



Process Control: Part II- Model Predictive Control (EE6225, AY2019/20, S1)

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11/10/2019	Topic 1	• INTRODUCTION AND PRELIMINARY
17/10/2019	Topic 2	• BASIC THEORY OF MODEL PREDICTIVE CONTROL: PART-I
24/10/2019	Topic 3	• BASIC THEORY OF MODEL PREDICTIVE CONTROL: PART-II
31/10/2019	Topic 4	• QUIZ AND OPERATION PRINCIPLE OF POWER CONVERTER*
07/11/2019	Topic 5	• APPLICATION OF MODEL PREDICTIVE CONTROL IN POWER CONVERTERS I
14/11/2019	Topic 6	• APPLICATION OF MODEL PREDICTIVE CONTROL IN POWER CONVERTERS II

*: Not compulsory, not required.



There will be **one** quiz for the AC motor drives part at **31/10/2019**:

- Quiz (10 marks): Topics to be tested covered **topics 1 to 3**;
- To answer a few compulsory questions within **60 minutes**;
- It is a **closed-book** Quiz;
- Student must present **ID (with photo)** for taking attendance;
- Zero mark will be given for **absentees** without valid reasons;
- Absentees must write in to the tutor through email within **THE SAME DAY OR EARLIER** of Quiz to request a make-up (Failure to do so will result in a zero mark).



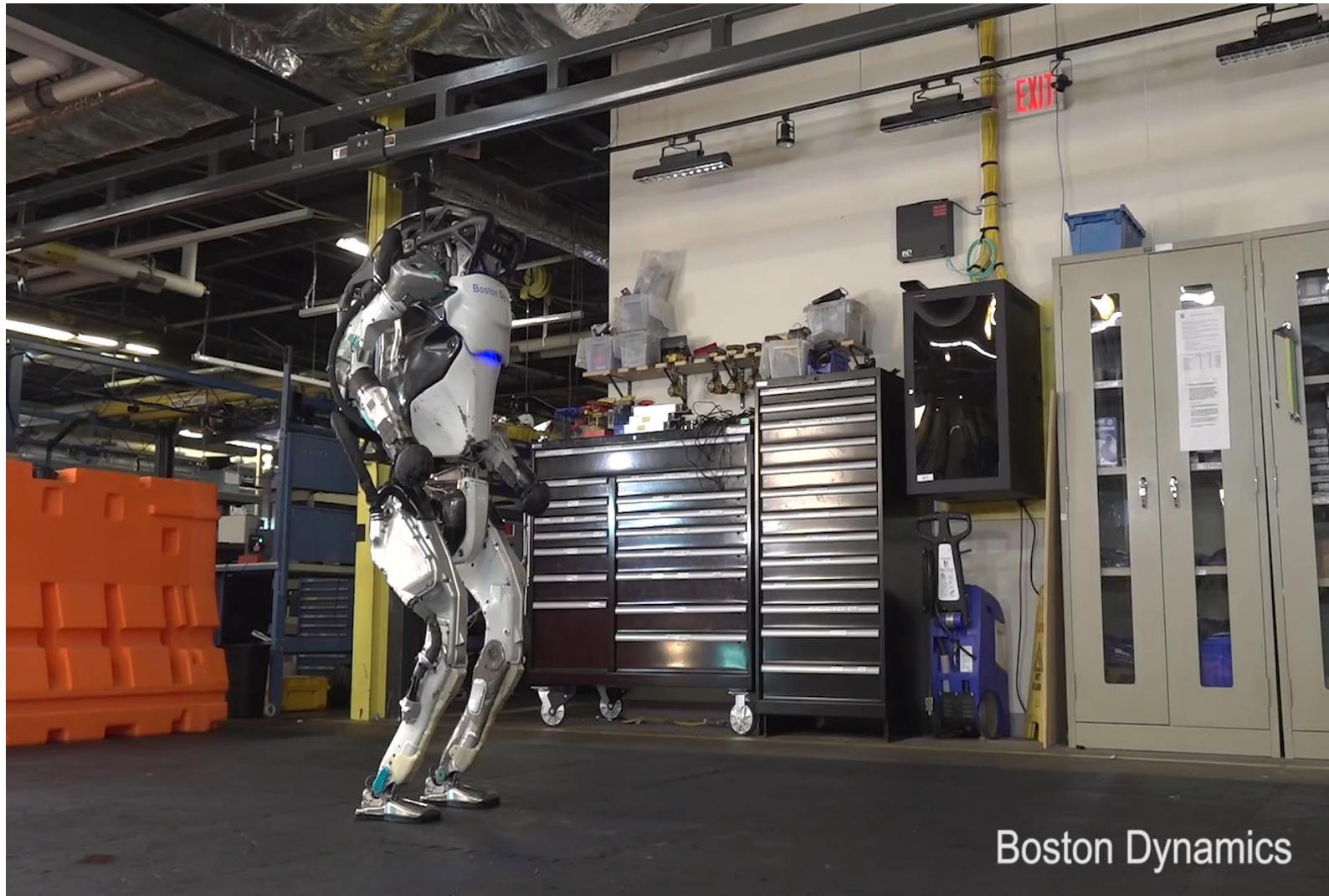
- Welcome to **answer questions on the class**
- **Each answer to the question + 1 points**
- The maximum is **5 points**
- Please let me know **your name and ID after the class**
or via email



INTRODUCTION AND PRELIMINARY OF THE MODEL PREDICTIVE CONTROL (MPC)

[10/10/2019]

- Why we need to learn MPC?
- What is MPC?





ORCA - Optimal RC Autonomous Racing

Model Predictive Contouring Control Static Obstacle Avoidance







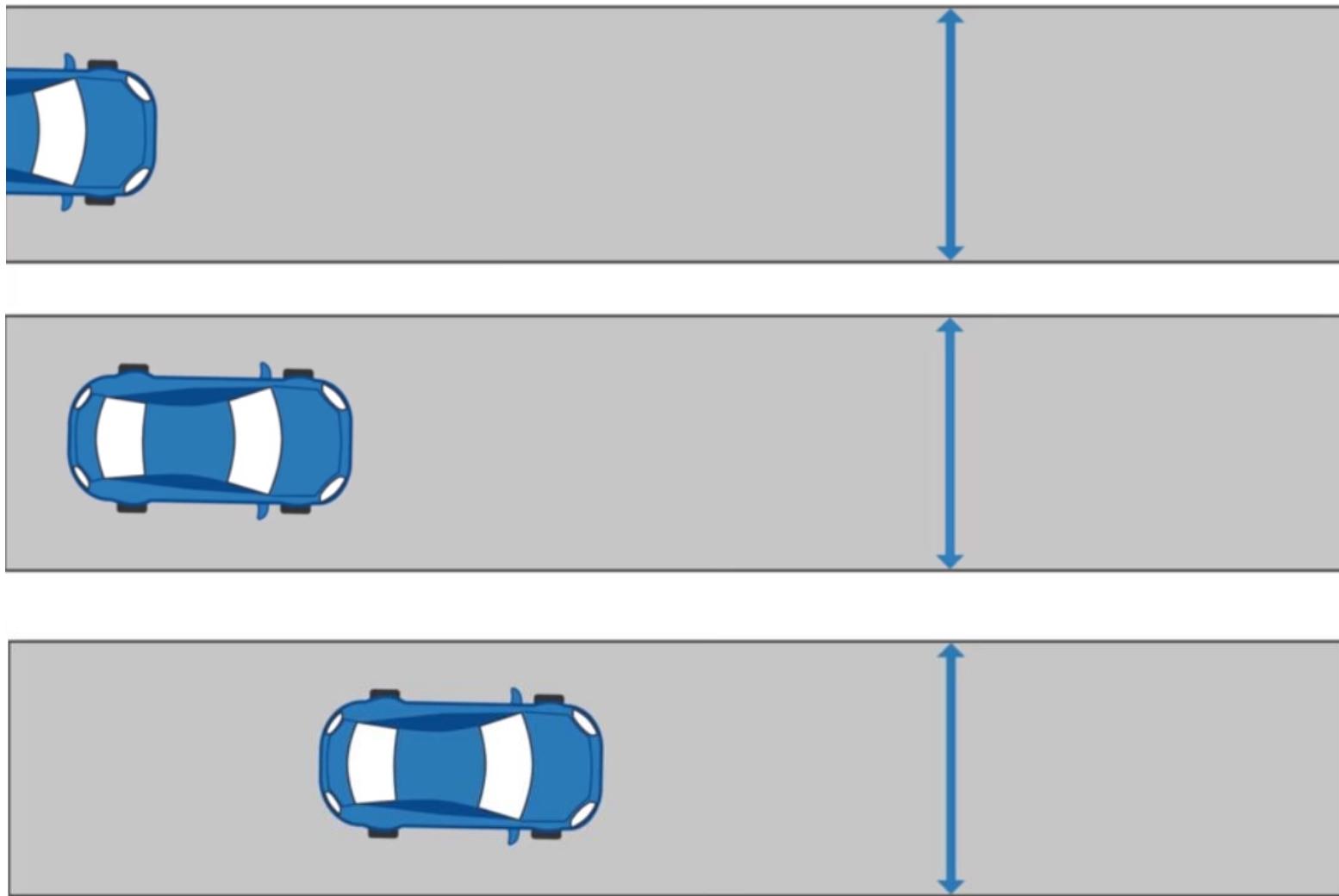
INTRODUCTION AND PRELIMINARY OF THE MODEL PREDICTIVE CONTROL (MPC)

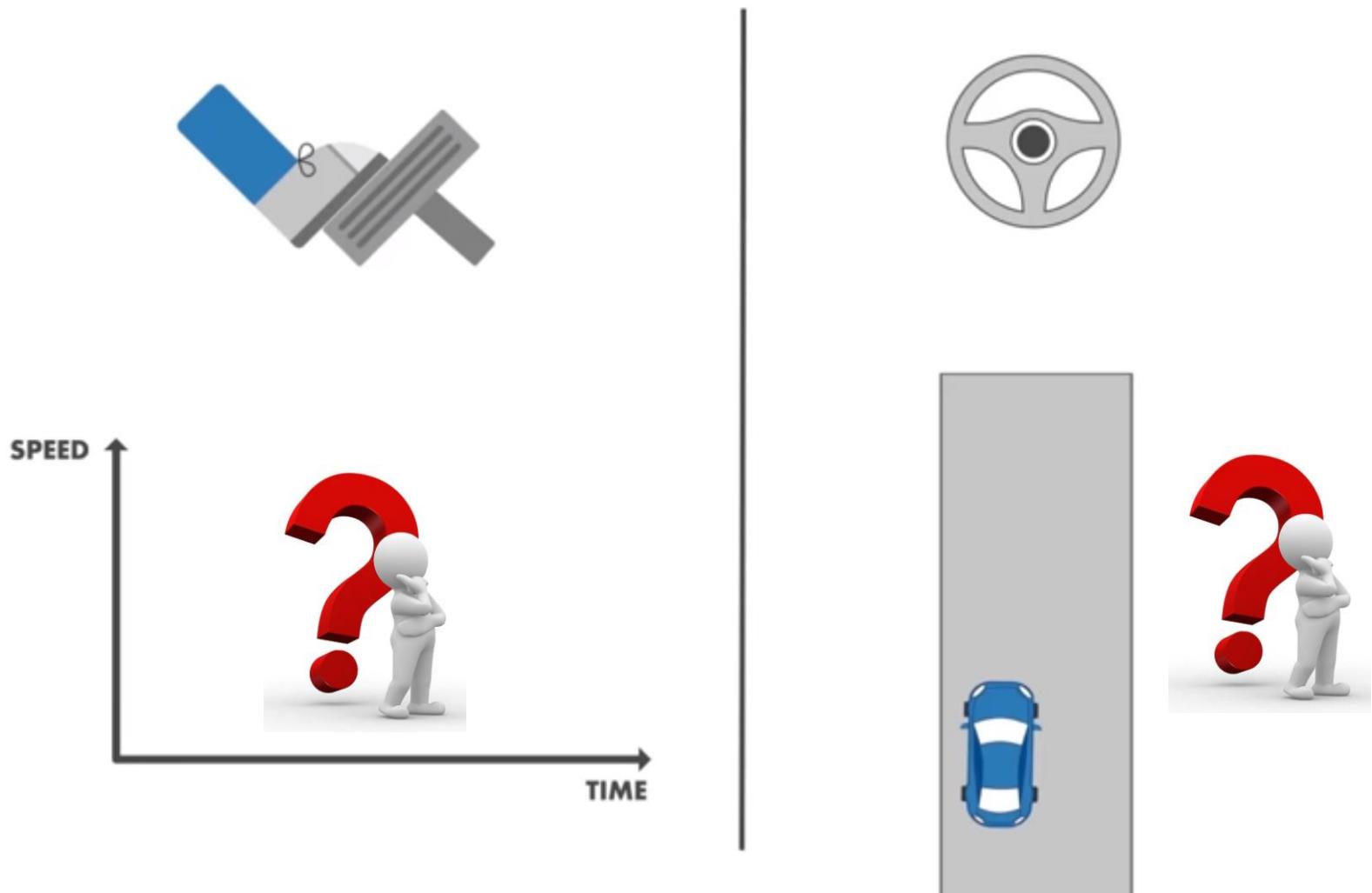
[10/10/2019]

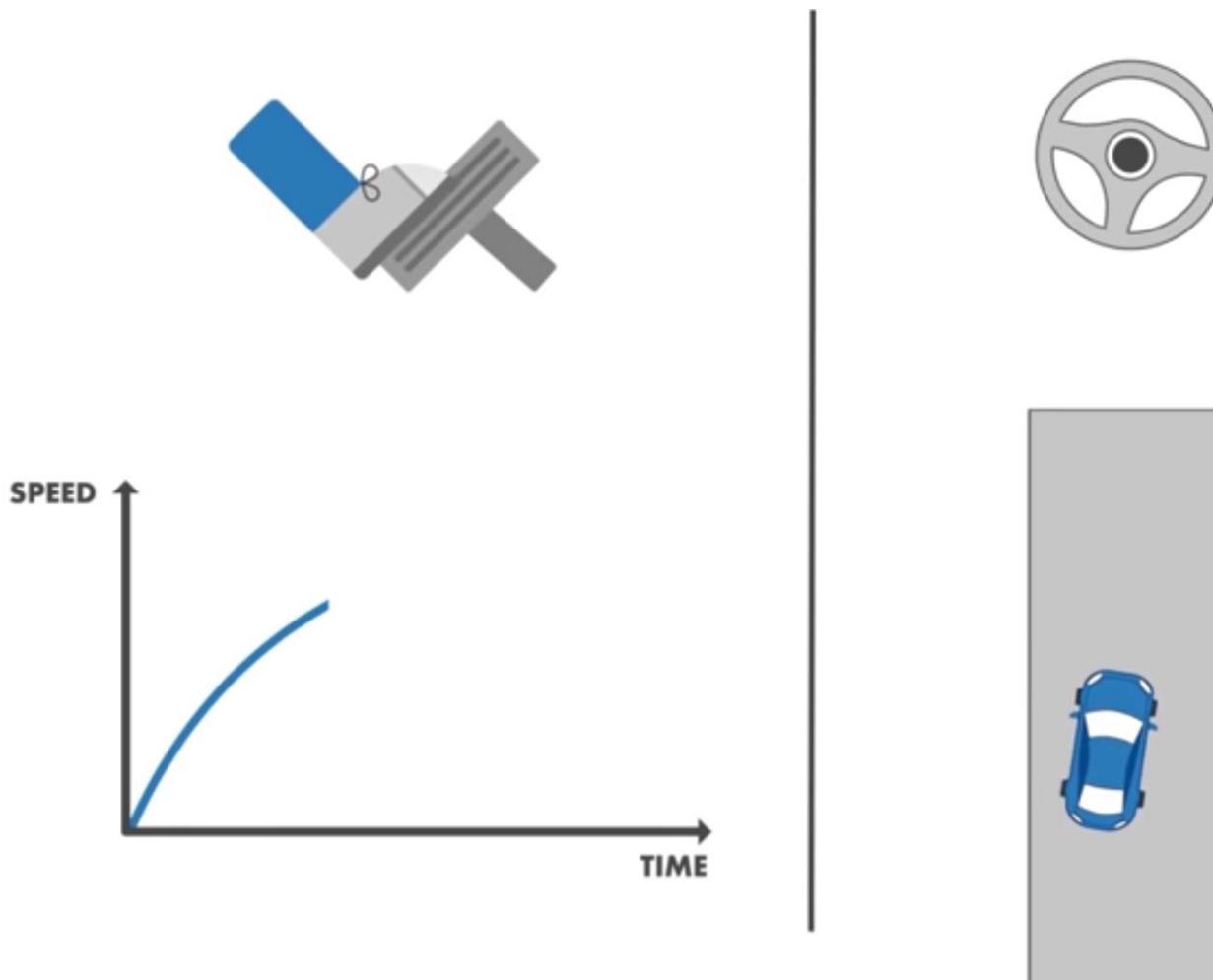
- Why we need to learn MPC?
- What is MPC?



A natural MPC example: drive car

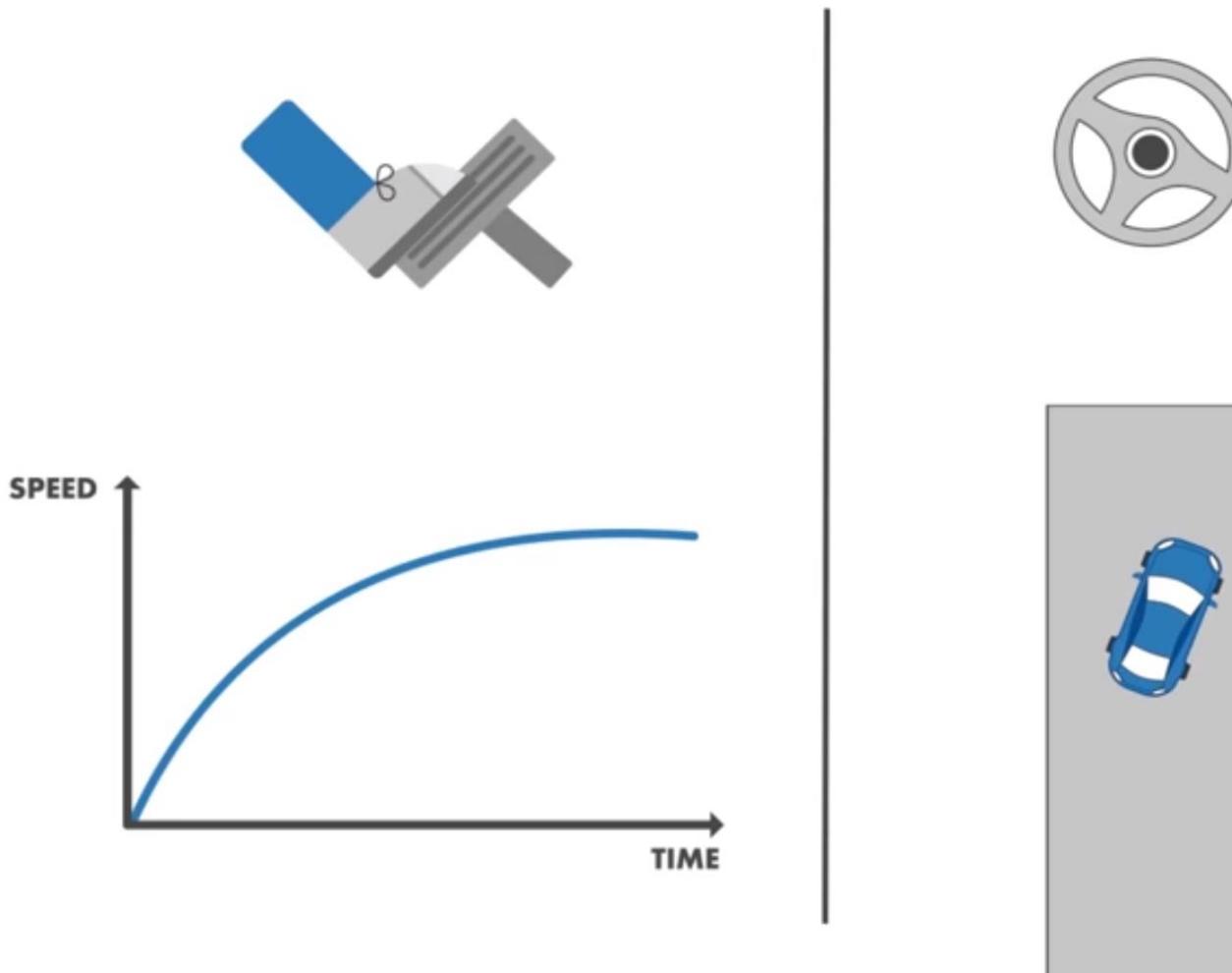


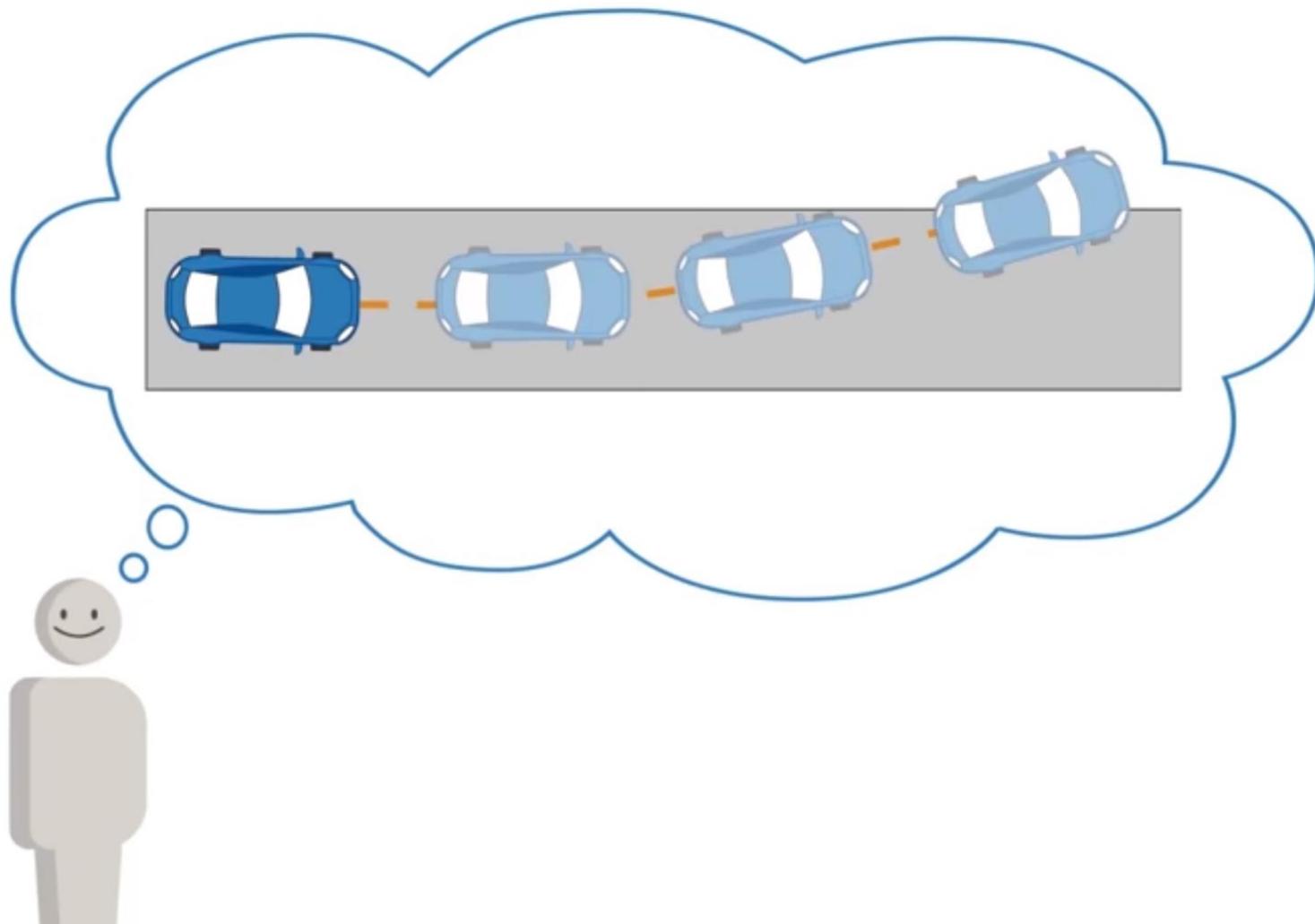


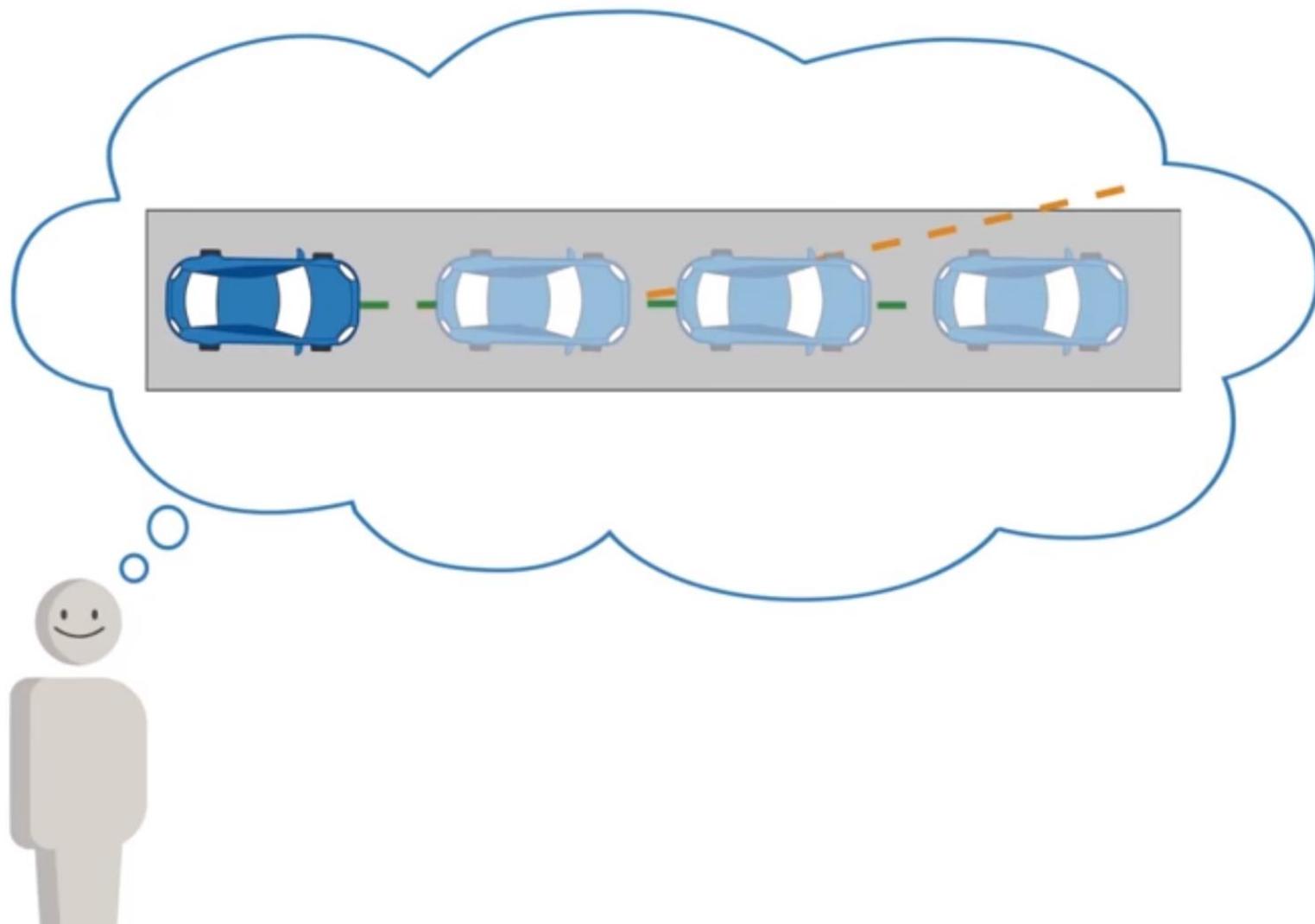


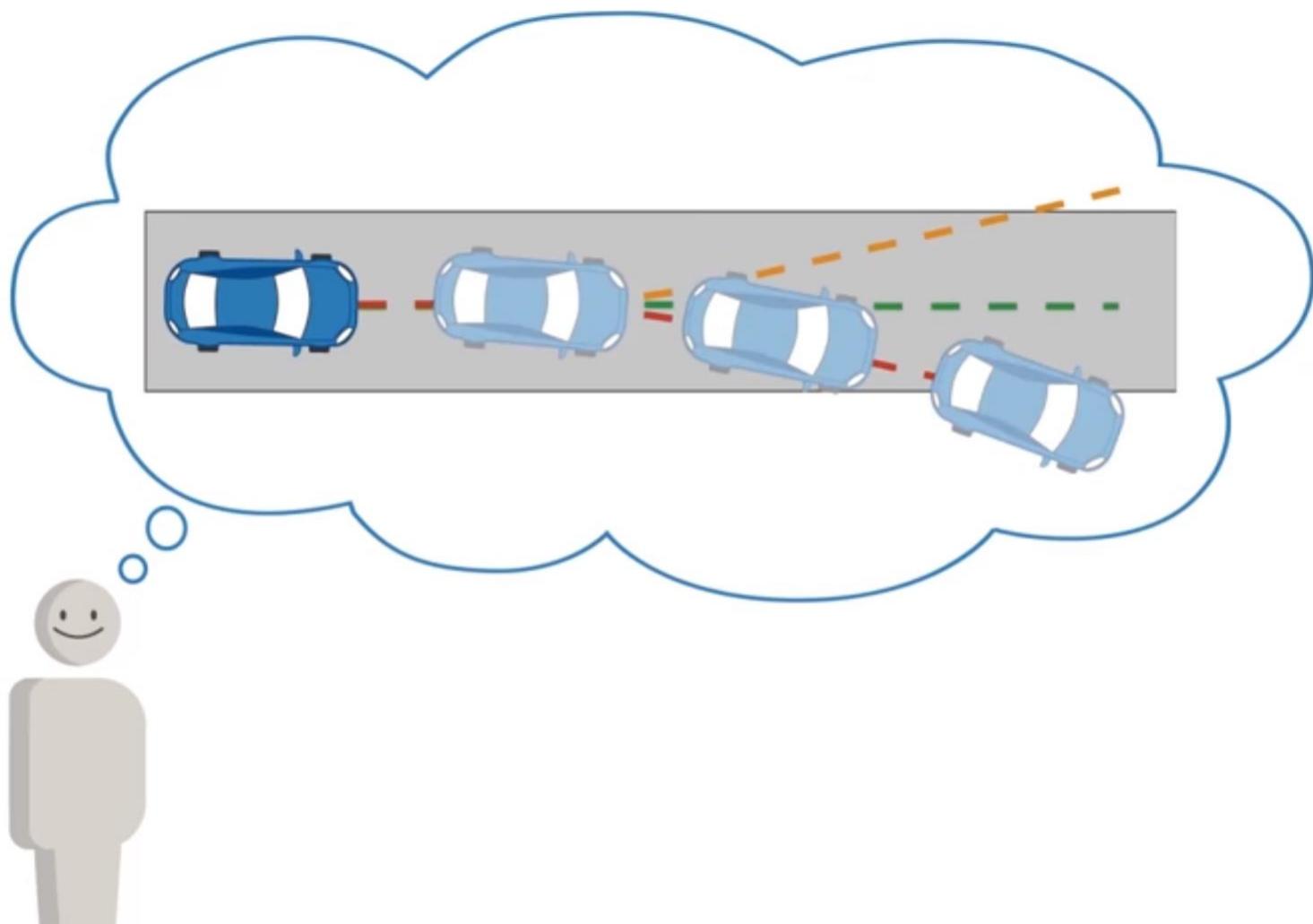


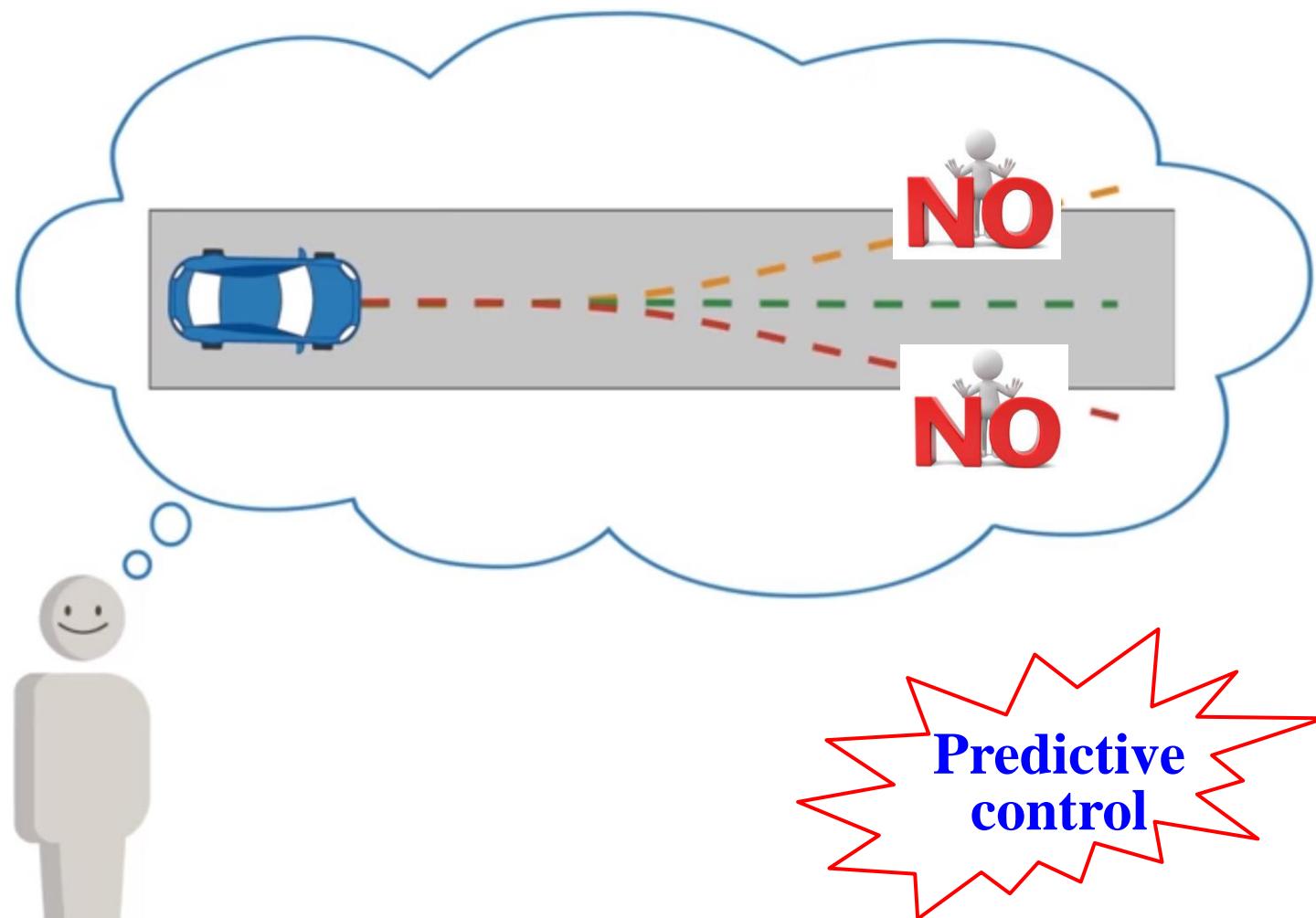
Moving the car via control speed and direction













INTRODUCTION AND PRELIMINARY OF THE MODEL PREDICTIVE CONTROL (MPC)

[10/10/2019]

- Why we need to learn MPC?
- What is MPC?



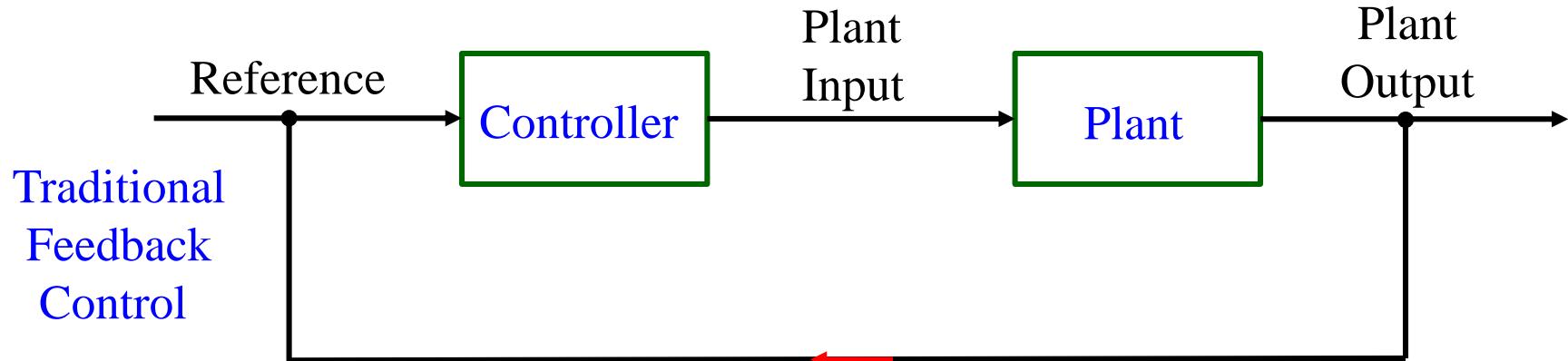
WHAT IS MPC?

- BASIC CONCEPT OF THE MPC
- DESIGN PARAMETERS OF THE MPC
- LINEAR AND NON-LINEAR MPC
- HOW TO RUN MPC FASTER?

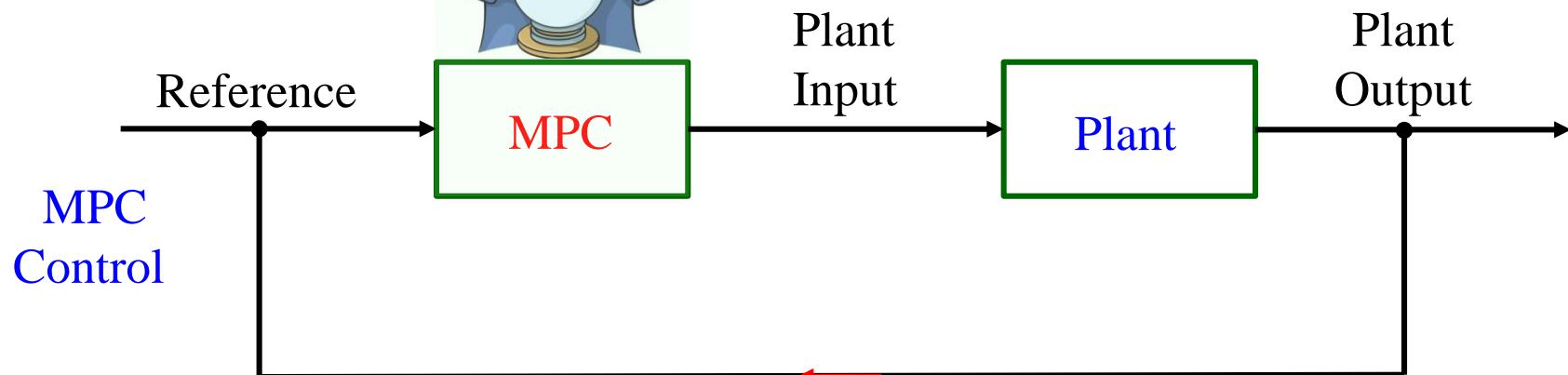


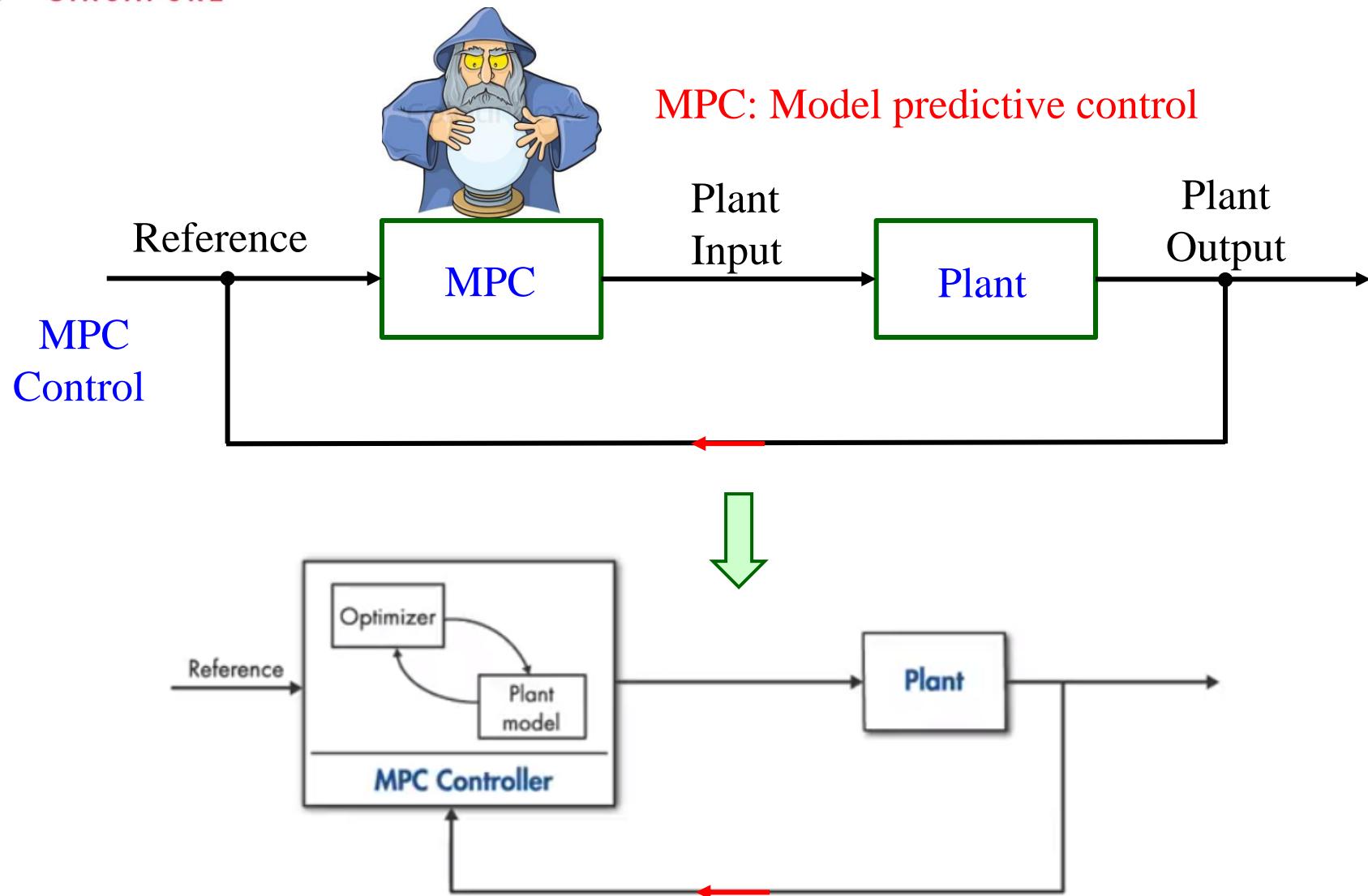
WHAT IS MPC?

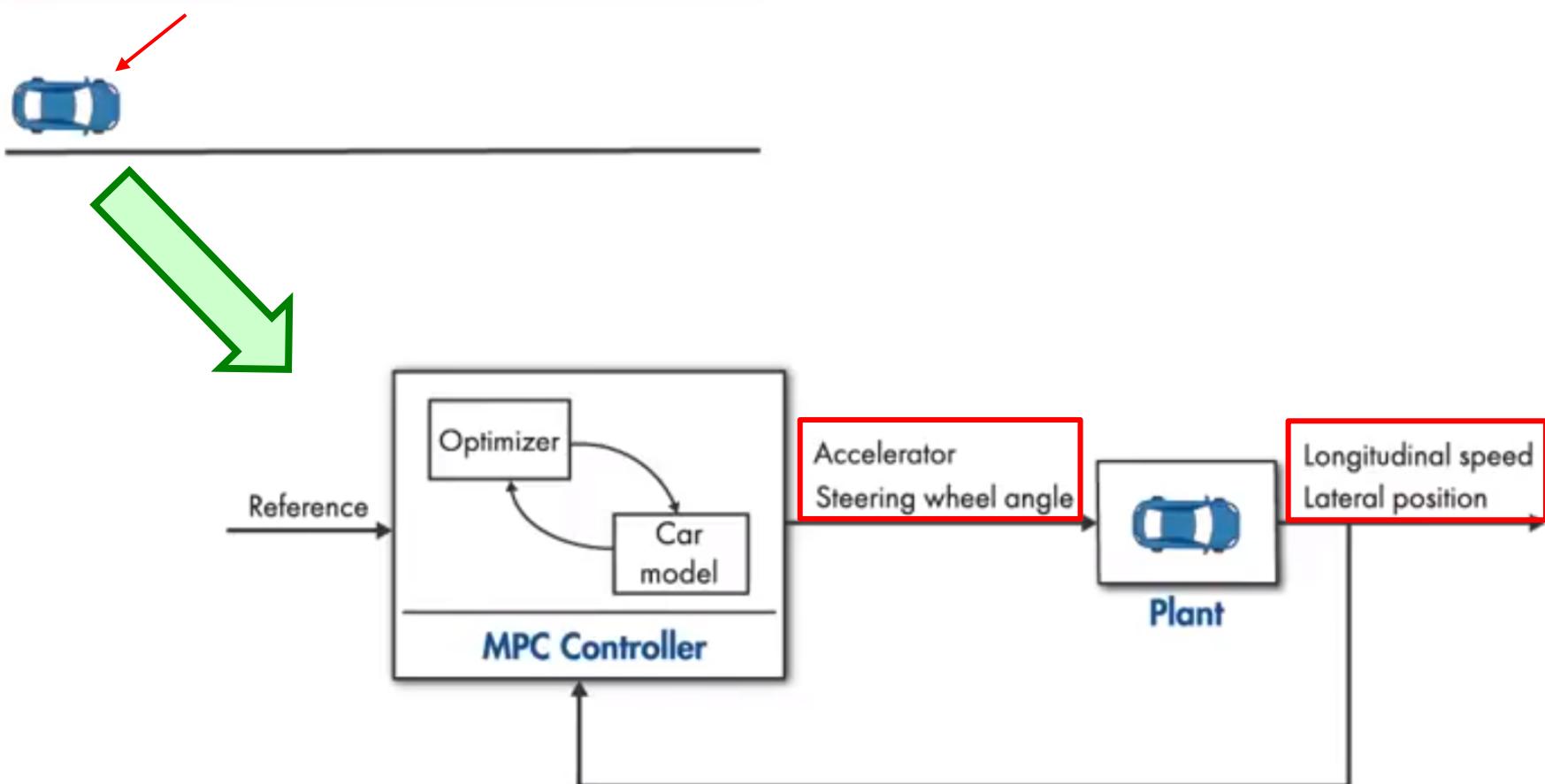
- **BASIC CONCEPT OF THE MPC**
- DESIGN PARAMETERS OF THE MPC
- LINEAR AND NON-LINEAR MPC
- HOW TO RUN MPC FASTER?



MPC: Model predictive control

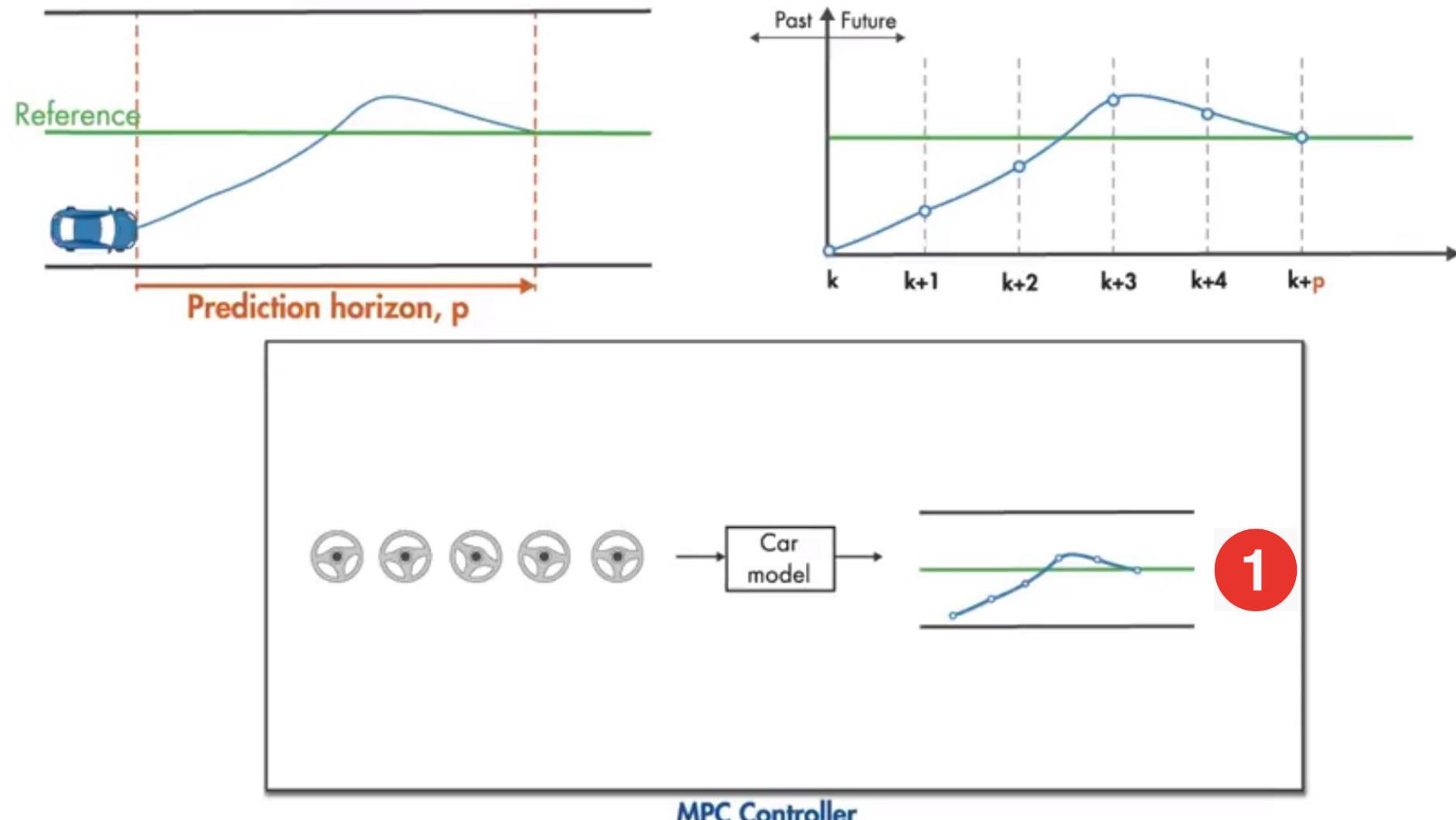






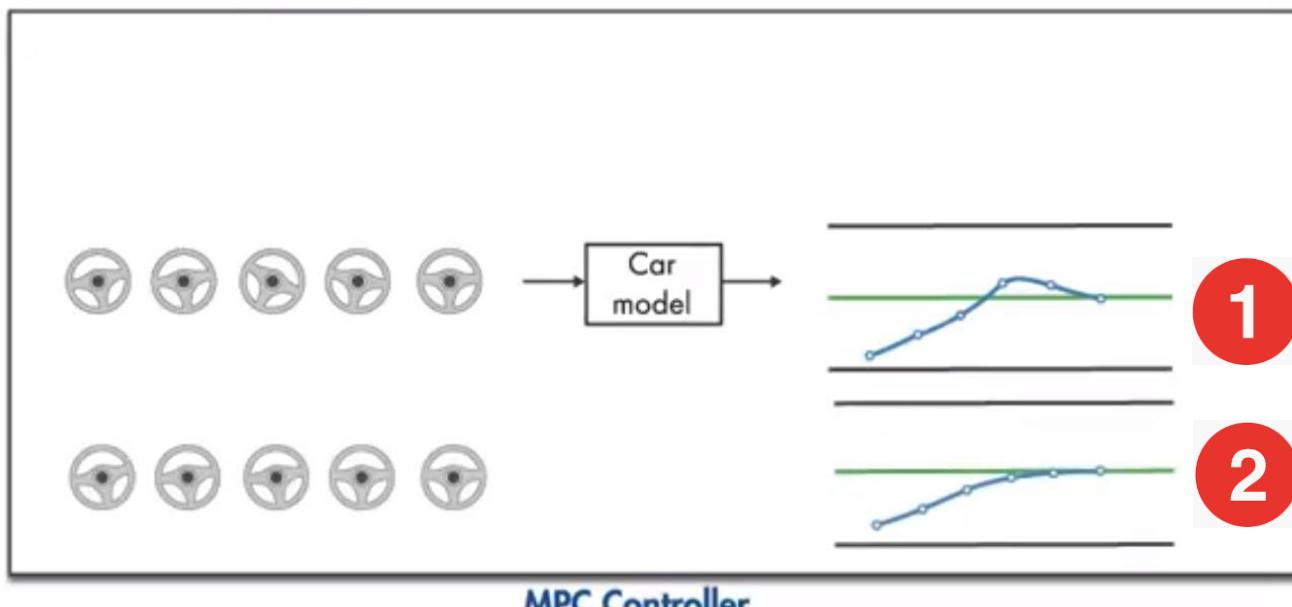
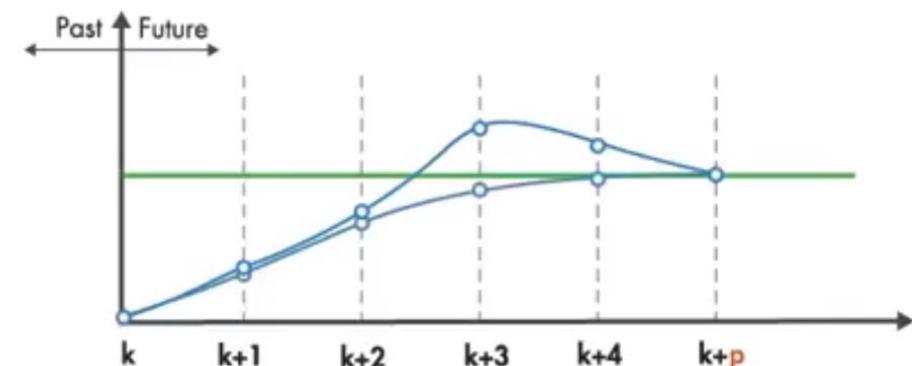
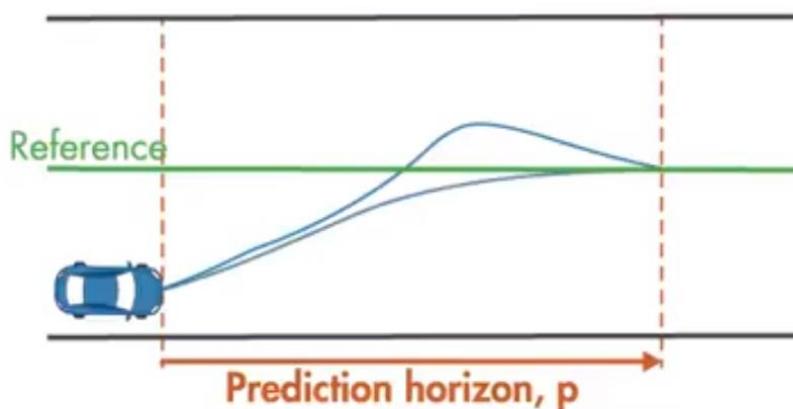


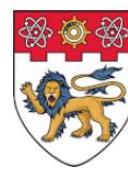
Explain the MPC by driving car: Prediction 1



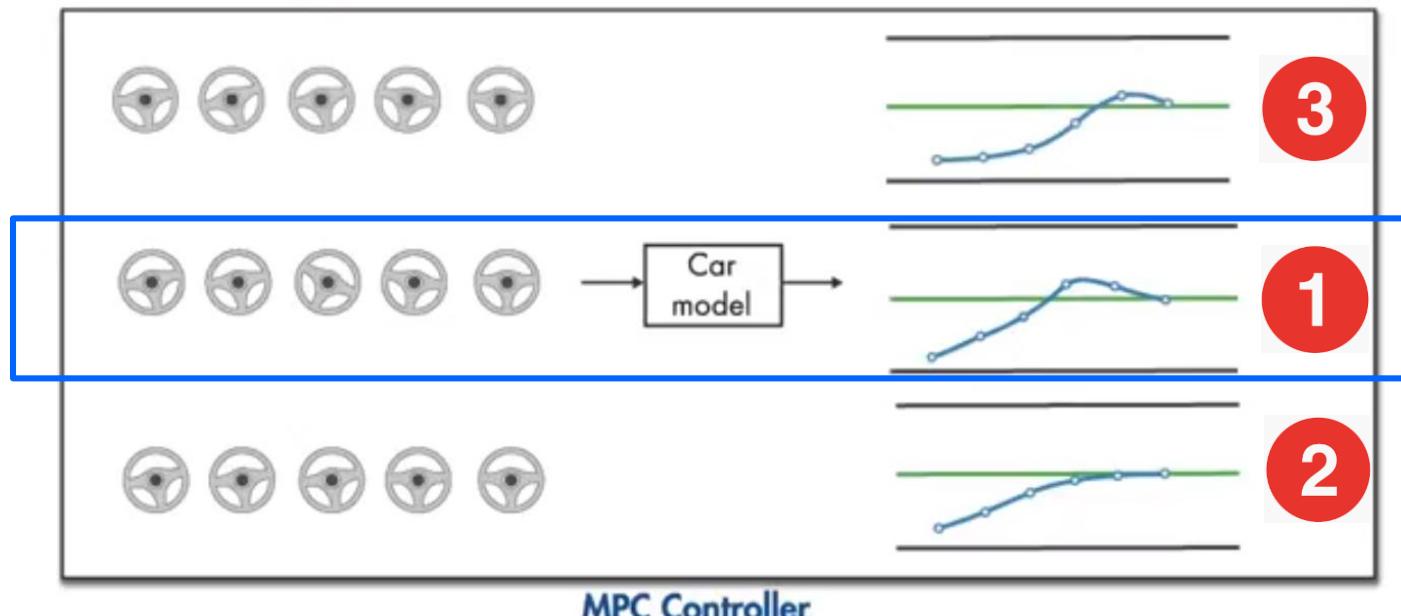
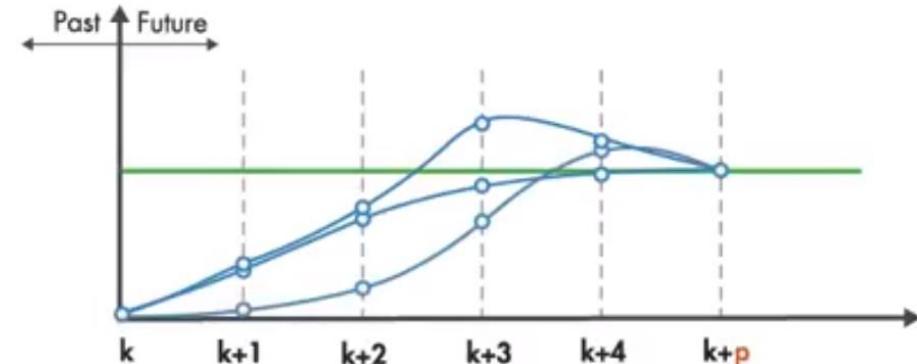
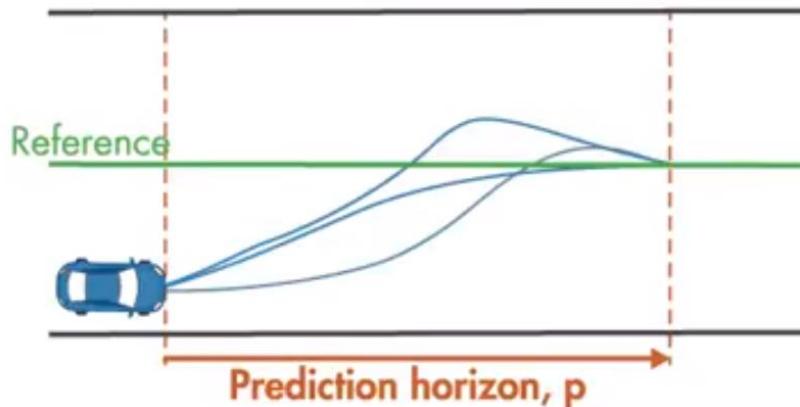


Explain the MPC by driving car: Prediction 2



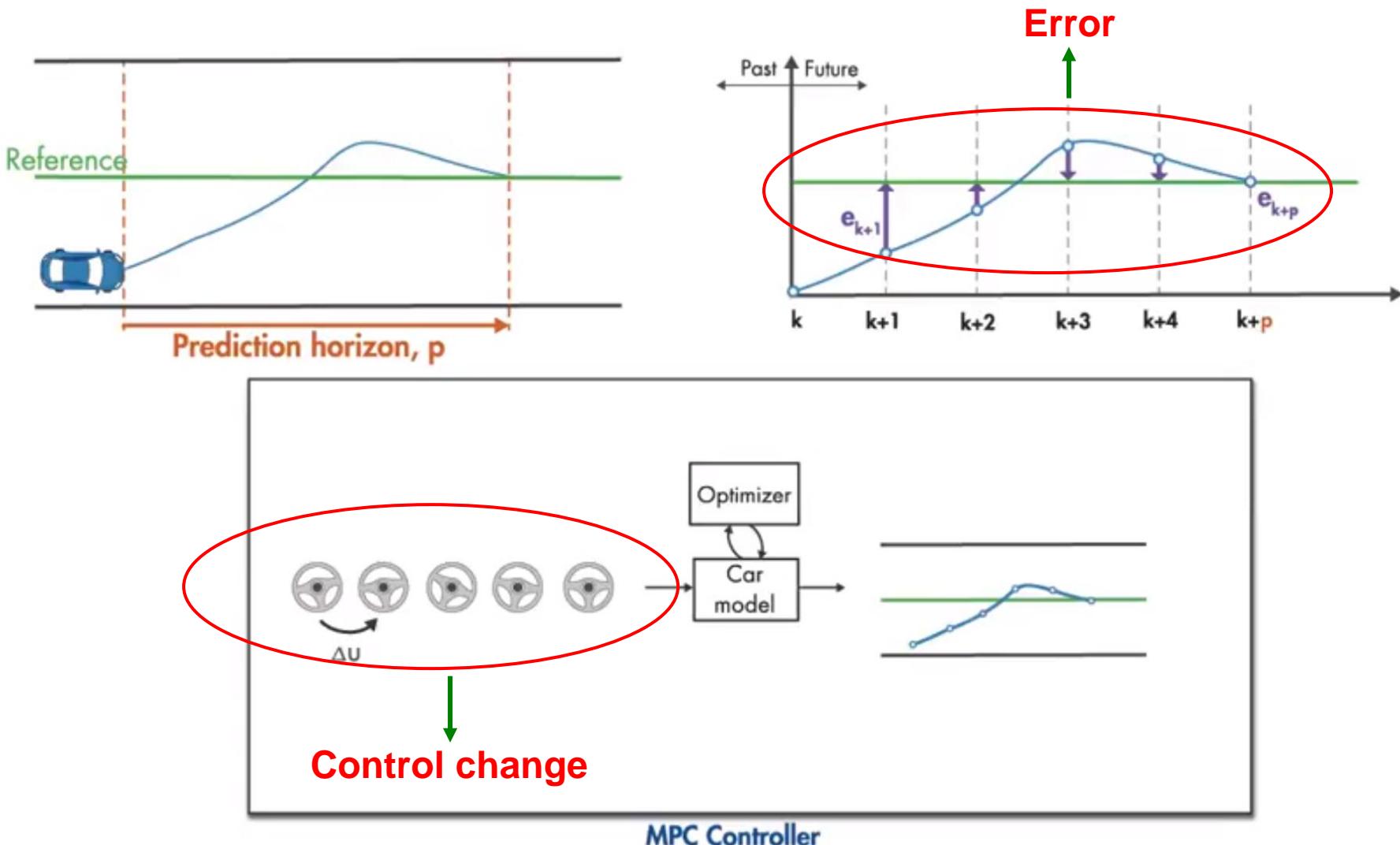


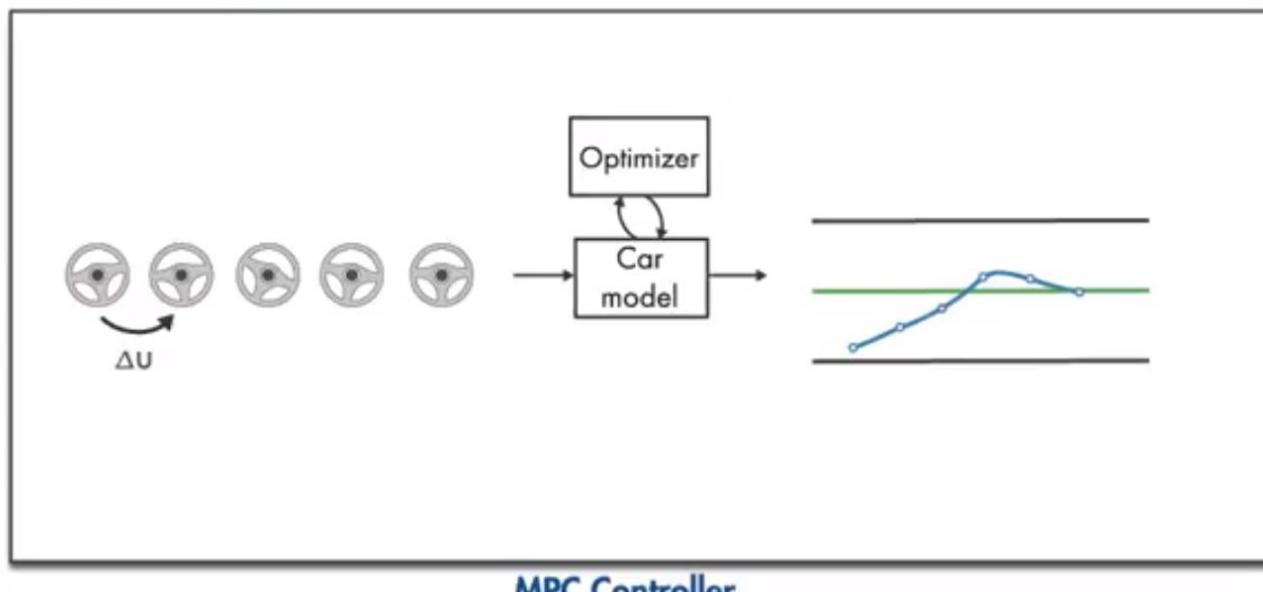
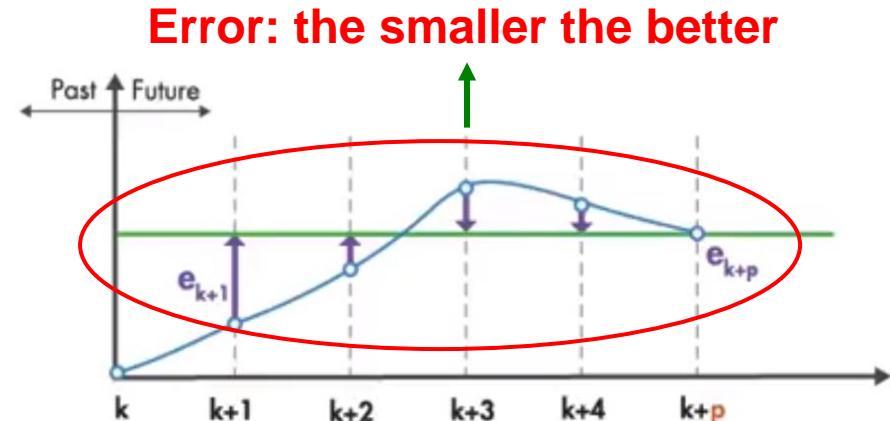
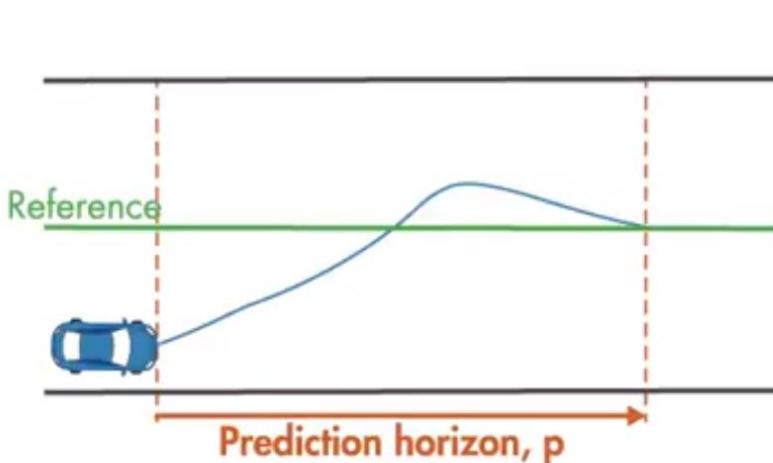
Explain the MPC by driving car: Prediction 3

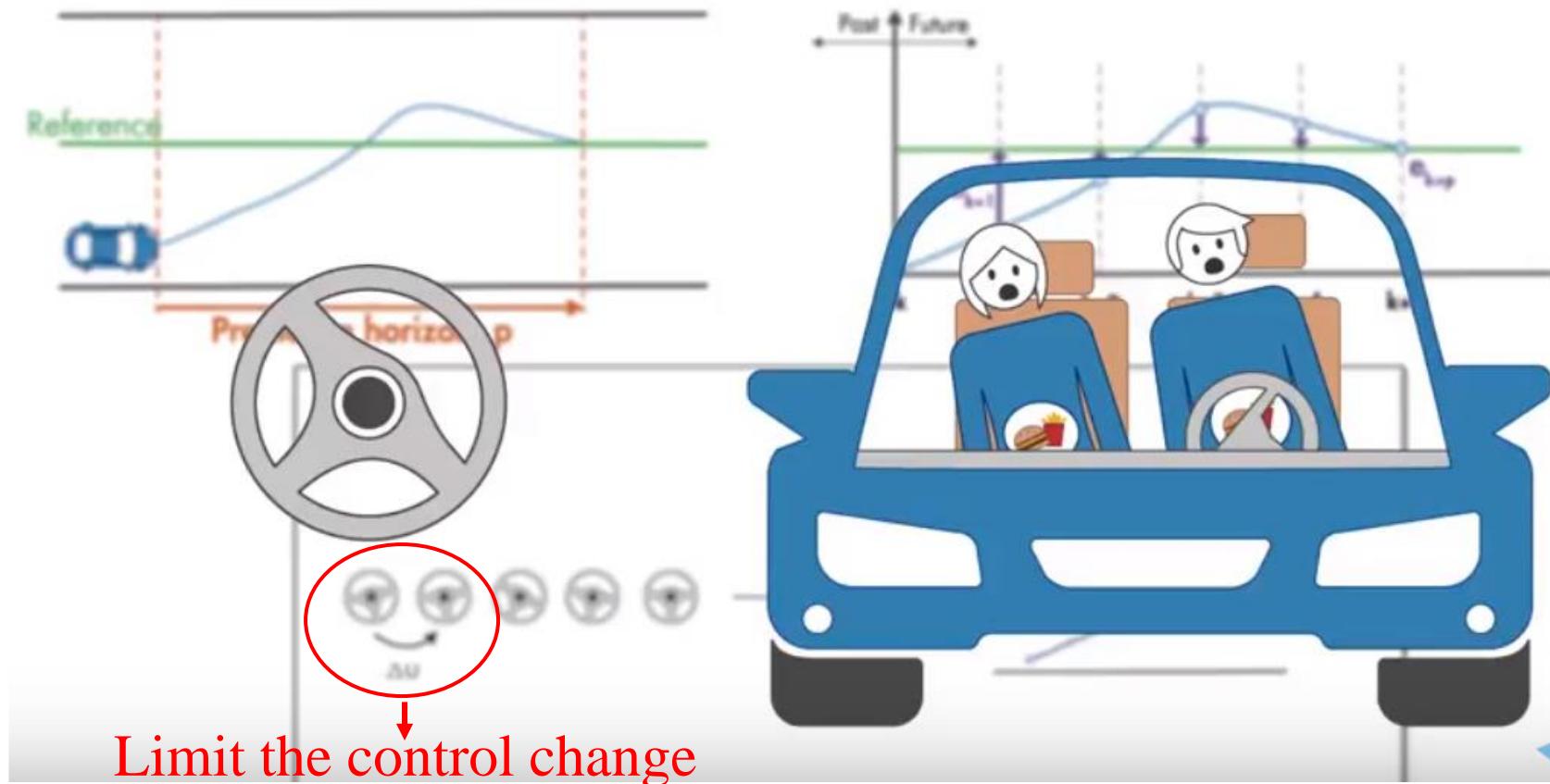




MPC issues of driving: Control change & error

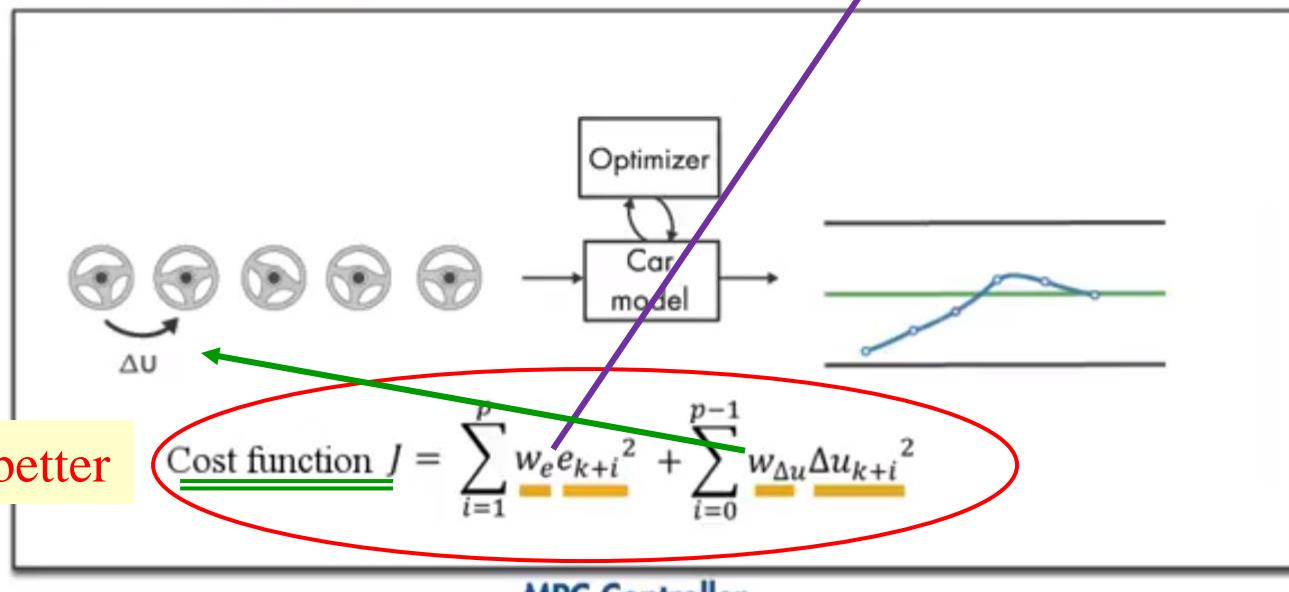
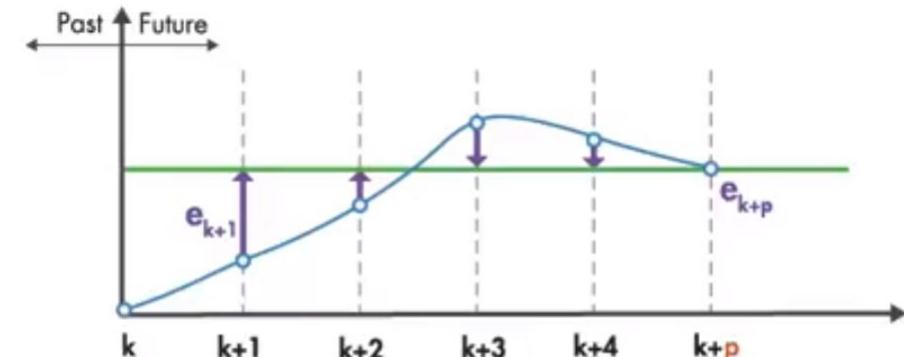
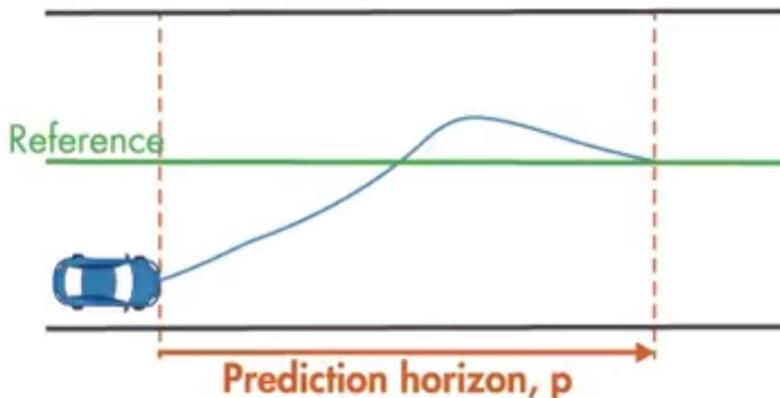






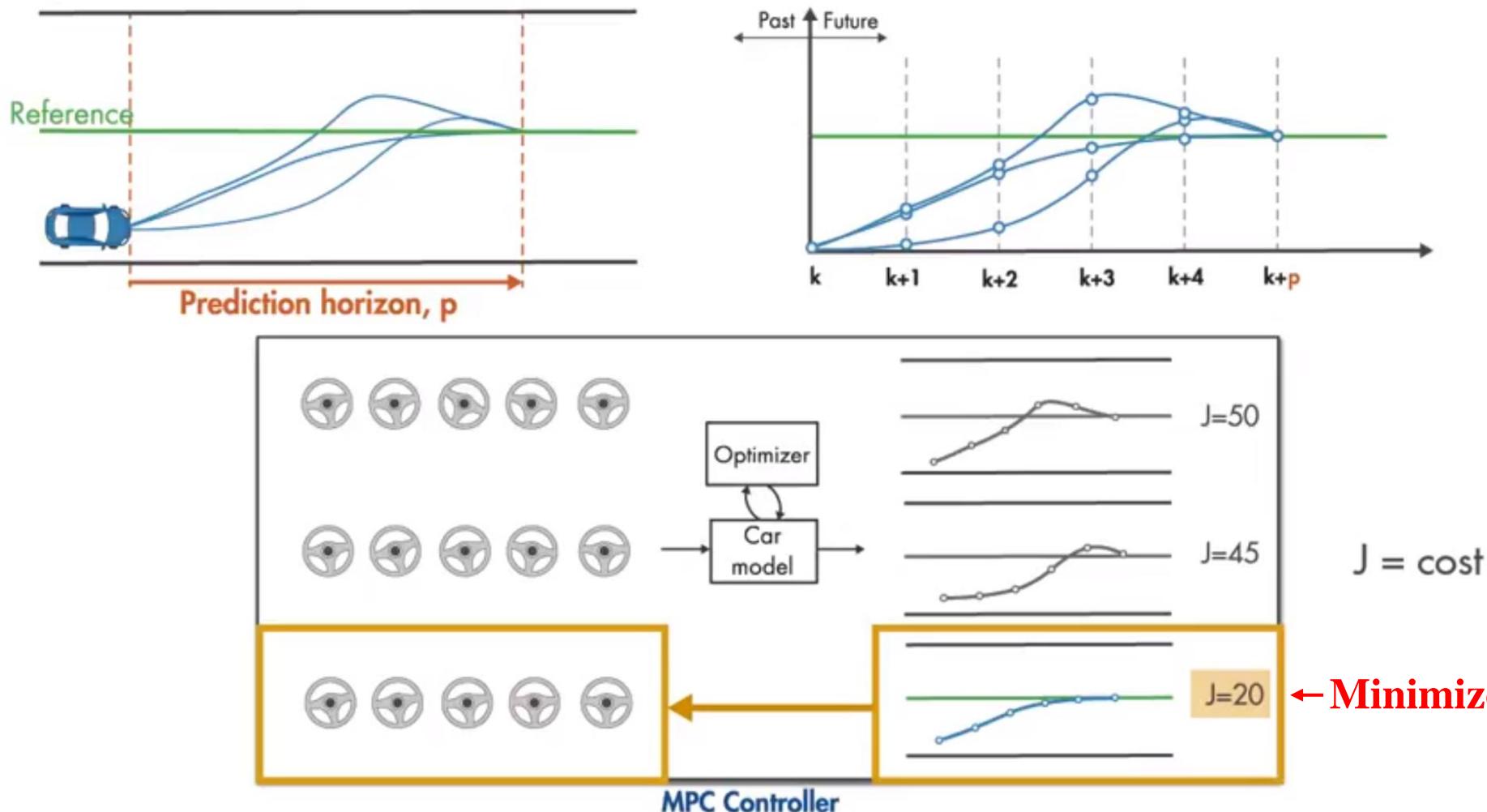


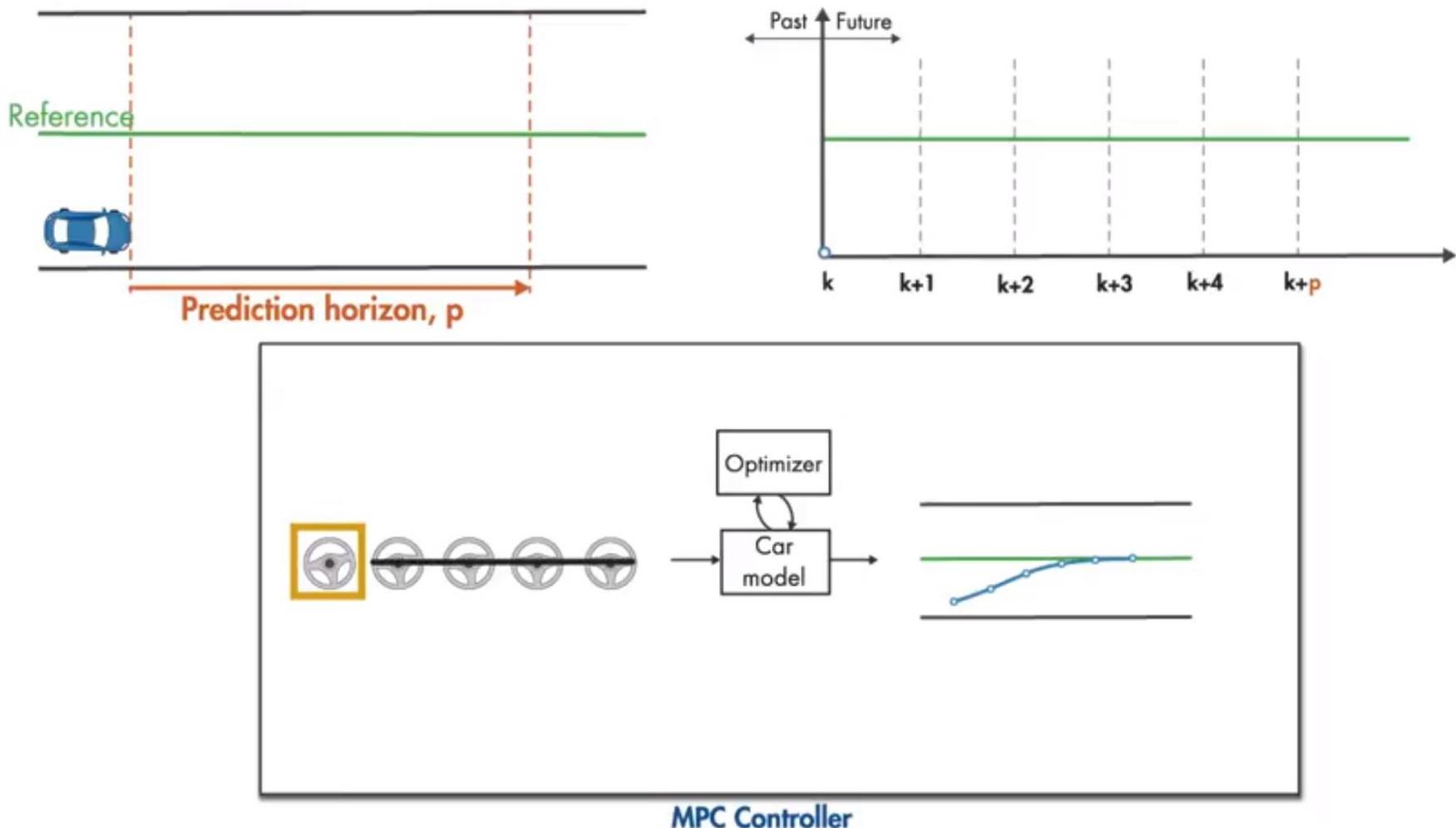
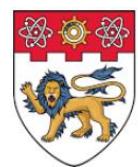
Cost function of the MPC to drive car

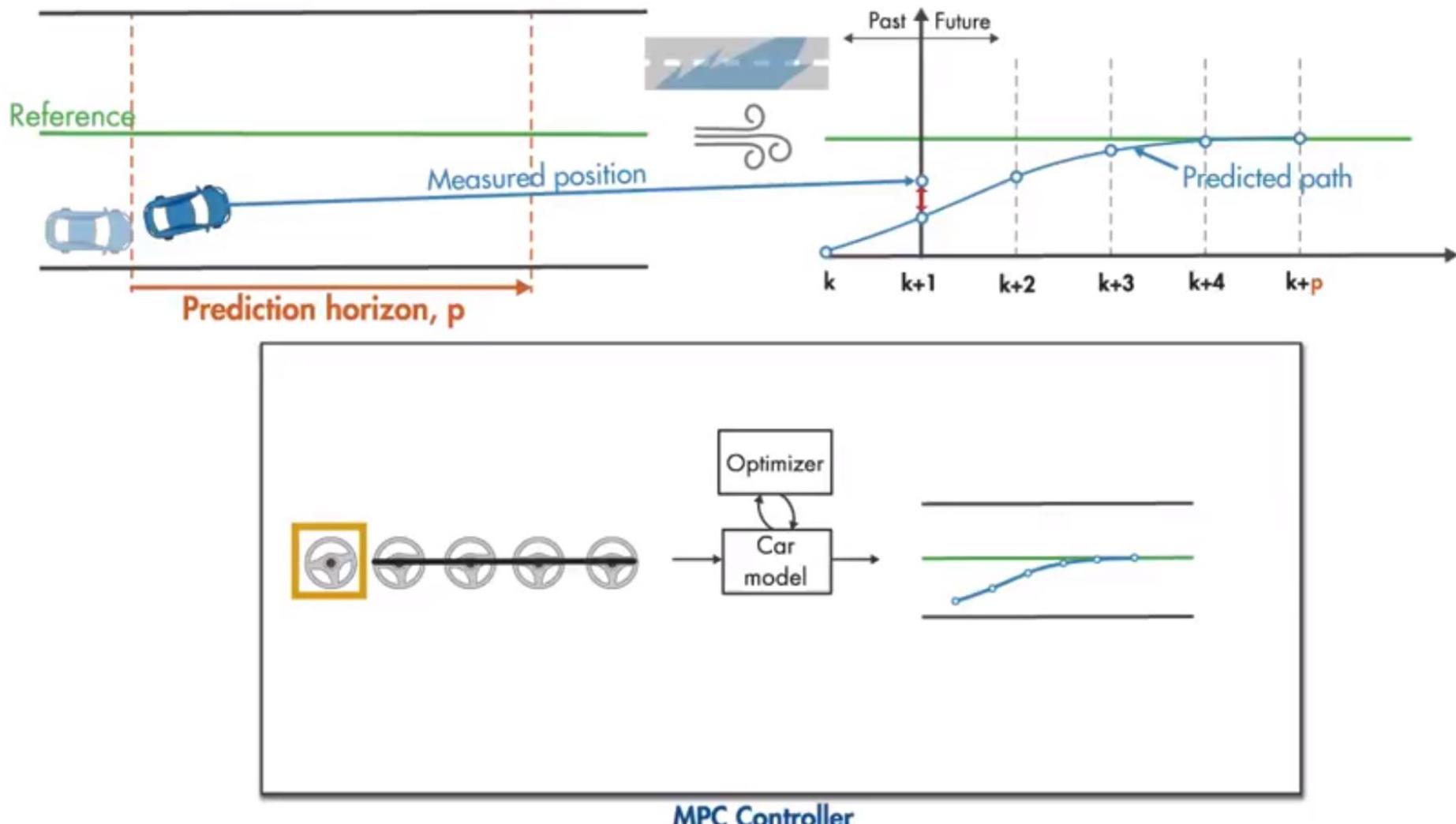




Minimize the cost function of the MPC

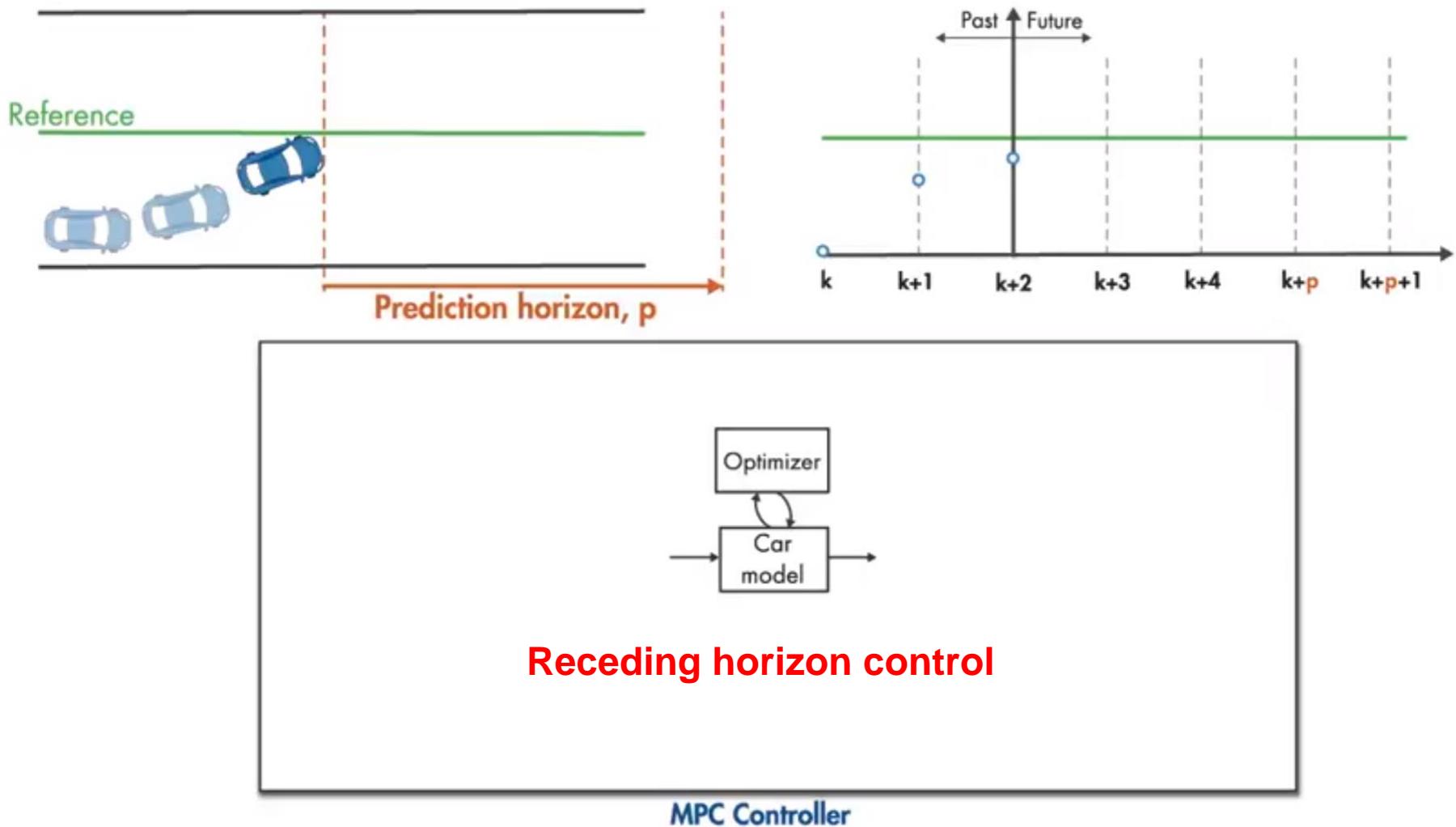








MPC procedure: timely optimization





WHAT IS MPC?

- BASIC CONCEPT OF THE MPC
- DESIGN PARAMETERS OF THE MPC
- LINEAR AND NON-LINEAR MPC
- HOW TO RUN MPC FASTER?



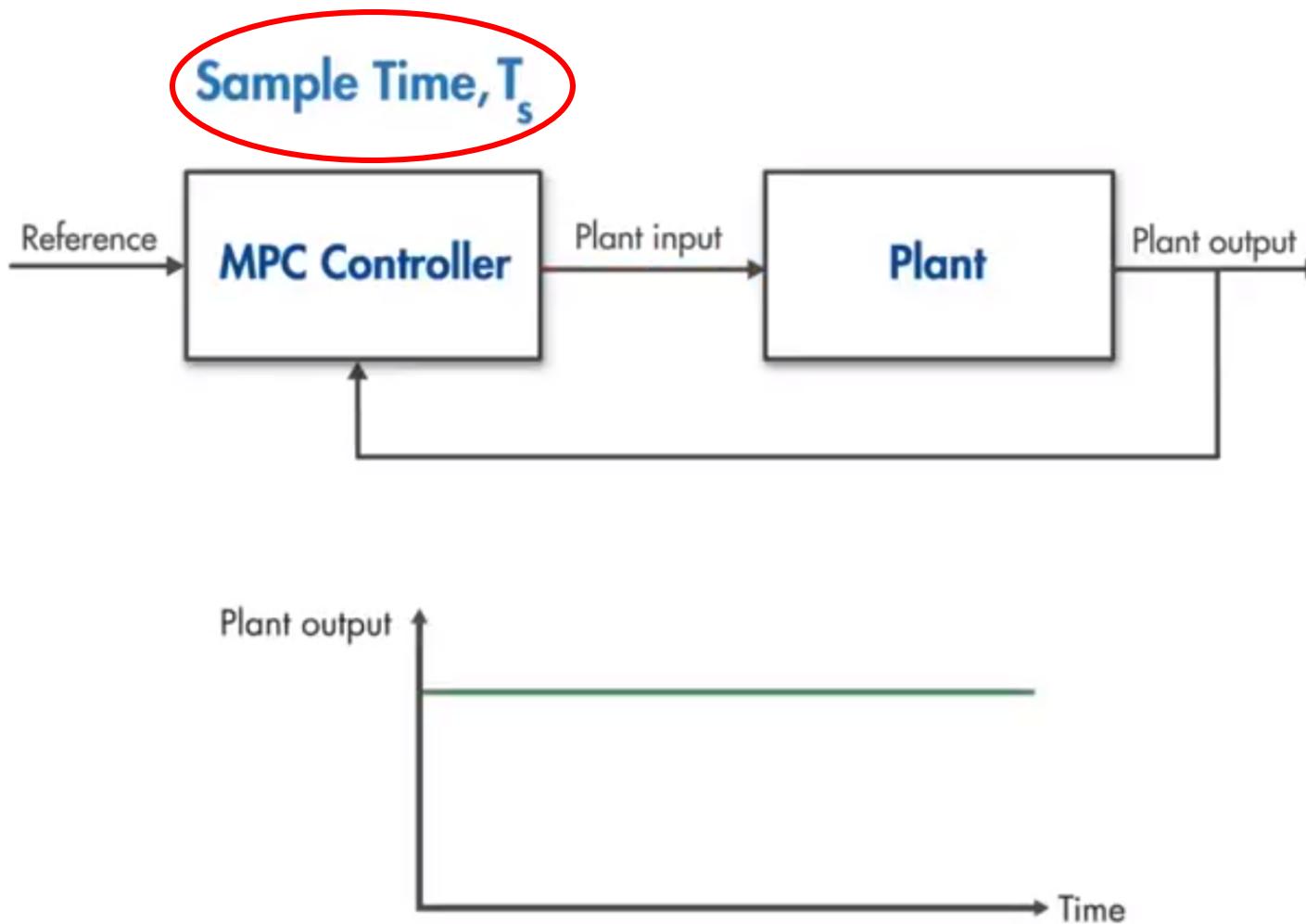
MPC design parameters

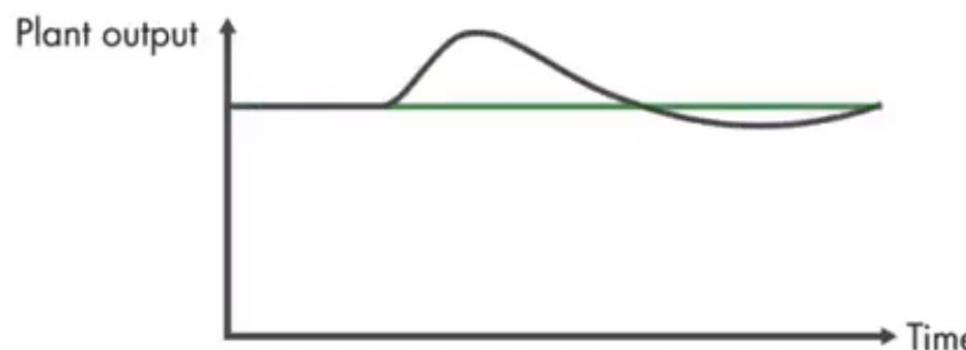
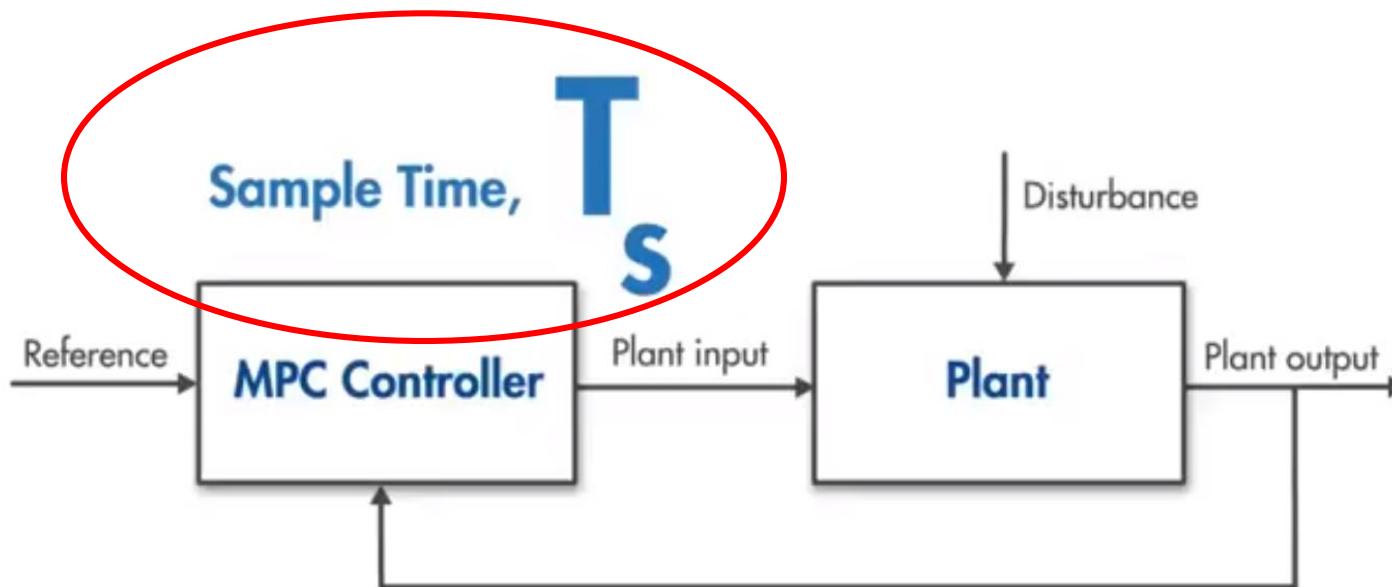
- Sampling time
- Prediction horizon
- Control horizon
- Constrains
- Weights

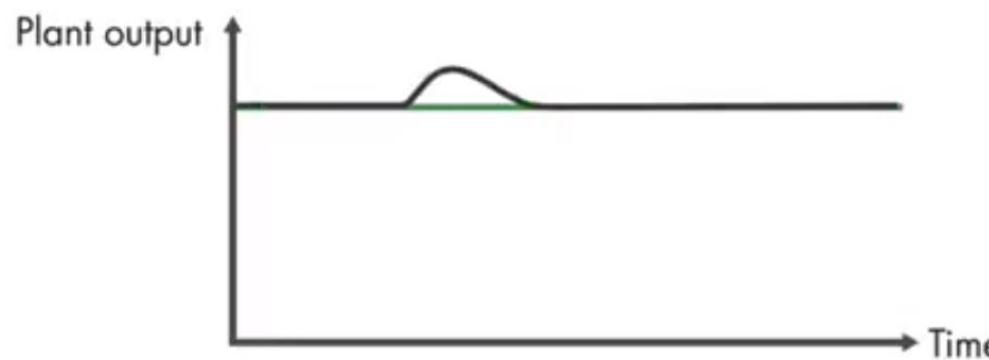
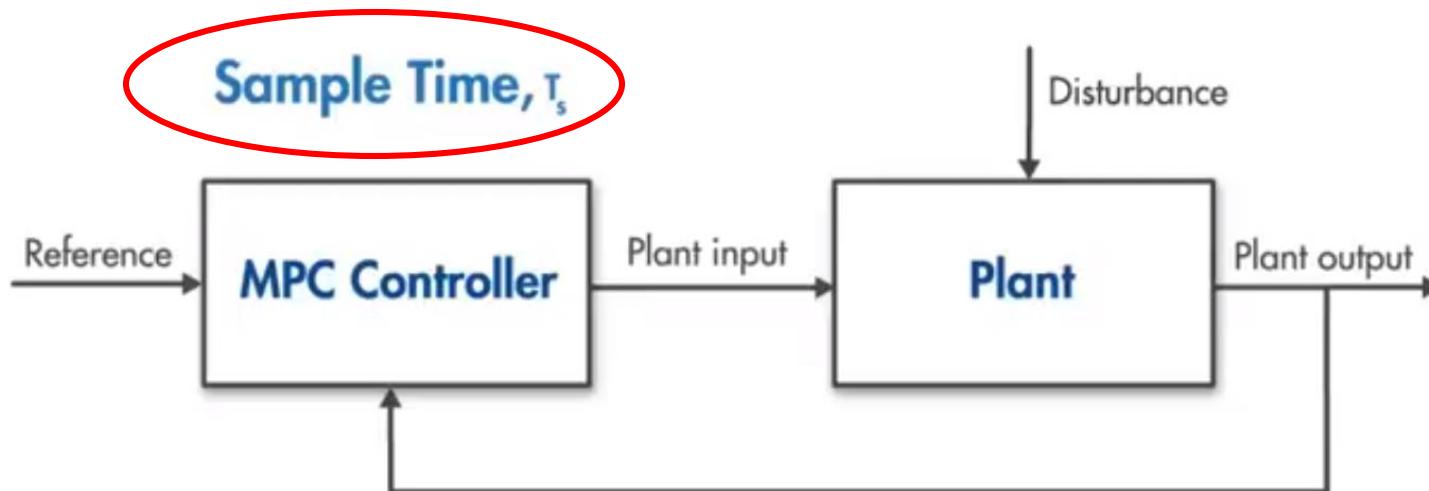


MPC design parameters

- Sampling time
- Prediction horizon
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TMS320F2833x, TMS320F2823x Digital Signal Controllers (DSCs)

1 Device Overview

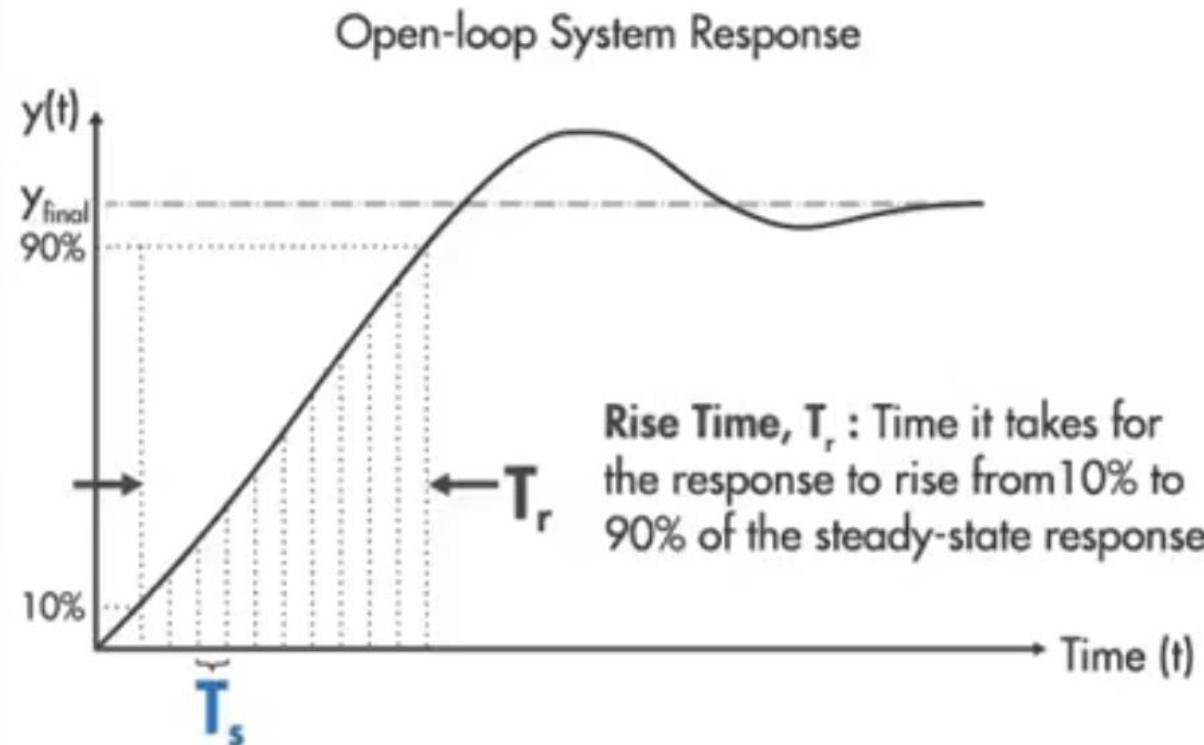
1.1 Features

- High-Performance Static CMOS Technology
 - Up to 150 MHz (6.67-ns Cycle Time)
 - 1.9-V/1.8-V Core, 3.3-V I/O Design
- High-Performance 32-Bit CPU (TMS320C28x)
 - IEEE 754 Single-Precision Floating-Point Unit (FPU) (F2833x Only)
 - 16 × 16 and 32 × 32 MAC Operations
 - 16 × 16 Dual MAC
 - Harvard Bus Architecture
 - Fast Interrupt Response and Processing
 - Unified Memory Programming Model
 - Code-Efficient (in C/C++ and Assembly)
- Six-Channel DMA Controller (for ADC, McBSP, ePWM, XINTF, and SARAM)
- 16-Bit or 32-Bit External Interface (XINTF)
 - More Than 2M × 16 Address Reach
- Enhanced Control Peripherals
 - Up to 18 PWM Outputs
 - Up to 6 HRPWM Outputs With 150 ps MEP Resolution
 - Up to 6 Event Capture Inputs
 - Up to 2 Quadrature Encoder Interfaces
 - Up to 8 32-Bit Timers (6 for eCAPs and 2 for eQEPs)
 - Up to 9 16-Bit Timers (6 for ePWMs and 3 XINTCTRs)
- Three 32-Bit CPU Timers
- Serial Port Peripherals
 - Up to 2 CAN Modules
 - Up to 3 SCI (UART) Modules
 - Up to 2 McBSP Modules (Configurable as SPI)
 - One SPI Module





Basic parameters of the MPC: Suitable T_s



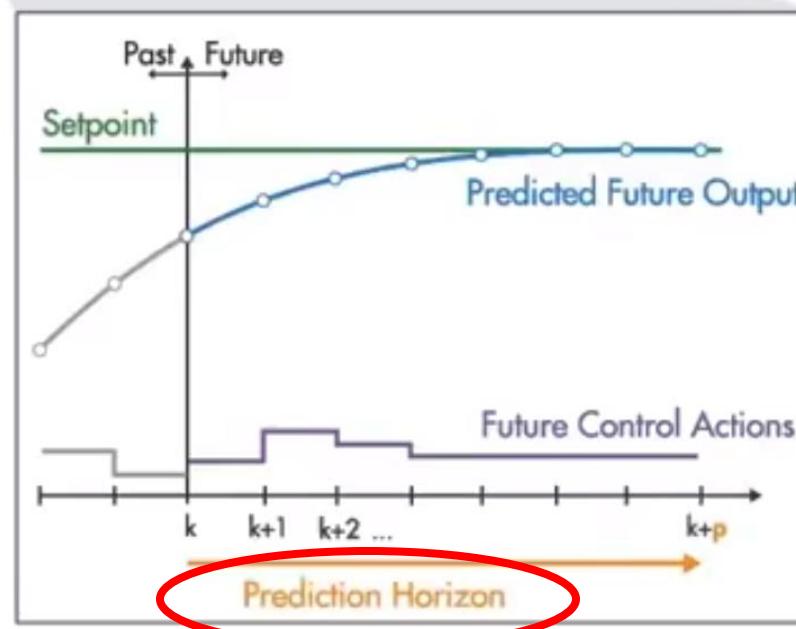
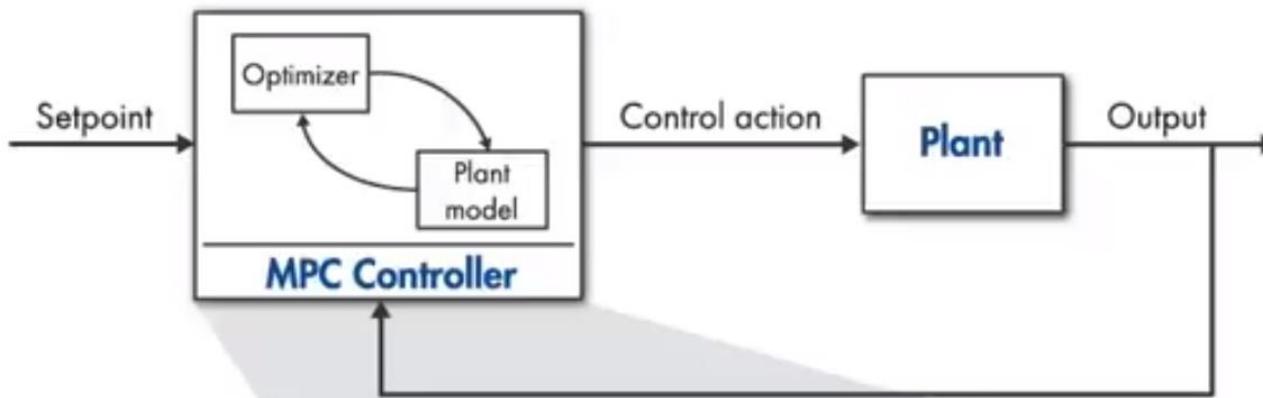
Sample Time, T_s : Controller execution rate

$$\frac{T_r}{20} \leq T_s \leq \frac{T_r}{10}$$



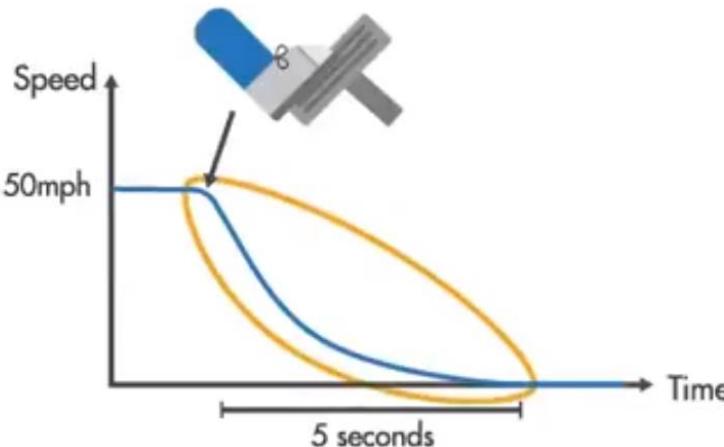
MPC design parameters

- Sampling time
- Prediction horizon
- Control horizon
- Constrains
- Weights

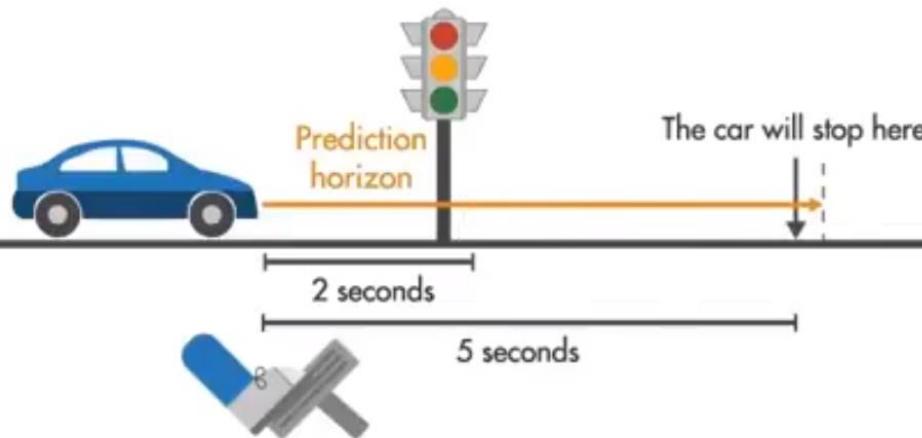




Result of small prediction horizon

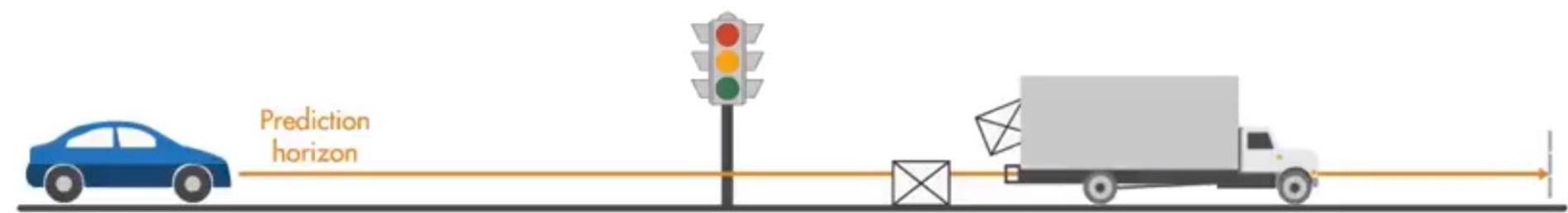
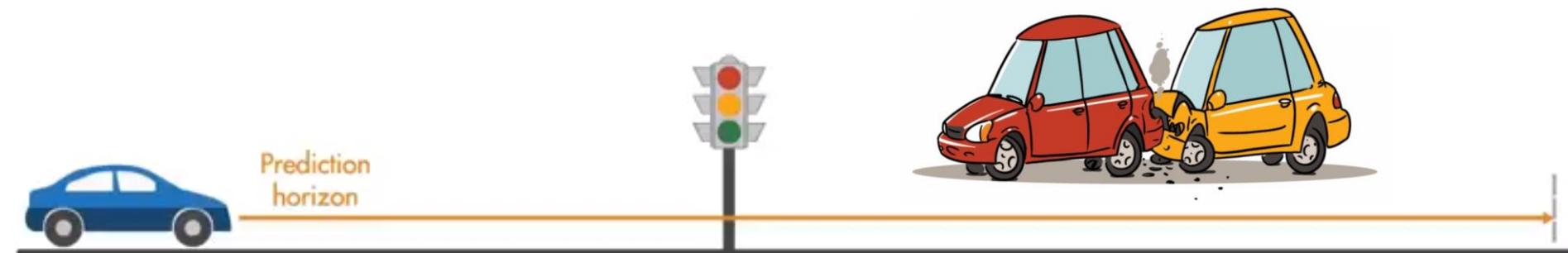


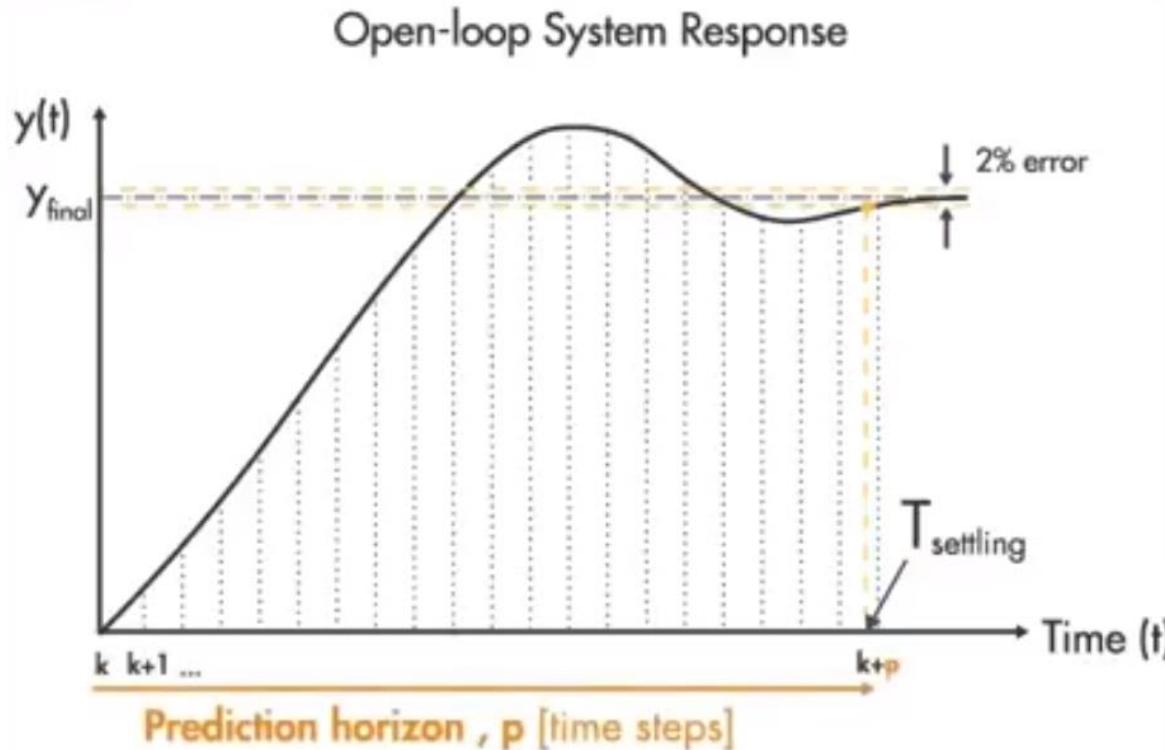
Small prediction horizon





Long prediction horizon





T_{settling} : Time it takes for the error $|y(t) - y_{\text{final}}|$ to fall to within 2% of y_{final}

$$\frac{T_r}{20} \leq T_s \leq \frac{T_r}{10}, \quad T_s: \text{Sample time}$$

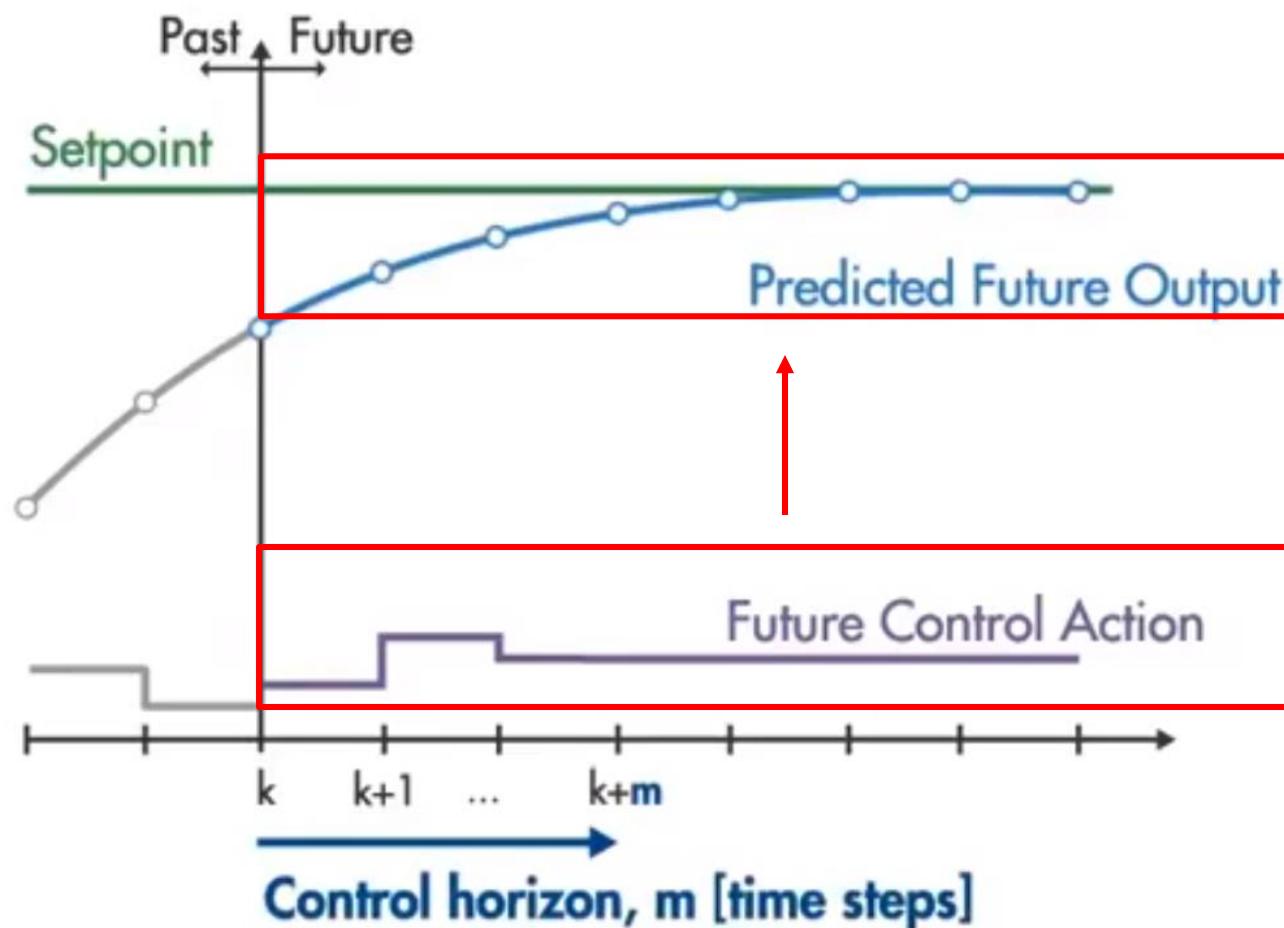
$$p \cdot T_s \geq T_{\text{settling}}$$



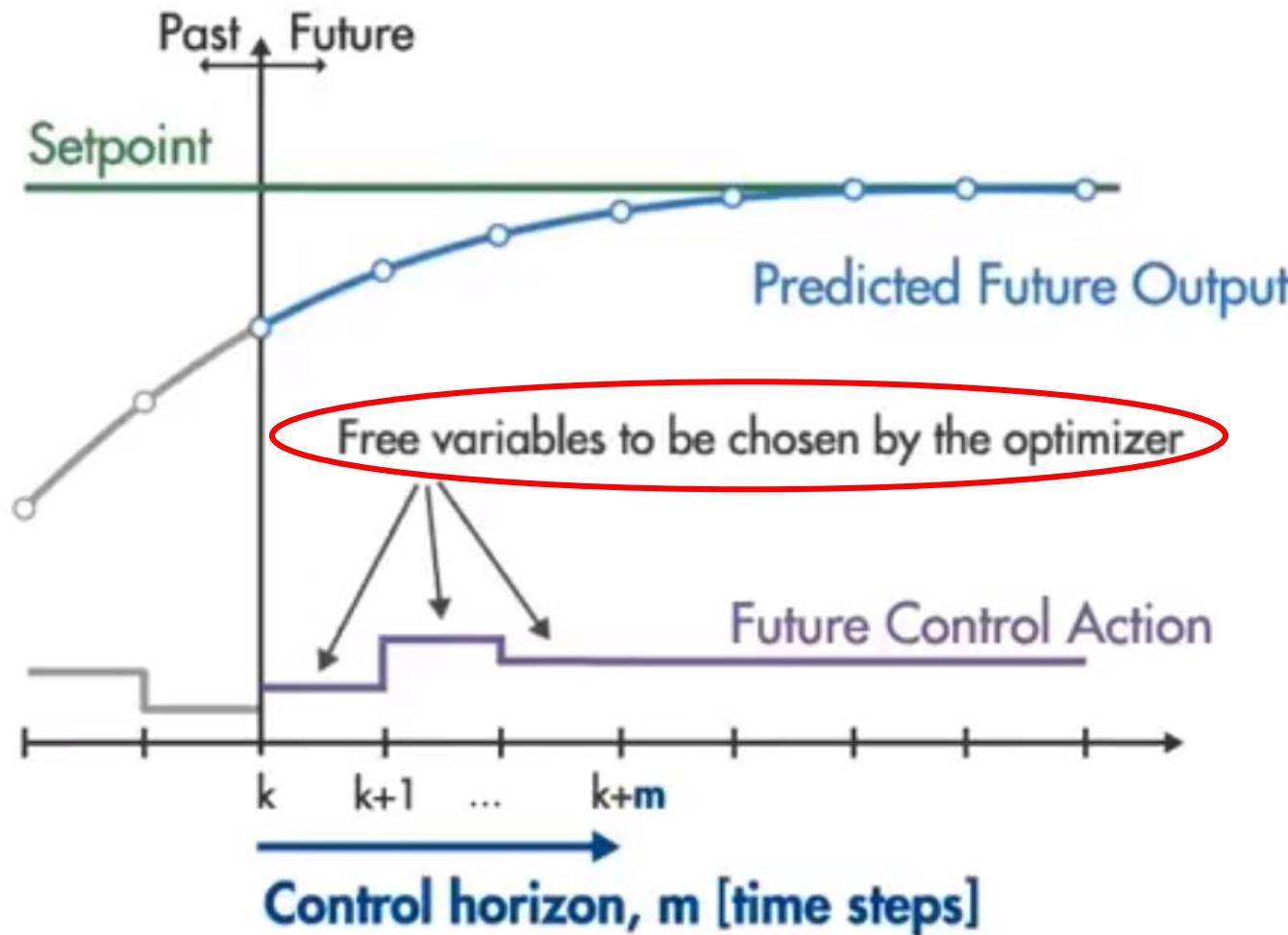
MPC design parameters

- Sampling time
- Prediction horizon
- Control horizon
- Constrains
- Weights

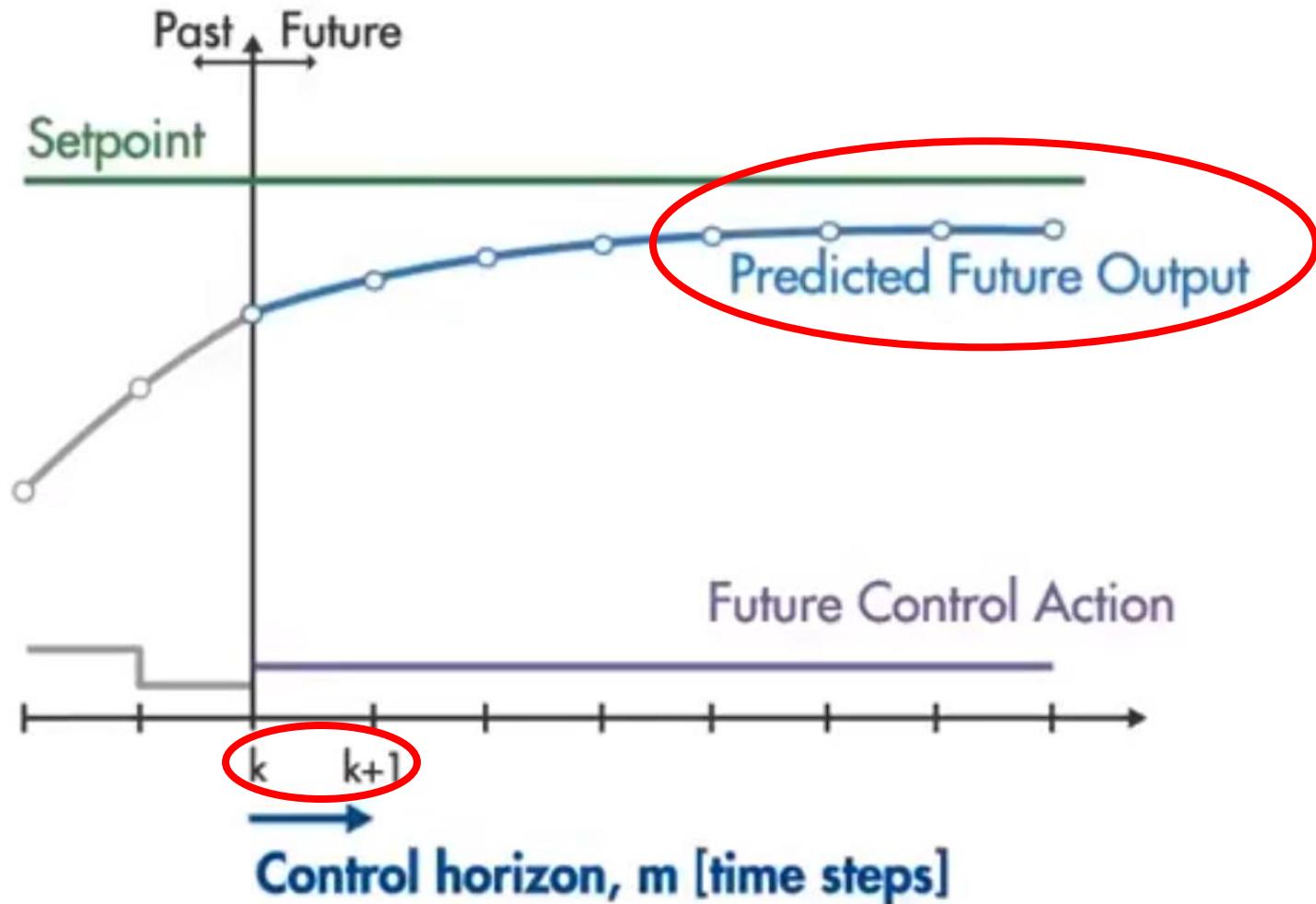
Basic parameters of the MPC: Control horizon



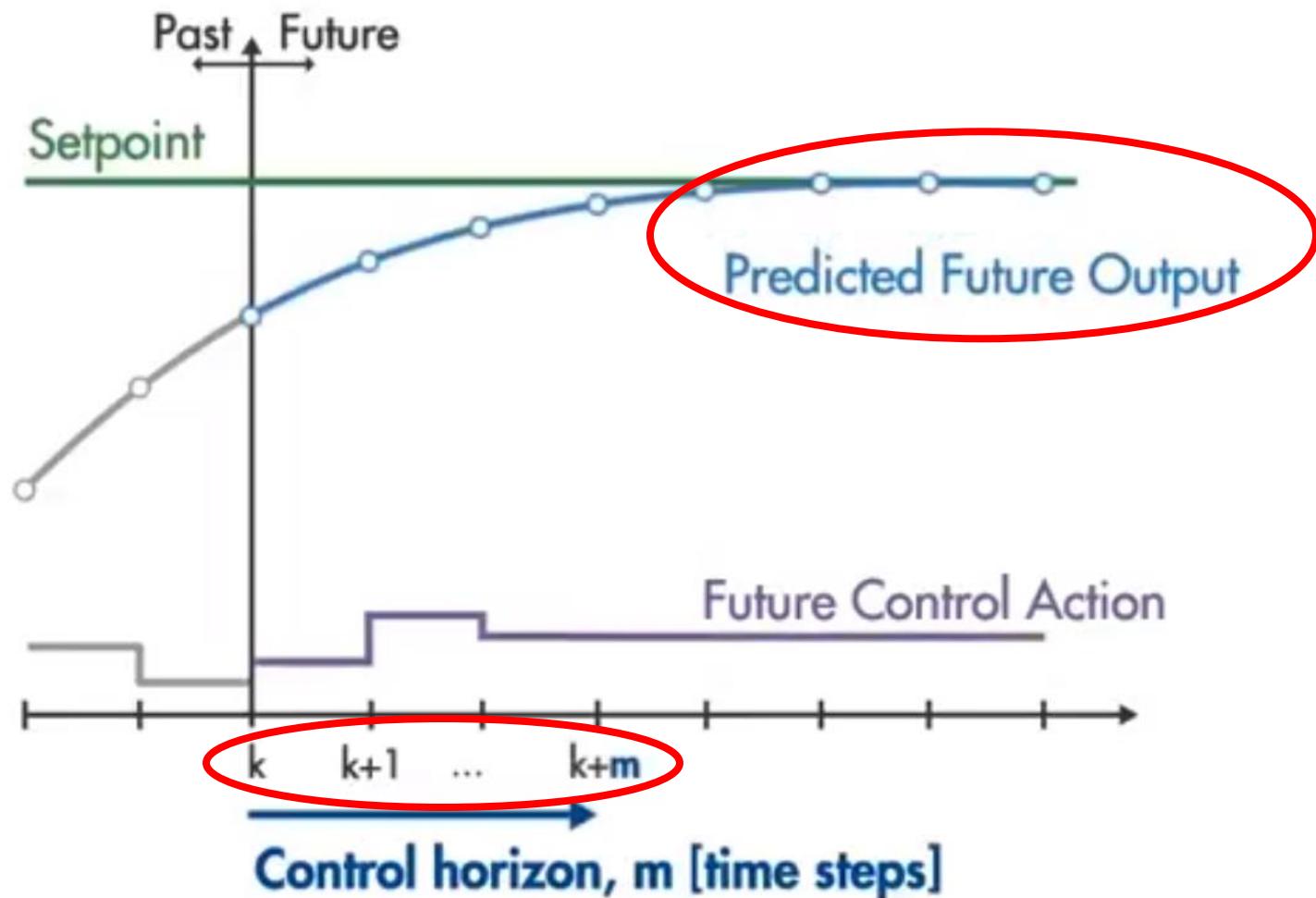
Free variables to be chosen by the optimizer



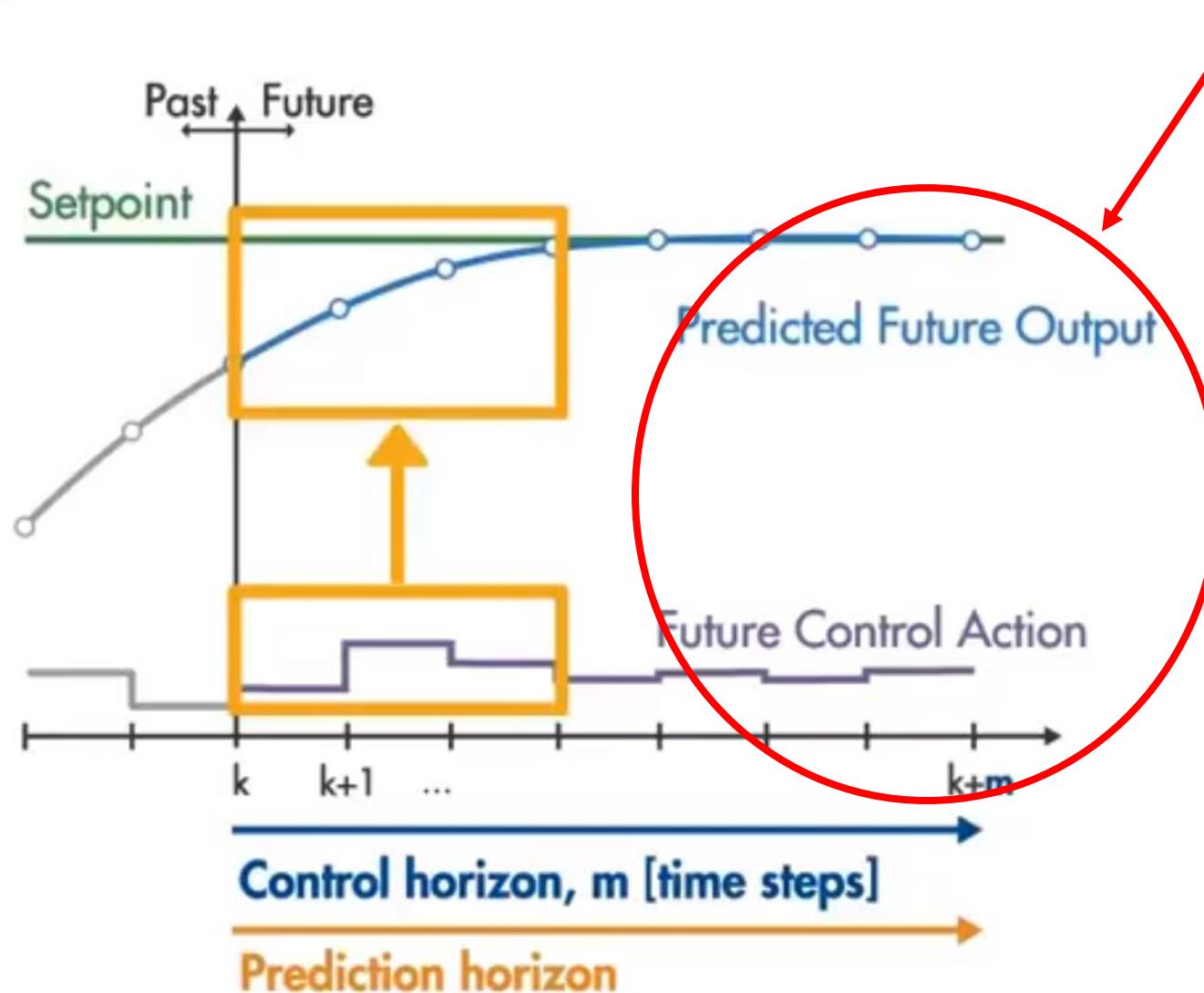
Result of small control horizon

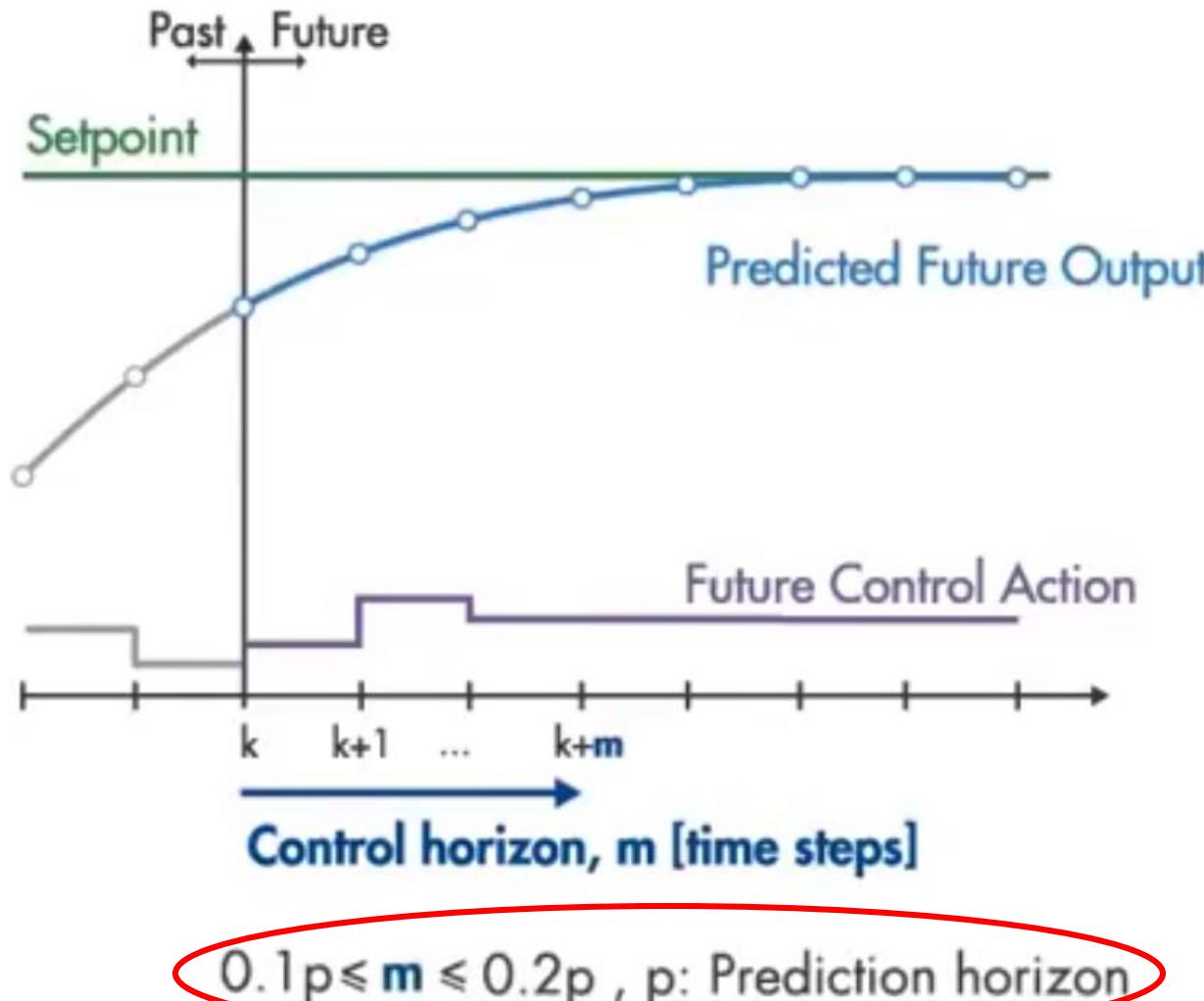


Increase control horizon becomes better



Control horizon = prediction horizon? (No need)





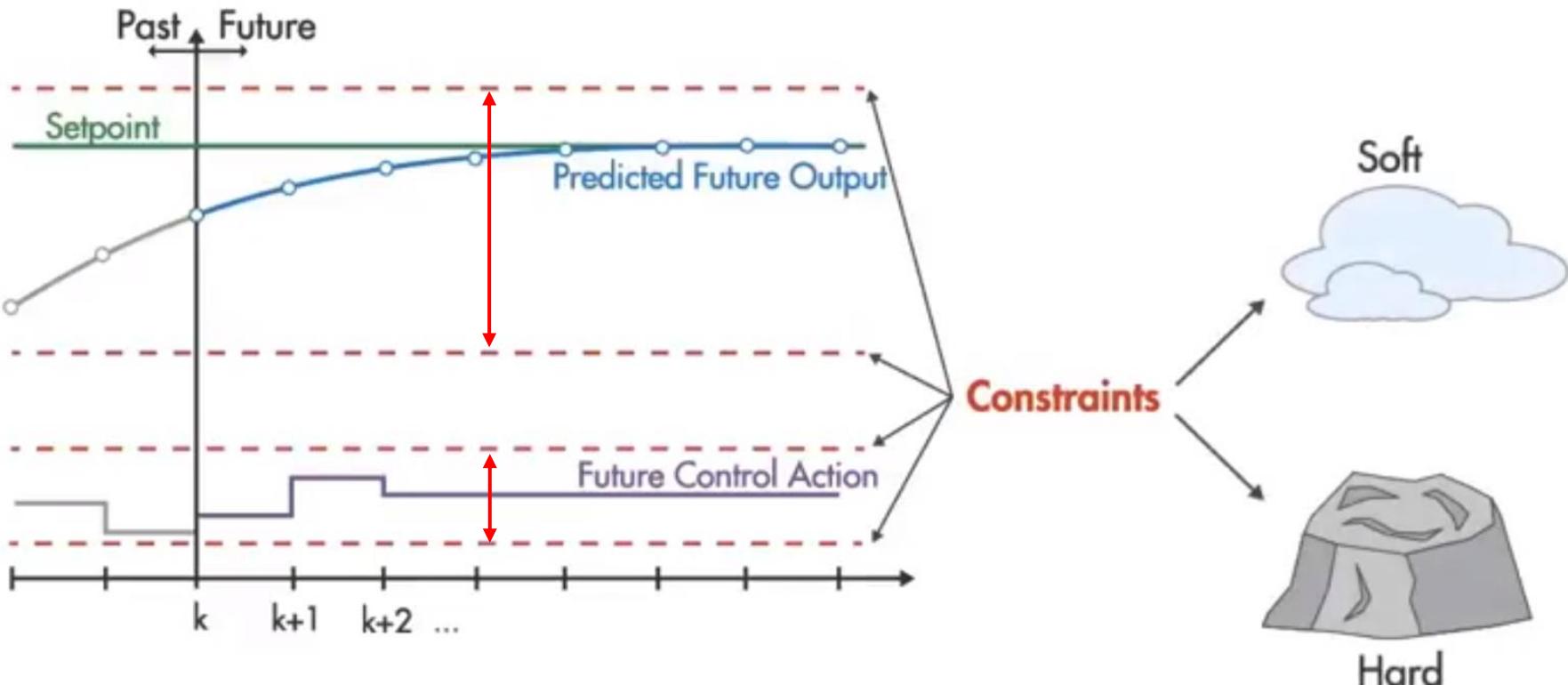
$$0.1p \leq m \leq 0.2p, p: \text{Prediction horizon}$$



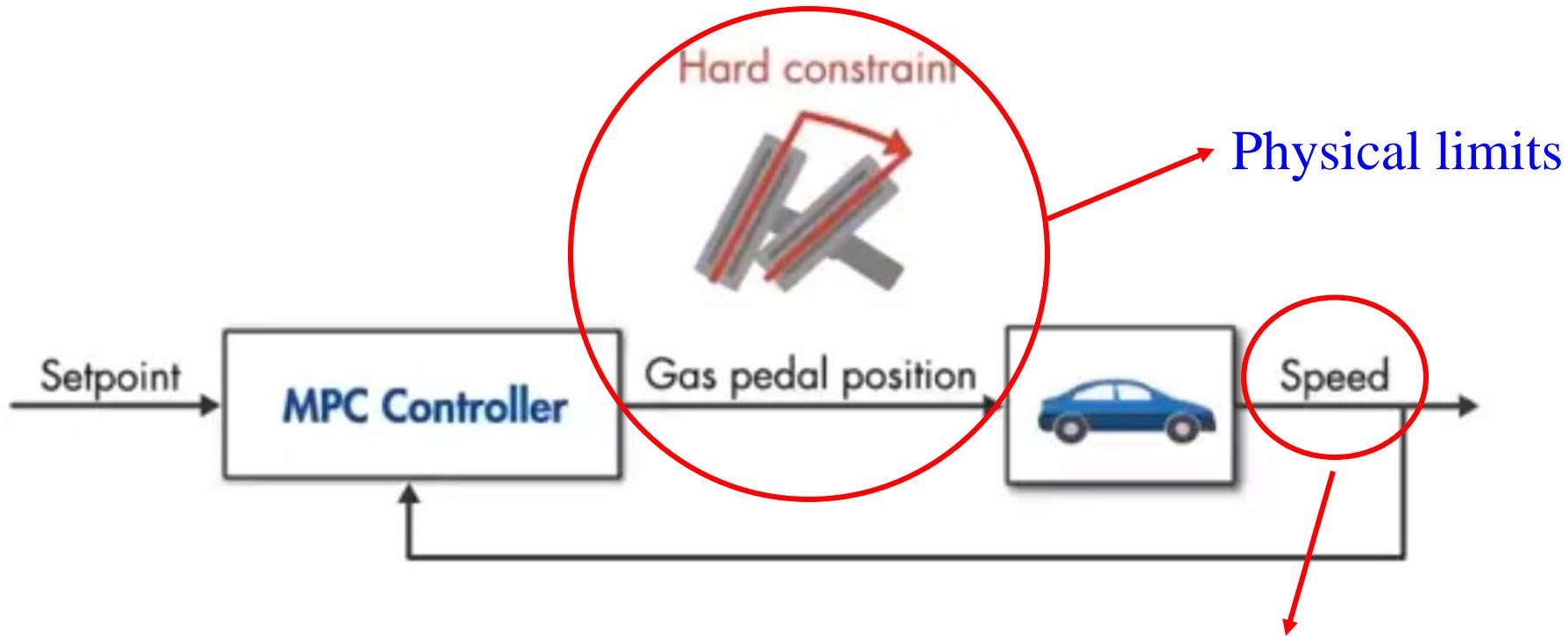
MPC design parameters

- Sampling time
- Prediction horizon
- Control horizon
- Constraints
- Weights

Basic parameters of the MPC: Constraints



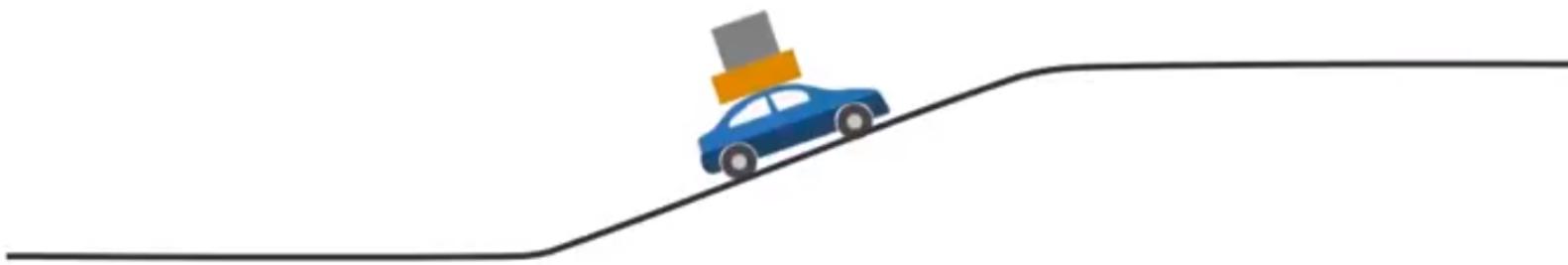
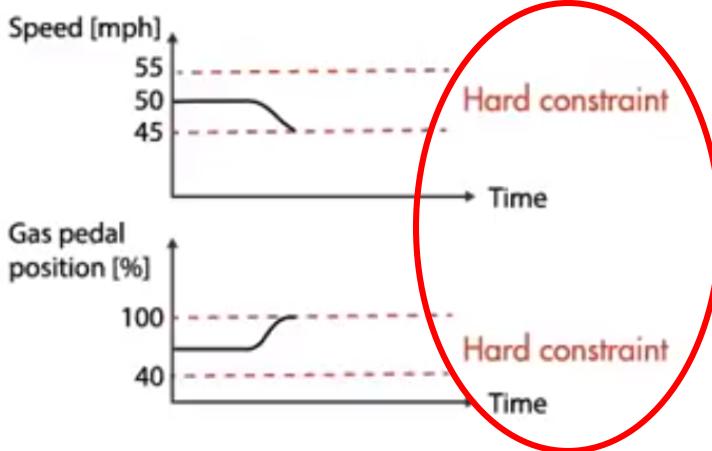
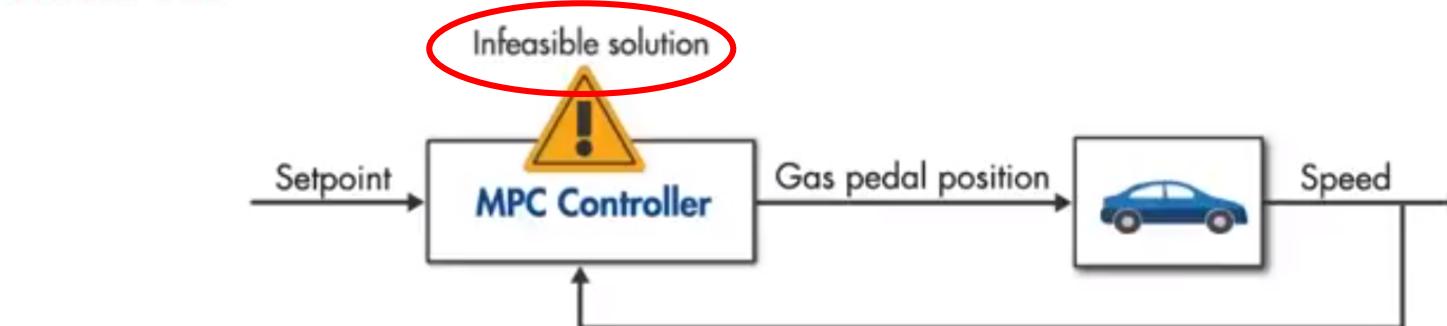
Explain hard and soft constraints by driving car



Can be hard constrain or soft constrains, which is determined by the controller

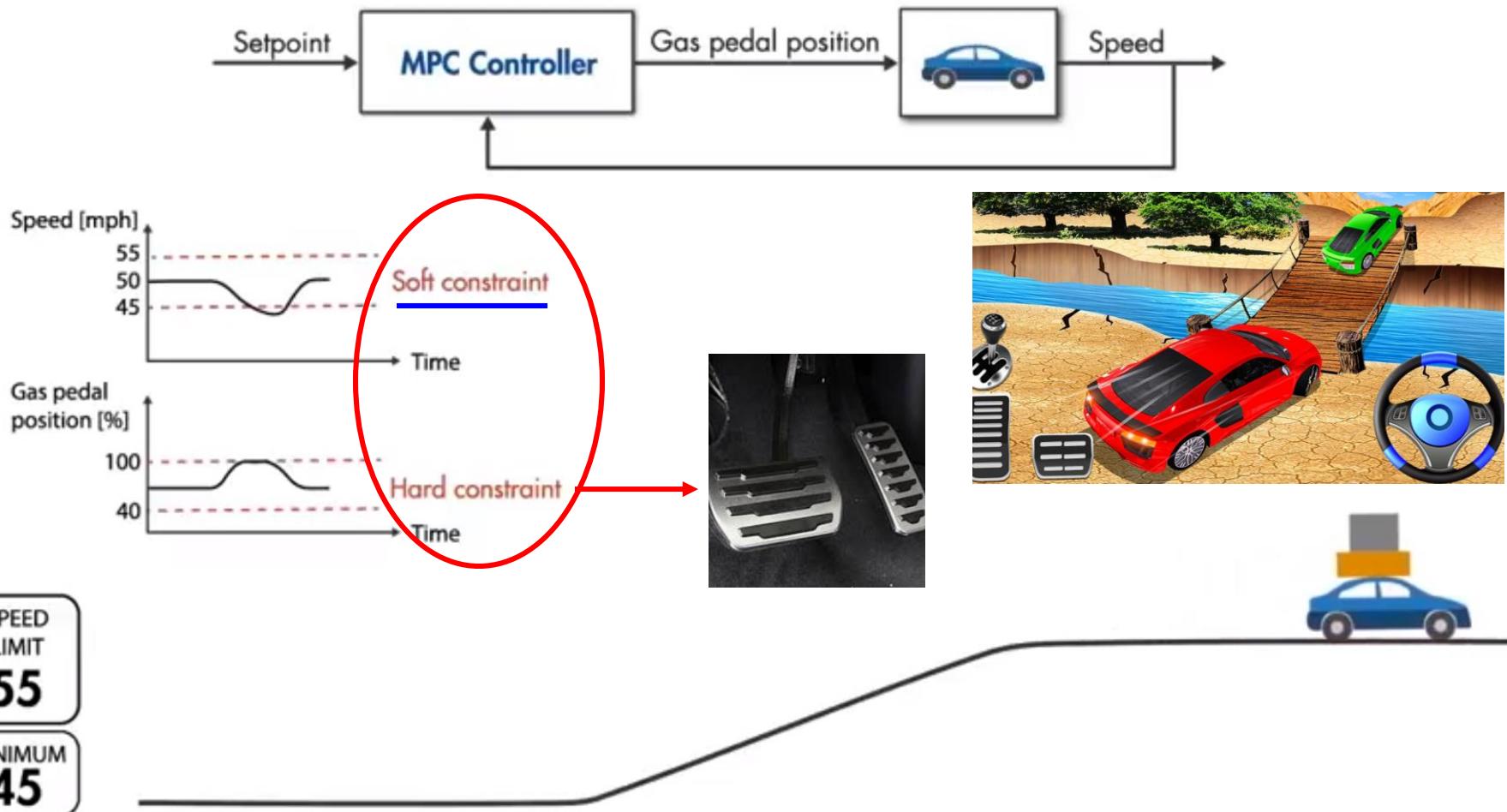


Hard + hard constraints = infeasible solution



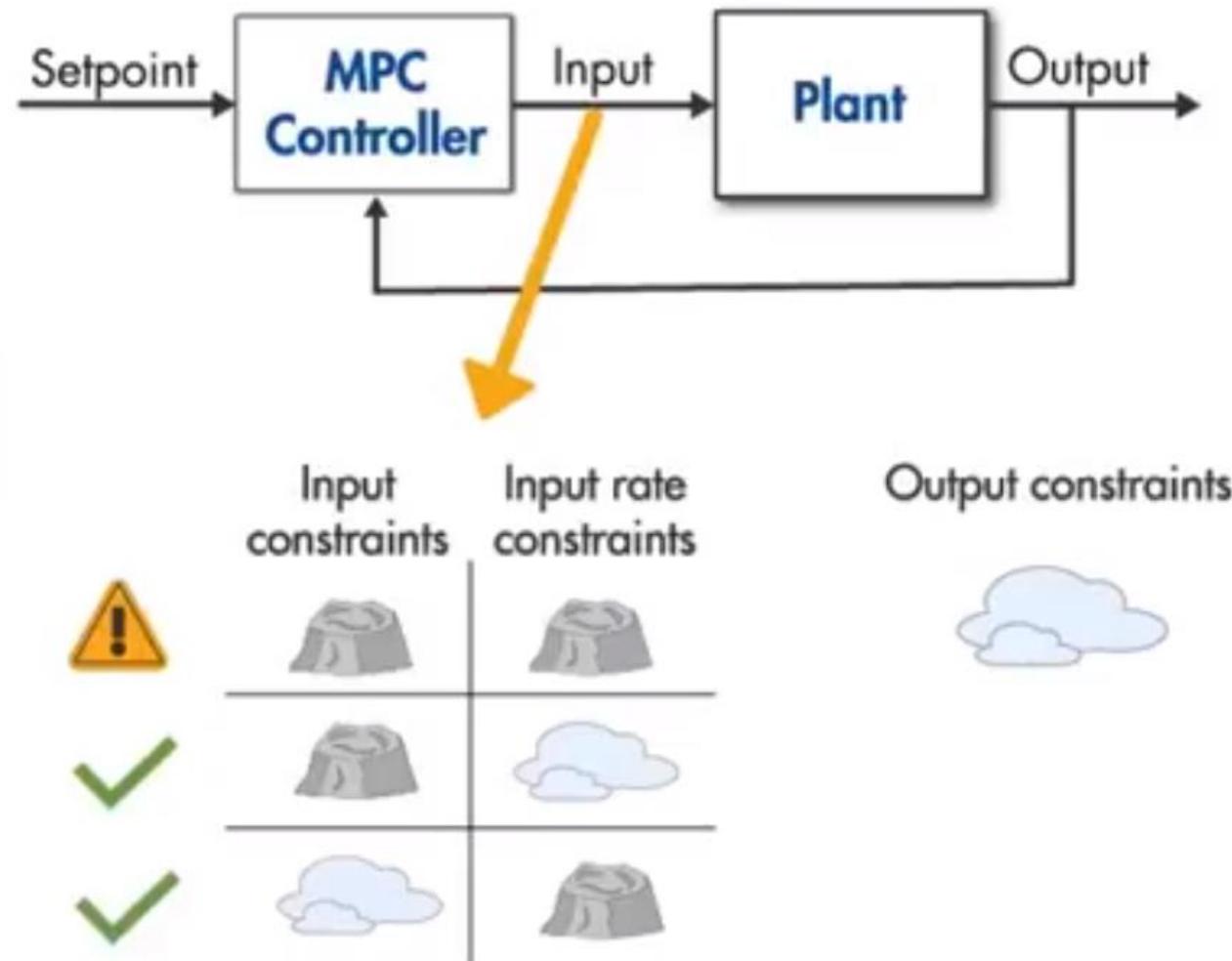


Select hard and soft constraints





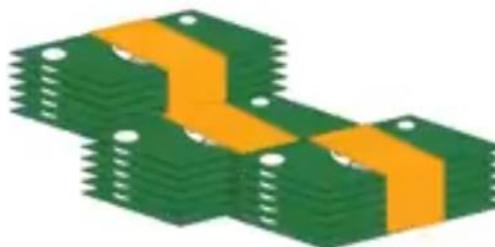
General selection experiences of constraints





MPC design parameters

- Sampling time
- Prediction horizon
- Control horizon
- Constrains
- Weights





Concepts of weights: daily life as an example

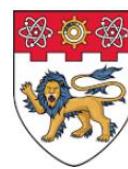


$$W_{\text{sleep}} = 50$$

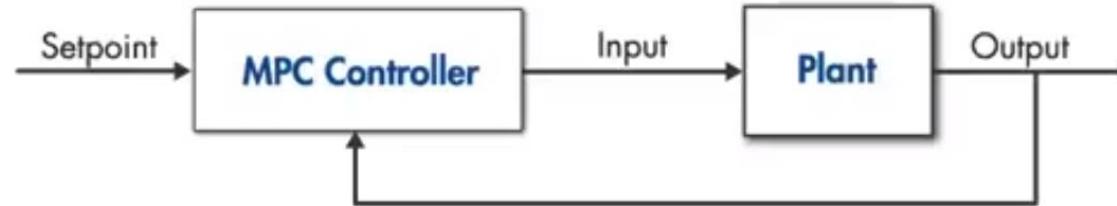
$$W_{\text{eat}} = 10$$

$$\frac{W_{\text{sleep}}}{W_{\text{eat}}} = 5 > 1$$

w: Weight



Weight's function 1: multi optimal objectives

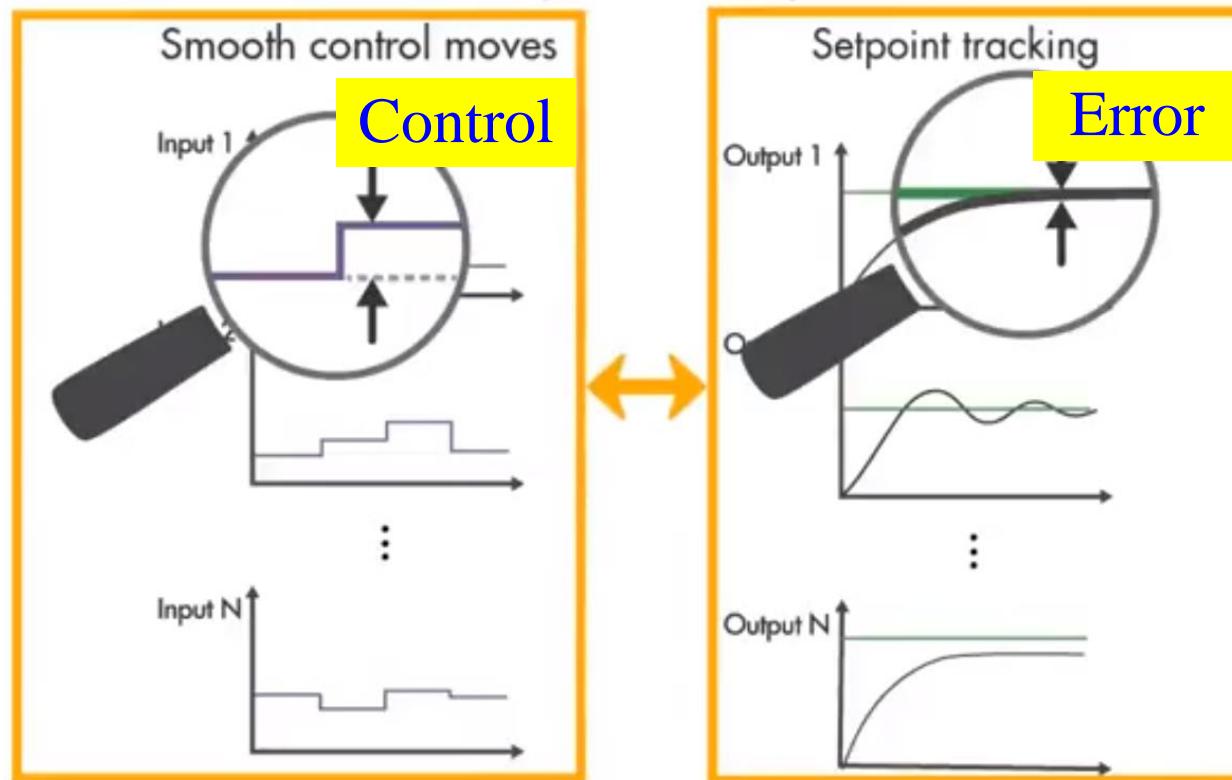


Goals

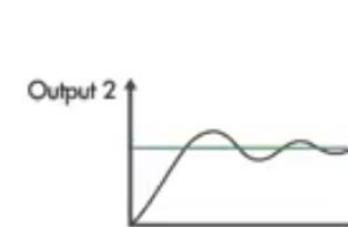
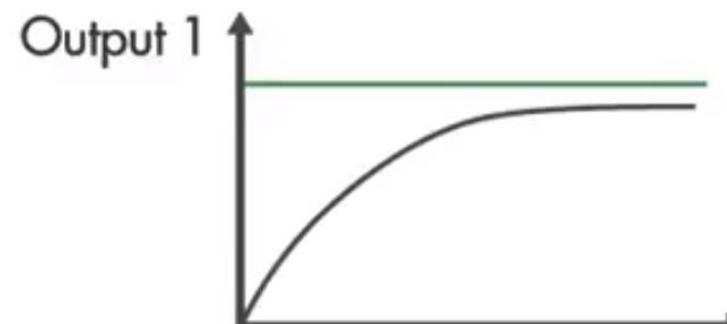
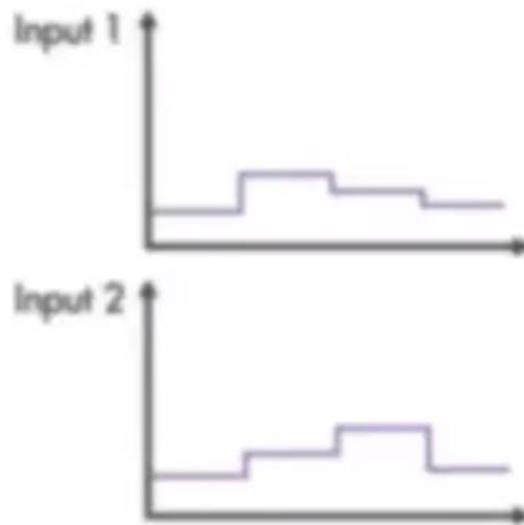


Control

Error



Weight's function 2: multi outputs



$$\frac{W_{\text{output1}}}{W_{\text{output2}}} > 1$$



MPC design parameters

- Sampling time
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WHAT IS MPC?

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Linear system



Linear constraints



Quadratic cost function



Linear time-invariant MPC



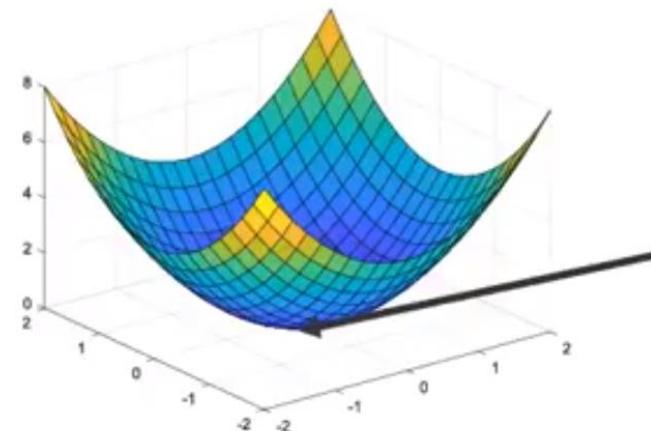
* Not compulsory

Linear system

Linear constraints

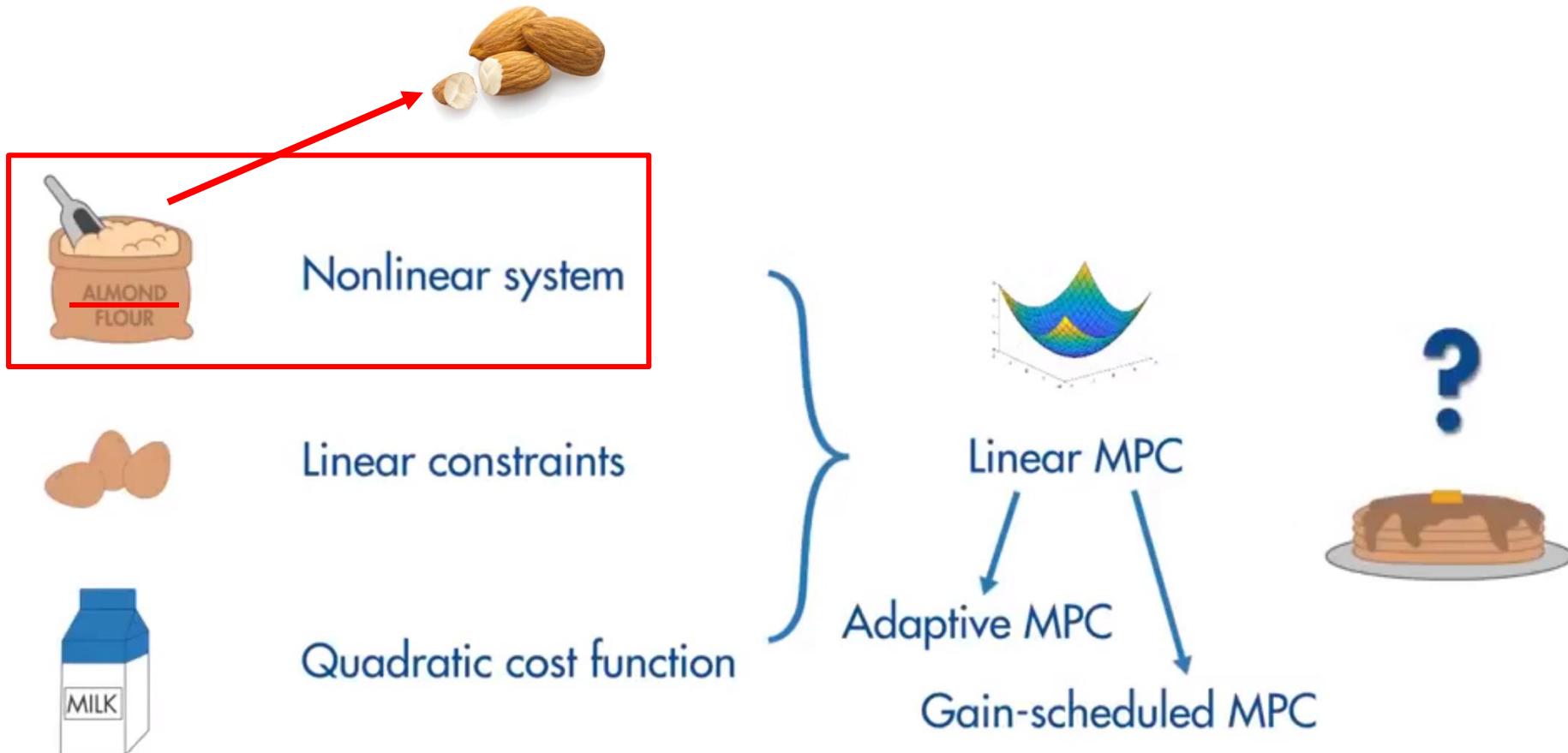
Quadratic cost function

Convex Optimization Problem

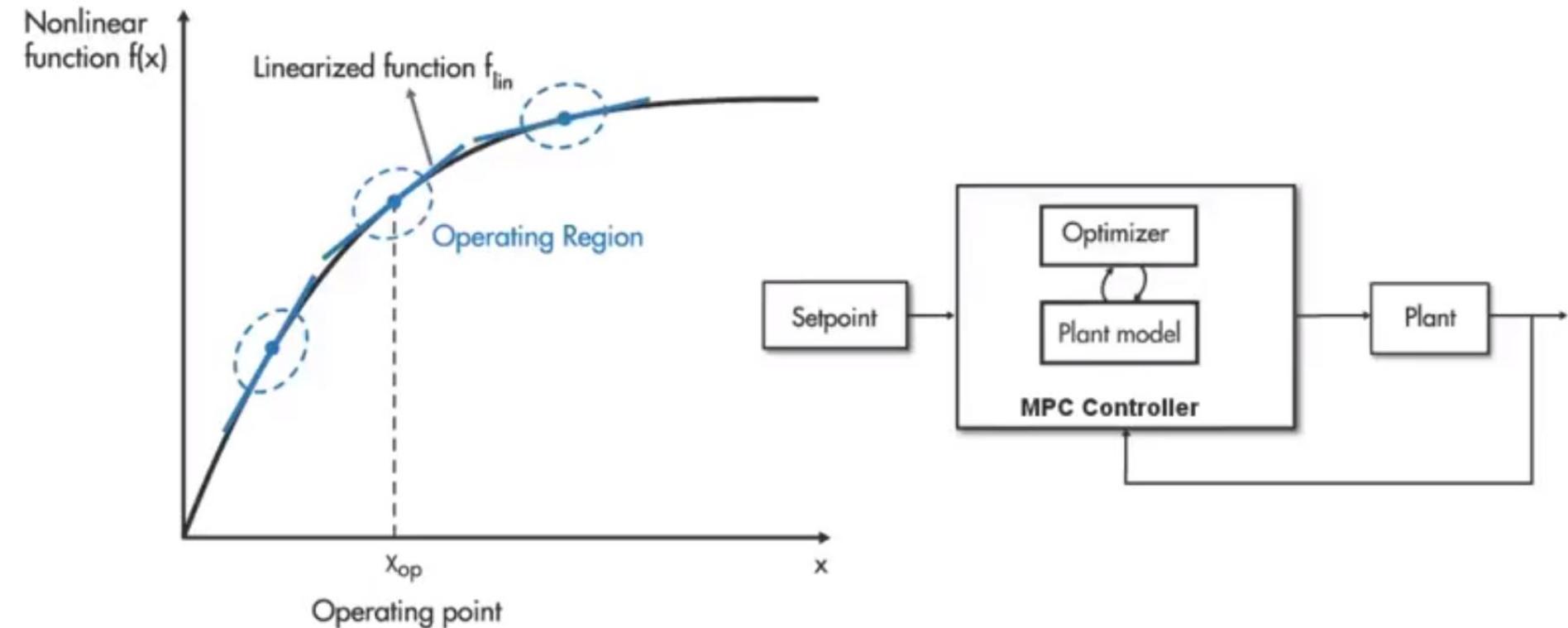


Global optimum

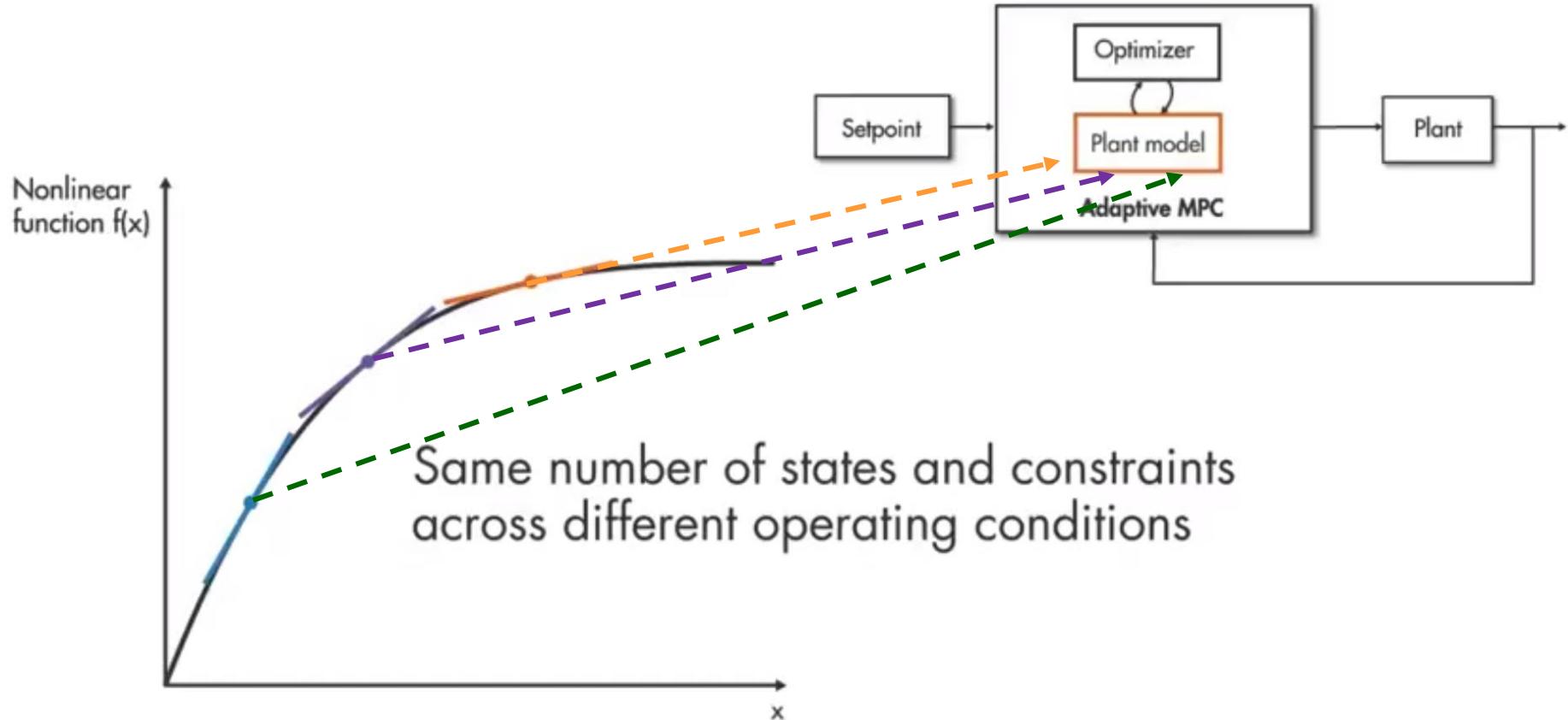
* Not compulsory



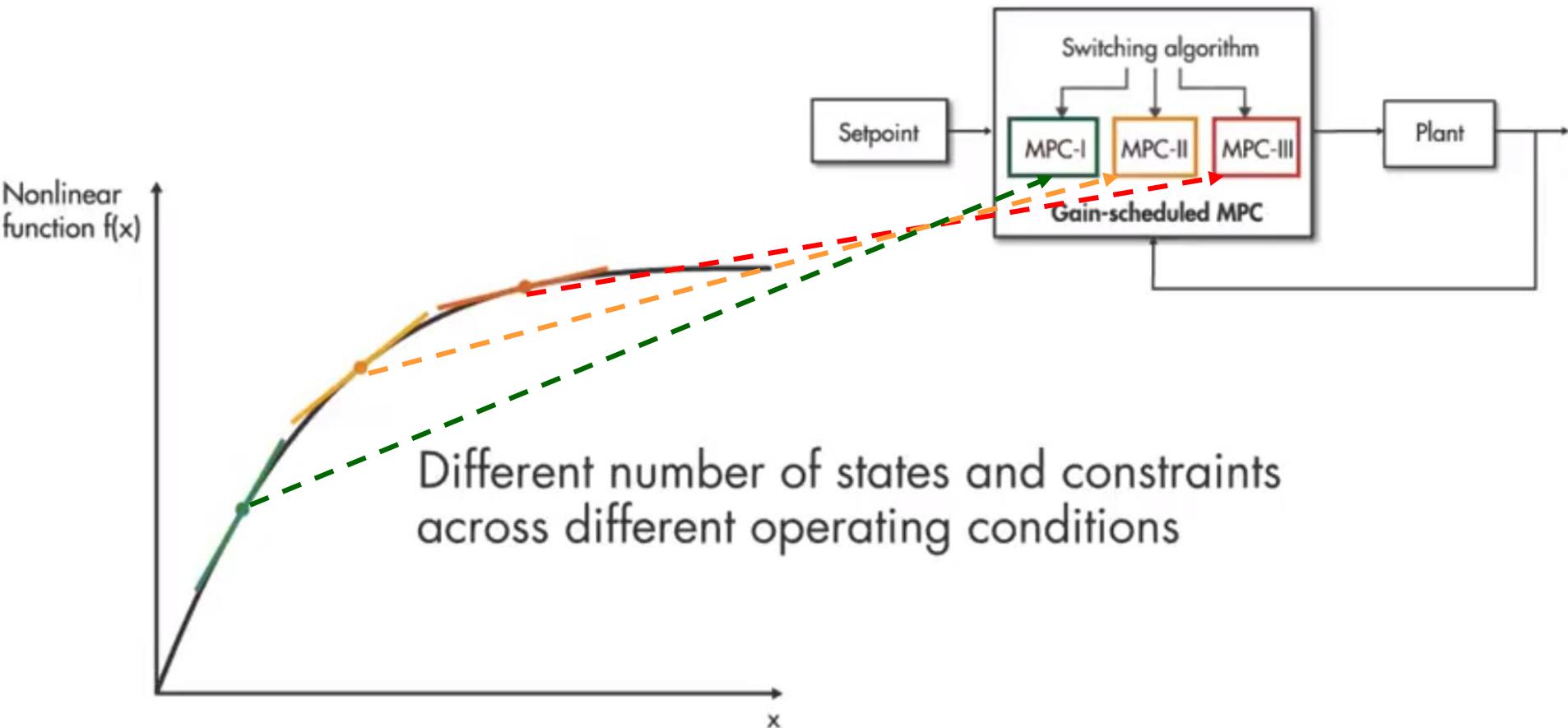
* Not compulsory



* Not compulsory

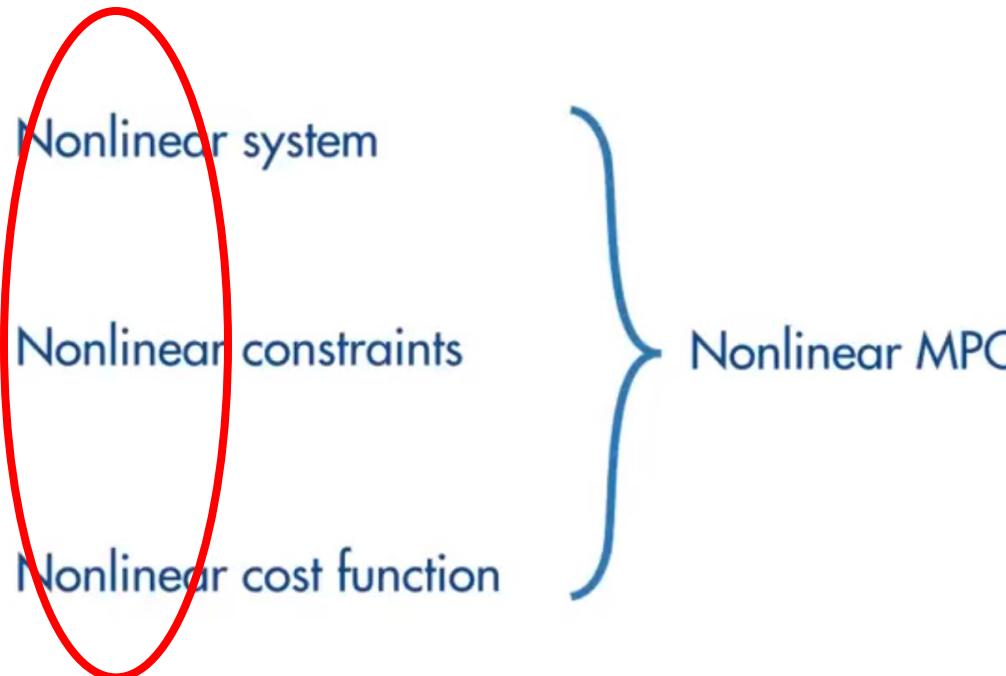


* Not compulsory

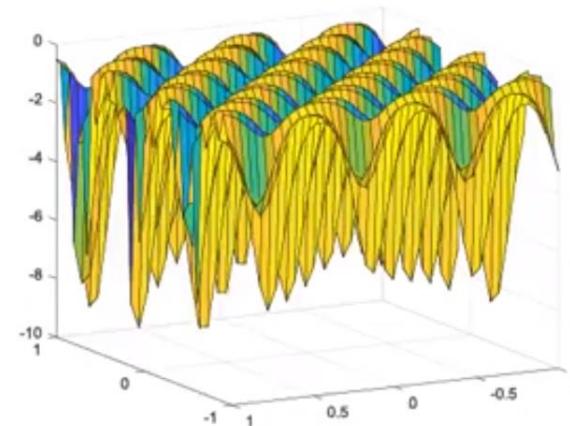


* Not compulsory

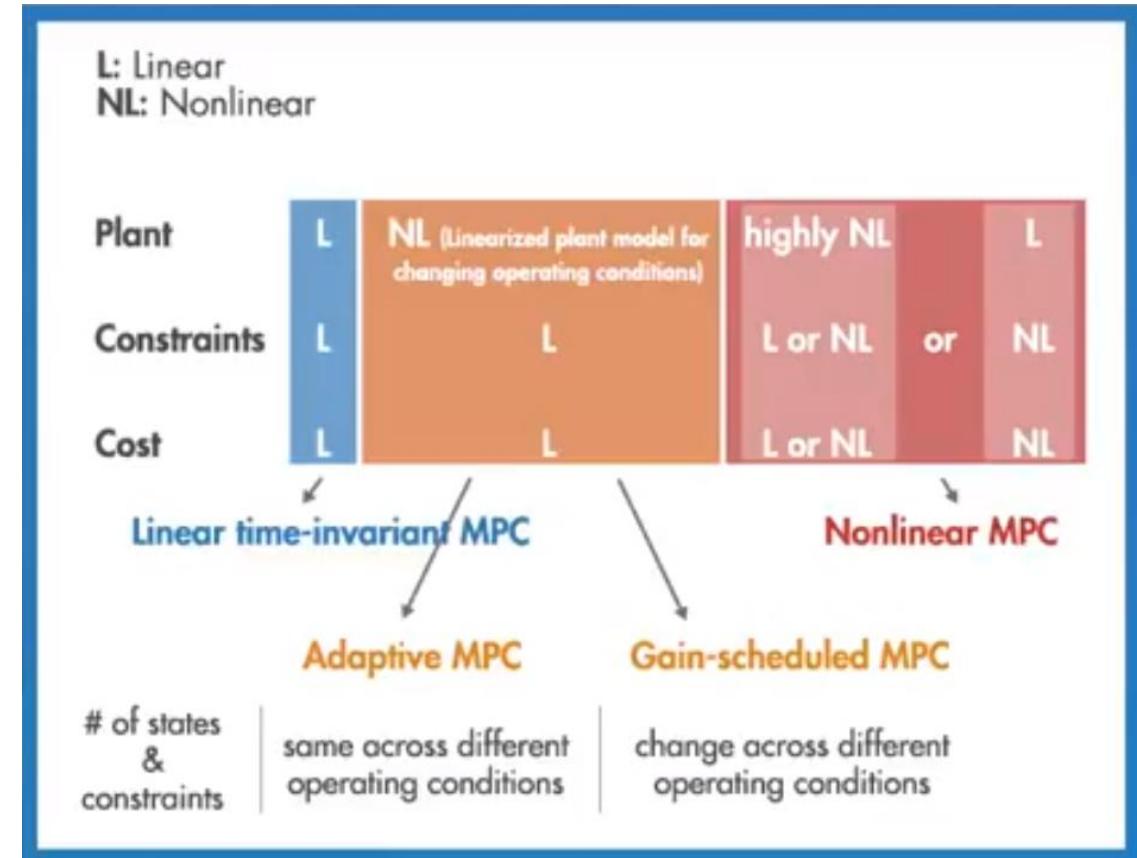
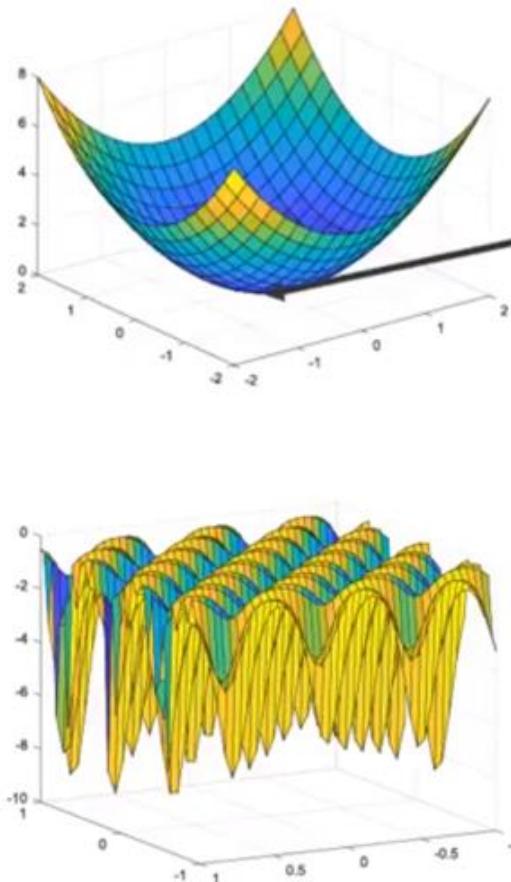
Non-linear MPC for the nonlinear system*



* Not compulsory



* Not compulsory



* Not compulsory

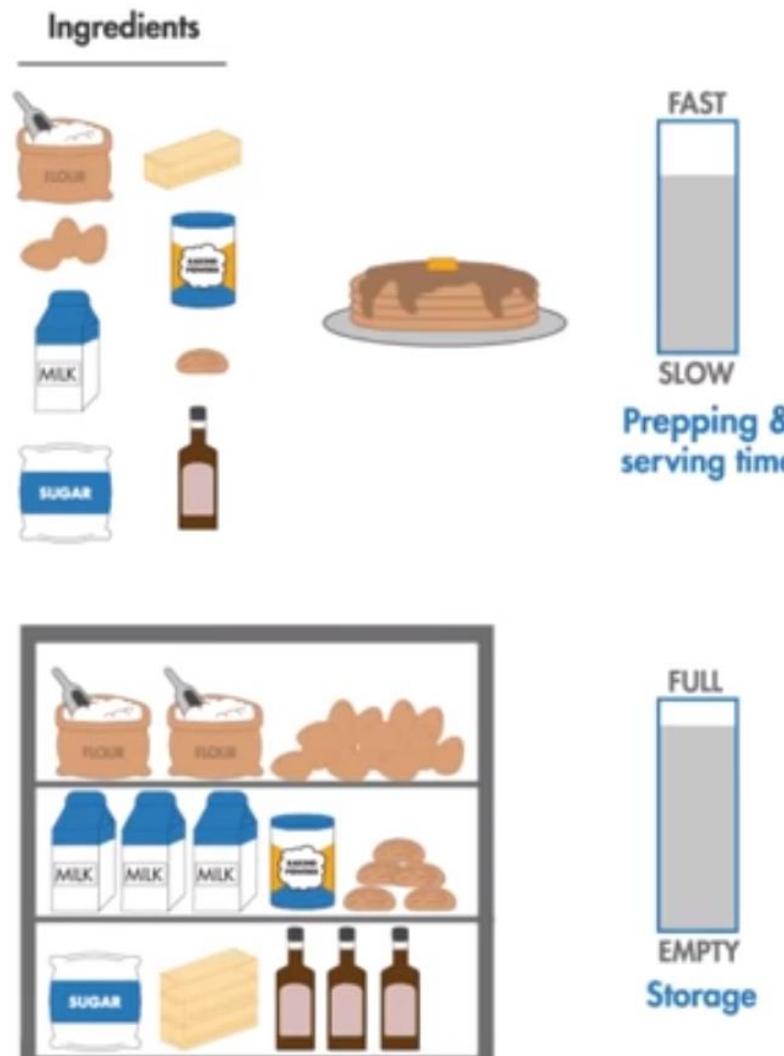


WHAT IS MPC?

- BASIC CONCEPT OF THE MPC
- DESIGN PARAMETERS OF THE MPC
- LINEAR AND NON-LINEAR MPC
- HOW TO RUN MPC FASTER?



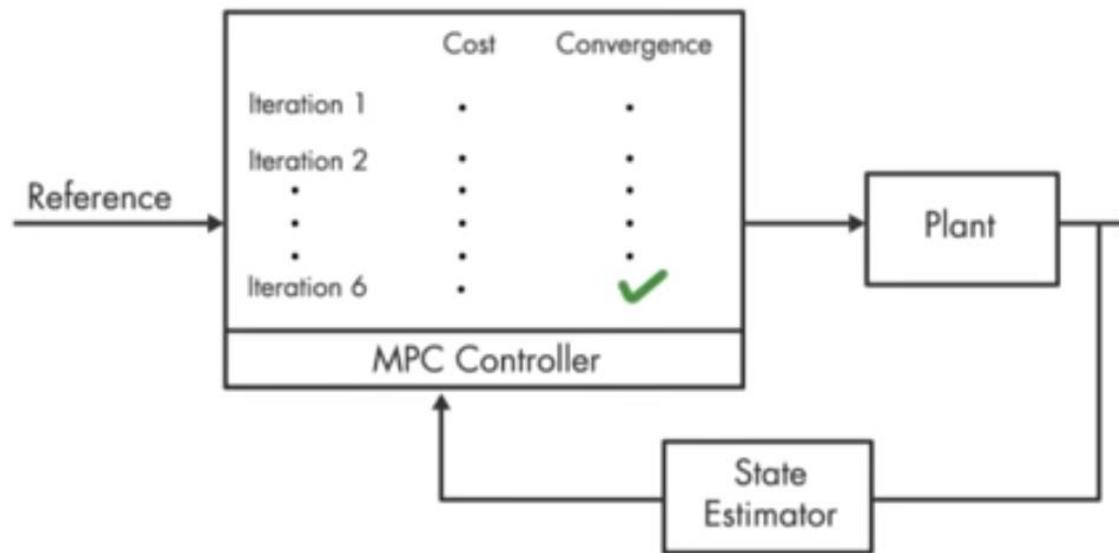
WHY WE NEED MPC FASTER?



* Not compulsory

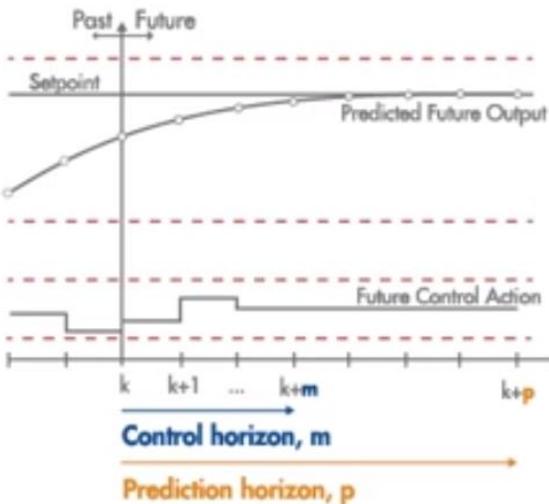


MPC solves an optimization problem at each time step



* Not compulsory

MPC Problem



QP Problem
(QP: Quadratic Programming)

$$\min_z \left(\frac{1}{2} z^T H z + f^T z \right) \quad \text{subject to constraints } Az \geq b$$

Number of **states**
Number of **constraints**
Length of the **control horizon**
Length of the **prediction horizon**



MPC complexity

z represents decision variables of the optimization problem and here we assume that it includes the **states** of the system.

* Not compulsory



Sample Time [seconds]



Process Industry



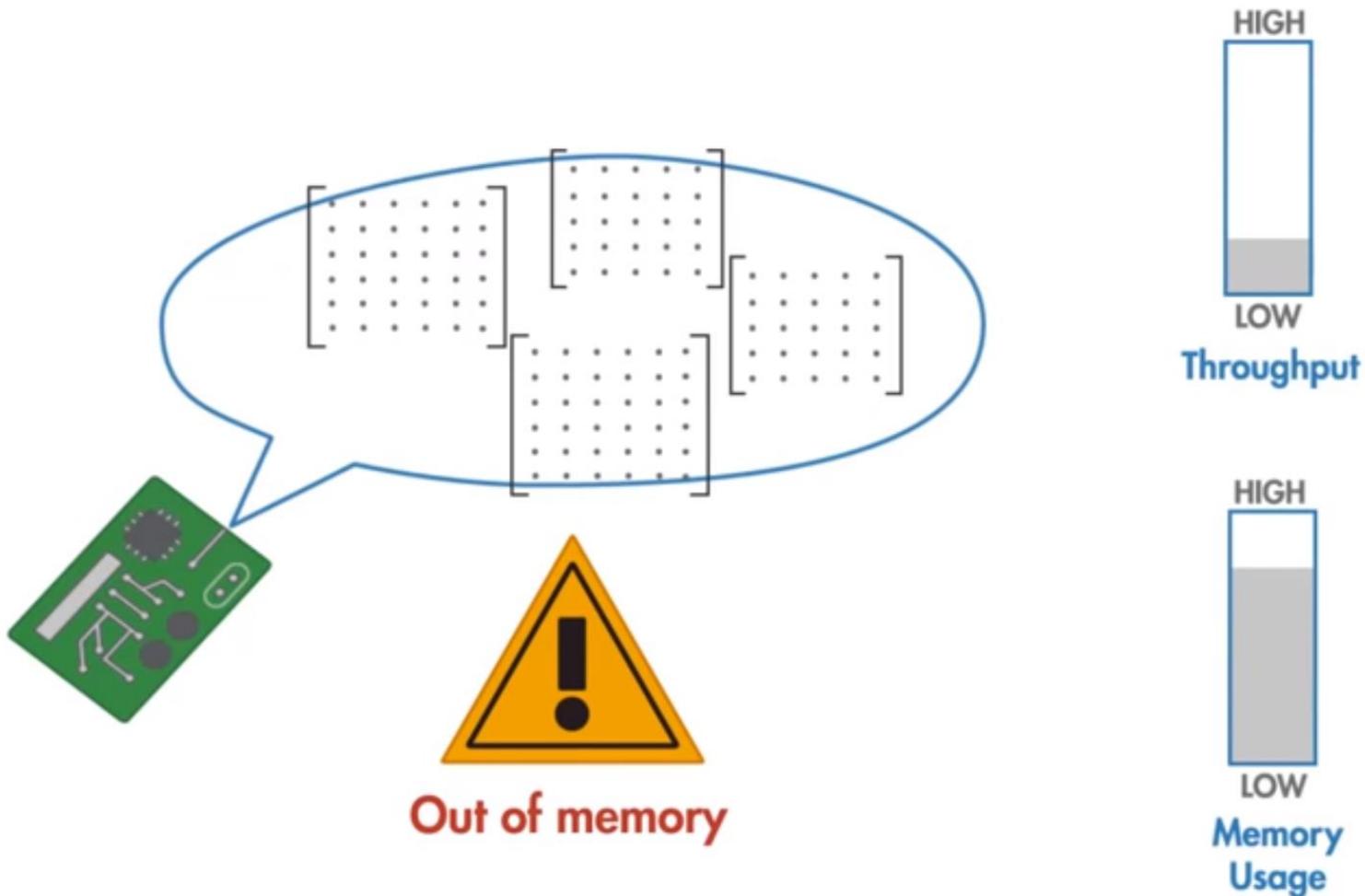
* Not compulsory



Sample Time [milliseconds]



* Not compulsory



* Not compulsory



HOW TO MAKE MPC FASTER?

- REMOVE UNNECESSARY ITEMS FROM MPC
- EXPLICIT MPC METHOD
- SUB-OPTIMAL MPC METHOD

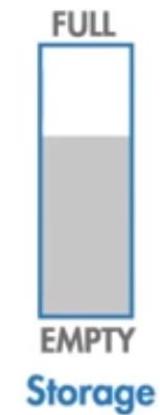
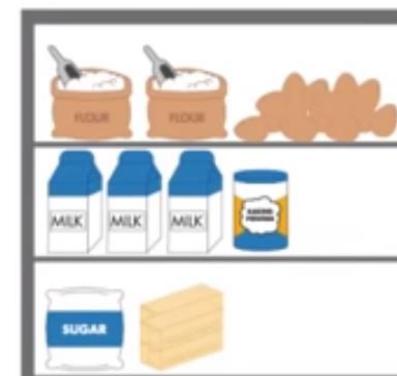
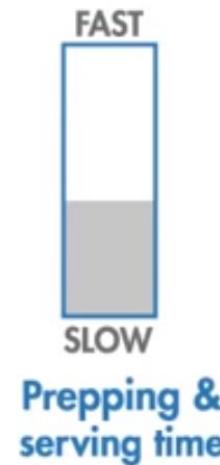


HOW TO MAKE MPC FASTER?

- REMOVE UNNECESSARY ITEMS FROM MPC
- EXPLICIT MPC METHOD
- SUB-OPTIMAL MPC METHOD



Ingredients



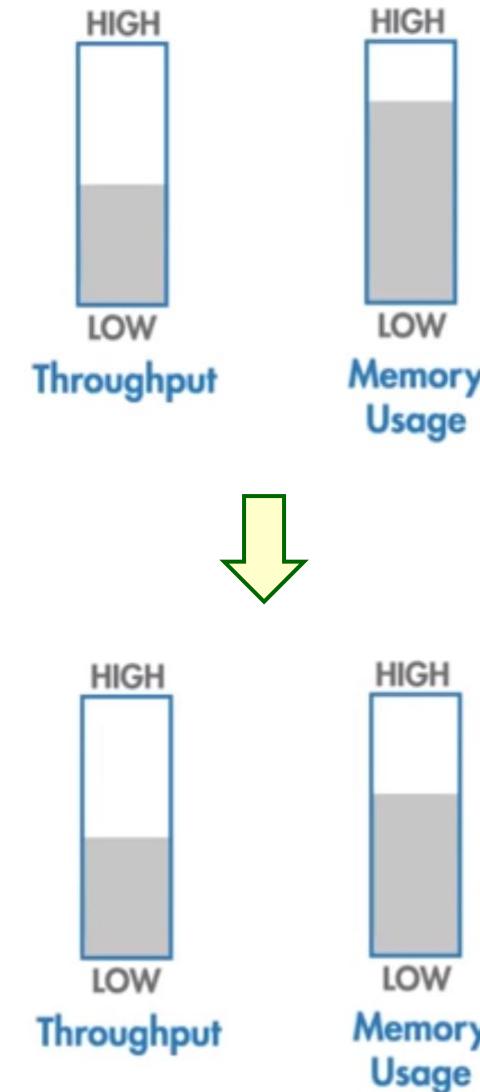
* Not compulsory



Model Order Reduction

State vector =

$$\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ \vdots \\ \vdots \\ \text{---} \\ x_{20} \\ \vdots \\ \vdots \\ \text{---} \\ x_{25} \\ \text{---} \\ x_{26} \\ \vdots \\ \text{---} \\ x_{33} \end{bmatrix}$$

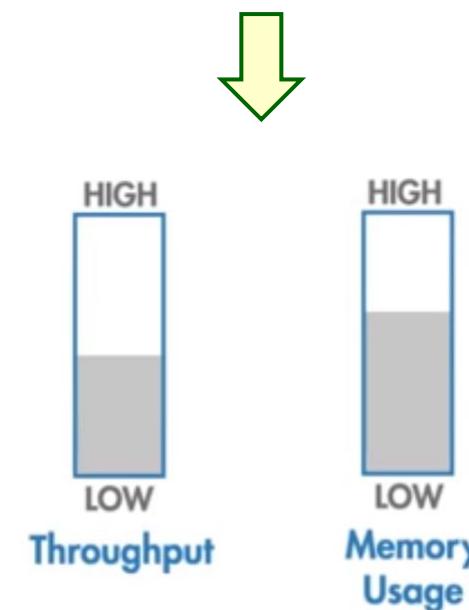


* Not compulsory



Tips For Running MPC faster:

- Model Order Reduction
- Shorter Prediction Horizon
- Shorter Control Horizon
- Reduced Number of Constraints
- Lower Precision Operations and Data Representation



* Not compulsory

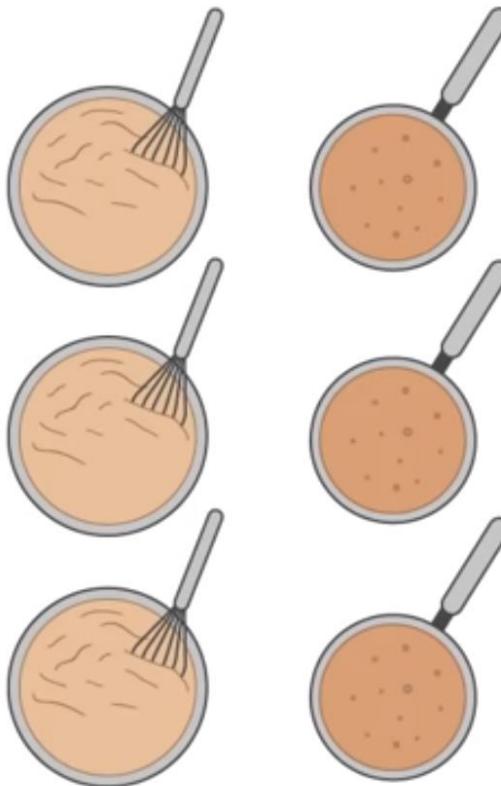


HOW TO MAKE MPC FASTER?

- REMOVE UNNECESSARY ITEMS FROM MPC
- EXPLICIT MPC METHOD
- SUB-OPTIMAL MPC METHOD



TRADITIONAL MPC

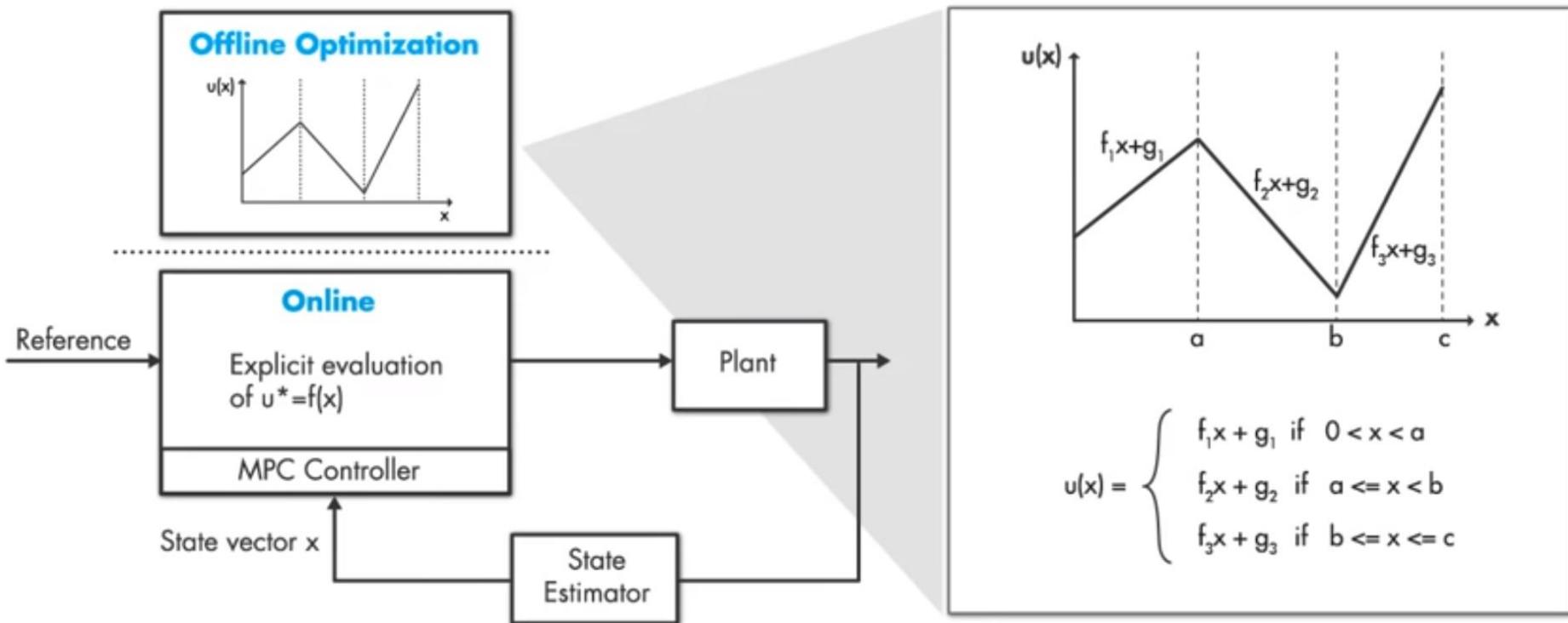


EXPLICIT MPC



* Not compulsory

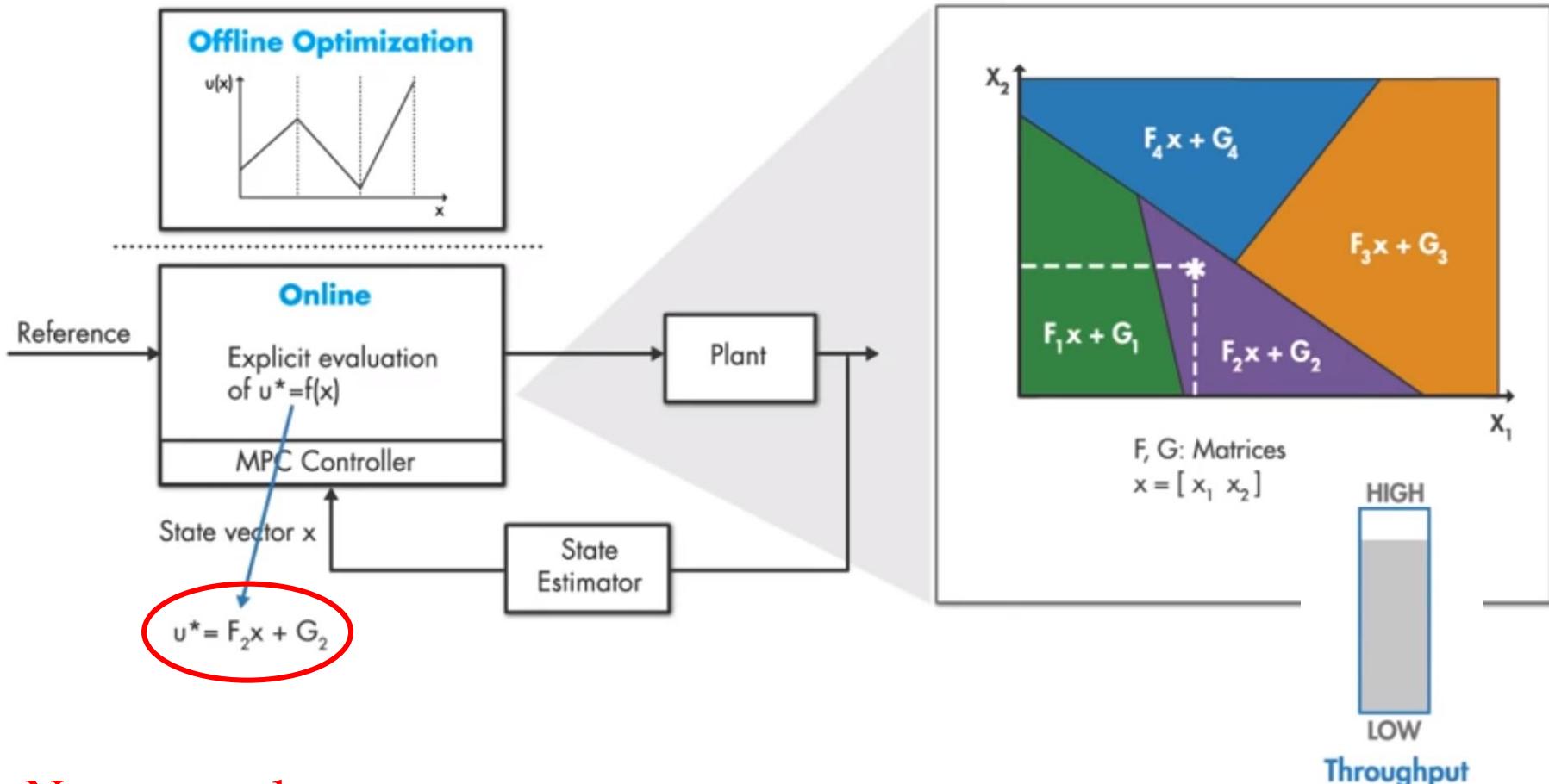
The operation principle of the explicit MPC*



* Not compulsory



The operation principle of the explicit MPC*



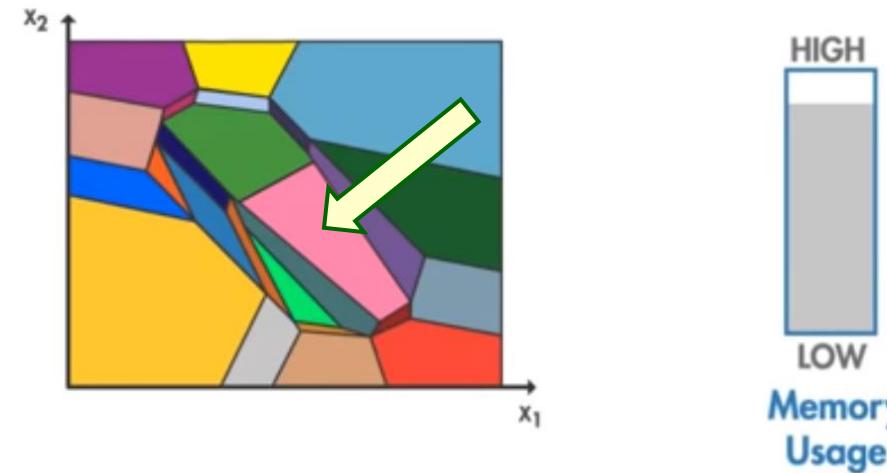
* Not compulsory



EXPLICIT MPC



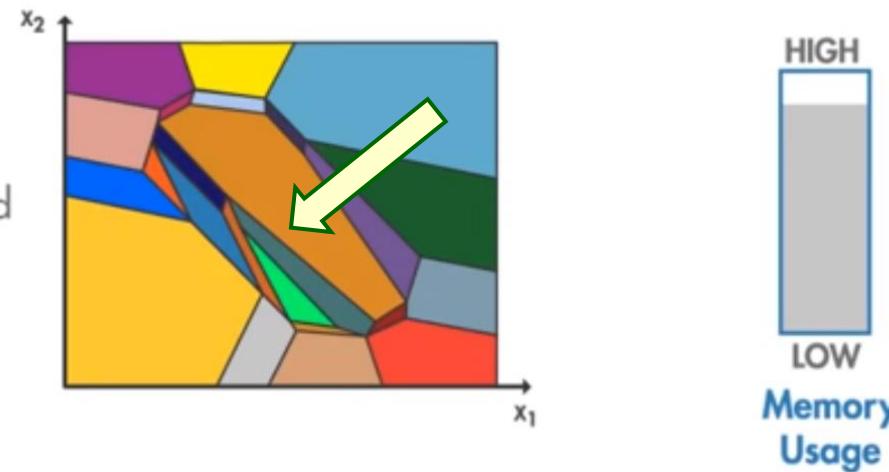
How to find the right regions quickly?



* Not compulsory



The solution is **not optimal** when region merging techniques are used to reduce the number of regions.



* Not compulsory

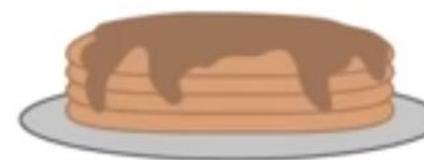
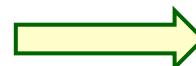


HOW TO MAKE MPC FASTER?

- REMOVE UNNECESSARY ITEMS FROM MPC
- EXPLICIT MPC METHOD
- SUB-OPTIMAL MPC METHOD

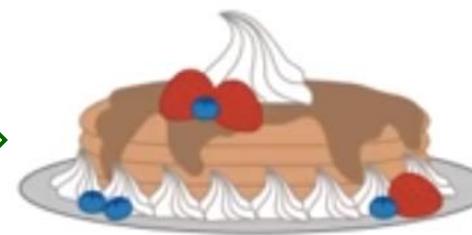


Sub-optimal



Prepping &
serving time

Optimal



* Not compulsory



	Cost	Convergence
Iteration 1	•	•
Iteration 2	•	•
Iteration 3	•	•
Iteration 4	•	•
Iteration 5	•	•
Iteration 6	•	•
Iteration 7	•	•
Iteration 8	•	•
Iteration 9	•	•
Iteration 10	•	✓

→ Suboptimal solution



Throughput



Throughput

Maximum number of iterations: 5

Execution time per iteration \times Maximum number of iterations < Controller sample time



* Not compulsory

Summary: how to make the MPC faster*

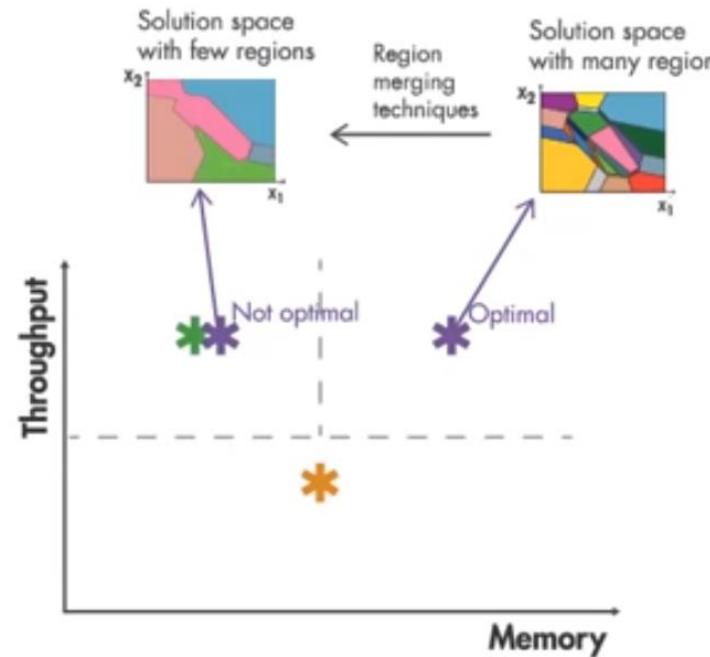
Methods for running MPC faster:

Quick tips

- Model order reduction
- Shorter prediction horizon
- Shorter control horizon
- Reduced number of constraints
- Lower precision operations and data representation

Explicit MPC

Suboptimal solution



* Not compulsory



- No quiz but need to submit a report before 08/11/2018
- Understand the concept of the MPC
- Understand the basic parameters of the MPC
- Linear MPC and non-linear MPC



Thank you!

Jackzhang@ntu.edu.sg

