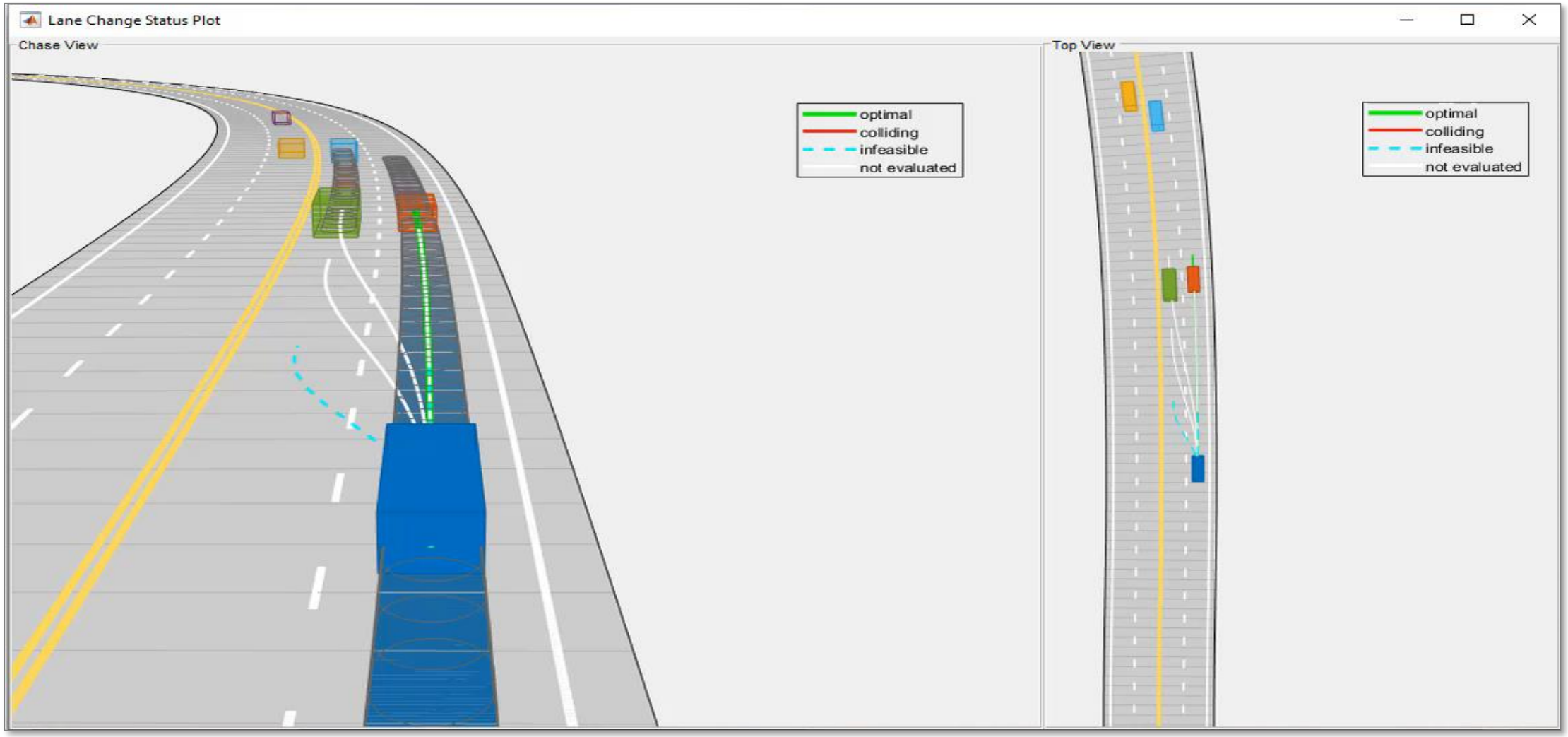
MATLAB EXPO
2021

高速场景自主换道运动规划开发

刘亮， MathWorks

MathWorks

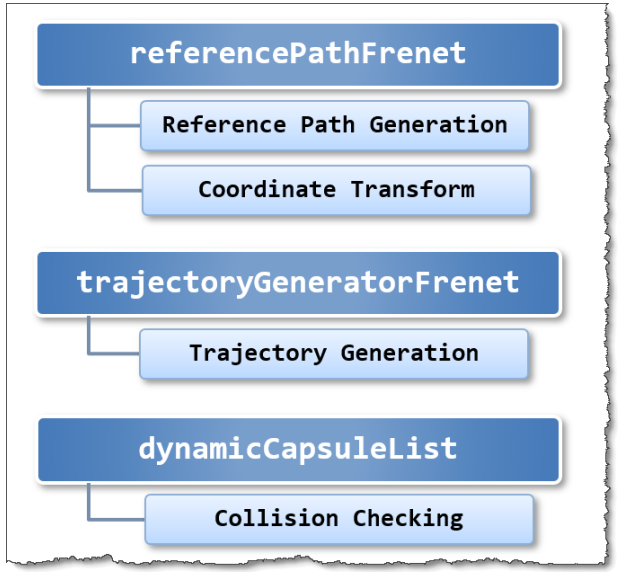
高速场景自主换道运动规划

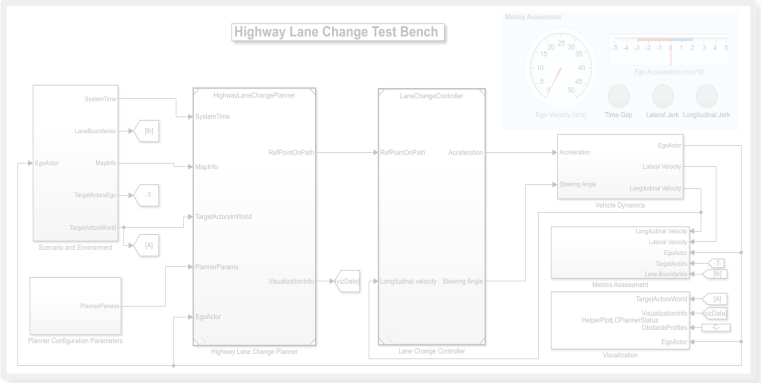


Automated Driving Toolbox™, Navigation Toolbox™, Model Predictive Control Toolbox™

R2021a

高速场景自主换道运动规划





基础部分

- 动机
- 运动规划框架
- 三个MATLAB函数
  - ✓ referencePathFrenet
  - ✓ trajectoryGeneratorFrenet
  - ✓ dynamicCapsuleList

实现运动规划和控制

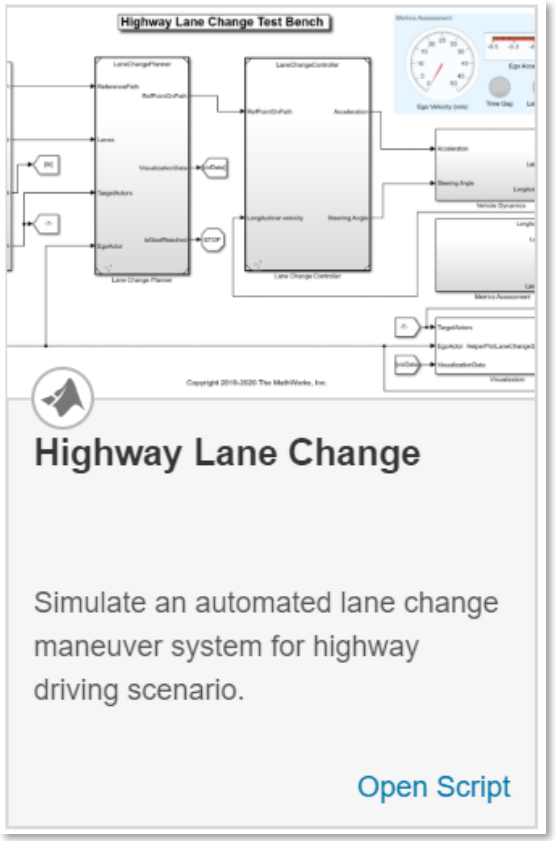
- 参考示例演示
- 高速场景自主换道规划架构
- 闭环控制算法

仿真测试

- 多场景的仿真
- 路网文件导入创建场景

示例——Lane Change Maneuver (LCM) system

R2020a



LCM初始版本

trajectoryOptimalFrenet

- Reference Path Generation
- Coordinate Transform
- Trajectory Generation
- Feasibility Checking
- Cost Evaluation
- Collision Checking

- 用户反馈
  - 关于功能可配置性和灵活性
  - 如何实现客户自定义?

模块化架构实现自定义设计

R2020a

LCM初始版本

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  - Reference Path Generation
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R2020b

- referencePathFrenet
  - Reference Path Generation
  - Coordinate Transform
- trajectoryGeneratorFrenet
  - Trajectory Generation
- dynamicCapsuleList
  - Collision Checking
- Feasibility Checking
- Cost Evaluation

- 模块化架构
(灰色部分由客户自定义)

模块化架构实现自定义设计

R2020a

LCM初始版本

R2020b

规划器更新
(MATLAB版本)

R2020b

- **referencePathFrenet**
  - Reference Path Generation
  - Coordinate Transform
- **trajectoryGeneratorFrenet**
  - Trajectory Generation
- **dynamicCapsuleList**
  - Collision Checking
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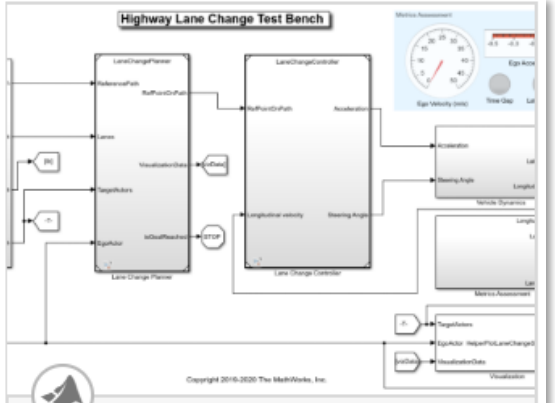
- Cost Evaluation

▪ 模块化架构
(灰色部分由客户自定义)

自主换道系统示例的演变

R2020a



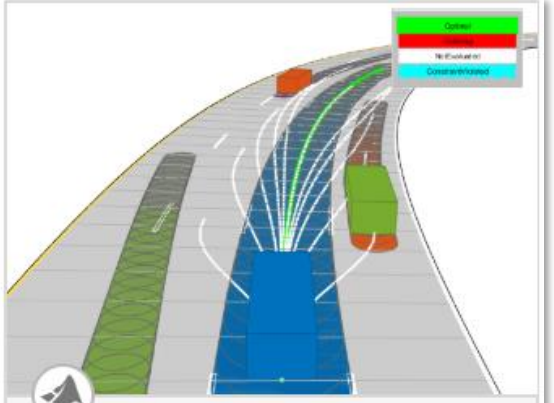
Highway Lane Change

Simulate an automated lane change maneuver system for highway driving scenario.

Open Script

LCM初始版本

R2020b



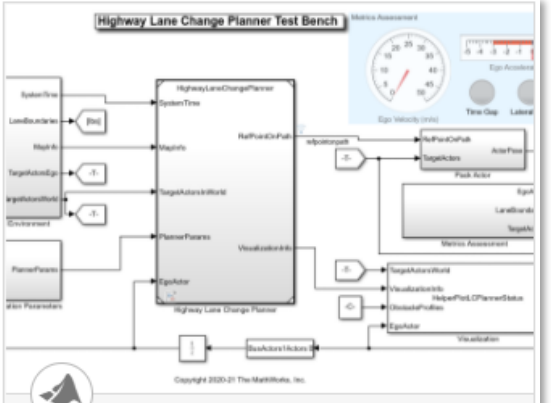
Highway Trajectory Planning Using Frenet Reference Path

Demonstrates how to plan a local trajectory in a highway driving scenario. This example uses a reference path and dynamic list of

Open Live Script

规划器更新
(MATLAB版本)

R2021a

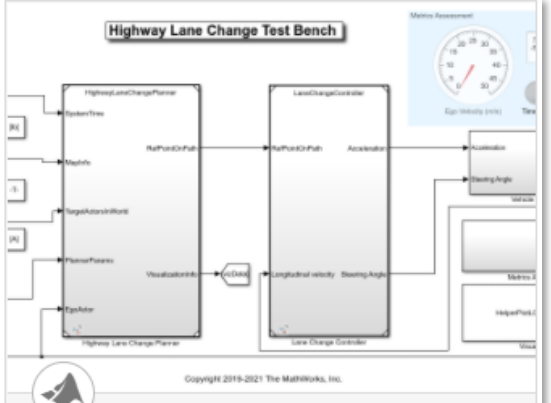


Generate Code for Highway Lane Change Planner

Design, test, and generate C++ code for a lane change planner for highway driving. This example closely follows the Highway

运动规划
(Simulink模型)

R2021a



Highway Lane Change

Design and test the planner and controller components of a lane change maneuver system designed for highway driving.

闭环仿真验证
(Simulink模型)

模块化架构

自主换道运动规划和闭环控制

referencePathFrenet
- Reference Path Generation
- Coordinate Transform

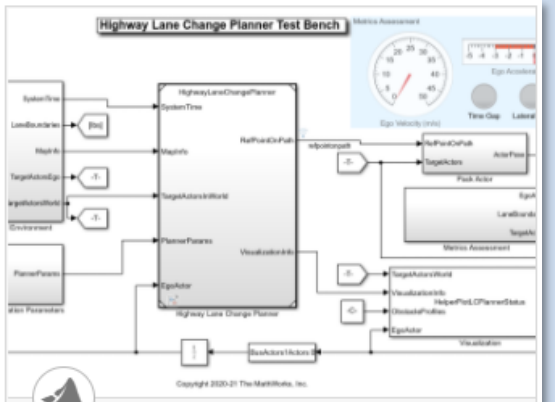
trajectoryGeneratorFrenet
- Trajectory Generation

dynamicCapsuleList
- Collision Checking

Feasibility Checking

Cost Evaluation

R2021a



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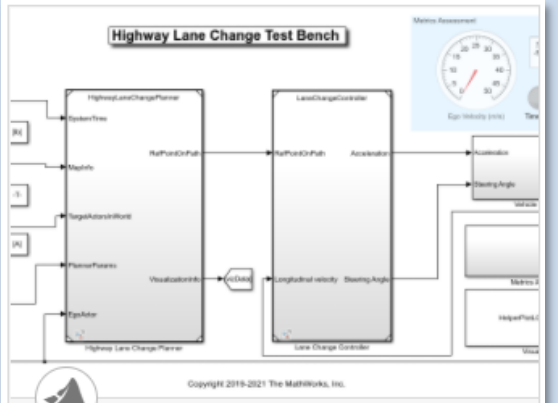

Highway Lane Change

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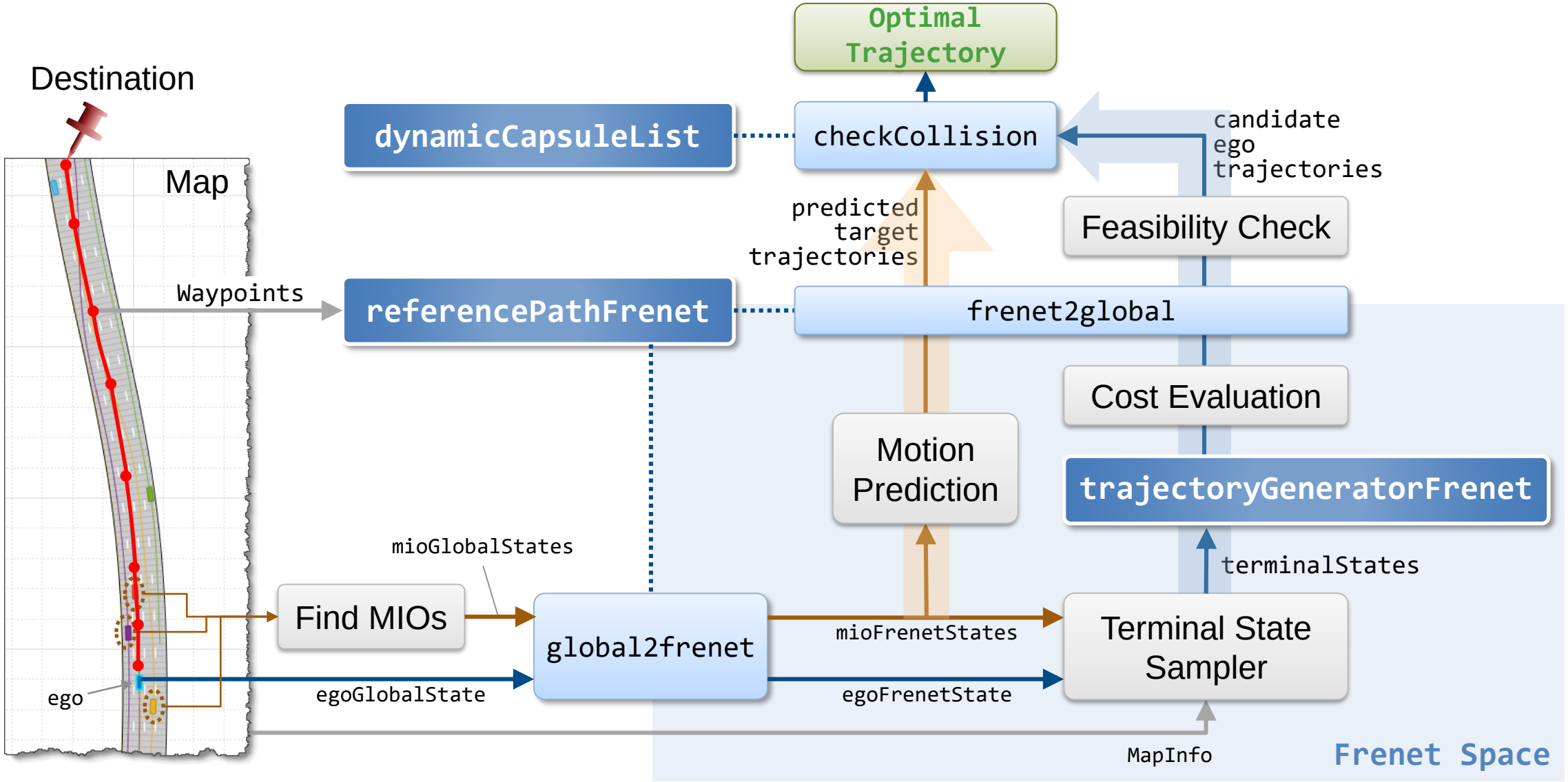
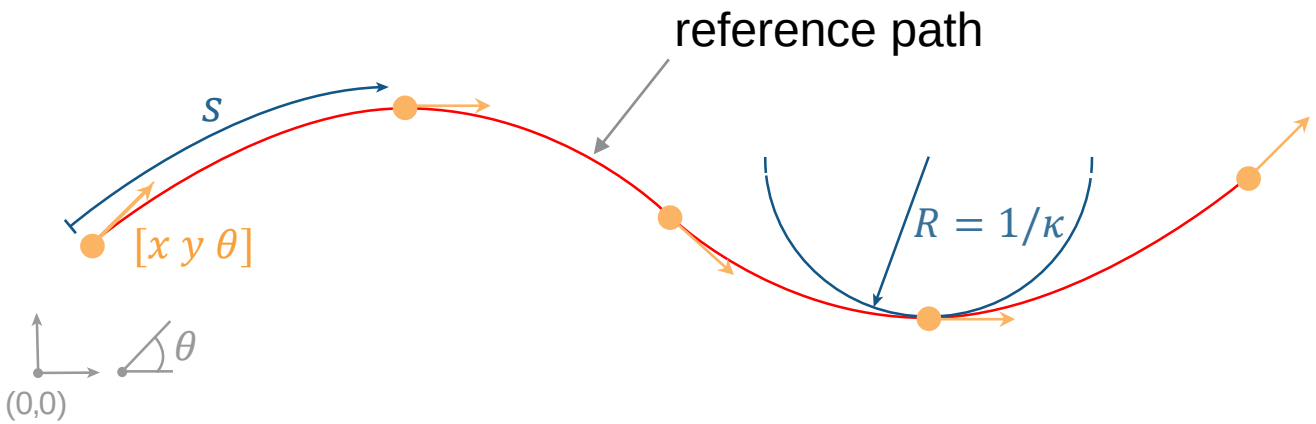
自主换道运动规划示意图



基于Frenet坐标系的轨迹规划

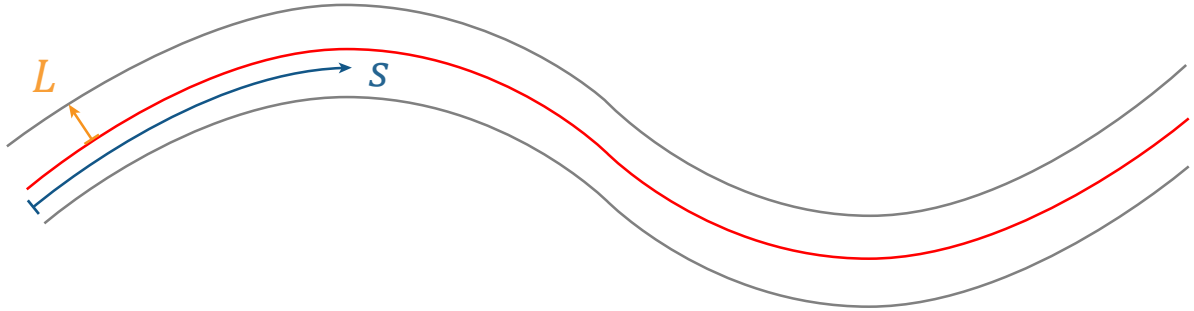
- 在Frenet坐标系下定义目标及其相对于参考路径（道路或车道中心）的轨迹。
- Frenet坐标系更直观的表示道路位置，简化了车辆在弯曲道路的轨迹规划。



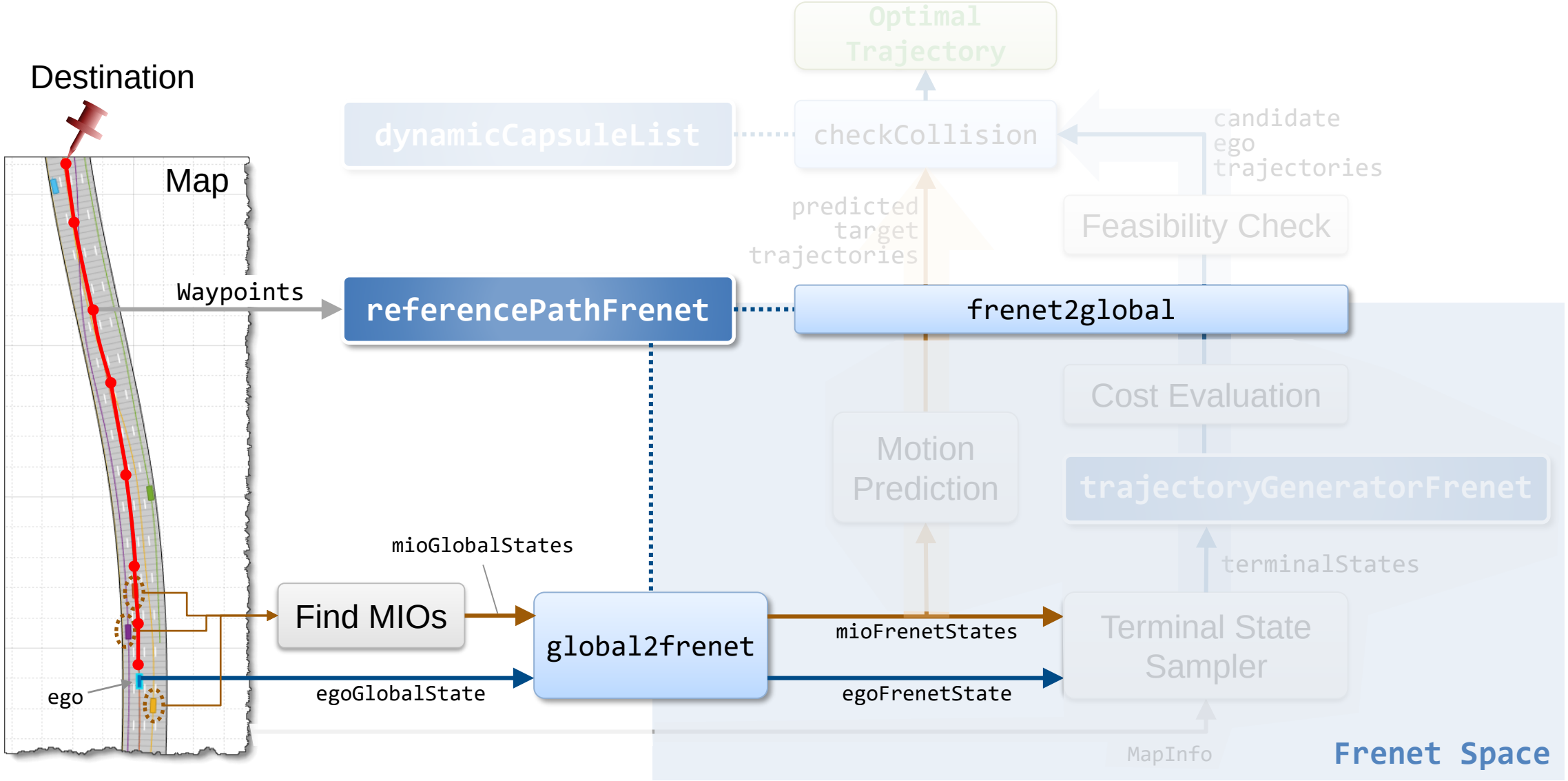
Global States: $[x\ y\ \theta\ \kappa\ v\ a]$

Frenet States: $[s\ \delta s\ \delta^2 s\ L\ \delta L\ \delta^2 L]$

- s : Arc length
- L : Perpendicular deviation from the direction of the reference path



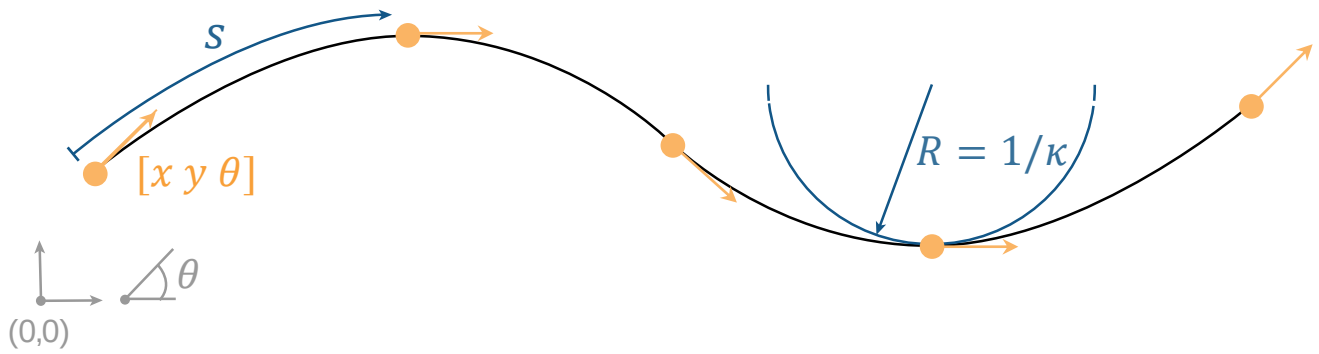
自主换道运动规划示意图——referencePathFrenet



referencePathFrenet

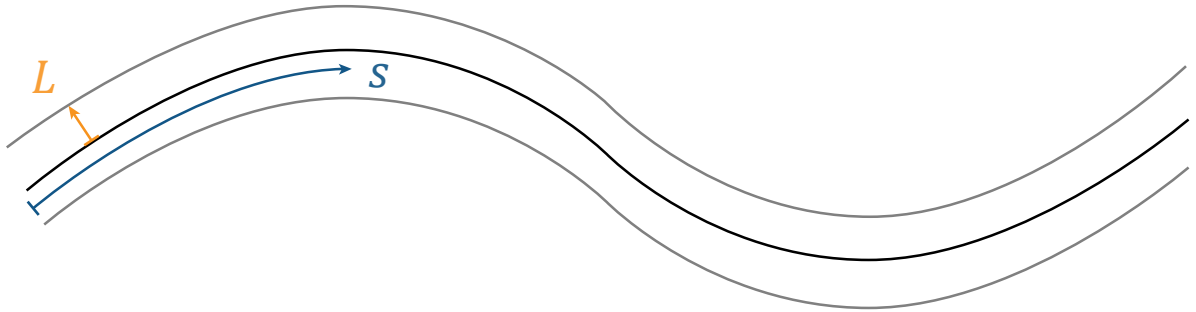
`referencePathFrenet`

- referencePathFrenet拟合了一组平滑的，分段的，连续的曲线到一组$[x\ y]$ or $[x\ y\ \theta]$形式的waypoints



Path Points: $[x\ y\ \theta\ \kappa\ \delta\kappa\ s]$
- κ : Curvature
- $\delta\kappa$: Derivative of curvature
- s : Arc length

- 将轨迹trajectories在笛卡尔坐标系与Frenet坐标之间转化 (`frenet2global`, `global2frenet`)



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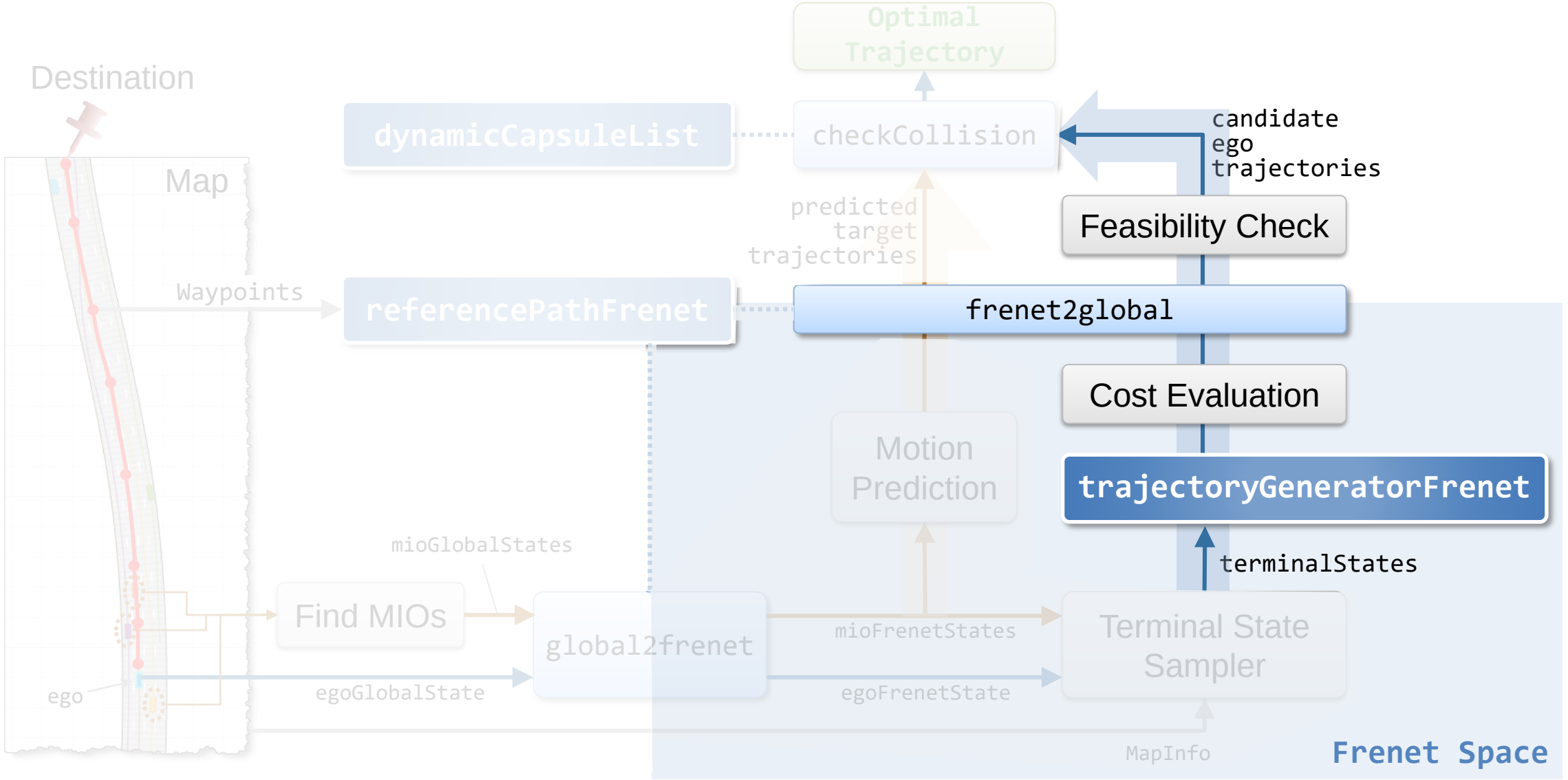
自主换道运动规划示意图——trajectoryGeneratorFrenet



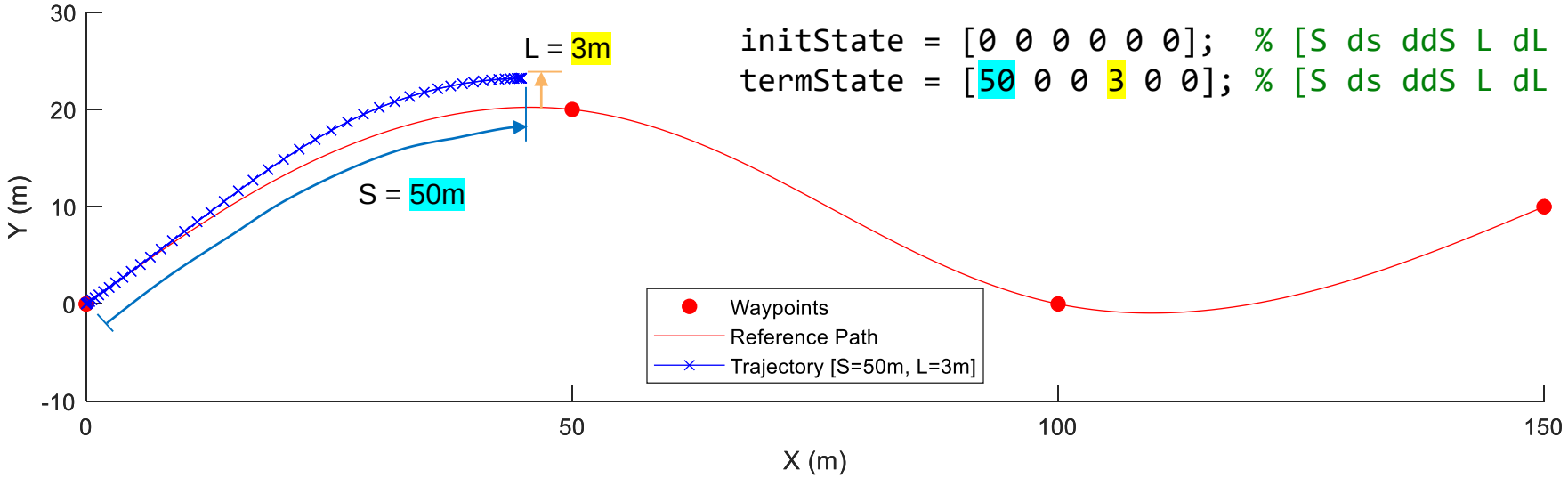
trajectoryGeneratorFrenet

trajectoryGeneratorFrenet

- 通过求解4阶或5阶多项式来生成轨迹——满足在Frenet坐标系下相对于参考路径的边界条件

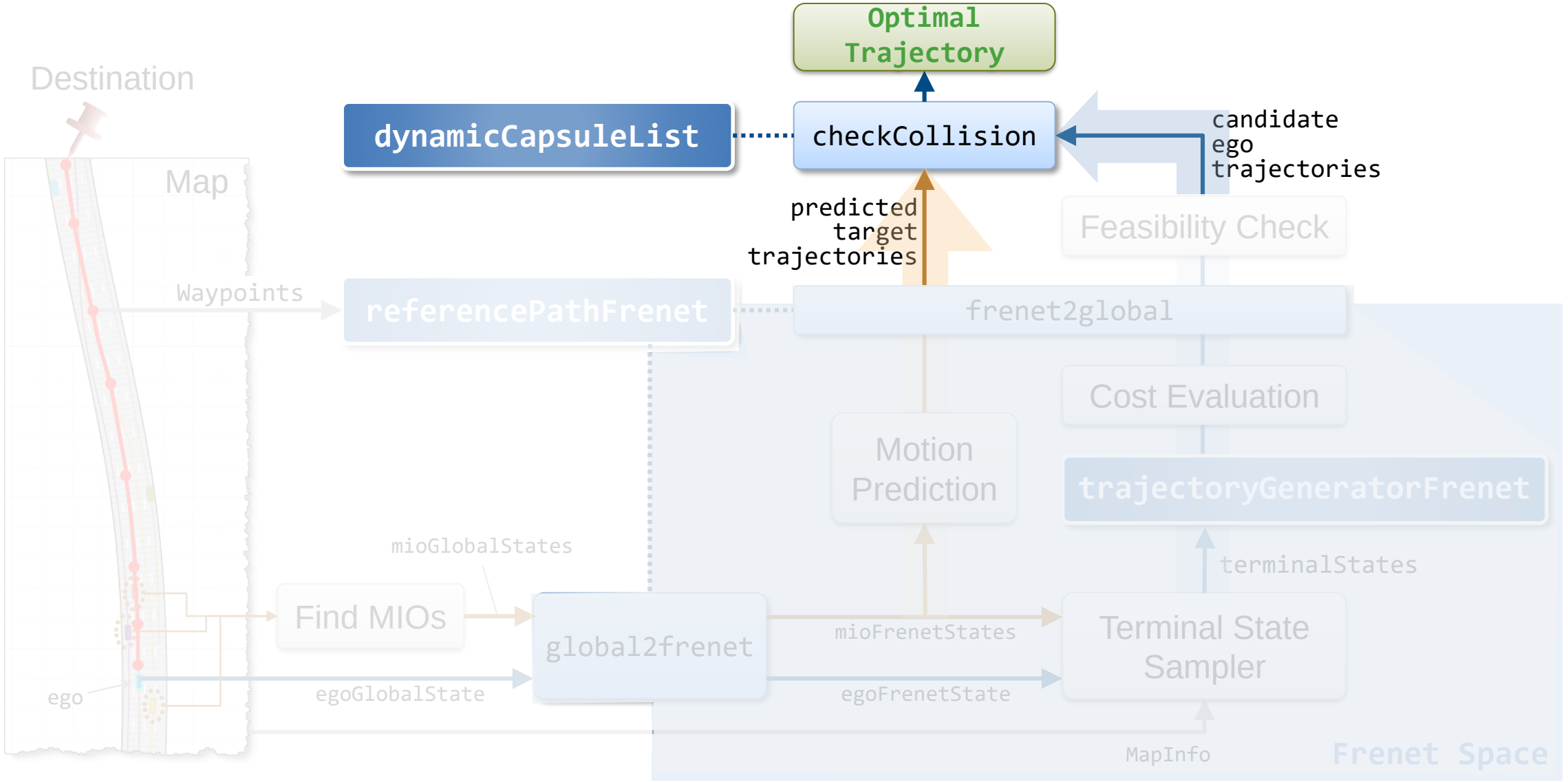
```
refPath = referencePathFrenet(waypoints);
connector = trajectoryGeneratorFrenet(refPath);

[frenetTraj,globalTraj] = ...
    connect(connector,initState,termState,timeSpan);
```




```
initState = [0 0 0 0 0 0];  % [S ds ddS L dL ddL]
termState = [50 0 0 3 0 0]; % [S ds ddS L dL ddL]
```

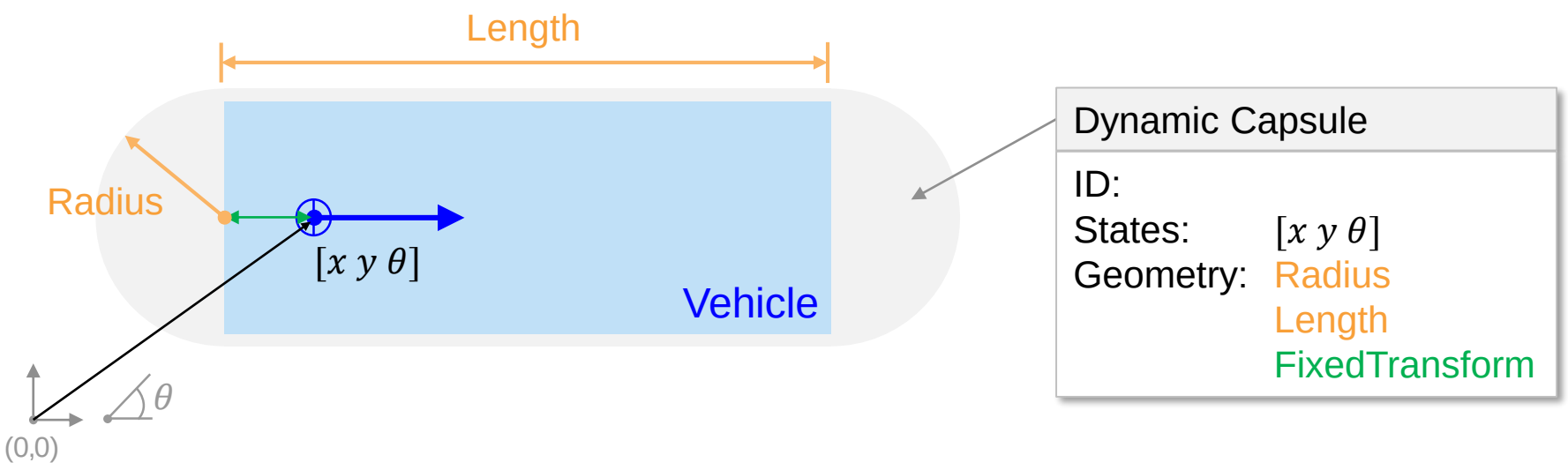
自主换道运动规划示意图——dynamicCapsuleList



dynamicCapsuleList

`dynamicCapsuleList`

- 管理基于胶囊型（capsule）的对象列表，用于碰撞检测



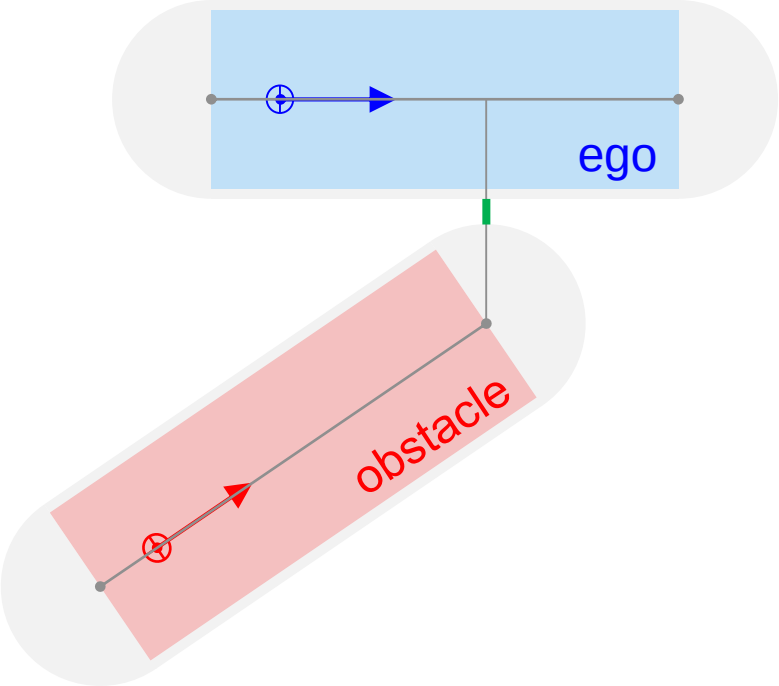
- 为什么使用Capsules?
  - 自动的在矩形目标对象前后建立一个缓冲区
  - 同时避免了矩形目标两边区域的膨胀
  - 可以高效的计算碰撞检测

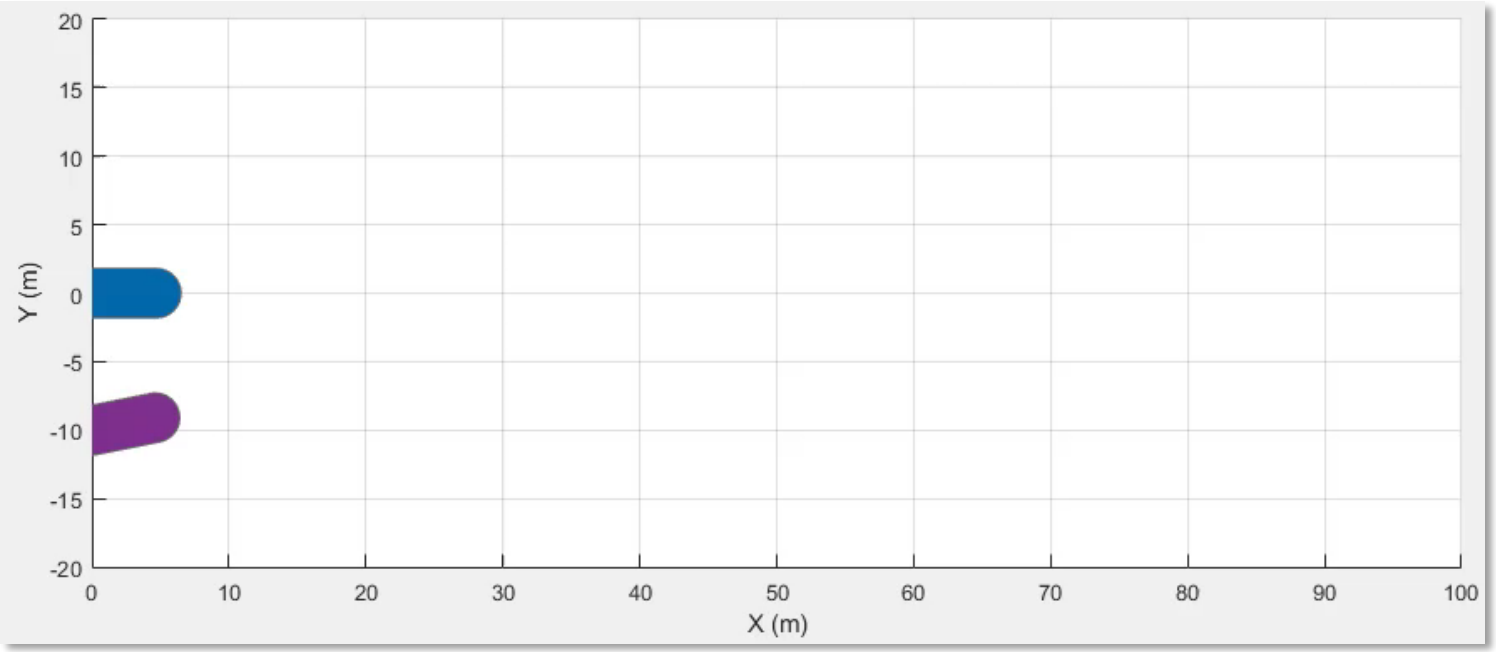
dynamicCapsuleList

dynamicCapsuleList

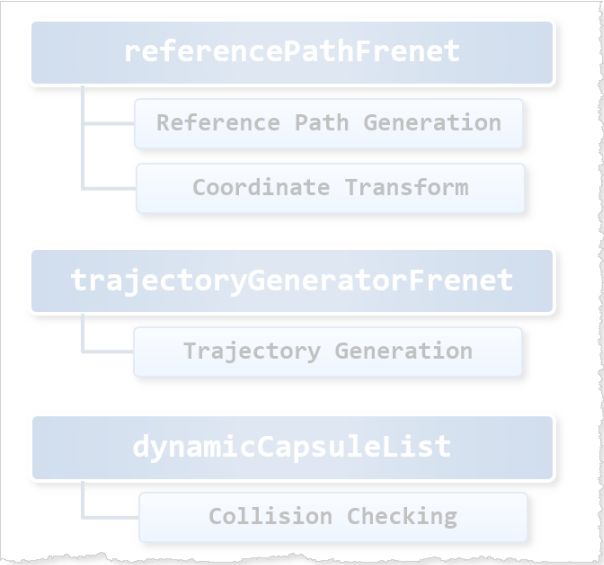
- 使用dynamicCapsuleList检测自车与障碍物之间的碰撞

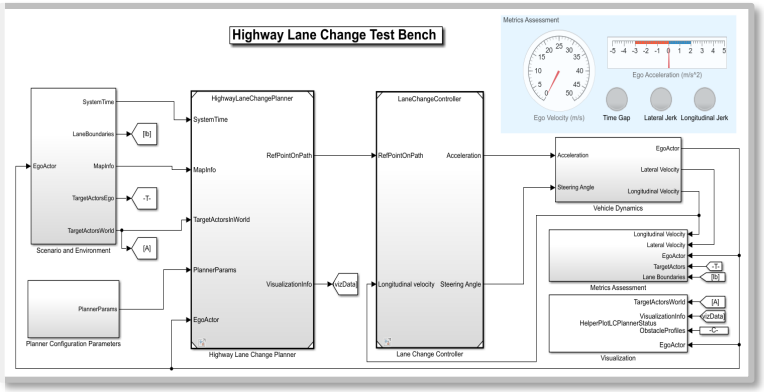
```
isColliding = checkCollision(capList)
```





高速场景自主换道的运动规划





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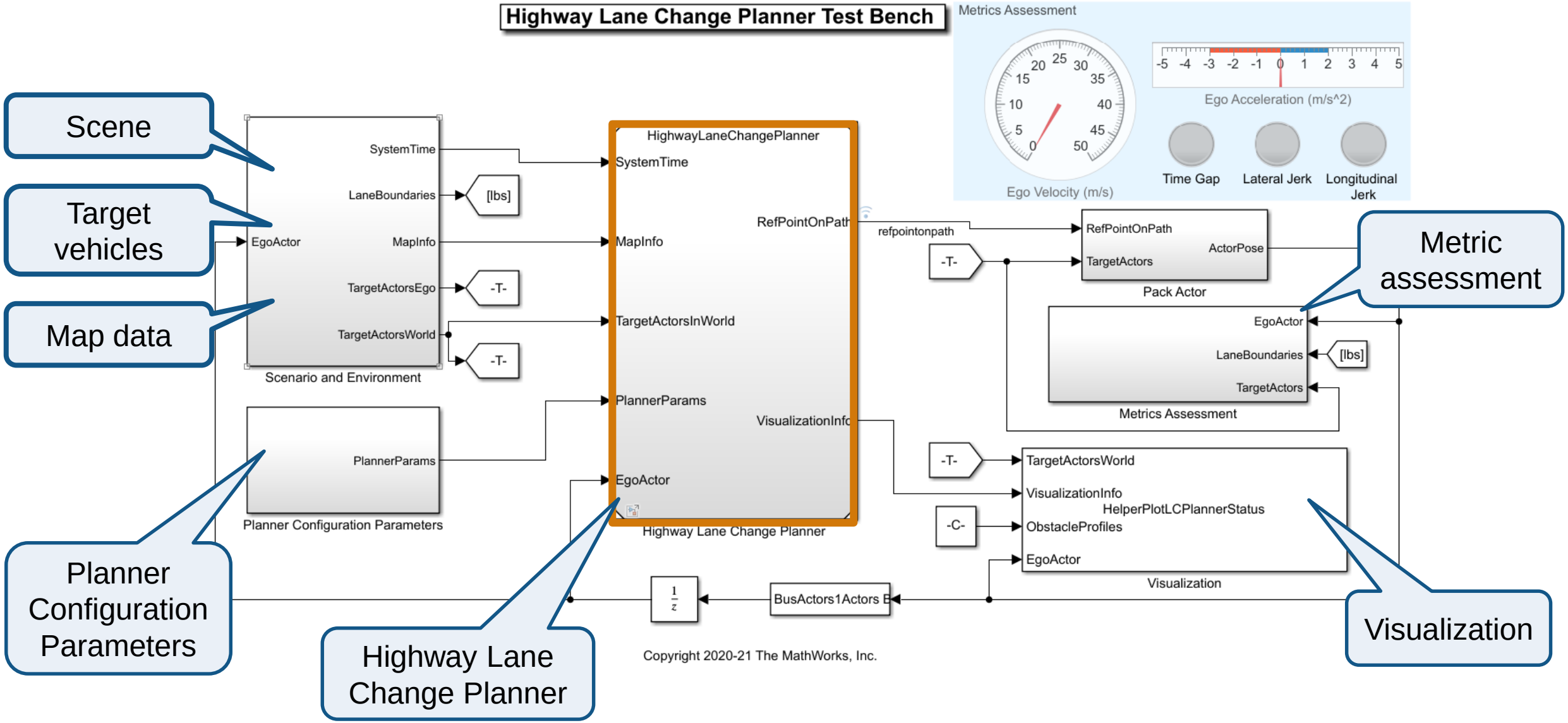
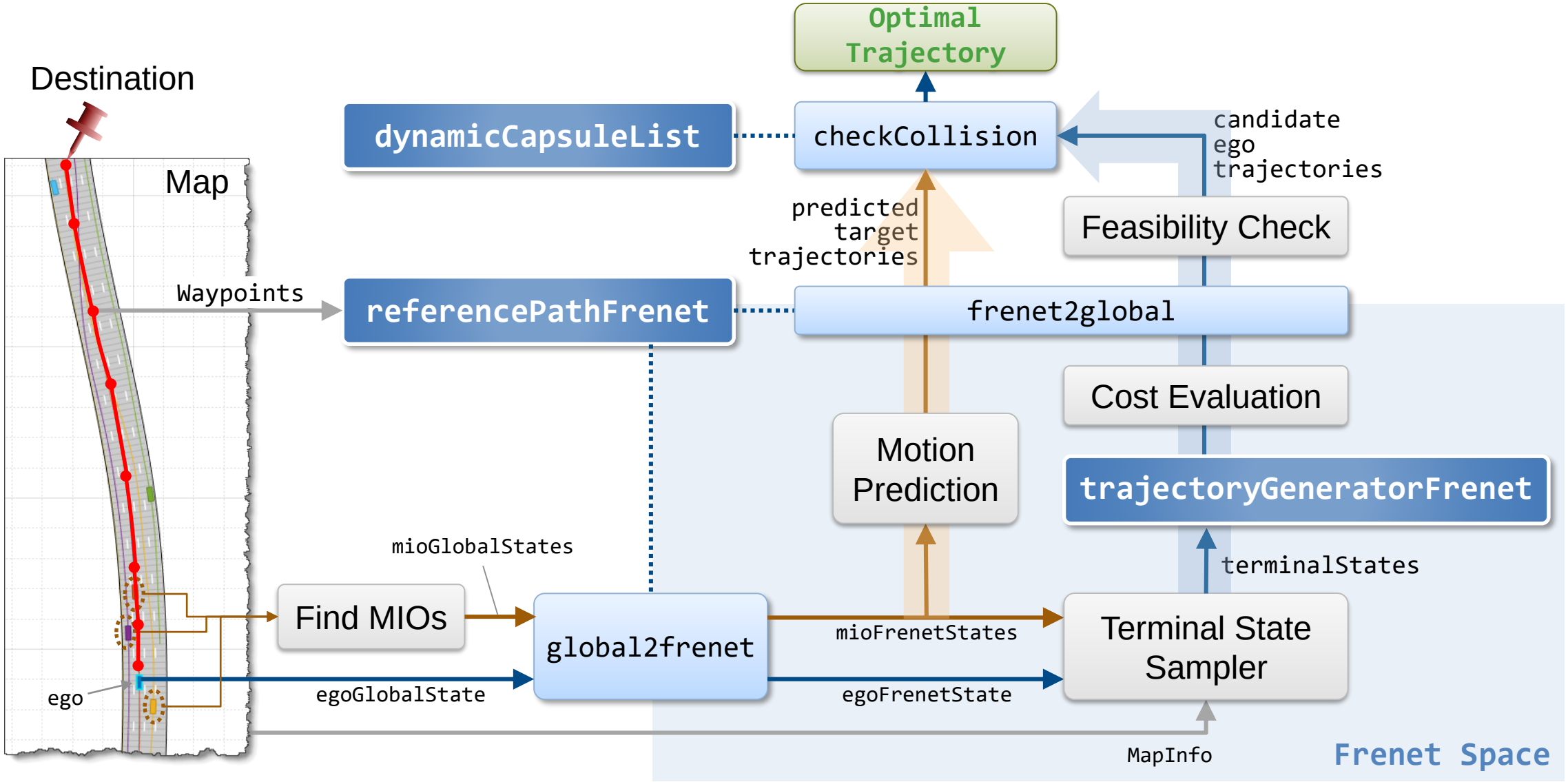
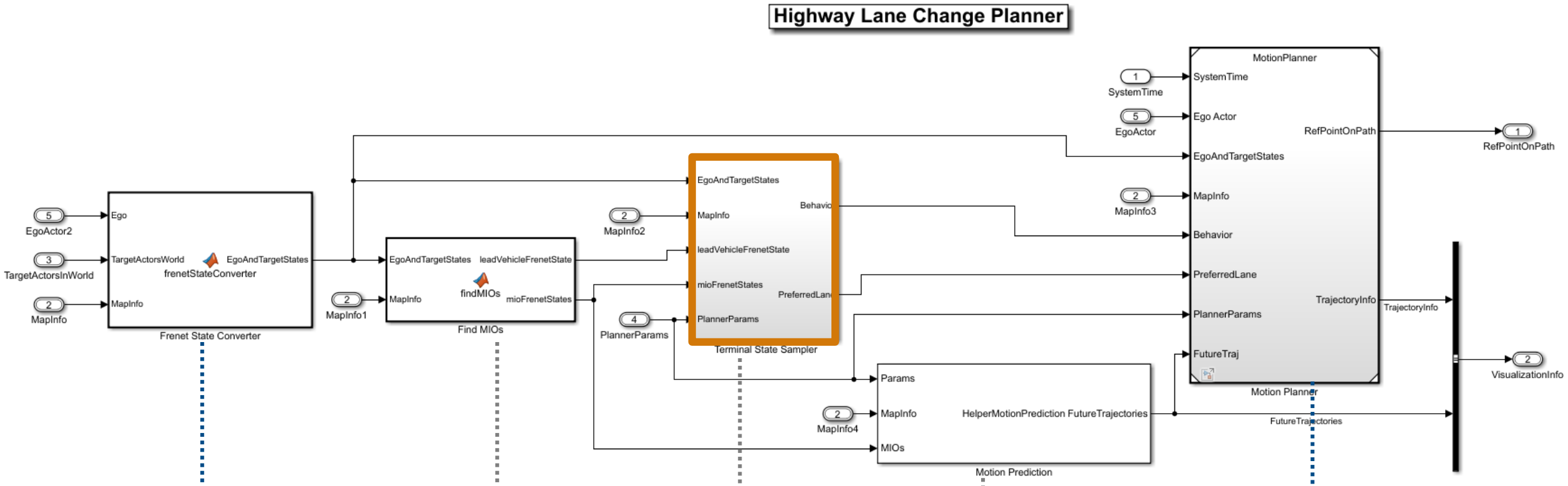
高速场景自主换道规划测试框架



高速场景自主换道运动规划示意图



高速场景自主换道运动规划



checkCollision

global2frenet

dynamicCapsuleList

referencePathFrenet

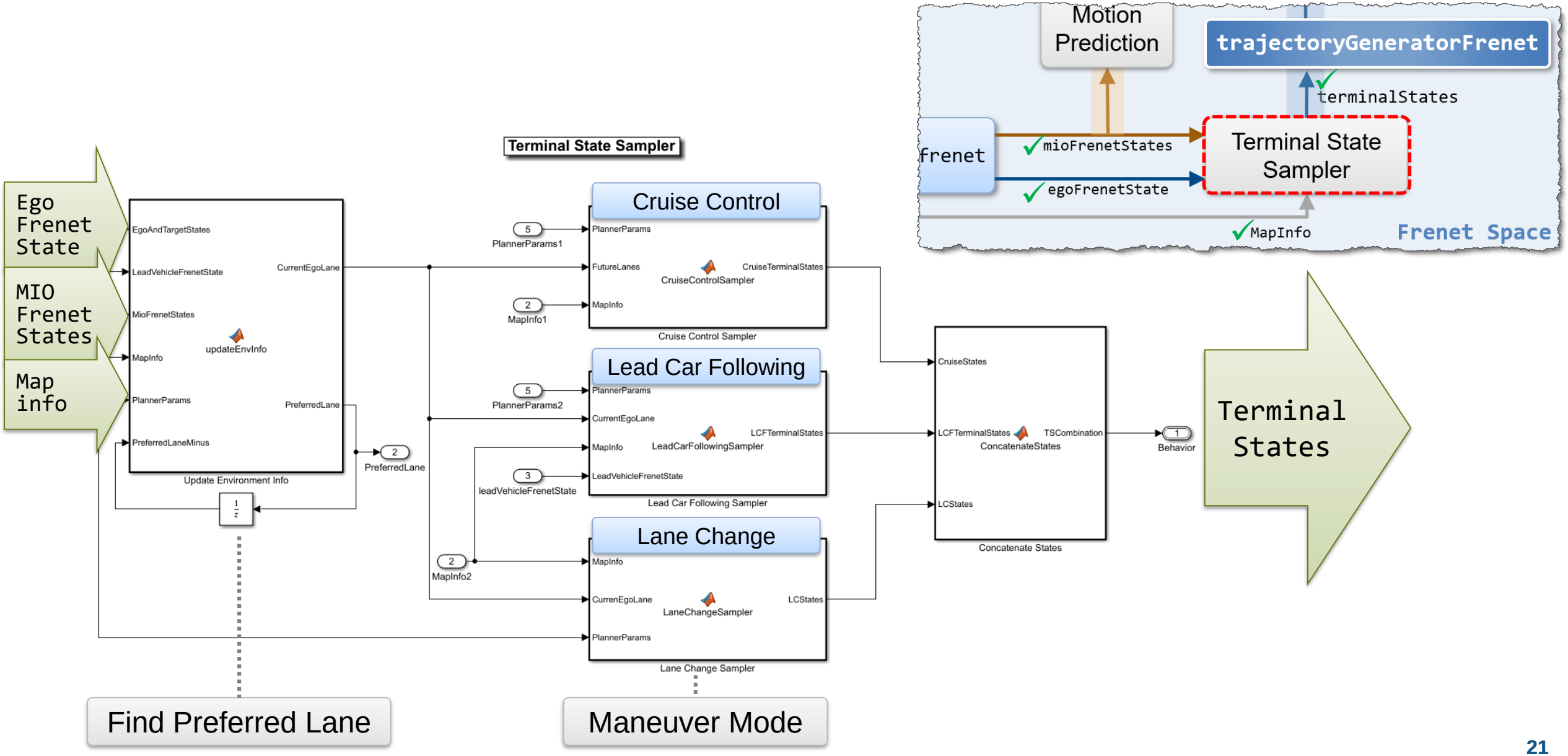
Find MIOs

Terminal State Sampler

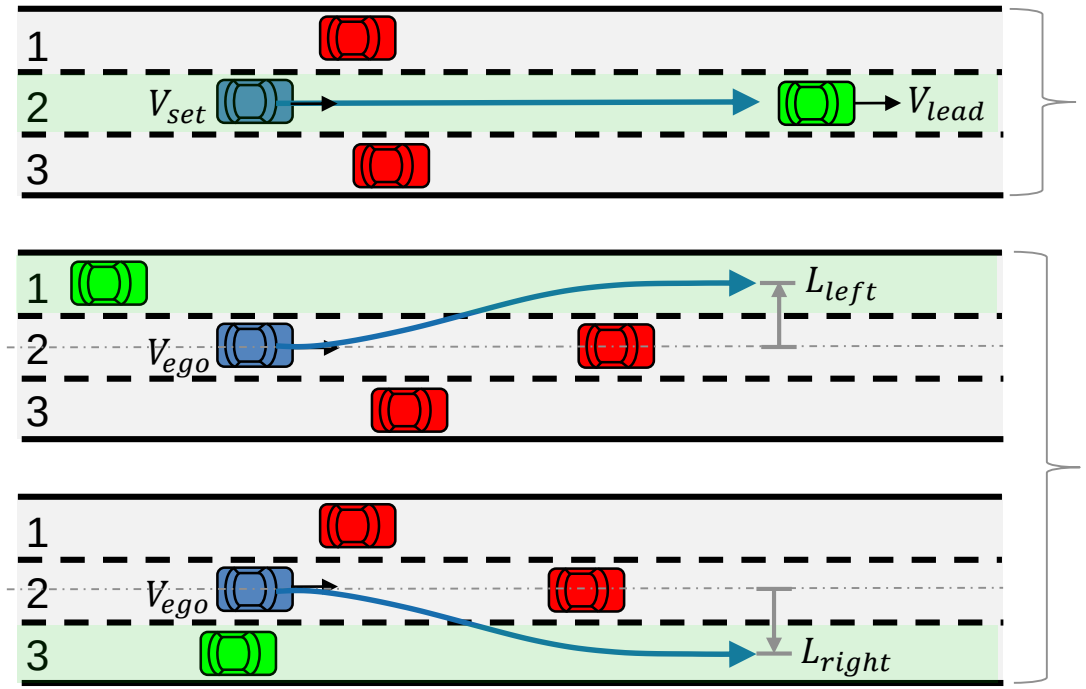
Motion Prediction

trajectoryGeneratorFrenet

高速场景自主换道运动规划：终点状态



优选车道和机动模式



	Terminal Frenet States					
	s	δs	$\delta^2 s$	L	δL	$\delta^2 L$
Cruise Control Mode	NaN	V_{set}	0	L_{ego}	0	0
Lead Car Following Mode	NaN	V_{lead}	0	L_{ego}	0	0
Lane Change Mode	NaN	V_{ego}	0	L_{left}	0	0
	NaN	V_{ego}	0	L_{right}	0	0

Unrestricted longitudinal position
→ use 4th-order polynomial

ego

unsafe target $(TTC_{ego-mio} < TTC_{safe})$

safe target $(TTC_{ego-mio} \geq TTC_{safe})$

where TTC = Time-to-collision

Frenet States: $[s\ \delta s\ \delta^2 s\ L\ \delta L\ \delta^2 L]$

- s : Arc length
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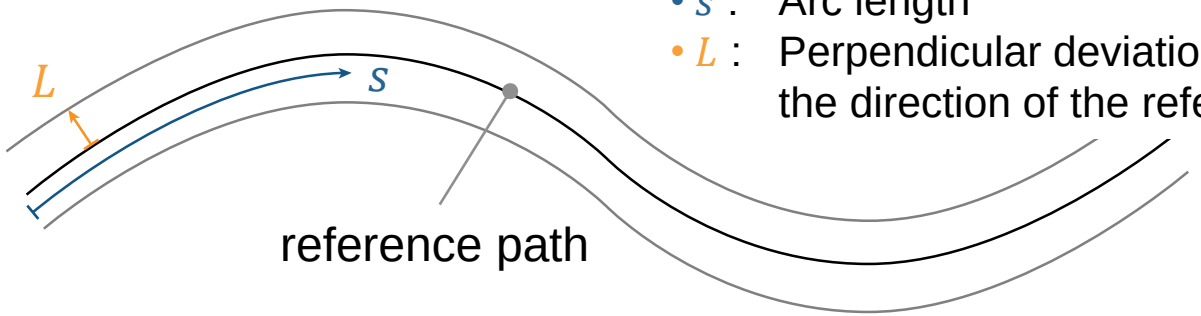

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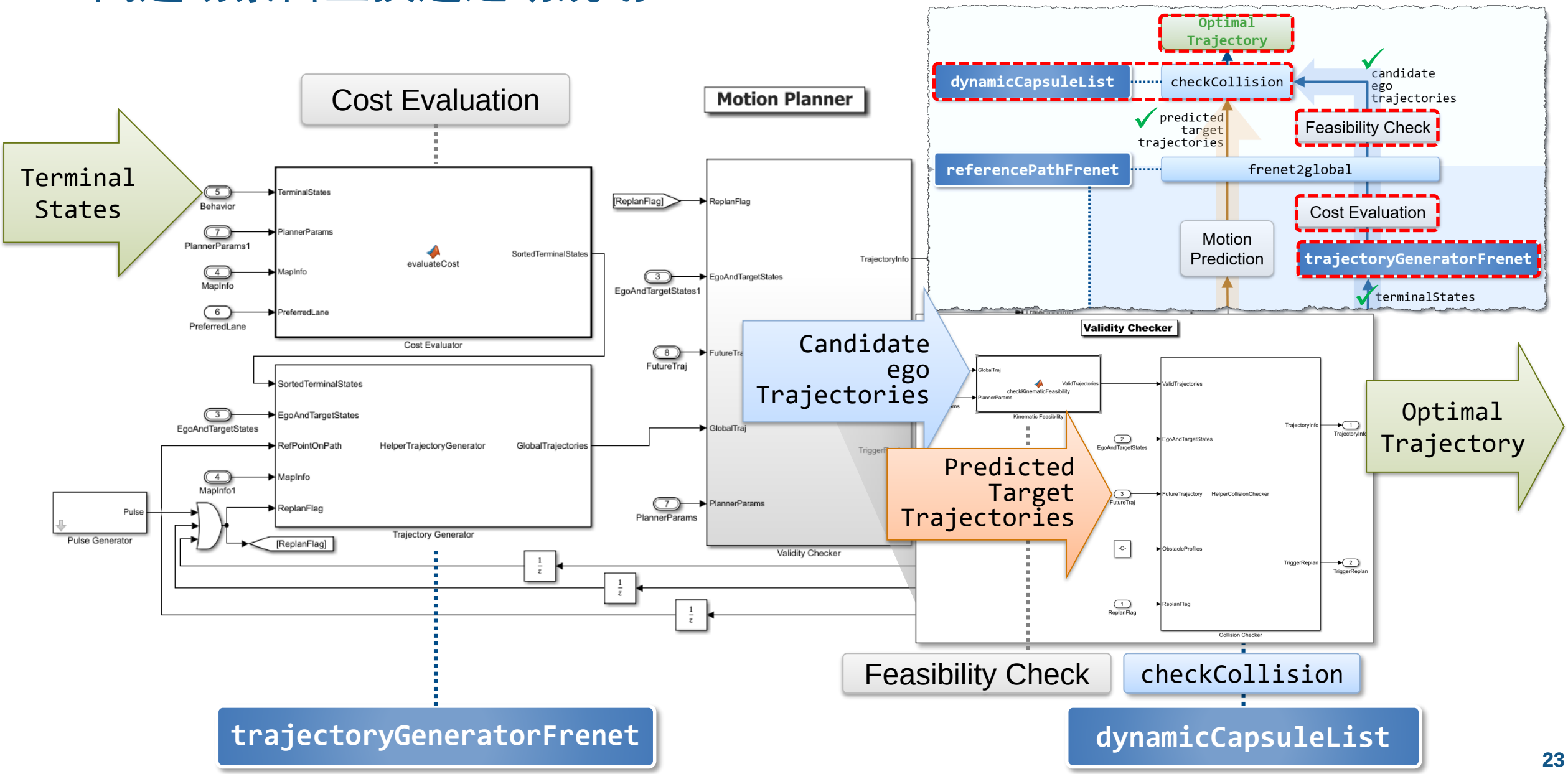
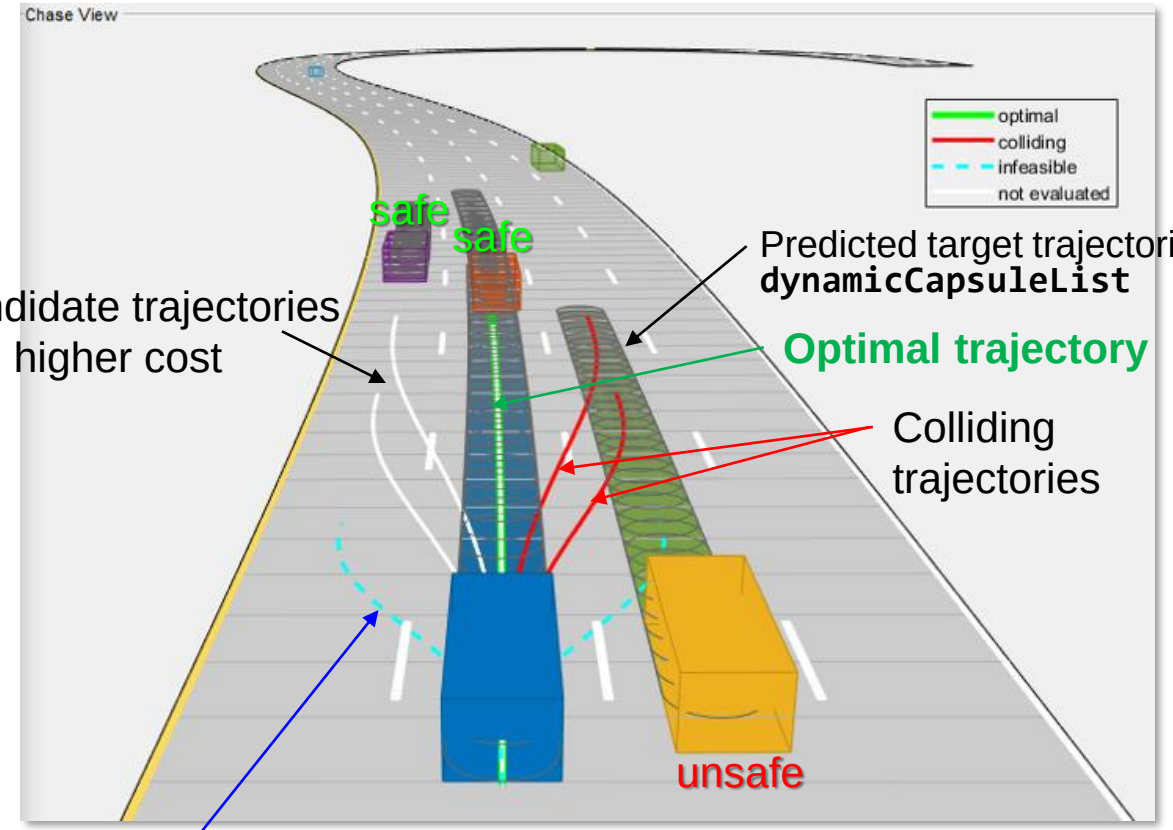


示例——如何寻找最优轨迹



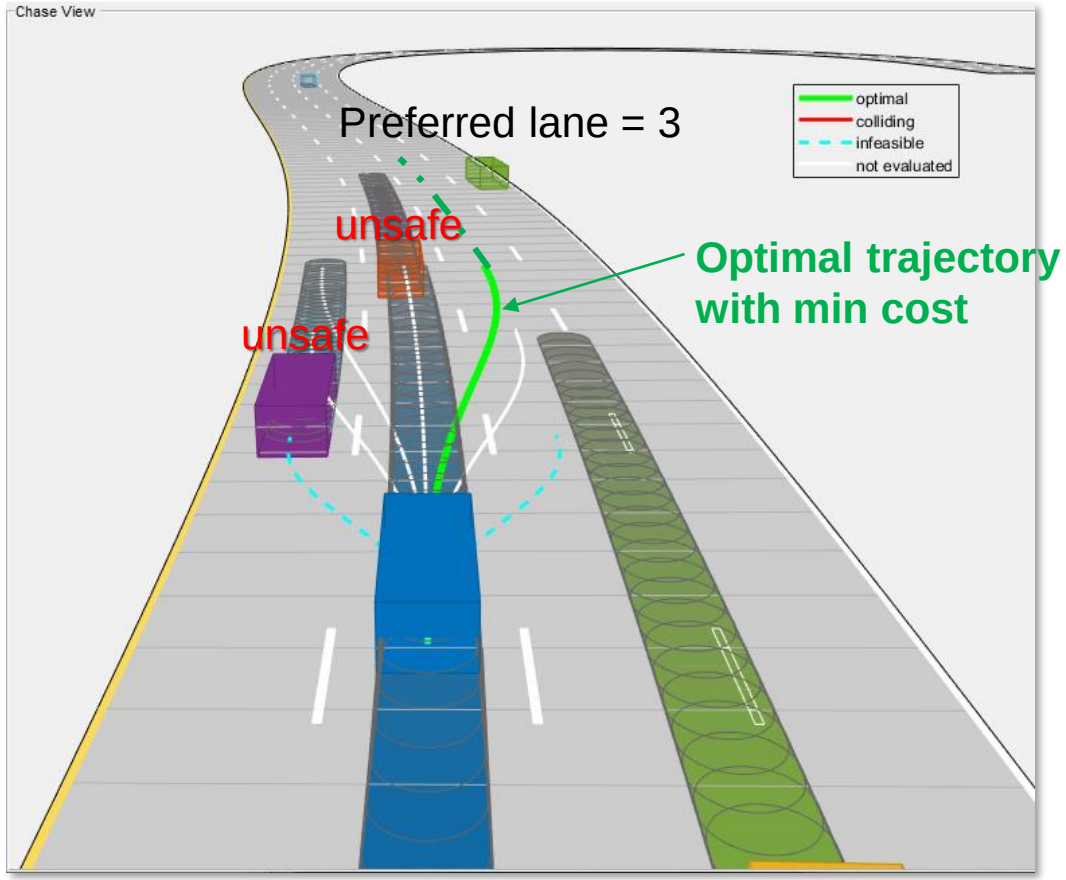
Candidate trajectories with higher cost

Predicted target trajectories using **`dynamicCapsuleList`**

Optimal trajectory

Colliding trajectories

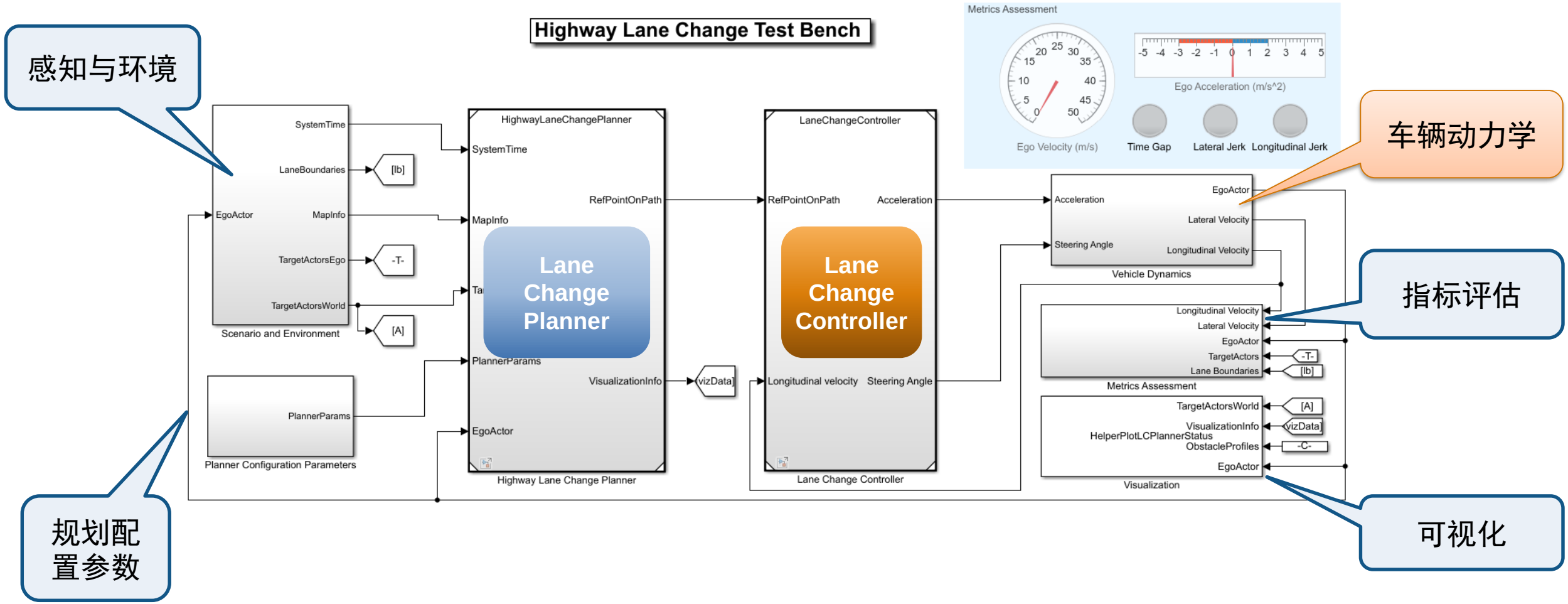
Infeasible trajectory (excessive yaw rate)



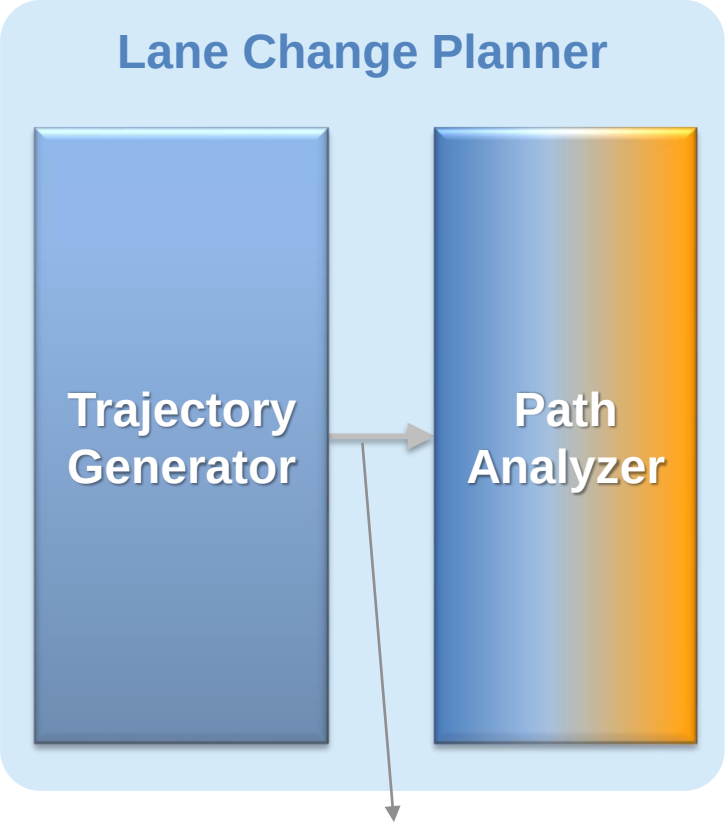
Optimal trajectory with min cost

safe

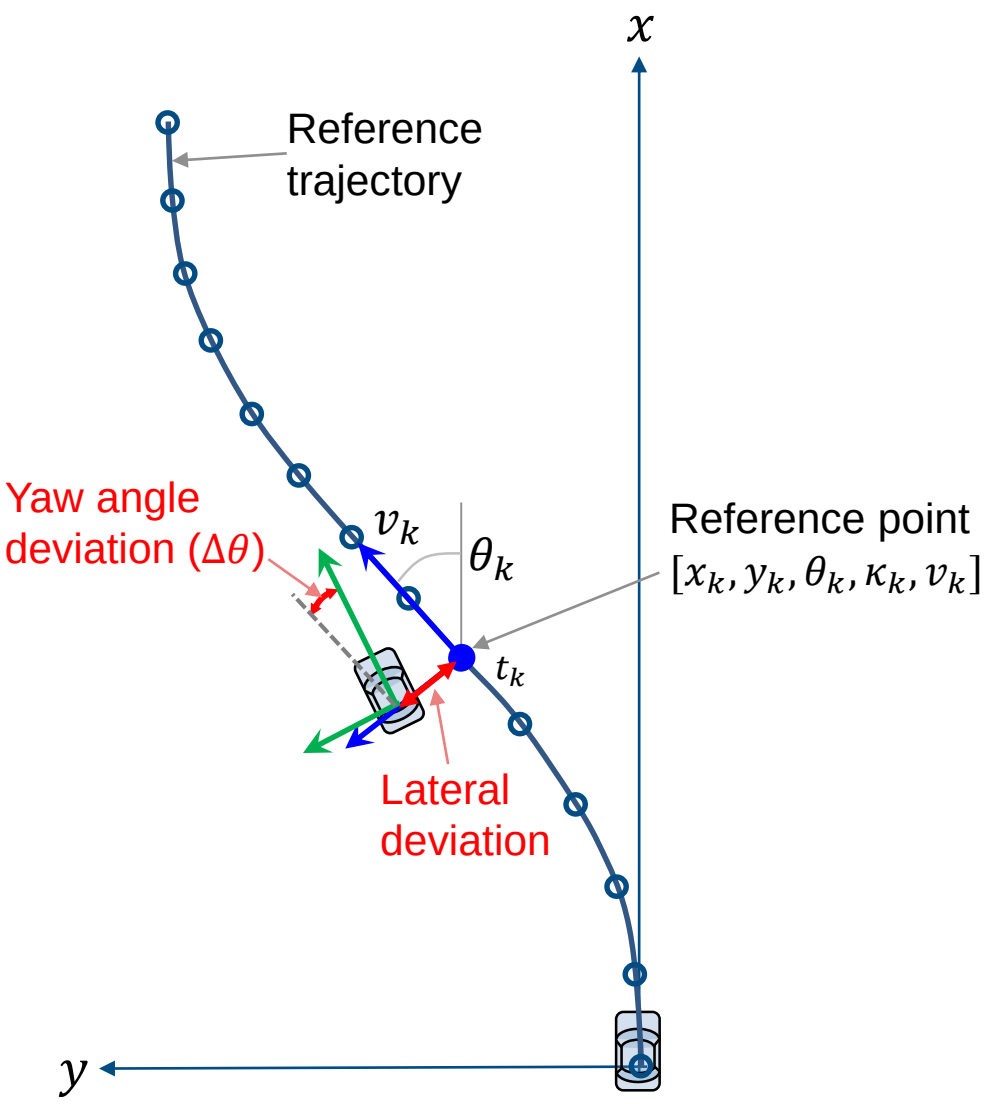
高速自主换道：闭环仿真系统



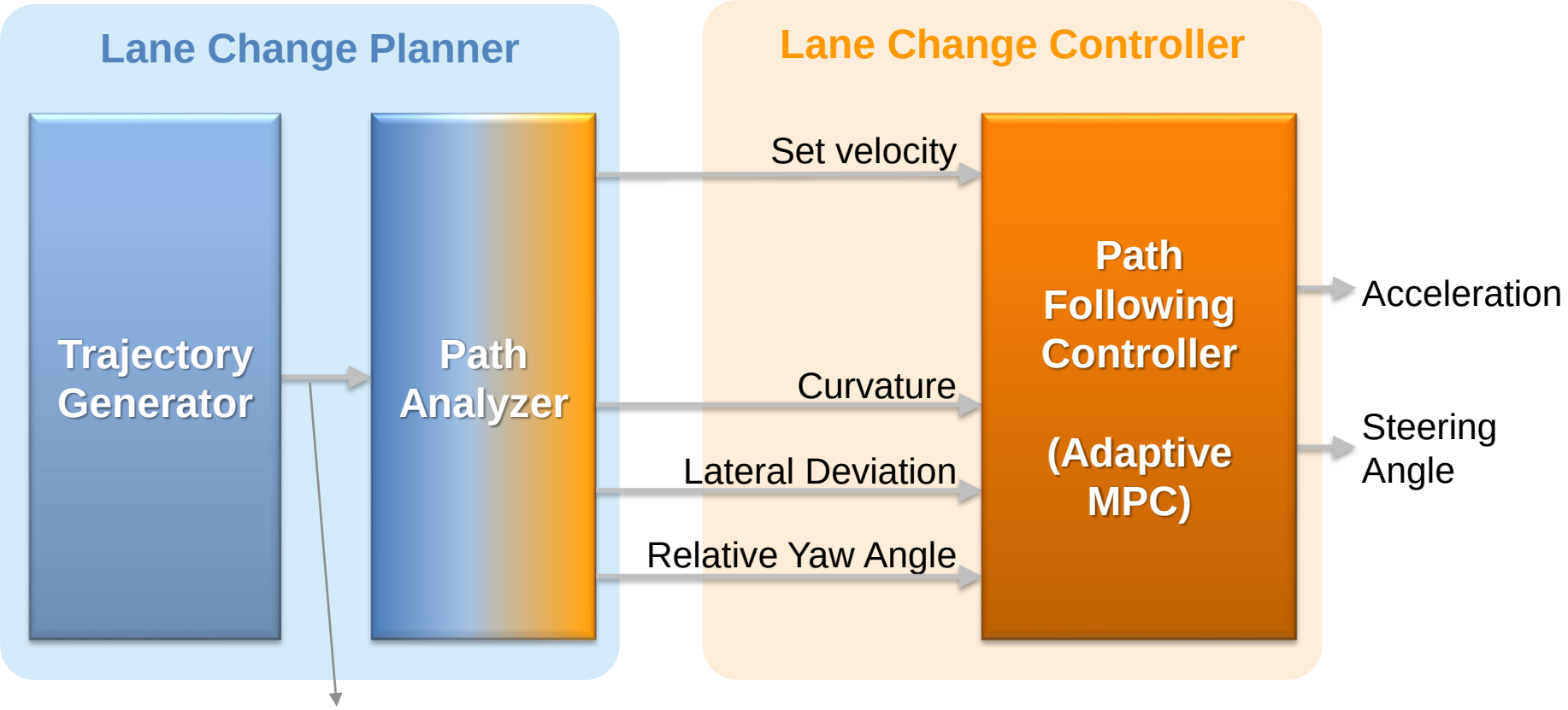
换道策略——规划



Optimal trajectory
→ Reference trajectory
(virtual lane center)

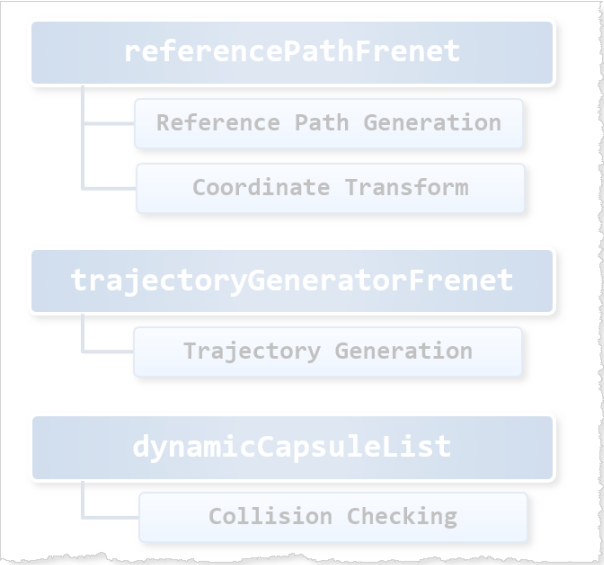


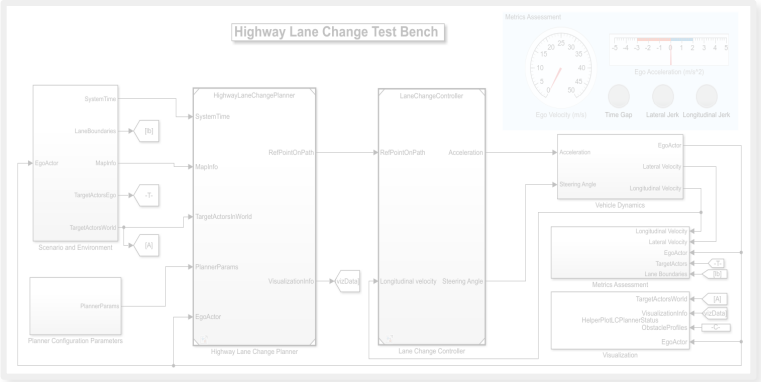
换道策略——规划+控制

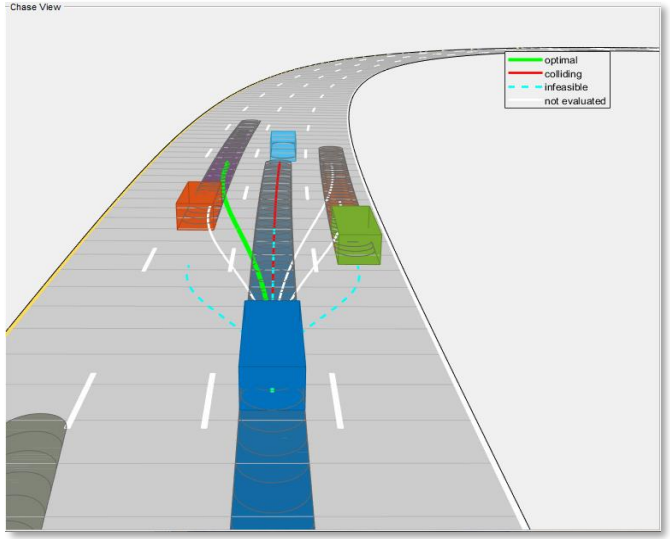


Optimal trajectory
→ Reference trajectory
(virtual lane center)

高速场景自主换道运动规划







基础部分

- 动机
- 运动规划框架
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- 参考示例演示
- 高速场景自主换道规划架构
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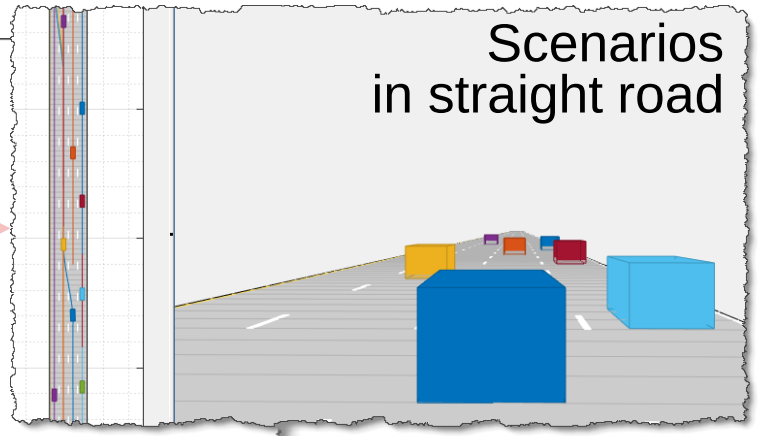
仿真测试

- 多场景的仿真
- 路网文件导入创建场景

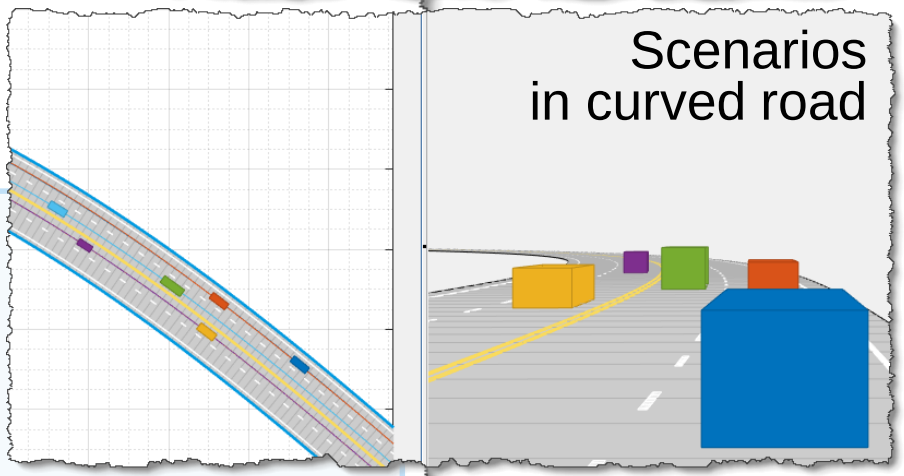
针对规划策略的多场景仿真测试

```
function helperSLHighwayLaneChangeSetup(nvp)

arguments
    nvp.scenarioFcnName {mustBeMember(nvp.scenarioFcnName,...
        ["scenario_LC_01_SlowMoving";...
        "scenario_LC_02_SlowMovingWithPassingCar";...
        "scenario_LC_03_DisabledCar";...
        "scenario_LC_04_CutInWithBrake";...
        "scenario_LC_05_SingleLaneChange";...
        "scenario_LC_06_DoubleLaneChange";...
        "scenario_LC_07_RightLaneChange";...
        "scenario_LC_08_SlowmovingCar_Curved";...
        "scenario_LC_09_CutInWithBrake_Curved";...
        "scenario_LC_10_SingleLaneChange_Curved";...
        "scenario_LC_11_MergingCar_HighwayEntry";...
        "scenario_LC_12_CutInCar_HighwayEntry";...
        "scenario_LC_13_DisabledCar_Ushape";...
        "scenario_LC_14_DoubleLaneChange_Ushape";...
        "scenario_LC_15_StopnGo_Curved"])} = "scenario_LC_15_StopnGo_Curved";
end
```



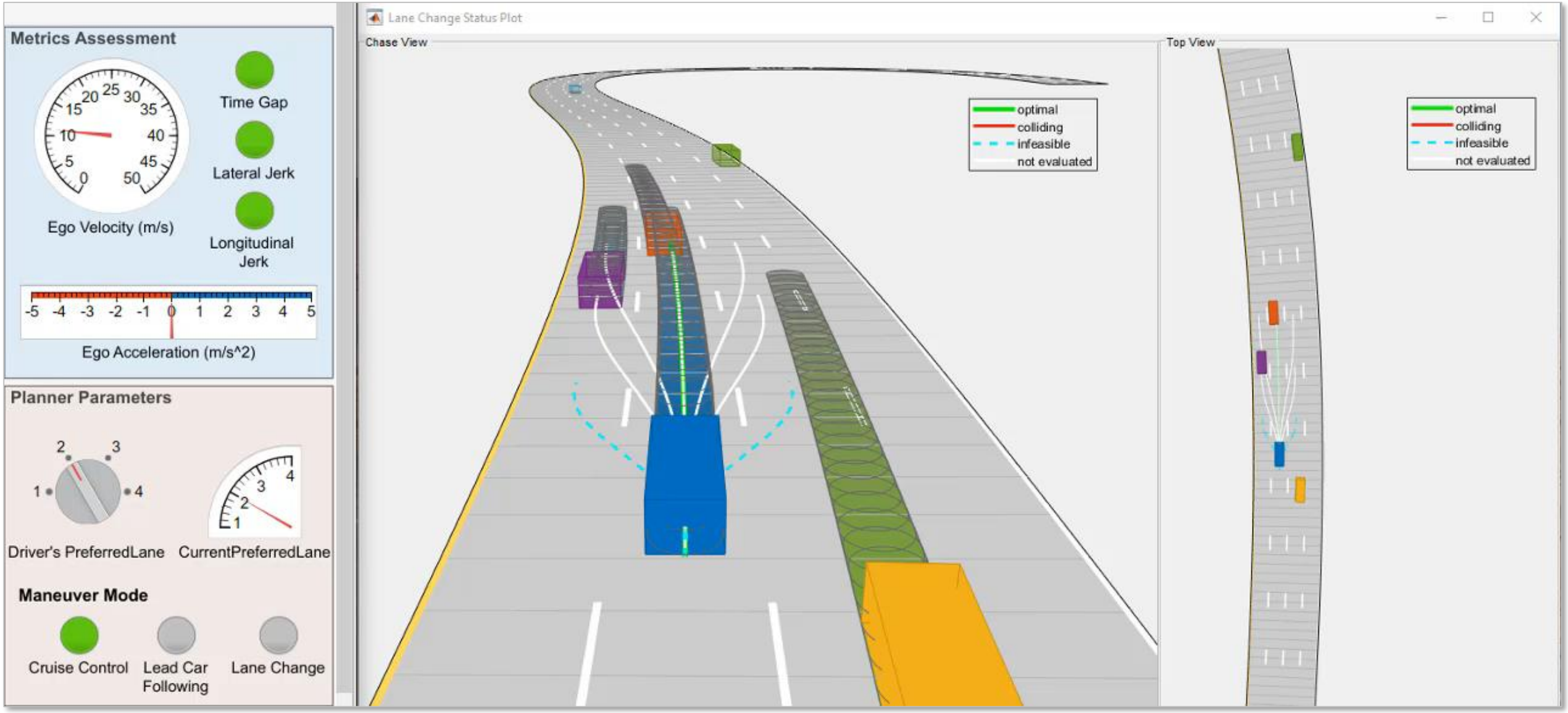
Scenarios
in straight road



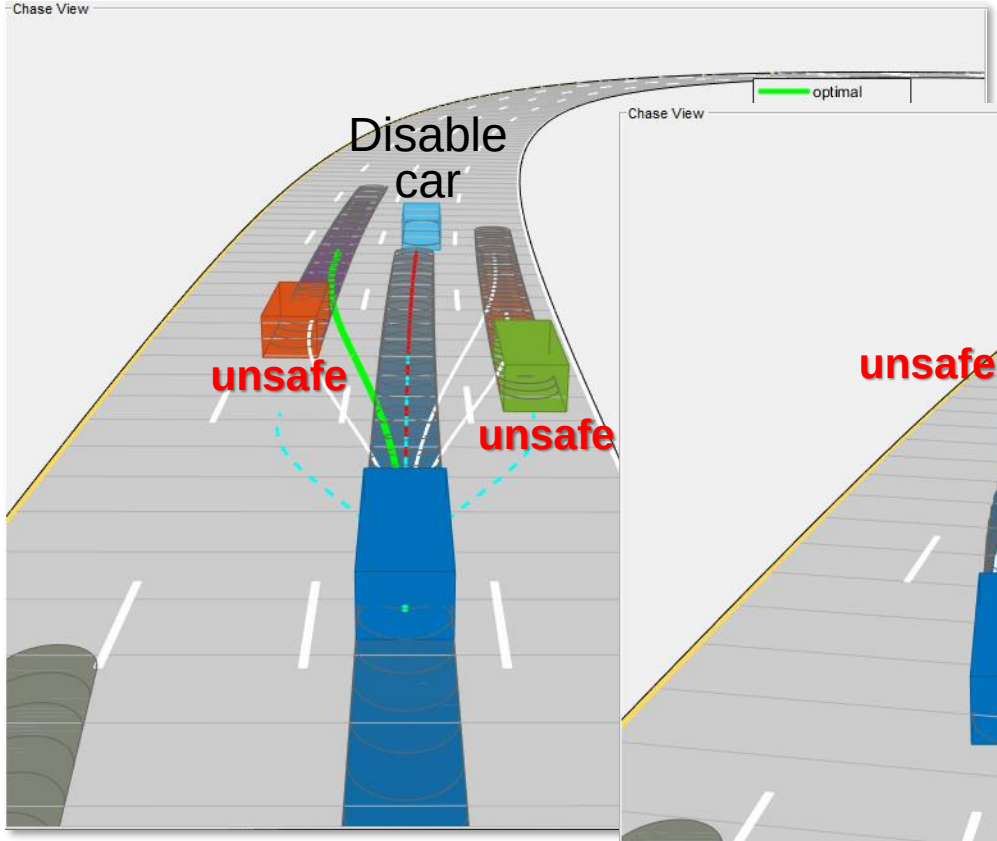
Scenarios
in curved road

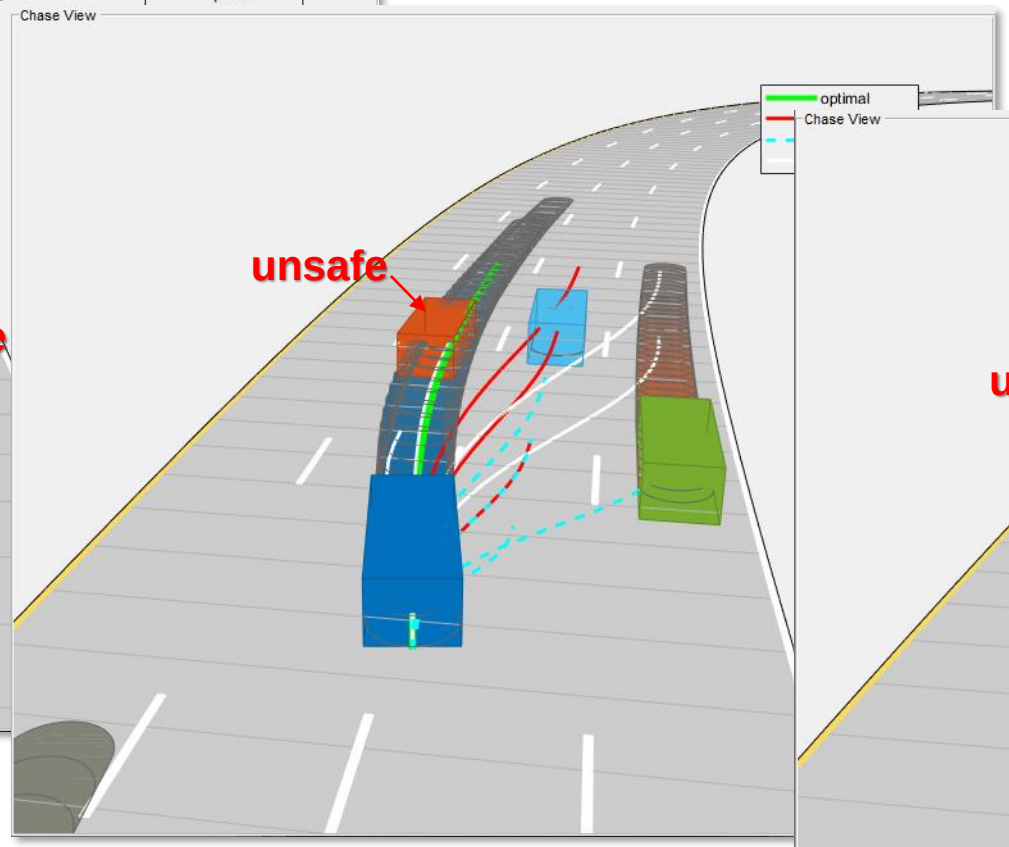
Scenarios
imported from HD map

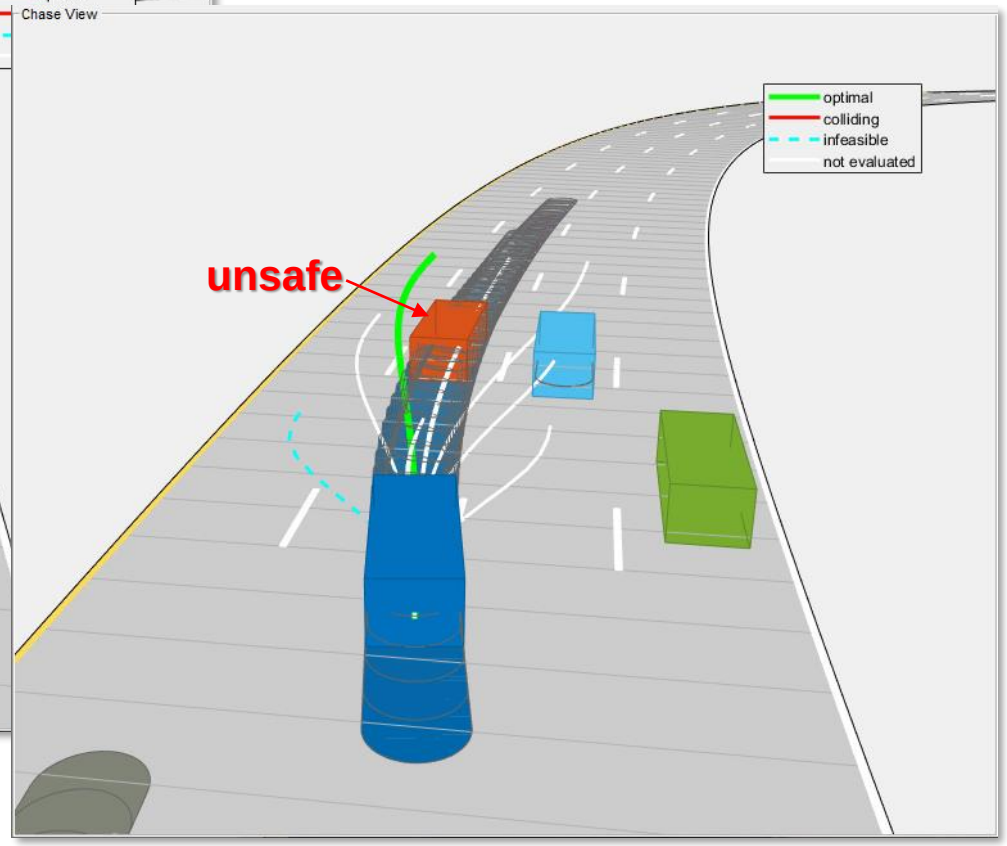
仿真场景14：scenario_LC_14_DoubleLaneChange_Ushape



避免与前方静止车辆碰撞





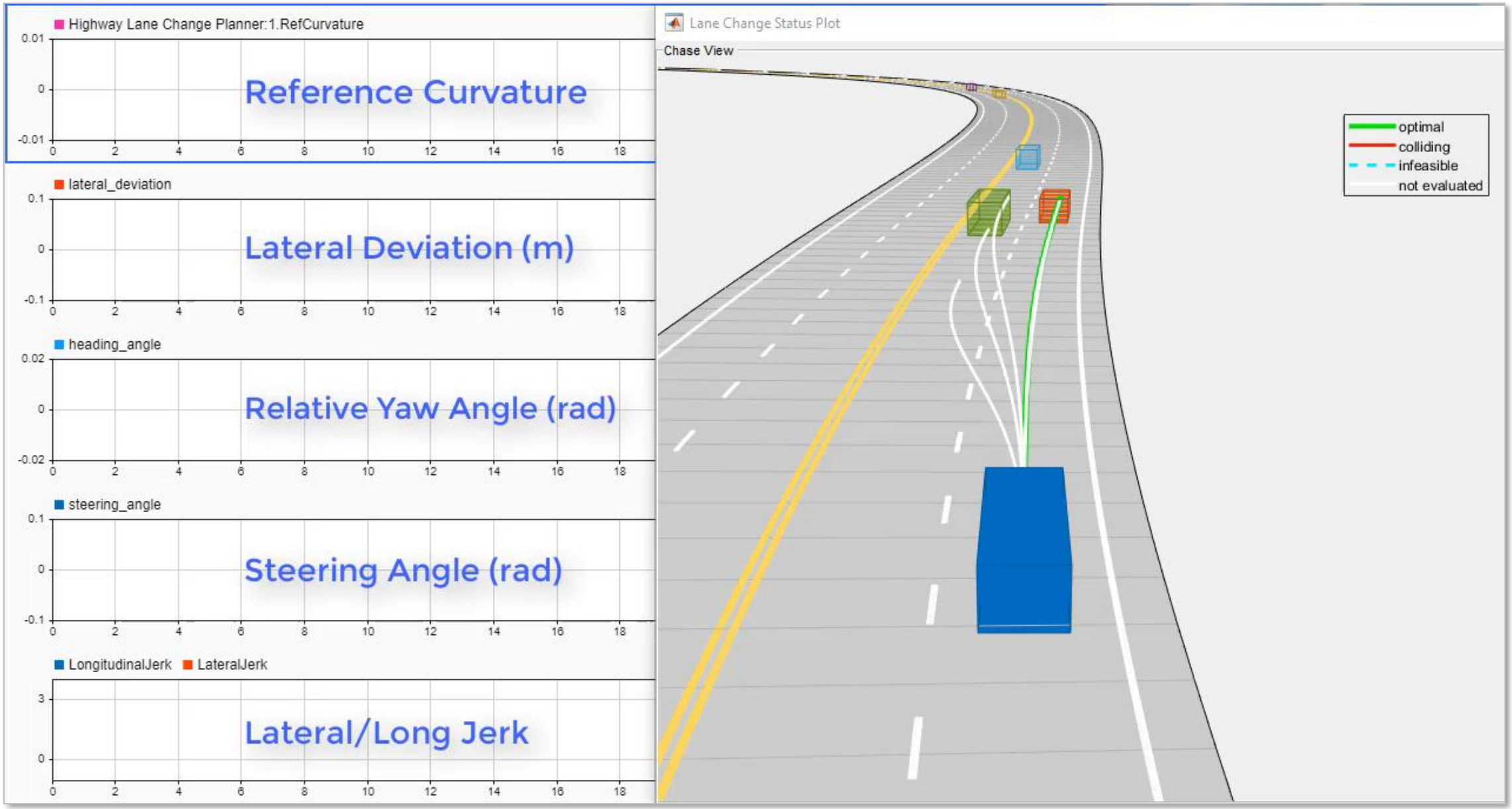


- 检测静止车辆
- 存在unsafe目标，换道轨迹相当激进的corner case

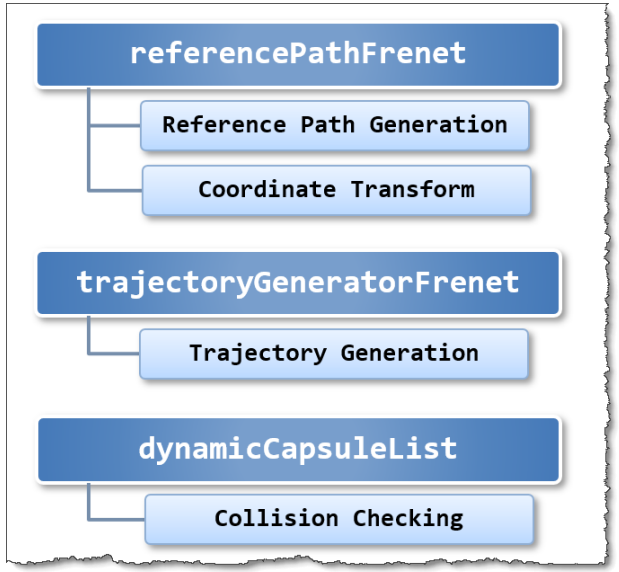
- 换道过程中存在碰撞危险

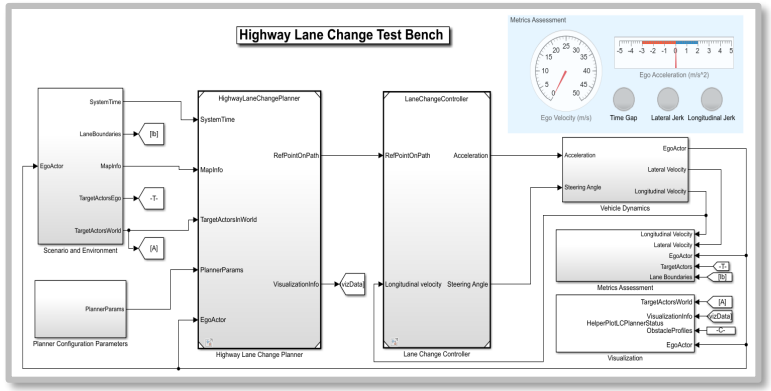
- 再次采取换道策略以避免碰撞

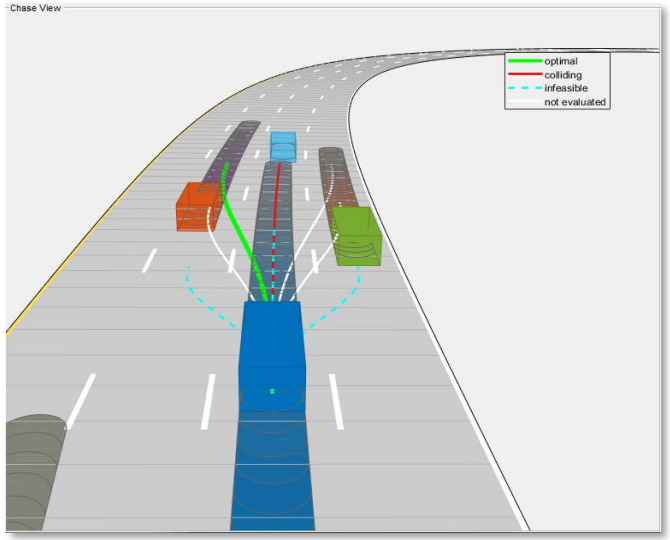
闭环系统仿真场景: scenario_LC_15_StopnGo_Curved



高速场景自主换道运动规划







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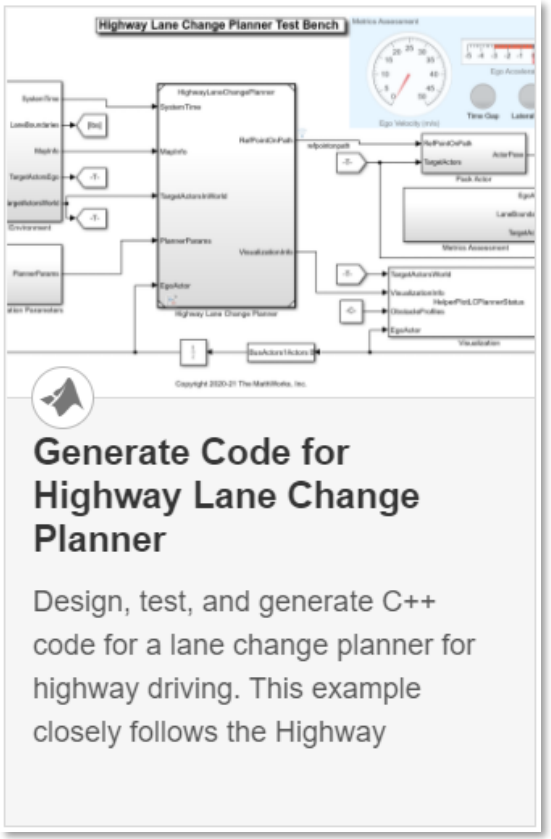
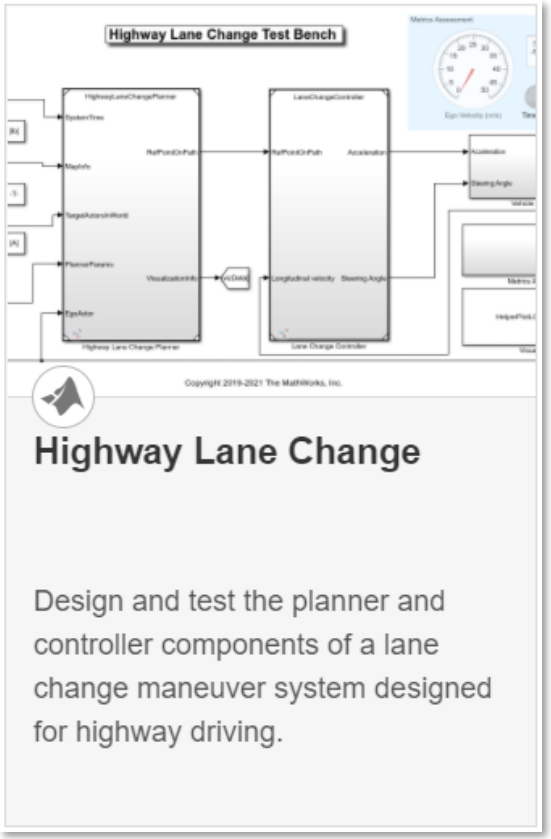
总结：关键信息



规划器代码生成



闭环系统
+ MPC控制
+ 车辆动力学

- 演示了如何设计和仿真测试高速自主换道策略
- 参考示例提供了自主开发和测试换道策略的良好框架
- Navigation and Automated Driving Toolbox 提供了高速自主换道策略主要的函数

`referencePathFrenet`

`trajectoryGeneratorFrenet`

`dynamicCapsuleList`

Automated Driving Toolbox™
Navigation Toolbox™
Model Predictive Control Toolbox™

R2021a

MATLAB EXPO 2021

谢谢！

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