_\psi \end{bmatrix} + \begin{bmatrix} 0 \\ \boxed{R_l\frac{C_f}{m}} \\ 0 \\ \frac{C_fL_f}{I_z} \end{bmatrix} \delta_f + \begin{bmatrix} 0 \\ -R_l\frac{C_fL_f}{mv_x} - v_x \\ 0 \\ -\frac{C_fL_f^2+C_rL_r^2}{Izv_x} \end{bmatrix} \dot{\psi}_{ref}$$

Remark
The contribution of the control input will be more important in the CoP case than in the CoG case due to the $R_l > 1$ term.

ERRORS MODEL

- **CoG model**

$$\frac{d}{dt}\begin{bmatrix} e_y \\ \dot{e}_y \\ e_\psi \\ \dot{e}_\psi \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -\frac{C_f+C_r}{mv_x} & \frac{C_f+C_r}{m} & -\frac{C_fL_f-C_rL_r}{mv_x} \\ 0 & 0 & 0 & 1 \\ 0 & -\frac{C_fL_f-C_rL_r}{I_zv_x} & \frac{C_fL_f-C_rL_r}{I_z} & -\frac{C_fL_f^2+C_rL_r^2}{I_zv_x} \end{bmatrix} \begin{bmatrix} e_y \\ \dot{e}_y \\ e_\psi \\ \dot{e}_\psi \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{C_f}{m} \\ 0 \\ \frac{C_fL_f}{I_z} \end{bmatrix} \delta_f + \begin{bmatrix} 0 \\ -\frac{C_fL_f-C_rL_r}{mv_x} - v_x \\ 0 \\ -\frac{C_fL_f^2+C_rL_r^2}{Izv_x} \end{bmatrix} \dot{\psi}_{ref}$$

- **CoP model**

$$\frac{d}{dt}\begin{bmatrix} e_{cop} \\ \dot{e}_{cop} \\ e_\psi \\ \dot{e}_\psi \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -R_l\frac{C_f}{mv_x} & R_l\frac{C_f}{m} & -\frac{R_lC_f(L_f-x_{cop})}{mv_x} \\ 0 & 0 & 0 & 1 \\ 0 & -\frac{C_fL_f-C_rL_r}{I_zv_x} & \frac{C_fL_f-C_rL_r}{I_z} & -\frac{C_fL_f(L_f-x_{cop})+C_rL_r^2}{I_zv_x} \end{bmatrix} \begin{bmatrix} e_{cop} \\ \dot{e}_{cop} \\ e_\psi \\ \dot{e}_\psi \end{bmatrix} + \begin{bmatrix} 0 \\ R_l\frac{C_f}{m} \\ 0 \\ \frac{C_fL_f}{I_z} \end{bmatrix} \delta_f + \begin{bmatrix} 0 \\ -R_l\frac{C_fL_f}{mv_x} - v_x \\ 0 \\ -\frac{C_fL_f^2+C_rL_r^2}{Izv_x} \end{bmatrix} \dot{\psi}_{ref}$$

Remark
$\dot{\psi}_{ref}$ acts on the error model as a disturbance.

ERRORS MODEL

- **CoG model**

$$\frac{d}{dt}\begin{bmatrix} e_y \\ \dot{e}_y \\ e_\psi \\ \dot{e}_\psi \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -\frac{C_f+C_r}{mv_x} & \frac{C_f+C_r}{m} & -\frac{C_fL_f-C_rL_r}{mv_x} \\ 0 & 0 & 0 & 1 \\ 0 & -\frac{C_fL_f-C_rL_r}{I_zv_x} & \frac{C_fL_f-C_rL_r}{I_z} & -\frac{C_fL_f^2+C_rL_r^2}{I_zv_x} \end{bmatrix} \begin{bmatrix} e_y \\ \dot{e}_y \\ e_\psi \\ \dot{e}_\psi \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{C_f}{m} \\ 0 \\ \frac{C_fL_f}{I_z} \end{bmatrix} \delta_f + \begin{bmatrix} 0 \\ -\frac{C_fL_f-C_rL_r}{mv_x} - v_x \\ 0 \\ -\frac{C_fL_f^2+C_rL_r^2}{Izv_x} \end{bmatrix} \dot{\psi}_{ref}$$

- **CoP model**

$$\frac{d}{dt}\begin{bmatrix} e_{cop} \\ \dot{e}_{cop} \\ e_\psi \\ \dot{e}_\psi \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -R_l\frac{C_f}{mv_x} & R_l\frac{C_f}{m} & -\frac{R_lC_f(L_f-x_{cop})}{mv_x} \\ 0 & 0 & 0 & 1 \\ 0 & -\frac{C_fL_f-C_rL_r}{I_zv_x} & \frac{C_fL_f-C_rL_r}{I_z} & -\frac{C_fL_f(L_f-x_{cop})+C_rL_r^2}{I_zv_x} \end{bmatrix} \begin{bmatrix} e_{cop} \\ \dot{e}_{cop} \\ e_\psi \\ \dot{e}_\psi \end{bmatrix} + \begin{bmatrix} 0 \\ R_l\frac{C_f}{m} \\ 0 \\ \frac{C_fL_f}{I_z} \end{bmatrix} \delta_f + \begin{bmatrix} 0 \\ -R_l\frac{C_fL_f}{mv_x} - v_x \\ 0 \\ -\frac{C_fL_f^2+C_rL_r^2}{Izv_x} \end{bmatrix} \dot{\psi}_{ref}$$

$$\Rightarrow \quad \frac{d}{dt}\xi(t) = A\xi(t) + B\delta_f(t) + \begin{bmatrix} 0 \\ d_2 \\ 0 \\ d_4 \end{bmatrix} \dot{\psi}_{ref}$$

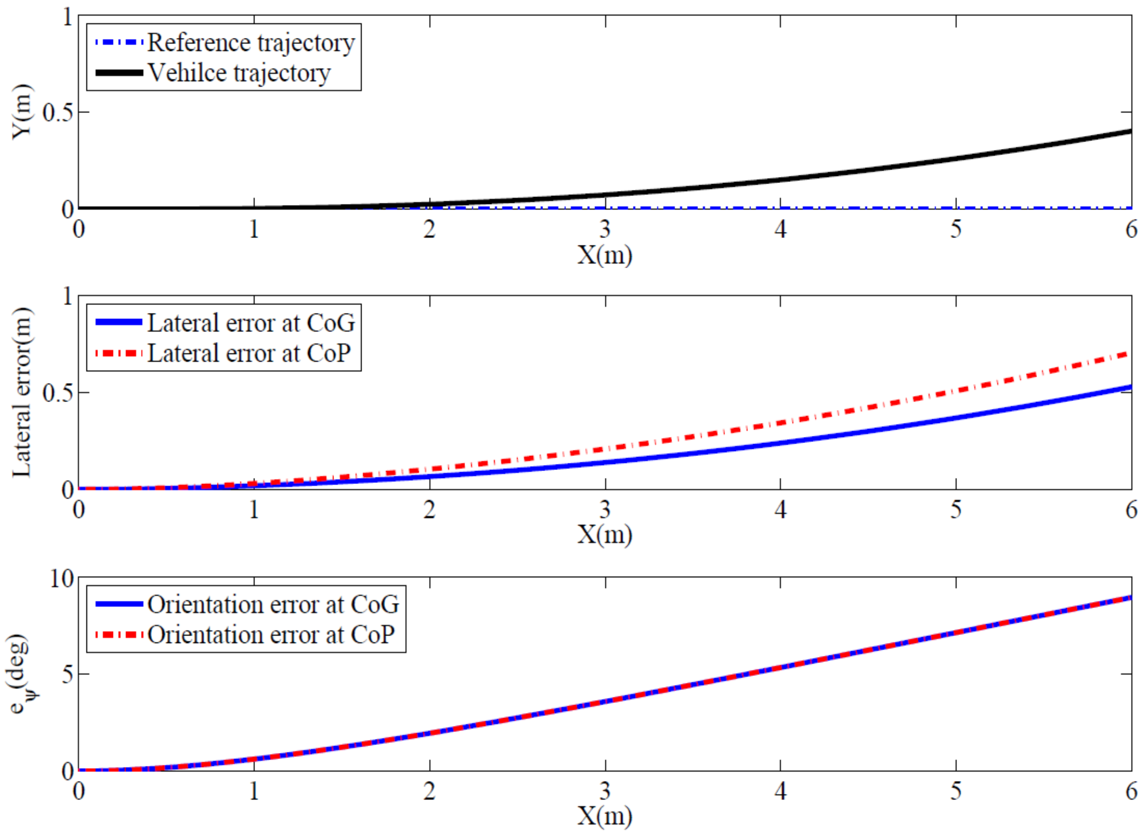
SIMULATION TEST ON OPEN LOOP

Objective

- Compare the behavior of CoGM and CoPM in a lane departure situation.

Simulation Conditions

- Lane departure situation.
- Reference trajectory is straight line.
- Constant speed $15\ m/s$.
- Constant steering wheel angle $5\ \text{deg}$.



SIMULATION TEST ON OPEN LOOP

Objective

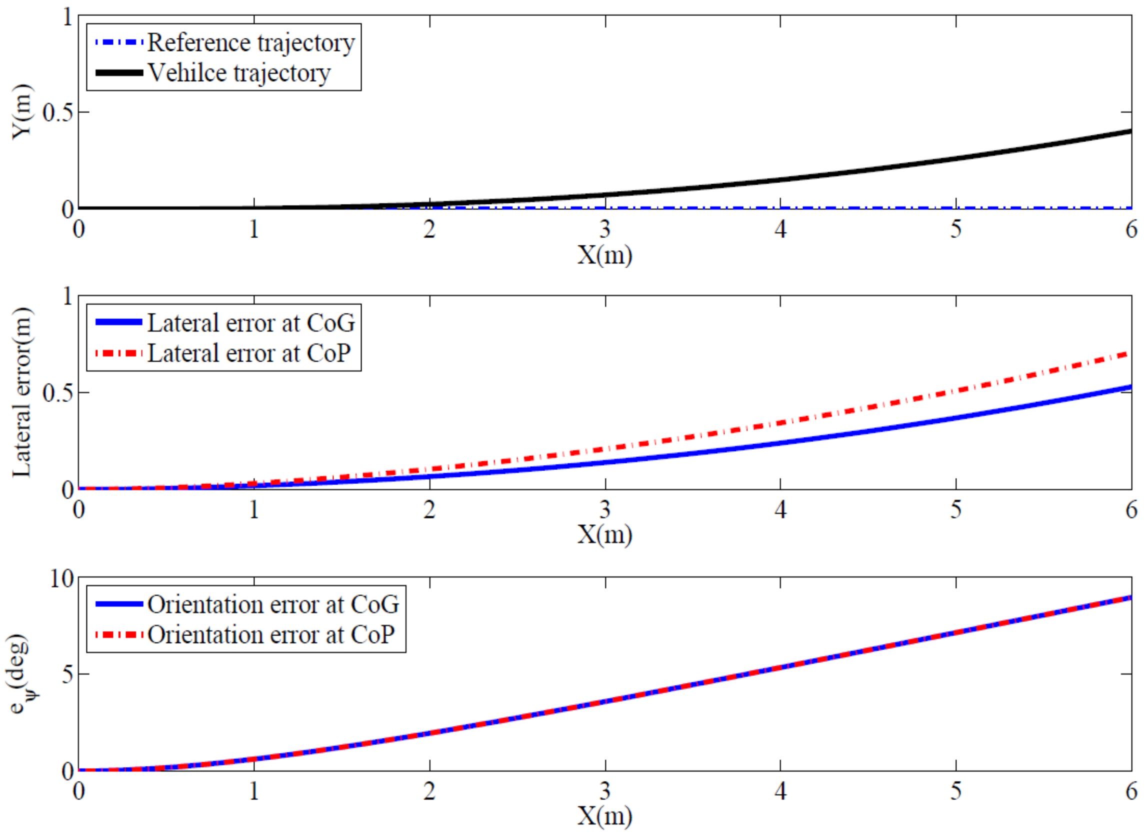
- Compare the behavior of CoGM and CoPM in a lane departure situation.

Simulation Conditions

- Lane departure situation.
- Reference trajectory is straight line.
- Constant speed $15\ m/s$.
- Constant steering wheel angle 5 deg.

Results

- The lateral error at the CoP is bigger than the lateral error at the CoG.
- The orientation errors are the same in both models.

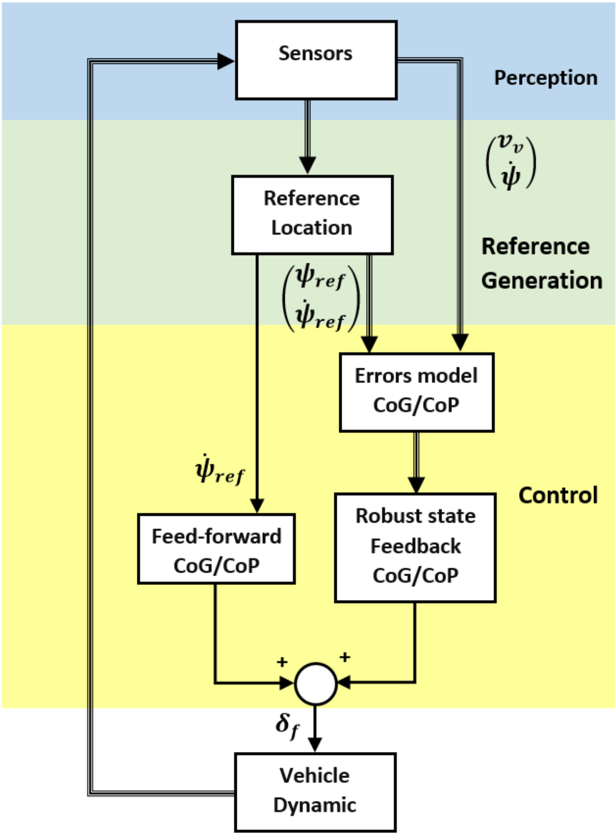


CONTROL DESIGN

$$\frac{d}{dt}\xi(t) = A\xi(t) + B\delta_f(t) + \begin{bmatrix} 0 \\ d_2 \\ 0 \\ d_4 \end{bmatrix} \dot{\psi}_{ref}$$

References

- ψ_{ref} desired yaw angle.
- $\dot{\psi}_{ref}$ desired yaw rate.



Proposed control law

$$\delta_f(t) = u_{FF}(t) + u_{FB}(t)$$

- Feed-Forward aims to eliminate the effect of the disturbance on a part of the state vector.
- Robust State-Feedback aims to stabilize the system in closed loop and to attenuate the effect of the disturbance.

CONTROL DESIGN: FEED-FORWARD

- **CoG Model**

$$u_{FF}(t) = \frac{m}{C_f}\left(\frac{C_f L_f - C_r L_r}{m v_x} + v_x\right)\dot{\psi}_{ref}(t)$$

- **CoP Model**

$$u_{FF}(t) = \frac{m}{C_f}\left(R_l \frac{C_f L_f}{m v_x} + v_x\right)\dot{\psi}_{ref}(t)$$

CONTROL DESIGN: FEED-FORWARD

- **CoG Model**

$$u_{FF}(t) = \frac{m}{C_f}\left(\frac{C_f L_f - C_r L_r}{m v_x} + v_x\right)\dot{\psi}_{ref}(t)$$

- **CoP Model**

$$u_{FF}(t) = \frac{m}{C_f}\left(R_l \frac{C_f L_f}{m v_x} + v_x\right)\dot{\psi}_{ref}(t)$$

By applying the control law

$$\delta_f(t) = u_{FF}(t) + u_{FB}(t)$$

$$\frac{d}{dt}\xi(t) = A\xi(t) + Bu_{FB}(t) + B\boxed{u_{FF}(t)} + \boxed{\begin{bmatrix} 0 \\ d_2 \\ 0 \\ d_4 \end{bmatrix}}\dot{\psi}_{ref} \quad \Rightarrow \quad \frac{d}{dt}\xi(t) = A\xi(t) + Bu_{FB}(t) + \boxed{\begin{bmatrix} 0 \\ 0 \\ 0 \\ d'_4 \end{bmatrix}}\dot{\psi}_{ref}$$

CONTROL DESIGN: ROBUST STATE FEEDBACK

$$\frac{d}{dt}\xi(t) = A\xi(t) + Bu_{FB}(t) + \begin{bmatrix} 0 \\ 0 \\ 0 \\ d'_4 \end{bmatrix} \dot{\psi}_{ref}$$

Robust state feedback action

$$u_{FB}(t) = -K\xi(t)$$

Objective

- Guarantee a decay rate exponential convergence α of the state vector $\xi(t)$.

  $$\exists \alpha > 0 : \quad \dot{V}(t) + 2\alpha V(t) < 0$$

- Guarantee an attenuation level γ of the disturbance $\dot{\psi}_{ref}$ on the state $\dot{e}_{\psi}$.

  $$||\dot{e}_{\psi}||_2^2 < \gamma^2 \left|\left|\dot{\psi}_{ref}\right|\right|_2^2$$

Lyapunov candidate

$V(t) = \xi^T(t)P\xi(t)$ and

$P = P^T > 0$.

CONTROL DESIGN: ROBUST STATE FEEDBACK

$$\frac{d}{dt}\xi(t) = A\xi(t) + Bu_{FB}(t) + \begin{bmatrix} 0 \\ 0 \\ 0 \\ d'_4 \end{bmatrix} \dot{\psi}_{ref}$$

Robust state feedback action
$u_{FB}(t) = -K\xi(t)$

Objective

- Guarantee a decay rate exponential convergence α of the state vector $\xi(t)$.
  $\exists\alpha > 0 : \quad \dot{V}(t) + 2\alpha V(t) < 0$
- Guarantee an attenuation level γ of the disturbance $\dot{\psi}_{ref}$ on the state $\dot{e}_{\psi}$.
  $||\dot{e}_\psi||_2^2 < \gamma^2 \, ||\dot{\psi}_{ref}||_2^2$

Lyapunov candidate
$V(t) = \xi^T(t)P\xi(t)$ and
$P = P^T > 0$.

Problem formulation

$$\begin{bmatrix} (A-BK)^T P + P(A-BK) + 2\alpha P + R^T R & PD' \\ (PD')^T & -\gamma I \end{bmatrix} < 0$$

Trade-off between
α Large decay rate and $\gamma < 1$.

SIMULATION TESTS

Double lane change maneuver

- The test consists in performing a double lane change maneuver at different speeds.

Simulation Conditions

- The track supposed to be flat.
- No vertical nor load transfer are considered.
- A 2D model is used for simulation purpose (with saturation on the lateral tire forces).

SIMULATION TESTS

Double lane change maneuver

- The test consists in performing a double lane change maneuver at different speeds.

Simulation Conditions

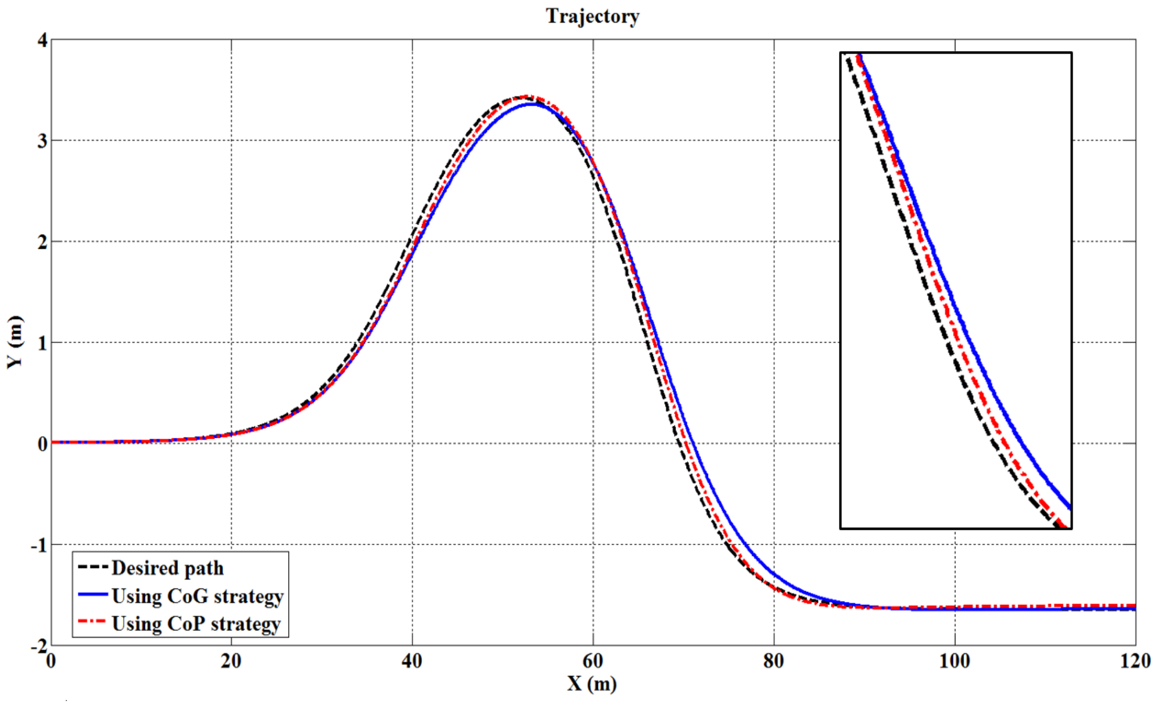
- The track supposed to be flat.
- No vertical nor load transfer are considered.
- A 2D model is used for simulation purpose (with saturation on the lateral tire forces).

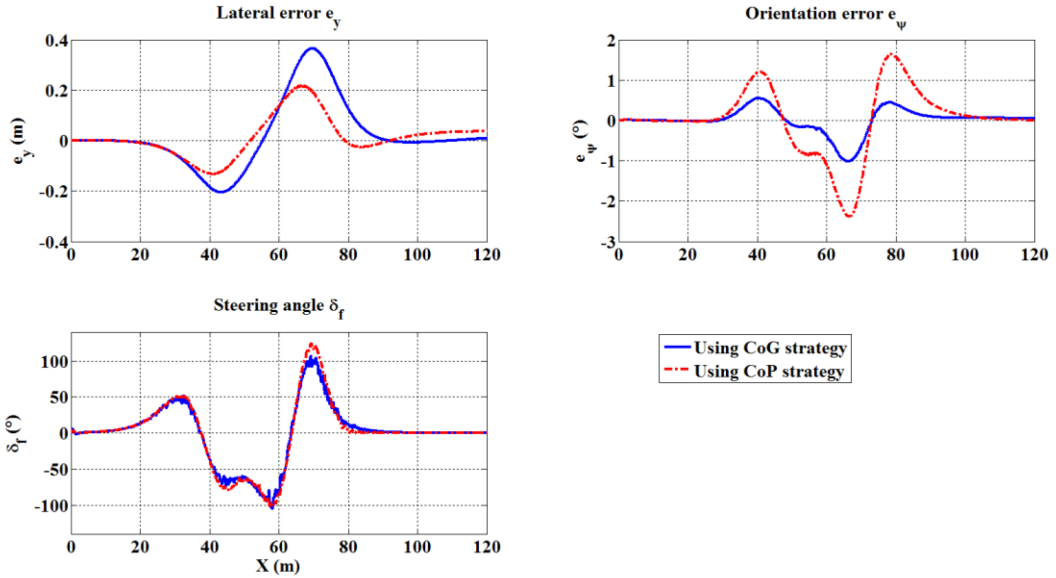
Robust state feedback design

- Controllers are designed at the constant speed $v_x = 25m/s$ (nominal speed).
- The LMI problem is programmed thanks to the Yalmip interface (Lofberg, 2004) coupled with the SeDuMi solver (Sturm, 1999).
- Decay rate $\alpha = 0.2$.
- Attenuation level $\gamma = 0.3$.

SIMULATION TESTS

Simulation test at the <u>nominal speed $v_x = 25m/s$.</u>



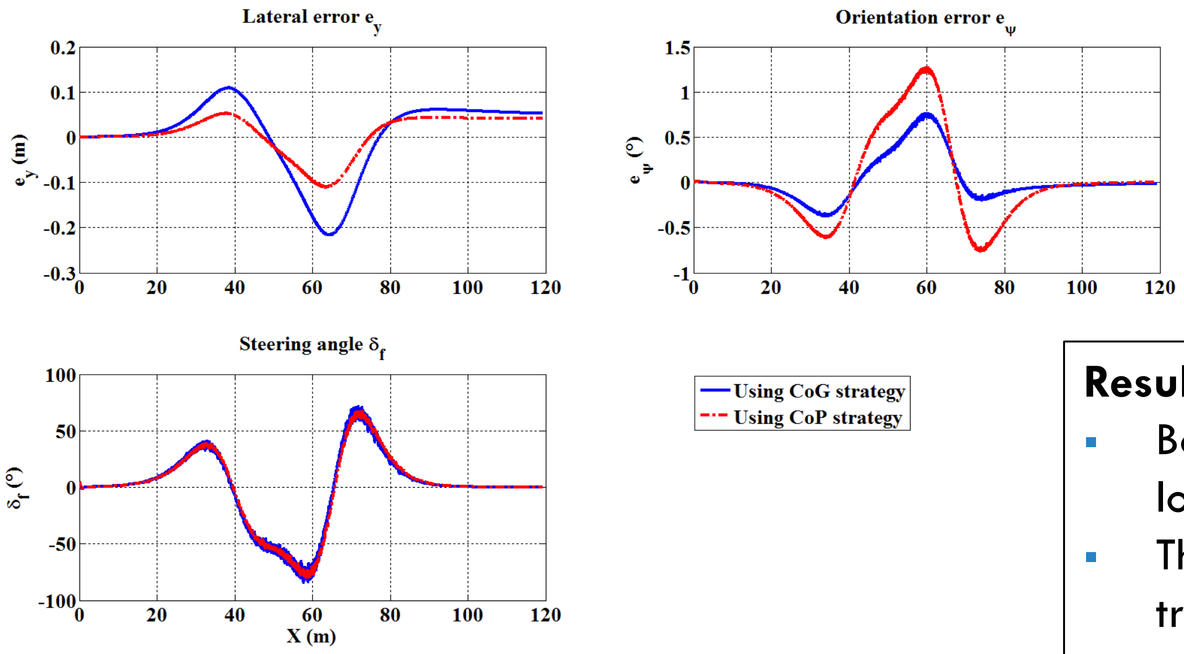


Result

- The CoP strategy offers an effective trajectory tracking in terms of the lateral error.

SIMULATION TESTS

Simulation test at a <u>different speed $v_x = 10m/s$.</u>



Results

- Both strategies are robust with respect to the longitudinal speed variation.
- The CoP strategy still offers an effective trajectory tracking in terms of the lateral error.

CONCLUSION & OUTLOOKS

Conclusion

- The CoP strategy ensures a better trajectory tracking and anticipates the lateral position error.
- Both strategies are robust with respect to the longitudinal speed variation.

Future works

- Enhance the lateral stability in critical situation by using the CoP strategy.

THANKS FOR YOUR ATTENTION ! QUESTION ?