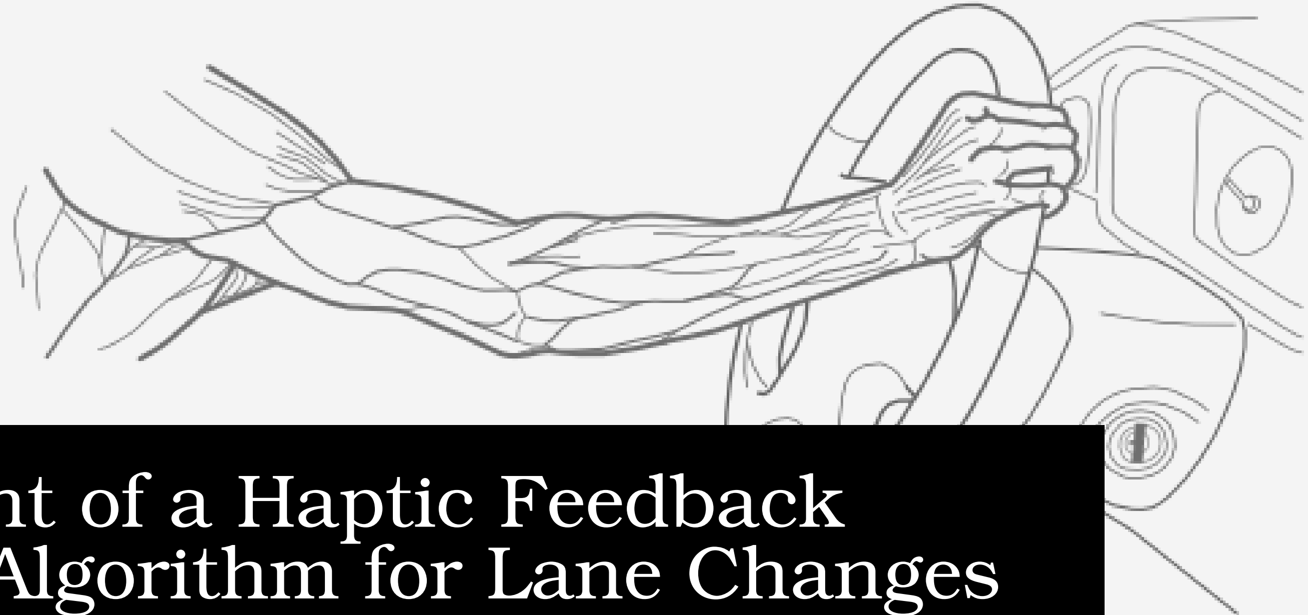
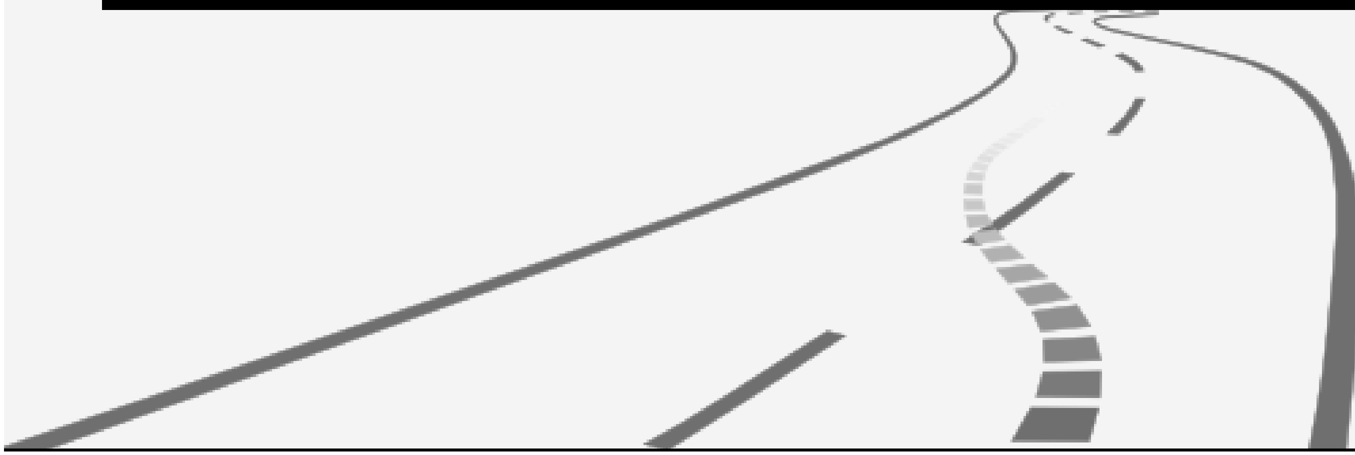


Development of a Haptic Feedback Transition Algorithm for Lane Changes

Using Neuromusculoskeletal Modeling

K.K. Tsoi, Aerospace Engineering - Control & Simulation

24-11-2010



Overview

1. Introduction
2. Problem Statement & Research Questions
3. Our Approach
4. Cybernetic Model
5. Results, Accomplishments & Conclusions

1.

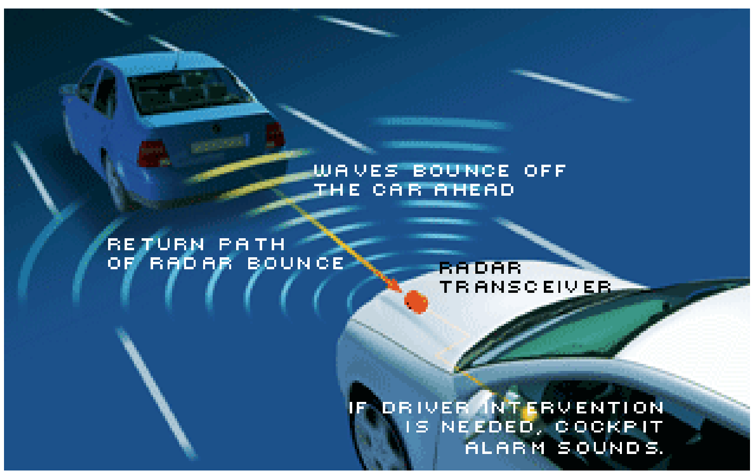
Introduction

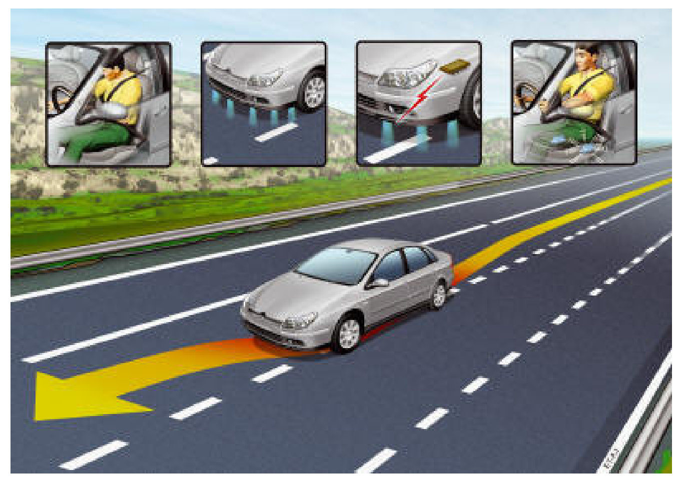
Road Safety Systems
Haptic Feedback
Lane Keeping Support System
Key Research Questions

Road Safety Systems

Improving Road Safety

- Passive safety systems (seatbelts & airbags)
- Active safety systems (ABS & ESC)
  - Task automation (ACC)
  - Response automation (LDWS)





Current Active Safety Systems

Disadvantages

- Task automation systems:

  Driver is taken out of the control-loop.

- Response automation systems:
  - discrete warnings [1]
  - reliability issues [2]

[1] Mulder, M. (2007). Haptic Gas Pedal Feedback for Active Car-Following Support.

[2] Goodrich, M. A., & Boer, E. R. (2000). Designing Human-Centered Automation: Tradeoffs in Collision Avoidance System Design.

Active Safety System that provides Haptic Feedback

Guidance via the Sense of Touch

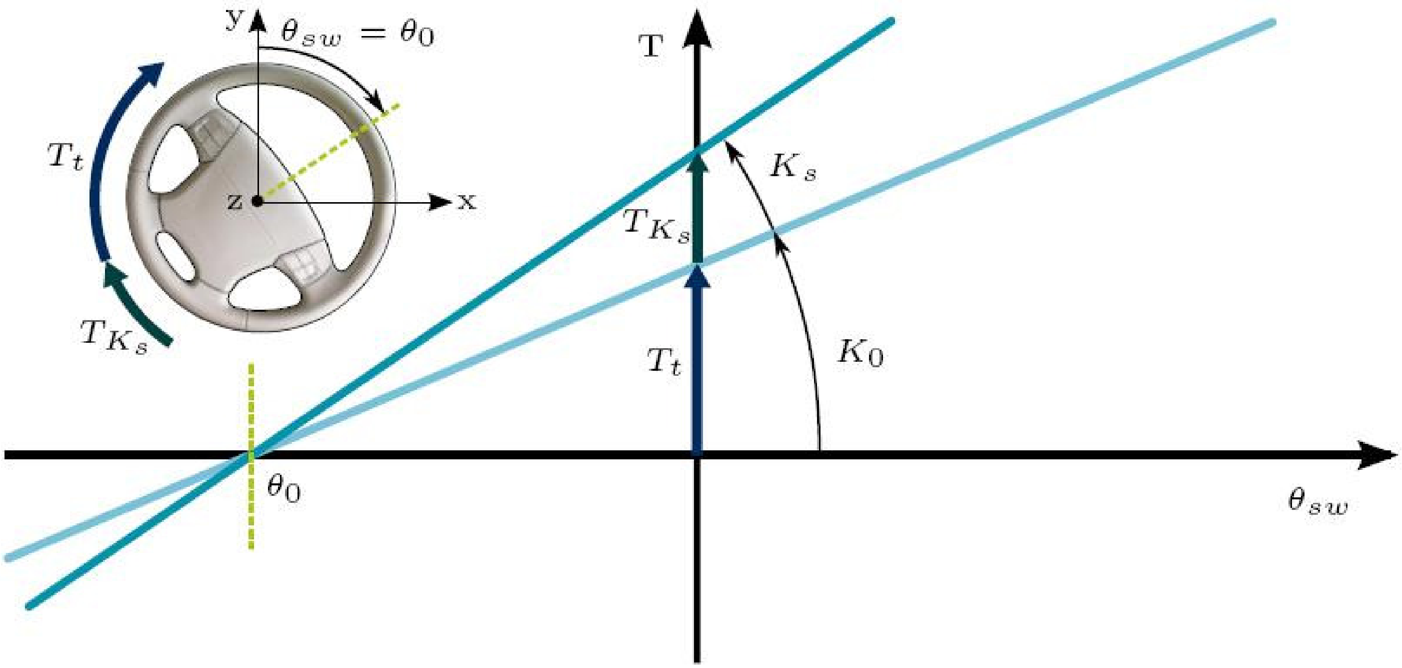
- Driver always stays in control.
- Decrease of visual demand.
- Increase of performance.

[3] Brandt, T., Sattel, T., & Bhm, M. (2007). Combining Haptic Human-Machine Interaction with Predictive Path Planning for Lane-Keeping and Collision Avoidance Systems.

Haptic Feedback Modalities [4]

Guidance via the Sense of Touch

- Torque Feedback (T_t)
- Stiffness Feedback (K_s)

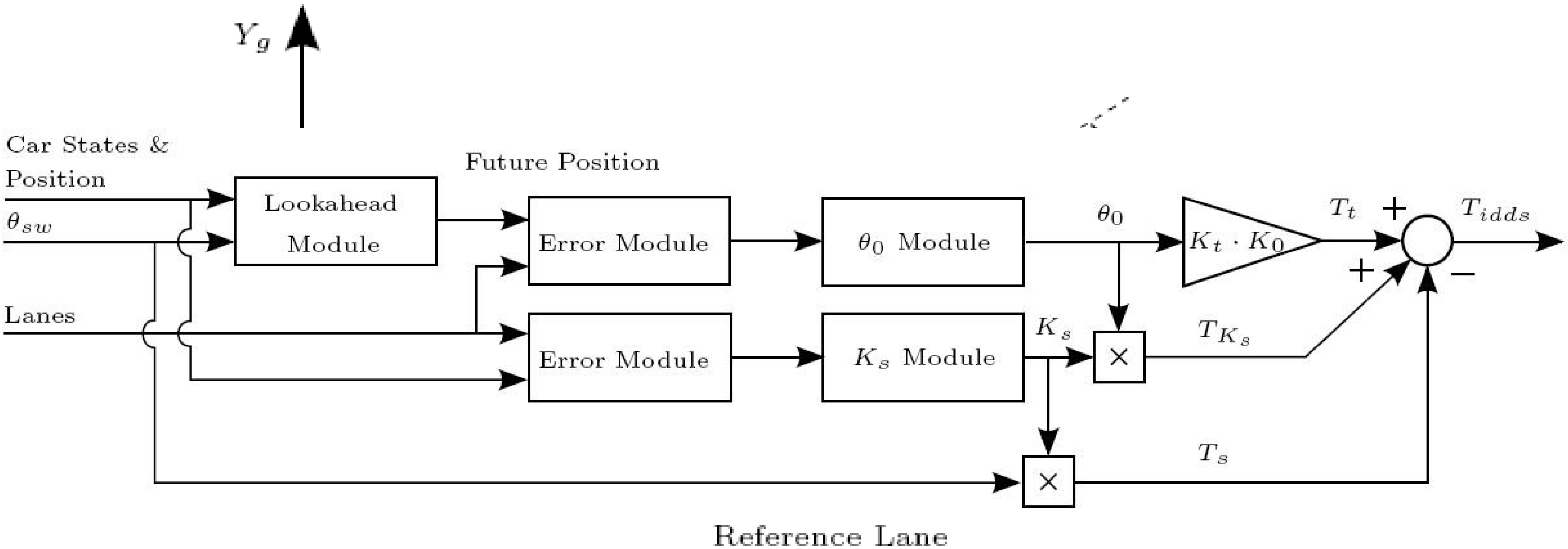


[4] Abbink, D. A., & Mulder, M. (2009). Exploring the Dimensions of Haptic Feedback Support in Manual Control.

Lane Keeping Support System [4]

LKSS

- Supports lateral control of cars.
- Provides continuous haptic feedback.

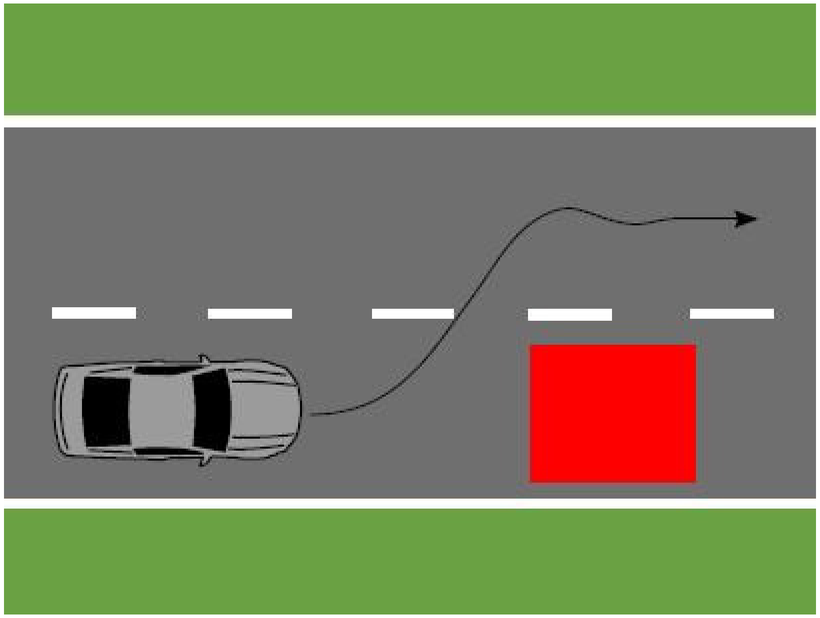


[4] Abbink, D. A., & Mulder, M. (2009). Exploring the Dimensions of Haptic Feedback Support in Manual Control.

Intelligent Driver Support System

Present & Future

- Present support: lane keeping
- Future support: lane changing & obstacle avoidance

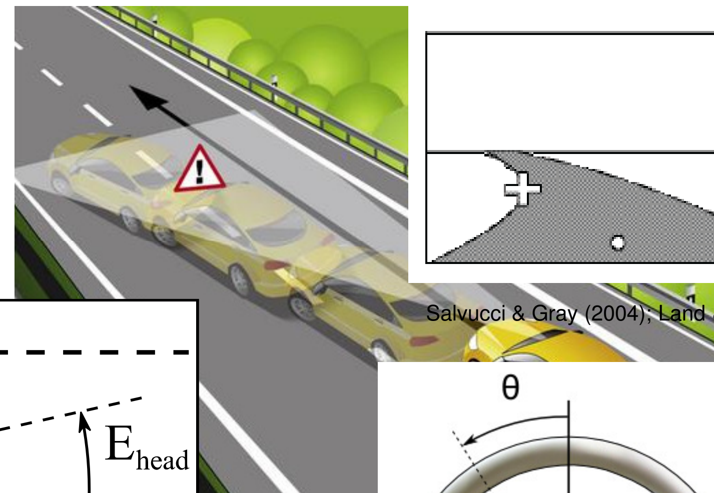


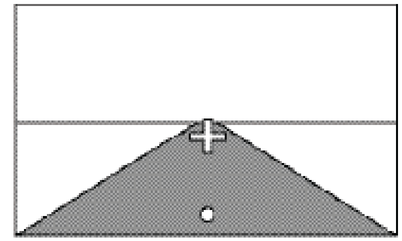
What is Haptic Feedback?

An Application Currently under Development

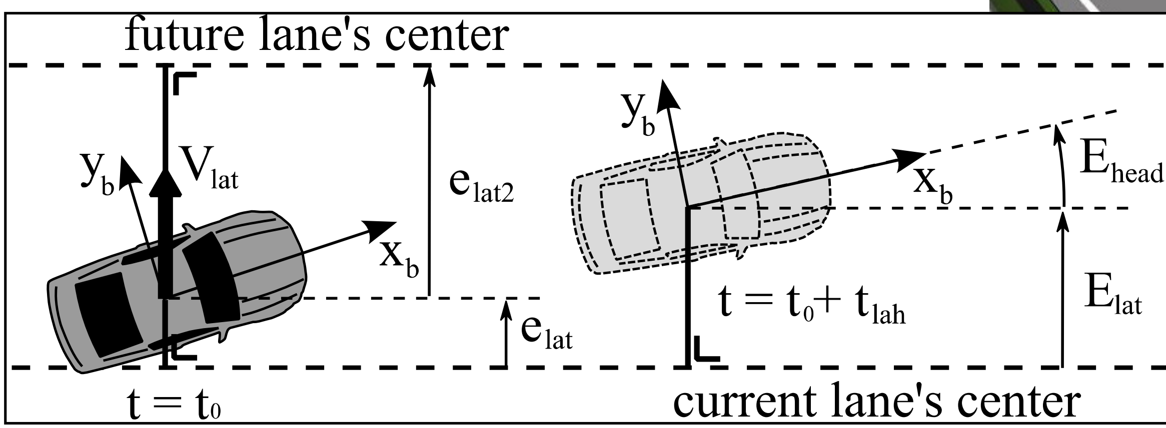
- Haptic Steering Wheel Guidance
  - Lane keeping assist

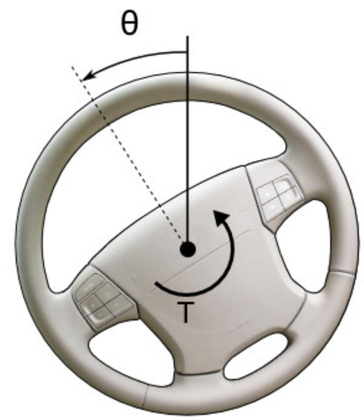
- Continuous Haptic Feedback





Salvucci & Gray (2004); Land & Lee (1994)

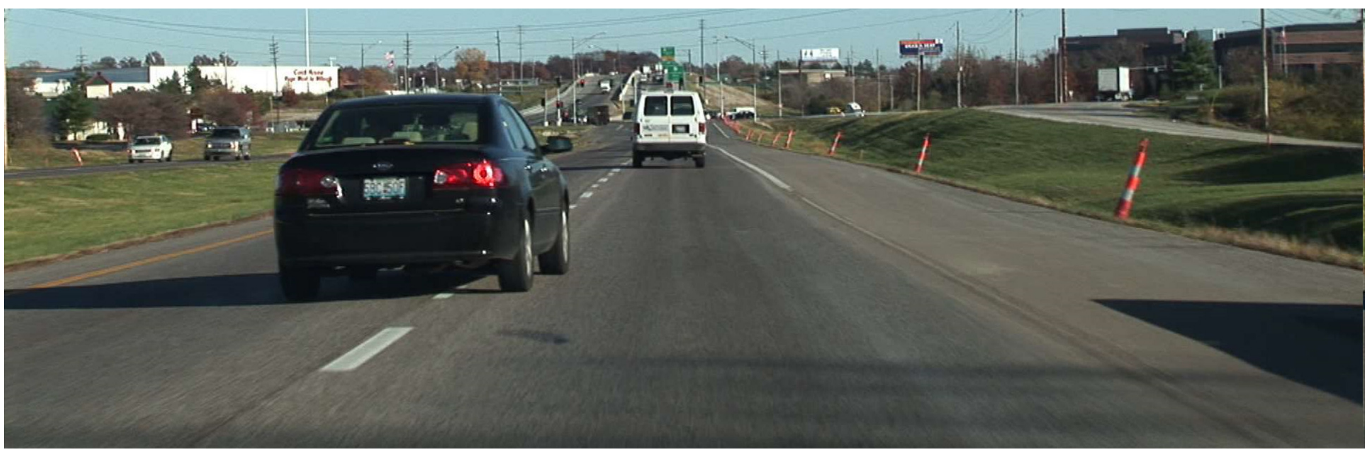




The Problem

- Continuous Haptic Steering Wheel Guidance
  - Lane keeping assist

- What happens when you want to change lanes???



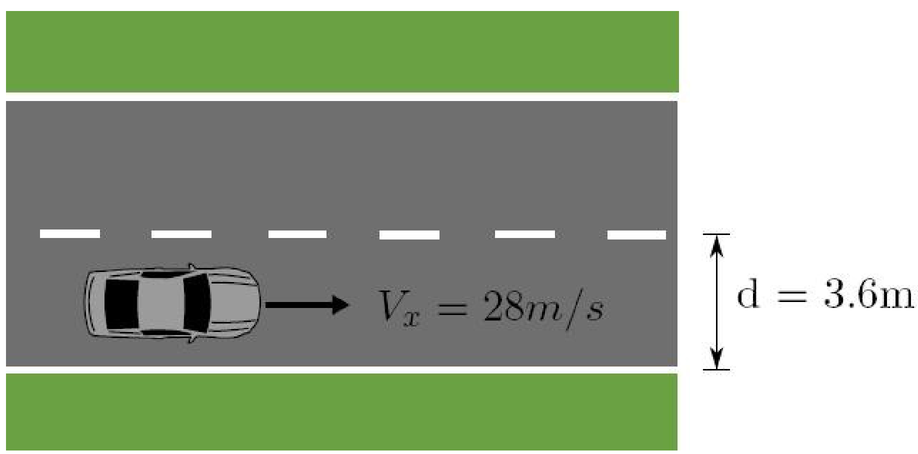
The Problem

- Continuous Haptic Steering Wheel Guidance
  - Lane keeping assist
- What happens when you want to change lanes???
- Lane keeping and lane changing are two mutually exclusive tasks
  - But we want to be able to provide continuous haptic feedback

Key Research Questions

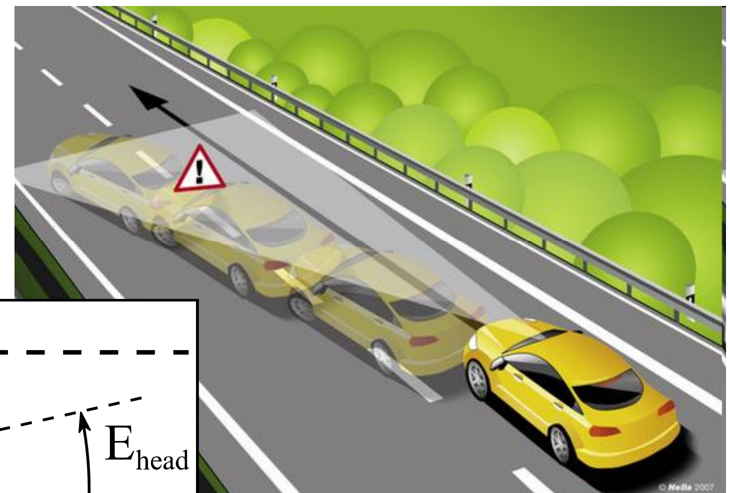
- How can the haptic feedback algorithm be designed such:
  - that it doesn't restrict drivers in making lane changes,
  - while preventing safety degrading lane deviations?

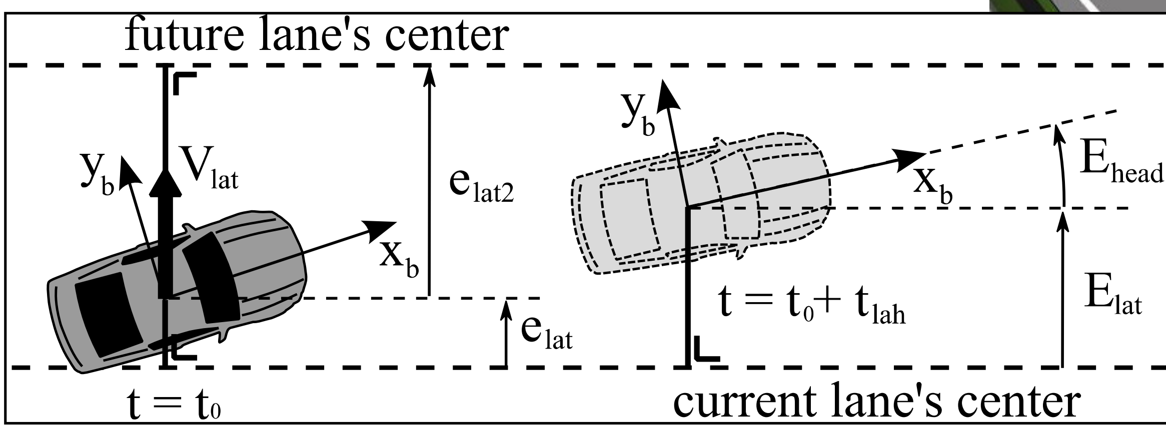
- Can the current LKSS be extended such that the haptic guidance transitions smoothly from one supporting task to another?



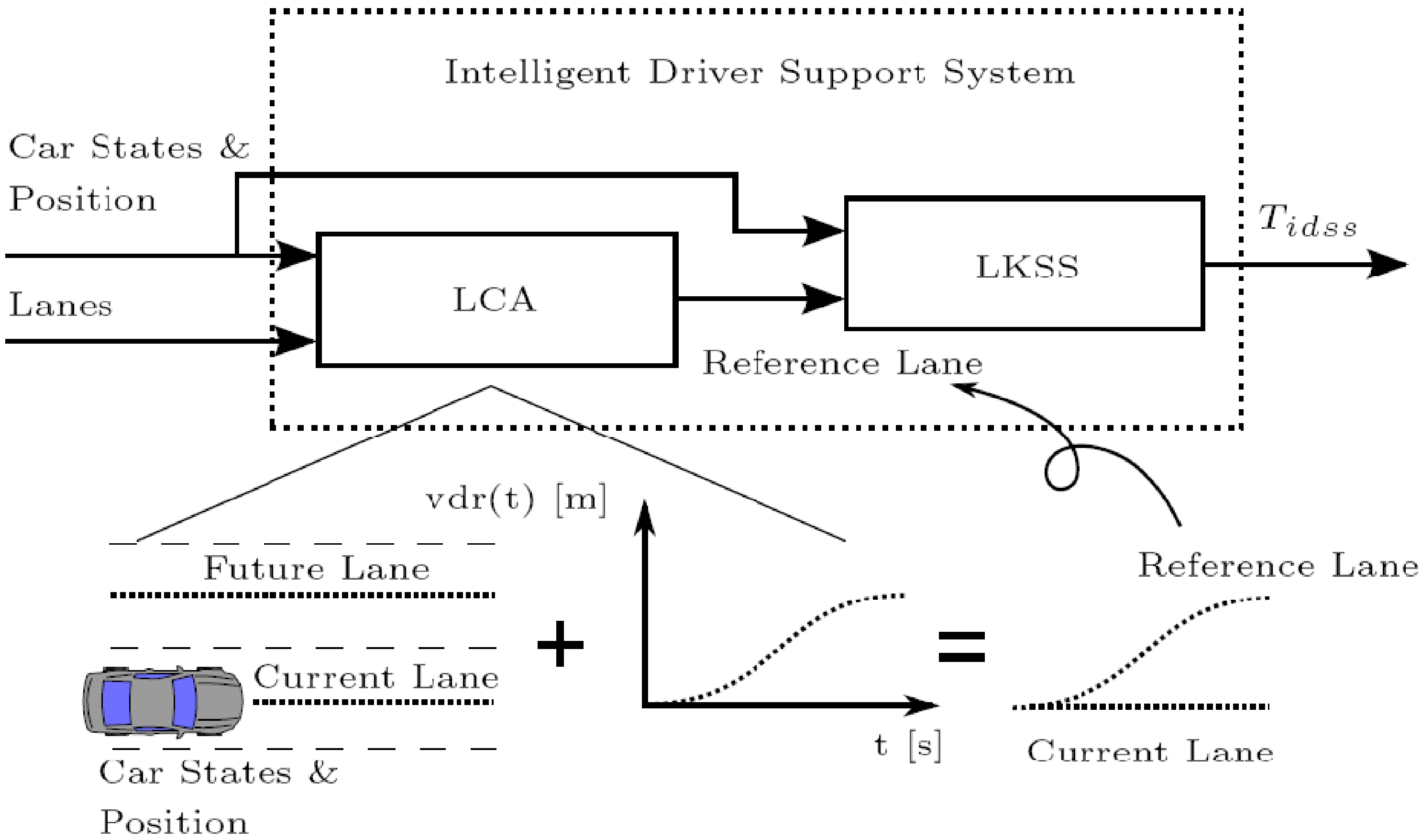
Our Approach

- Lane Keeping Support
  - Traces lane center
- Lane Change Support
  - “reroutes” the lane center



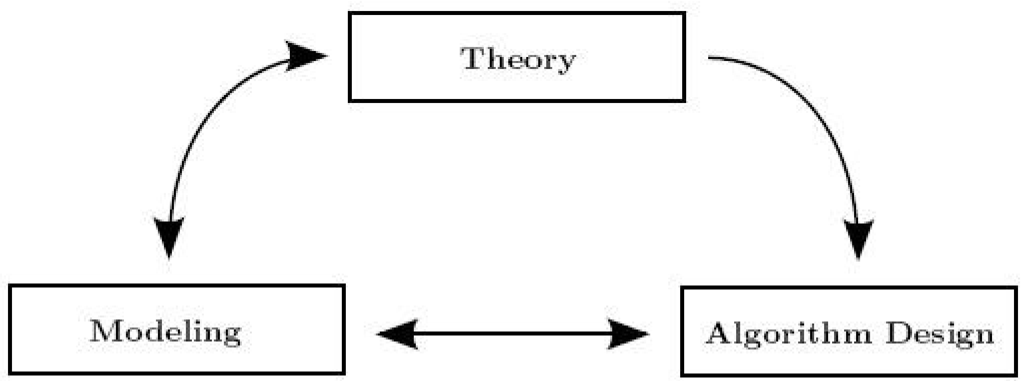


Our Approach: Lane Change Algorithm



Research Approach

- Human-centered approach: development of the LCA taking the driver into account (neuromusculoskeletal modeling).
- 3-step design cycle [5]



[5] Mulder, M. (2007). Haptic Gas Pedal Feedback for Active Car-Following Support.

2.

Cybernetic Model

Why is it needed?
What does it comprise?
Obtaining Model Parameters
Simulations

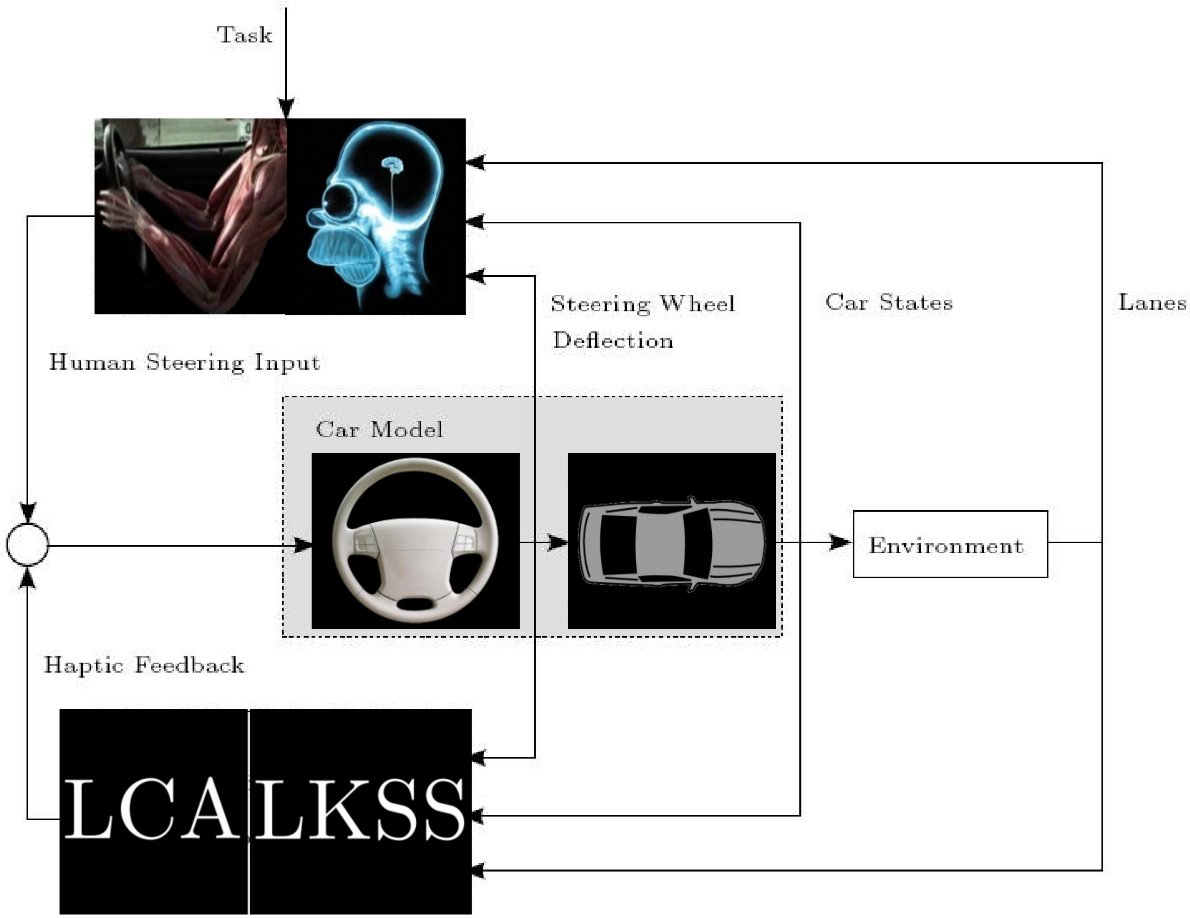
Why is the cybernetic model needed?

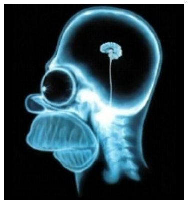
Need & Requirement

- Need:
  - To assess the haptic support algorithm.
  - To learn how haptic support affects the driver steering behavior.

- Requirement:
  - The model should include interactions between:
    - Driver
    - Steering Wheel Dynamics
    - Car Dynamics
    - IDSS (LKSS & LCA)

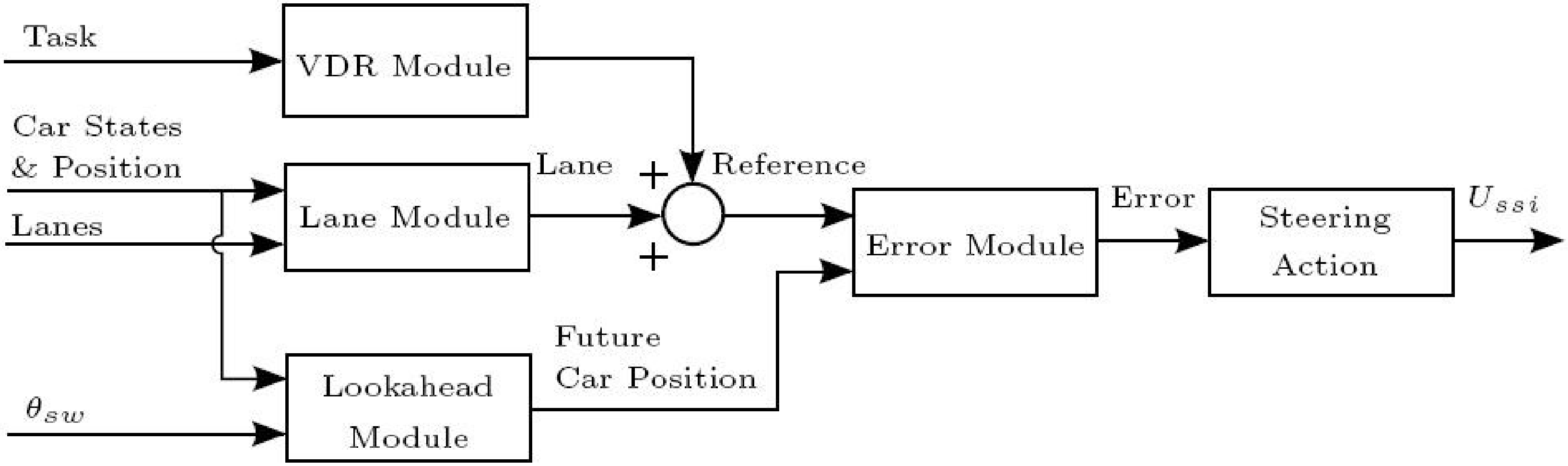
Cybernetic Model





Cortical Control
Driver Model

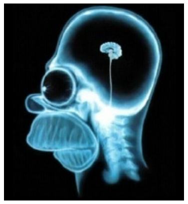
- Preview controller [6] that minimizes the error of the car w.r.t. a reference path: $U_{ssi} = f(e_{ref})$.
- Can perform two tasks: lane keeping & lane changing.

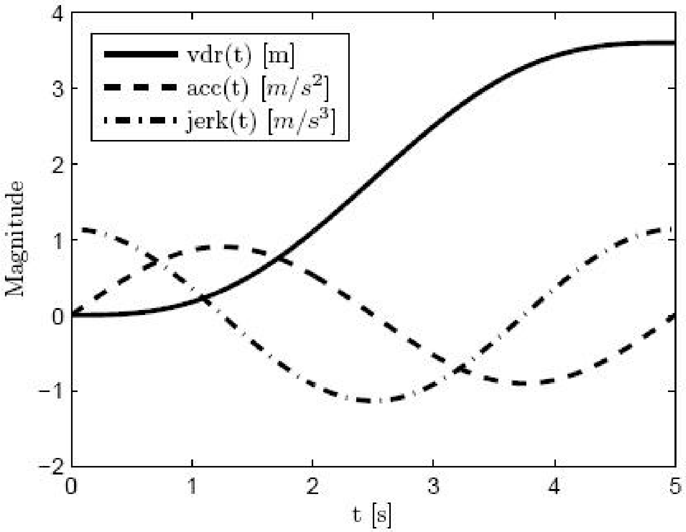


[6] Weir, D., & McRuer, D. (1970). Dynamics of driver vehicle steering control.

Virtual Desired Reference [7]

Cortical Control Model





$$vdr(t) = \frac{-d_y}{2\pi} sin\left(\frac{2\pi\ t}{t_{lc}}\right) + \frac{d_y}{t_{lc}}\ t$$

$$acc(t) = \frac{2\pi\ d_y}{t_{lc}^2} sin\left(\frac{2\pi\ t}{t_{lc}}\right)$$

$$jerk(t) = \frac{4\pi^2\ d_y}{t_{lc}^3} cos\left(\frac{2\pi\ t}{t_{lc}}\right)$$

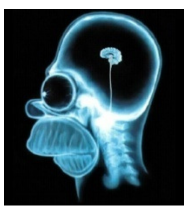
- Lateral acceleration < 2 m/s^2
- Lateral jerk < 2.5 m/s^3

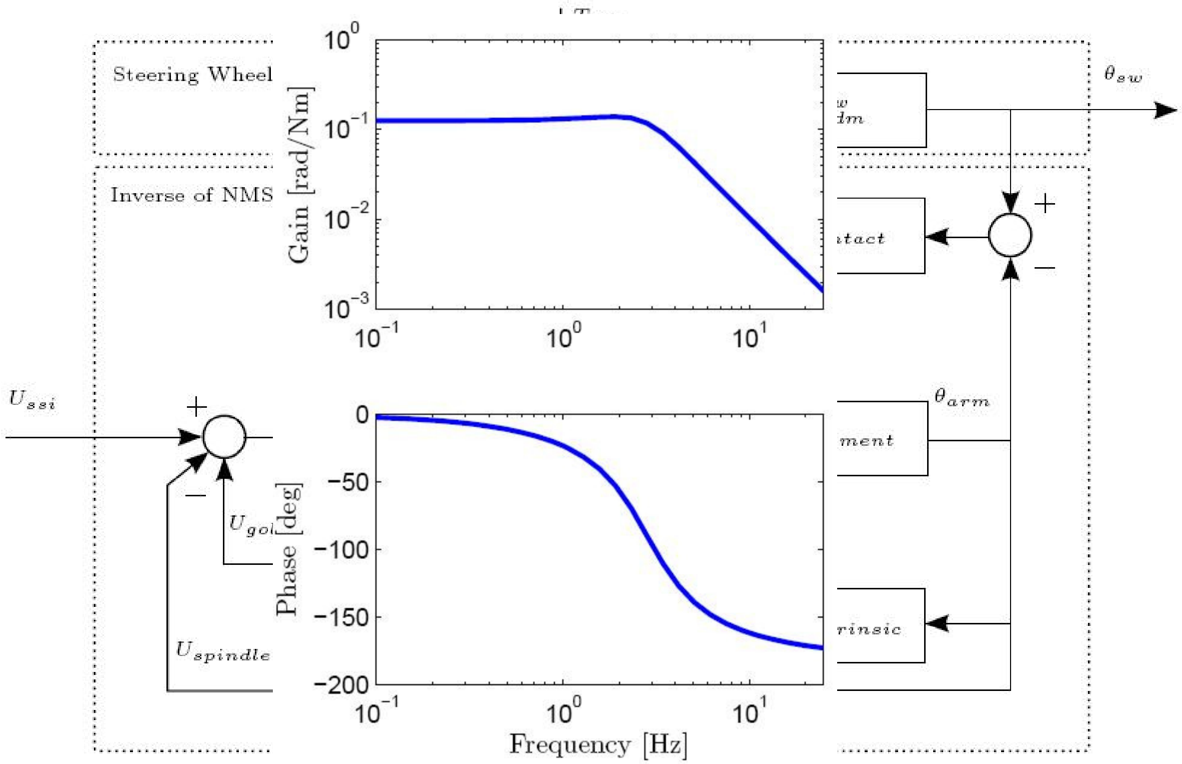
[7] Kanaris, A., Kosmatopoulos, E. B., & Ioannou, P. A. (2001). Strategies and Spacing Requirements for Lane Changing and Merging in Automated Highway Systems.

Neuromusculoskeletal Model [8]

Driver Model

- Models the physiological properties of the human arms.
- It is modeled as an endpoint admittance.



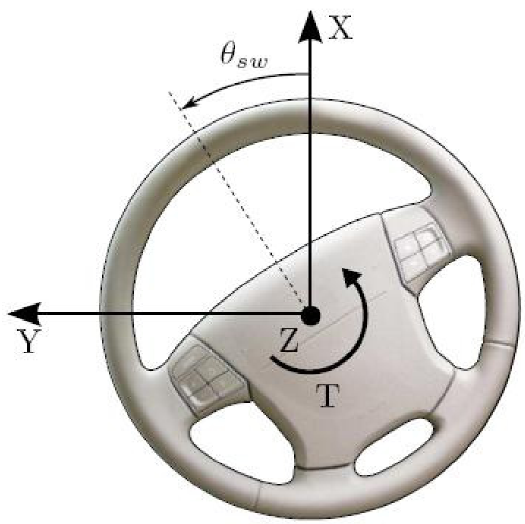


[8] Abbink, D. A. (2006). Neuromuscular Analysis of Haptic Gas Pedal Feedback during Car Following.

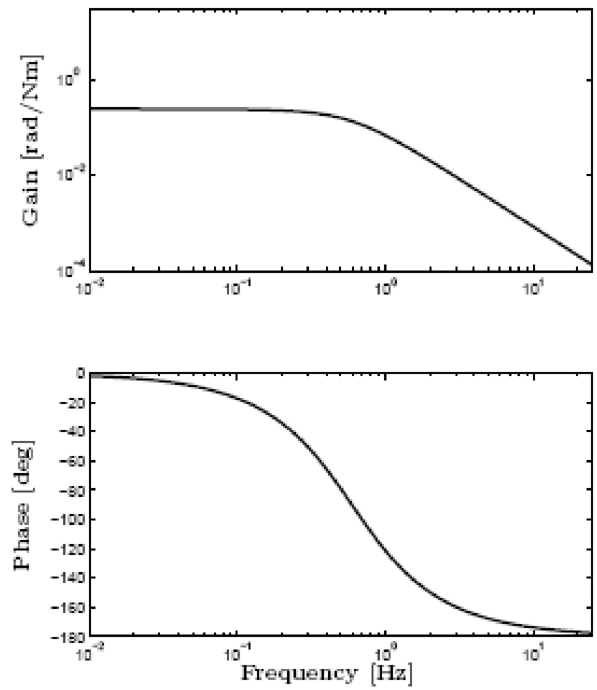
Steering Wheel Dynamics

Car Model

- Mass-spring-damper system
- The constant stiffness represents the centering behavior of the steering wheel.

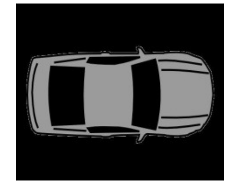


$$H^{sw}_{adm}(s)$$

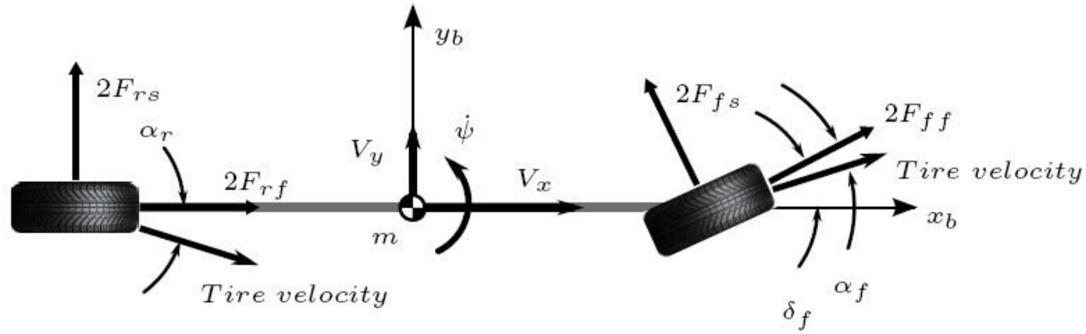


Vehicle Dynamics

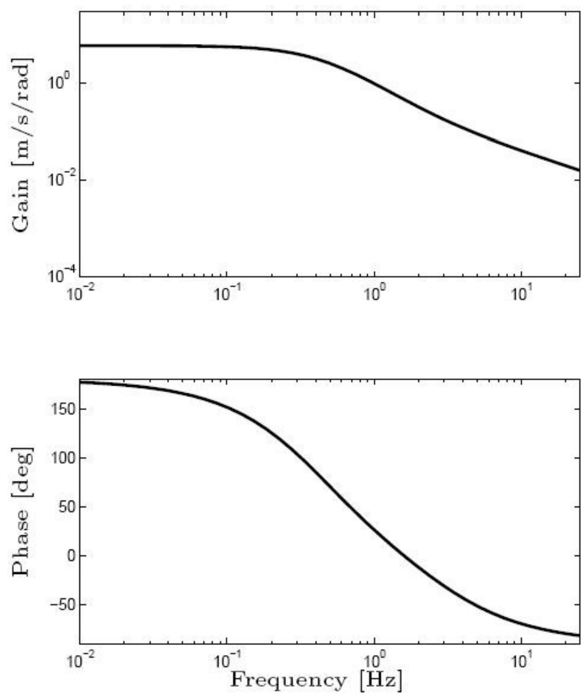
Car Model



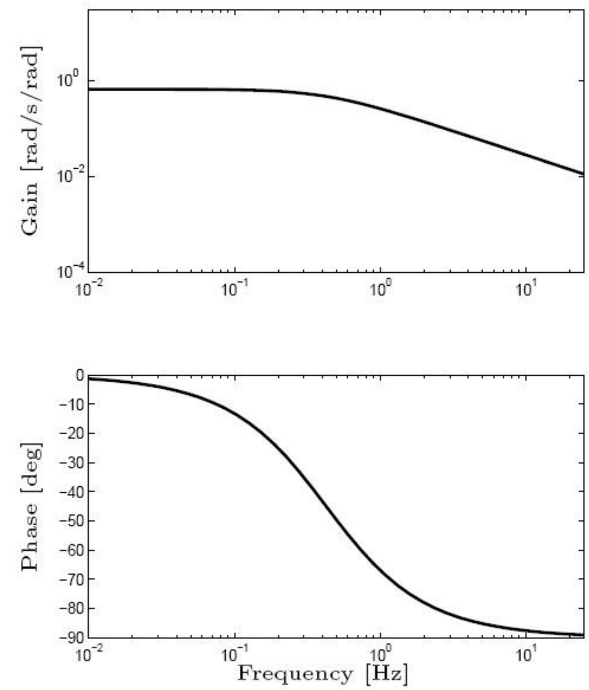
- 2 DOF bicycle model
- Linear tire dynamics



$$H_{\theta_{sw},V_y}(s) \quad =$$



$$H_{\theta_{sw},\dot{\psi}}(s) \quad =$$

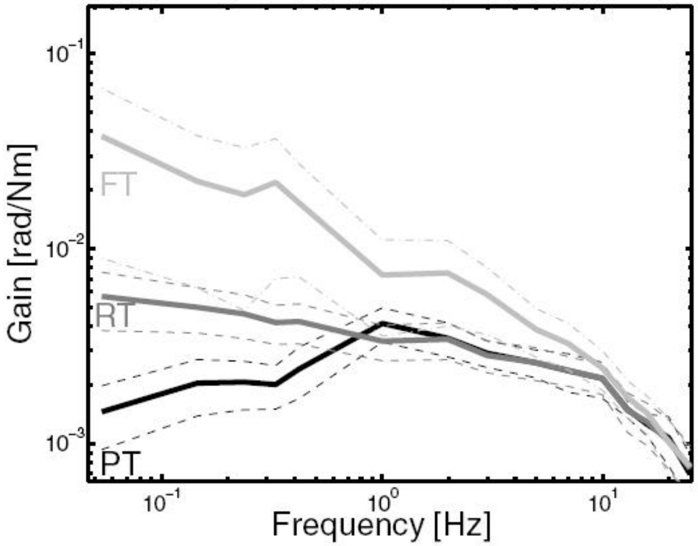


Parameters of the NMS Model

How are these obtained?

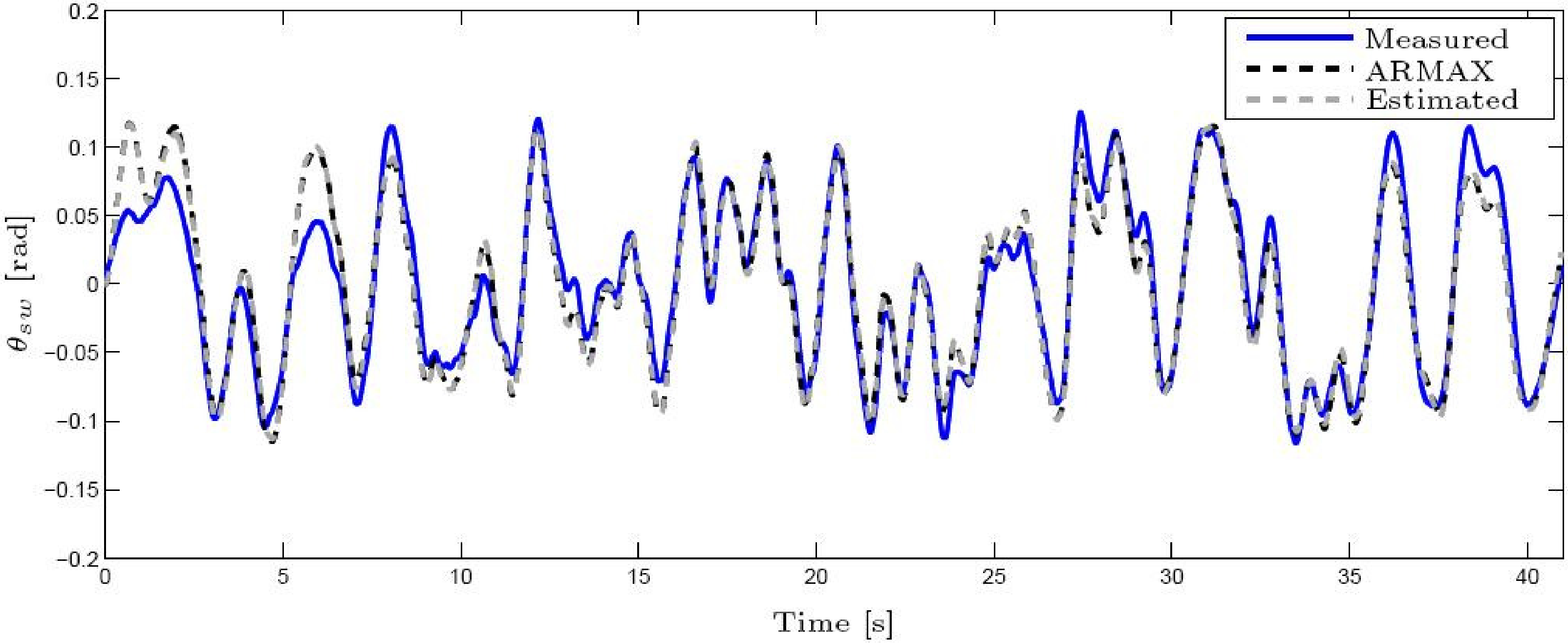
- The parameters are obtained with a System Identification and Parameter Estimation (SIPE) analysis.
- Data sets from experiments conducted at DUT are used, where drivers performed classical tasks behind a steering wheel.

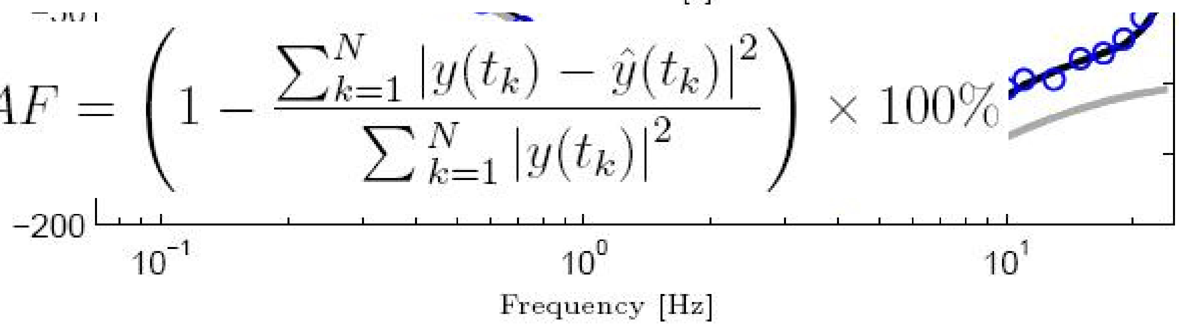
- Classical tasks:
  - Position Task
  - **Relax Task**
  - Force Task



[8] Abbink, D. A. (2006). Neuromuscular Analysis of Haptic Gas Pedal Feedback during Car Following.

SIPE Results

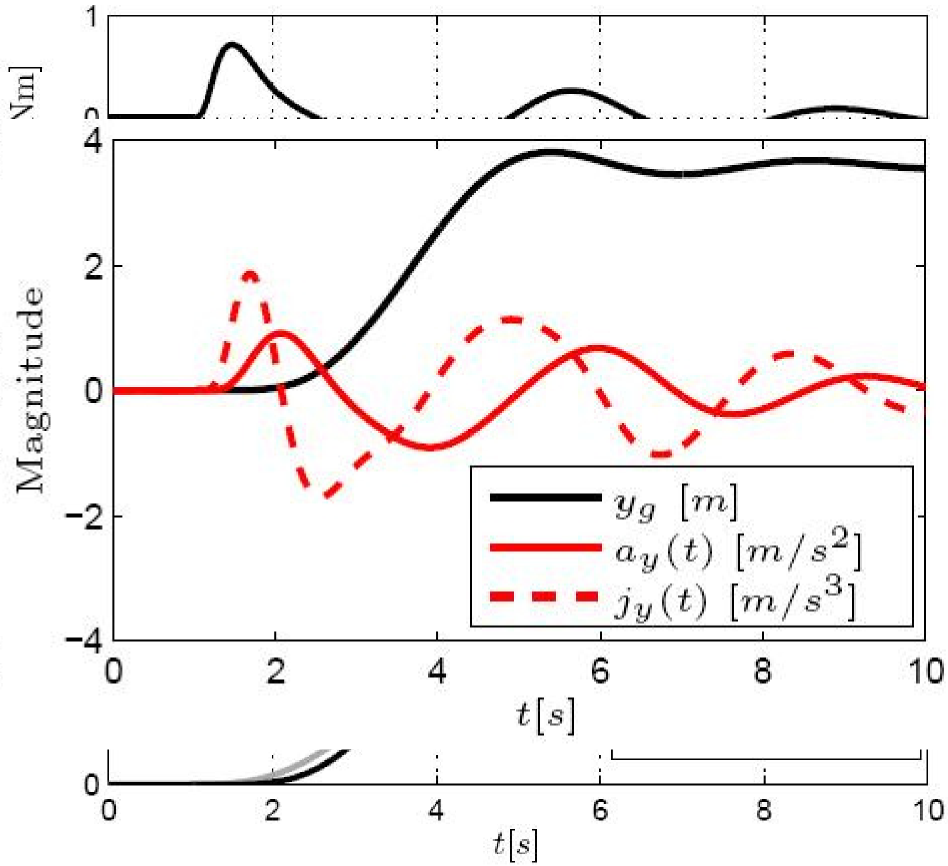


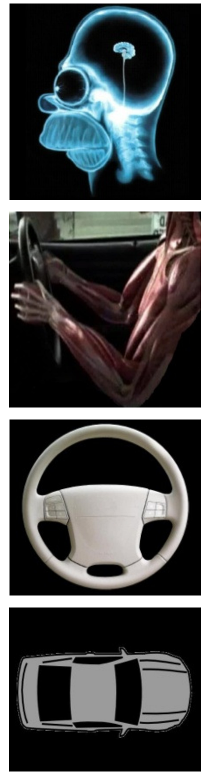


$$VAF = \left(1 - \frac{\sum_{k=1}^{N} |y(t_k) - \hat{y}(t_k)|^2}{\sum_{k=1}^{N} |y(t_k)|^2}\right) \times 100\%$$

Human-car Model

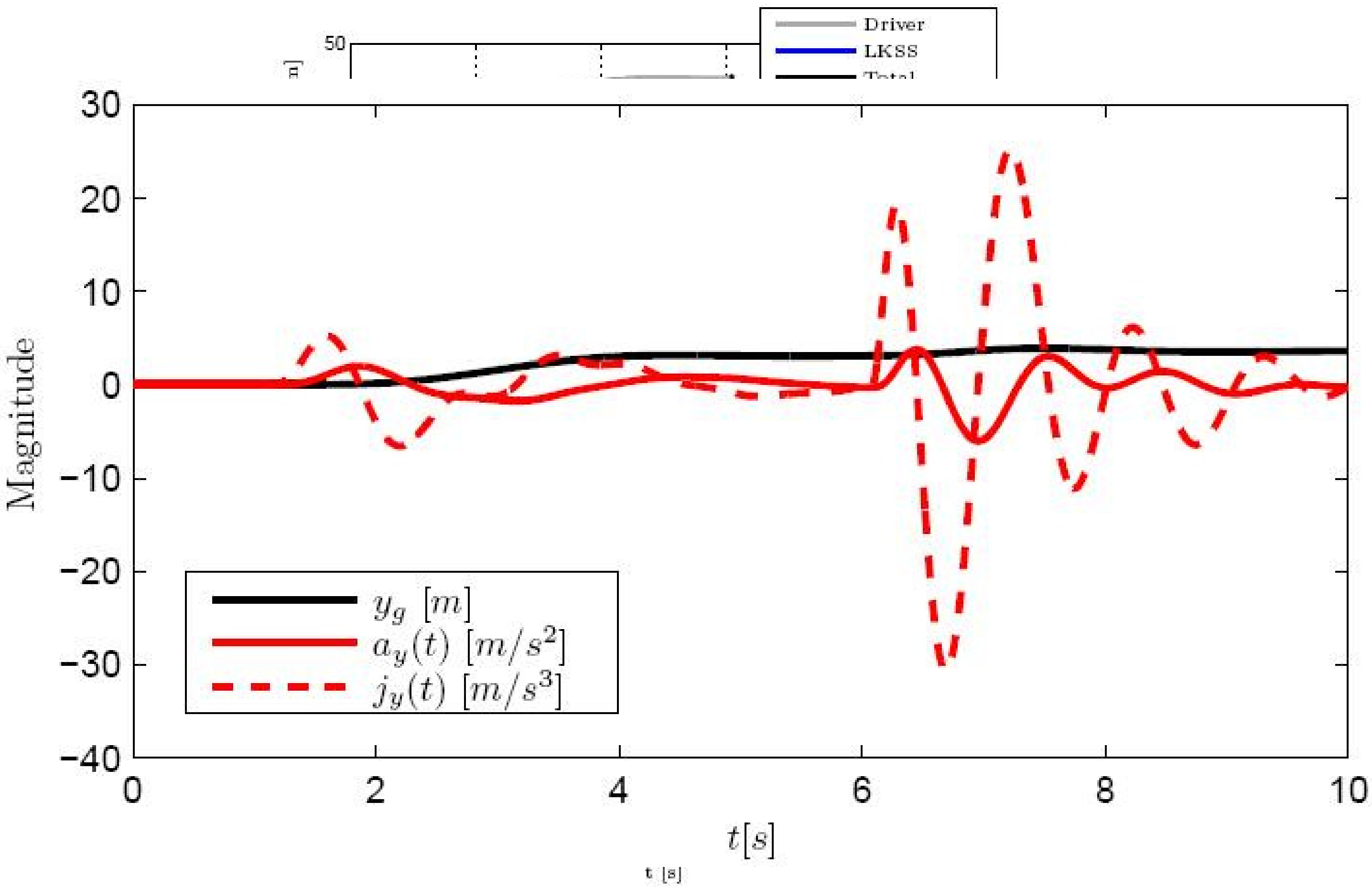
Simulating an Unsupported Lane Change

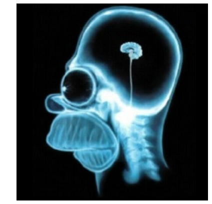


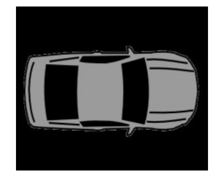


Human-car Model with LKSS

Simulating a Lane Change with LKSS support







3.

Lane Change Algorithm

Philosophy
Modules
Simulations

Recapitulation

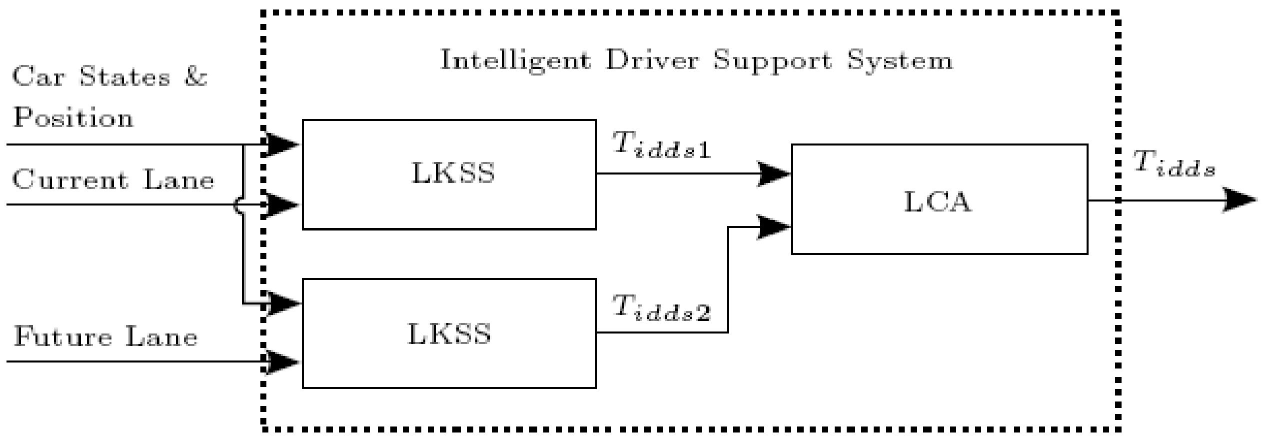
- Lane Keeping Support System provides haptic support for lane keeping (LK).
- The Lane Change Algorithm should make it possible to have a smooth transition of haptic support.
- The Lane Change Algorithm should be designed such that it extends the current LKSS.

LCA

LCA Philosophy

Behind the LKSS

- Advantage: freedom to manipulate the haptic guidance directly
- Disadvantages: It is complex to merge two haptic guidance signals.

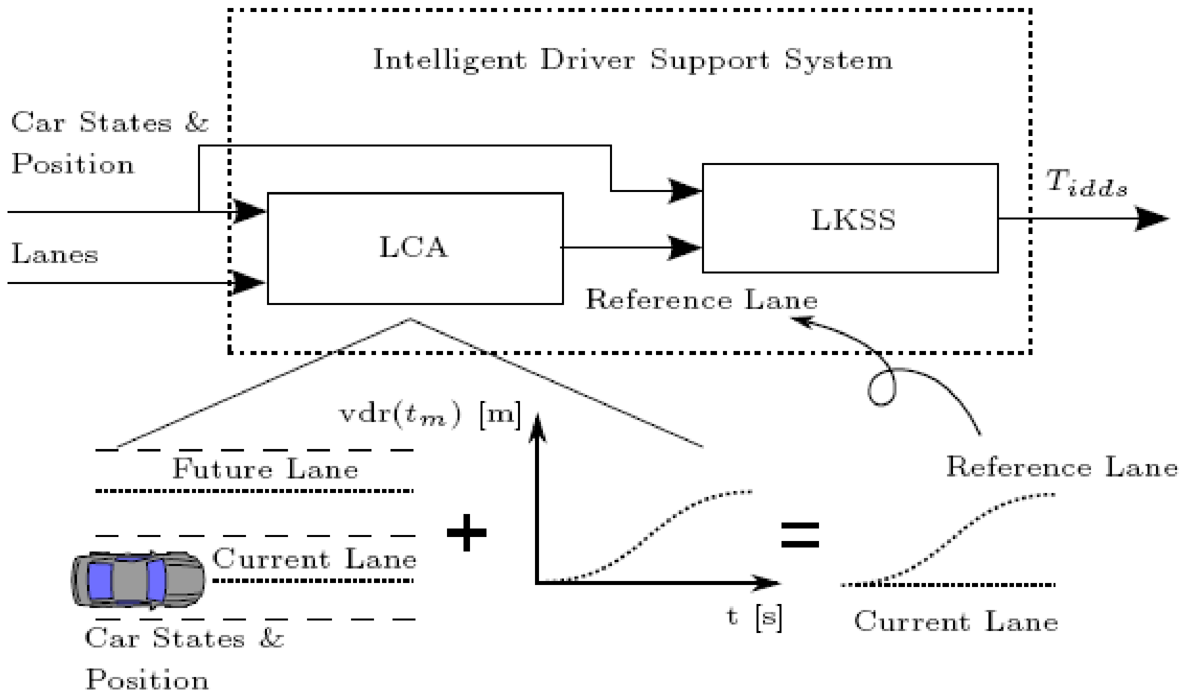


LCA Philosophy

In Front of the LKSS

LCA

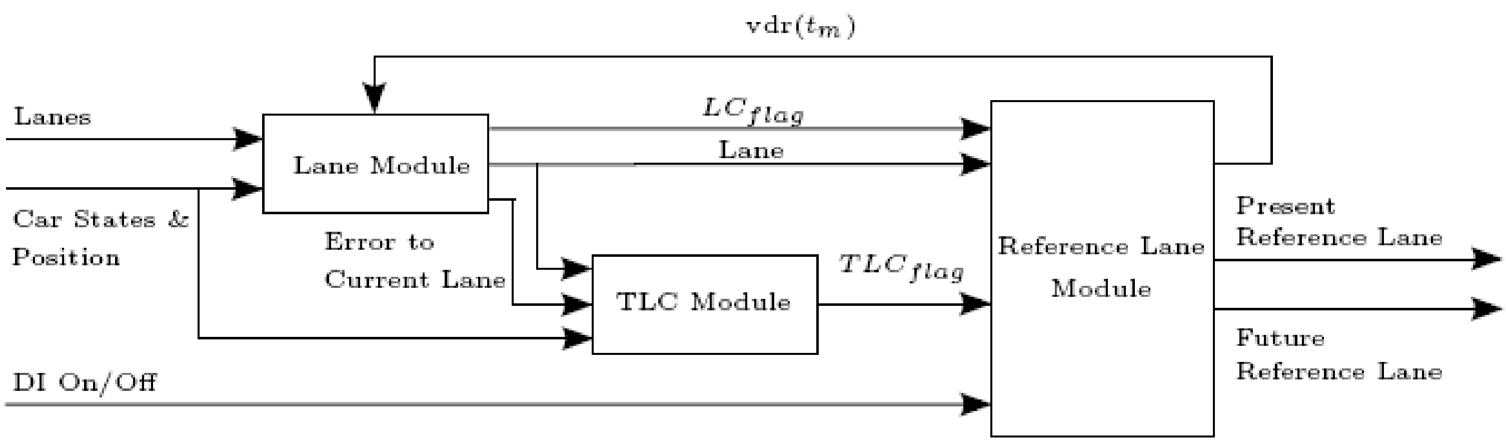
- Advantage: straight forward approach.
- Disadvantage: haptic guidance cannot be manipulated directly.



LCA Modules

LCA

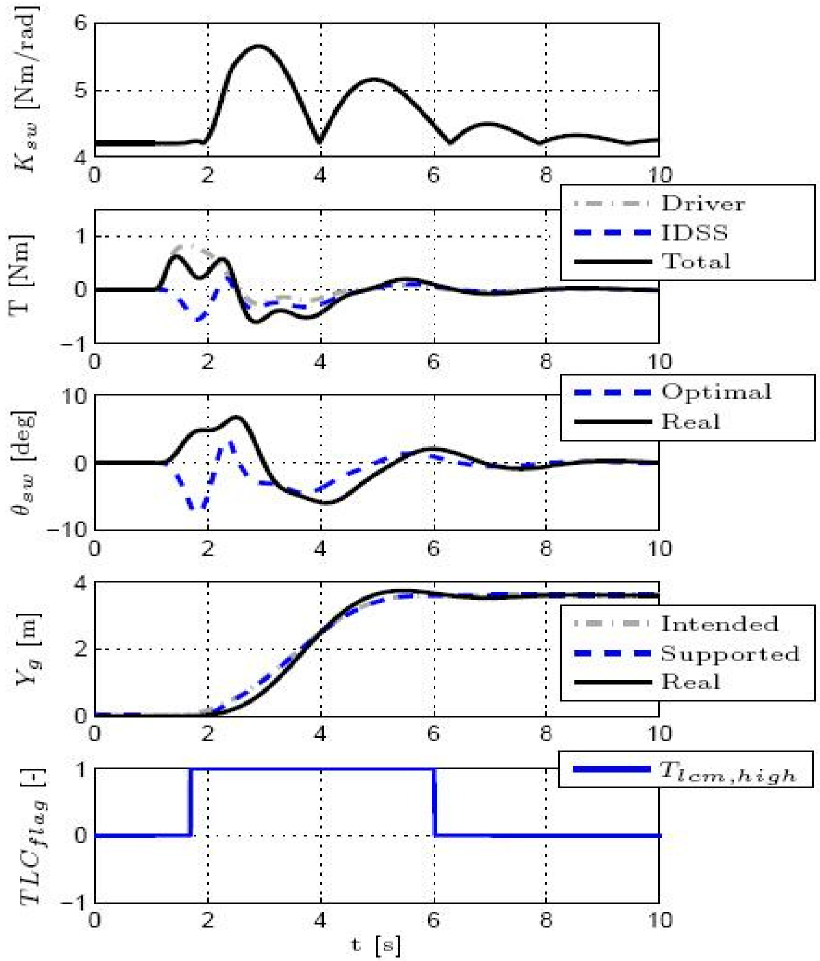
- Lane module determines the current lane and when a LC has been completed.
- TLC module predicts in which amount of time the car is leaving the current lane and gives a flag when, TLC < T_{lcm}.
- Reference lane module adds a VDR to the current lane when a LC occurs (TLC < T_{lcm}).

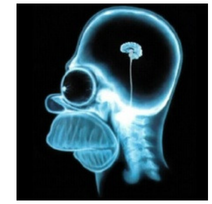


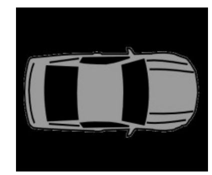
TUDelft

Cybernetic Model
Simulation Result

Supported Lane Change





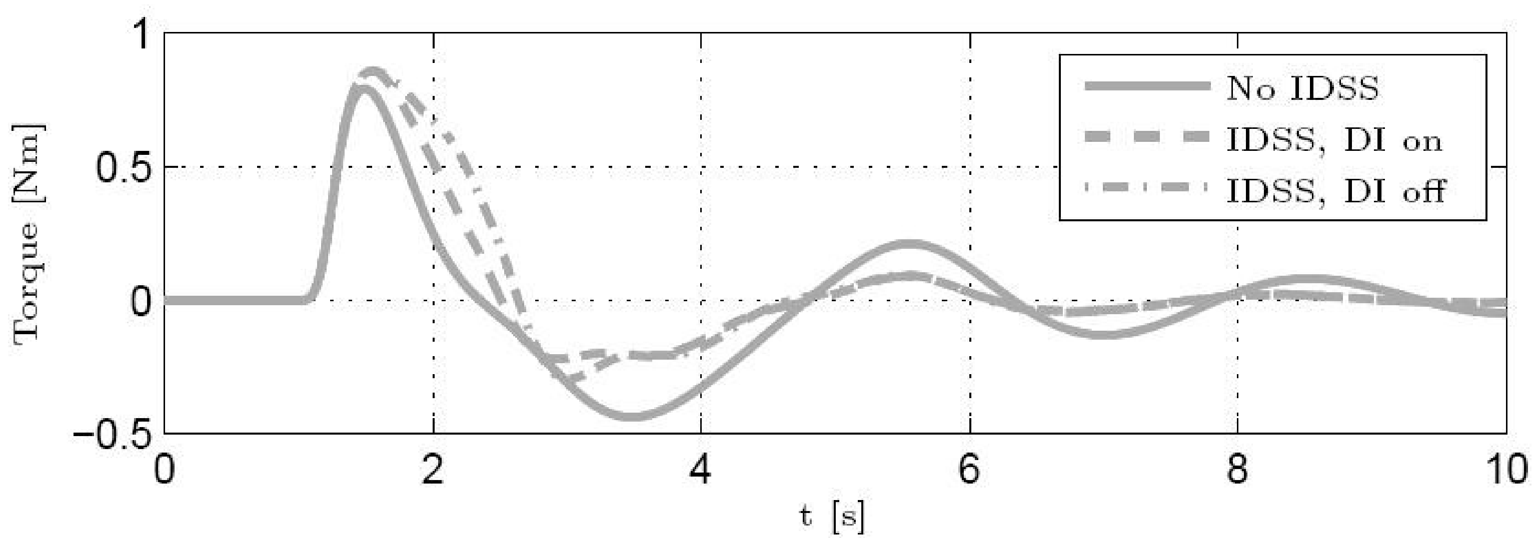


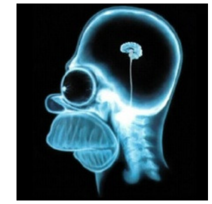
LKSS

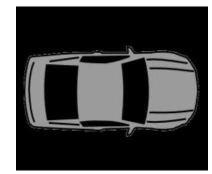
LCA

Unsupported vs. Supported

Required Steering Input from the Driver







LKSS

LCA

4.

Proposed IDSS investigated in more Detail

Effect of LCA on the LK support function?

Effect of different NMS settings on IDSS effectiveness?

Accomplishments

- A cybernetic model has been constructed that can be used to design haptic feedback support systems

- A haptic transition algorithm has been developed that smoothly transitions the haptic feedback from LK to LC and vice versa.

- The developed LCA allows the driver to make lane changes while still letting the LKS function properly

Accomplishments after Graduation

- Fixed-base driving simulator experiment

- Publication: Tsoi, K.K., Mulder, M. and Abbink, D.A. (2010). Balancing Safety and Support: Changing Lanes with a Haptic Lane-keeping Support System. *Proceedings of the IEEE International Conference on Systems, Man, and Cybernetics*, Istanbul, Turkey, pp. 1236-1243.

Conclusions

- Simulations indicate that during a supported lane change the required steering torque is higher in the beginning (up to 15%)
  - Confirmed in driving simulation experiment

Conclusions

- Simulations indicate that during a supported lane change the required steering torque is higher in the beginning (up to 15%)
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- During the supported lane change the steering effort decreases by approximately 50% once the lane change support is initiated
  - No change observed in driving simulation experiment

Conclusions

- Simulations indicate that during a supported lane change the required steering torque is higher in the beginning (up to 15%)
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  - No change observed in driving simulation experiment

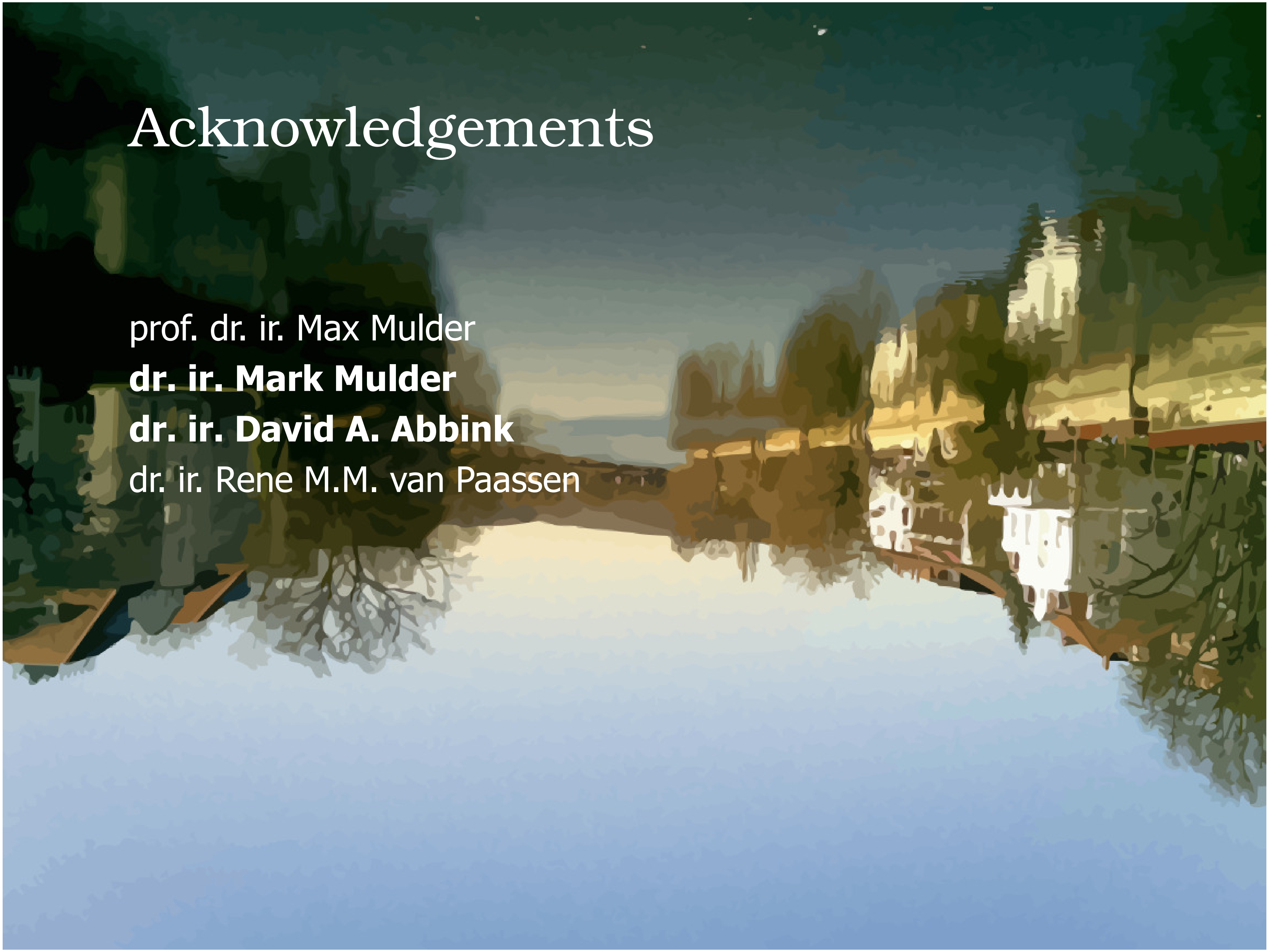
- The effectiveness of the haptic guidance on the steering behavior decreases when the compliance of the driver decreases
  - The algorithm sometimes did not properly anticipate the driver's behavior

Conclusions

- Simulations indicate that during a supported lane change the required steering torque is higher in the beginning (up to 15%)
  - Confirmed in driving simulation experiment
- During the supported lane change the steering effort decreases by approximately 50% once the lane change support is initiated
  - No change observed in driving simulation experiment
- The effectiveness of the haptic guidance on the steering behavior decreases when the compliance of the driver decreases
  - The algorithm sometimes did not properly anticipate the driver's behavior
- The LCA is compatible with different NMS systems, which indicates that it is compatible for different drivers
  - The LCA did not significantly change the execution path of the lane change

?

Questions



Acknowledgements

prof. dr. ir. Max Mulder

dr. ir. Mark Mulder

dr. ir. David A. Abbink

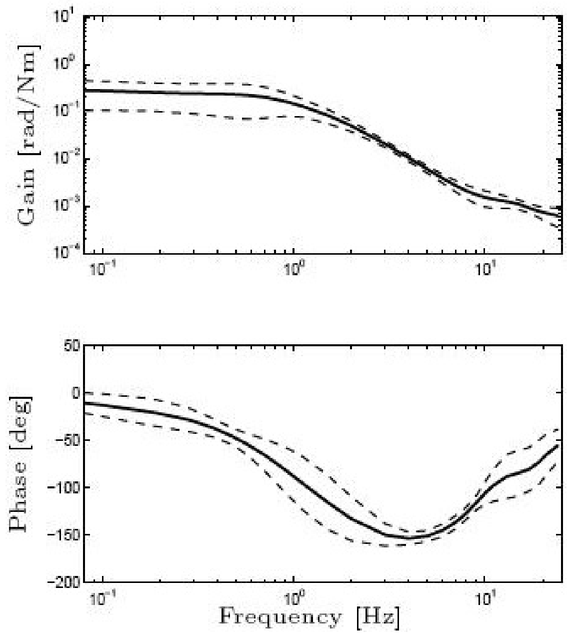
dr. ir. Rene M.M. van Paassen

System Identification

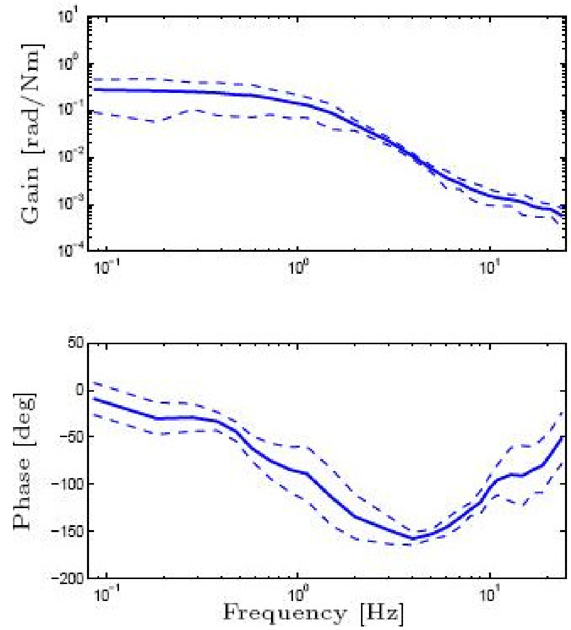
SIPE

- Obtain a non-parametric frequency response function (FRF).
- Choose a model (NMS model) to fit on the FRF.

ARMAX estimation averaged over eight subjects

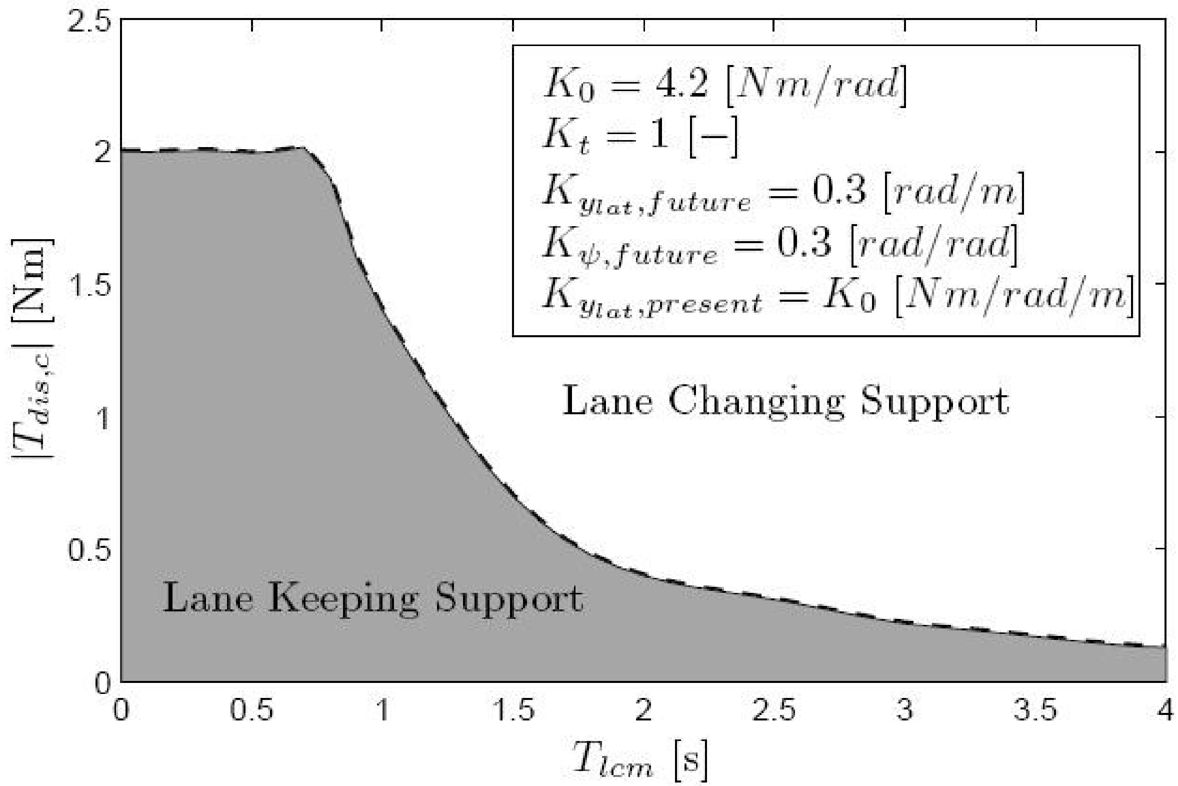


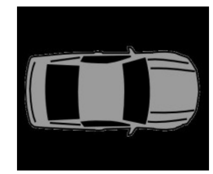
Raw spectral estimation averaged over eight subjects



Influence of LCA on the Lane Keeping Support Work Domain

- IDSS supports lane change when TLC < T_{lcm}.

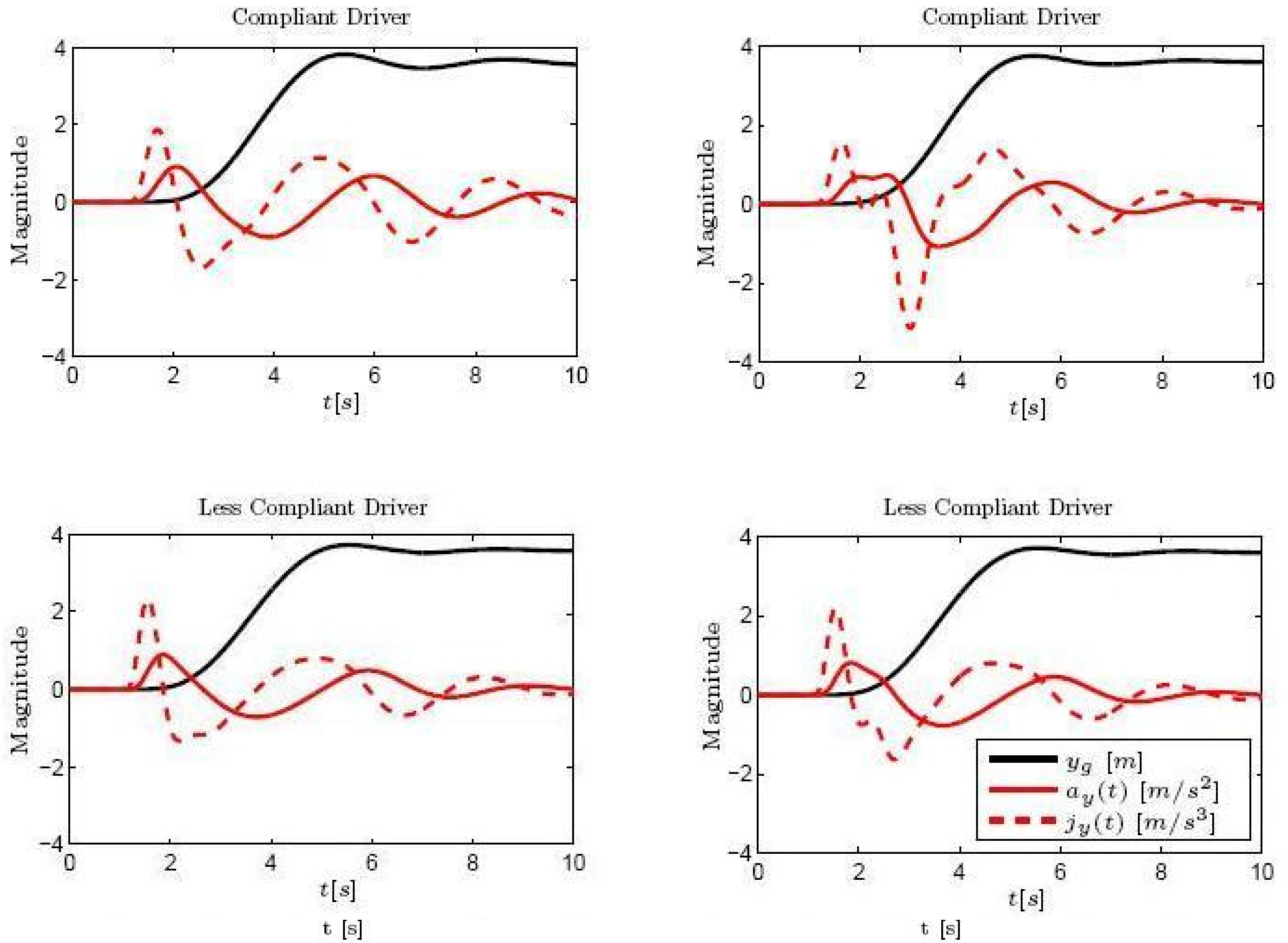


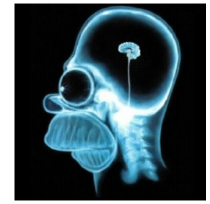


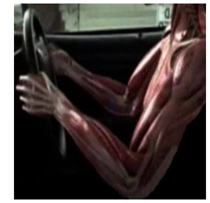
LKSS

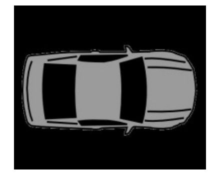
LCA

Influence of Different NMS Model Parameters on IDSS Effectiveness









LKSS

LCA

Parameter Estimation

SIPE

- Minimizing the error between the parametric transfer function and the non-parametric FRF:
  - Lsqnonlin() in Matlab, is used.
  - Initial parameter values chosen randomly.
  - Constraints: (initial) parameter > 0.

- Obtained parameters values were comparable to an independent study, [9].

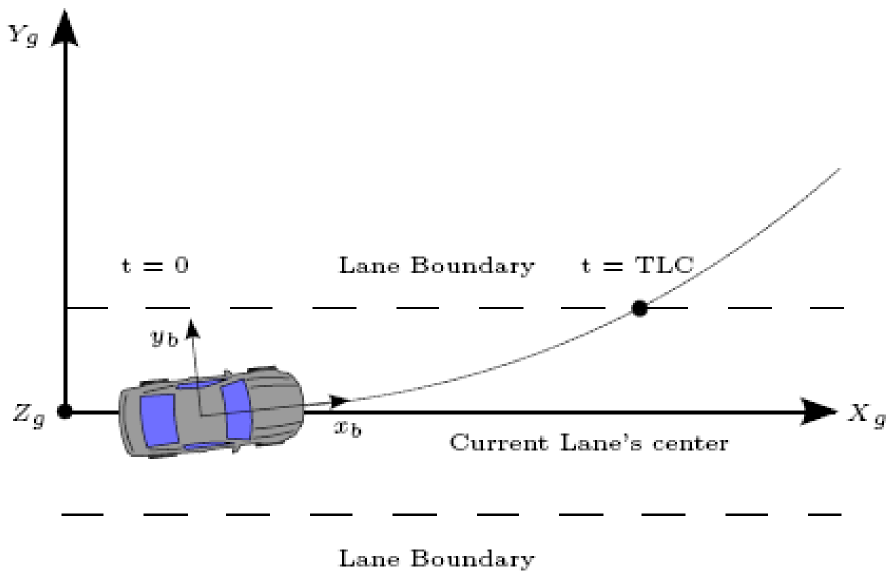
[9] Pick, A. J., & Cole, D. J. (2007). Dynamic properties of a drivers arms holding a steering wheel.

Chosen LCA Philosophy

In Front of the LKSS

LCA

- Initiated based on the time to line crossing (TLC), [10].
- In order to initiate the LCA and to keep it activated: TLC < T_{lcm}.
- Two values of the threshold T_{lcm} are used: DI on/off.
- VDR is chosen for a five-second lane change.



[10] van Winsum, W., de Waard, D., & Brookhuis, K. A. (1999). Lane change manoeuvres and safety margins.