



Learning-Based Behavior Planning for Automated Driving

Real-World Integration and Deployment

Jean-Pierre Busch, **Guido Linden**, Jan Bergmann, Lutz Eckstein

*Aachen Automotive Colloquium
Kurhaus Aachen, 6th October 2026*

Motivation

State of the Art – Motion Planning

 Waymo



Modular / End-to-End

 Wayve



End-to-End

 Tesla

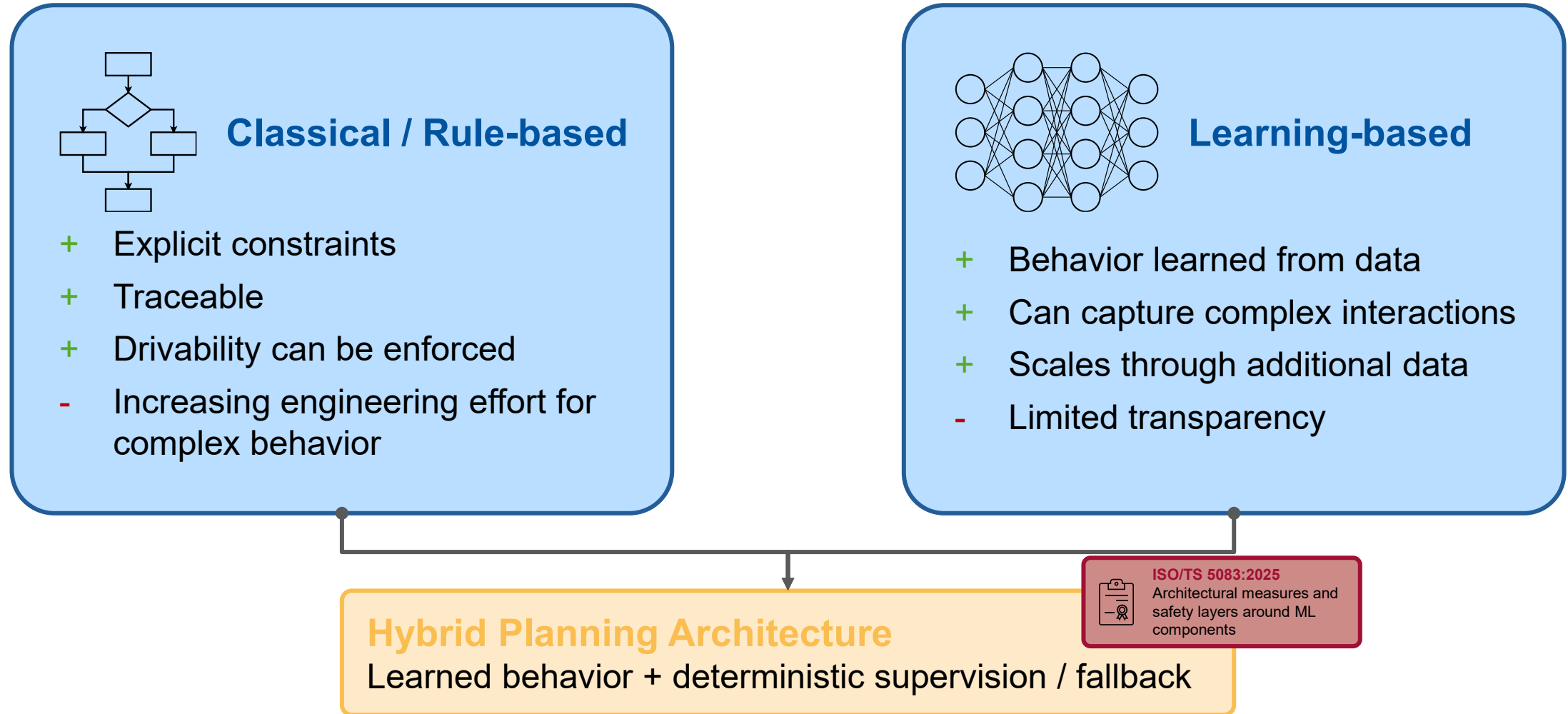


Vision-based

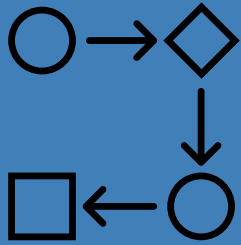


Learning-based planning is becoming a key component of urban automated driving

Complementary strengths of learning-based and classic algorithms



Overview – Hybrid Planning Architecture



**Hybrid Planning
Architecture**



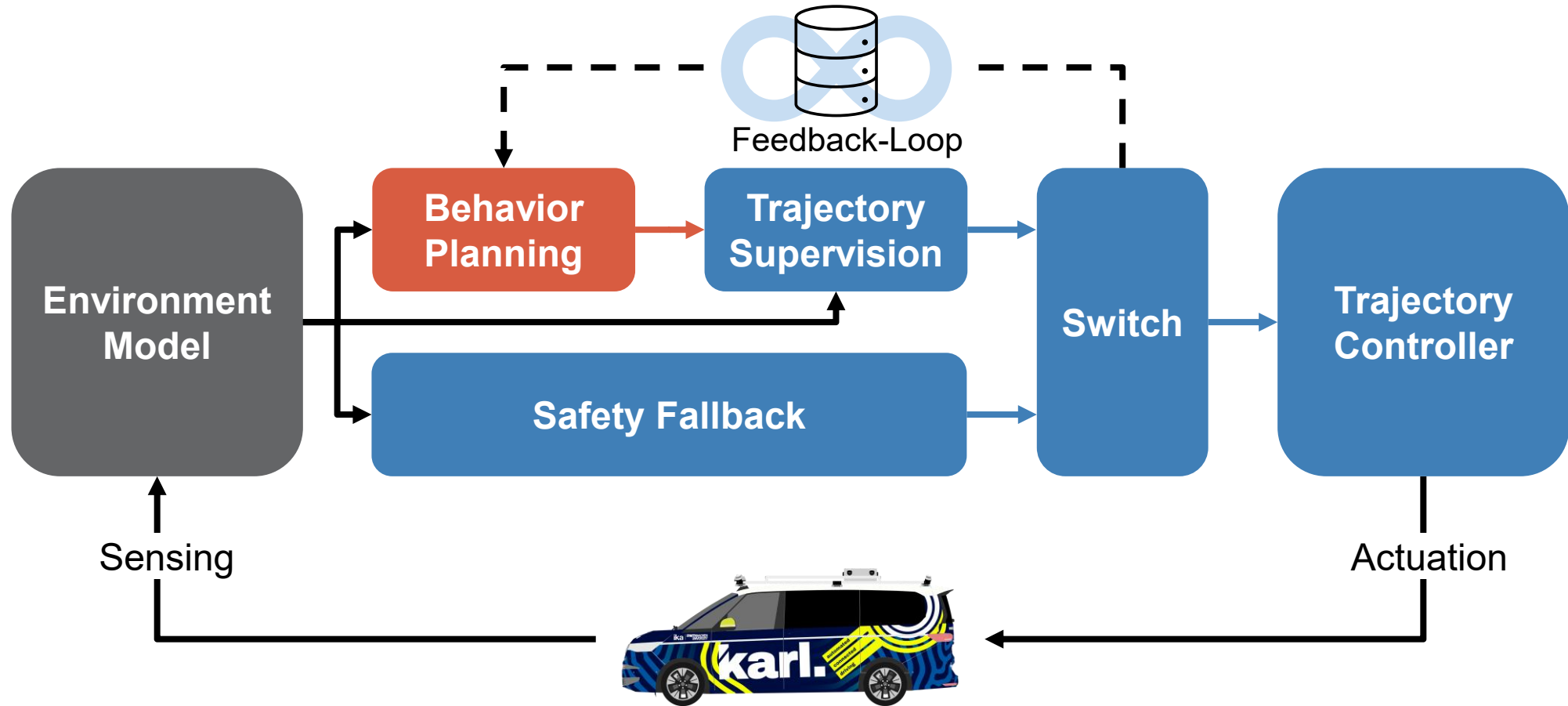
**Open-Source ROS 2
Implementation**



**Real-World Vehicle
Integration**

Hybrid Planning Architecture

General Overview



● Learning-based

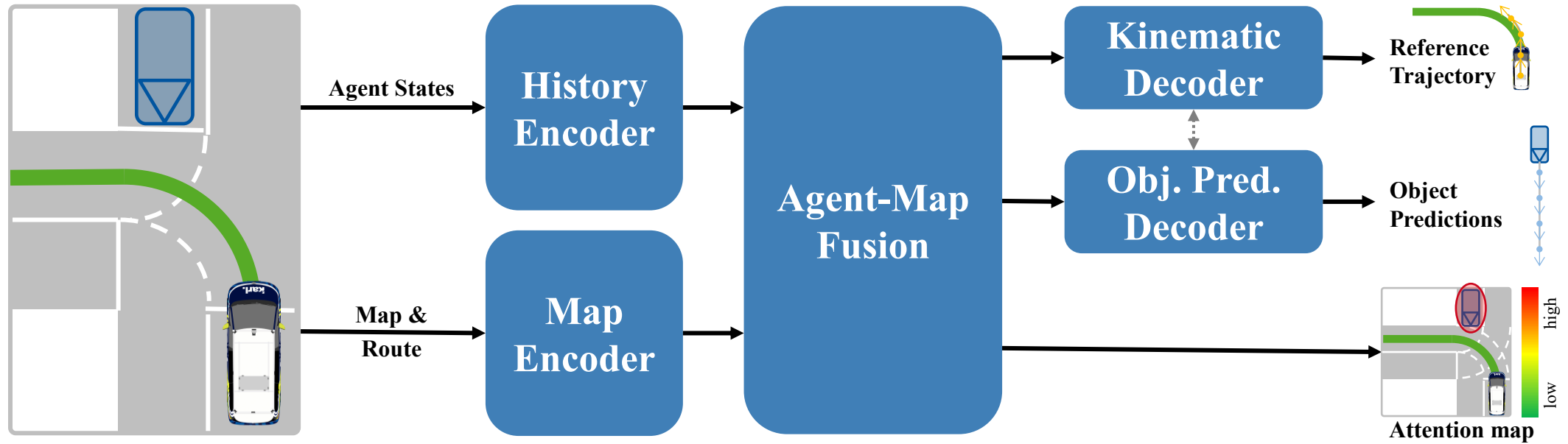
● Rule-based

→ Reference Trajectory

→ Drivable Trajectory

Learning-based Behavior Planning

Model Architecture, Interfaces and Dataset



Training Data – Driving Dataset

Real-world urban driving in Ingolstadt, Germany

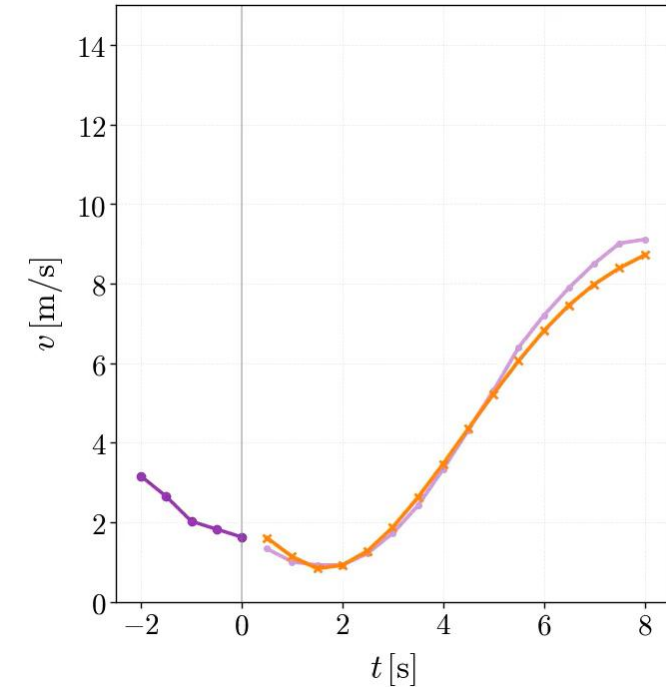
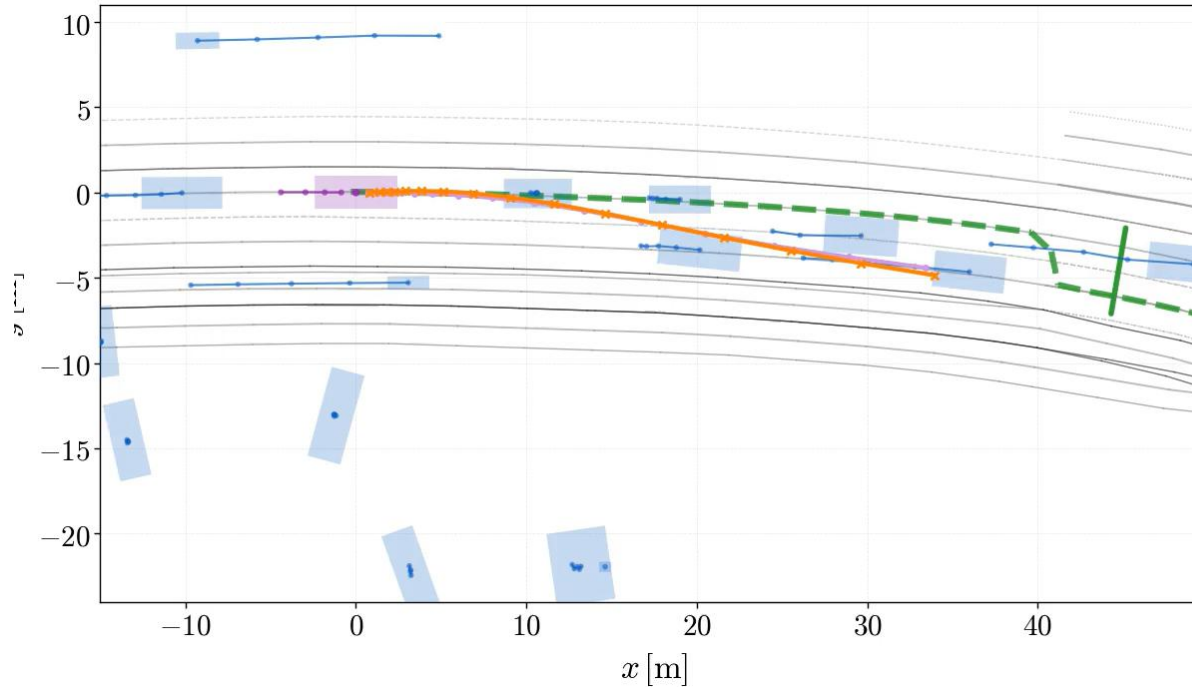
 3 → Day Dusk Night Drives → Recording Times	 ~ 18 km Same route	 ~ 105 min Total duration	 34,438 (Day, Night) Training samples	 16,518 (Dusk) Validation samples
---	--	--	--	--

[2], [3], [4]

Learning-based Behavior Planning

Open-loop Evaluation – Key results on Driving

● Route ● Map ● Ego (history & future) ● Objects (history) ● Predicted Reference Trajectory



0.74 m / 1.83 m
Pos. ADE (4 s / 8 s)



0.37 / 0.56 m/s
Vel. ADE (4 s / 8 s)



1.9° / 2.6°
Head. ADE (4 s / 8 s)



0.3% / 2.3%
Collision ratio (4 s / 8 s)

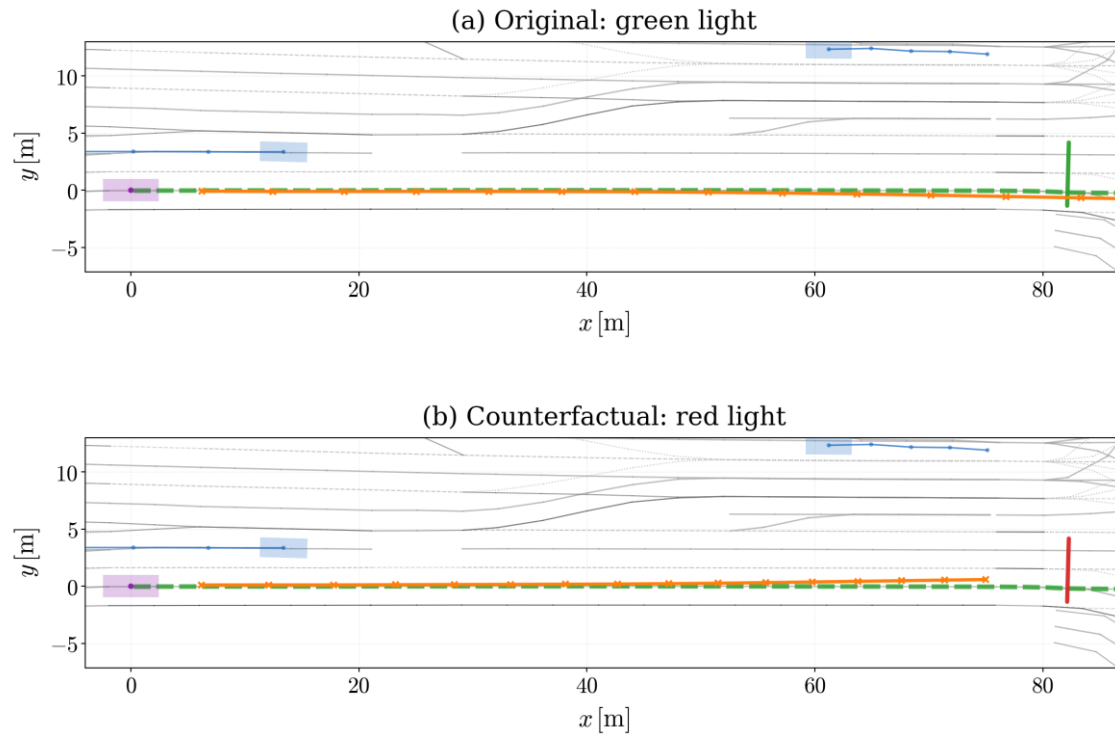
Learning-based Behavior Planning

Open-loop Evaluation – Counterfactual Examples



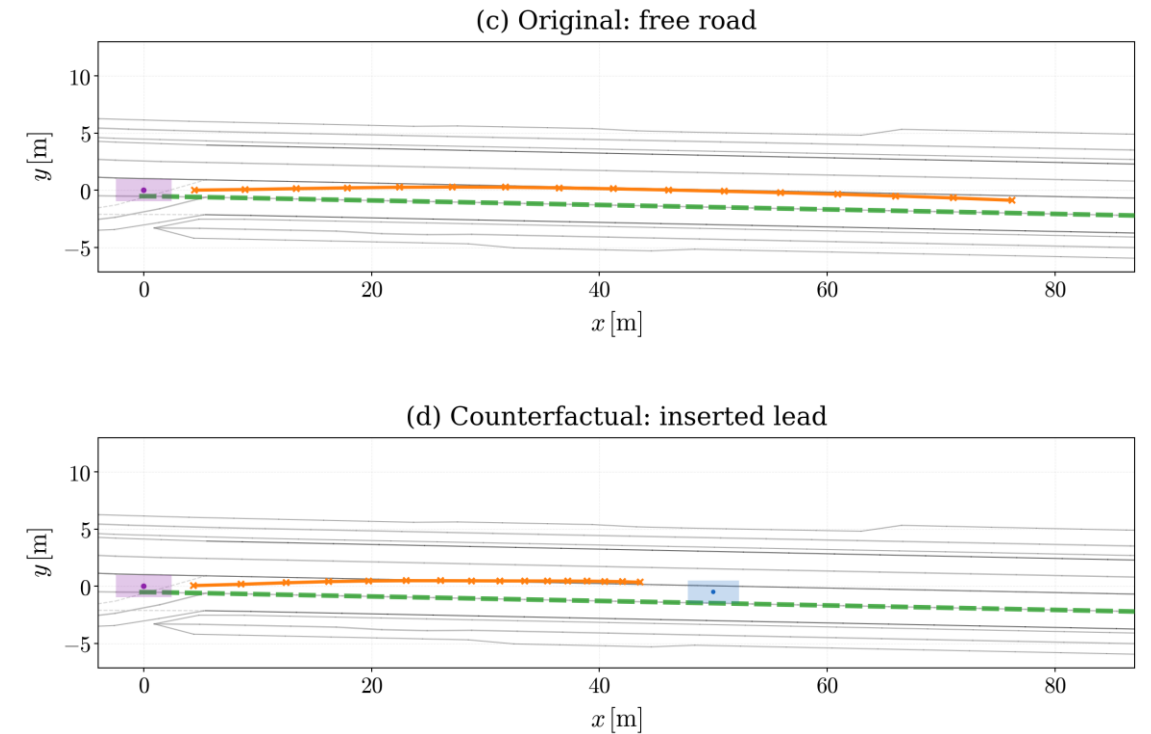
Traffic-light response

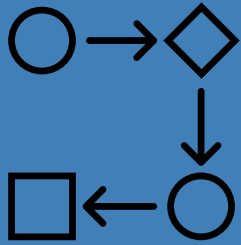
Changing green to red should shift the prediction to a stop before the stop line



Interaction response

Inserting a stopped lead vehicle should induce deceleration and following behavior





**Hybrid Planning
Architecture**



**Open-Source ROS 2
Implementation**



**Real-World Vehicle
Integration**

Open-Source Software

OpenADStack: Implemented as hardware-agnostic ROS 2 Services



OpenADS – openads-project.github.io

An open-source ecosystem for automated-driving research



OpenADSim

Simulation for testing OpenADStack



OpenADStack

Modular ROS 2 Reference Stack



Microservice Architecture

Using Docker Compose or Kubernetes for Deployment



Open Automated Driving

Stack | Sim | Suite | Safety



OpenADS – openads-project.github.io

An open-source ecosystem for automated-driving research



OpenADSim

Simulation for testing OpenADStack



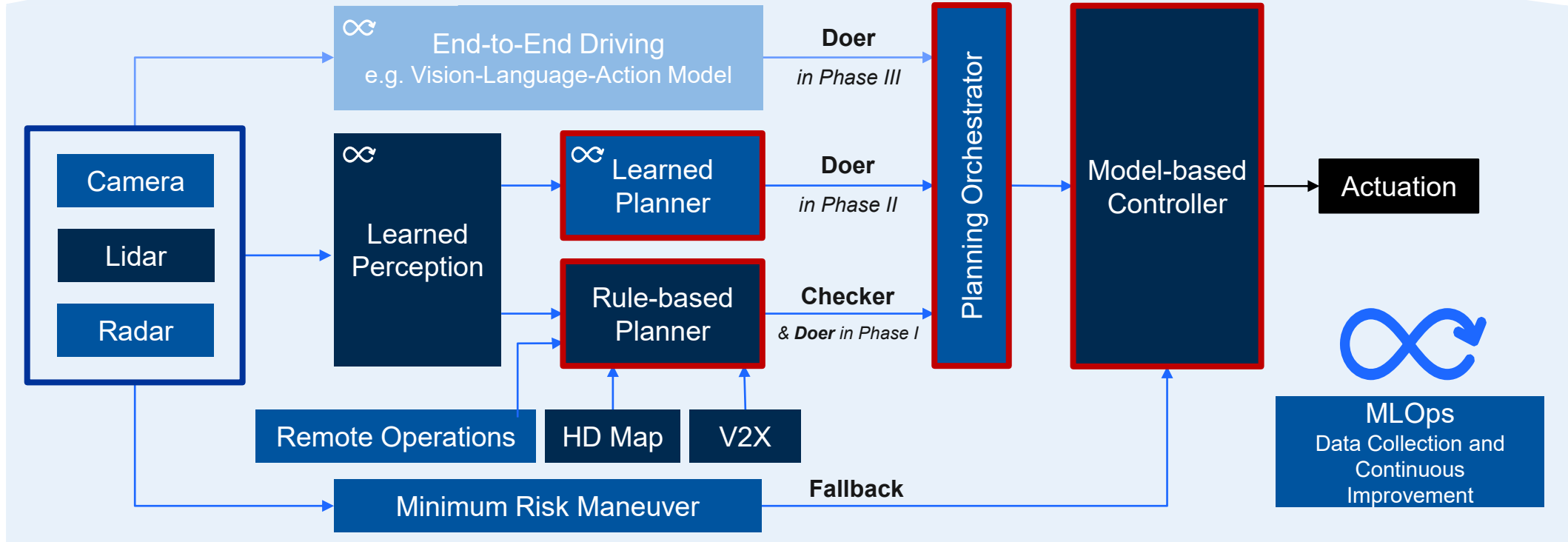
OpenADStack

Modular ROS 2 Reference Stack



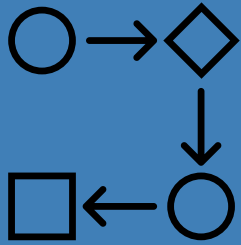
Microservice Architecture

Using Docker Compose or Kubernetes for Deployment



[5], [6]

Contribution Overview – Real-World Vehicle Integration



**Hybrid Planning
Architecture**



**Open-Source ROS 2
Implementation**



**Real-World Vehicle
Integration**

Real-World Vehicle Integration

Research Vehicle “karl.”



German Testing Approval for public road traffic
(§16 AFGBV)

karl. is a customizable and extensible research platform designed for **developing and validating** innovative functions for **automated and connected driving**. [7]

**Level 4
Automated Driving**

**Cooperative &
Connected Driving**

Remote Operation

Data Recording

Sensors



9 Stereo
Cameras



4+1 ToF/FMCW
Lidars



5 4D
Radars

Connectivity



RTK
GNSS/INS



ITS-G5 / C-
V2X



Dual-Active
5G

Control



Drive-by-Wire System for
Lateral/Longitudinal Control

Compute



HPC GPU
Linux Workstation



2 Embedded GPU
Linux SoCs

Software

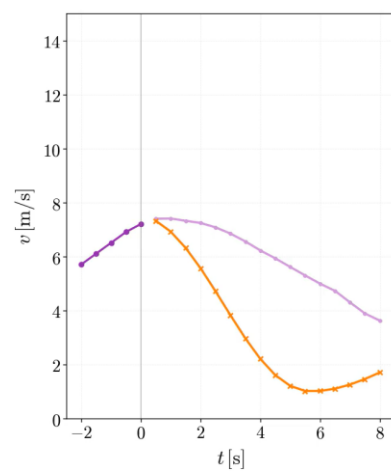
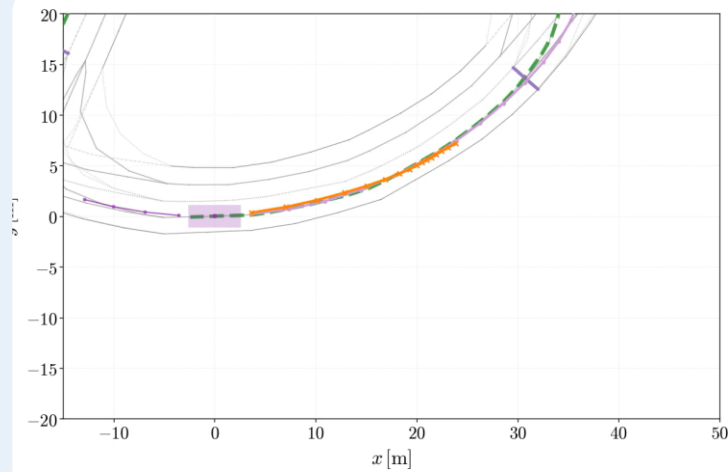


Containerized In-House ROS 2
Automated Driving Stack

Real-World Vehicle Integration

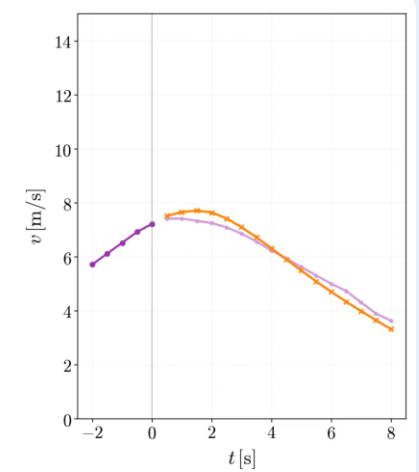
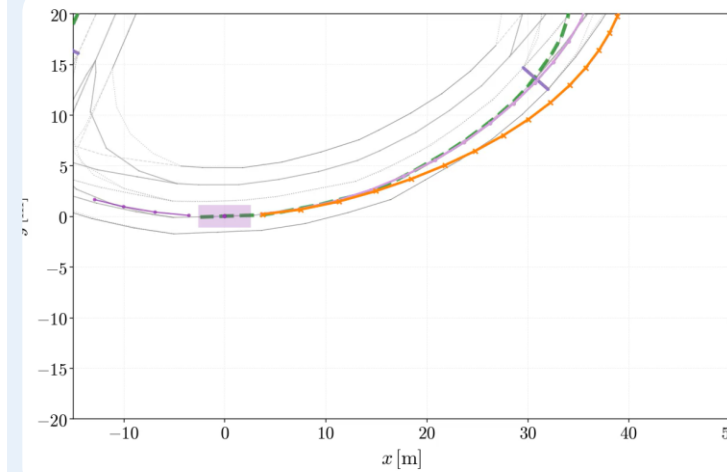
Model Adaptation – From Driving data to the ika test track

Before adaptation



same
scenario

After adaptation



Pos. ADE (8s)

7.83 m $\rightarrow$ 1.7 m



Vel. ADE (8s)

2.15 m/s $\rightarrow$ 0.51 m/s



Head. ADE (8s)

10.0° $\rightarrow$ 2.9°

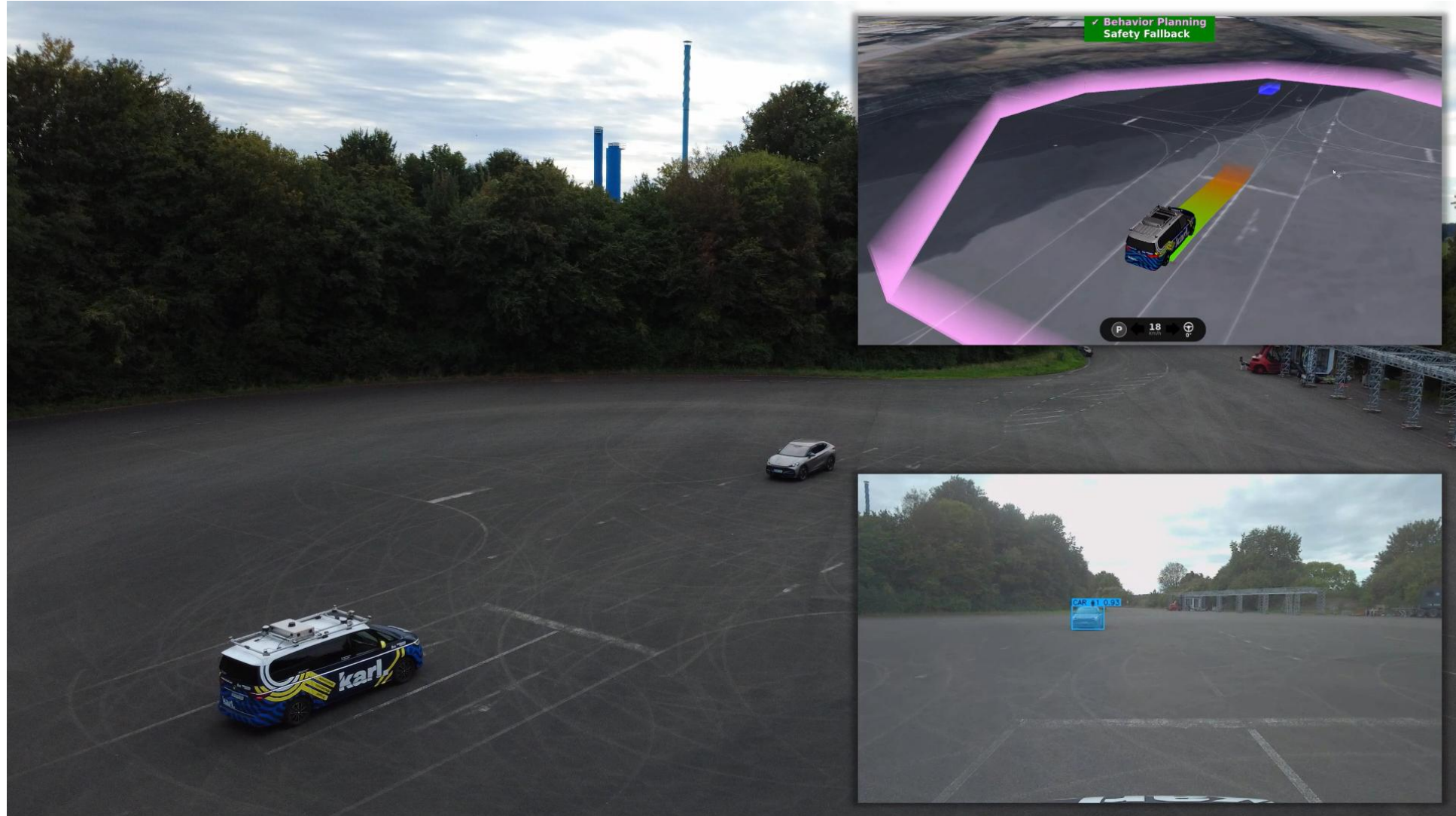


Collision rate (8s)

26.7% $\rightarrow$ 0.0%

Real-World Vehicle Integration

Closed-loop demonstration



Key takeaways and future work



Hybrid architecture implemented

selected components open-sourced in **OpenADS**



Learning-based planner evaluated open-loop

successful adaptation to a **new target domain**



Integrated and demonstrated closed-loop

on research vehicle **karl**.



Next: public-road operation

data collection & broader **closed-loop evaluation**



Open-Source Software

<https://github.com/openads-project>

Thank you very much for your attention

Guido Linden M.Sc.
Group Leader Connectivity

Institute for Automotive Engineering (ika)
RWTH Aachen University

+49 241 80 25645

guido.linden@ika.rwth-aachen.de

www.ika.rwth-aachen.de

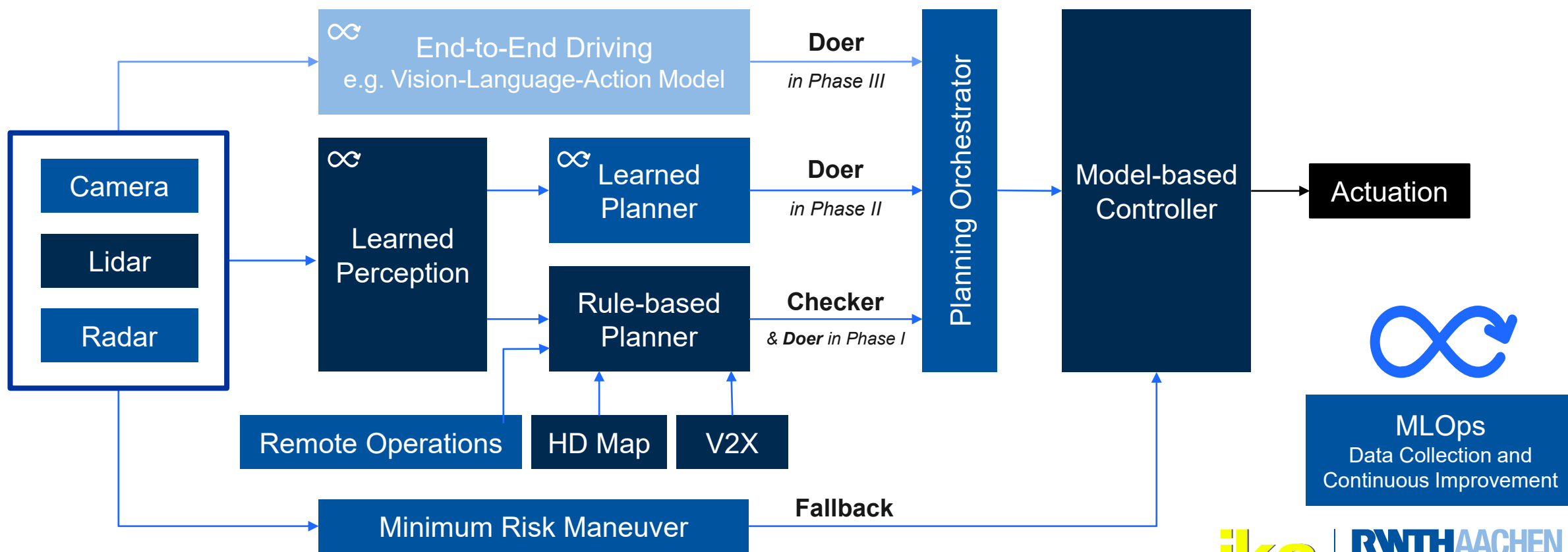
References

- [1] ISO, *Road vehicles — Safety for automated driving systems — Design, verification and validation*, ISO/TS 5083:2025, 2025.
- [2] J. Cheng et al., “*Rethinking Imitation-based Planners for Autonomous Driving*,” IEEE ICRA, 2024.
- [3] J. Cheng, Y. Chen, and Q. Chen, “*PLUTO: Pushing the Limit of Imitation Learning-based Planning for Autonomous Driving*,” arXiv:2404.14327, 2024.
- [4] D. Rößle et al., “*DrivIng: A Large-Scale Multimodal Driving Dataset with Full Digital Twin Integration*,” arXiv:2601.15260, 2026.
- [5] OpenADS, *Open-source ecosystem for automated-driving research*, GitHub organization, github.com/openads-project.
- [6] J.-P. Busch, L. Reiher, and L. Eckstein, “*Enabling the Deployment of Any-Scale Robotic Applications in Microservice-Based Service-Oriented Architectures through Automated Containerization*,” IEEE ICRA, 2024.
- [7] J.-P. Busch et al., “*karl. — A Research Vehicle for Automated and Connected Driving*,” IEEE IV, 2026.

BACKUP

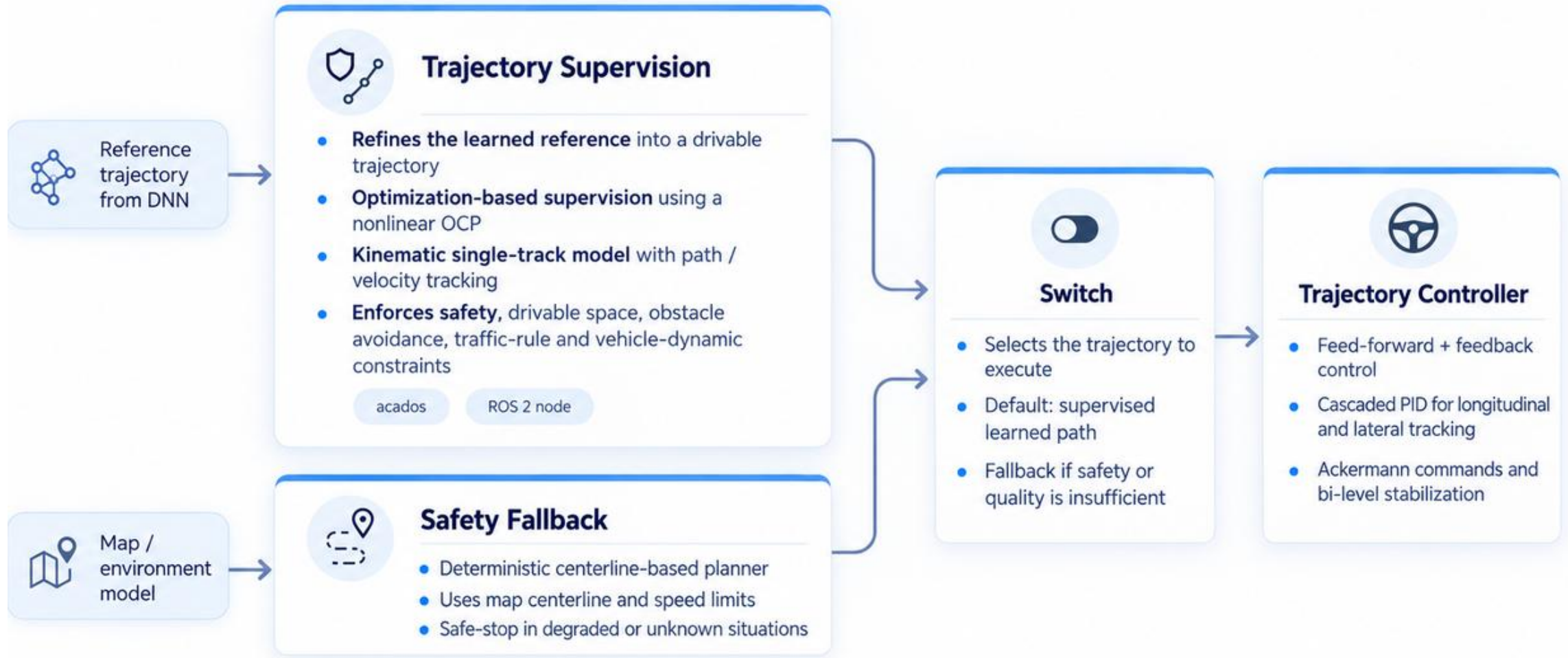


Phase	Roadmap	AD Stack Architecture	Goal
I	✓ Published	Learned Perception + Rule-based Planner	Fast test operation for data collection
II	📅 2026	Learned Planner + Rule-based Checker	Establish MLOps for data-driven improvement
III	📅 2027	End-to-End Driving + Rule-based Checker	Scale & solve long-tail challenges



Rule-based Modules

Deterministic safety layer around the learned planner



Real-world demonstration

Qualitative Evaluation

