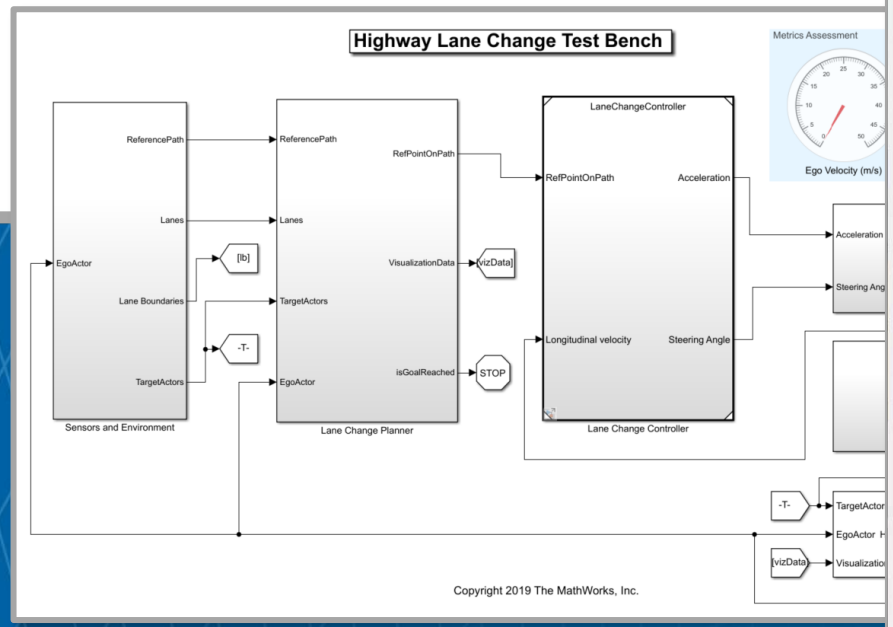
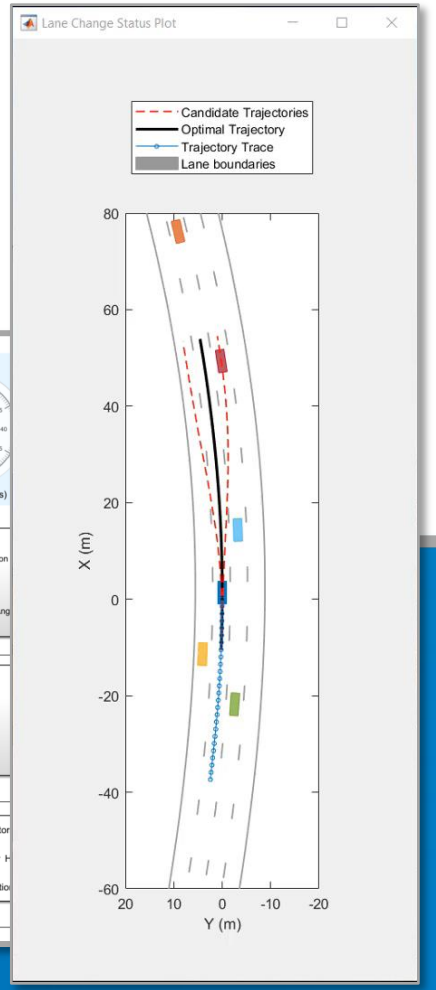
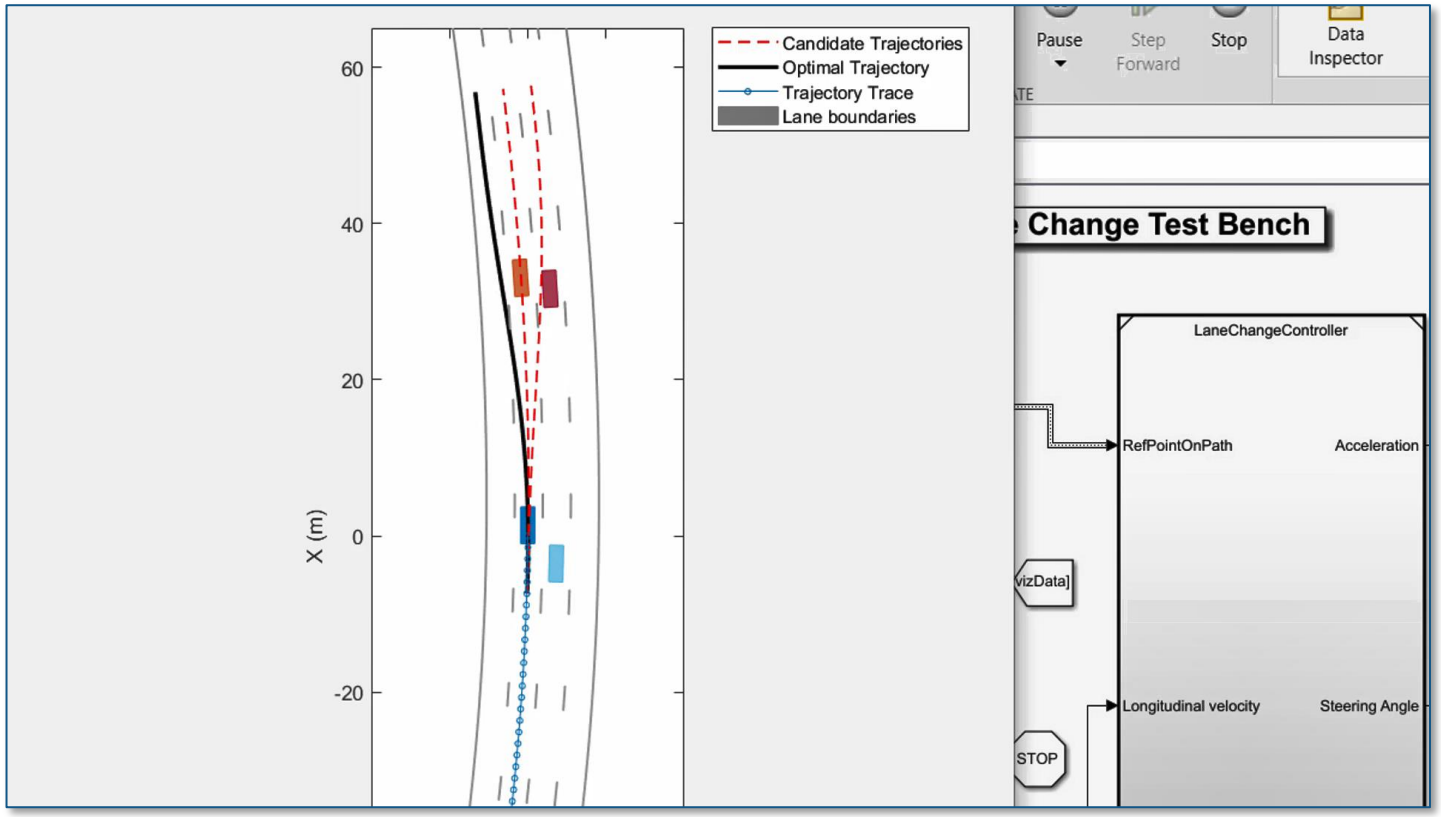
Developing Planning and Controls for Highway Lane Change Maneuvers





Seo-Wook Park
Application Engineering
ADAS / Automated Driving
spark@mathworks.com

Highway Lane Change



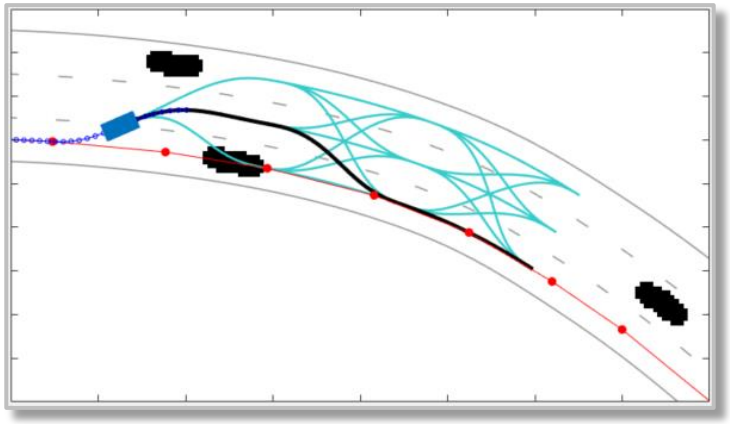
- Automated lane change maneuver (LCM) system for highway driving scenario (straight & curved roads)
- Generates a collision-free, optimal trajectory for lane change using `trajectoryOptimalFrenet`
- Behavior layer to configure motion planner
- State validator for collision checking
- Lane following controller using MPC

Highway Lane Change

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

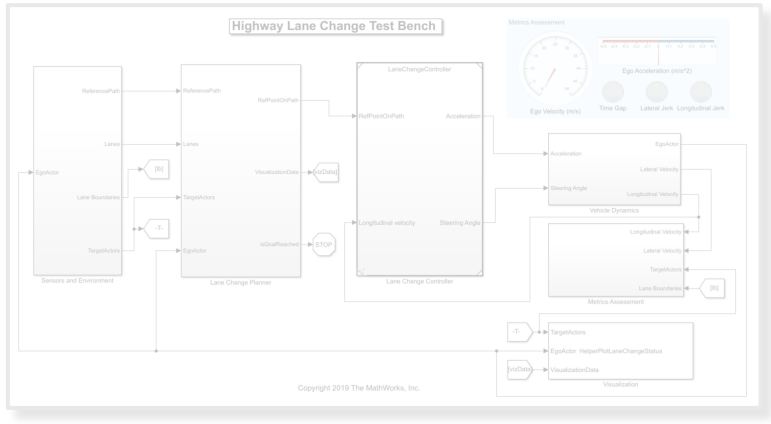
Updated R2020a

Highway Lane Change



Learn motion planner

- Optimal trajectory generation in Frenet coordinate
- Planner parameters
- Simulate trajectory planning with occupancy map



Integrate motion planner and controller

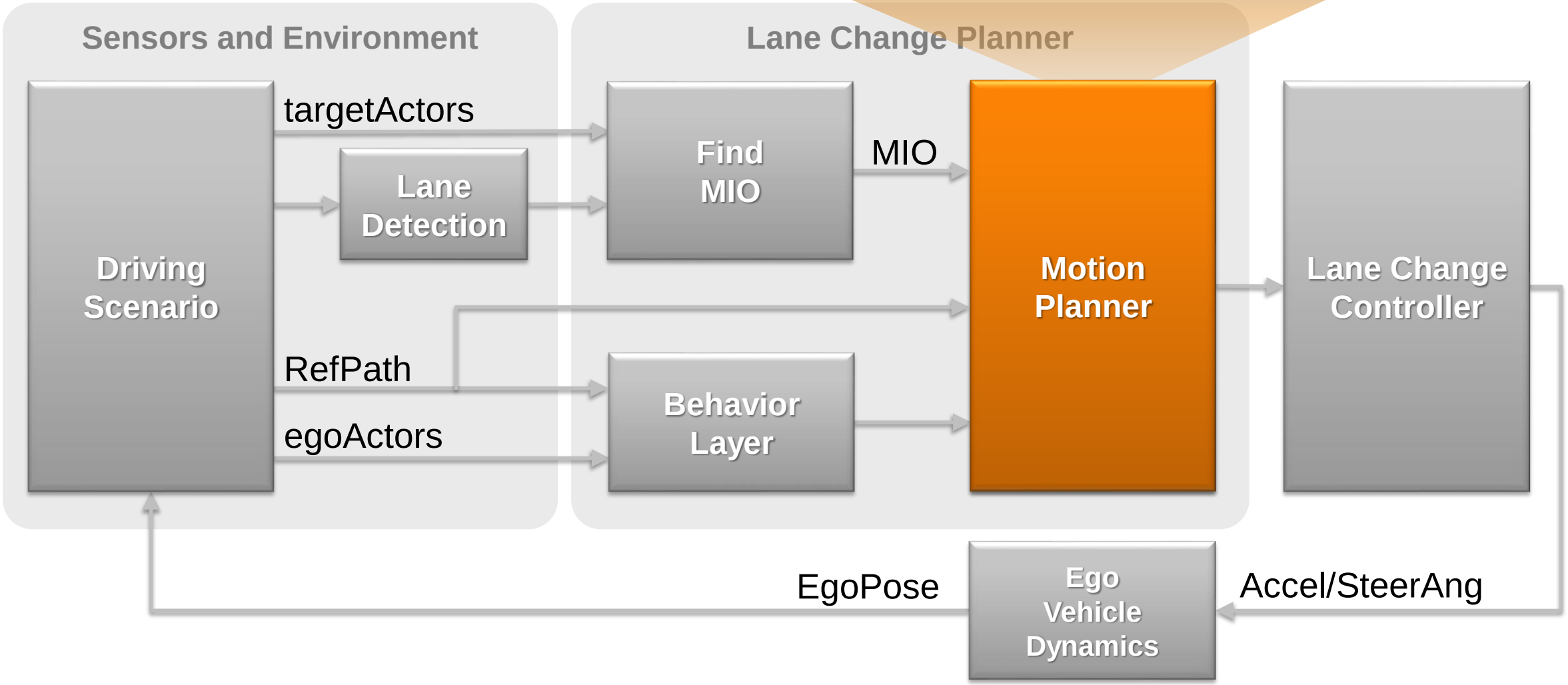
- Learn through reference example
- Architecture of highway lane change
- Simulate closed-loop controller with test scenarios

Test with real-world scenario

- Create scenario from HD map
- Update setup script and model
- Run simulation with new scenario

Architecture of Highway Lane Change

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



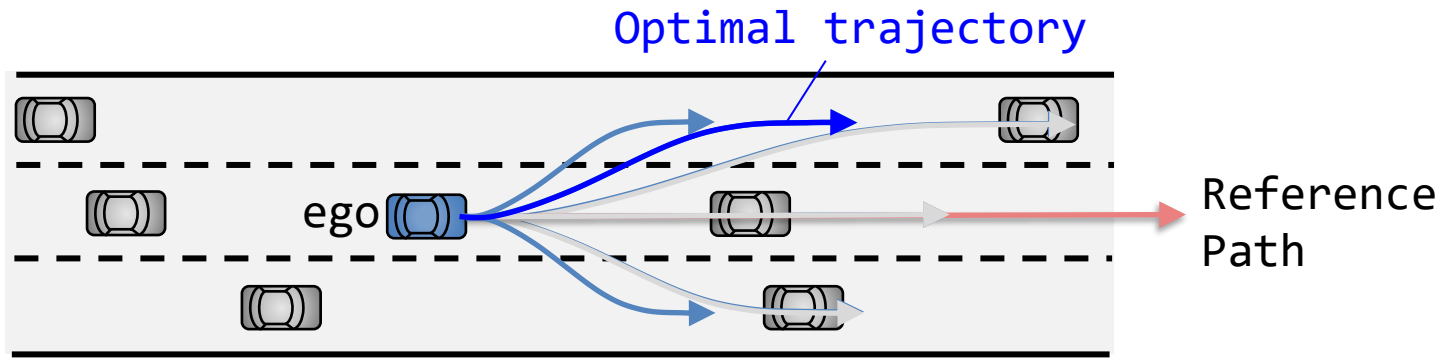
Optimal Trajectory Generation

- `trajectoryOptimalFrenet` function generates an optimal, feasible, and collision-free trajectory for the reference path

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

reference path

state validator
for collision checking



Navigation Toolbox™

R2019b

State Validator for collision checking

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

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

1) Assign 2-D occupancy grid map with binary values

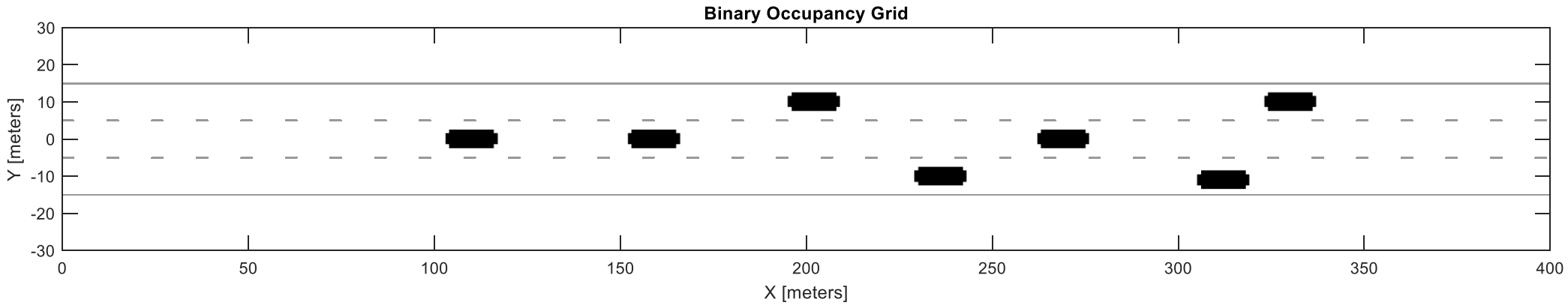
```
% Or, use occupancyMap
stateValidator.Map = occupancyMap(width,height);
```

2) Assign 2-D occupancy grid map with probabilistic values (0..1)

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

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

3) Use custom state validator



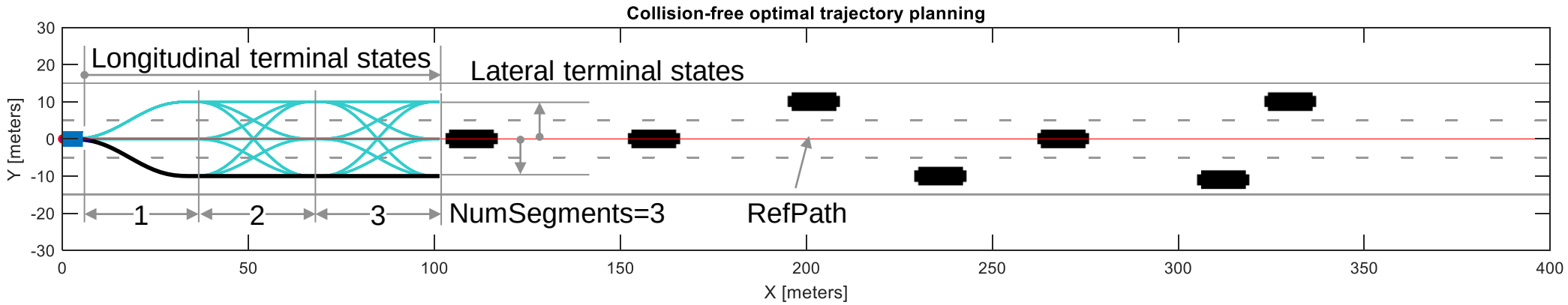
Planner parameters

- Terminal states
- No. of longitudinal segments
- Feasibility parameters

```
% 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;
```



Optimal Trajectory Generation

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

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

↓

Evaluate cost for all candidate trajectories

↓

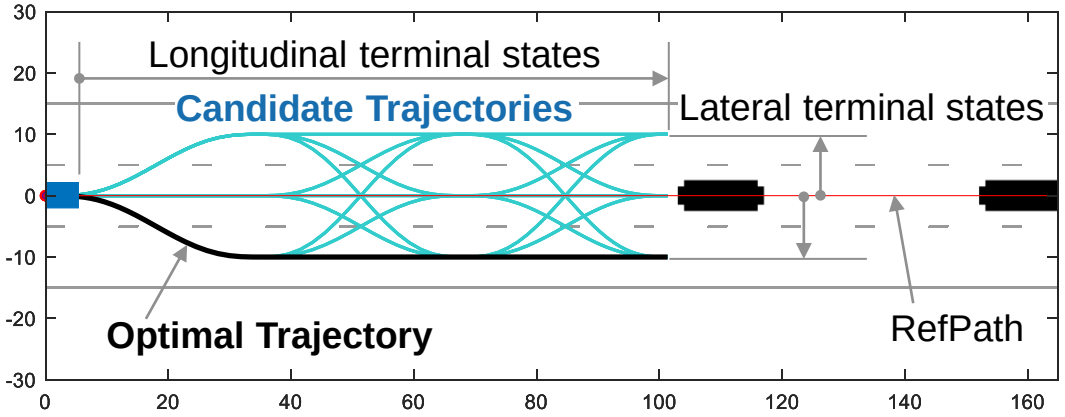
Check feasibility for all candidate trajectories

↓

Check collision using state validator

↓

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



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

Feasibility parameters:
- MaxCurvature, MaxAcceleration

validatorOccupancyMap
Custom state validator

Generate trajectory in Frenet coordinate using quintic polynomial

- Quintic polynomial

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

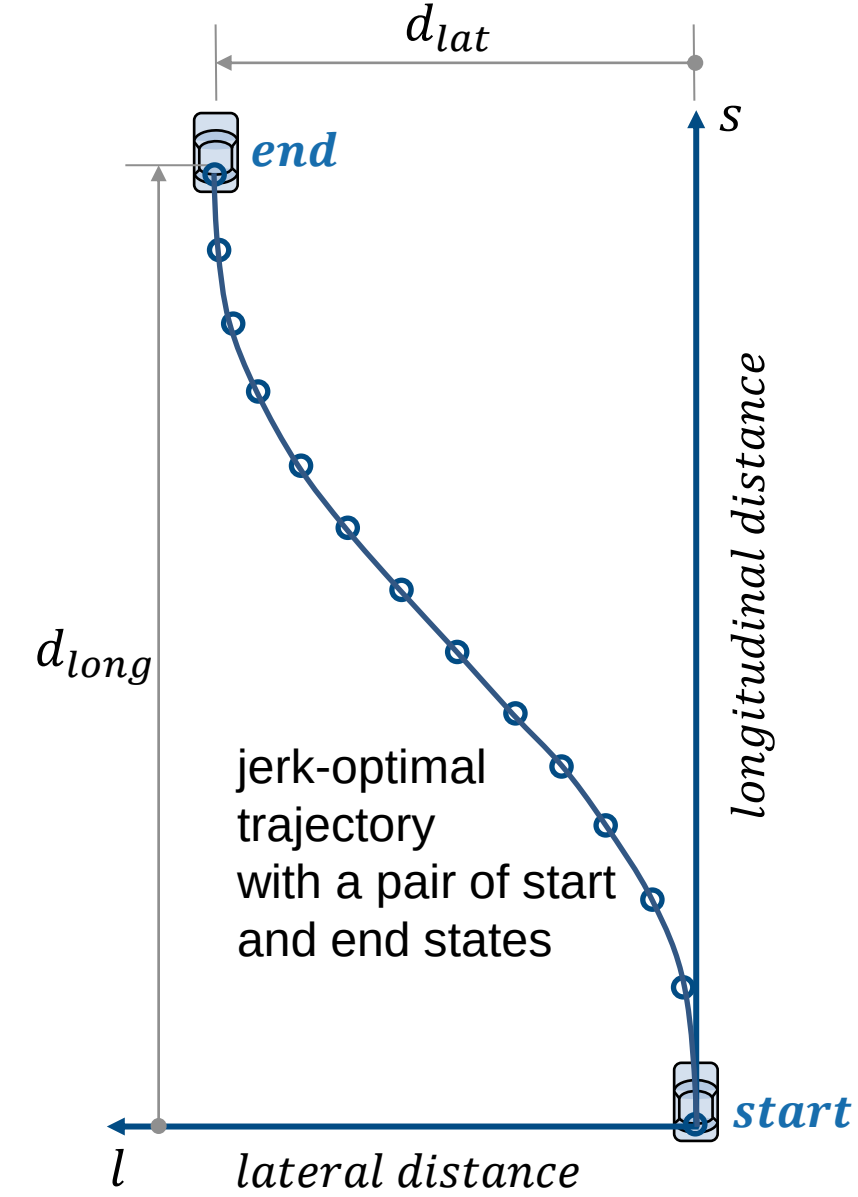
$$where\ s = longitudinal\ or\ lateral\ distance$$

- Start boundary conditions $(t = 0)$

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

- End boundary conditions $(t = t_f)$

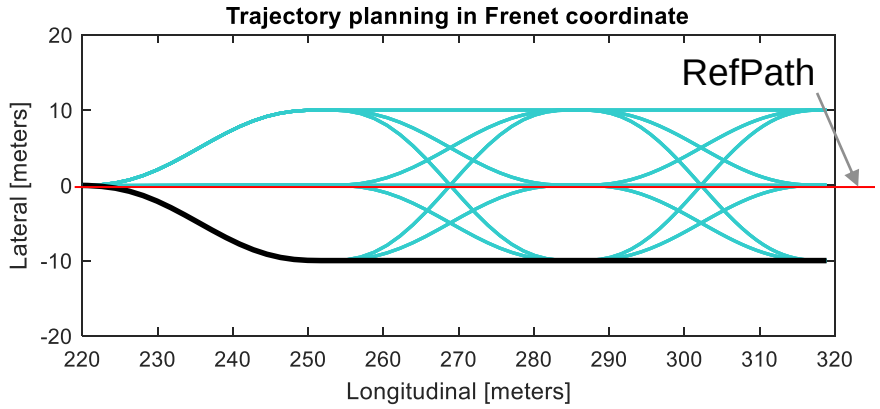
$$a_5t_f^5 + a_4t_f^4 + a_3t_f^3 + a_2t_f^2 + a_1t_f + a_0 = s_{end}$$
$$5a_5t_f^4 + 4a_4t_f^3 + 3a_3t_f^2 + 2a_2t_f + a_1 = \dot{s}_{end}$$
$$20a_5t_f^3 + 12a_4t_f^2 + 6a_3t_f + 2a_2 = \ddot{s}_{end}$$



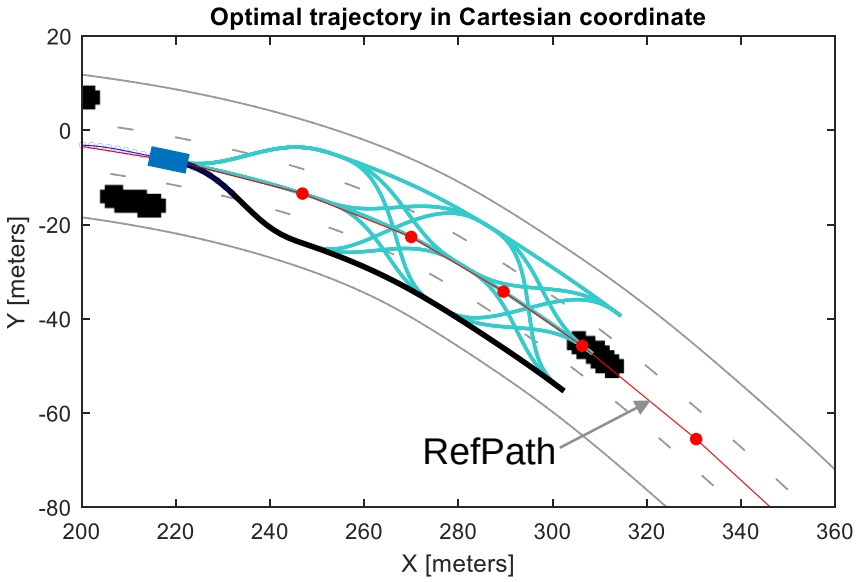
Frenet Coordinate

Advantage of trajectory generation in Frenet coordinate

- Frenet system represents an object and its trajectory with respect to the reference path (road center or lane center).



- This approach dramatically simplifies the problem of trajectory generation when a car is traveling on a curved road.



Convert Frenet states ↔ Cartesian states

Frenet states

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

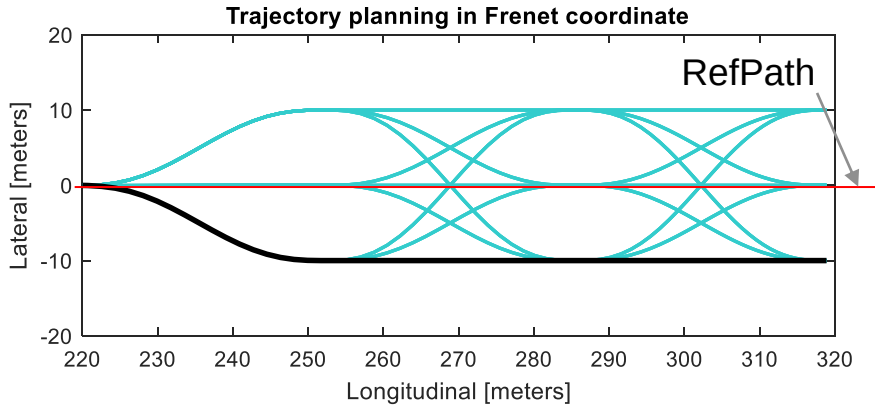
- s : arc length (longitudinal distance)
- l : normal distance (lateral distance) from reference path

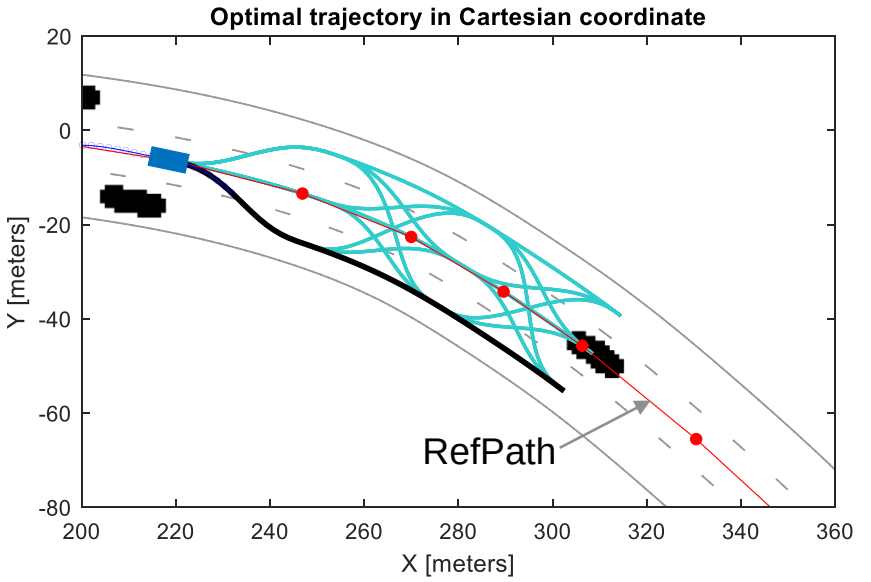
`frenet2cart` `cart2frenet`

Cartesian state

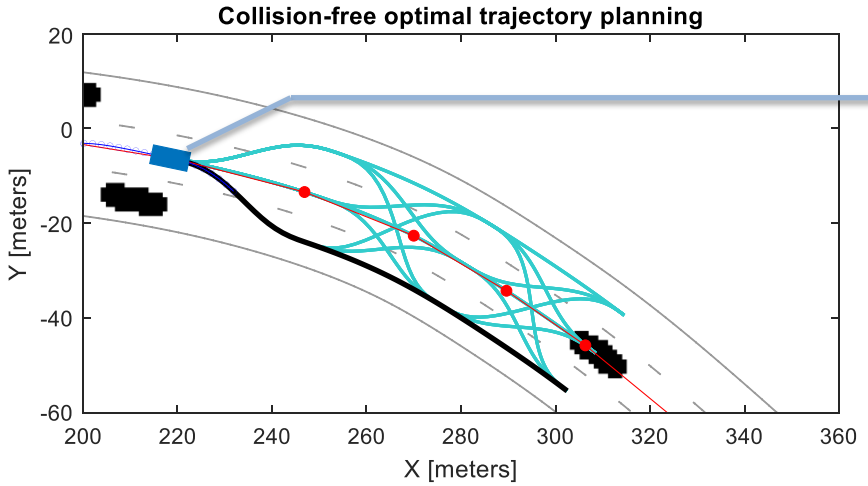
$$[x, y, \theta, \kappa, v, a]$$

- x, y : position in meters
- θ : orientation angle in radians
- κ : curvature in m^{-1}
- v : velocity in $\mathrm{m/s}$
- a : acceleration in $\mathrm{m/s^2}$





Convert Frenet states ↔ Cartesian states



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

`cart2frenet`

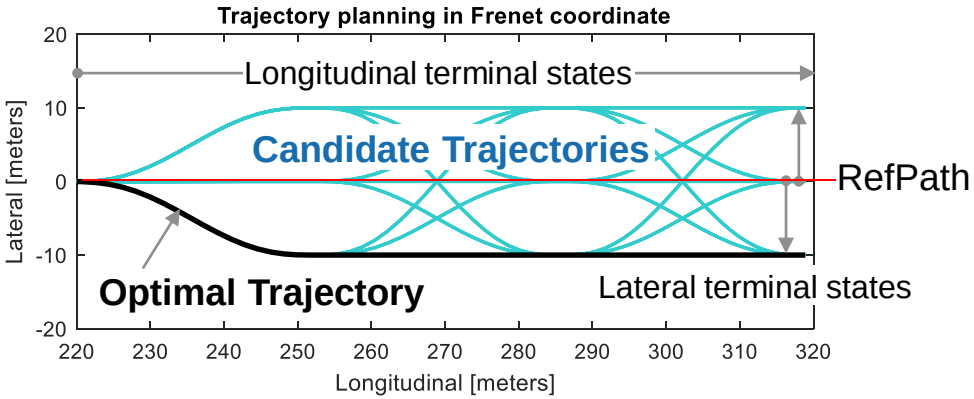
Start Frenet state
$\left[s, \frac{ds}{dt}, \frac{d^2s}{dt^2}, l, \frac{dl}{ds}, \frac{d^2l}{ds^2}\right]$

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

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

`frenet2cart`

Trajectory generation in Frenet states



Optimal Trajectory Planning in Frenet Space - shipping example

Navigation Toolbox™

R2019b

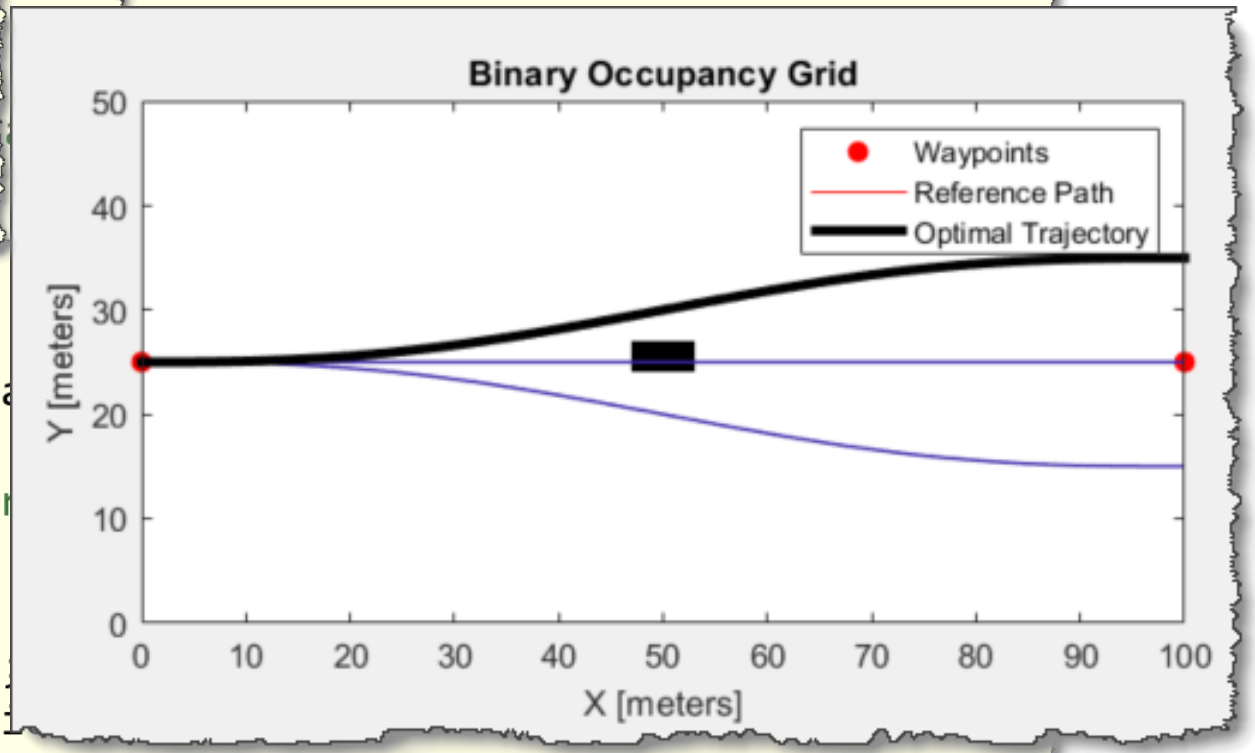
```
%% Step 1) Create and Assign Map to State Validator
%% Step 2) Initialize the planner object and set planner parameters
%% Step 3) Trajectory Planning
%% Step 4) Trajectory Visualization

% Visualize the map and the trajectories.
show(map)
hold on
show(planner,'Trajectory','all')
```

```
llow.
```

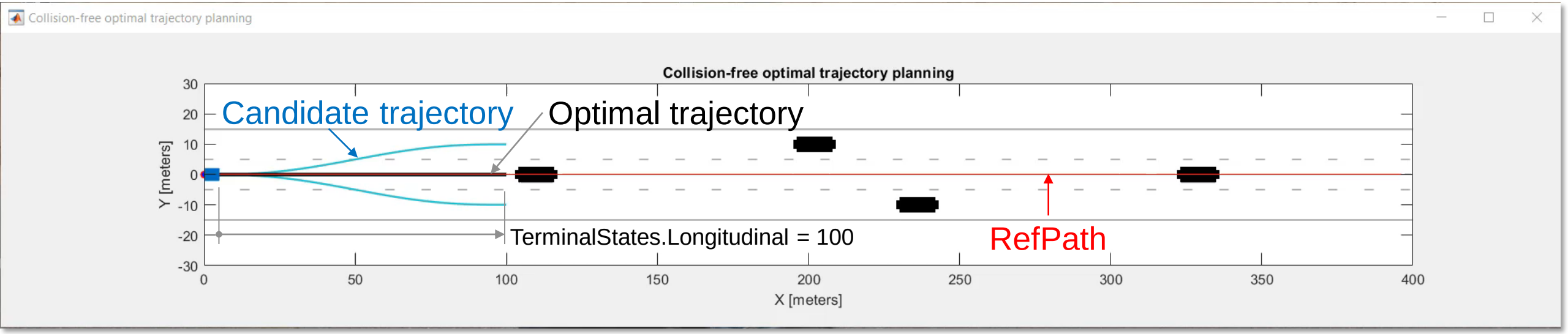
```
% and the custom cost function.
planner =
trajectoryOptimalFrenet(refPath,stateValida

% Assign longitudinal terminal state, later
% values.
planner.TerminalStates.Longitudinal = 100;
planner.TerminalStates.Lateral = -10:10:10;
planner.FeasibilityParameters.MaxAccelerati
```



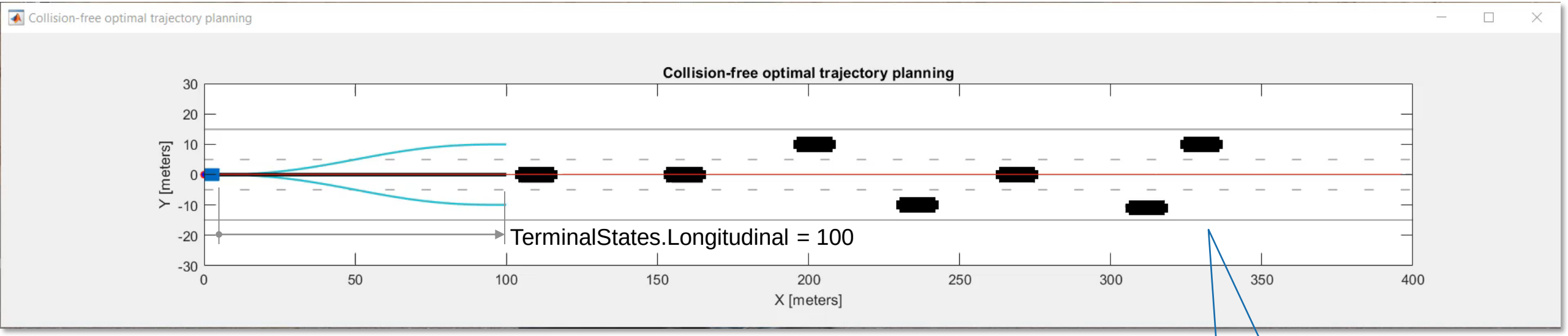
Optimal Trajectory Planning with binary occupancy map : Straight road

- TerminalStates.Longitudinal = 100
- NumSegments = 1



Optimal Trajectory Planning with binary occupancy map : Straight road with dense traffic condition

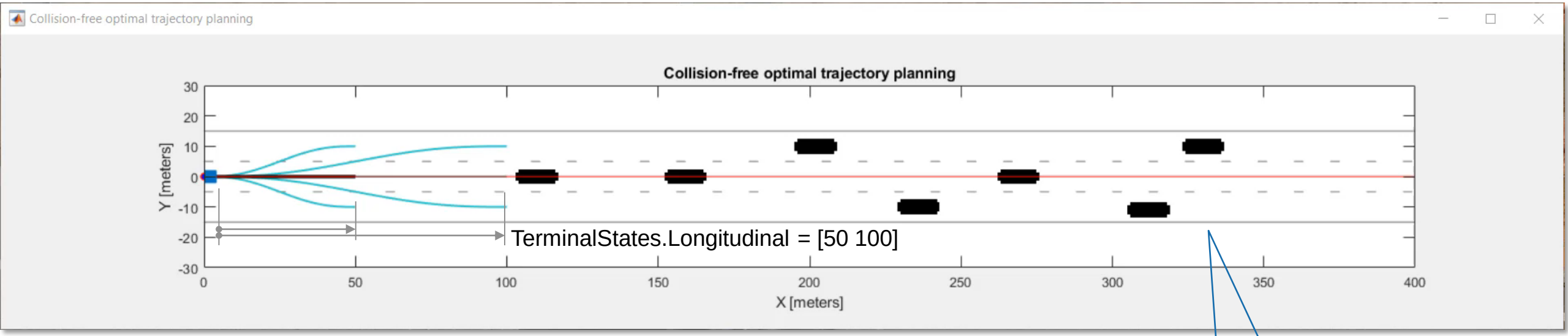
- TerminalStates.Longitudinal = 100
- NumSegments = 1



Dense traffic condition

Optimal Trajectory Planning with binary occupancy map : Straight road with dense traffic condition

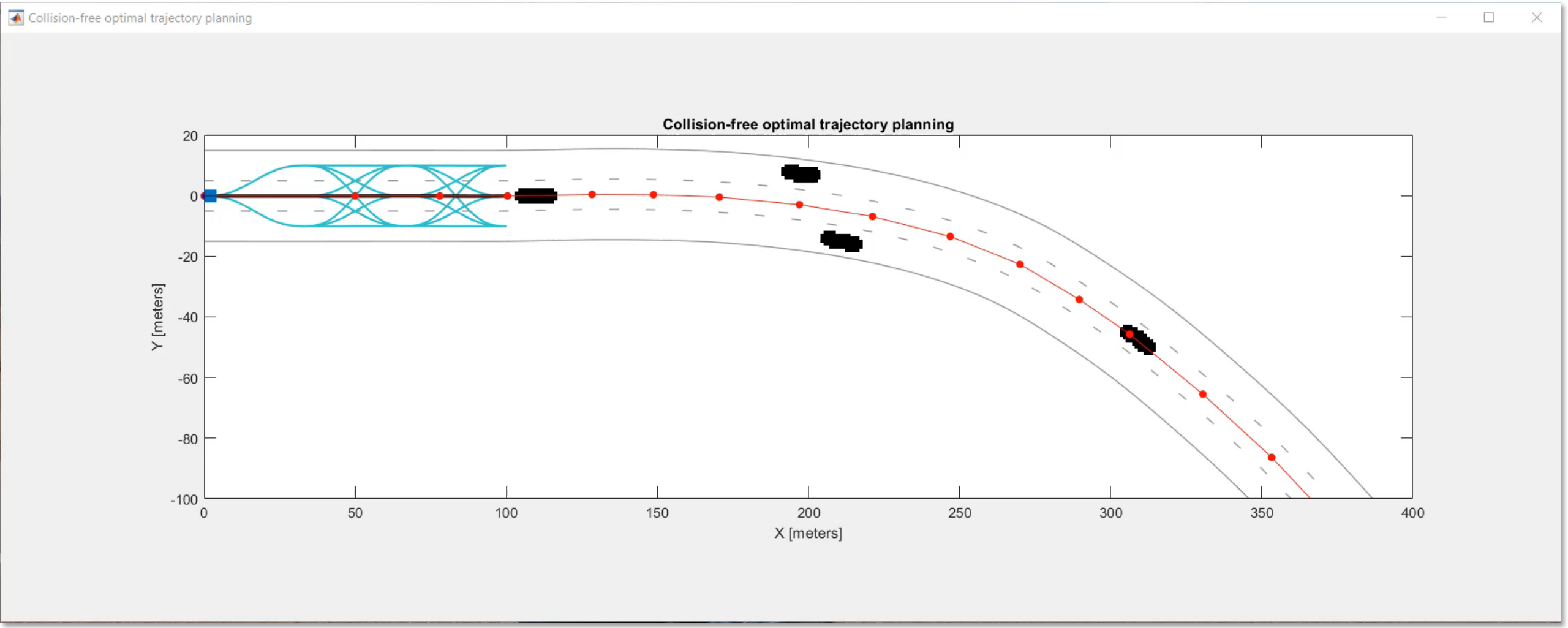
- TerminalStates.Longitudinal = [50 100]
- NumSegments = 1



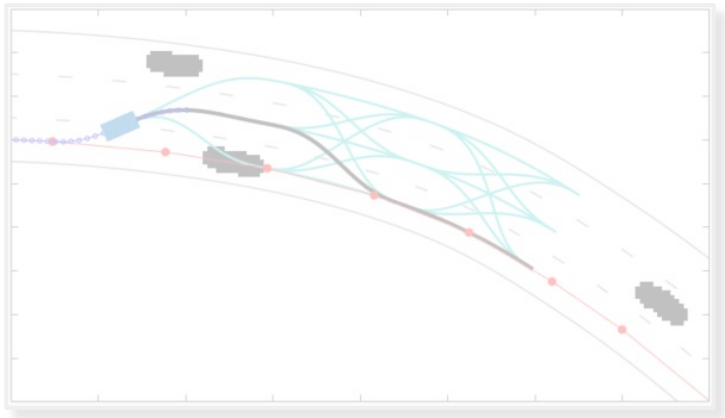
Dense traffic condition

Optimal Trajectory Planning with binary occupancy map : Curved road

- TerminalStates.Longitudinal = 100
- NumSegments = 3

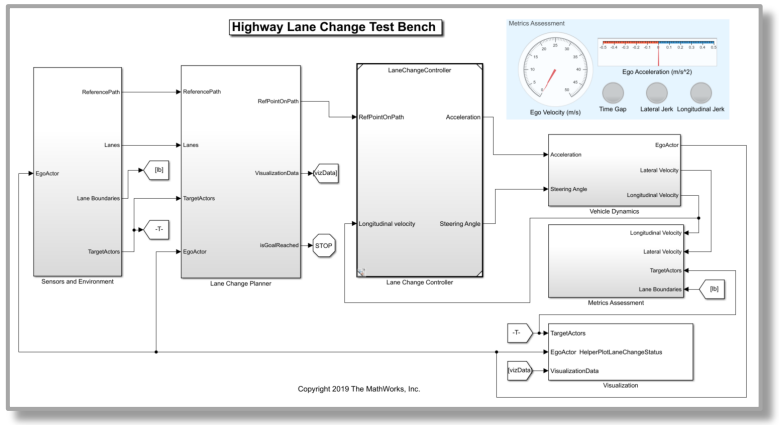


Highway Lane Change



Learn motion planner

- Optimal trajectory generation in Frenet coordinate
- Planner parameters
- Simulate trajectory planning with occupancy map



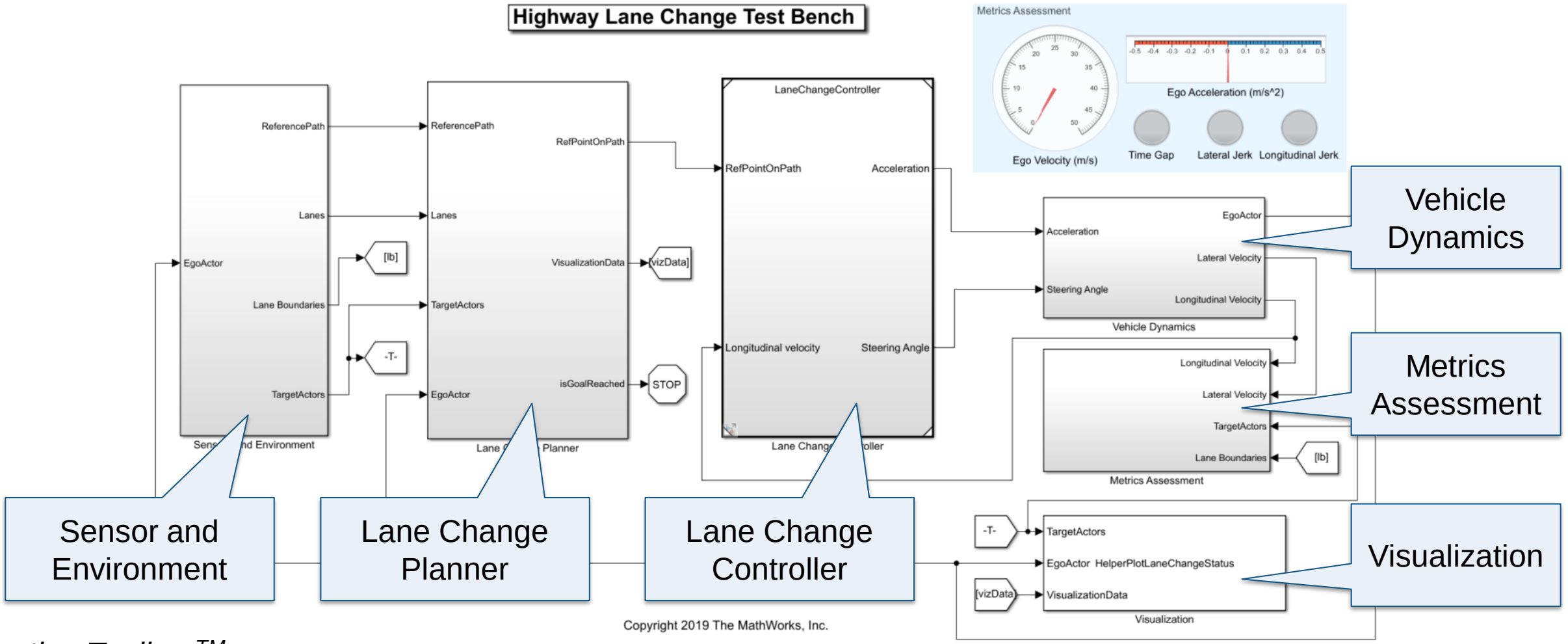
Integrate motion planner and controller

- Learn through reference example
- Architecture of highway lane change
- Simulate closed-loop controller with test scenarios

Test with real-world scenario

- Create scenario from HD map
- Update setup script and model
- Run simulation with new scenario

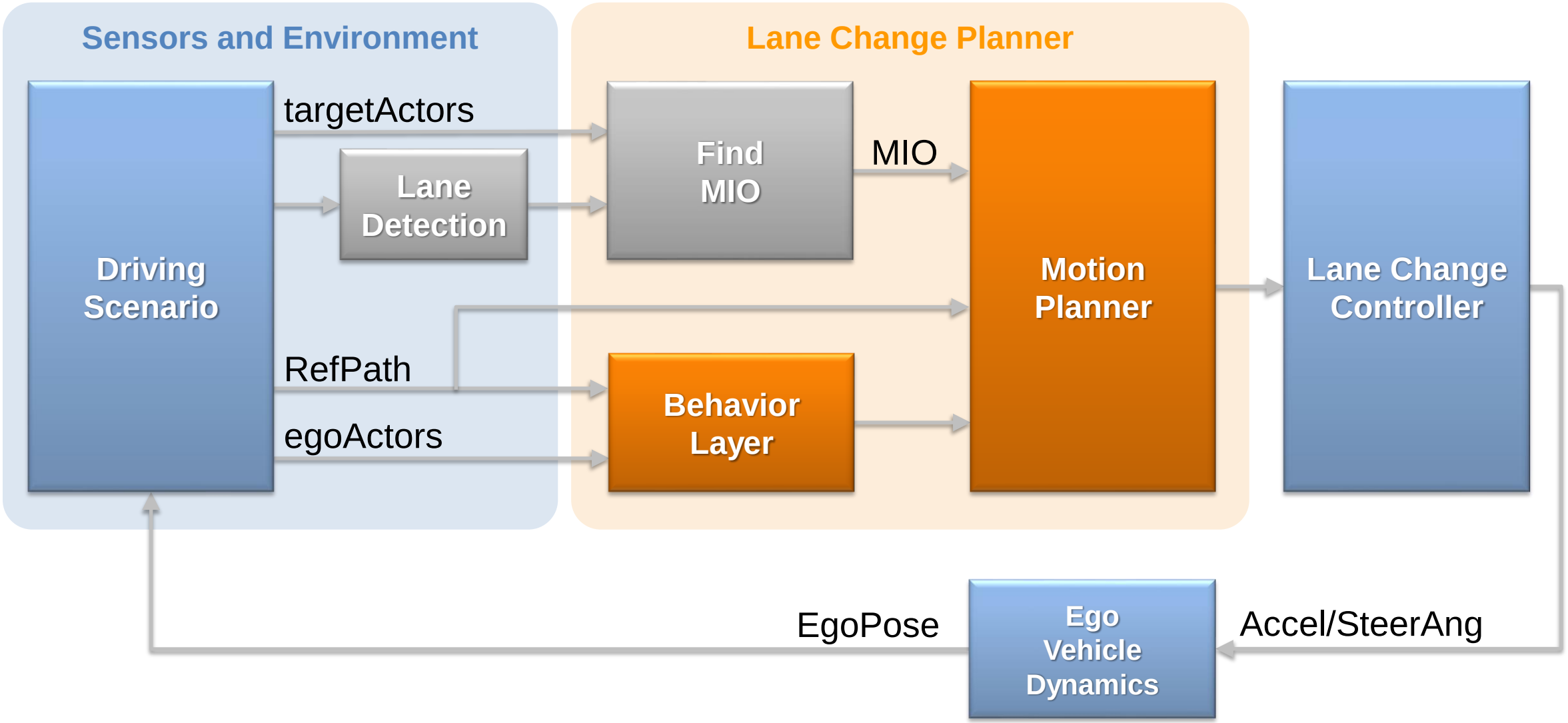
Test Bench Model for Highway Lane Change



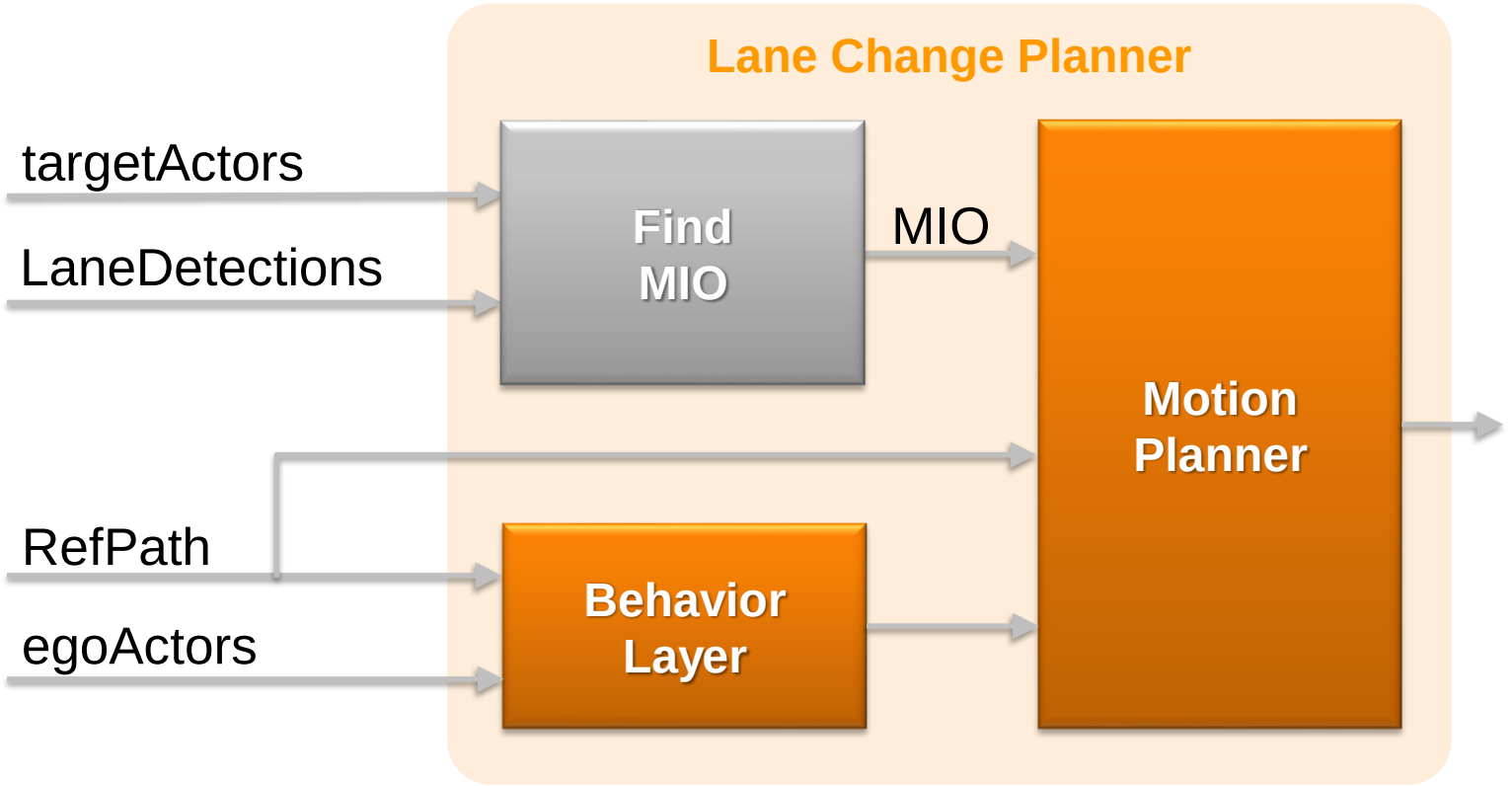
Navigation Toolbox™
Automated Driving Toolbox™

R2020a

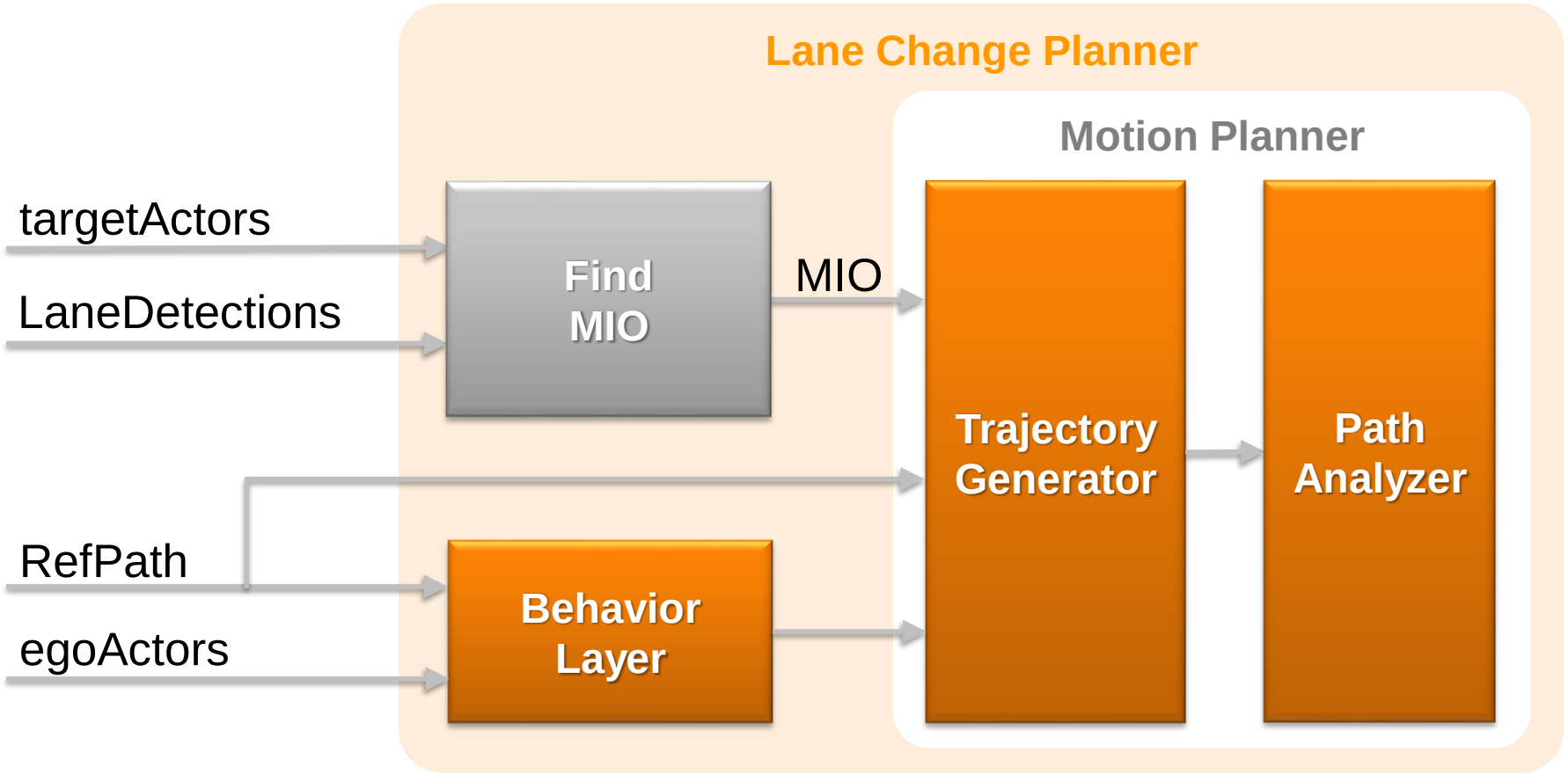
Architecture of Highway Lane Change



Lane Change Planner

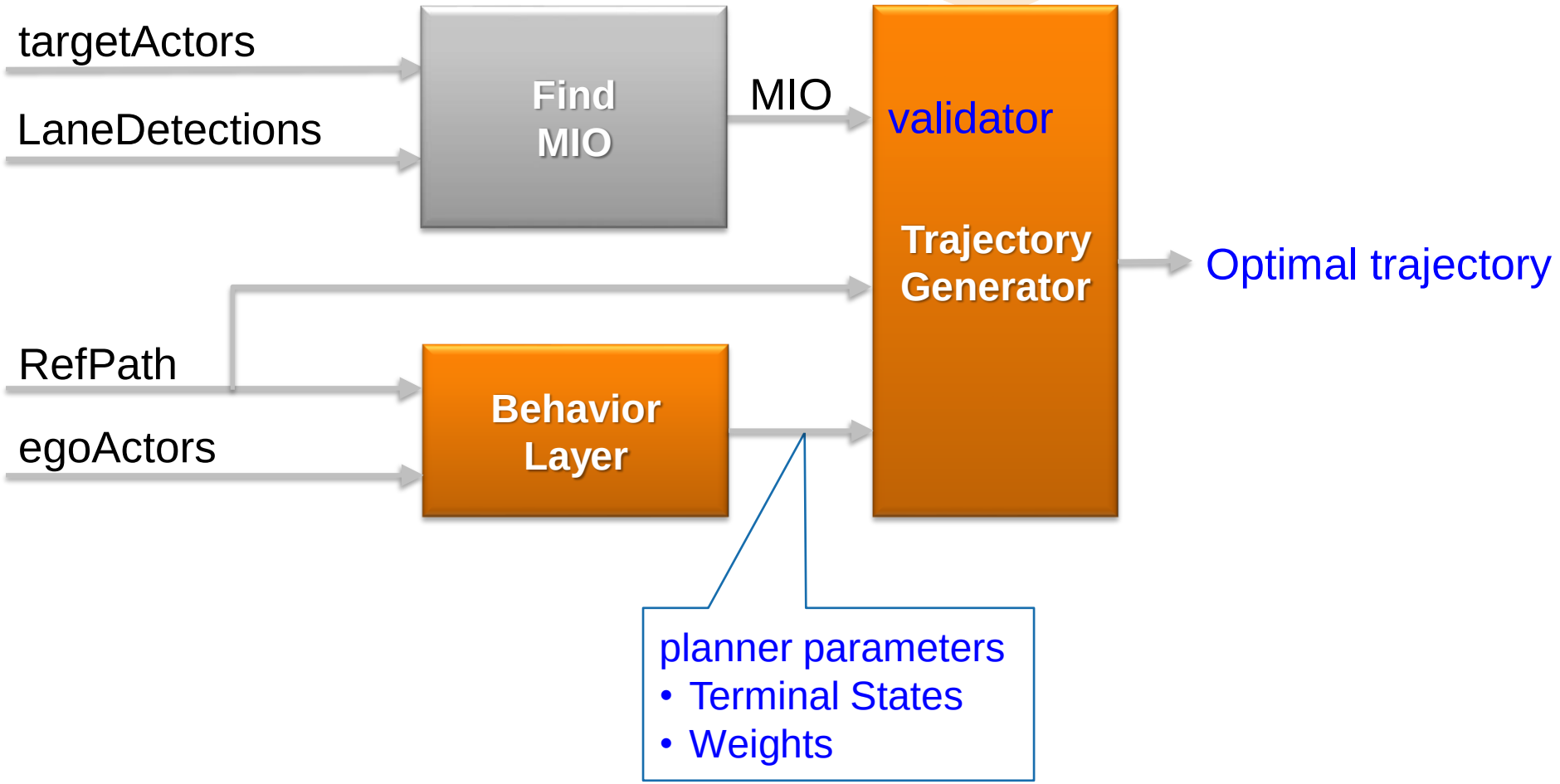


Lane Change Planner



Lane Change Planner

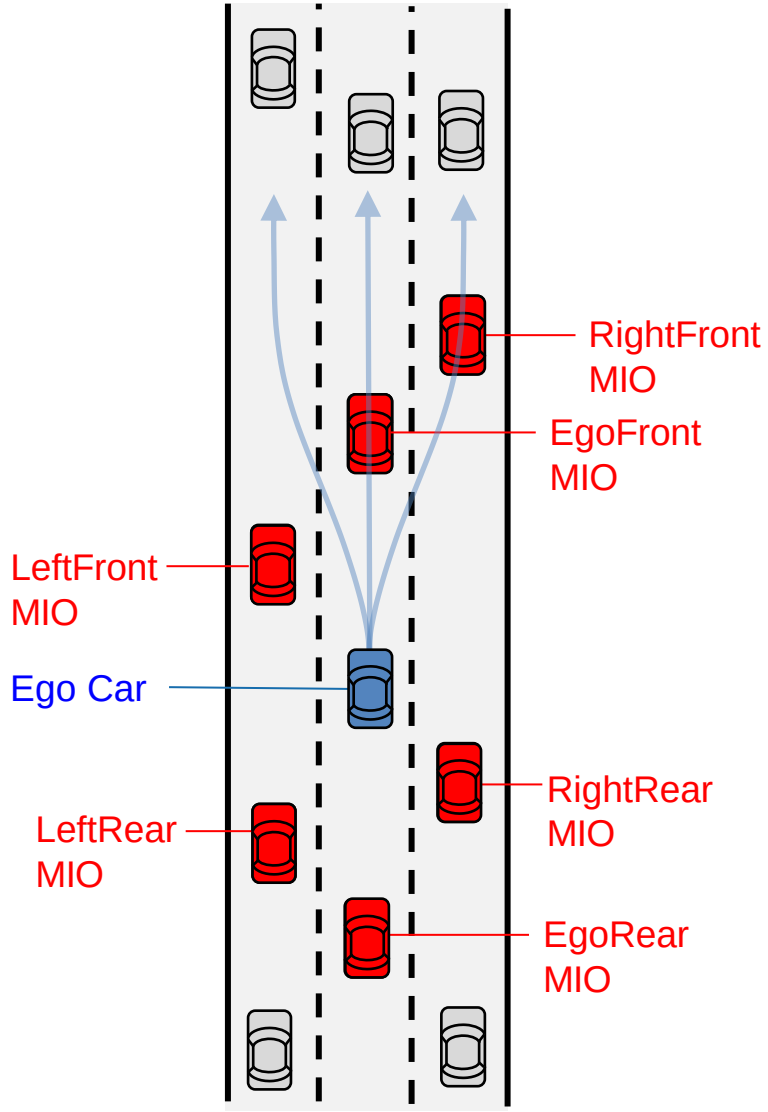
```
planner = trajectoryOptimalFrenet(refPath,validator)
```



Find Most Important Objects (MIO)

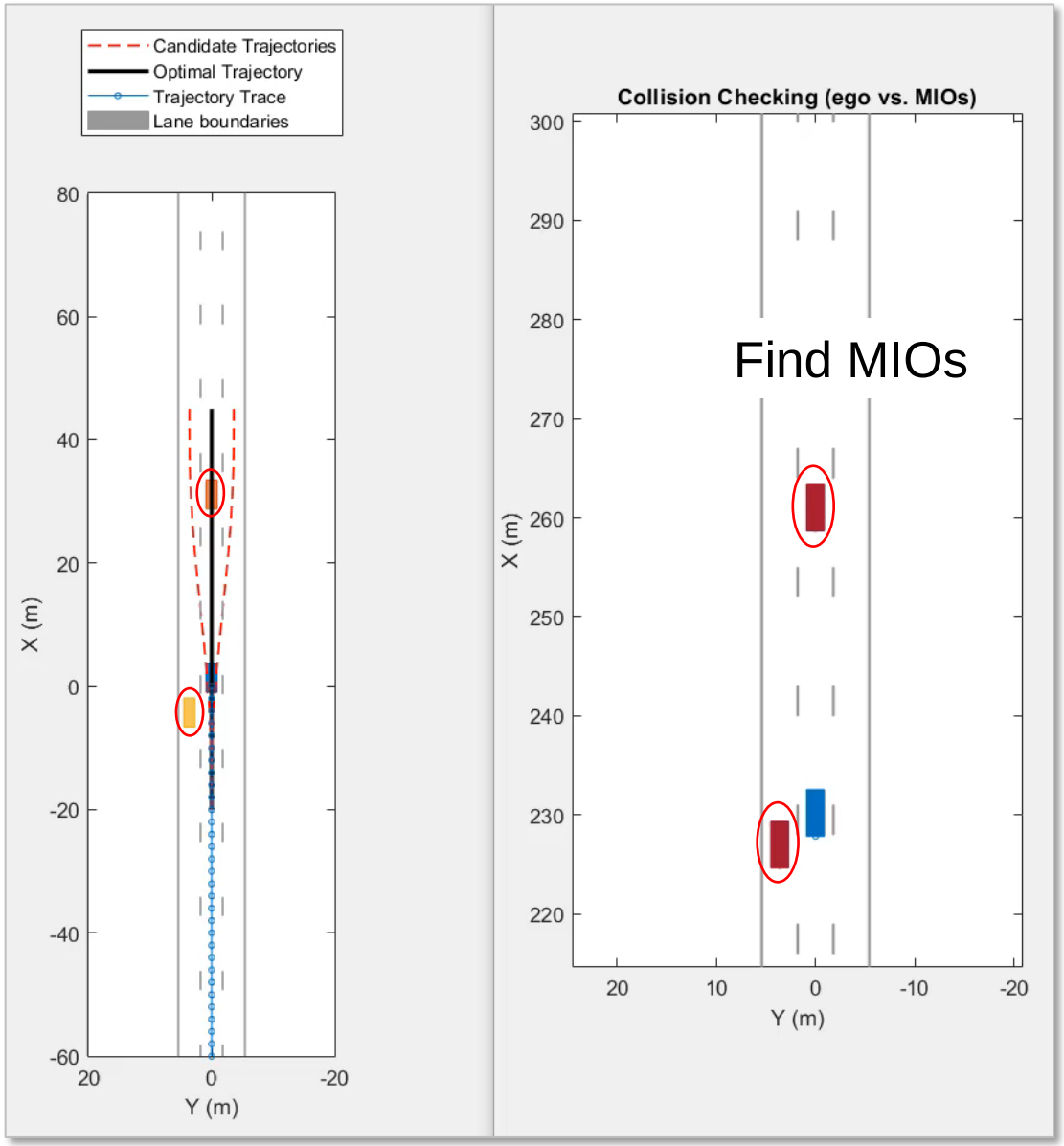

```
planner = trajectoryOptimalFrenet(refPath,validator)
```

- Find MIOs in ego and neighbor lanes
- MIOs are provided for the custom state validator for collision checking.

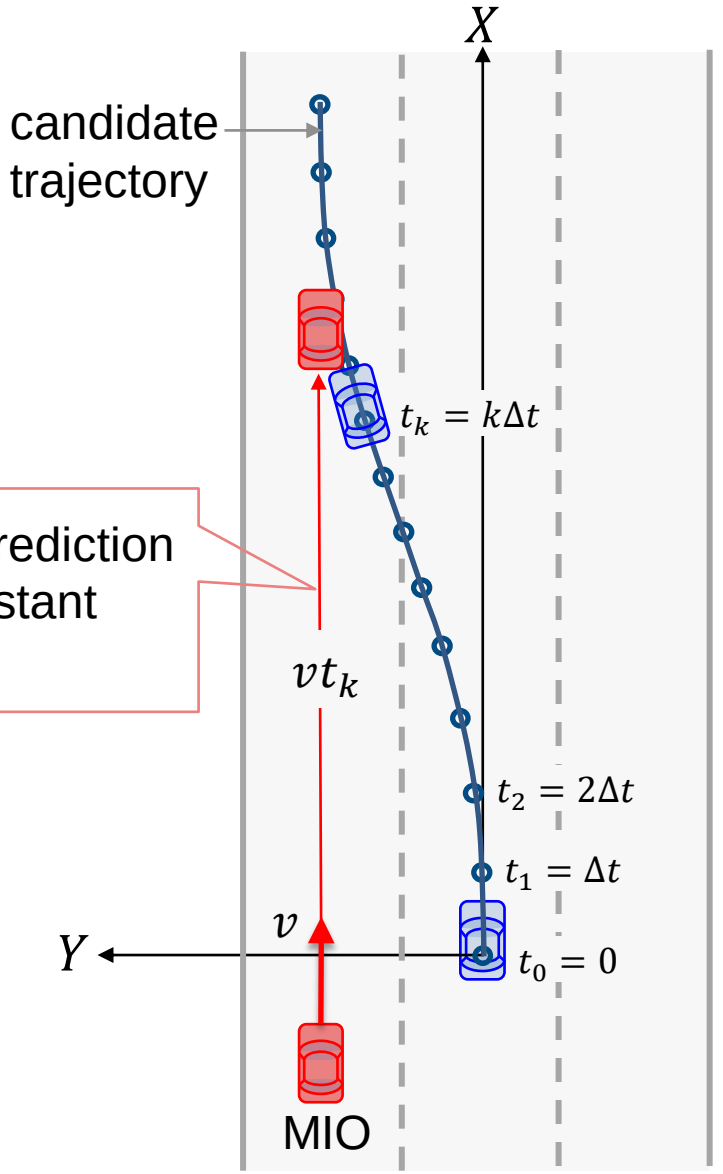


Max. 6 MIOs

Custom State Validator for Collision checking



MIO motion prediction based on constant speed model



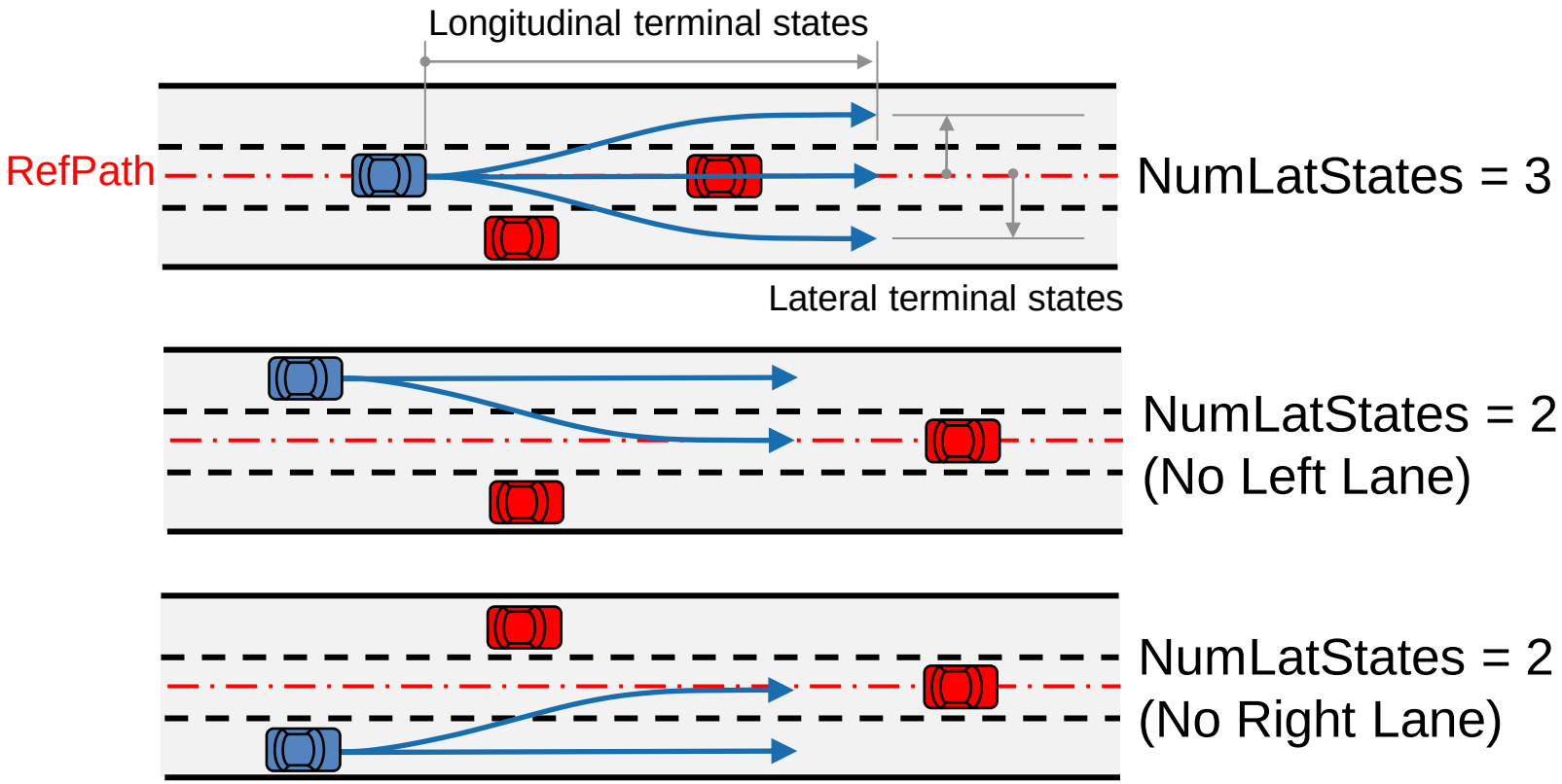
Behavior Layer

RefPath

egoActors

Behavior Layer

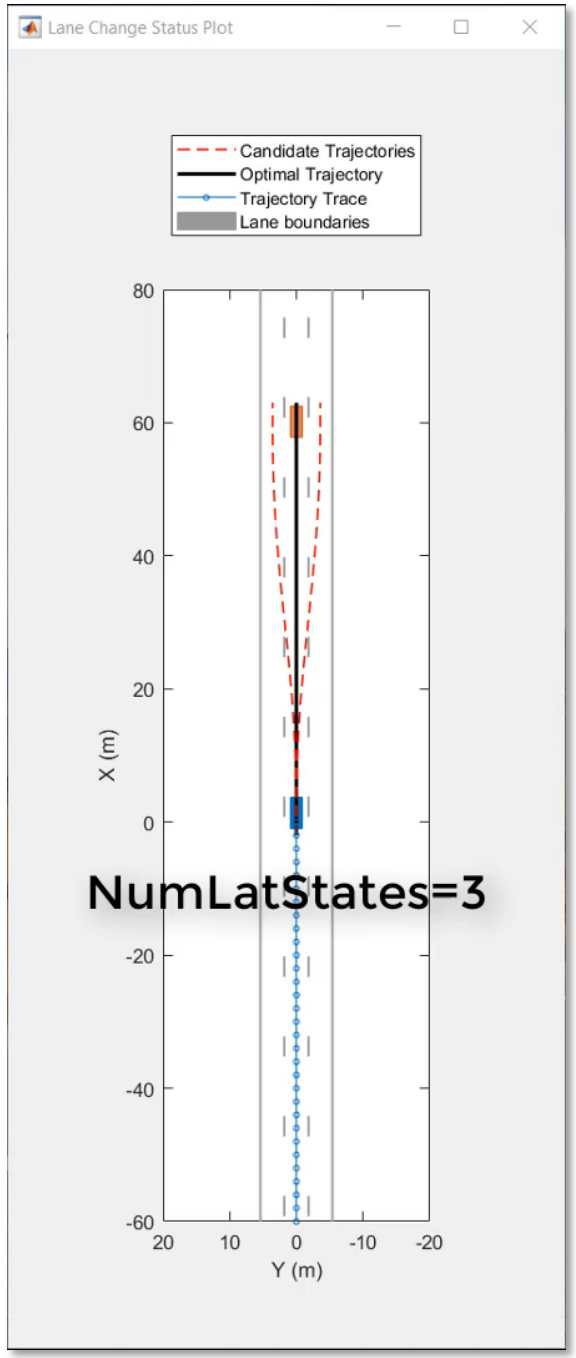
planner parameters
- Terminal States
- Weights



NumLatStates = 3

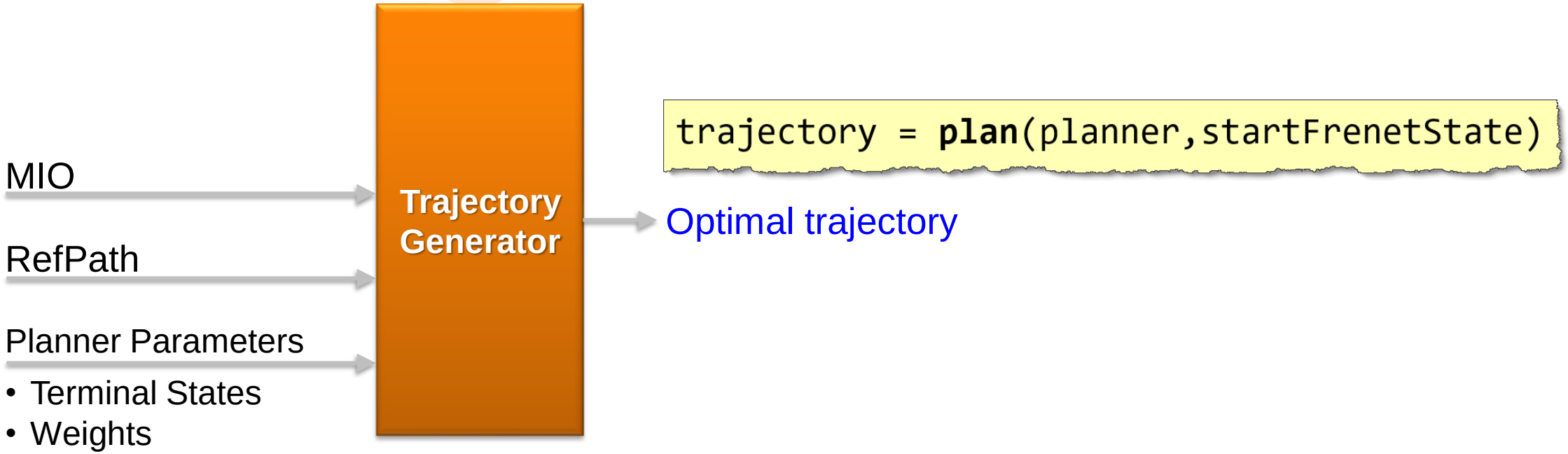
NumLatStates = 2
(No Left Lane)

NumLatStates = 2
(No Right Lane)



Motion Planner ▷ Trajectory Generator

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




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

Motion Planner ▷ Periodic Re-planning

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

1s

Re-plan

MIO

RefPath

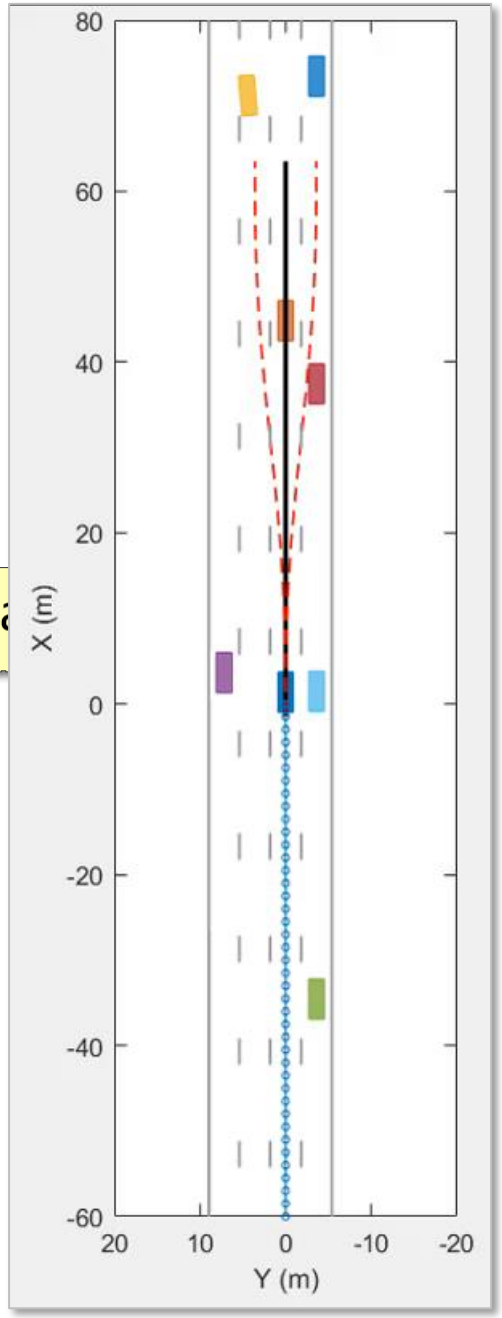
Planner Parameters

- Terminal States
- Weights

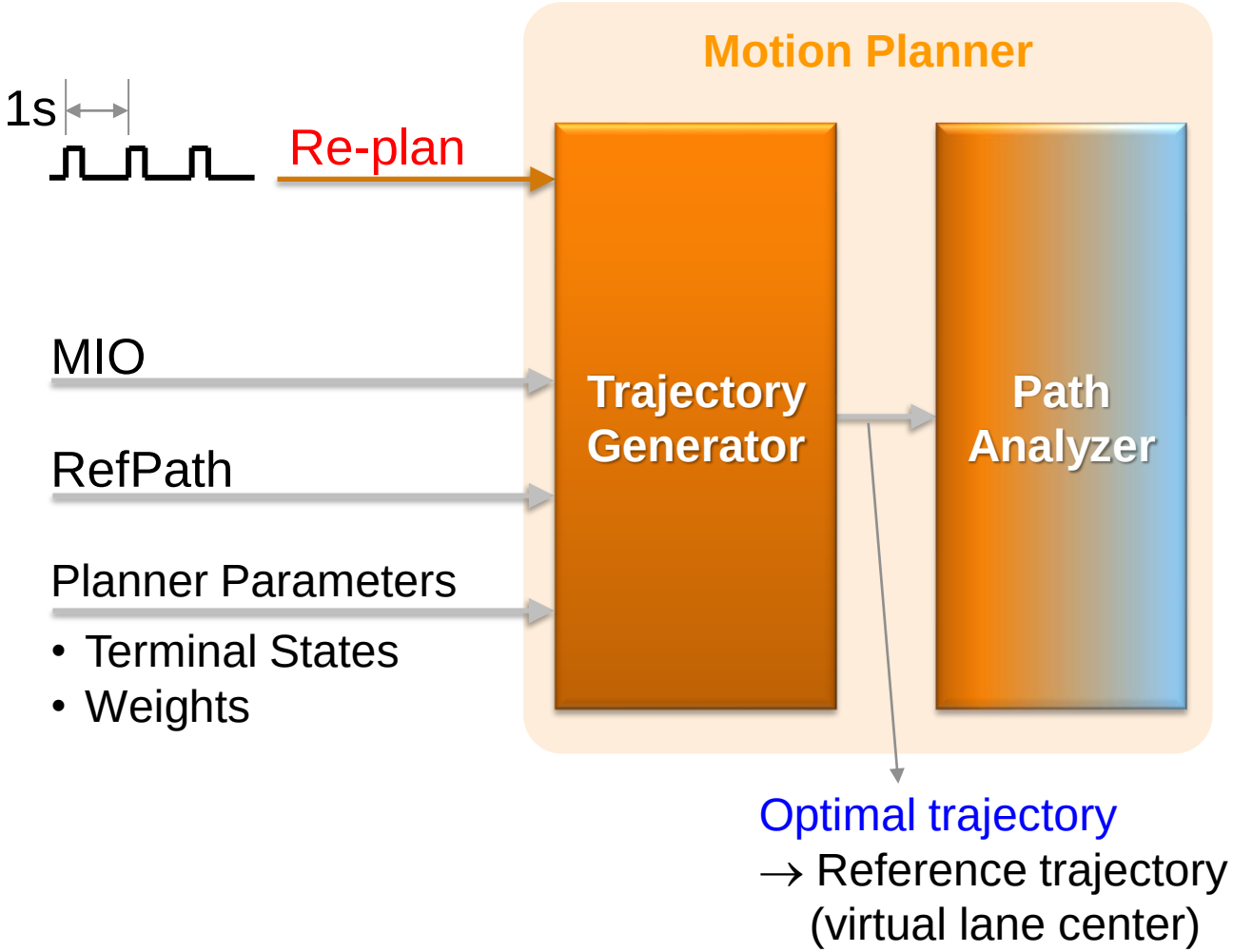
Trajectory Generator

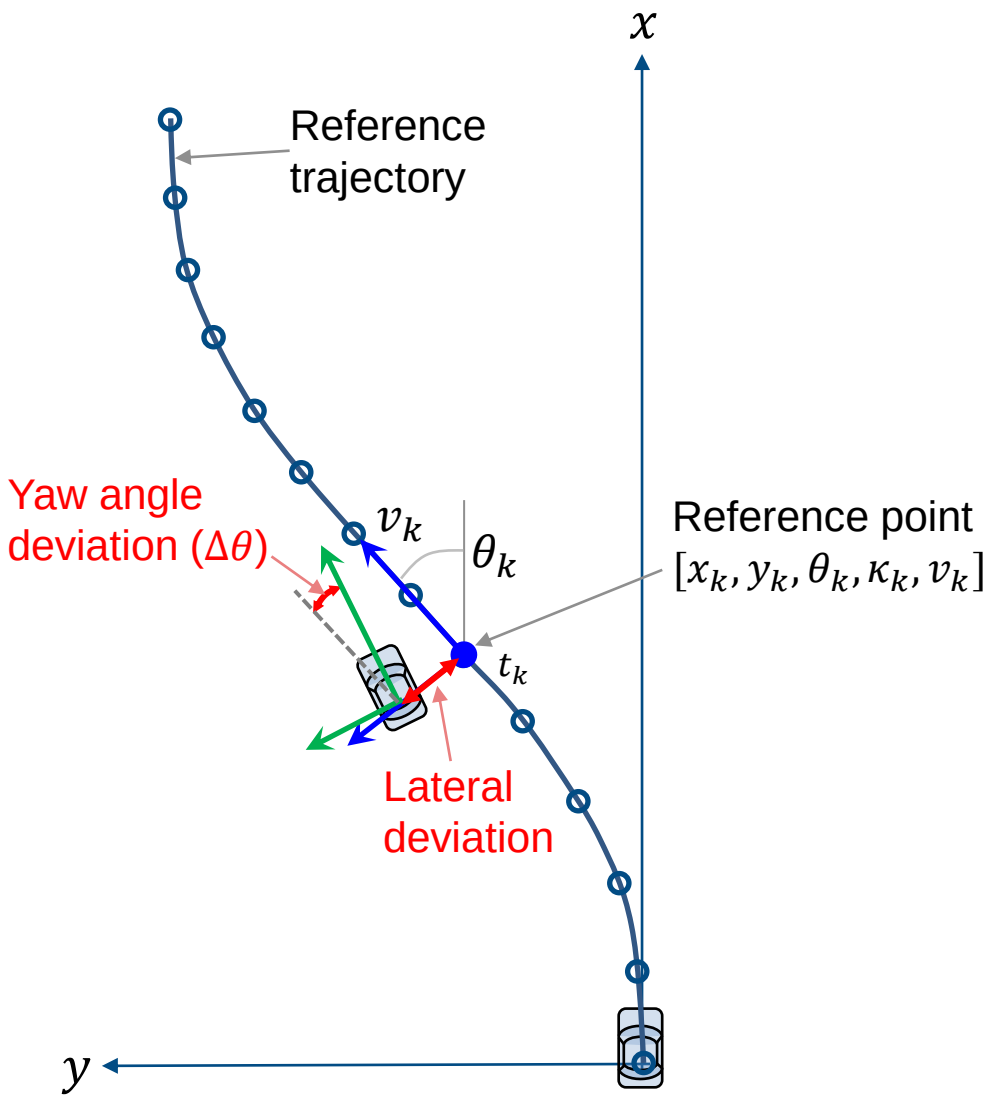
```
trajectory = plan(planner,sta
```

Optimal trajectory

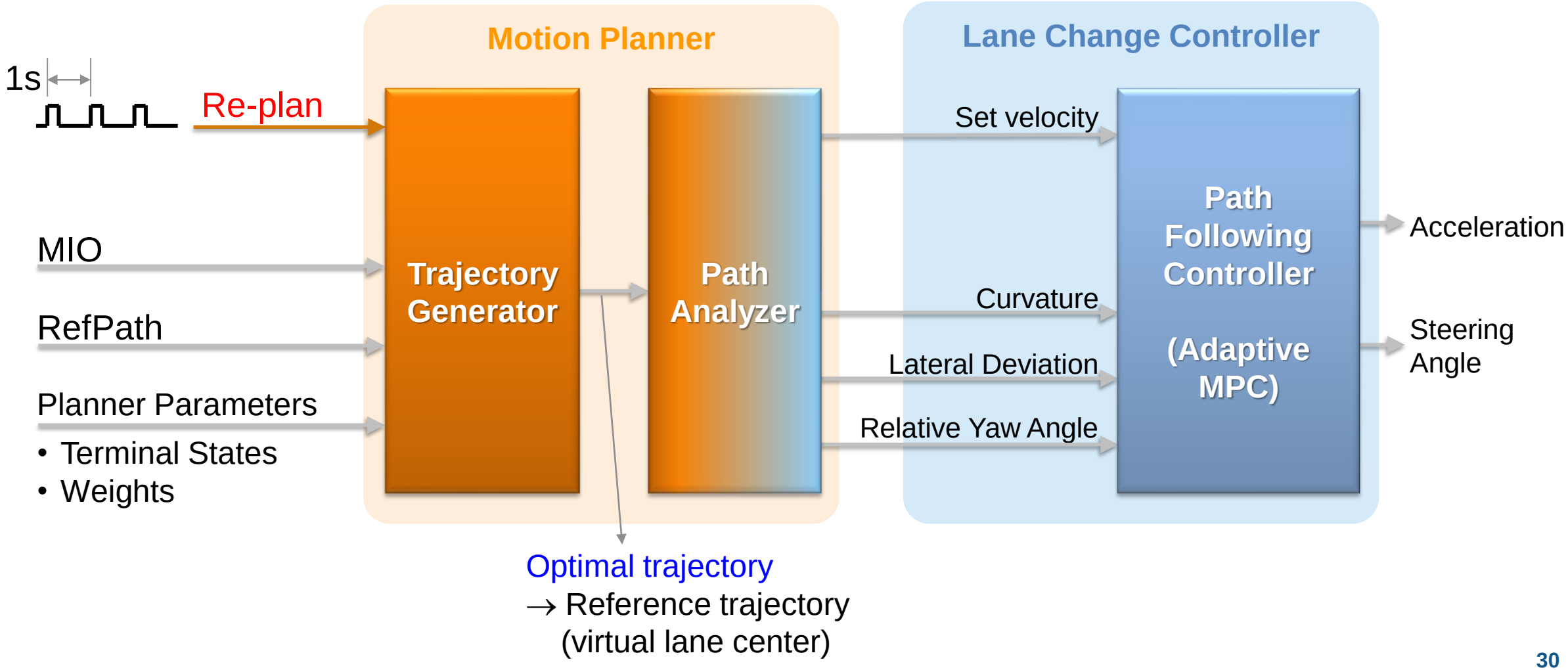


Motion Planner ▷ Path Analyzer

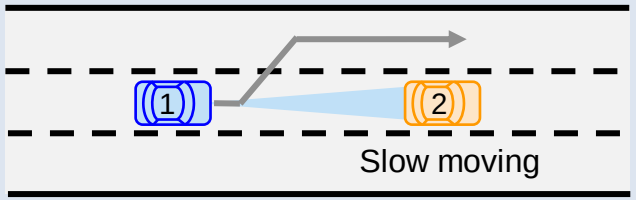




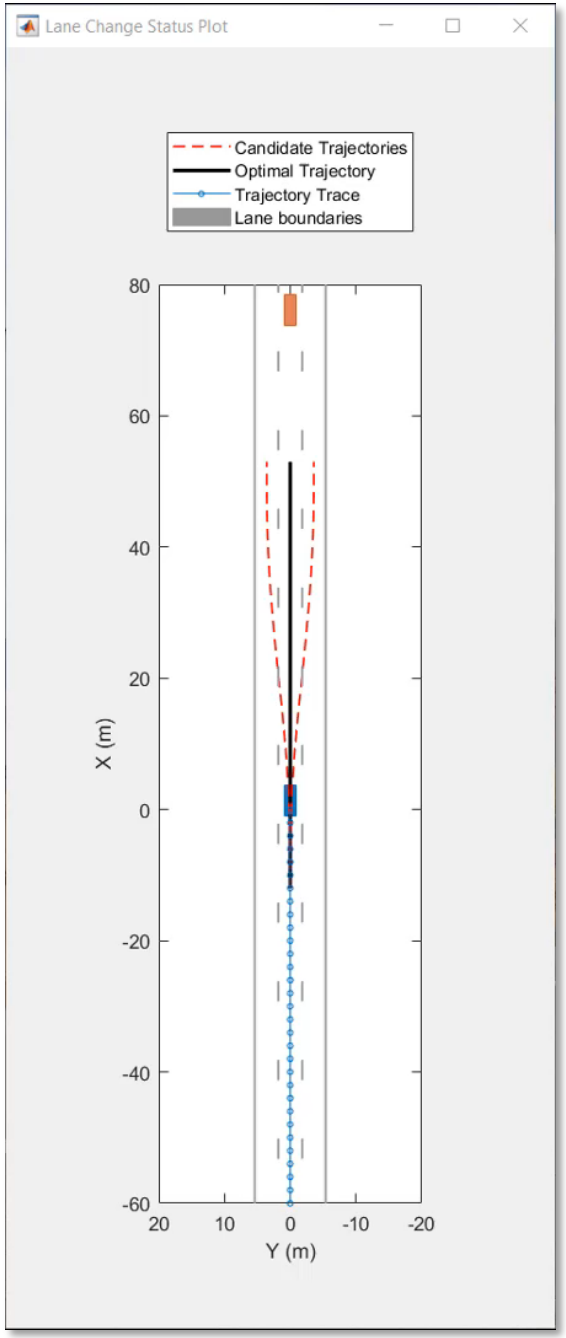
Motion Planner and Lane Change Controller



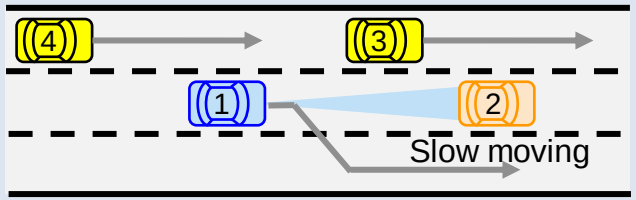
Simulate Highway Lane Change with Test Scenarios

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

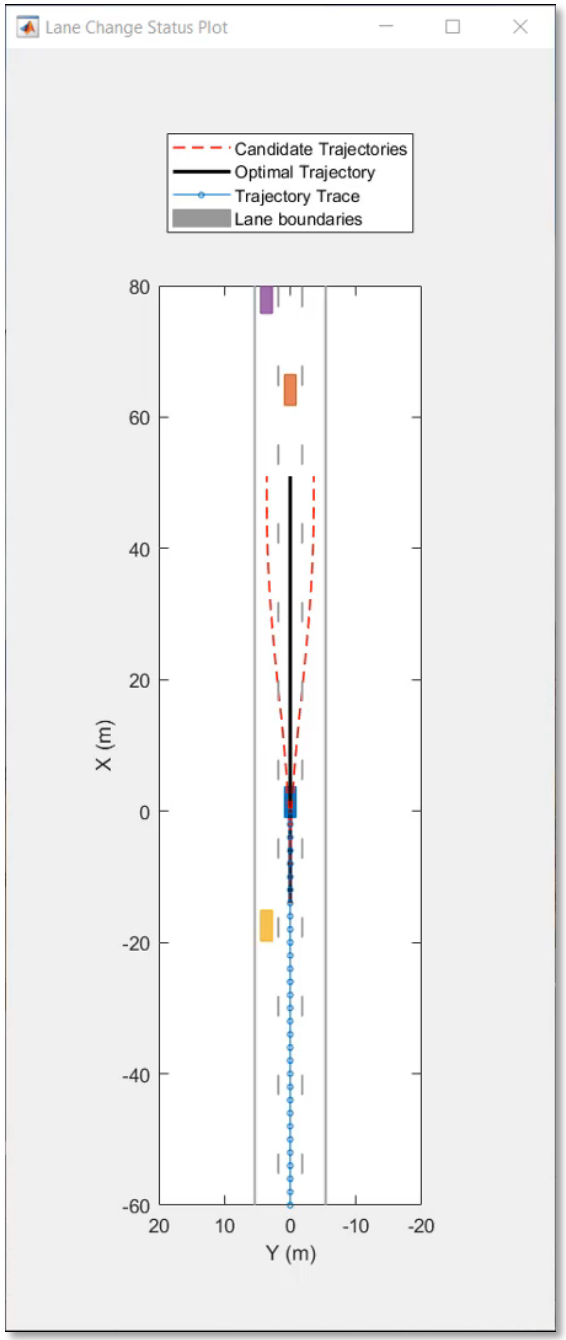
HWT : Headway time
HW : Headway
v_set : set velocity for ego car



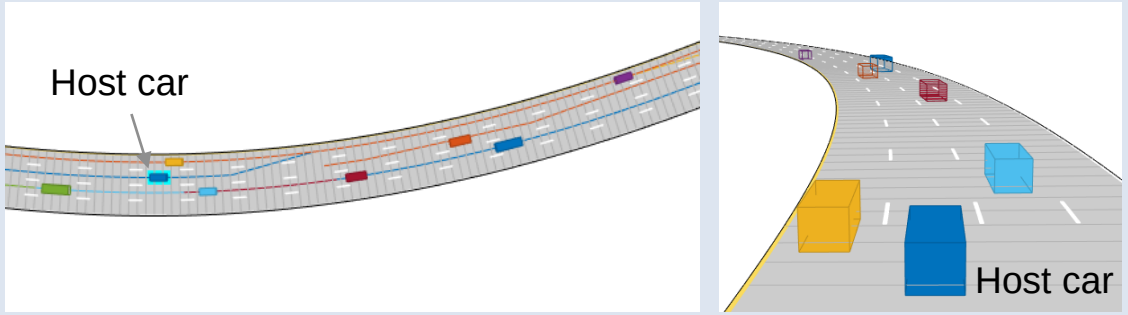
Simulate Highway Lane Change with Test Scenarios

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)

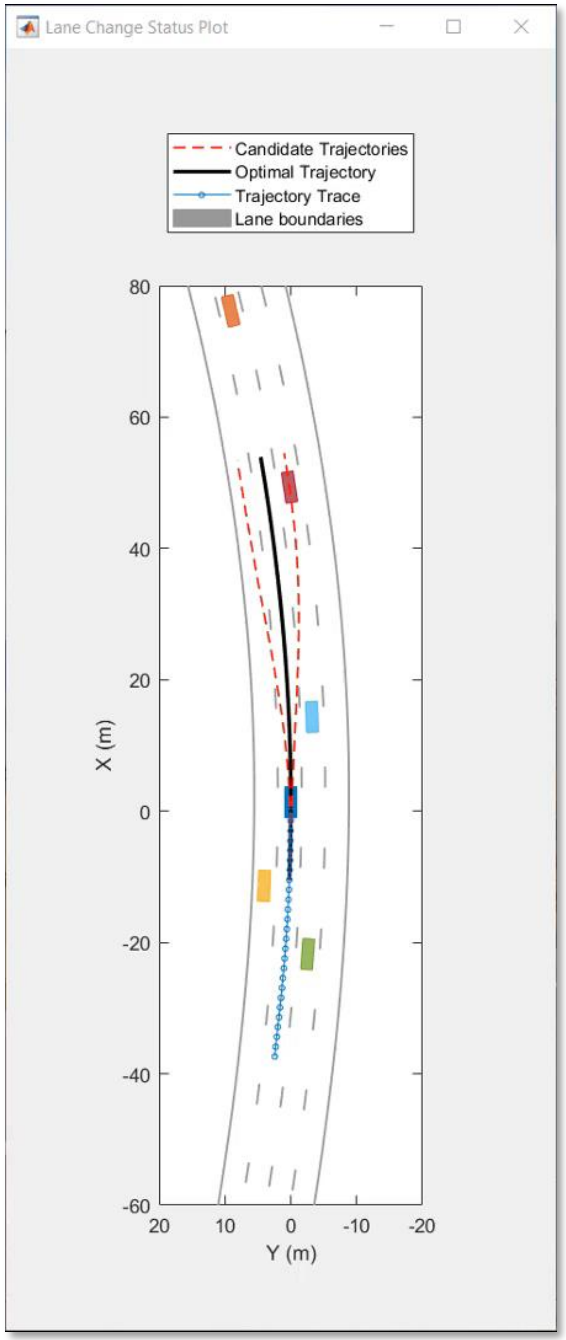
HWT : Headway time
HW : Headway
v_set : set velocity for ego car



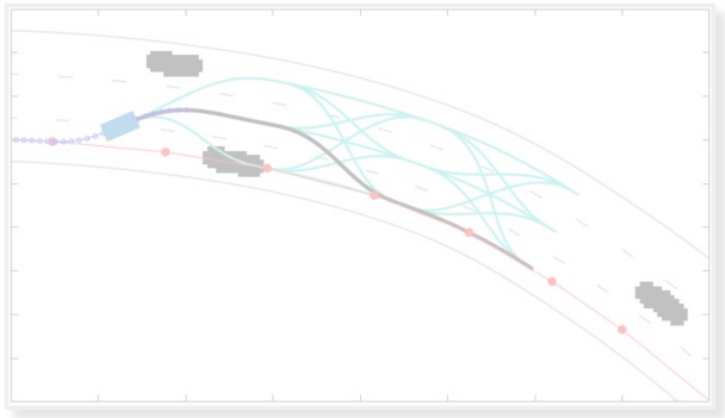
Simulate Highway Lane Change with Test Scenarios

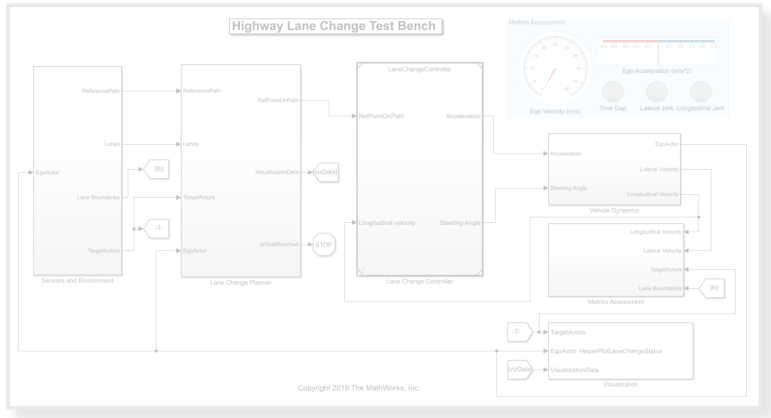
Test Name	scenario_LC_10_SingleLaneChange_Curved
Test Description	Passing slow moving lead car to left lane in curved road 
(1) Host Car	initial velocity = 15m/s v_set = 15m/s
(2) Lead Car	Slow moving
Other Cars	Dense traffic

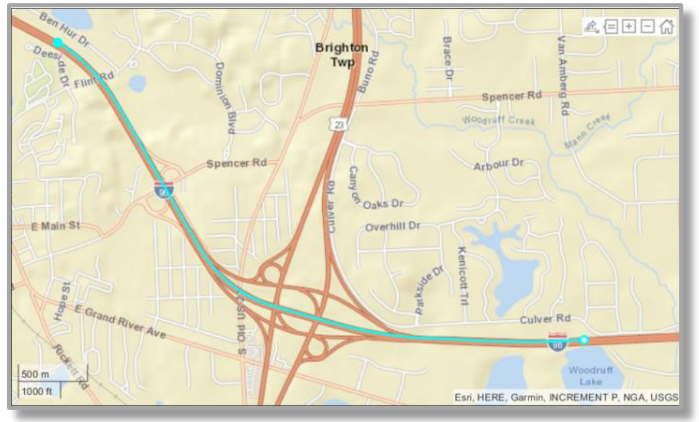
HWT : Headway time
HW : Headway
v_set : set velocity for ego car



Highway Lane Change







Learn motion planner

- Optimal trajectory generation in Frenet coordinate
- Planner parameters
- Simulate trajectory planning with occupancy map

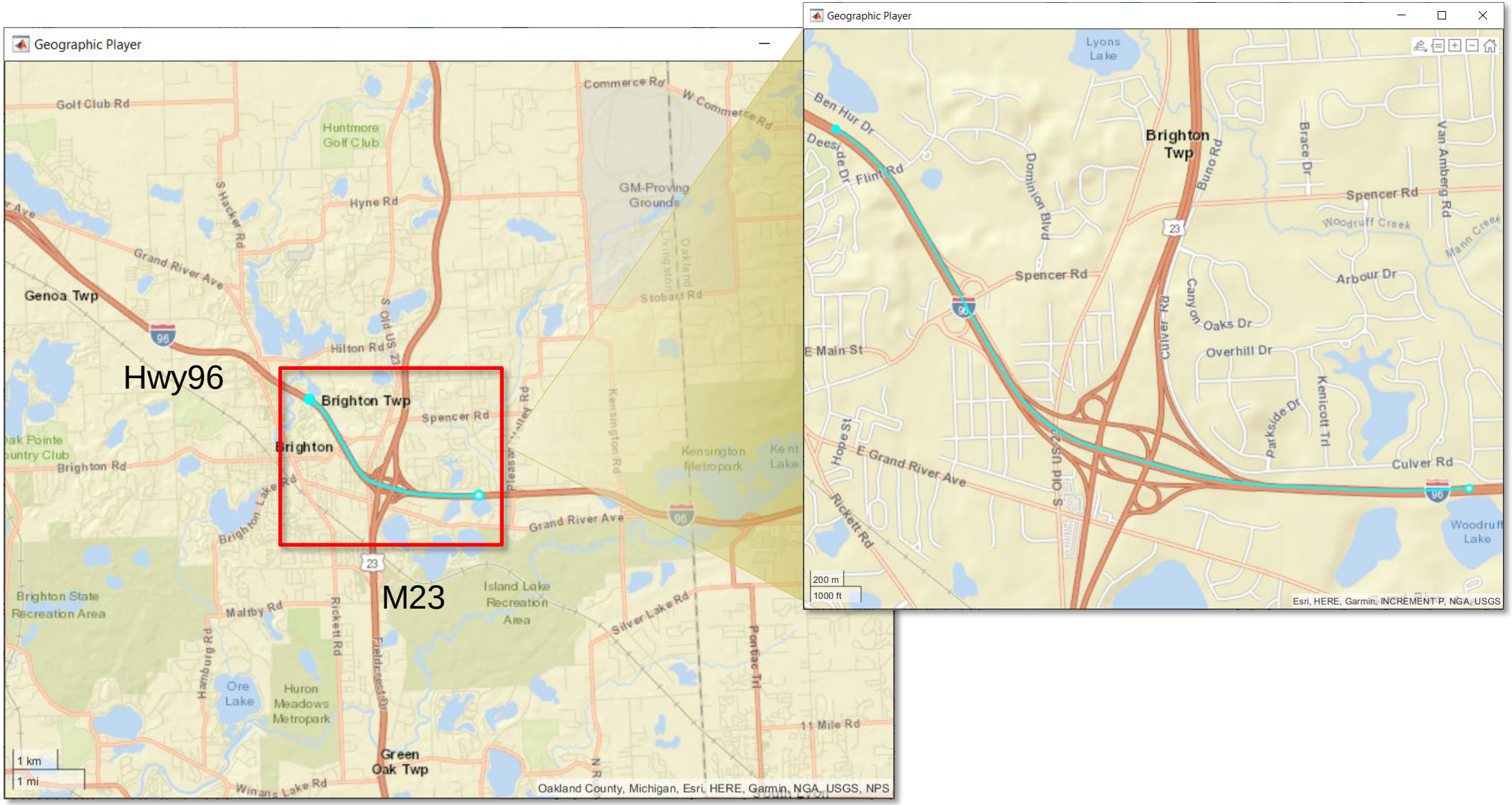
Integrate motion planner and controller

- Learn through reference example
- Architecture of highway lane change
- Simulate closed-loop controller with test scenarios

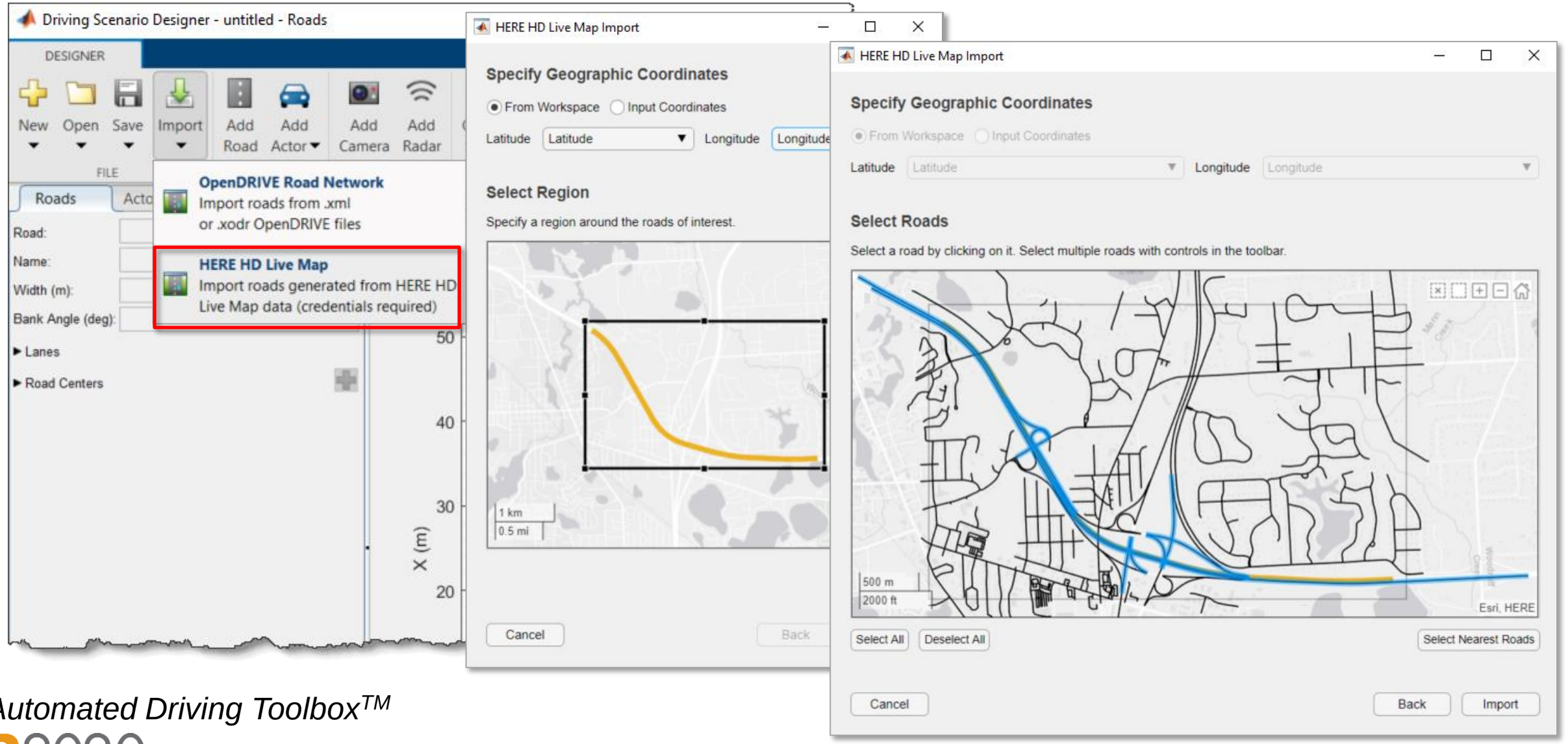
Test with real-world scenario

- Create scenario from HD map
- Update setup script and model
- Run simulation with new scenario

Create highway road network from HD map



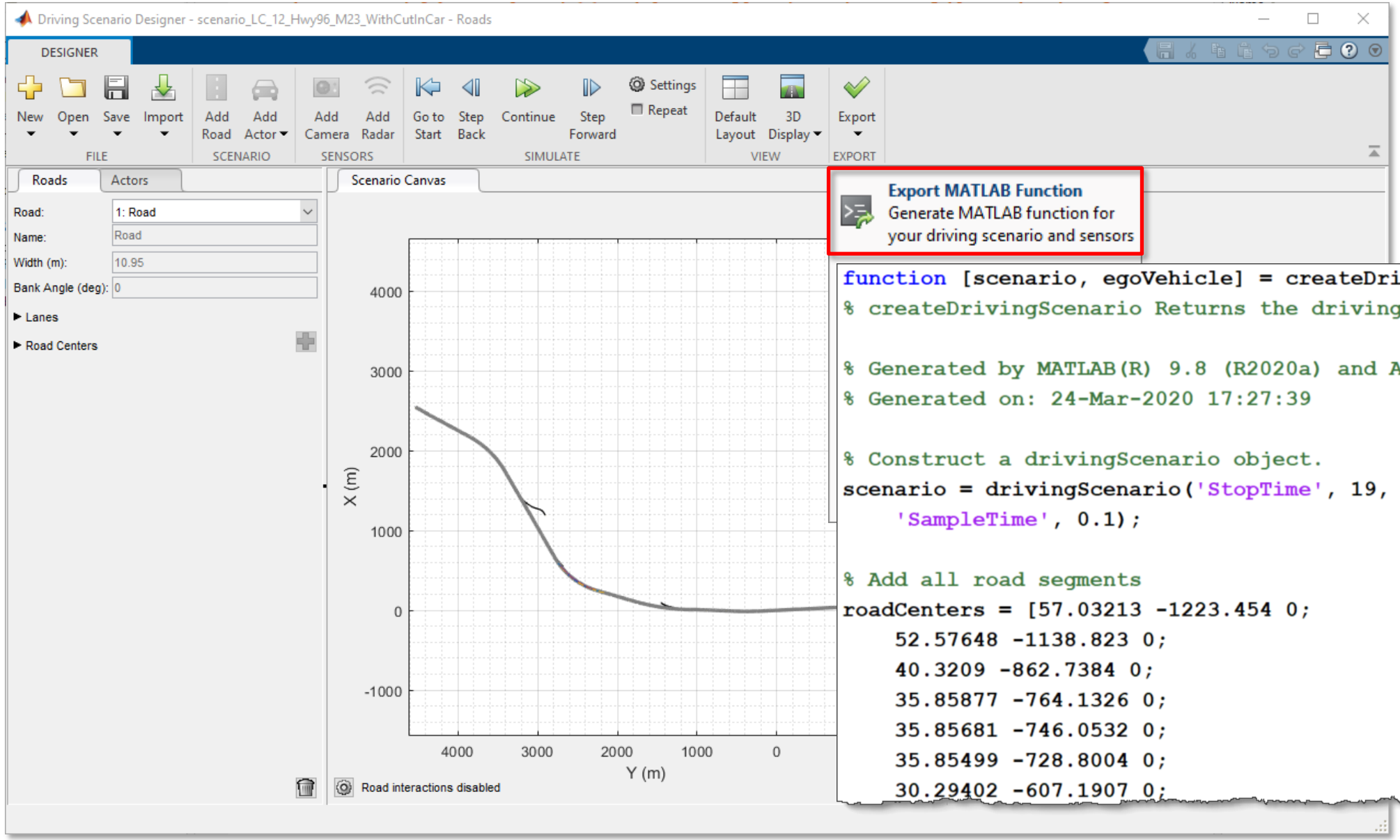
Import HERE HD Live Map into Driving Scenario



Automated Driving Toolbox™

R2020a

Add actors and export driving scenario with MATLAB Function




```
function [scenario, egoVehicle] = createDrivingScenario()
% createDrivingScenario Returns the drivingScenario defined in

% Generated by MATLAB(R) 9.8 (R2020a) and Automated Driving To
% Generated on: 24-Mar-2020 17:27:39

% Construct a drivingScenario object.
scenario = drivingScenario('StopTime', 19, ...
    'SampleTime', 0.1);

% Add all road segments
roadCenters = [57.03213 -1223.454 0;
    52.57648 -1138.823 0;
    40.3209 -862.7384 0;
    35.85877 -764.1326 0;
    35.85681 -746.0532 0;
    35.85499 -728.8004 0;
    30.29402 -607.1907 0;
```

Setup driving scenario and workspace variables

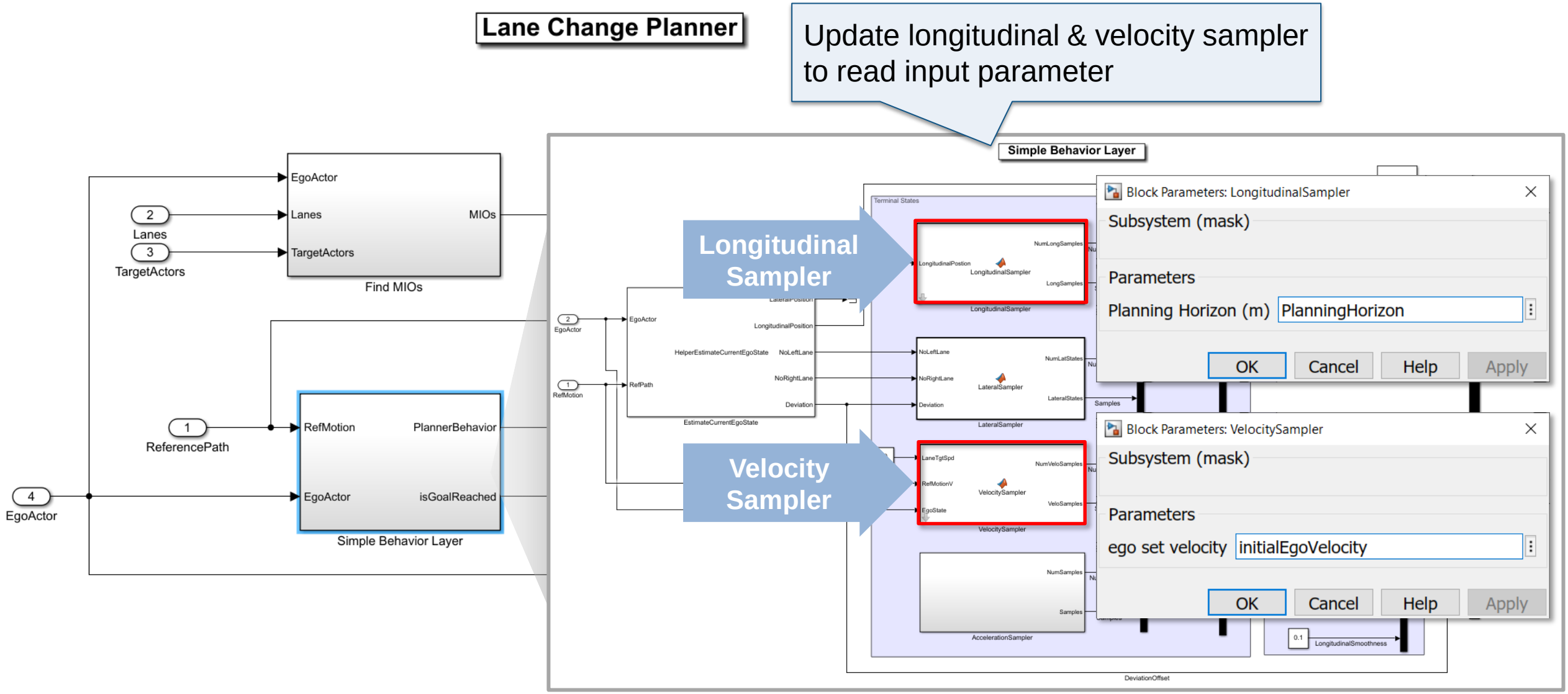
```
function helperSLHighwayLaneChangeSetup(varargin)

%% Inputs
% Scenario function name
defaultScenarioFcnName = "scenario_LC_06_DoubleLaneChange";
validScenarioFcnNames = [...
        "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_Hwy96_M23_WithMergingCar"
        "scenario_LC_12_Hwy96_M23_WithCutInCar"];
```

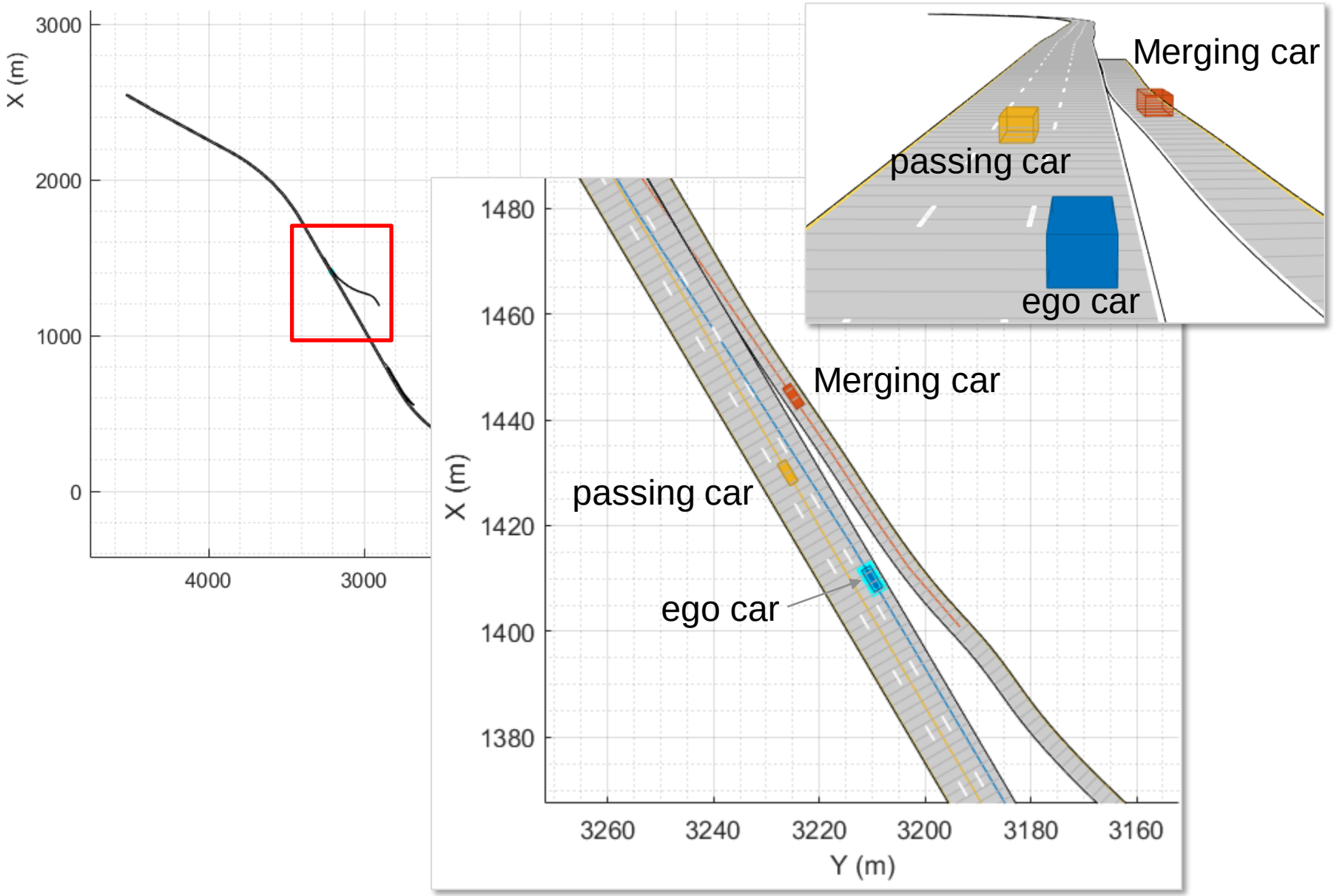
Add new driving scenario

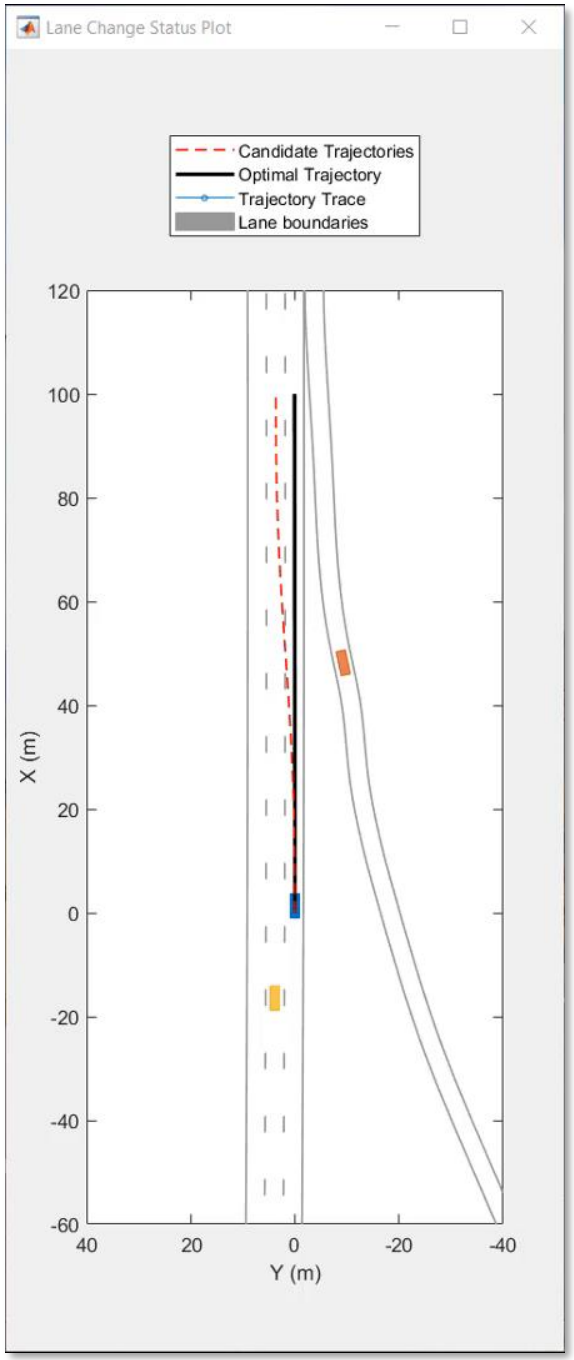
```
Command Window
>> helperSLHighwayLaneChangeSetup("scenario_LC_11_Hwy96_M23_WithMergingCar")
fx >>
```

Update Lane Change Planner ▷ Simple Behavior Layer

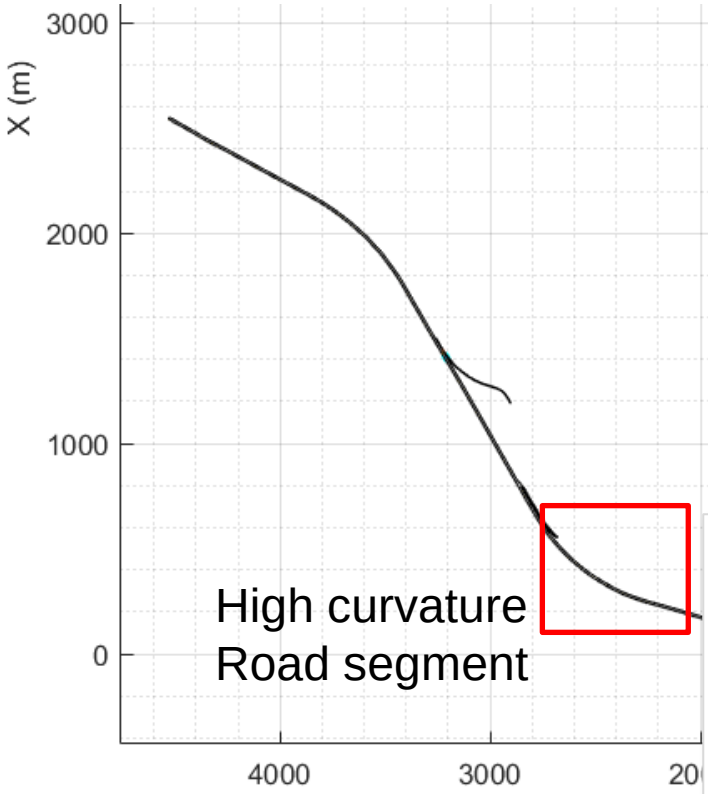


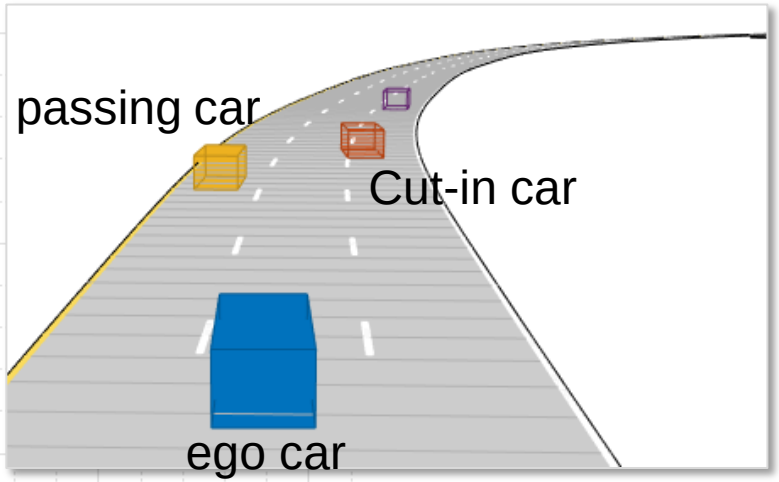
scenario_LC_11_Hwy96_M23_WithMergingCar

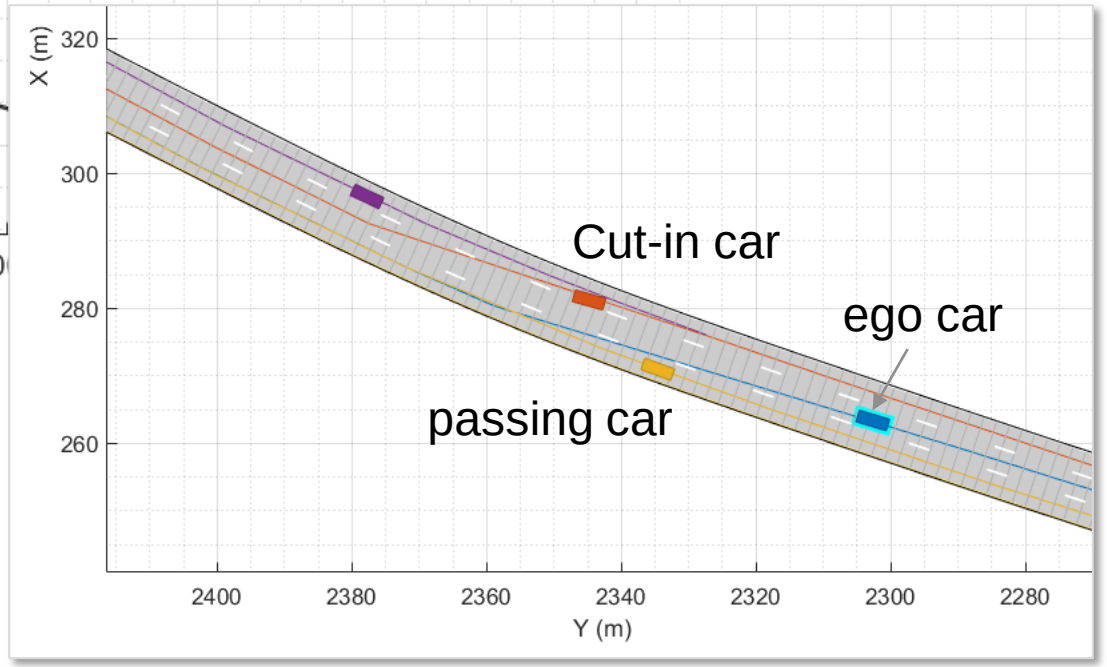


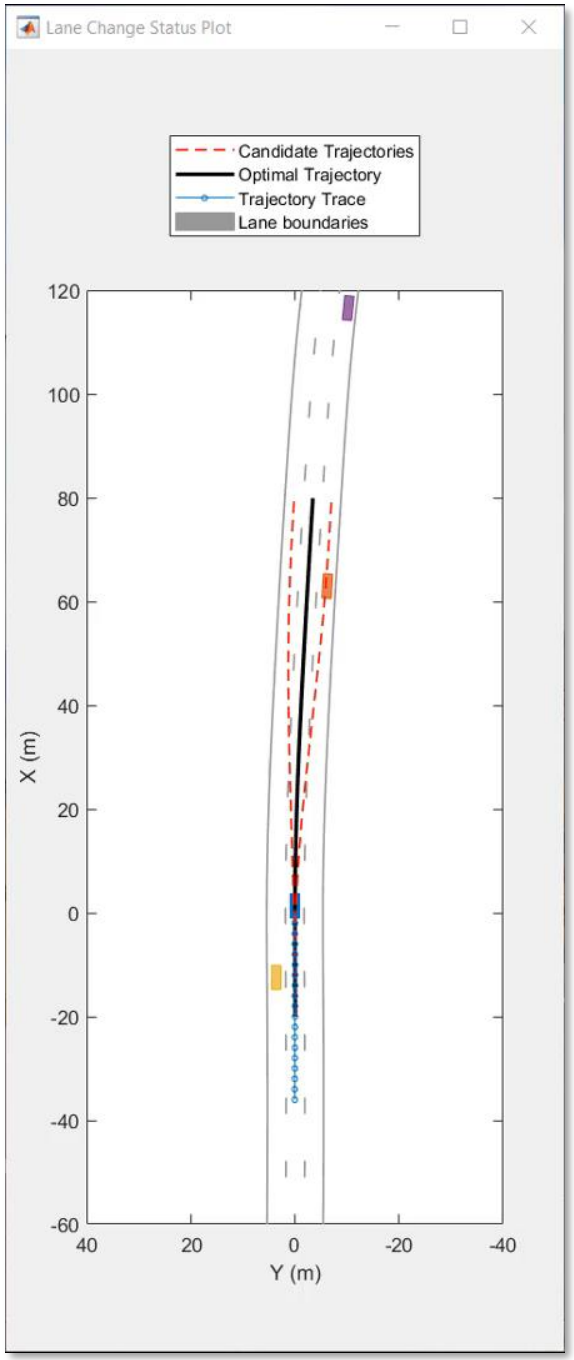


scenario_LC_12_Hwy96_M23_WithCutInCar

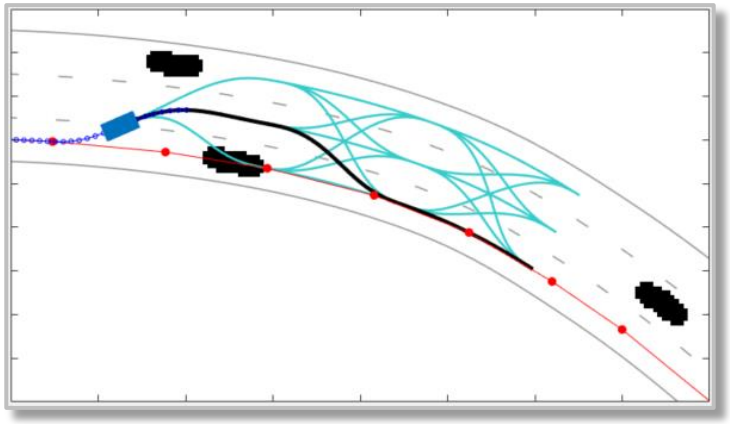


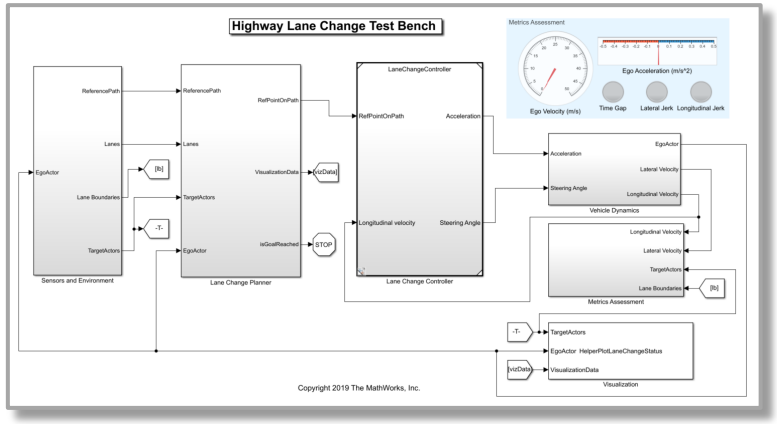


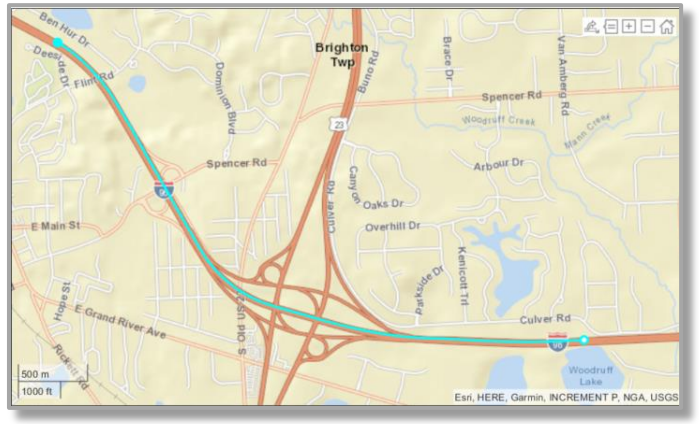




Recap: Highway Lane Change







Learn motion planner

- Optimal trajectory generation in Frenet coordinate
- Planner parameters
- Simulate trajectory planning with occupancy map

Integrate motion planner and controller

- Learn through reference example
- Architecture of highway lane change
- Simulate closed-loop controller with test scenarios

Test with real-world scenario

- Create scenario from HD map
- Update setup script and model
- Run simulation with new scenario

Presenter contact info and poll questions

Please contact me at spark@mathworks.com with questions

- Poll question : I found this technique the most interesting
  a. Motion planner for lane change
  b. MPC path following controller
  c. Driving scenario creation
  d. Import HD map into driving scenario

- If you would like to an individual follow-up, please let us know in the WebEx poll area.