2020 MathWorks 中国汽车年会

开发用于高速公路变道动作的规划和控制算法

王鸿钧
MathWorks中国区资深应用工程师

MathWorks®

仿真高速公路变道动作

Highway Lane Change

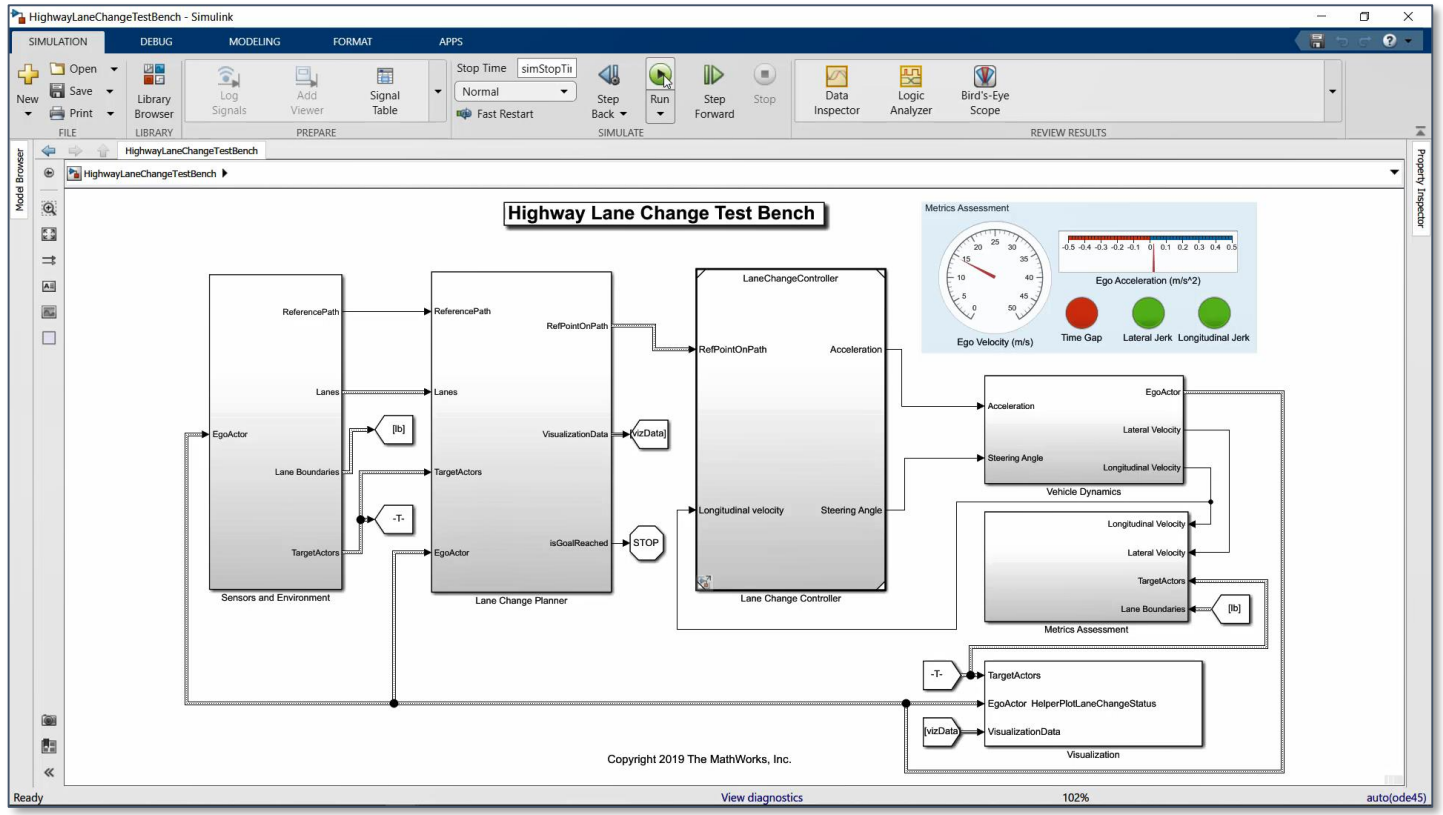
- 寻找车辆周围的关键目标（MIOs）
- 生成避免碰撞的最优变道轨迹
- 根据当前位置计算参考路径点
- 采用模型预测控制（MPC）跟随路径

Navigation Toolbox™

Model Predictive Control Toolbox™

Automated Driving Toolbox™

Updated R2020a



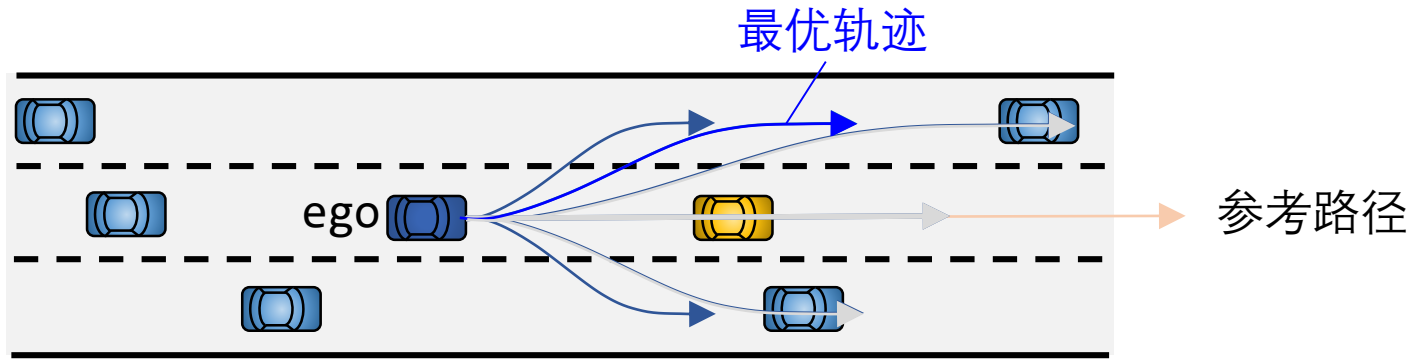
运动规划器组件

规划器 – trajectoryOptimalFrenet

- 针对参考路径，生成一个可实现，避免碰撞，最优的轨迹

```
planner = trajectoryOptimalFrenet(refPath,validator)
```

  - `refPath` ：参考路径
  - `validator` ：用于检查碰撞的状态校验



Navigation Toolbox™
R2019b

碰撞状态校验

```
% Create a state validator object for collision checking
stateValidator = validatorOccupancyMap;

% Create and Assign binaryOccupancyMap to the state validator
stateValidator.Map = binaryOccupancyMap(width,height);
```

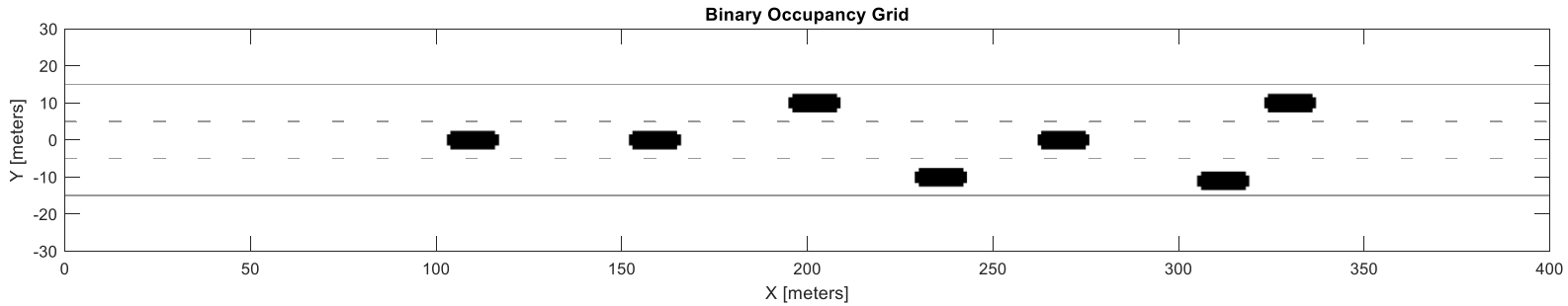
1) 基于二进制 2-D 占据栅格地图

```
% Or, use occupancyMap
stateValidator.Map = occupancyMap(width,height);
```

2) 基于概率值 2-D 占据栅格地图 (0~1)

```
% Or, create a custom state validator object
stateValidator = MyCustomStateValidator;

classdef MyCustomStateValidator < nav.StateValidator & ...
        matlabshared.planning.internal.EnforceScalarHandle
```

3) 自定义状态校验算法



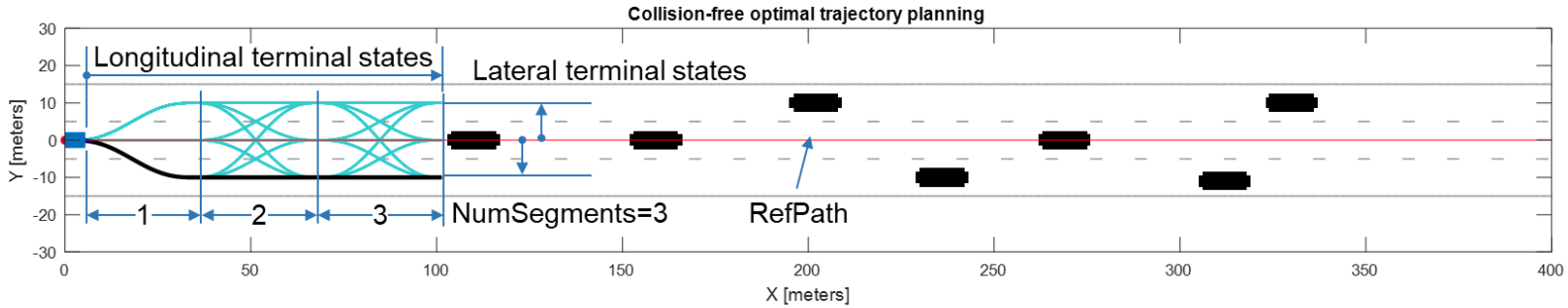
规划器参数

```
% Assign terminal states for longitudinal state, lateral deviation,
% speed, time, and acceleration
planner.TerminalStates.Longitudinal = 100;
planner.TerminalStates.Lateral = -10:10:10;
planner.TerminalStates.Speed = 8;
planner.TerminalStates.Time = 7;
planner.TerminalStates.Acceleration = 0;

% Assign number of partitions for the longitudinal terminal state
planner.NumSegments = 3;

% Assign maximum acceleration and curvature values for feasibility
planner.FeasibilityParameters.MaxCurvature = 0.1;
planner.FeasibilityParameters.MaxAcceleration = 10;
```

1) 终点状态

2) 纵向分段数量

3) 可实现性参数



生成最优轨迹

```
trajectory = plan(planner,startFrenetState)
```

Samples multiple candidate trajectories for each pair of states (start, terminal states)

↓

Evaluate cost for all candidate trajectories

↓

Check feasibility for all candidate trajectories

↓

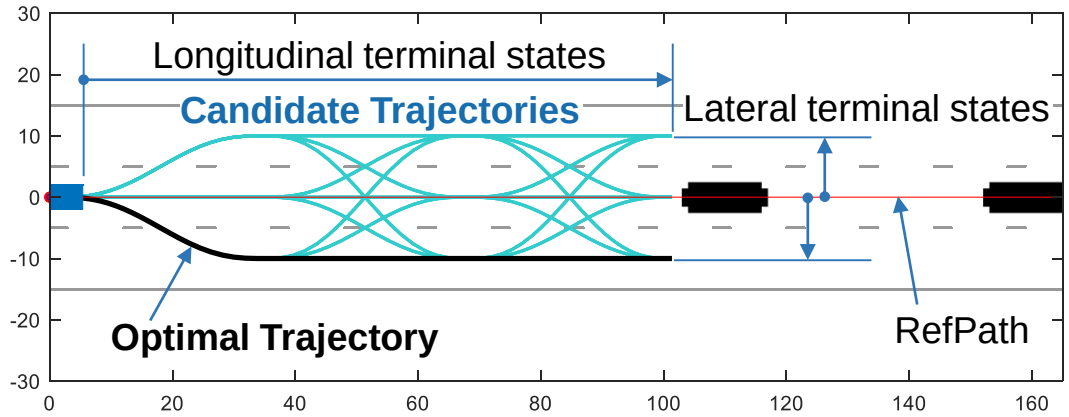
Check collision using state validator

↓

Choose a feasible trajectory with the least cost → optimal, feasible, and collision-free trajectory

权重分配

- Time, Arc length, Deviation
- Lateral/longitudinal smoothness



五次多项式参考轨迹

- 五次多项式

$$s(t) = a_5t^5 + a_4t^4 + a_3t^3 + a_2t^2 + a_1t + a_0$$
$$\dot{s}(t) = 5a_5t^4 + 4a_4t^3 + 3a_3t^2 + 2a_2t + a_1$$
$$\ddot{s}(t) = 20a_5t^3 + 12a_4t^2 + 6a_3t + 2a_2$$

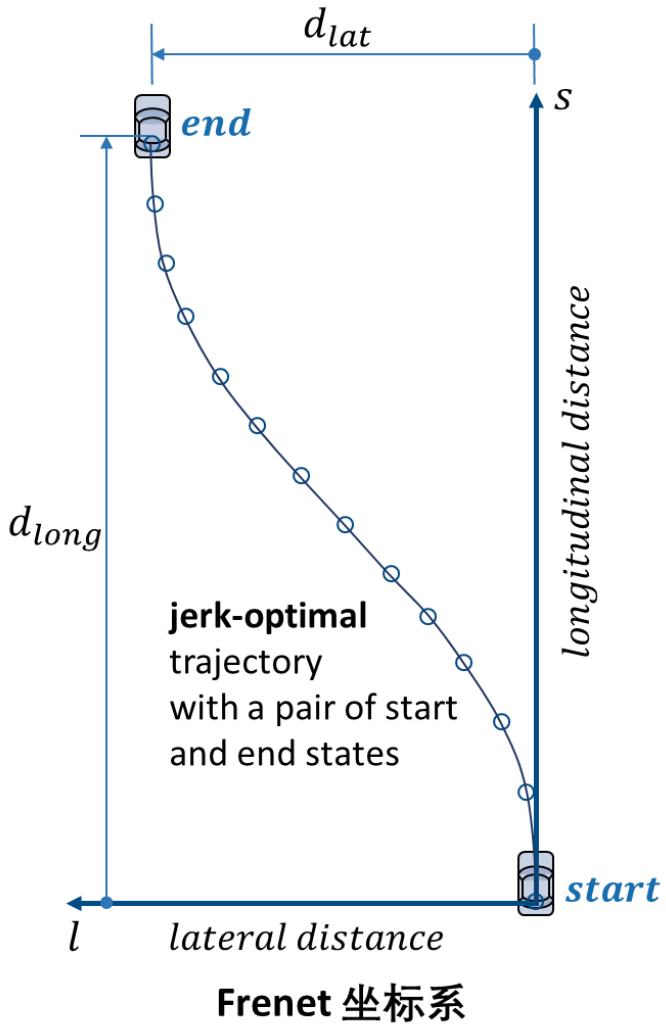
$where\ s = longitudinal\ or\ lateral\ distance$

- 起点边界条件 $(t = 0)$

$$a_0 = s_{start}$$
$$a_1 = \dot{s}_{start}$$
$$2a_2 = \ddot{s}_{start}$$

- 终点边界条件 $(t = t_f)$

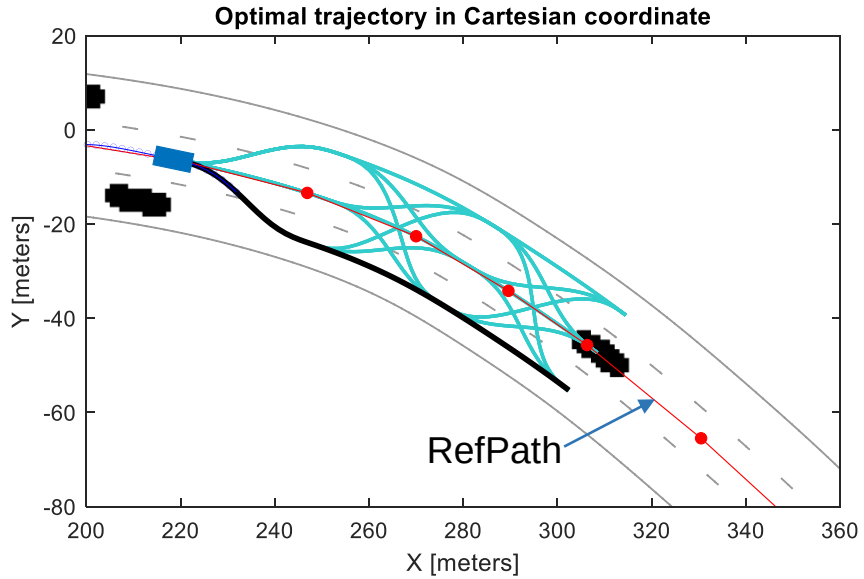
$$a_5t_f^5 + a_4t_f^4 + a_3t_f^3 + a_2t_f^2 + a_1t_f + a_0 = s_{end}$$
$$5a_5t_f^4 + 4a_4t_f^3 + 3a_3t_f^2 + 2a_2t_f + a_1 = \dot{s}_{end}$$
$$20a_5t_f^3 + 12a_4t_f^2 + 6a_3t_f + 2a_2 = \ddot{s}_{end}$$



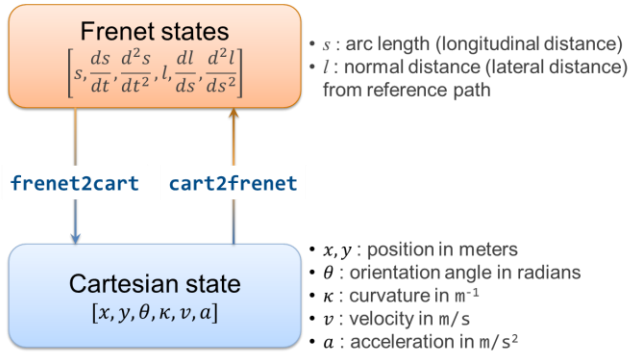
Frenet 坐标系

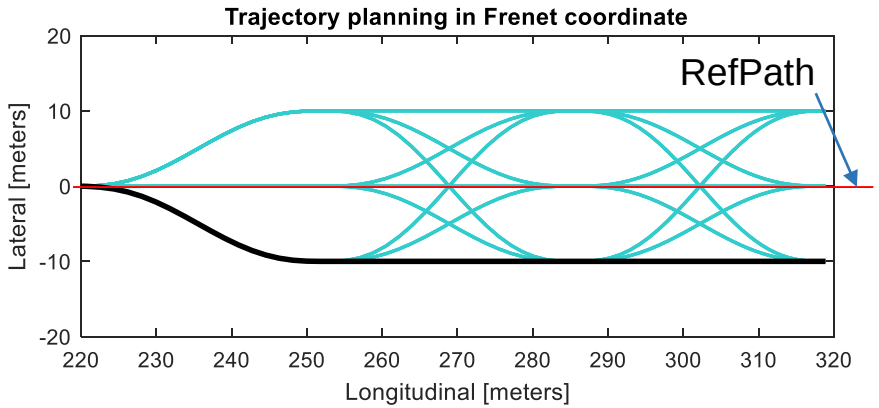
Frenet 坐标系的好处

- 是物体及其轨迹相对参考路径（道路或车道中心线）的表达
- 这种方法极大简化了车辆在弯道上行驶时的轨迹生成问题



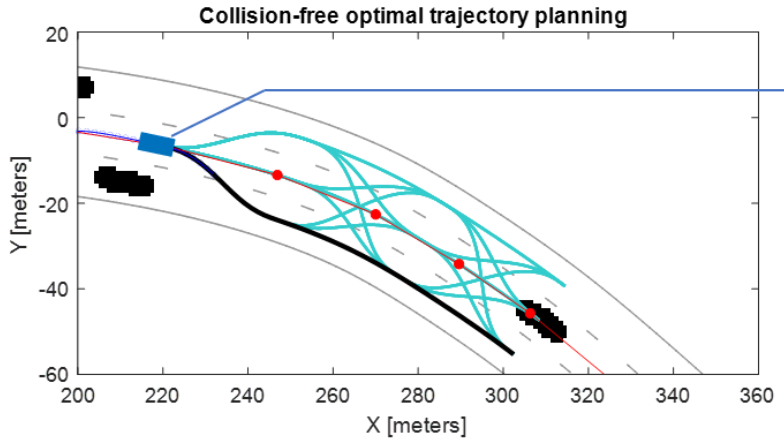
直角坐标系





Frenet 坐标系

Frenet 坐标系 ↔ 直角坐标系



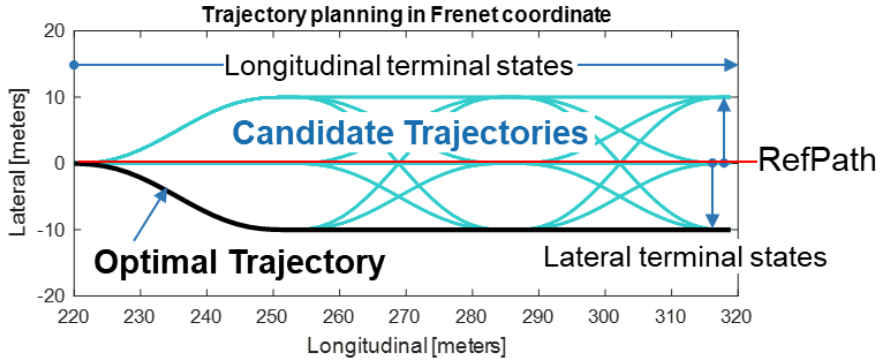
Current Cartesian state
$[x, y, \theta, \kappa, v, a]$

`cart2frenet`

Start Frenet state
$\left[s, \frac{ds}{dt}, \frac{d^2s}{dt^2}, l, \frac{dl}{ds}, \frac{d^2l}{ds^2}\right]$

Optimal trajectory in Cartesian state
$[x, y, \theta, \kappa, v, a, t]$

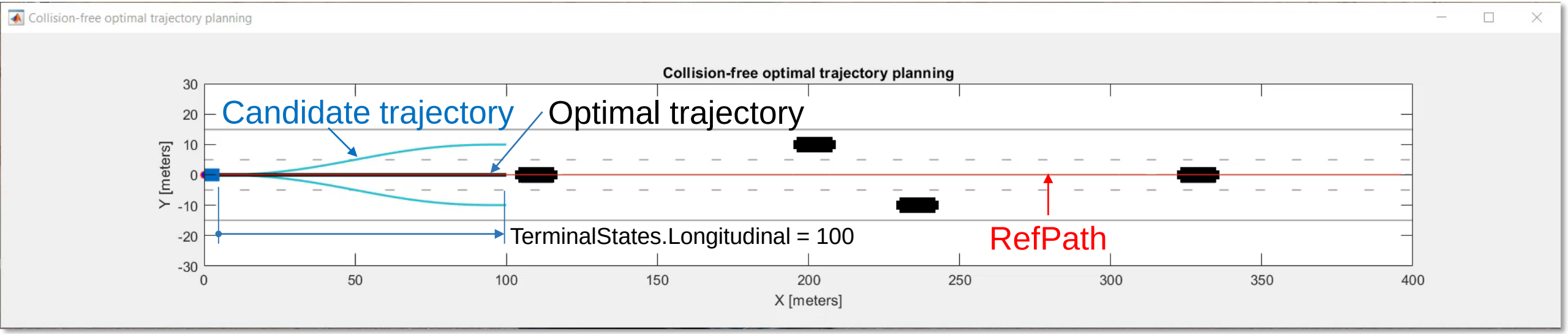
```
trajectory = plan(planner,startFrenetState)
```



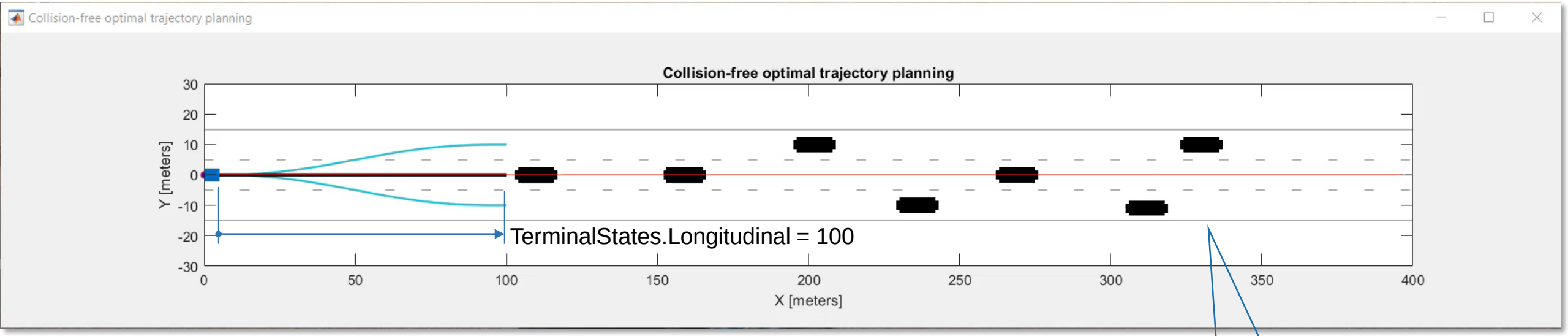
`frenet2cart`

Trajectory generation in Frenet states

调节规划器的参数

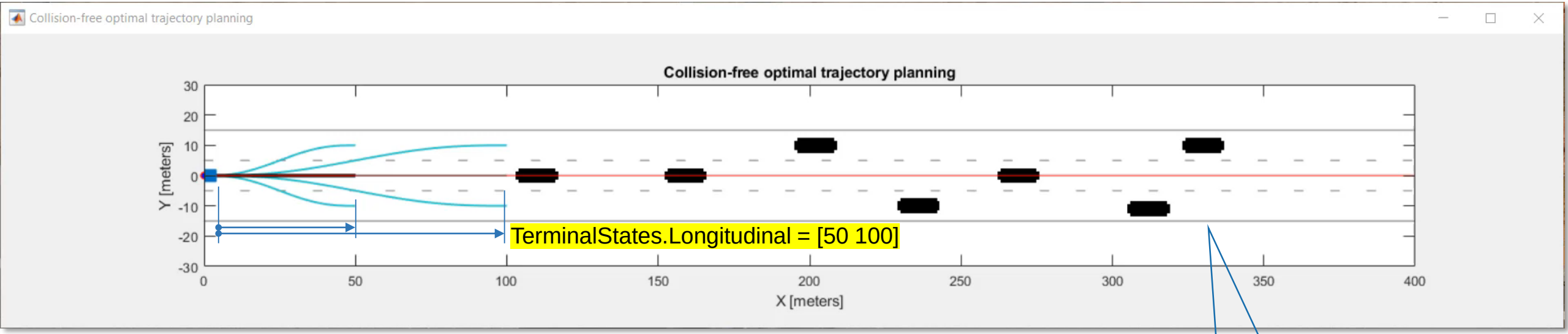

Collision-free optimal trajectory planning
Collision-free optimal trajectory planning
Candidate trajectory
Optimal trajectory
TerminalStates.Longitudinal = 100
RefPath
Y [meters]
X [meters]
30
20
10
0
-10
-20
-30
0
50
100
150
200
250
300
350
400

调节规划器的参数



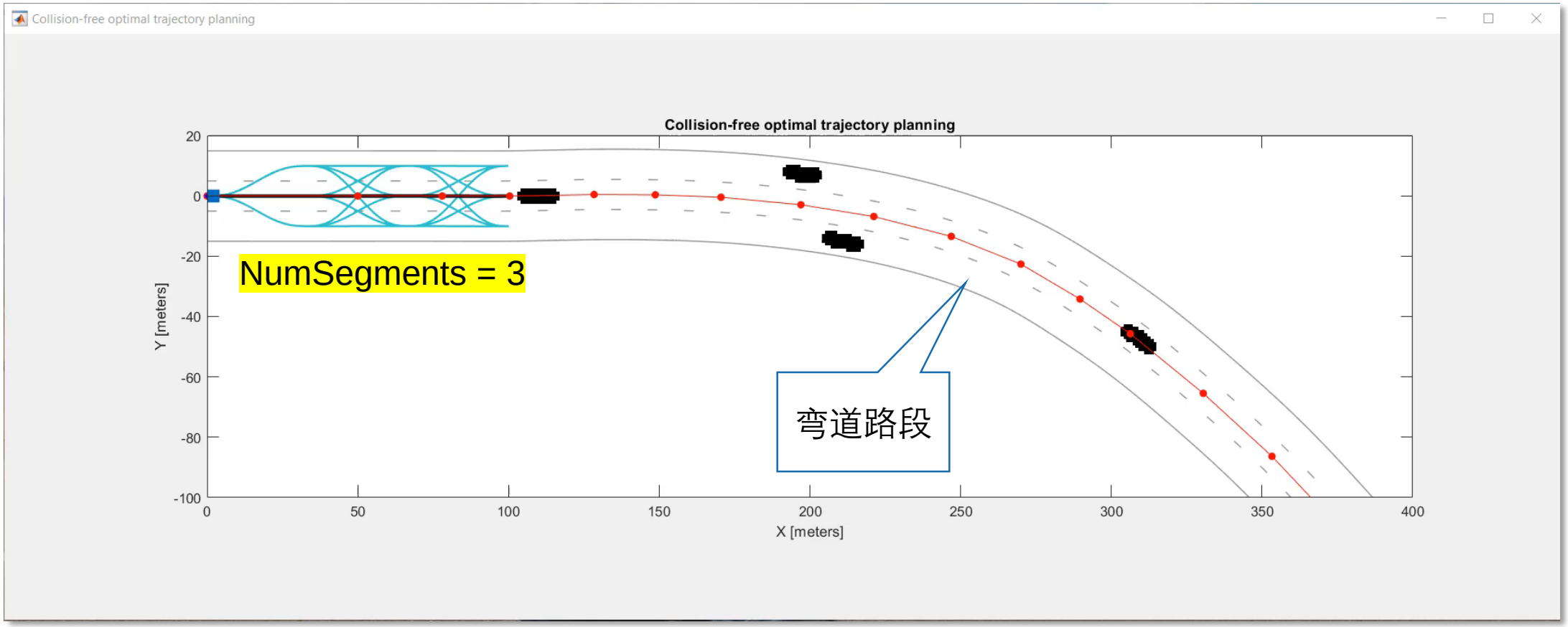
密集的车流

调节规划器的参数



密集的车流

调节规划器的参数

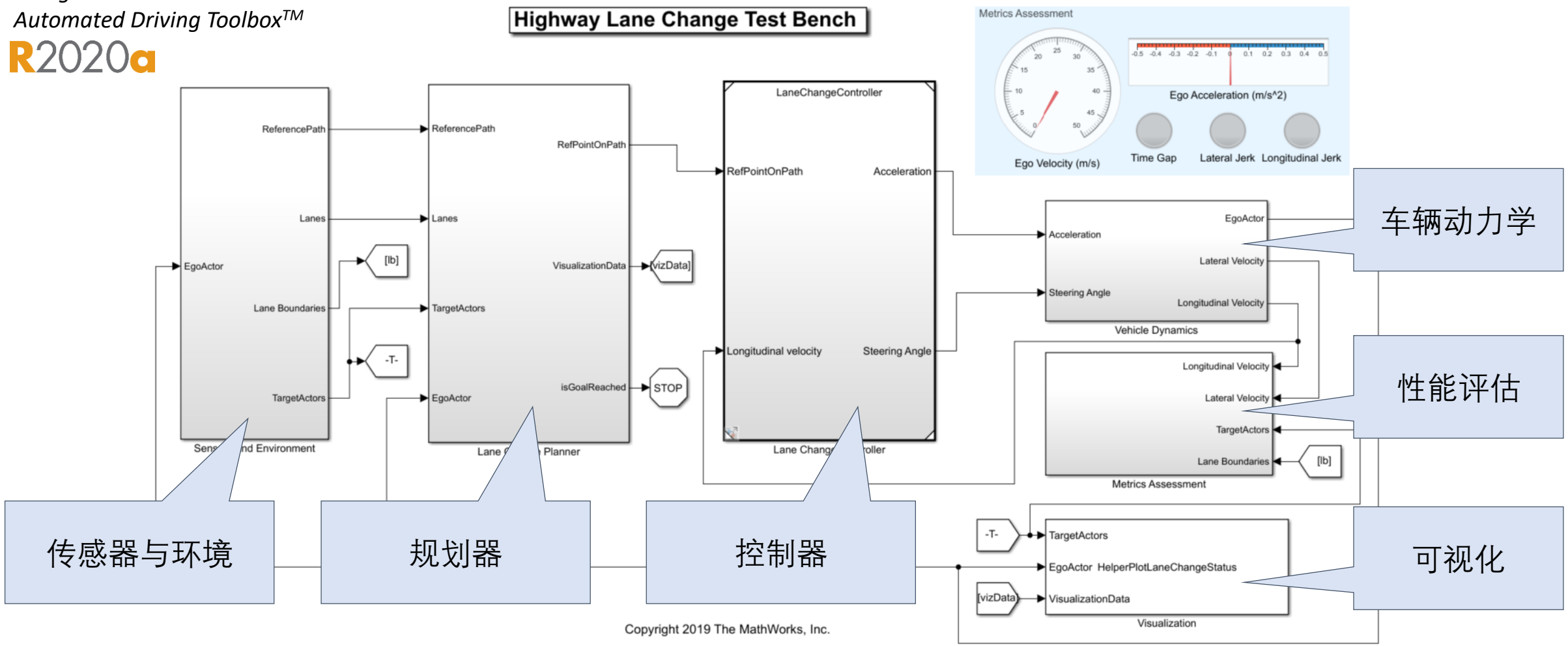

Collision-free optimal trajectory planning
Collision-free optimal trajectory planning
NumSegments = 3
弯道路段
Y [meters]
X [meters]
20
0
-20
-40
-60
-80
-100
0
50
100
150
200
250
300
350
400

集成规划器与控制器

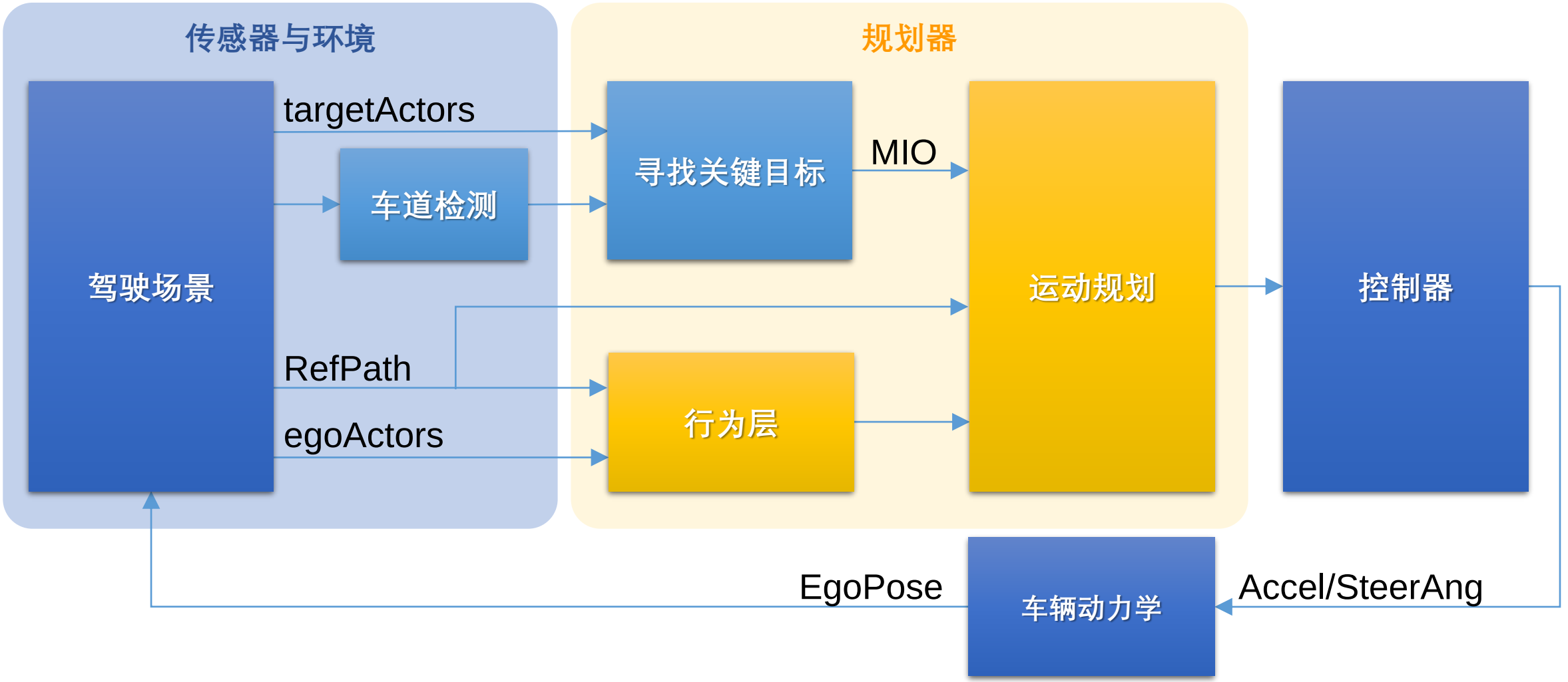
高速公路变道示例的框架

Navigation Toolbox™
Automated Driving Toolbox™

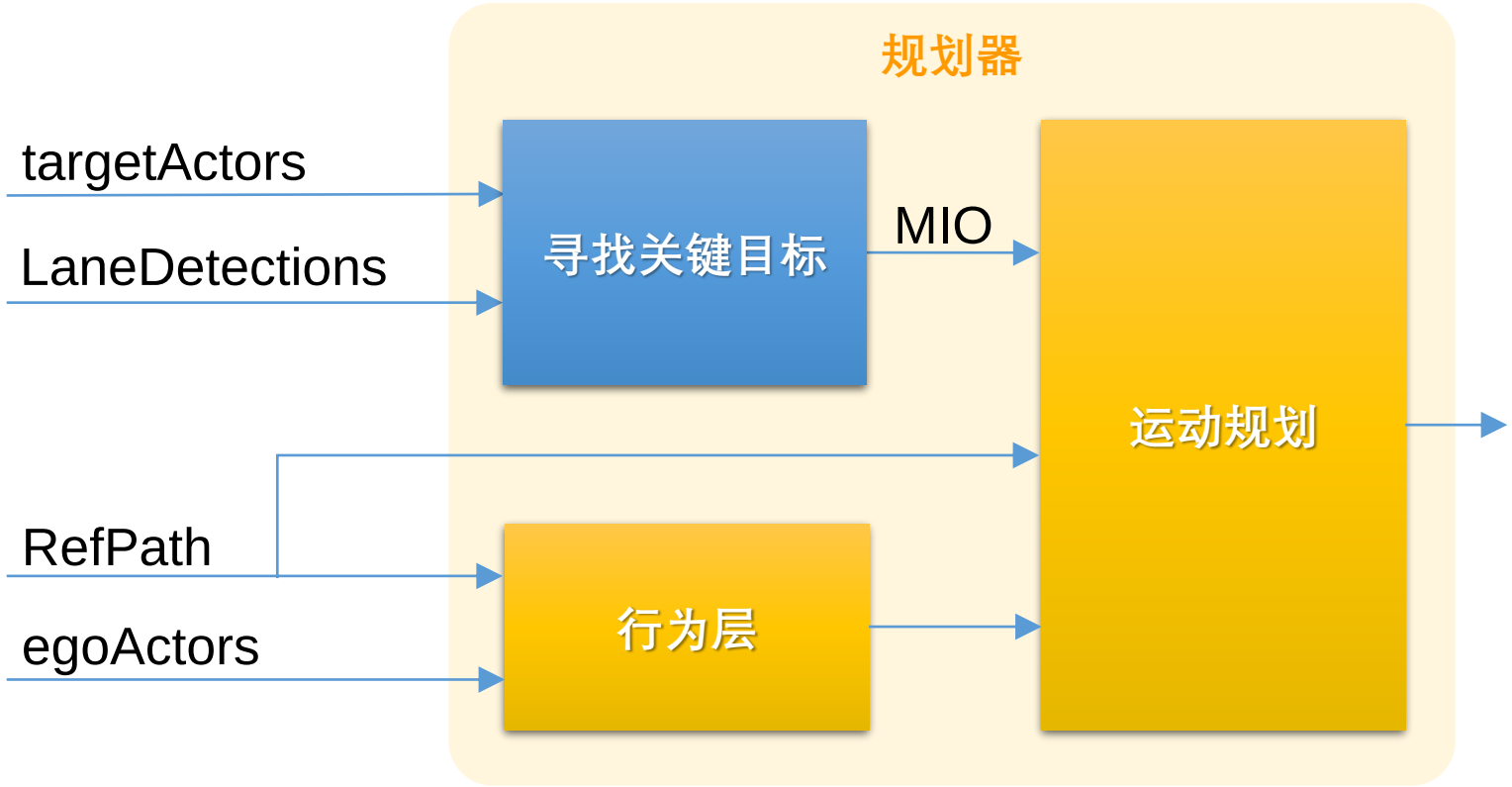
R2020a



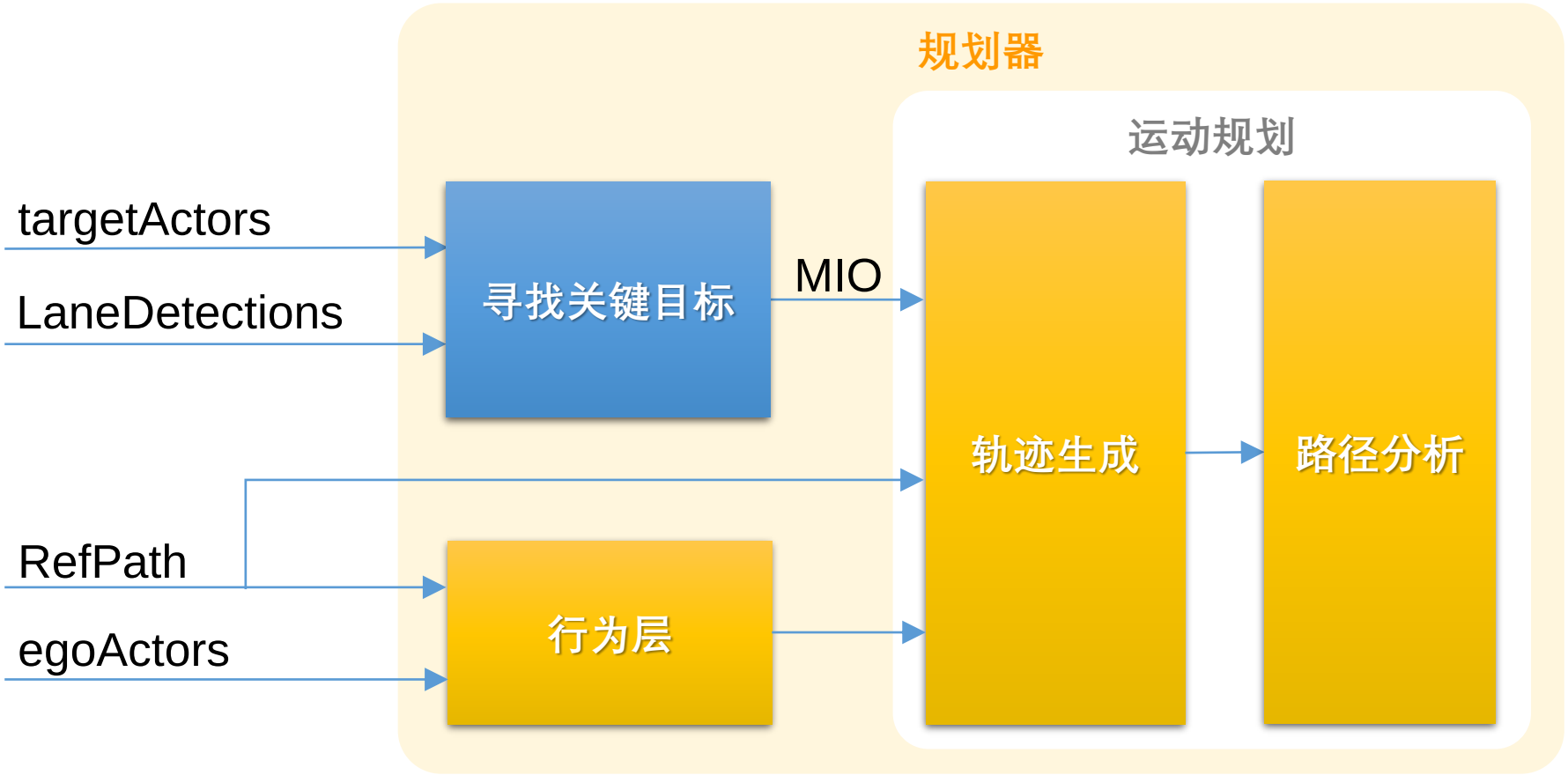
高速公路变道示例的框架



规划器结构

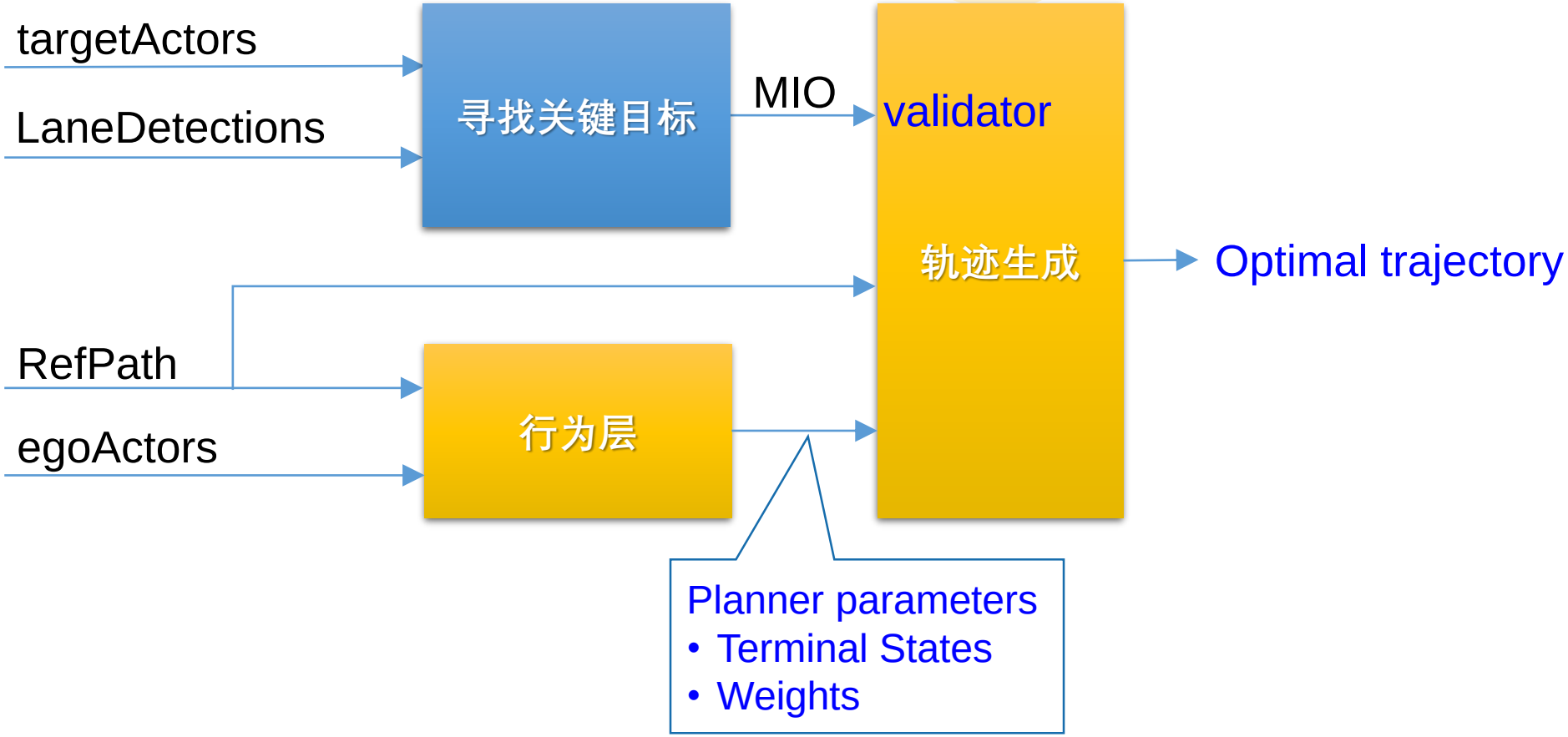

规划器
targetActors
LaneDetections
寻找关键目标
MIO
运动规划
RefPath
egoActors
行为层

规划器结构

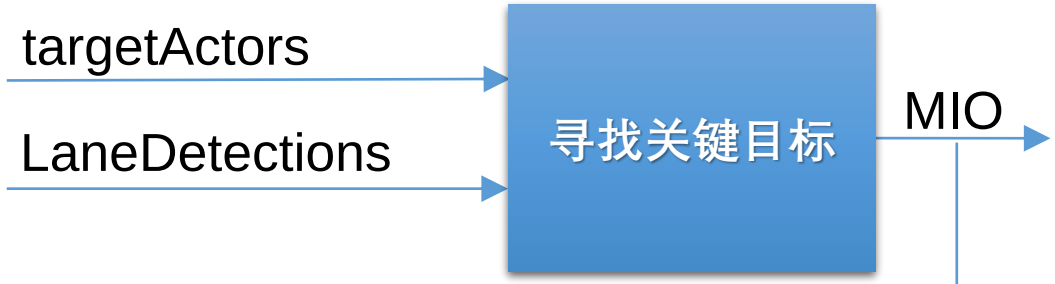

规划器
运动规划
targetActors
LaneDetections
寻找关键目标
MIO
轨迹生成
路径分析
RefPath
egoActors
行为层

规划器结构

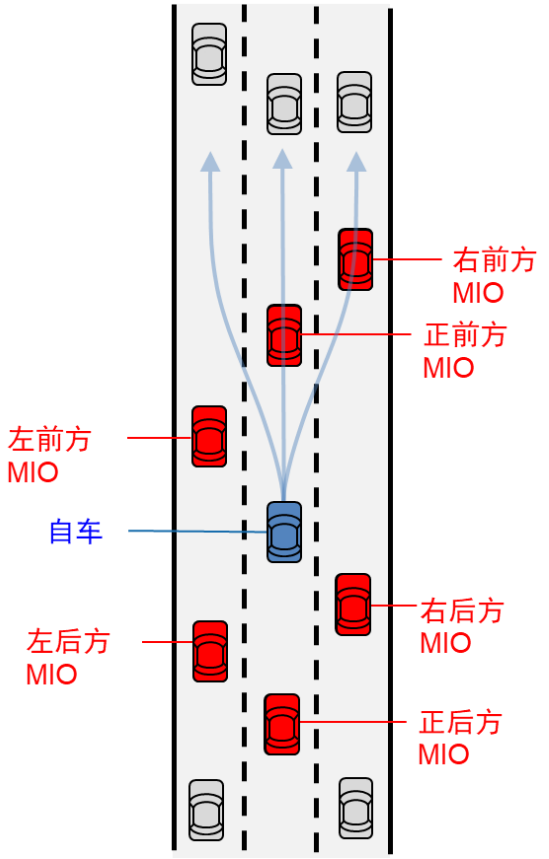
```
planner = trajectoryOptimalFrenet(refPath,validator)
```



寻找关键目标（MIO）

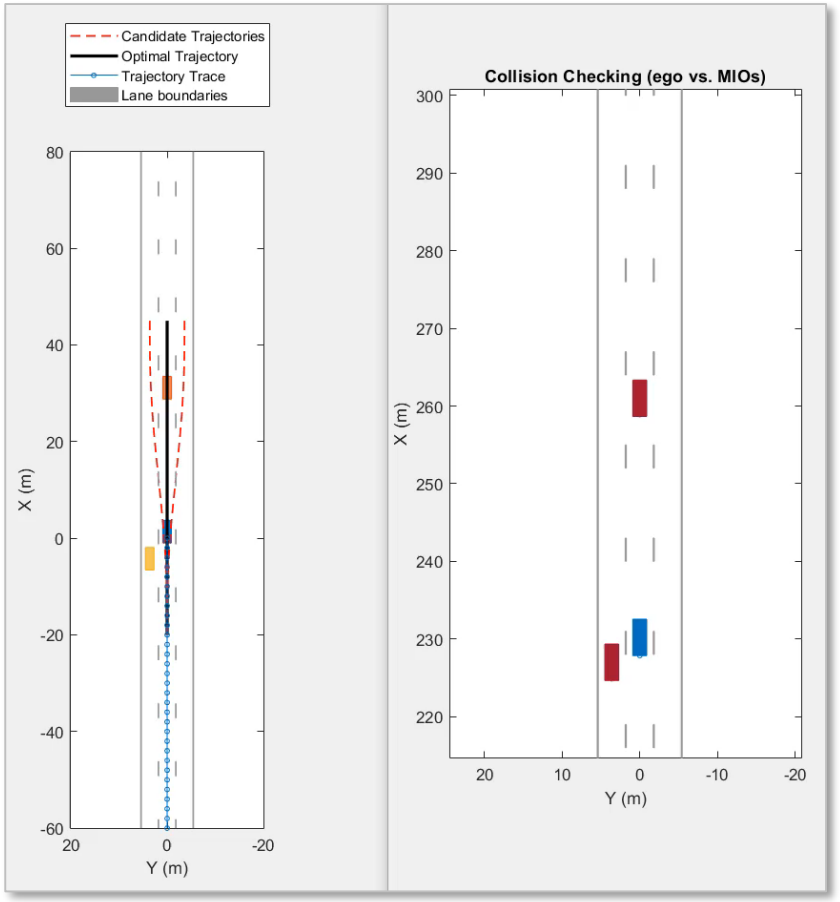


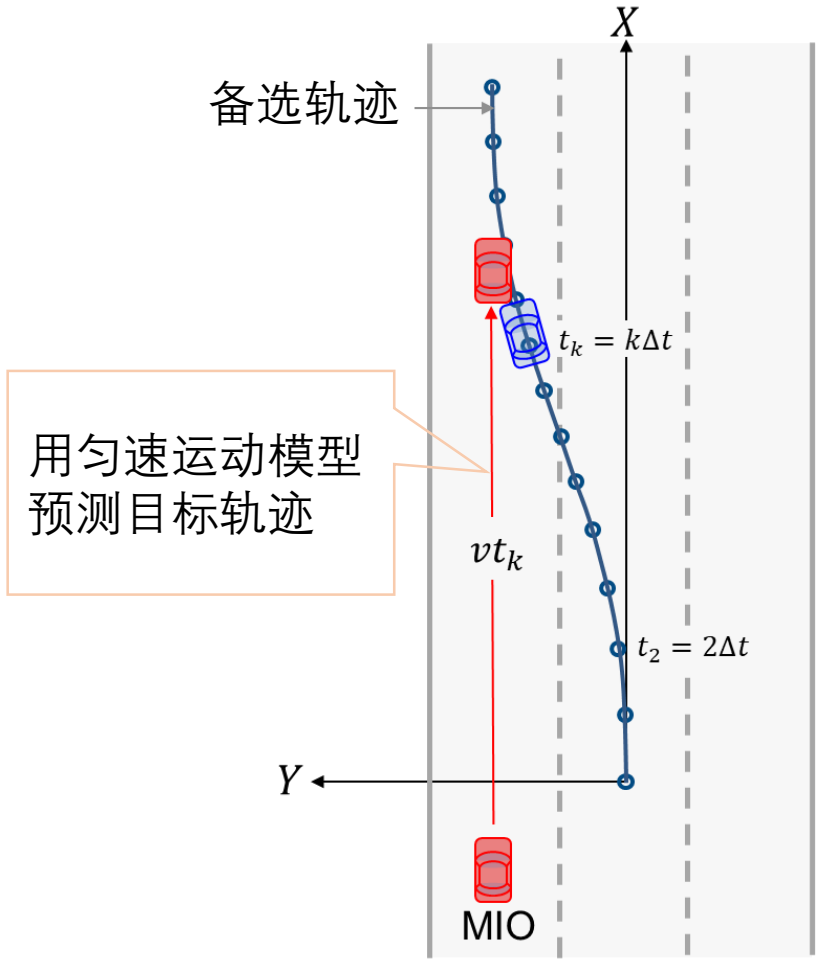

```
planner = trajectoryOptimalFrenet(refPath,validator)
```



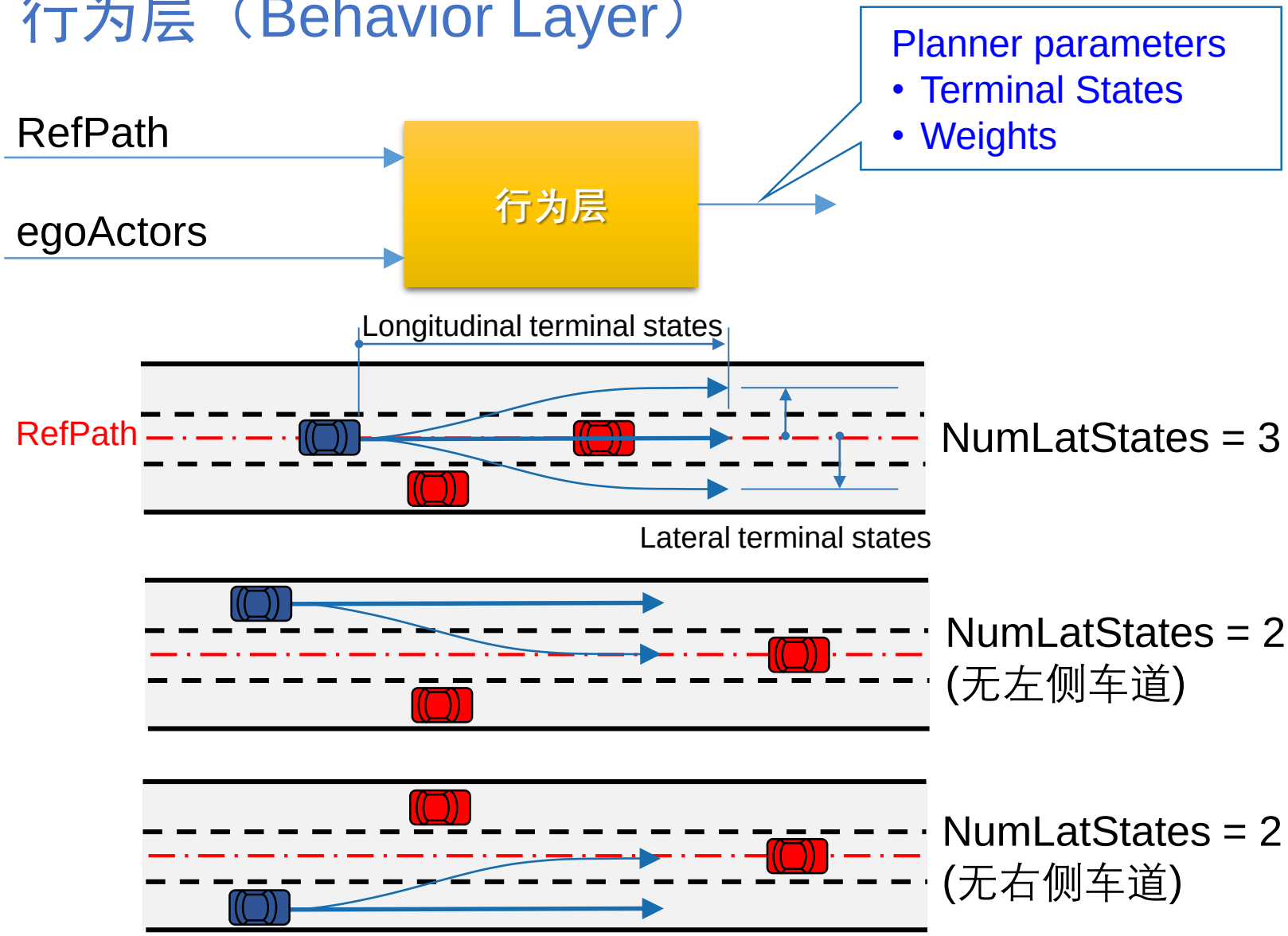
- 寻找当前车道及相邻车道上的关键目标（最多6个）
- 提供给自定义的状态校验器进行碰撞检测

状态校验器（validator）



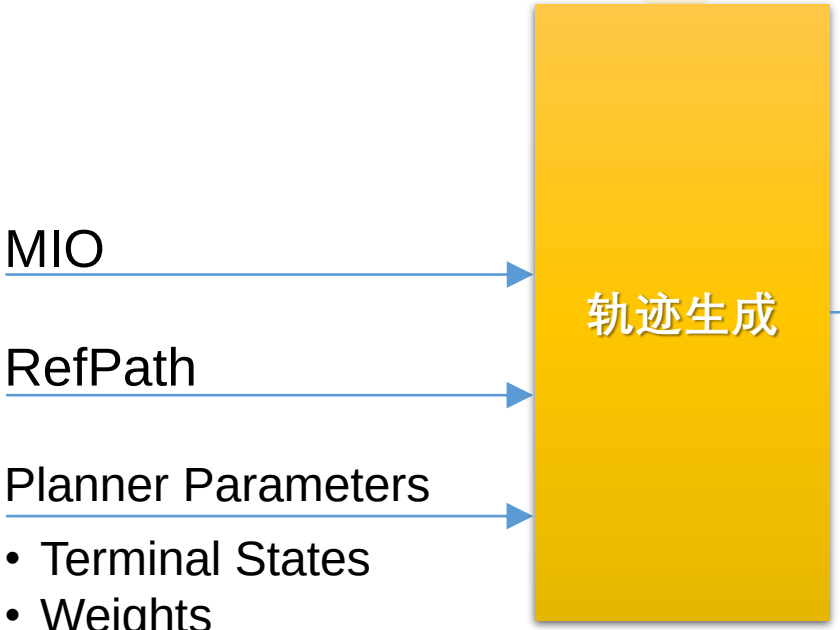


行为层（Behavior Layer）



运动规划 ▷ 轨迹生成

```
planner = trajectoryOptimalFrenet(refPath,validator)
```

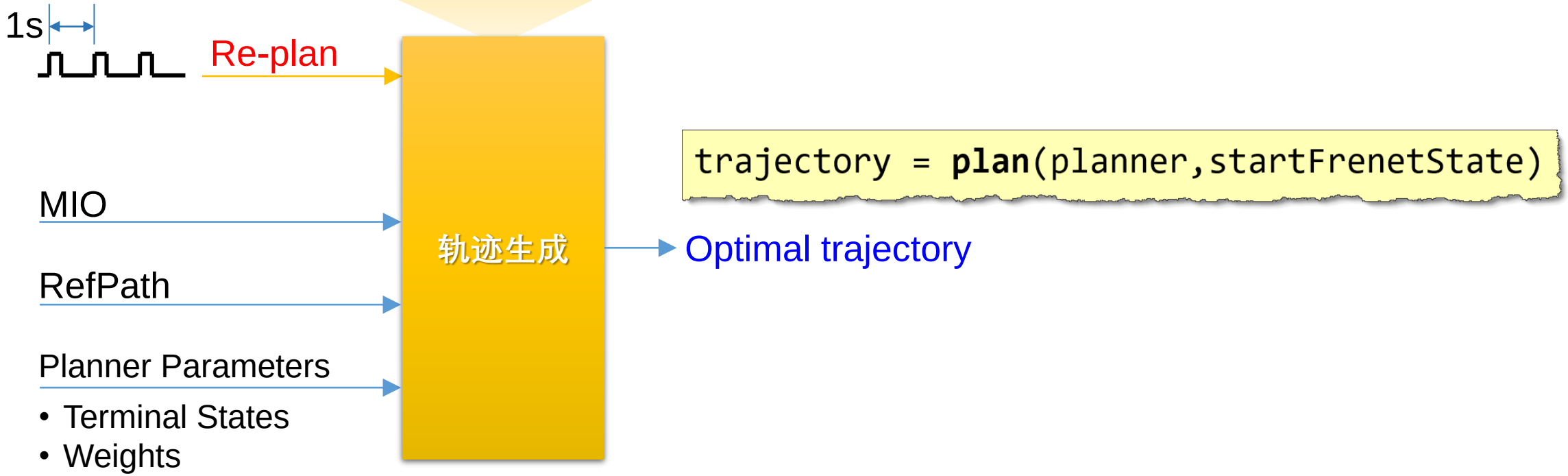



```
trajectory = plan(planner,startFrenetState)
```

Optimal trajectory

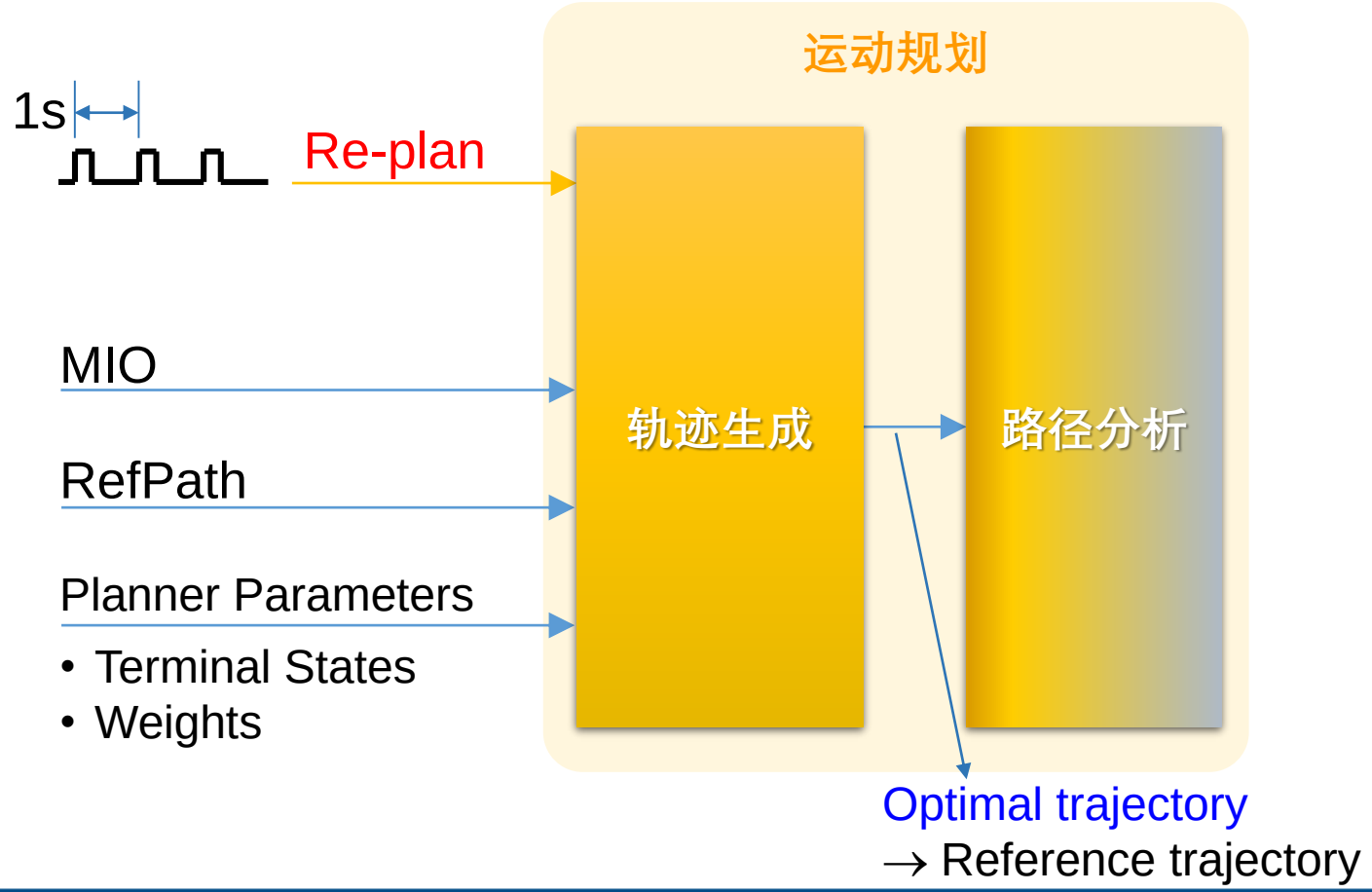
运动规划 ▷ 周期性规划

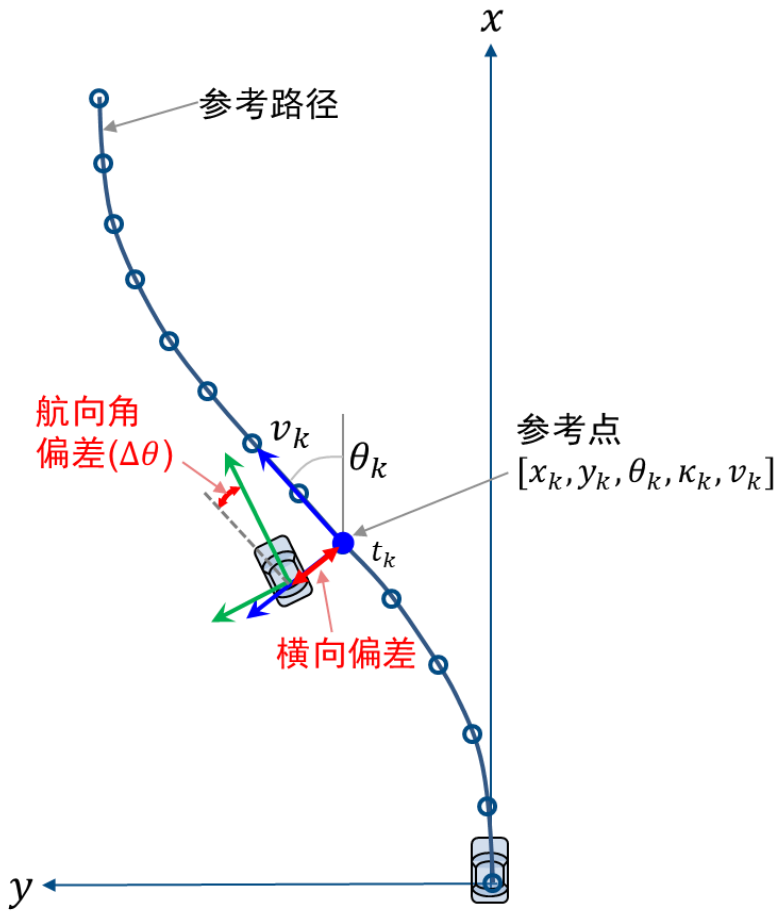
```
planner = trajectoryOptimalFrenet(refPath,validator)
```



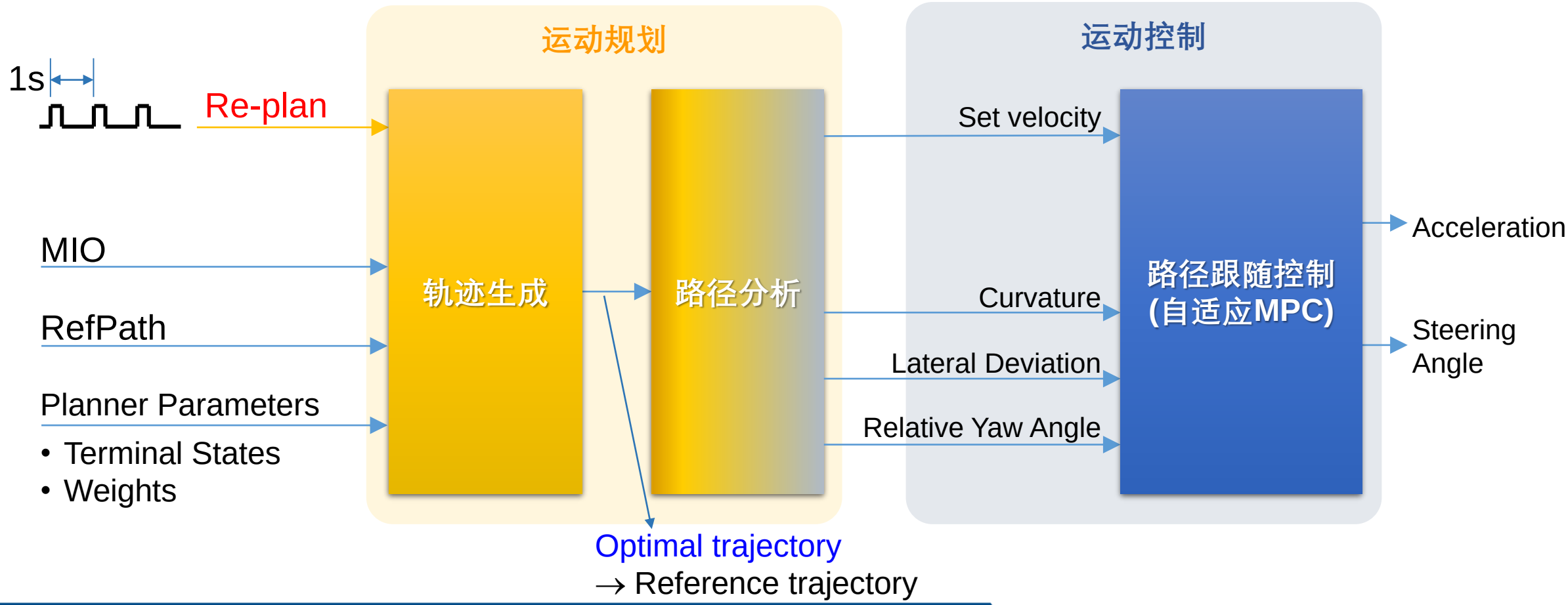

```
trajectory = plan(planner,startFrenetState)
```

运动规划 ▷ 路径分析


运动规划
1s
Re-plan
MIO
RefPath
Planner Parameters
• Terminal States
• Weights
轨迹生成
路径分析
Optimal trajectory
→ Reference trajectory

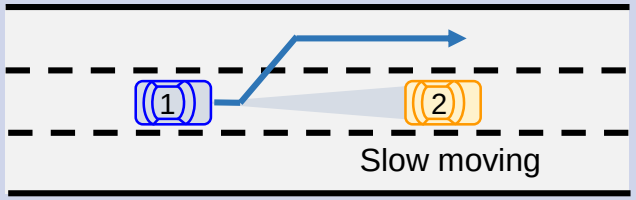

x
参考路径
航向角
偏差(Δθ)
v_k
θ_k
参考点
$[x_k, y_k, \theta_k, \kappa_k, v_k]$
t_k
横向偏差
y

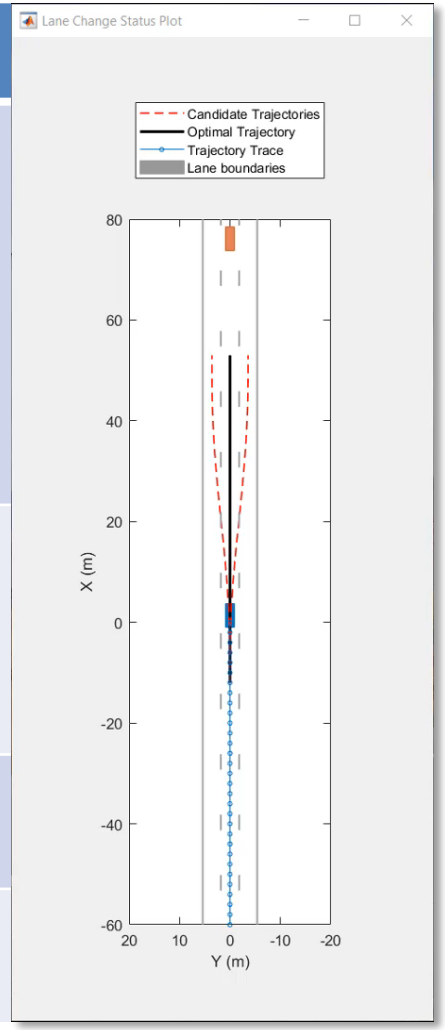
运动控制


1s
Re-plan
MIO
RefPath
Planner Parameters
• Terminal States
• Weights
运动规划
轨迹生成
路径分析
运动控制
Set velocity
Curvature
Lateral Deviation
Relative Yaw Angle
路径跟随控制
(自适应MPC)
Acceleration
Steering
Angle
Optimal trajectory
→ Reference trajectory

仿真简单道路场景（直道左侧超车）

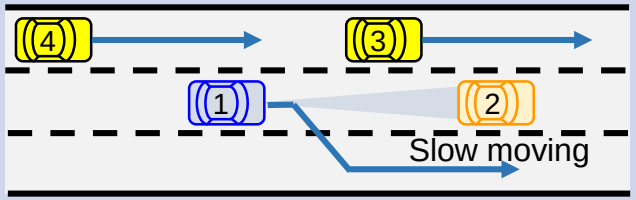
HWT : Headway time
HW : Headway
v_set : set velocity for ego car

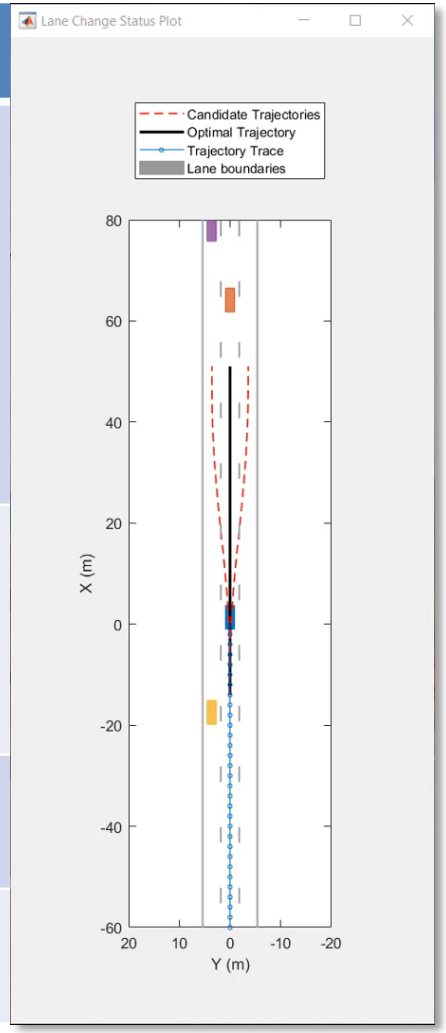
Test Name	scenario_LC_01_SlowMoving
Test Description	Passing slow moving lead car 
(1) Host Car	initial velocity = 20m/s HWT = 6.5sec HW = 130m v_set = 20m/s
(2) Lead Car	constant velocity = 10m/s
Other Cars	None



仿真简单道路场景（直道右侧超车）

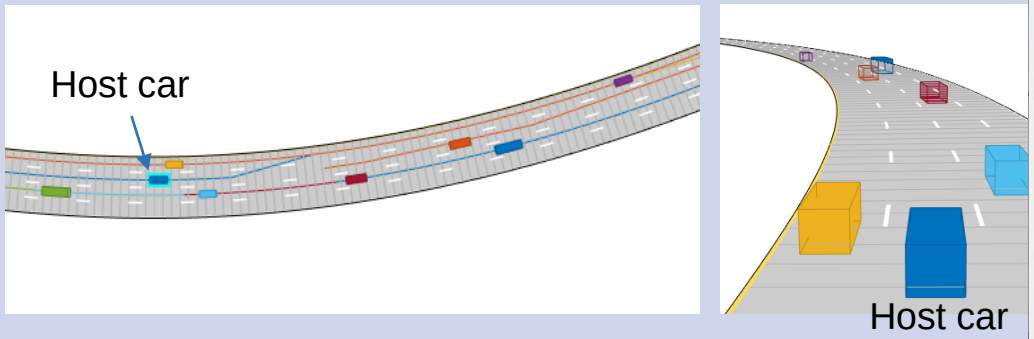
HWT : Headway time
HW : Headway
v_set : set velocity for ego car

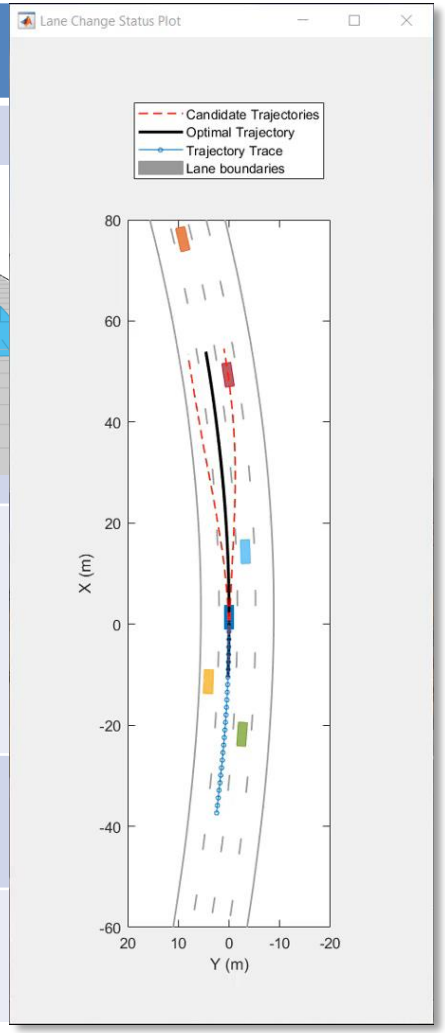
Test Name	scenario_LC_07_RightLaneChange
Test Description	Passing slow moving lead car to right lane 
(1) Host Car	initial velocity = 20m/s HWT = 6sec HW = 120m v_set = 20m/s
(2) Lead Car	constant velocity = 10m/s
Other Cars	Constant velocity = 25m/s (3rd car in left lane) Constant velocity = 24m/s (4th car in left lane)



仿真简单道路场景（弯道左侧超车）

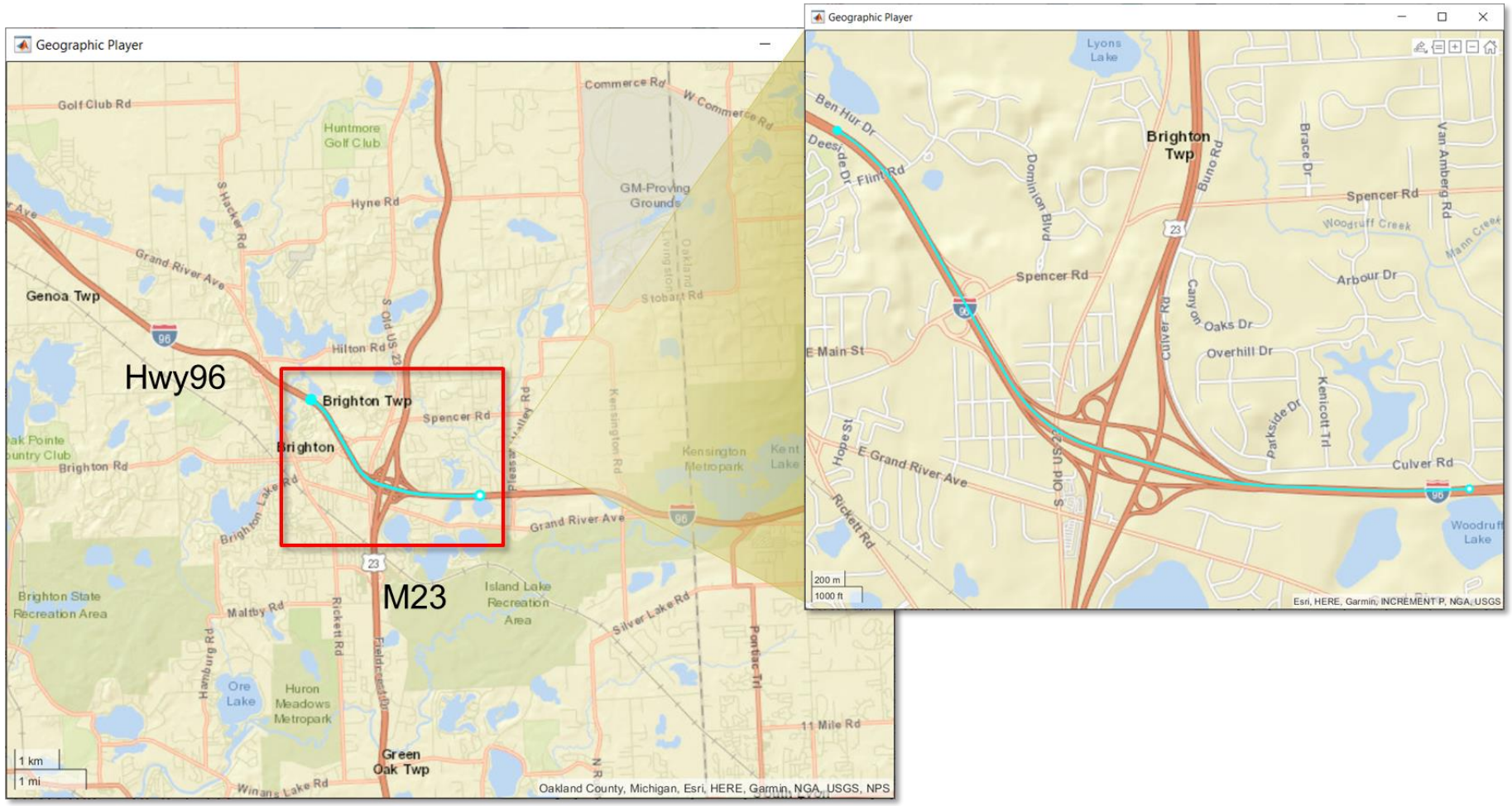
HWT : Headway time
HW : Headway
v_set : set velocity for ego car

Test Name	scenario_LC_10_SingleLaneChange_Curved
Test Description	Passing slow moving lead car to left lane in curved road 
(1) Host Car	initial velocity = 15m/s v_set = 15m/s
(2) Lead Car	Slow moving
Other Cars	Dense traffic

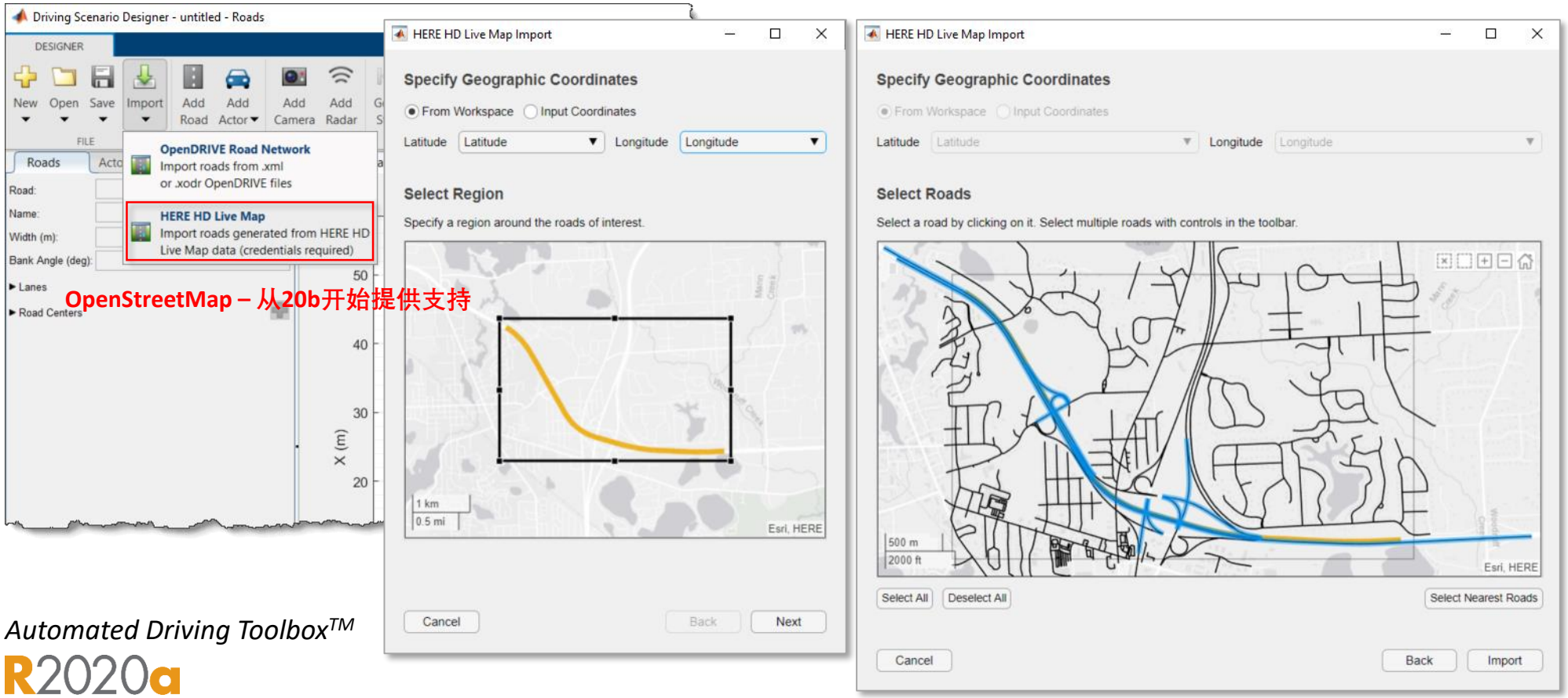


导入地图数据进行测试

浏览地图中的高速路网


Geographic Player
Hwy96
M23
Brighton Twp
Brighton
Genoa Twp
Spencer Rd
Grand River Ave
Hilton Rd
Hyne Rd
Commerce Rd
W Commerce Rd
Golf Club Rd
Huntmore Golf Club
GM-Proving Grounds
Kensington Metropark
Island Lake Recreation Area
Brighton State Recreation Area
Huron Meadows Metropark
Ore Lake
Maltby Rd
Silver Lake Rd
11 Mile Rd
Green Oak Twp
Oakland County, Michigan, Esri, HERE, Garmin, NGA, USGS, NPS
Geographic Player
Lyons Lake
Ben Hur Dr
Deesside Dr
Flint Rd
Dominion Blvd
Buno Rd
Brace Dr
Van Amberg Rd
Woodruff Creek
Arbour Dr
Canyon Oaks Dr
Overhill Dr
Culver Rd
Kenicott Trl
Parkside Dr
E Main St
Hope St
E Grand River Ave
Ricketts Rd
Culver Rd
Woodruff Lake
200 m
1000 ft
Esri, HERE, Garmin, INCREMENT P, NGA, USGS

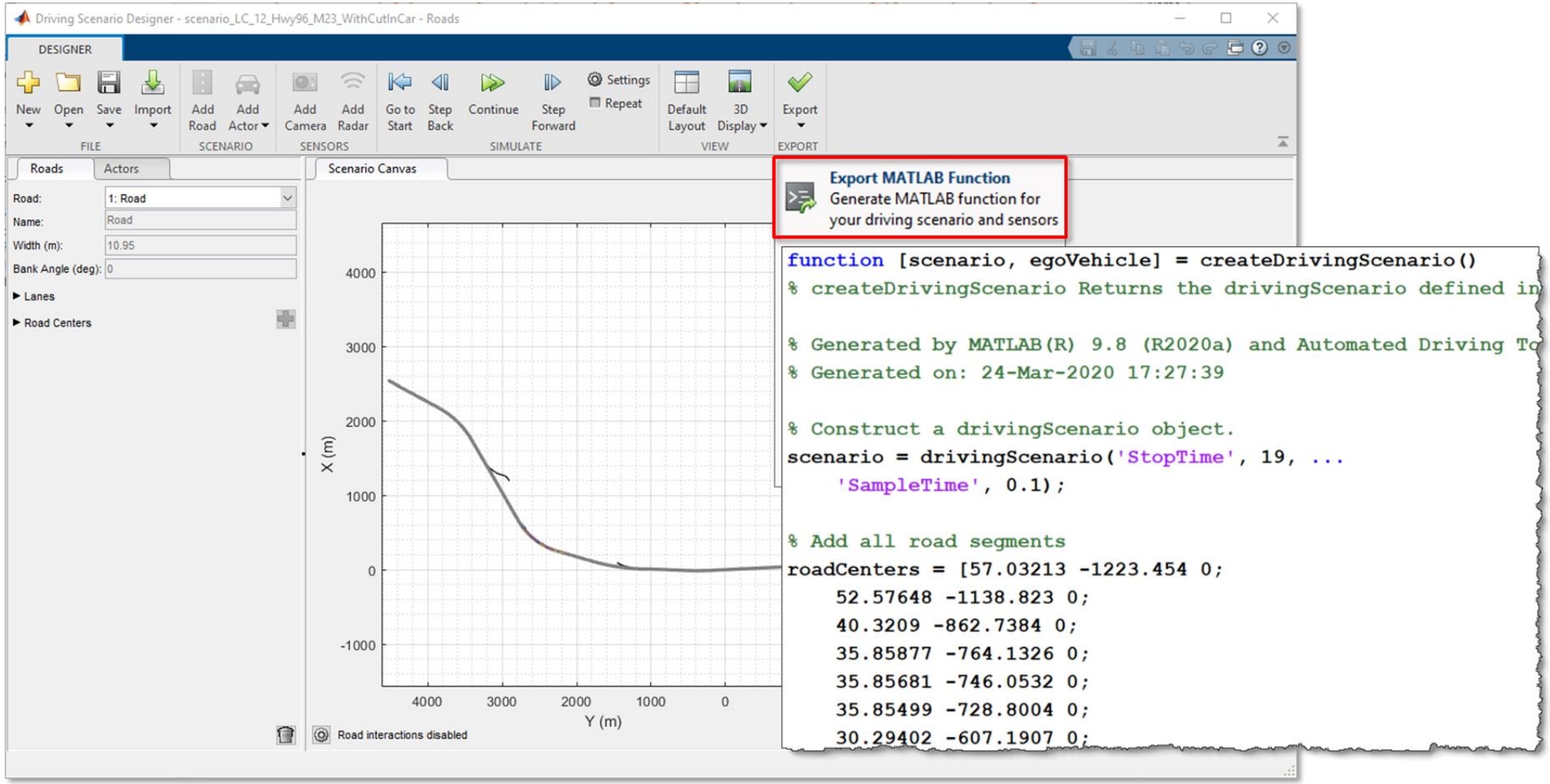
将地图导入驾驶场景设计器
HERE HD Live Map



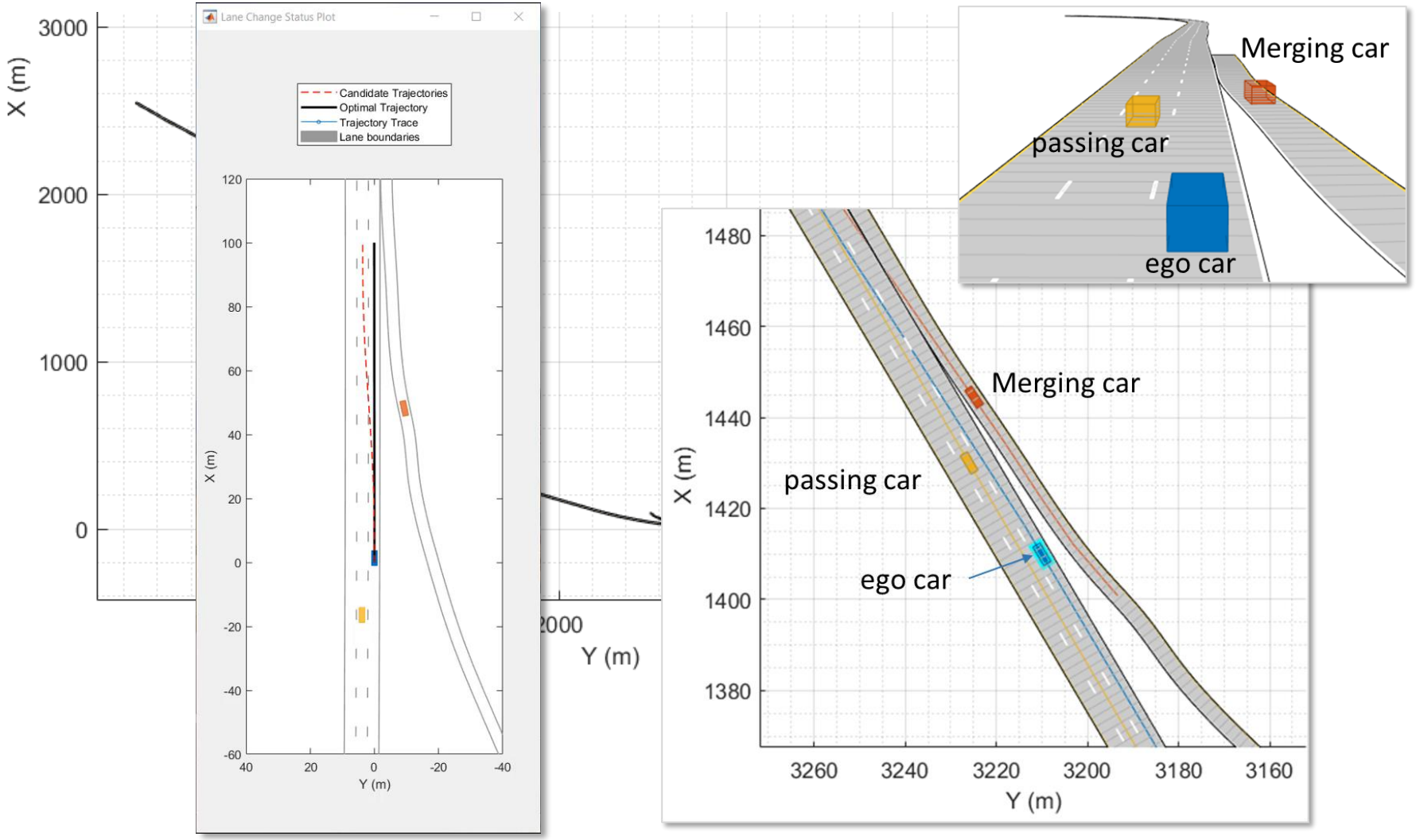
Automated Driving Toolbox™

R2020a

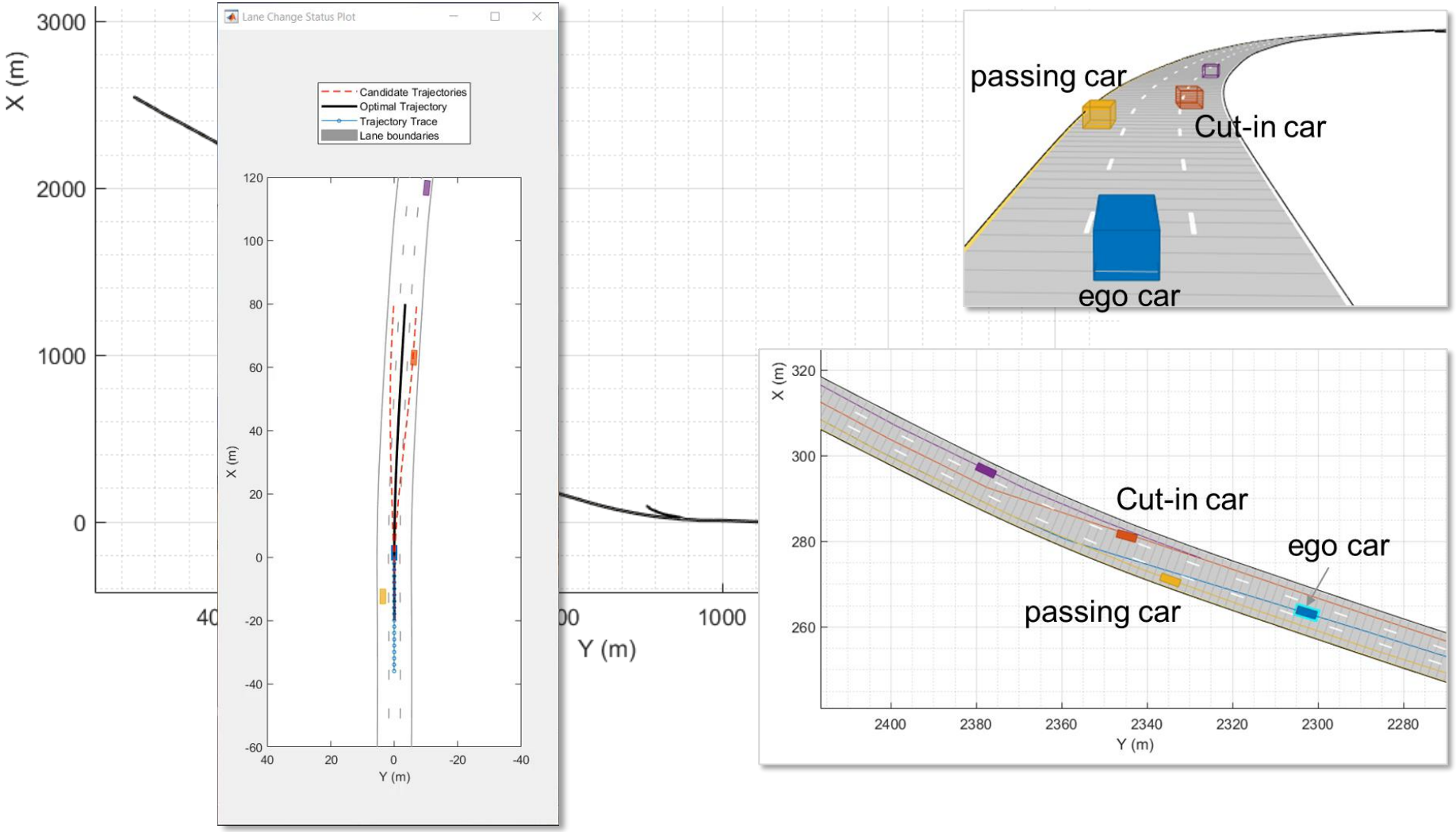
添加交通参与者并导出场景



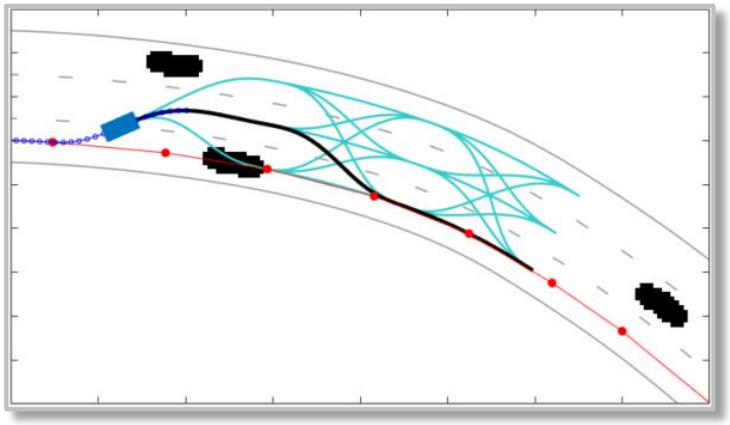
scenario_LC_11_Hwy96_M23_WithMergingCar



scenario_LC_12_Hwy96_M23_WithCutInCar

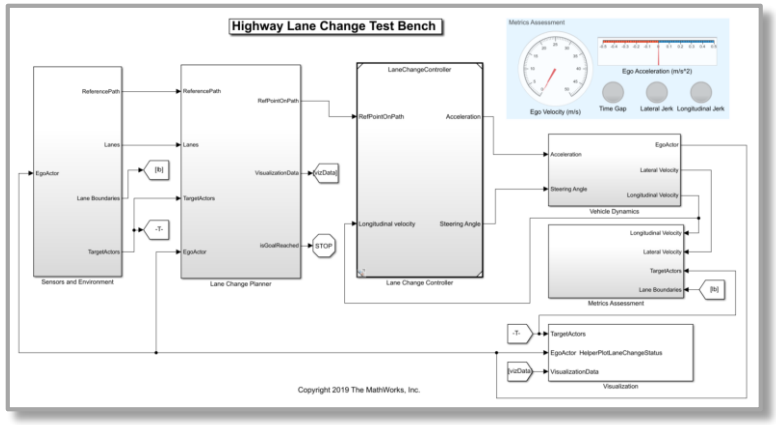


内容总结



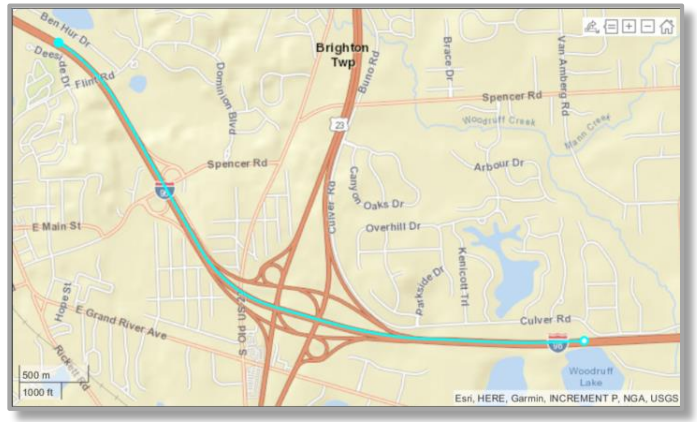
运动规划器组件

- Frenet坐标系下的最优轨迹生成
- 规划器的参数设置
- 使用占据栅格地图仿真规划器



集成规划器与控制器

- 高速公路变道示例的架构
- 仿真使用简单道路创建的场景



导入地图数据进行测试

- 导入高精度地图道路数据
- 仿真使用真实道路创建的场景