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The UnCoVerCPS Verification Approach to Automated Driving

Daniel Heß

Motivation: Safety of (Highly) Automated Vehicles

- AV are Safety critical, **Cyber-Physical Systems**
- High degree of **Adaptability** and **Decisional Autonomy** required

➔ Testing at its limit:

Official press release from Robert Bosch GmbH [1]: "*If you were to test an automated car like a 'normal' vehicle, you'd have to drive it for several 100,000 years. Therefore, entirely new testing processes need to be developed for automated vehicles and the entire industry is still in the early stages, in this regard.*"

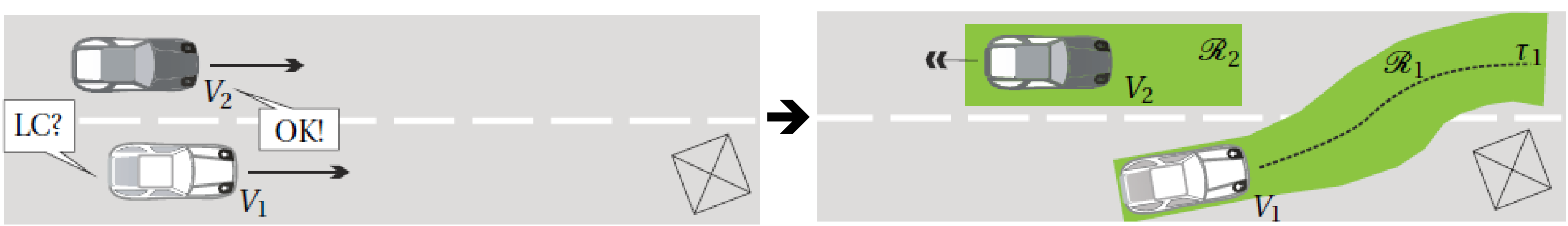
➔ Offline Verification at its limit („verification barrier"):

Estimation of the number of variables for classical verification approach [2]:
•(4) For every surrounding vehicle: Position (x,y), velocity, orientation
•(3) For each lane: Width, curvature, change of curvature
•(8) Ego-vehicle: Position (x,y), velocity, orientation, yaw rate, slip angle, road friction, current loading
Assuming that for each variable we only consider 20 values and do not distinguish between vehicle types (car, truck, pedestrian, motorbike, bicycle), that we consider no more than 10 surrounding vehicles and no more than 5 lanes, we obtain a problem description with
$(20^4)^{10} * (20^3)^5 * 20^8 \approx 10^8$ variables

[1] http://videoportal.bosch-presse.de/en/clip/_/Abt/CC/robert-bosch-gmbh-abstatt-chassis-systems-control-30
[2] M. Althoff and J. M. Dolan, "Set-based computation of vehicle behaviors for the online verification of autonomous vehicles," in Proc. of the 14th IEEE Conference on Intelligent Transportation Systems, 2011, pp. 1162–1167.

UnCoVerCPS (2015-2018)

- **Unifying Control** and **Verification** of **Cyber-Physical Systems**
- EU Horizon 2020, http://cps-vo.org/group/UnCoVerCPS
- Objectives:
  - Model-based development & online verification ➔ guarantee safety in unknown environment
  - Cross-domain approach: Synthesizing and verifying controllers on-the-fly
  - Develop a tool chain implementing the concepts
  - Demonstration of "Safe Cooperative Automated Driving"

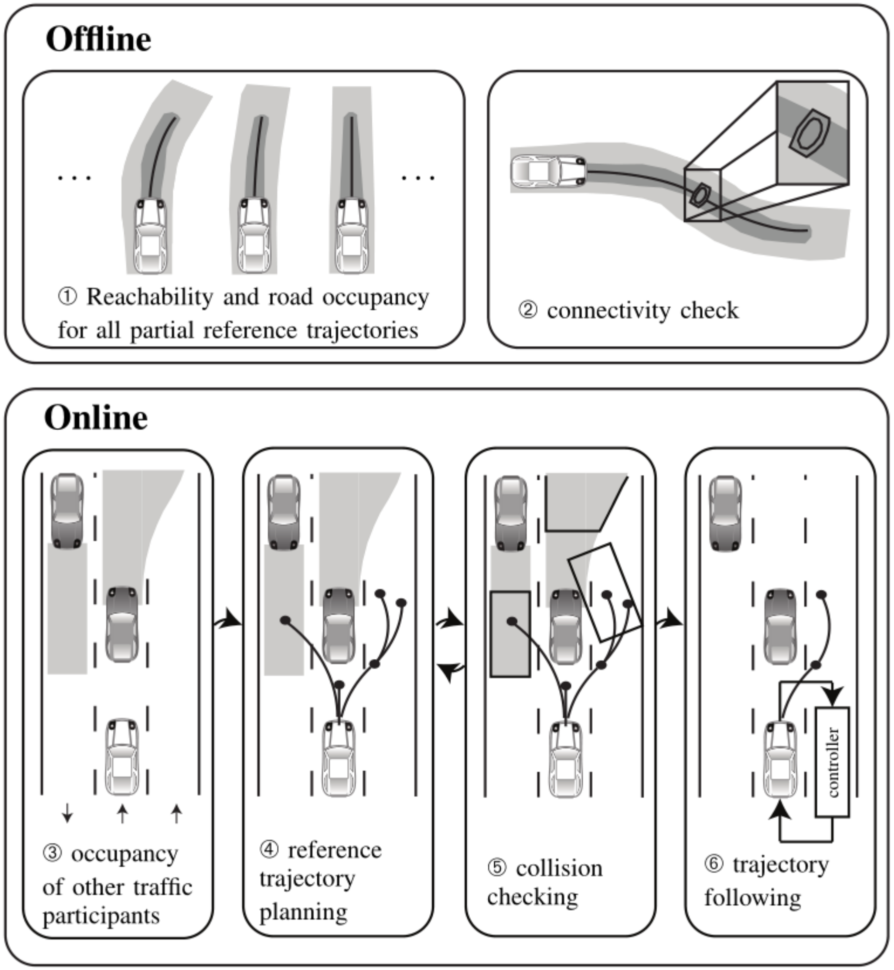


- ✓ Tech. Univ. München (Lead)
- ✓ Univ. J. Fourier Grenoble
- ✓ Univ. Kassel
- ✓ Politecnico di Milano
- ✓ GE Global Research EU
- ✓ Robert Bosch GmbH
- ✓ DLR
- ✓ Esterel Technologies
- ✓ Tecnalia
- ✓ R.U. Robotics Ltd

Agenda

- Motivation and Overview of the UnCoVerCPS Project
- Our Approach to Safe Automated Driving
- Testing, Offline- and Online-Verification Steps
- Generation of Safe Maneuver Automata
- Emergency Maneuver Planning
- Conclusion

Our Approach to Safe Automated Driving



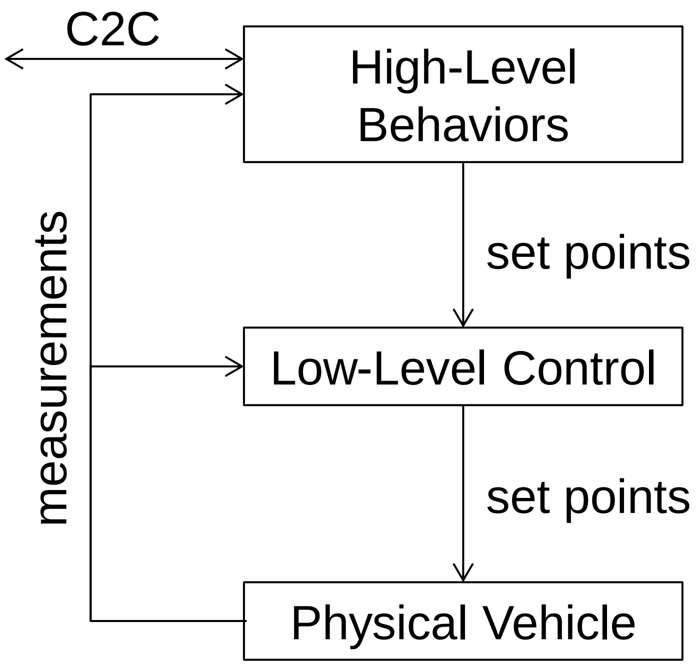
1. Verification of the closed-loop behavior for short maneuver stubs „safe motion primitives“
   ➔ Reachable sets of system state
   ➔ Occupancy of x-y-t-space
2. Initial conditions for sequencing of the motion primitives
   ➔ Safe Maneuver Automaton
3. Prediction of other participants with formal guarantees

4.-5. Planning of a safe overall maneuver

6. Execution of maneuver

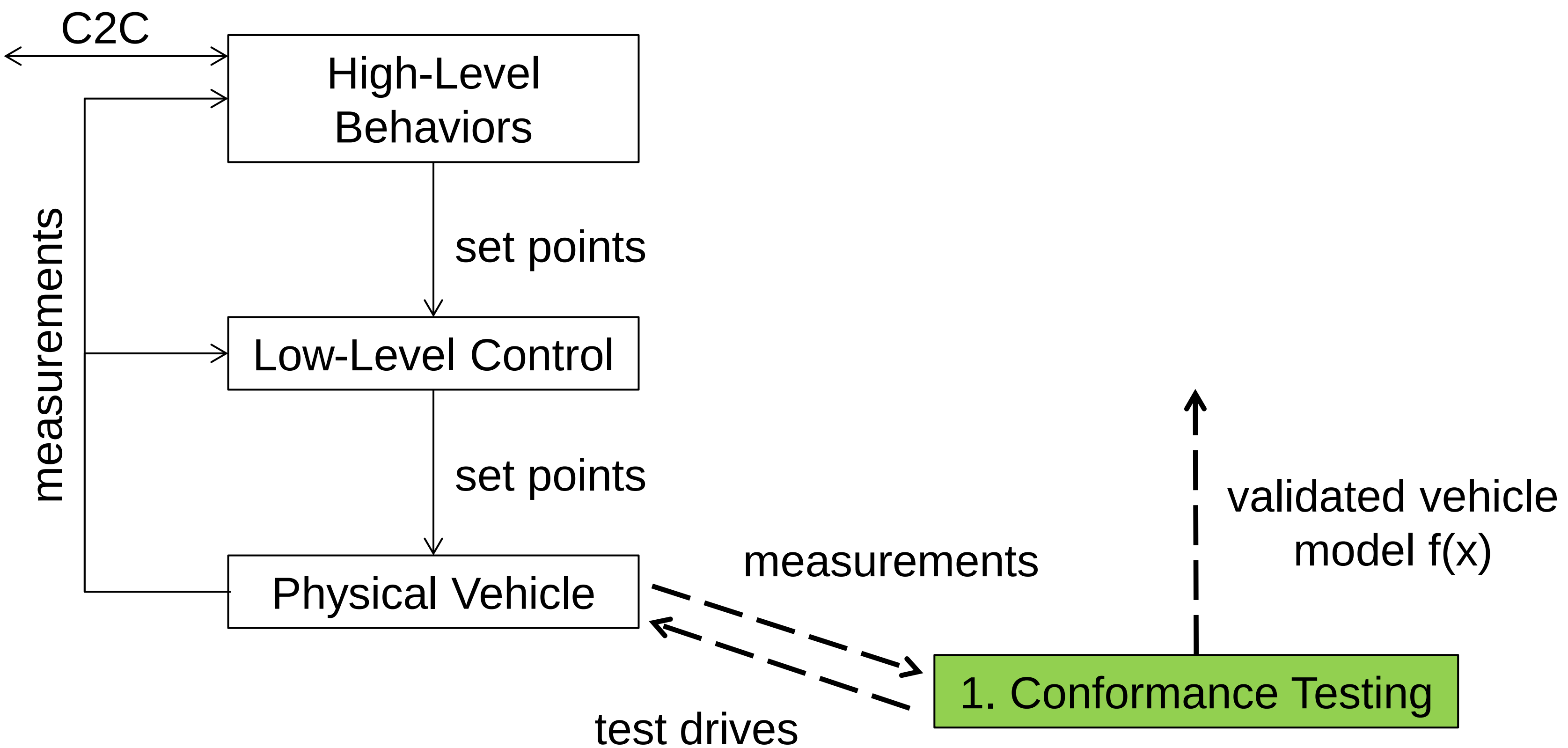
[3] D. Heß, M. Althoff, T. Sattel. Formal verification of maneuver automata for parameterized motion primitives. In 2014 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2014), , 1474-1481, IEEE 2014.

Testing, Offline- and Online Verification Process

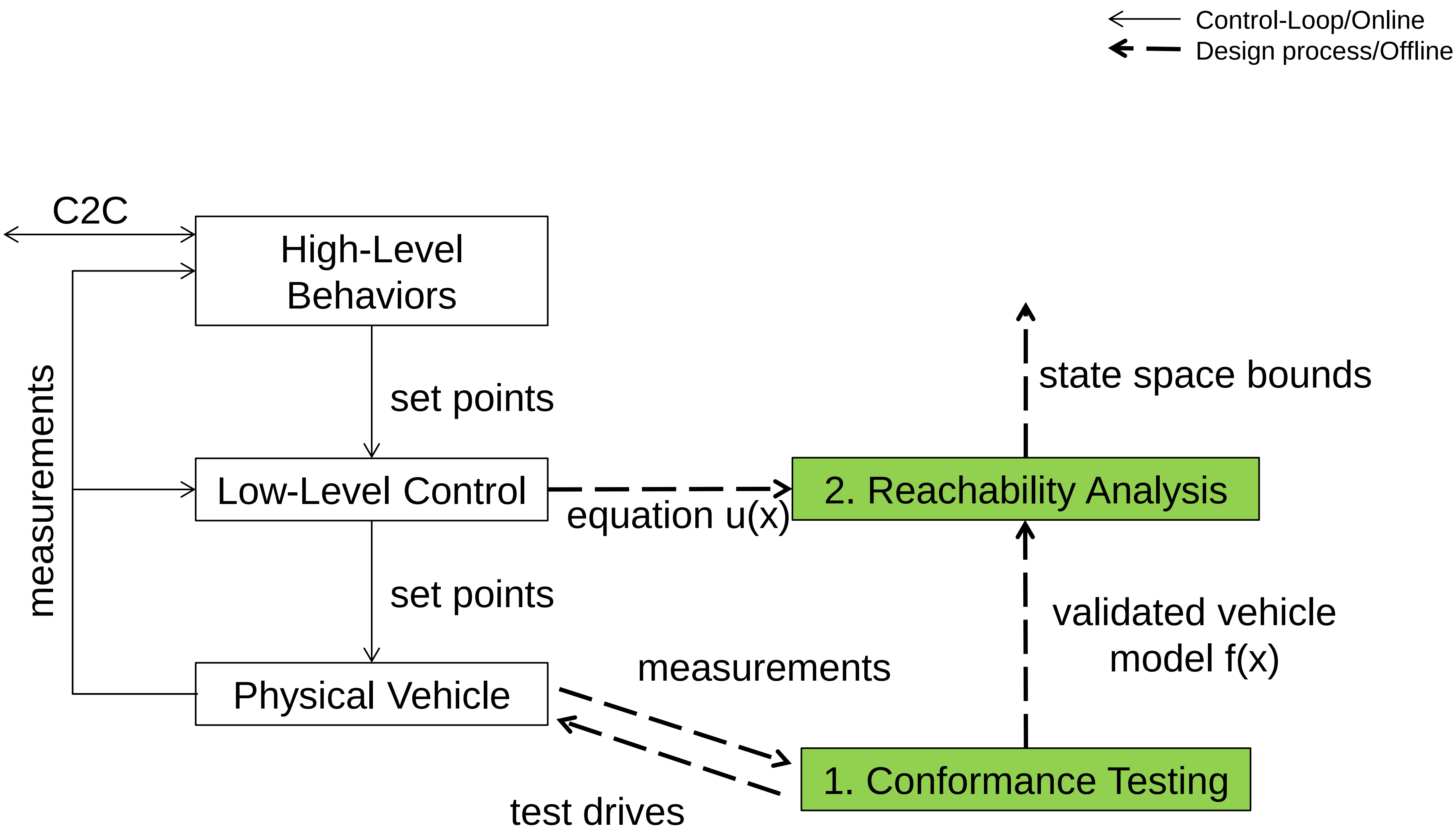


Testing, Offline- and Online Verification Process - 1

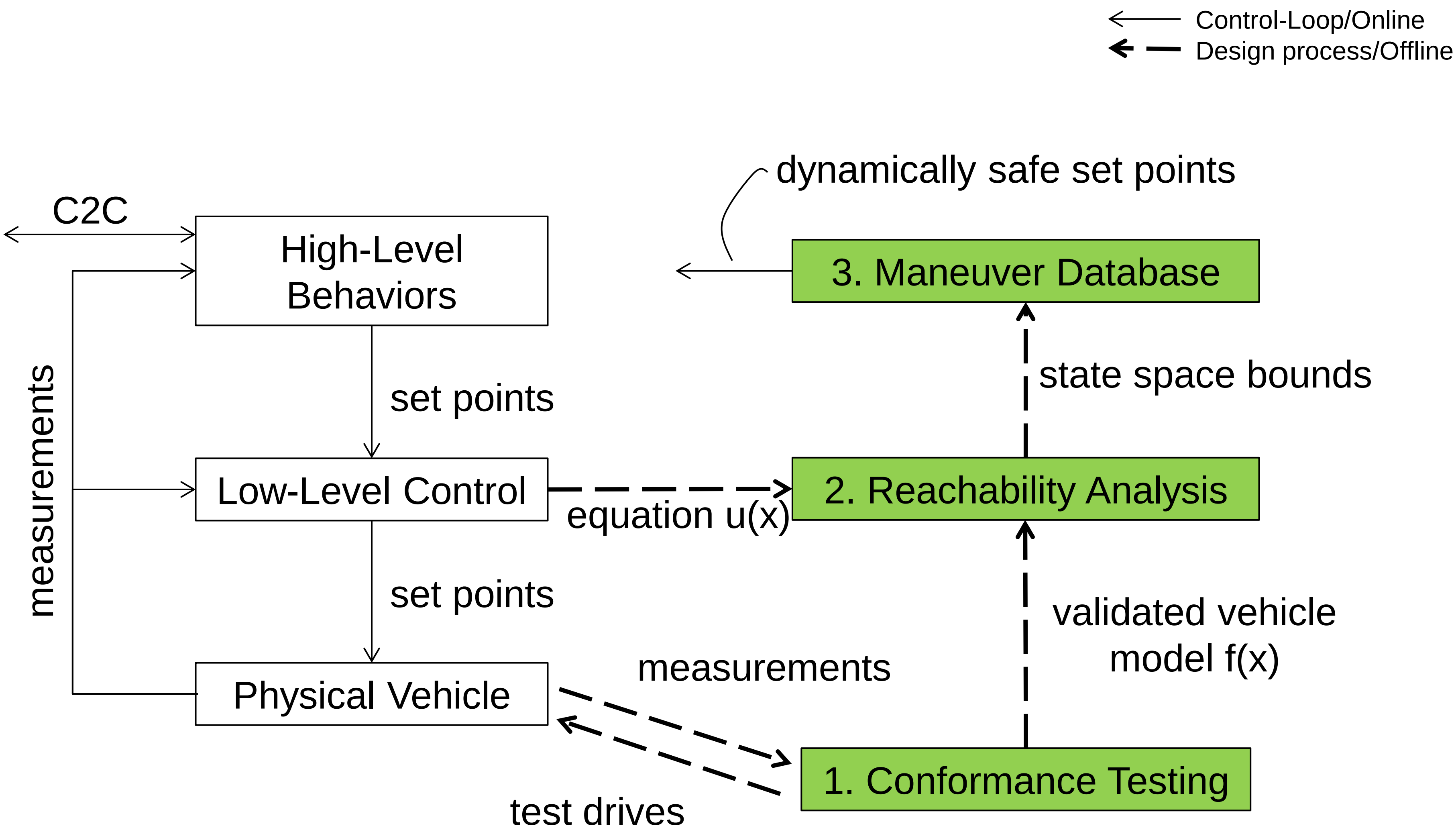
Control-Loop/Online
Design process/Offline



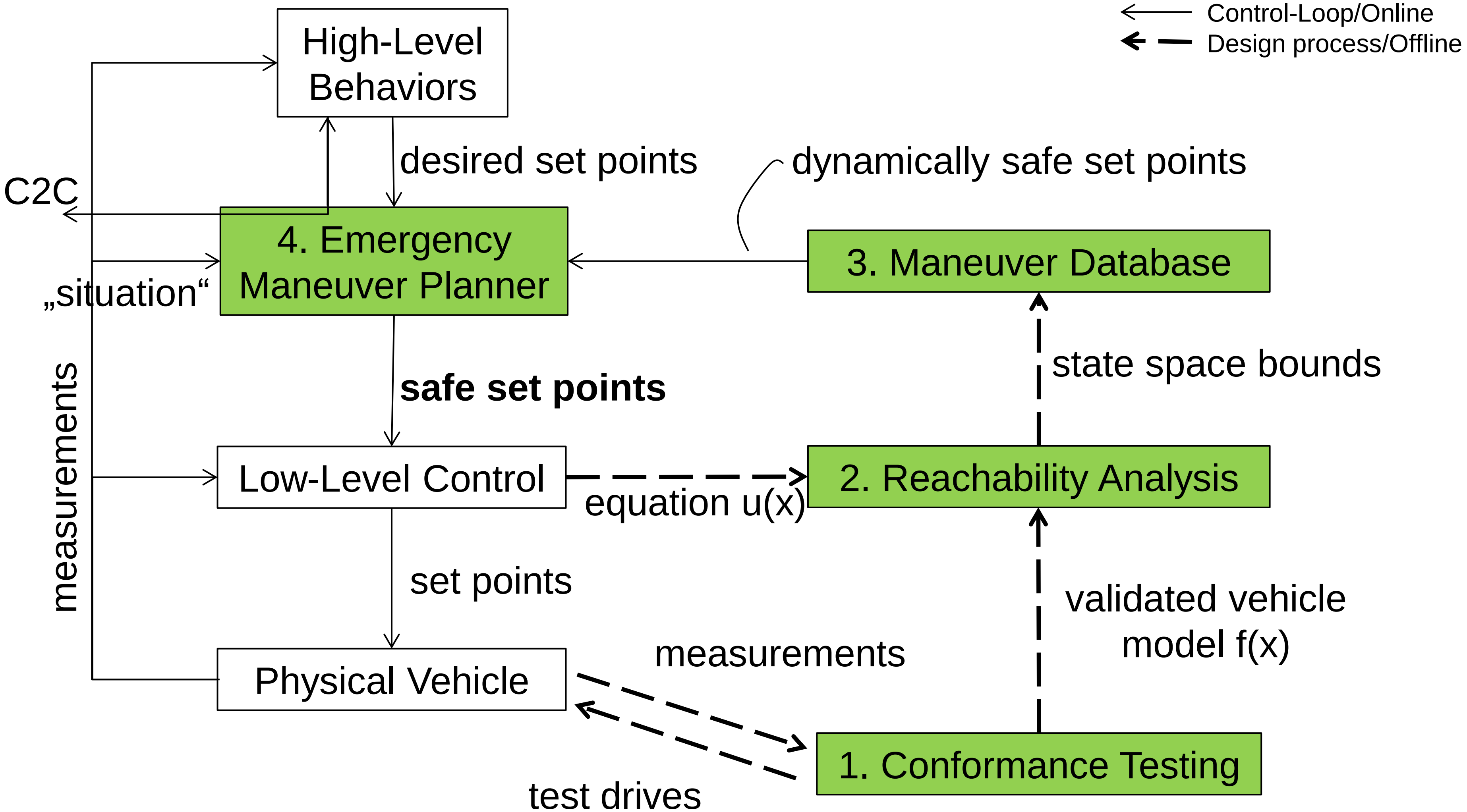
Testing, Offline- and Online Verification Process - 2



Testing, Offline- and Online Verification Process - 3



Testing, Offline- and Online Verification Process - 4



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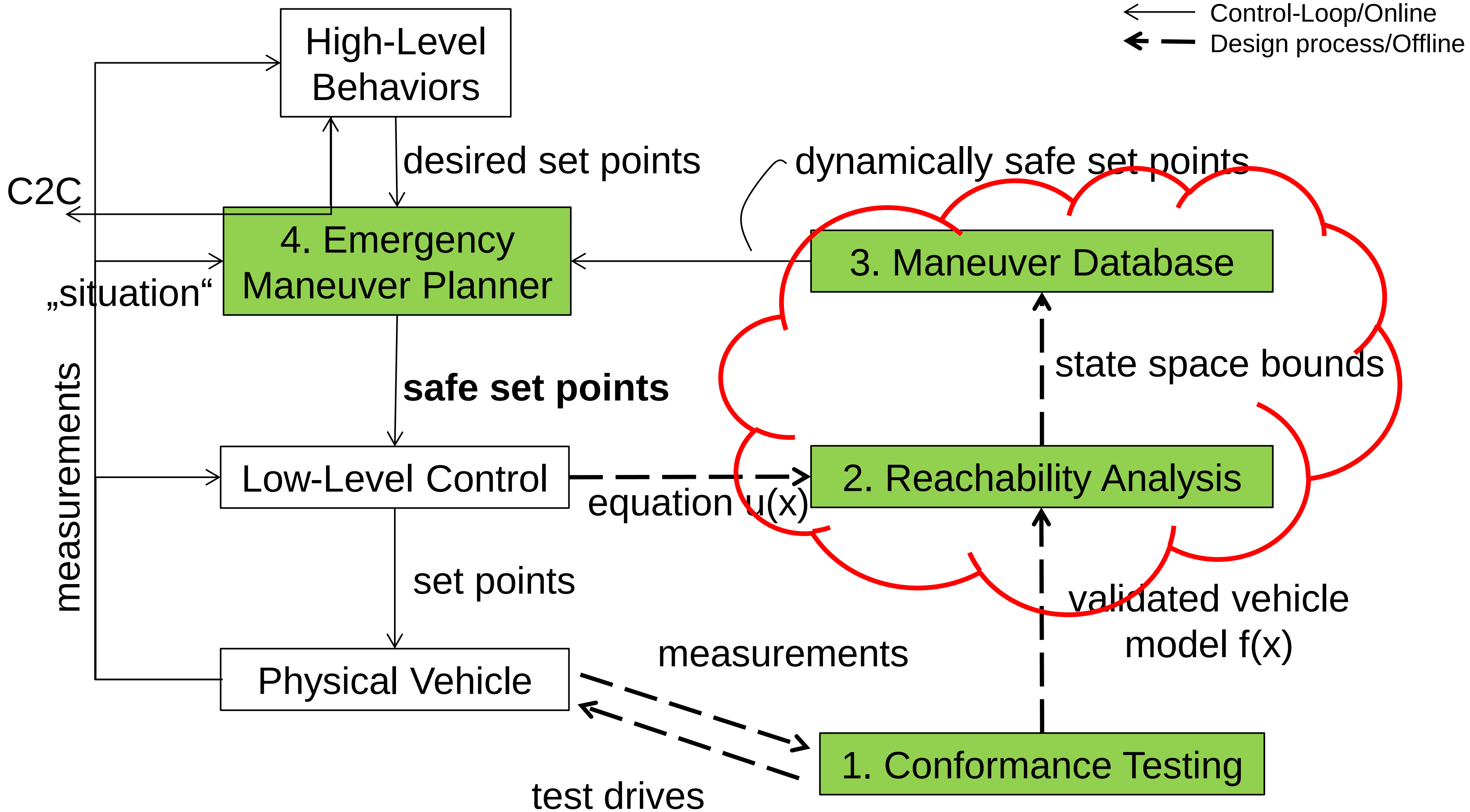
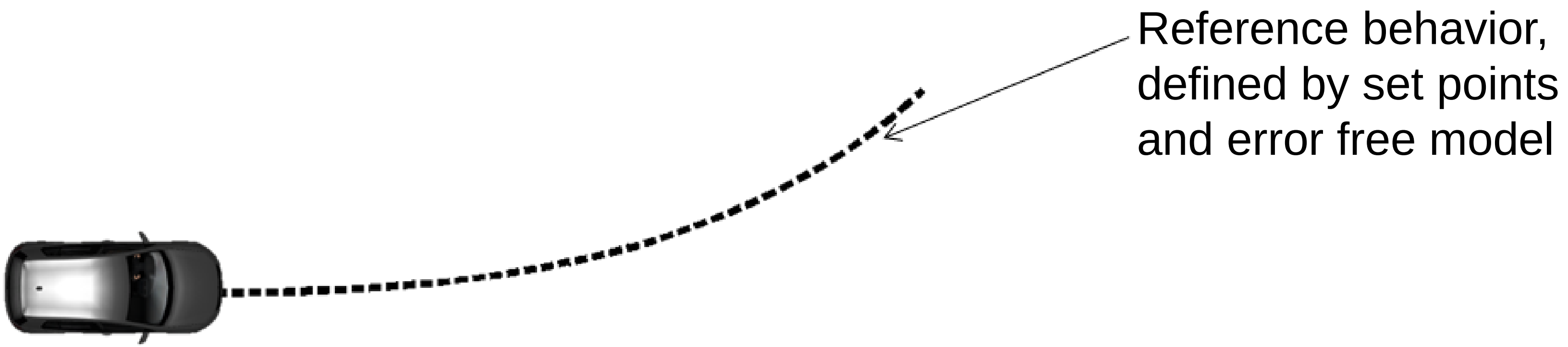


Computation of a Safe Maneuver Automaton (offline)



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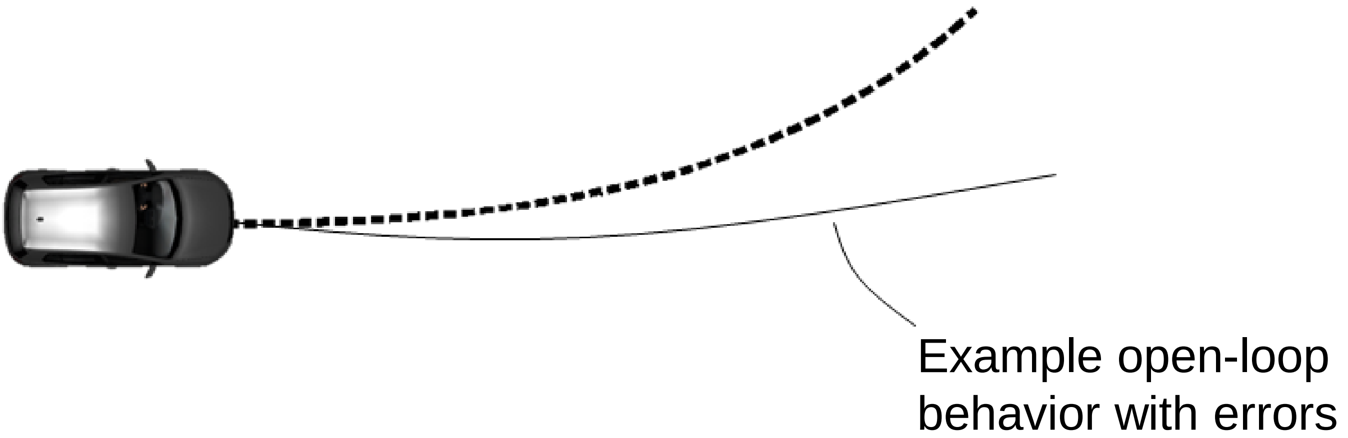

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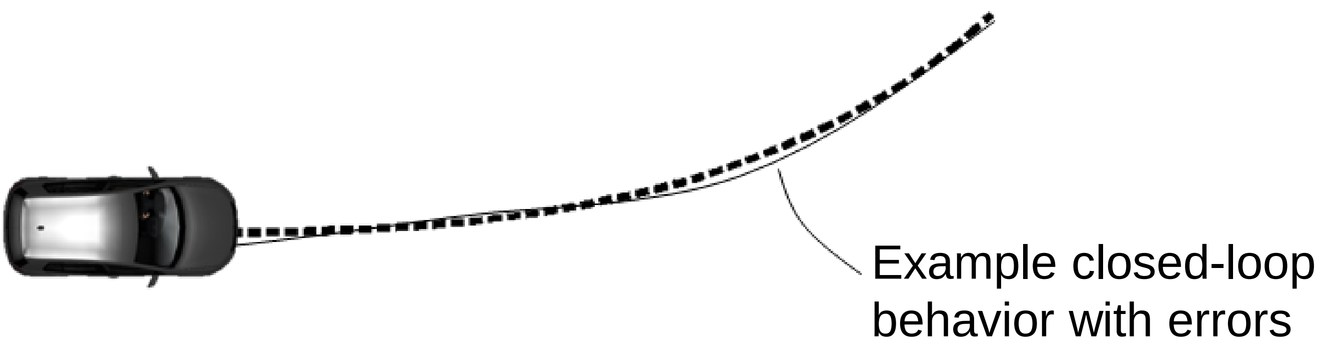

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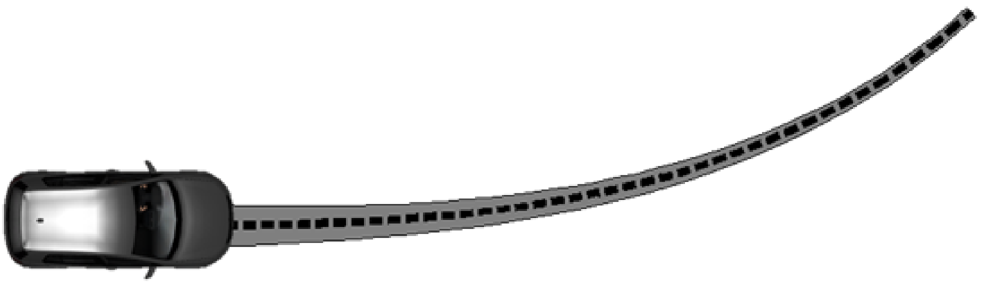


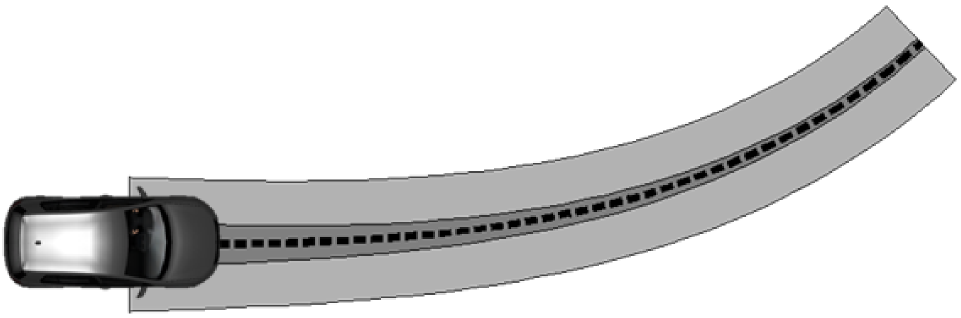
Reference behavior

Set of reachable system states $R_1(t)$ (containing **all** closed-loop behaviors with errors)

Comput Reachable Set trajectory $R_1(t)$

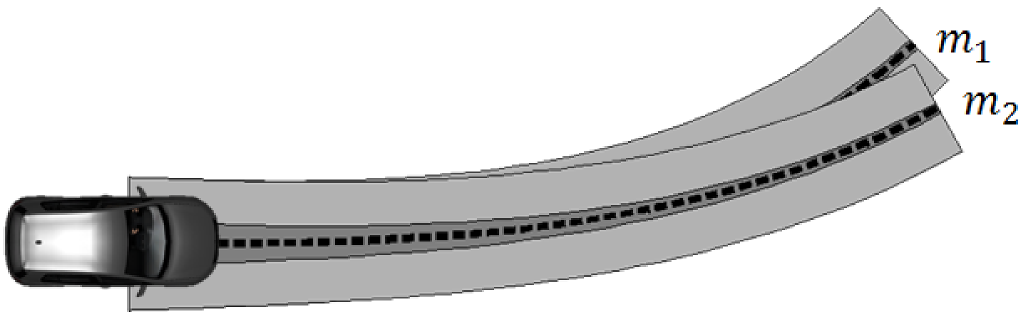
- For closed loop system
  - with bounded disturbances
  - with given set point / reference behavior
- For an initial set $R_1(0)$
- With an end set $R_1(t_f)$

Computation of a Safe Maneuver Automaton (offline)



- Nominal trajectory τ_1^*
- Set of reachable system states $R_1(t)$ (containing **all** closed-loop behaviors with errors)
- Set of positions possibly covered by vehicle body ➔ Used for collision tests

Computation of a Safe Maneuver Automaton (offline)




Nominal trajectory τ_1^*


Set of reachable system states $R_1(t)$ (containing **all** closed-loop behaviors with errors)


Set of positions possibly covered by vehicle body
➔ Used for collision tests

1. Repeat computation of reachable sets for multiple, short maneuvers

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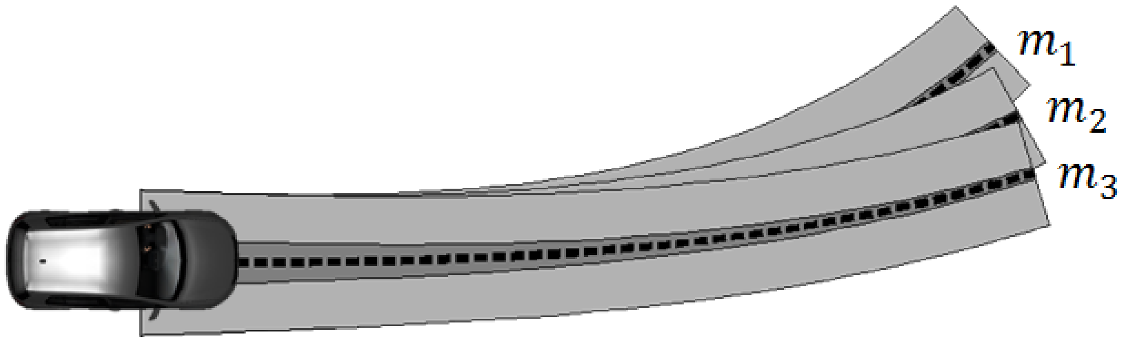

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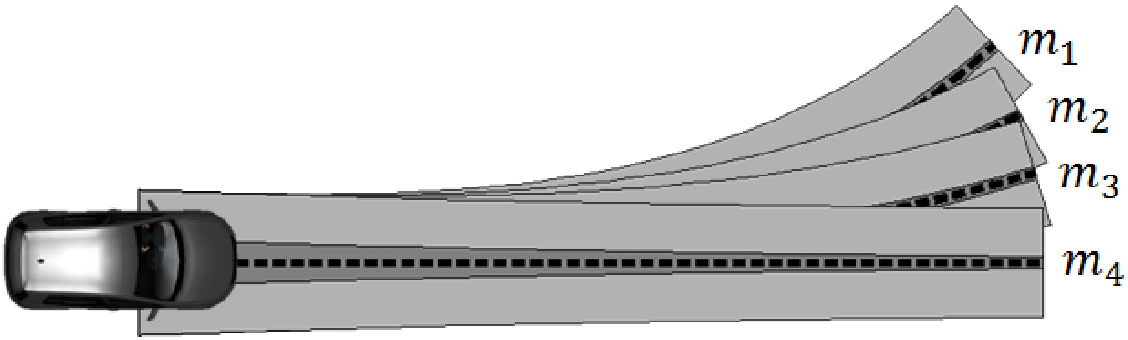

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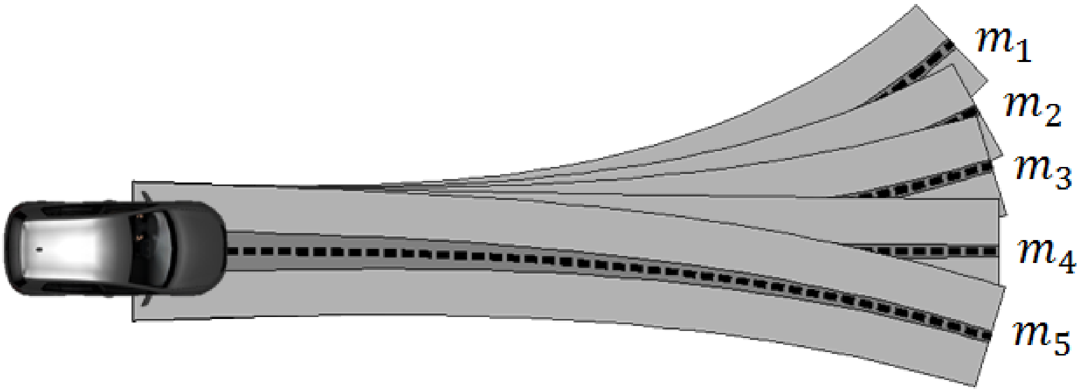

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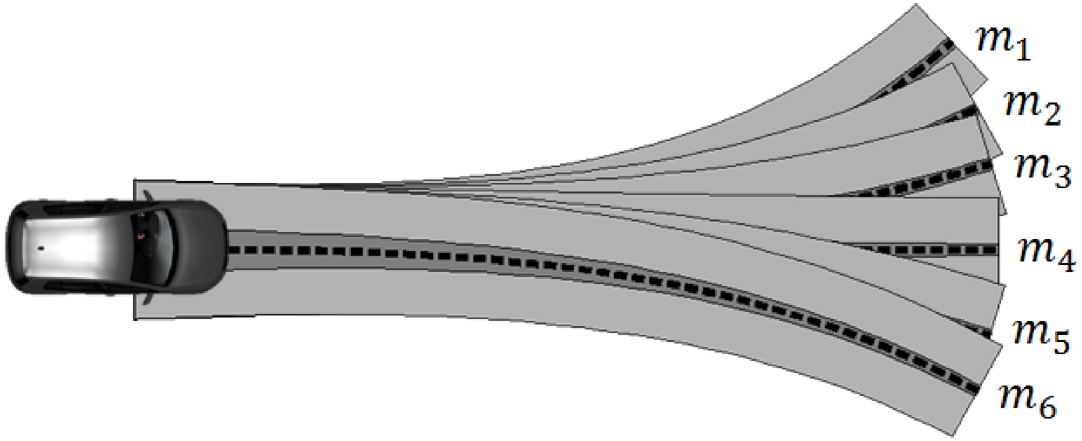

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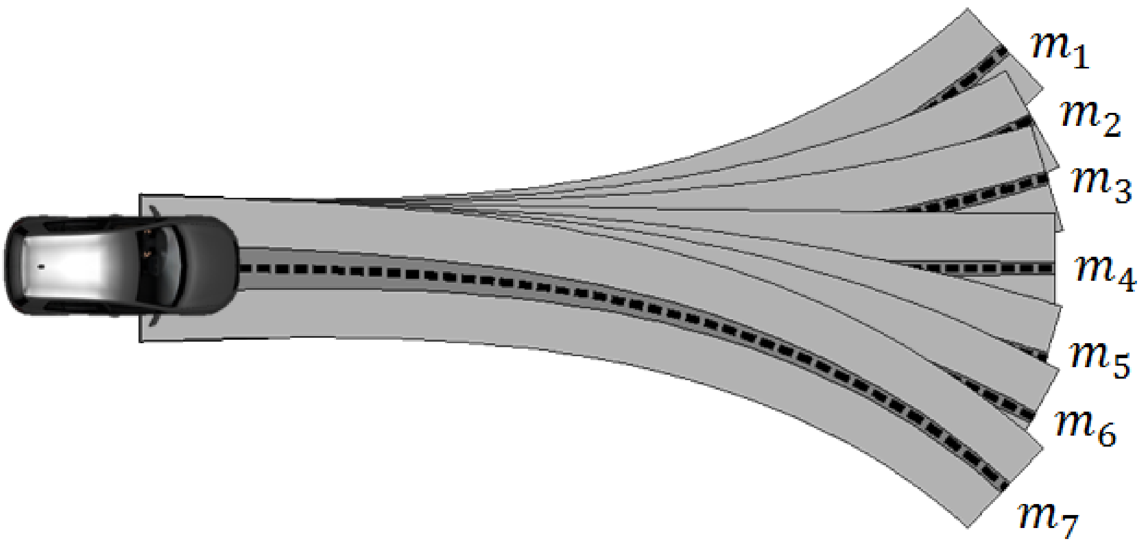

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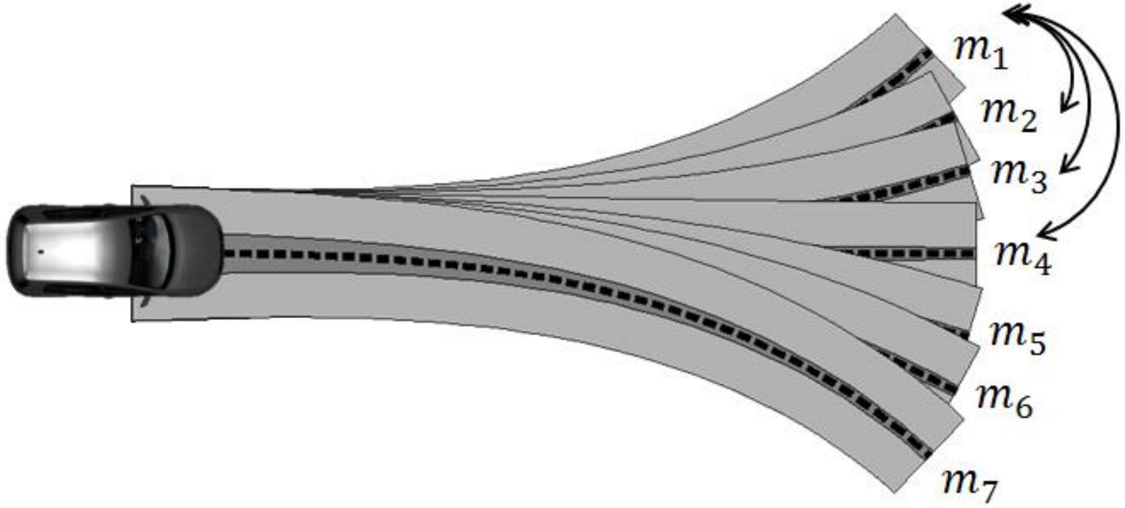

Nominal trajectory τ_1^*

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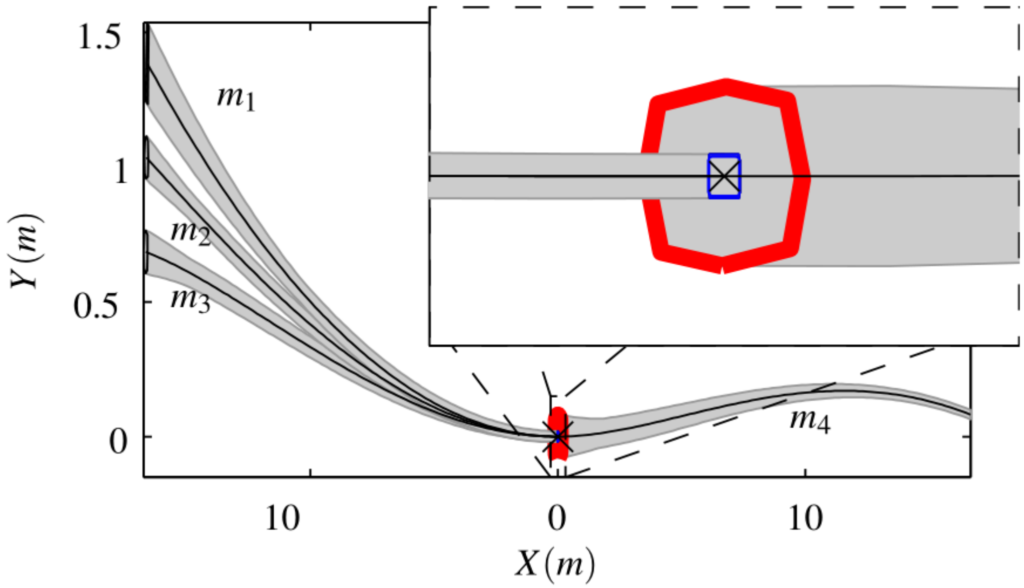
Set of positions possibly covered by vehicle body
➔ Used for collision tests

1. Repeat computation of reachable sets for multiple, short maneuvers
2. Decide which maneuvers can be safely connected

➔ Defines order of online execution

Computation of a Safe Maneuver Automaton (offline)

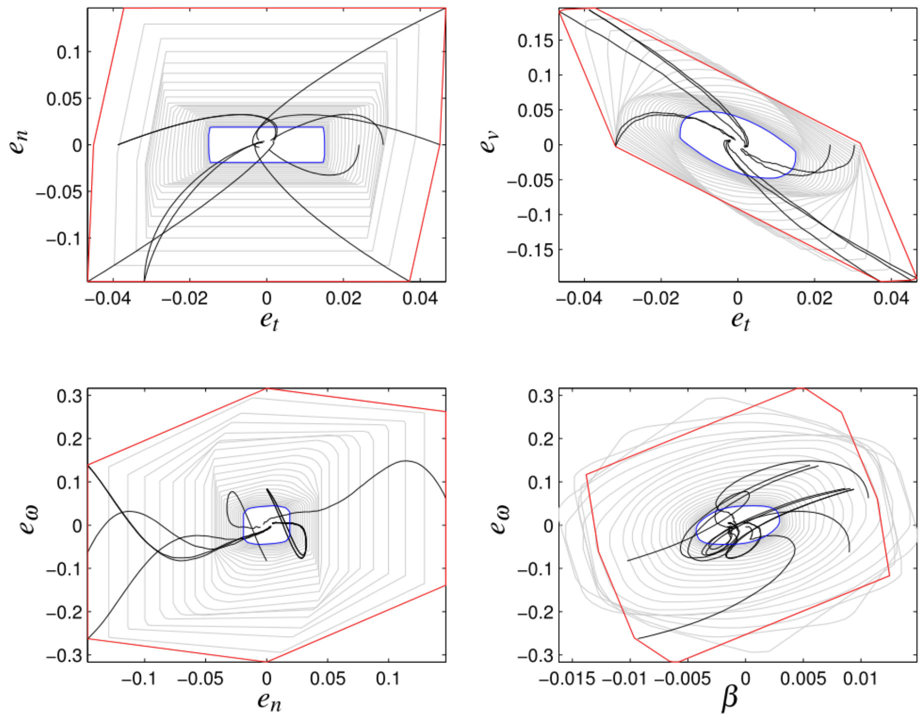
Safe Maneuver Sequences:



- Final set of maneuvers 1-3
- Initial set of maneuver 4

➔ m_4 can be executed after m_1, m_2 or m_3

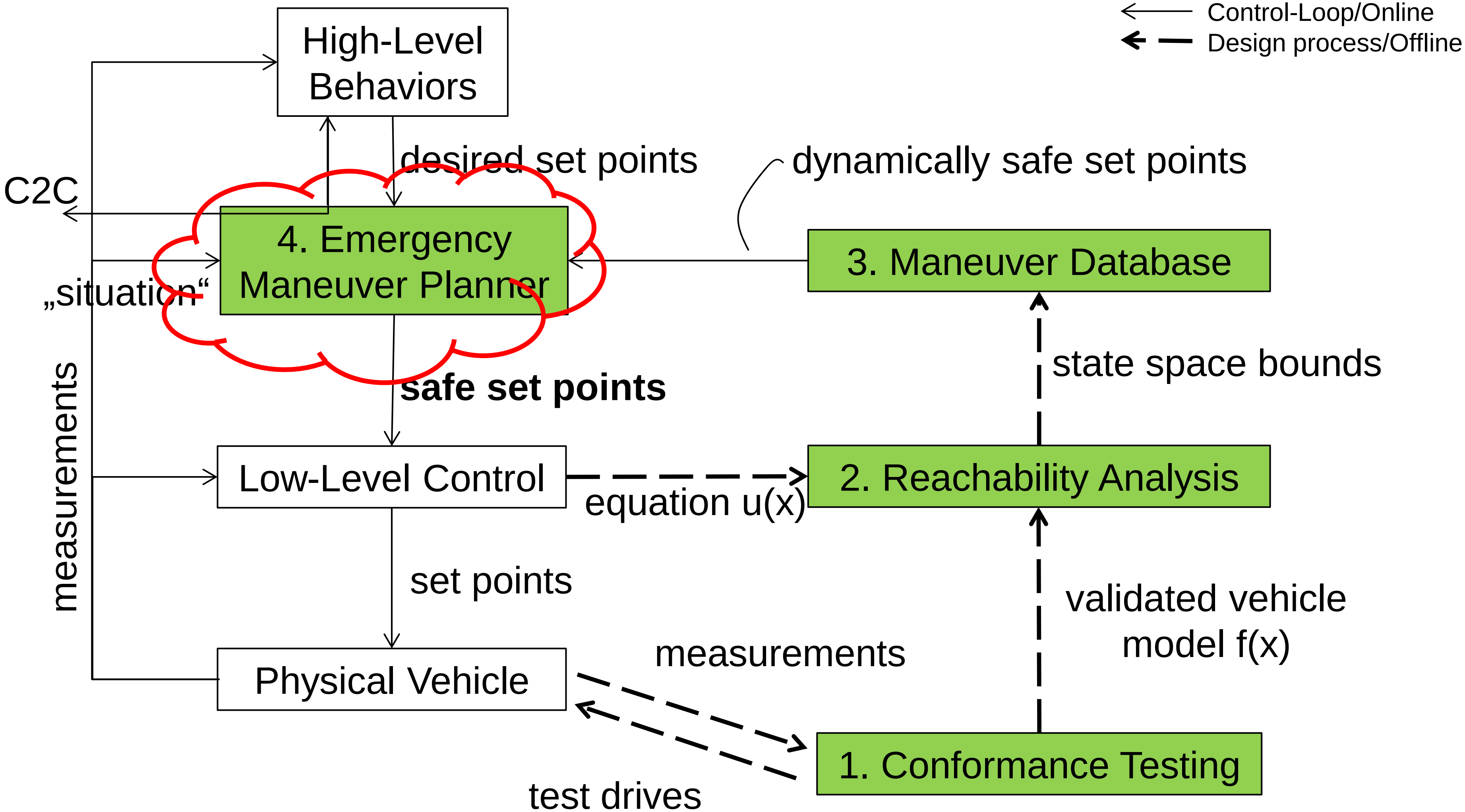
Computation of a Safe Maneuver Automaton (offline)



- System state: Tracking error
  - e_t longitudinal deviation
  - e_n lateral deviation
  - e_φ heading error
  - e_v velocity error
  - e_ω yaw rate error
  - e_β slip angle error

- **Red:** $R_i(0)$ initial set, before maneuver i
- **Blue:** $R_i(T_i)$ final set, after maneuver i
- Gray: Intermediate sets
- Black: Example traces

Testing, Offline- and Online Verification Process - 4

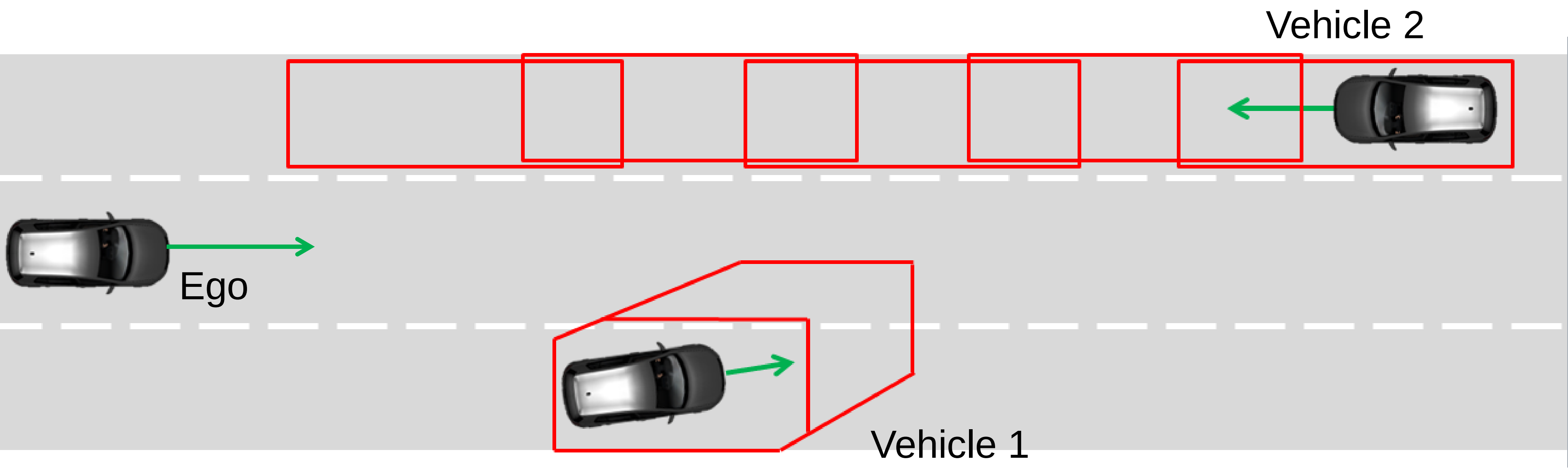


Emergency Maneuver Planning (online)

- Emergency Maneuver Planner answers following questions:
  - A High-Level Behavior **selects a certain set point**.
    - ➔Is it safe to execute?
  - A High-Level Behavior **agrees to a cooperation request**.
    - ➔Is it safe to accept the additional constraints?

- Yes - if a safe emergency maneuver exists
  - which starts after execution of the set point
  - which brings the vehicle to a stand-still
  - which respects all safety constraints
  - which respects the additional cooperation constraints

Emergency Maneuver Planning (online)



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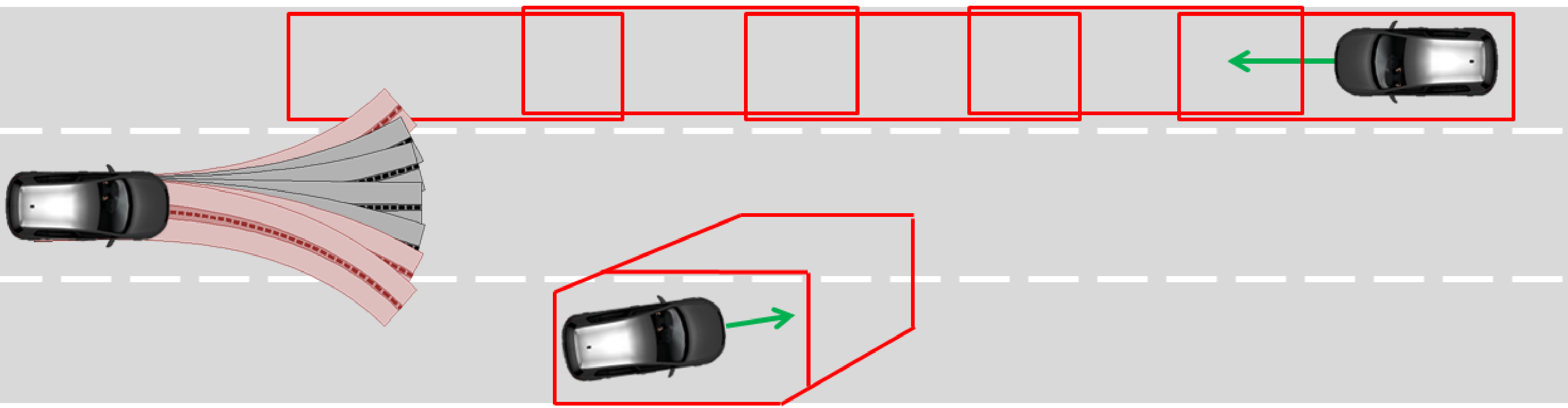

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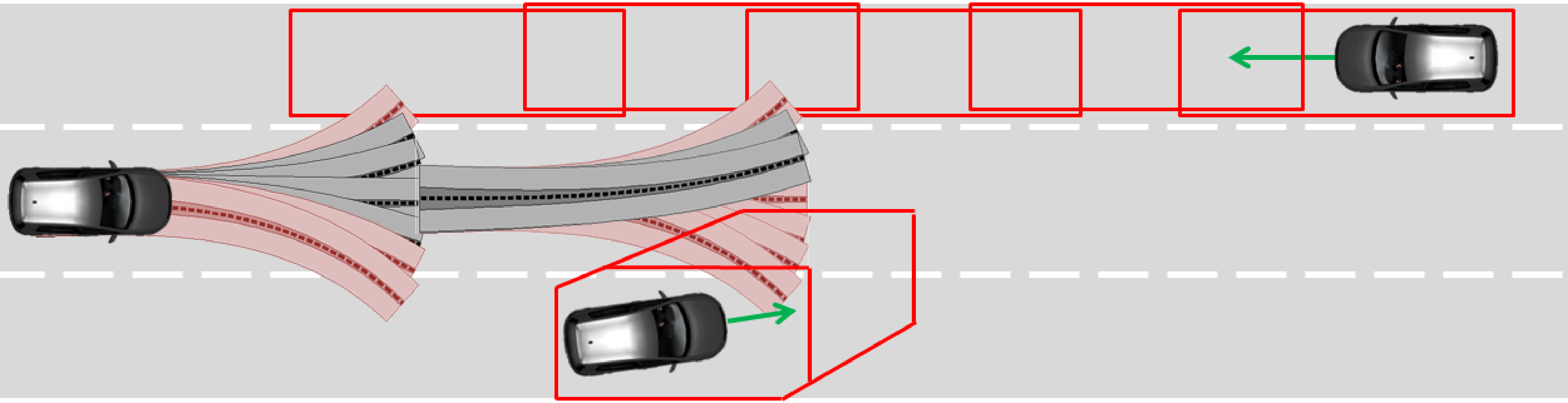

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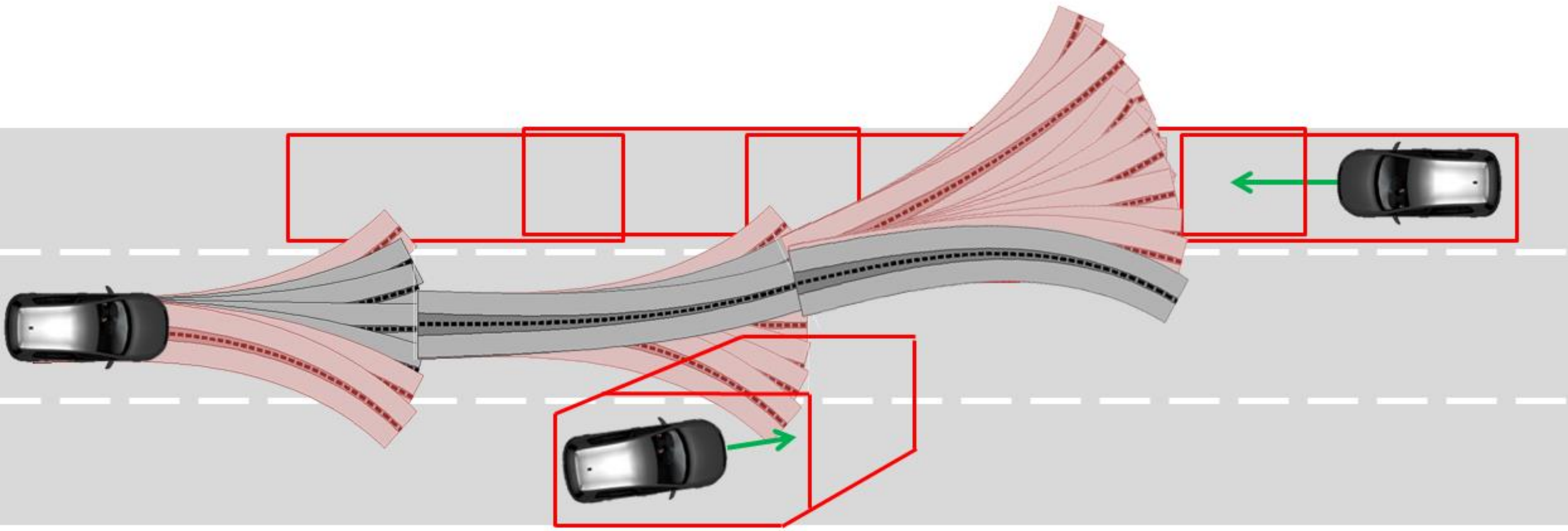

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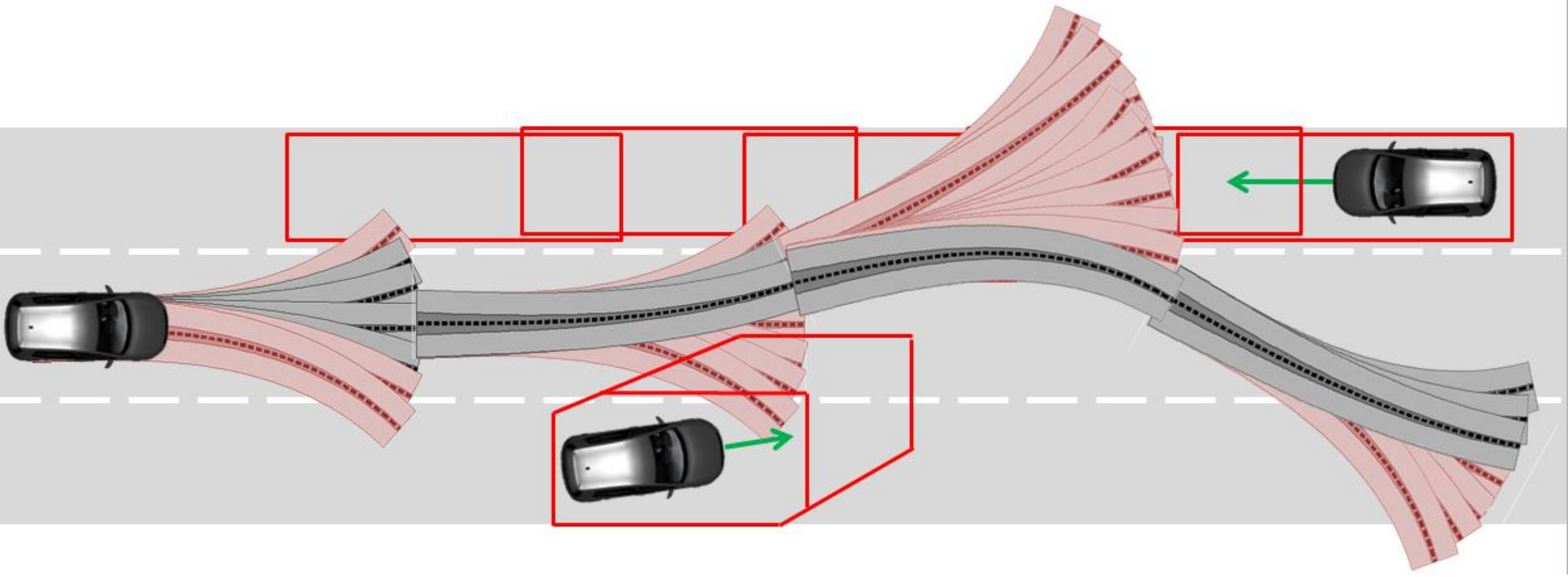

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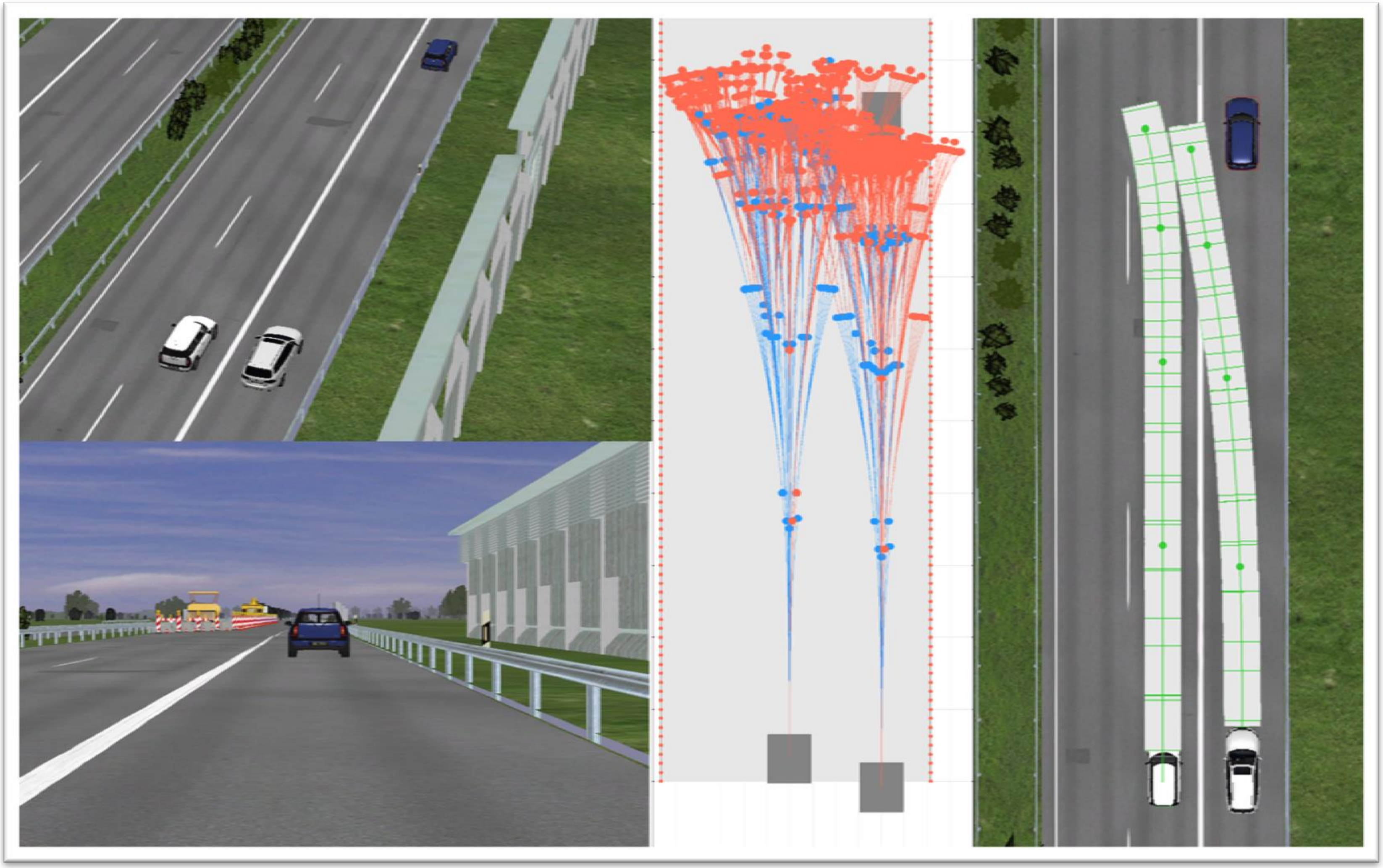


DLR

Conclusions

- Validation of Auomated Vehicles is hard
  - If using either offline verification or testing exclusively

- The UnCoVerCPS approach
  - Uses a combination of testing, offline verification and online verification
  - Requires relatively little test km to validate vehicle model
  - Provides a safe high-level cooperation mechanism
  - Guarantees* low-level control performance for validated vehicle model
  - Guarantees* safety of the high-level decisions by acting as a gateway

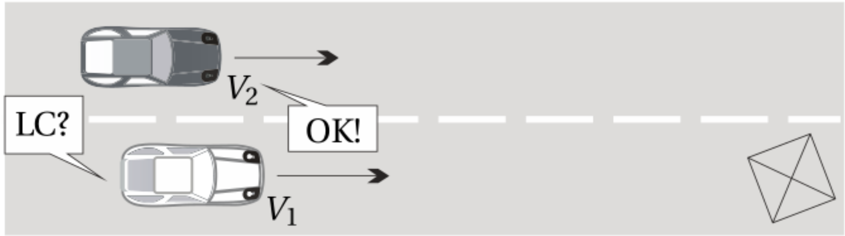
    * “Formal Guarantees” under comprehensive assumptions:
    - Errors have to remain inside specified bounds
    - Other traffic participants have to adhere to specified rules

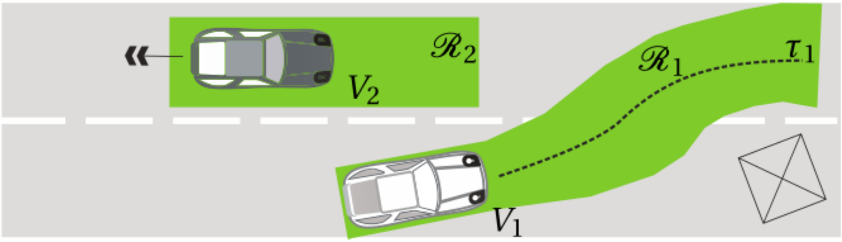
Thoughts:

- Other high-level driving behaviors no longer have to be considered safety critical
- Ideal for combination with informal, highly sophisticated approaches?

Challenges & Future Work

- Detailed analysis of computing speed and false positive rate
- Software/Simulation Demo: AAET 2017, Braunschweig, Feb. 2017
- Real-Life Demo with two cooperating vehicles: Braunschweig in mid 2018





[DLR, FASCar 2]

[TECNALIA @ GCDC 2016]

[TECNALIA, Twizzy]