HL Klemove

Vehicle control

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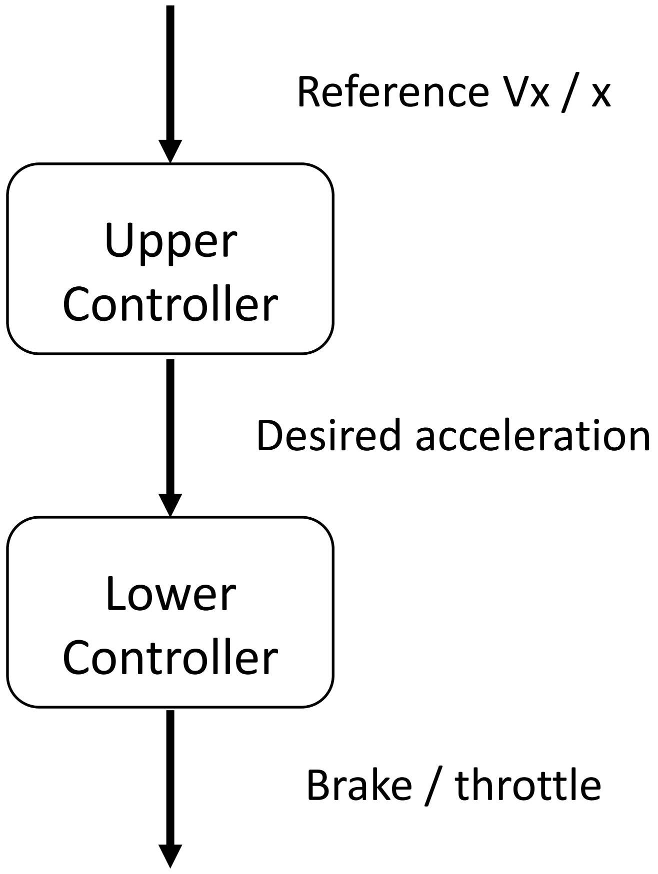
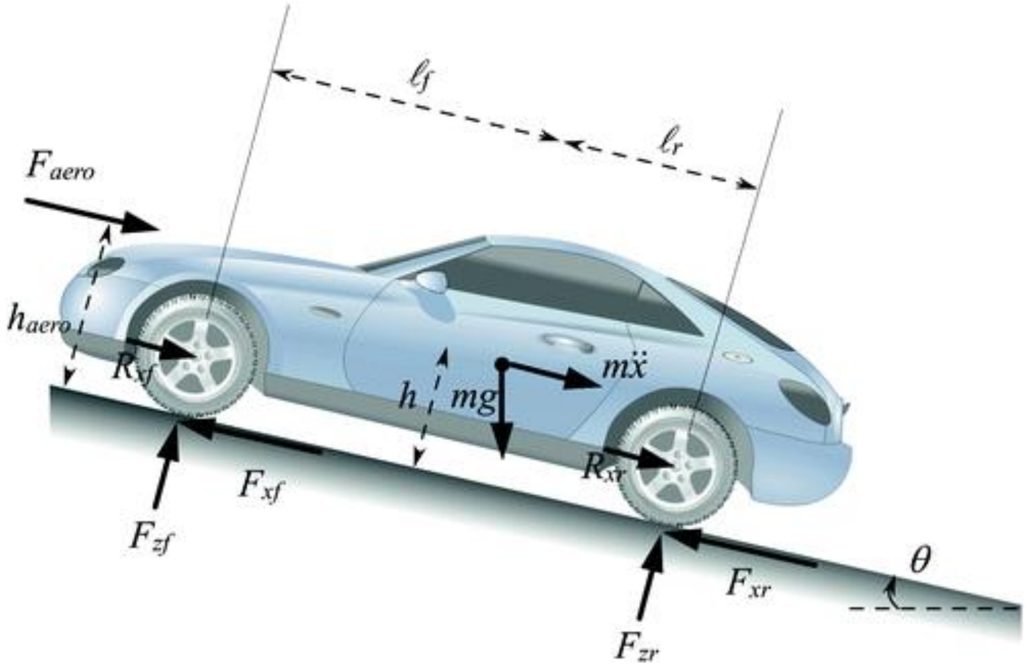


HL Klemove

Longitudinal control

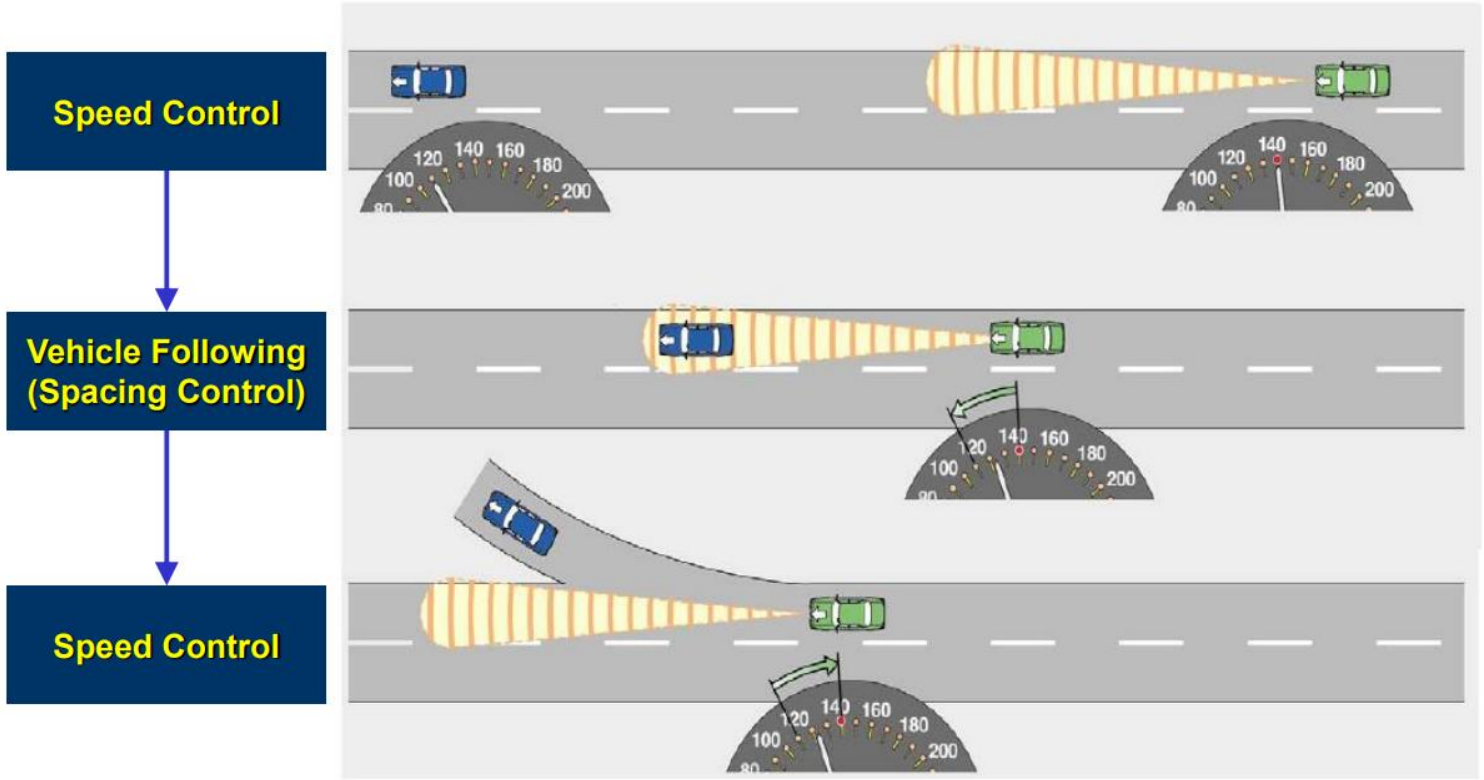
- Dynamic model



$$m\ddot{x} = F_{xf} + F_{xr} - F_{aero} - R_{xf} - R_{xr} - mgsin\theta$$

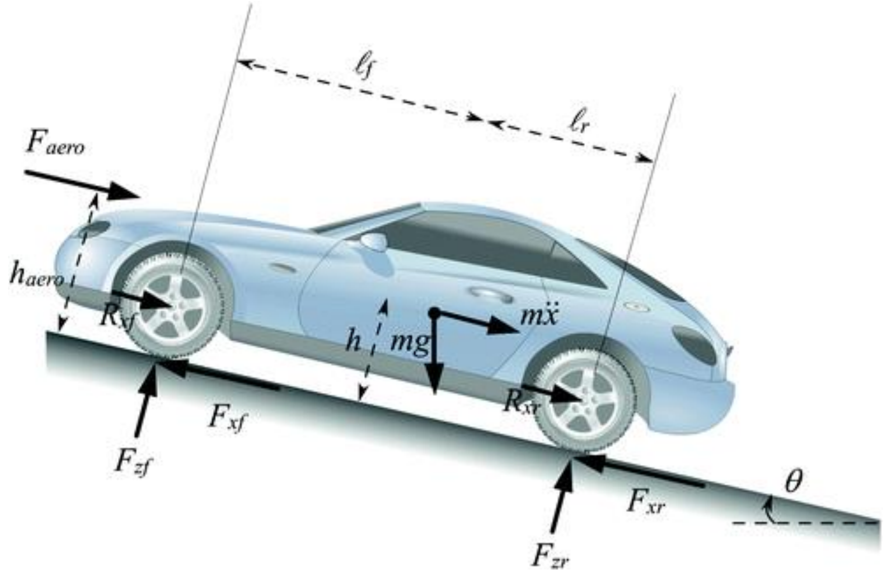
Longitudinal control

- Control policy



Longitudinal control

- Speed control
  - PI Controller. Why?



$$m\ddot{x} = F_{xf} + F_{xr} - F_{aero} - R_{xf} - R_{xr} - mgsin\theta$$

Longitudinal control

- Spacing control
  - Constant spacing

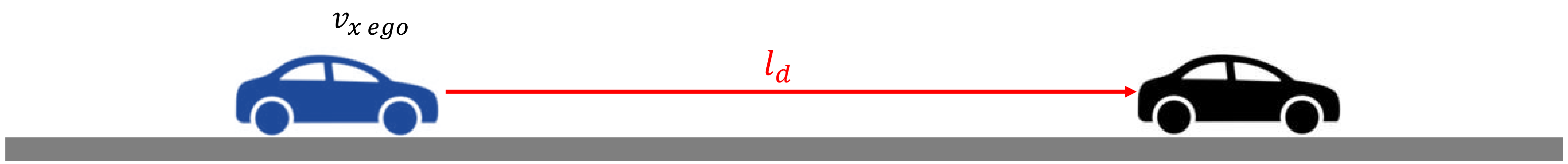
$$l_d = const$$

  - Constant time gap

$$l_d = v_x h$$

$$h = const$$

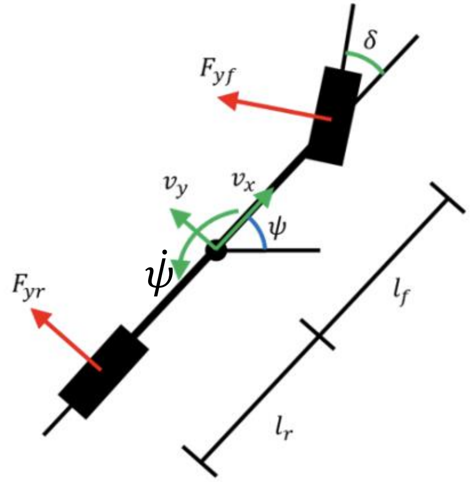
  - PD Controller. Why?



Lateral Control

- Dynamic model
  - Recall

$$\frac{d}{dt}\begin{pmatrix} y \\ \dot{y} \\ \psi \\ \dot{\psi} \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & -\frac{2C_{\alpha f} + 2C_{\alpha r}}{m v_x} & 0 & -v_x - \frac{2C_{\alpha f} l_f - 2C_{\alpha r} l_r}{m v_x} \\ 0 & 0 & 0 & 1 \\ 0 & -\frac{2C_{\alpha f} l_f - 2C_{\alpha r} l_r}{I v_x} & 0 & -\frac{2C_{\alpha f} {l_f}^2 + 2C_{\alpha r} {l_r}^2}{I v_x} \end{pmatrix} \begin{pmatrix} y \\ \dot{y} \\ \psi \\ \dot{\psi} \end{pmatrix} + \begin{pmatrix} 0 \\ \frac{2C_{\alpha f}}{m} \\ 0 \\ \frac{2C_{\alpha f} l_f}{I} \end{pmatrix} \delta$$



  - Error definition for control

$$e_1 = y - y_{ref}$$

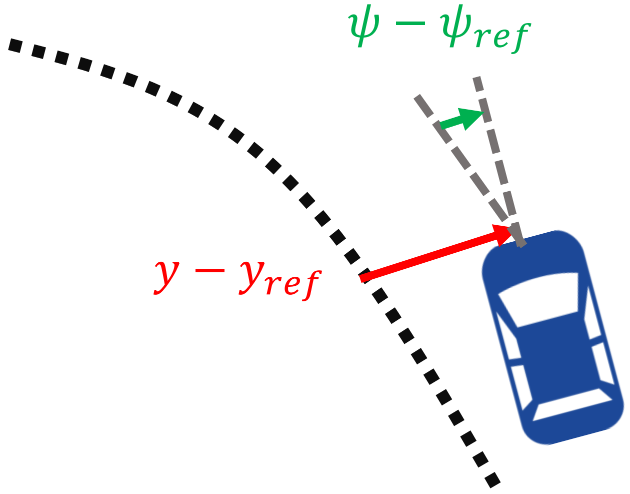
$$\dot{e}_1 = \frac{d}{dt}(y - y_{ref}) = \dot{y} + v_x(\psi - \psi_{ref})$$

$$\ddot{e}_1 = \frac{d^2}{dt^2}(y - y_{ref}) = \ddot{y} + v_x(\dot{\psi} - \dot{\psi}_{ref})$$

$$e_2 = \psi - \psi_{ref}$$

$$\dot{e}_2 = \dot{\psi} - \dot{\psi}_{ref}$$

$$e_2 = \ddot{\psi} - \ddot{\psi}_{ref}$$



Lateral control

- Dynamic model
  - Error dynamics

$$\frac{d}{dt}\begin{pmatrix} e_1 \\ \dot{e}_1 \\ e_2 \\ \dot{e}_2 \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & -\frac{2C_{af}+2C_{ar}}{mV_x} & \frac{2C_{af}+2C_{ar}}{m} & -\frac{2C_{af}l_f-2C_{ar}l_r}{mV_x} \\ 0 & 0 & 0 & 1 \\ 0 & -\frac{2C_{af}l_f-2C_{ar}l_r}{IV_x} & \frac{2C_{af}l_f-2C_{ar}l_r}{I} & -\frac{2C_{af}{l_f}^2+2C_{ar}{l_r}^2}{IV_x} \end{pmatrix}\begin{pmatrix} e_1 \\ \dot{e}_1 \\ e_2 \\ \dot{e}_2 \end{pmatrix} + \begin{pmatrix} 0 \\ \frac{2C_{af}}{m} \\ 0 \\ \frac{2C_{af}l_f}{I} \end{pmatrix}\delta + \underline{\begin{pmatrix} 0 \\ -V_x-\frac{2C_{af}l_f-2C_{ar}l_r}{mV_x} \\ 0 \\ -\frac{2C_{af}{l_f}^2+2C_{ar}{l_r}^2}{IV_x} \end{pmatrix}\dot{\psi}_{ref}}$$

$$\dot{e} = Ae + B_1\delta + \underline{B_2\dot{\psi}_{ref}}$$

Lateral control

- Dynamic model
  - Controller

$$\begin{cases} \dot{e} = Ae + B_1\delta + B_2\dot{\psi}_{ref} \\ \delta = -Ke \end{cases}$$

$$\dot{e} = (A - B_1K)e + \underline{B_2\dot{\psi}_{ref}}$$

$$\delta_{curv} = \frac{L}{R} + \frac{{v_x}^2}{R}\left(\frac{m_f}{2C_{\alpha f}} - \frac{m_r}{2C_{\alpha r}}\right)$$

Lateral control

- Steering wheel angle for path curvature
  - Kinematic model with tire slip
    - 결과론 적 방법 : 일정한 delta 를 유지할 때 주행하는 경로의 R(Curvature)

If $R \gg L$,

$$L \approx R\theta = R(\delta - \alpha_f + \alpha_r) \Rightarrow \delta = \frac{L}{R} + \alpha_f - \alpha_r$$

    - Dynamics

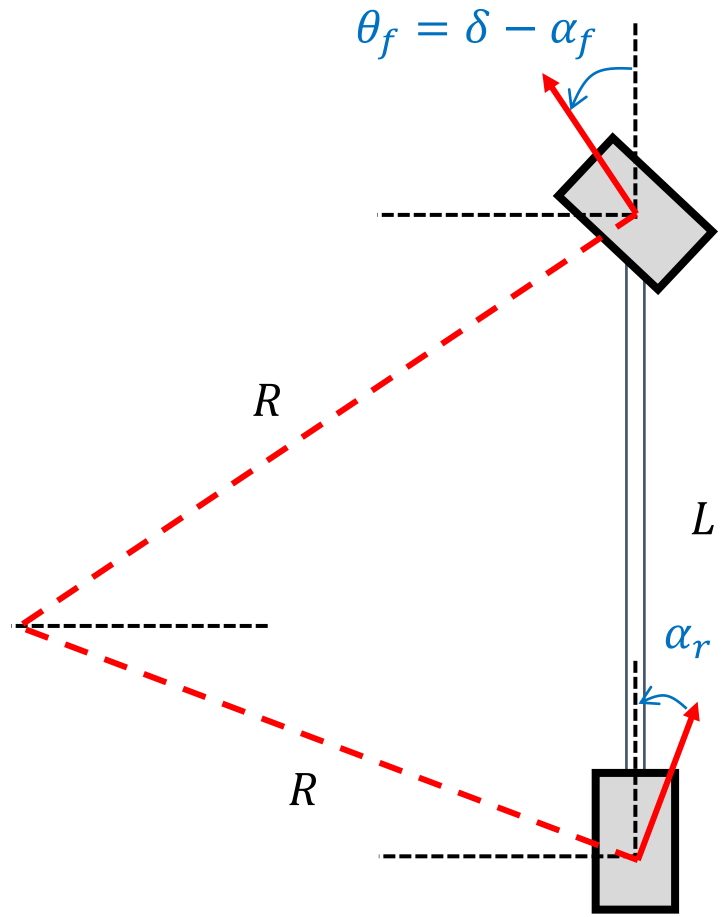
$$\begin{cases} F_{yf} + F_{yr} = \dfrac{m{v_x}^2}{R} \\ F_{yf} l_f - F_{yr} l_r = 0 \end{cases} \Rightarrow \begin{aligned} F_{yf} &= \frac{{v_x}^2}{R} \cdot \frac{m l_r}{L} = \frac{m_f {v_x}^2}{R} \\ F_{yr} &= \frac{{v_x}^2}{R} \cdot \frac{m l_f}{L} = \frac{m_r {v_x}^2}{R} \end{aligned}$$

    - From tire model

$$F_{yf} = 2C_{\alpha f}\alpha_f$$

$$F_{yr} = 2C_{\alpha r}\alpha_r$$

$$\delta = \frac{L}{R} + \left(\frac{m_f}{2C_{\alpha f}} - \frac{m_r}{2C_{\alpha r}}\right)\frac{{v_x}^2}{R}$$



Lateral control

- Understeer gradient

$$\delta = \frac{L}{R} + \left(\frac{m_f}{2C_{\alpha f}} - \frac{m_r}{2C_{\alpha r}}\right)\frac{{v_x}^2}{R}$$

$$\delta = \frac{L}{R} + k_v a_y \quad , k_v = \left(\frac{m_f}{2C_{\alpha f}} - \frac{m_r}{2C_{\alpha r}}\right)$$

① $m_f = m_r$

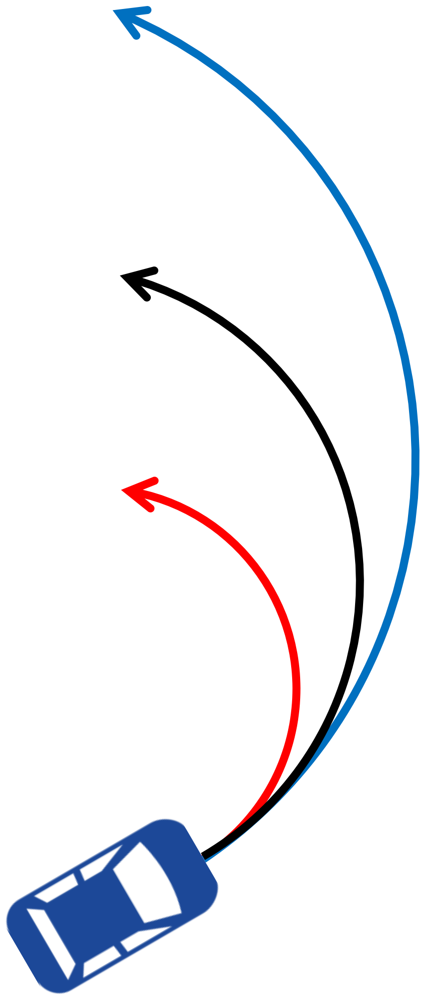
$k_v = 0 \quad , \delta = \frac{L}{R}$: Neutral steer

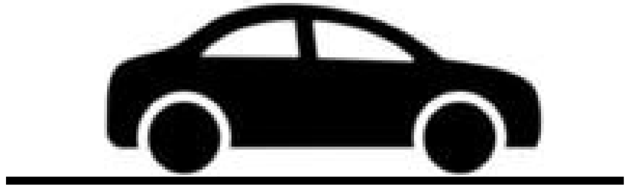
② $m_f > m_r$

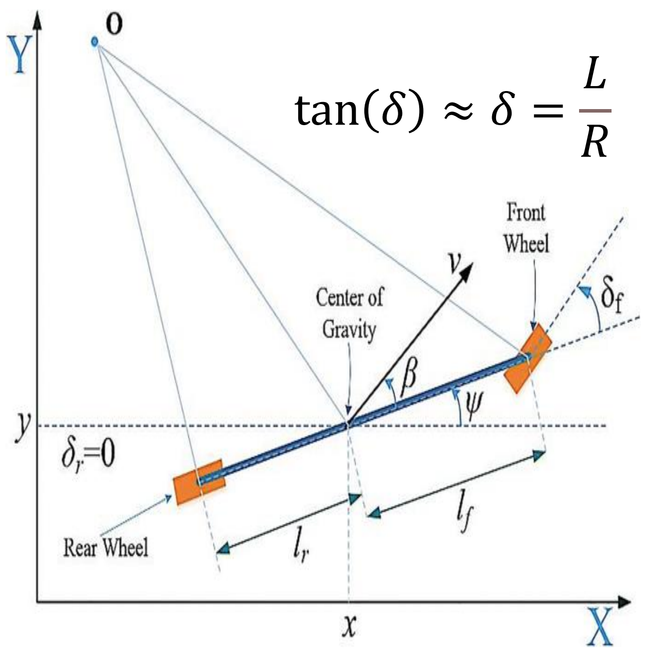
$k_v > 0 \quad , \delta > \frac{L}{R}$: Understeer

② $m_f < m_r$

$k_v < 0 \quad , \delta < \frac{L}{R}$: Oversteer







$$\tan(\delta) \approx \delta = \frac{L}{R}$$

Lateral control

- Which controller to use?

$$\underbrace{\dot{e} = Ae + B_1\delta}_{\text{Feedback controller design}} + \underbrace{B_2\dot{\psi}_{ref}}_{\text{Feedforward controller design}}$$

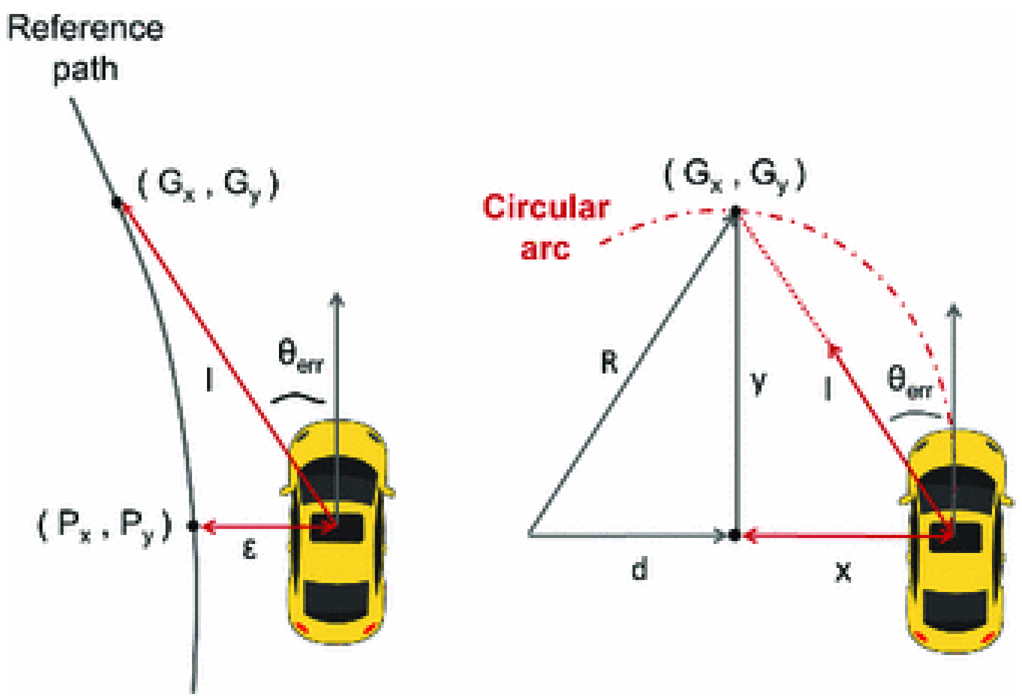
Feedback controller design

Feedforward controller design

$$\delta = \frac{L}{R} + \left(\frac{m_f}{2C_{\alpha f}} - \frac{m_r}{2C_{\alpha r}}\right)\frac{{v_x}^2}{R}$$

Lateral control

- Pure pursuit path tracking algorithm
  - invented by CMU and widely used
  - Finds a control which makes robot move toward goal smoothly.
  - Kinematic model based simple tracking algorithm



Lateral control

- Pure pursuit path tracking algorithm

2.1 Geometric Vehicle Model

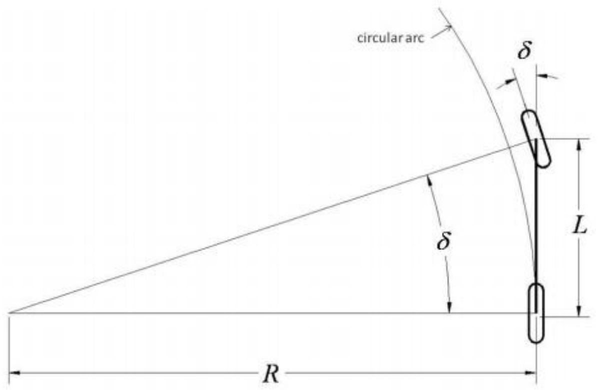


Figure 9: Geometric Bicycle Model

$$\tan(\delta) \approx \delta = \frac{L}{R}$$

2.2 Pure Pursuit

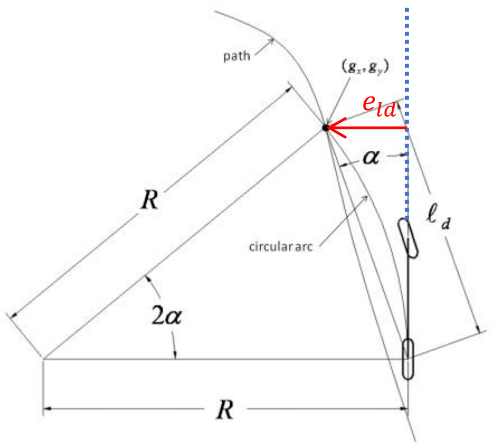


Figure 10: Pure Pursuit geometry

Sine 법칙

$$\frac{l_d}{\sin(2\alpha)} = \frac{R}{\sin\left(\frac{\pi}{2} - \alpha\right)}$$

$$\frac{l_d}{2\sin(\alpha)\cos(\alpha)} = \frac{R}{\cos(\alpha)}$$

$$\sin(\alpha) = \frac{l_d}{2R} = \frac{e_{ld}}{l_d}$$

$$\tan(\delta) \text{ or } \delta = \frac{L}{R} = \frac{2e_{ld}L}{{l_d}^2}$$

- Snider, J. M. (2009). Automatic steering methods for autonomous automobile path tracking. Robotics Institute, Pittsburgh, PA, Tech. Rep. CMU-RITR-09-08.

Lateral control

- Pure pursuit path tracking algorithm

$$l_d^{\,2} = x^2 + y^2$$

$$r^2 = y^2 + d^2 = y^2 + x^2 + r^2 - 2xr \qquad (x + d = r)$$

$$r = \frac{x^2 + y^2}{2x}$$

$$\tan(\delta) = \frac{L}{r} = \frac{2xL}{x^2 + y^2}$$

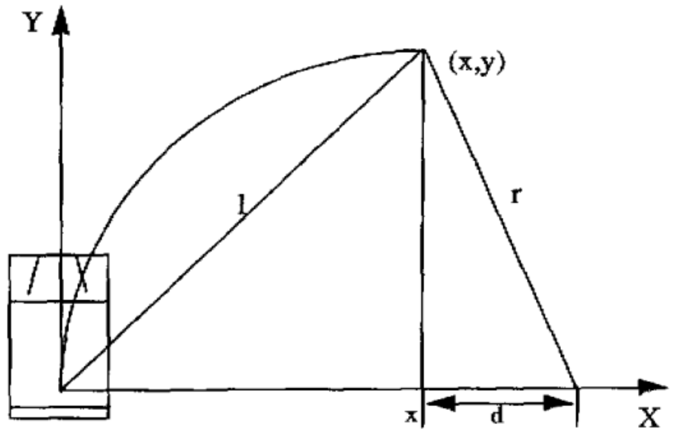


Figure 1. Geometry of the Algorithm.

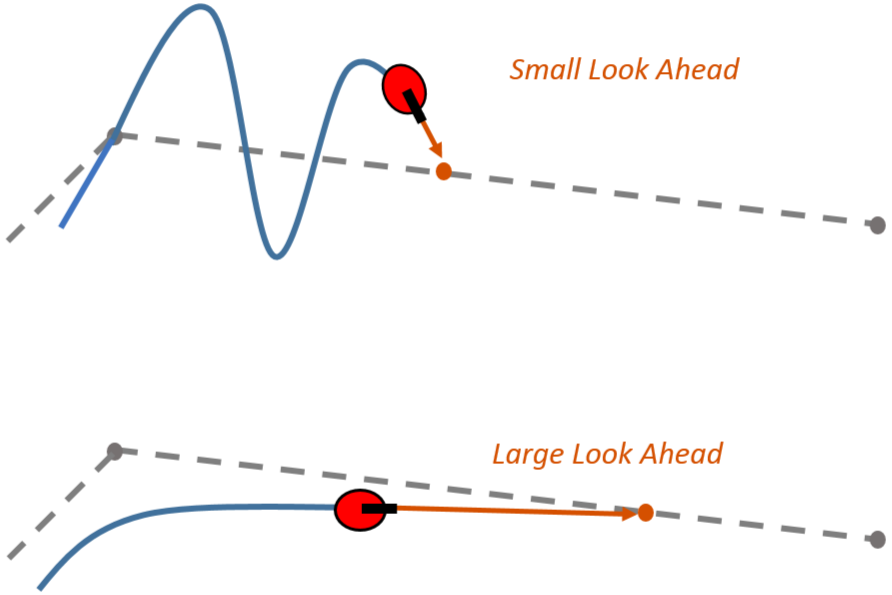
$$x^2 + y^2 = l^2 \qquad (2.1)$$

$$x + d = r \qquad (2.2)$$

- R. Craig Conlter, “Implementation of the Pure Pursuit Path Tracking Algorithm” (1992)

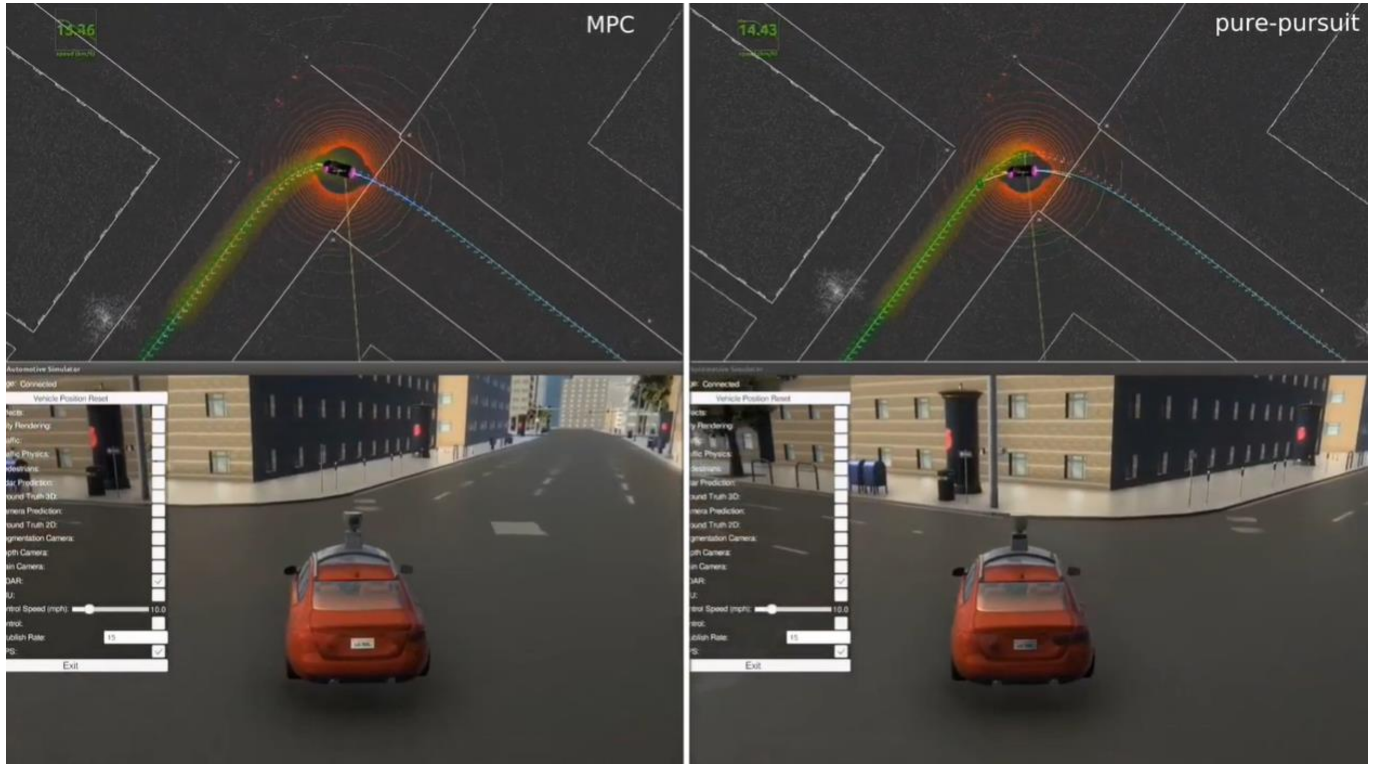
Lateral control

- Pure pursuit path tracking algorithm
  - How to decide lookahead point(distance)



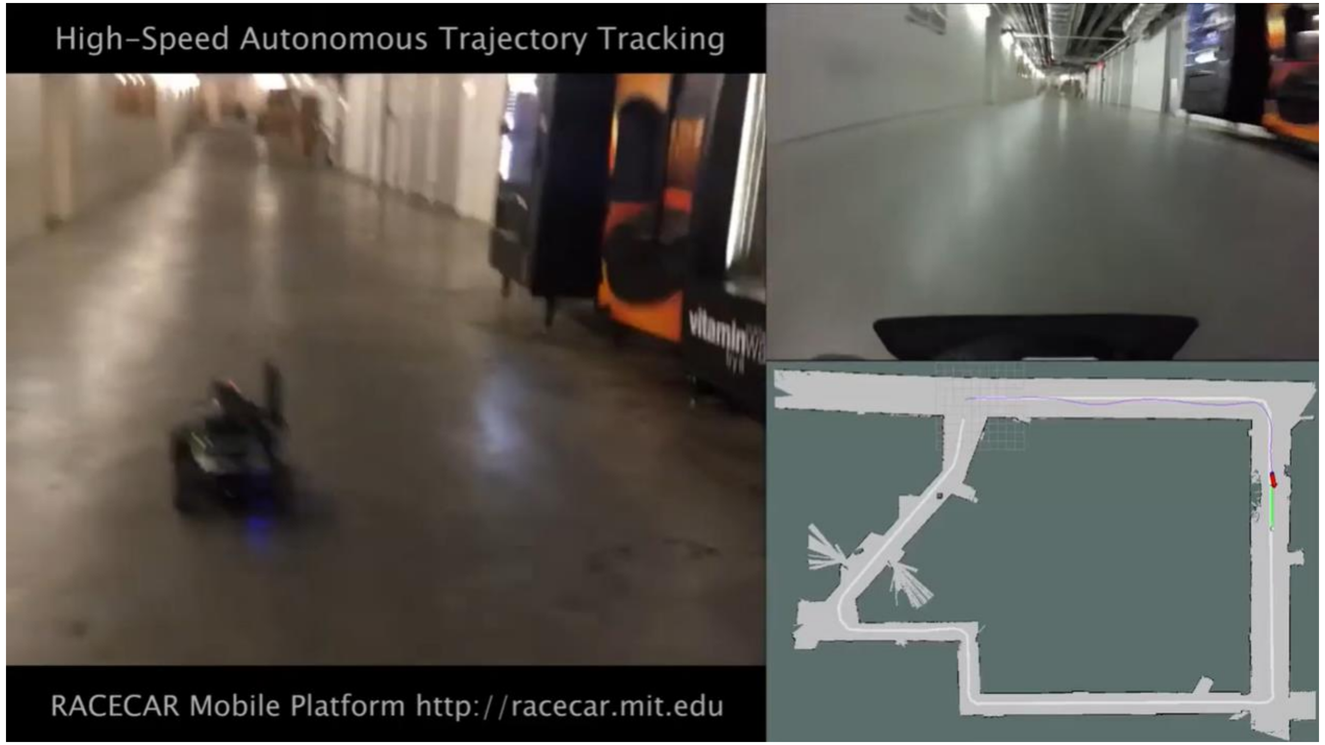
Lateral control

- Pure pursuit path tracking algorithm
  - Examples
    - Comparing pure-pursuit and MPC for Autoware trajectory following with LGSVL simulator
    - https://youtu.be/qgK_ciDFMoM



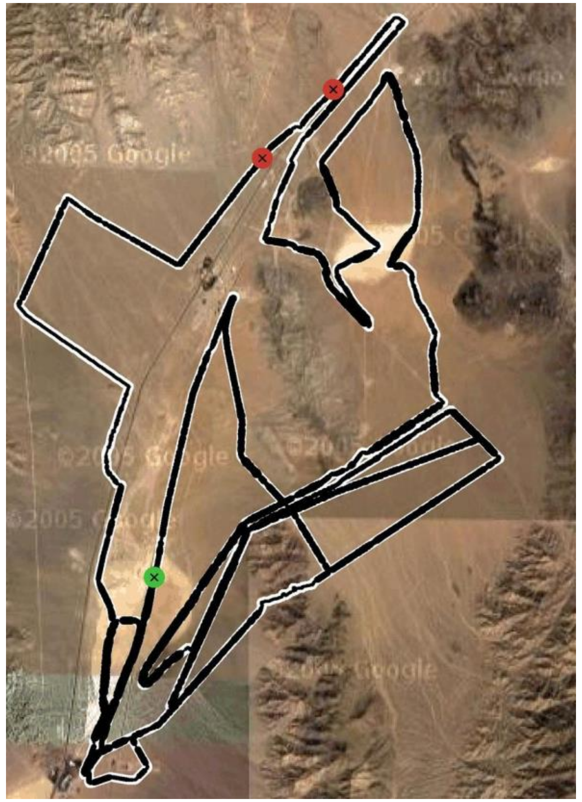
Lateral control

- Pure pursuit path tracking algorithm
  - Examples
    - Fast Autonomous RC Car - Pure Pursuit Trajectory Tracking
    - https://youtu.be/9fzzp6oxid4



Lateral control

- Stanley method
  - 미국 국방부의 고등 연구 계획국(DARPA, Defense Advanced Research Projects Agency)에서 개최
  - 약 240km 구간을 완주하는 것이 목표
  - 2004년 Challenge에서는 단 한팀도 완주하지 못함 (최고기록은 CMU의 11.78km)
  - 2005년 Challenge에서는 22대의 자율주행 차량이 11.78km 돌파, 5대의 차량이 완주

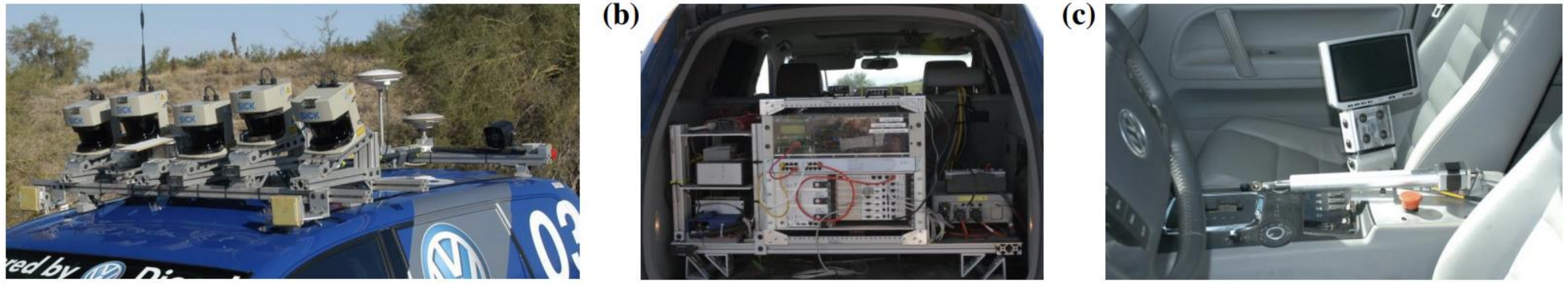


차량	팀 이름	팀 소재지	경과시간 (h:m)	결과
스탠리	스탠포드 경주팀	캘리포니아주 팔로 알토, 스탠포드대	6:54	우승
샌드스톰	레드 팀	펜실베이니아주 피츠버그, 카네기 멜론대	7:05	2위
하이랜더	레드팀 투		7:14	3위
캣-5	팀 그레이	루이지애나주, 메타이어, 그레이 보험 회사	7:30	4위
테라맥스	팀 테라맥스	위스콘신주, 오시코시, 오시코시 트럭	12:51	10시간 제한 초과 5위

Lateral control

- Stanley method

(a) (b) (c)



Stanley: The Robot that Won the DARPA Grand Challenge

Sebastian Thrun, Mike Montemerlo, Hendrik Dahlkamp, David Stavens, Andrei Aron, James Diebel, Philip Fong, John Gale, Morgan Halpenny, Gabriel Hoffmann, Kenny Lau, Celia Oakley, Mark Palatucci, Vaughan Pratt, and Pascal Stang
Stanford Artificial Intelligence Laboratory
Stanford University
Stanford, California 94305

Sven Strohband, Cedric Dupont, Lars-Erik Jendrossek, Christian Koelen, Charles Markey, Carlo Rummel, Joe van Niekerk, Eric Jensen, and Philippe Alessandrini
Volkswagen of America, Inc.
Electronics Research Laboratory
4009 Miranda Avenue, Suite 100
Palo Alto, California 94304

Gary Bradski, Bob Davies, Scott Ettinger, Adrian Kaehler, and Ara Nefian
Intel Research
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Santa Clara, California 95052

Pamela Mahoney
Mohr Davidow Ventures
3000 Sand Hill Road, Bldg. 3, Suite 290
Menlo Park, California 94025

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- https://youtu.be/NG_O4RyQqGE

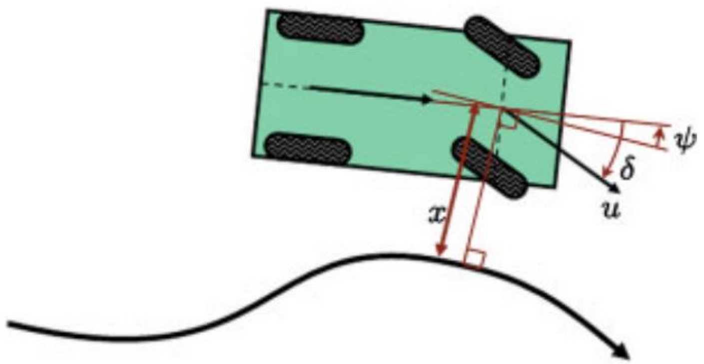
Lateral control

- Stanley method

Trajectory to follow

Pose → **Stanley Steering Controller** → Steering commands (20Hz)

Velocity estimate



$$\delta(t) = \psi(t) + \tan^{-1}\left(\frac{kx(t)}{u(t) + \varepsilon}\right)$$

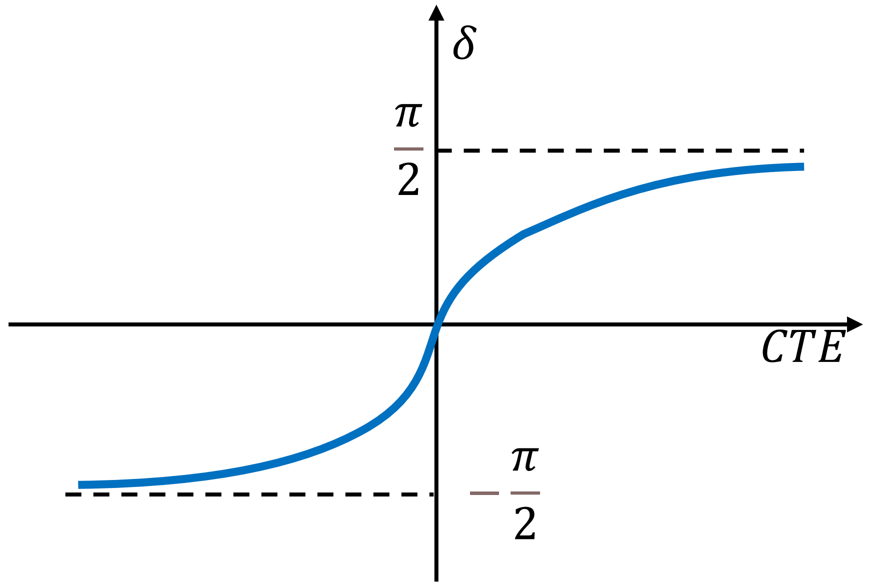
Lateral control

- Stanley method
  - How it works?

$$\delta(t) = \psi(t) + \tan^{-1}\left(\frac{kx(t)}{u(t) + \varepsilon}\right)$$

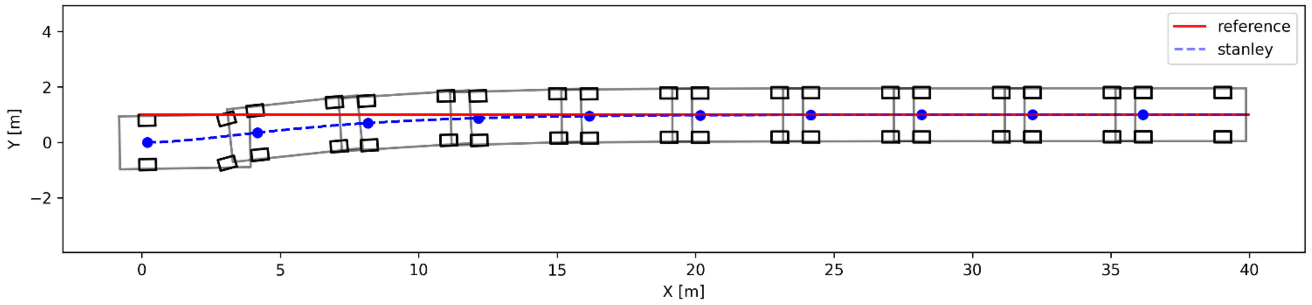
For heading angle error $\delta(t) = \psi(t)$

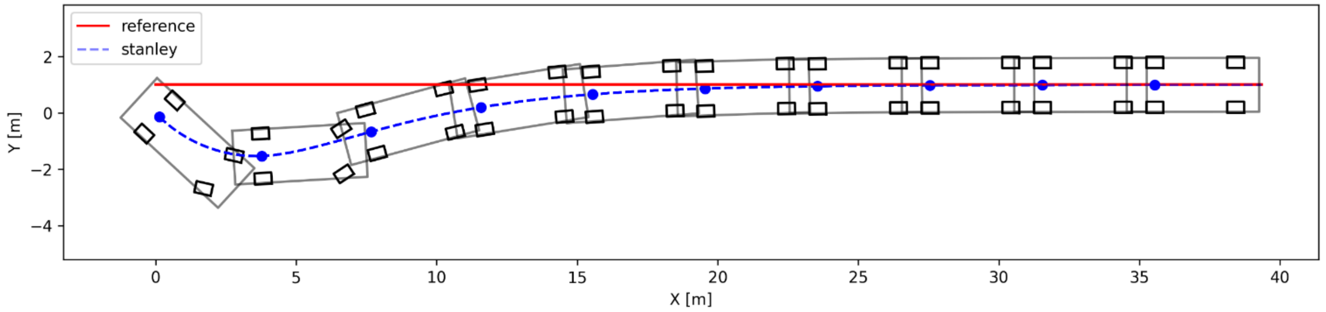
For cross track error(CTE) $\tan^{-1}\left(\frac{x}{v_x}\right)$

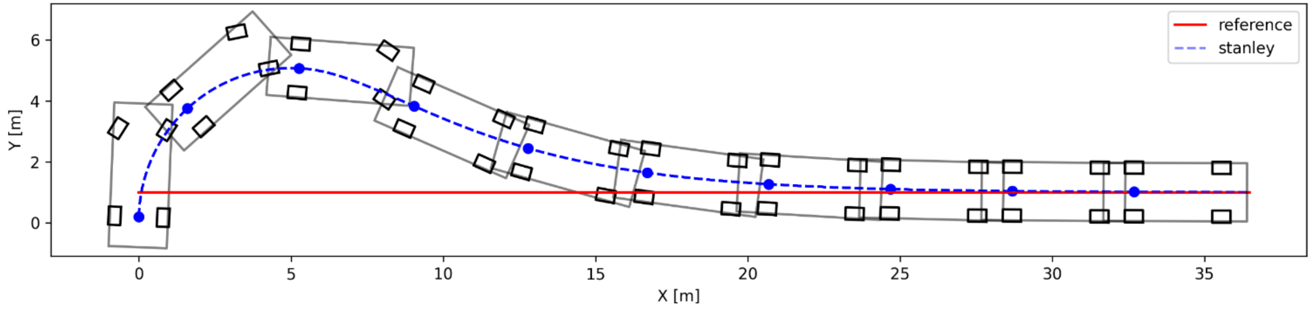


Lateral control

- Stanley method
  - Simple example







HL Klemove

Thank You