Closed-Loop Control of a Combustion Engine Model

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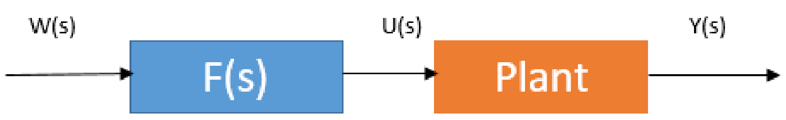
Agenda

- Background
- Controllers
- Problem
- Goals
- Controller choice
- Controller analysis and design
- Conclusion

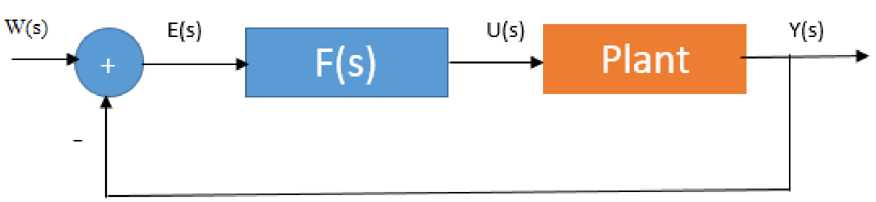
Background

Feed-forward &Feedback control loops (Plant →P(s))

Feed-forward



Feedback



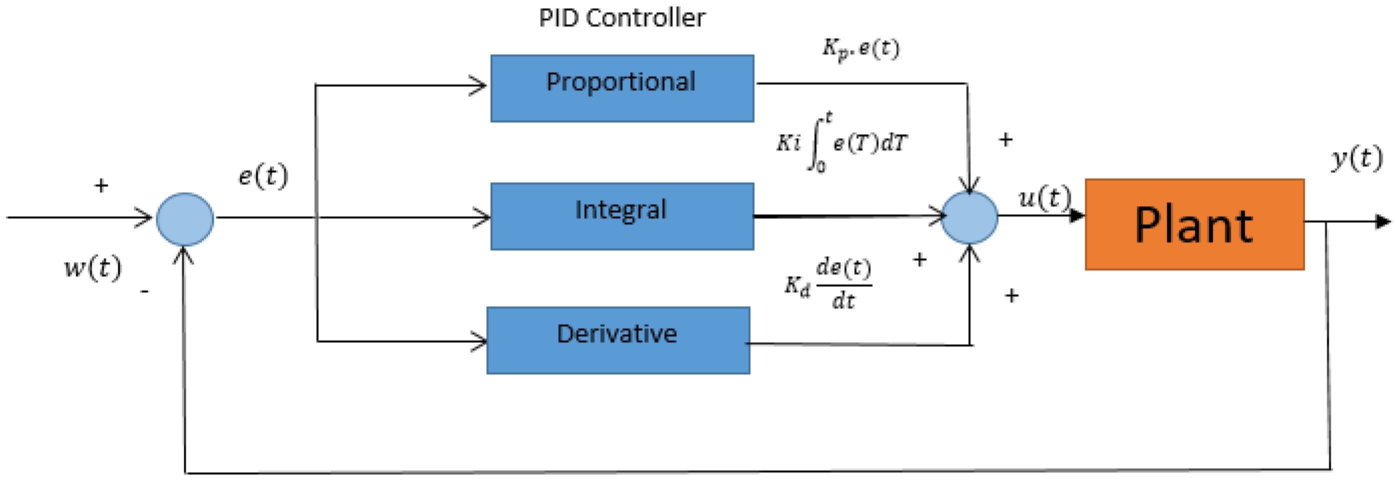
$$F(s) = P(s)^{-1}$$

$F(s)P(s)$ very high

$$G(s) = \frac{F(s)P(s)}{1 + F(s)P(s)}$$

Controllers: Proportional-Integral-Derivative (PID)

$$u(t) = K_p.e(t) + K_i.\int_0^t e(T)dT + K_d\frac{d.e(t)}{dt}$$



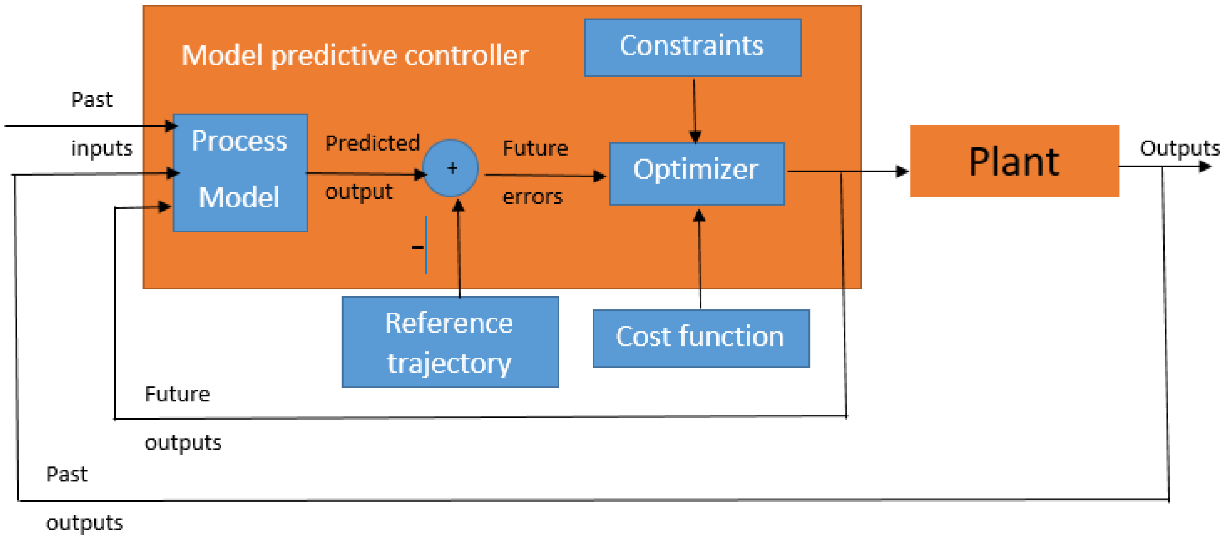
Controllers: Model Predictive control (MPC)

$$\min_{u} \Sigma_{j=k}^{k+N-1}(x^T(j|k)Qx(j|k) \; + \; u^T(j|k)Ru(j|k))$$

subject to

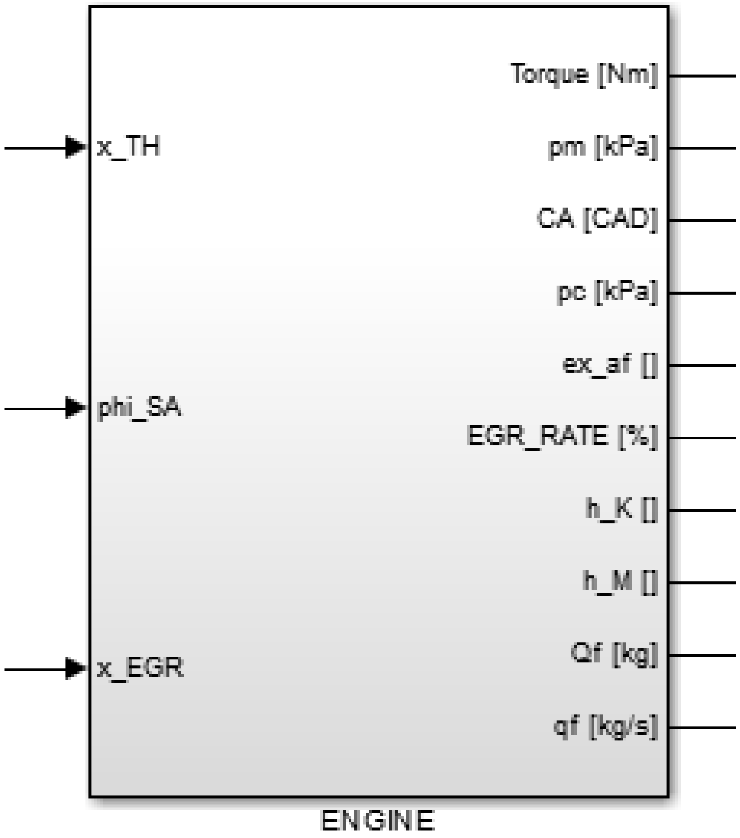
$$u(k+j|k) \in U$$

$$x(k+j|k) = Ax(k+j-1|k) + Bu(k+j-1|k)$$



Problem

Design an optimal closed-loop control for a gasoline combustion engine taking into consideration actuators and limitations of the system (knocking & misfiring).



Goals

- The main goal is to increase the efficiency of the engine model while following the desired torque trajectory

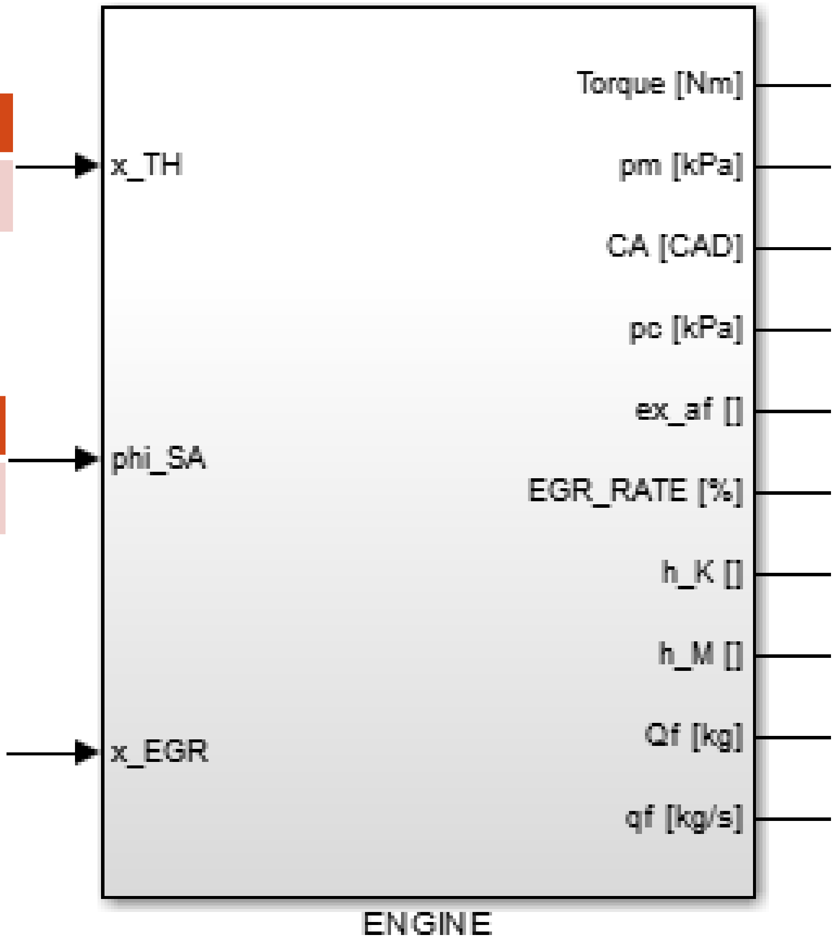
- Achieve the following desirable outputs:
  1. Reducing knocking and misfiring.
  2. Adjusting the EGR valve position to maximize energy output of the engine.
  3. Minimizing the over all fuel consumption.

Simulation Scenarios: ONE

Type	Min	Max	Seed
PRBS	5	90	0.1

Type	Min	Max	Seed
PRBS	-30	60	0.111

Type	Min	Max	Seed
PRES	0	100	0.0813



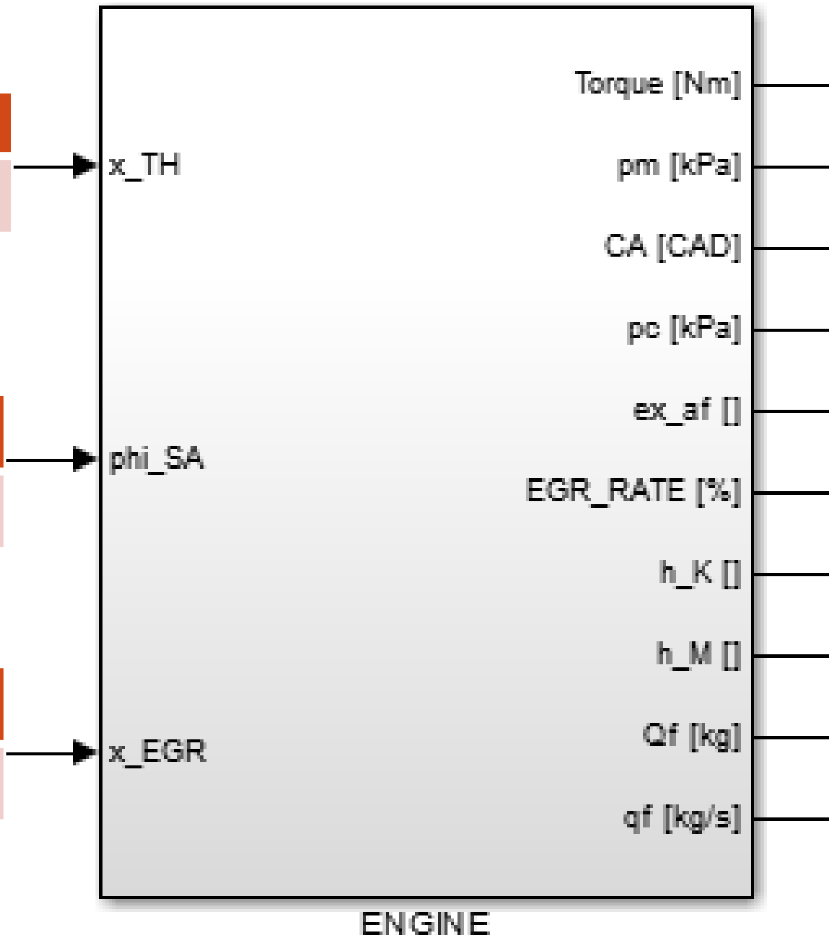
Output

Simulation Scenarios: TWO

Type	Min	Max	Seed
PRBS	5	90	0.1

Type	Amplitude
Constant	5

Type	Amplitude
Constant	5



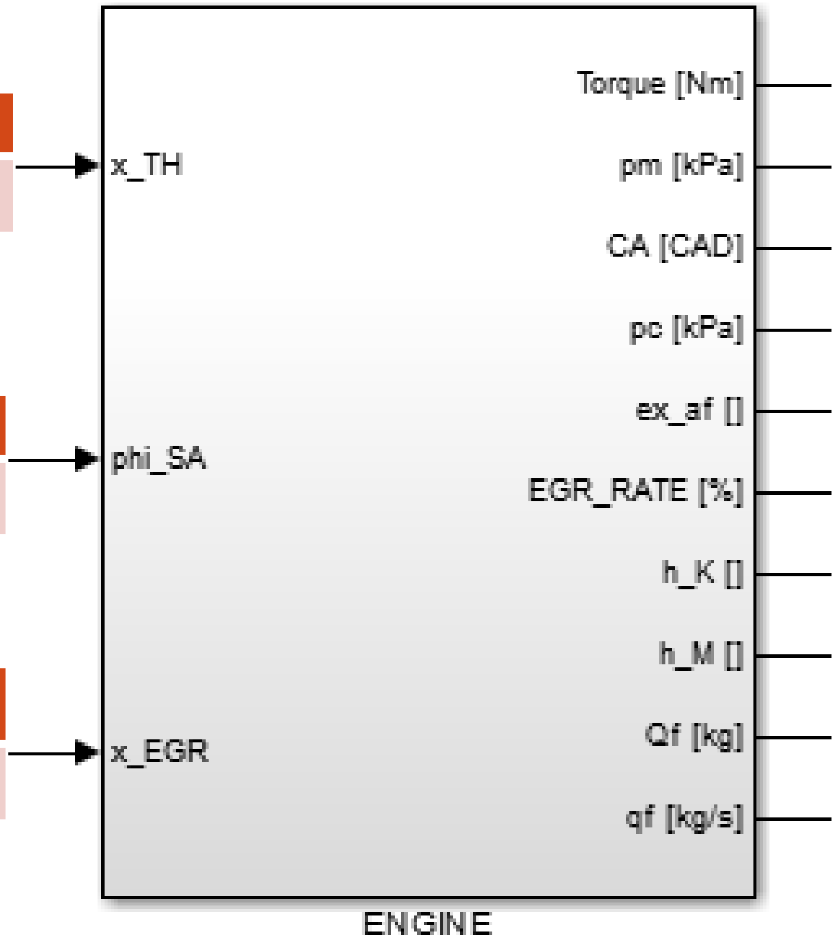
Output

Simulation Scenarios: THREE

Type	Min	Max	Step time
Step	5	90	30

Type	Min	Max	Seed
PRBS	-30	60	0.111

Type	Amplitude
Constant	5



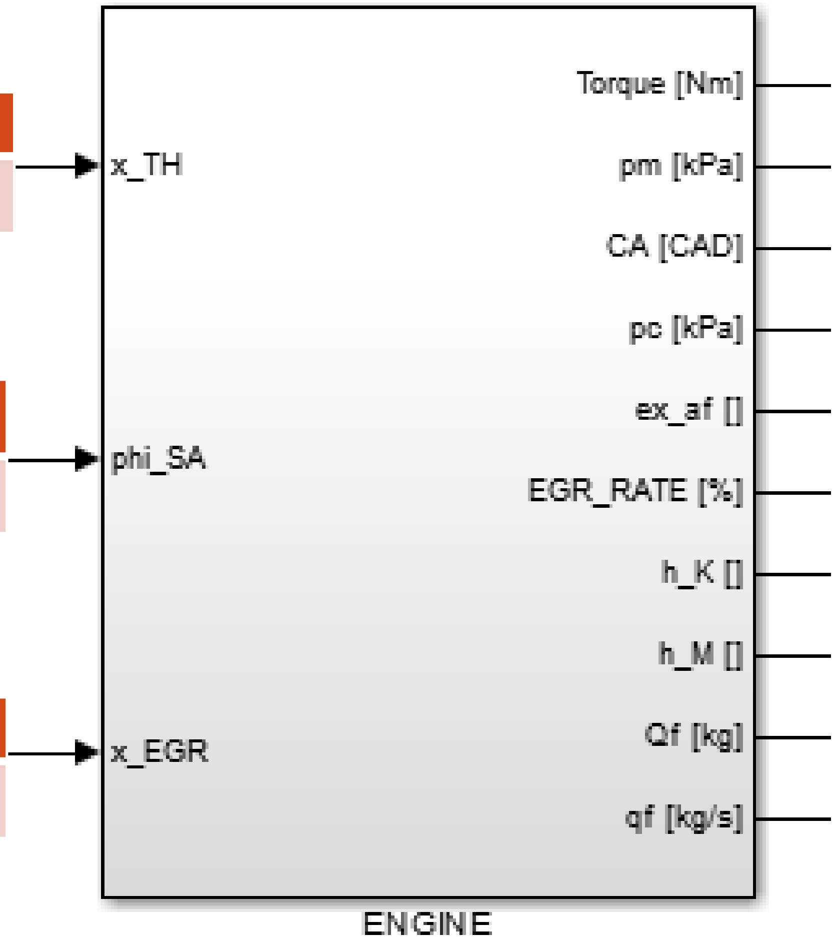
Output

Simulation Scenarios: FOUR

Type	Min	Max	Step time
Step	5	90	30

Type	Amplitude
Constant	60

Type	Min	Max	Seed
PRBS	-30	60	0.111



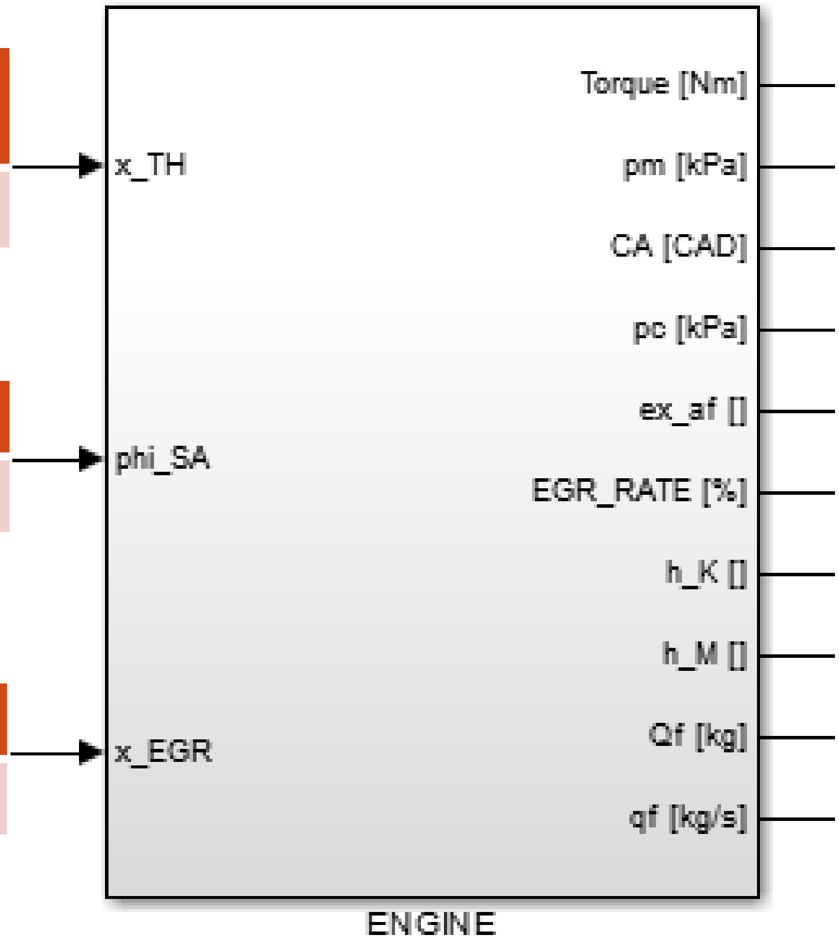
Output

Simulation Scenarios: FIVE

Type	Step width	Initial value	Step height
Step	10	5	2

Type	Amplitude
Constant	60

Type	Amplitude
Constant	100



Output

Conclusion of Scenarios ONE-FIVE

- Scenarios revealed strong coupling between inputs and outputs
  - Henceforth, MPC controller should be used.

MPC Controller Design: Steps

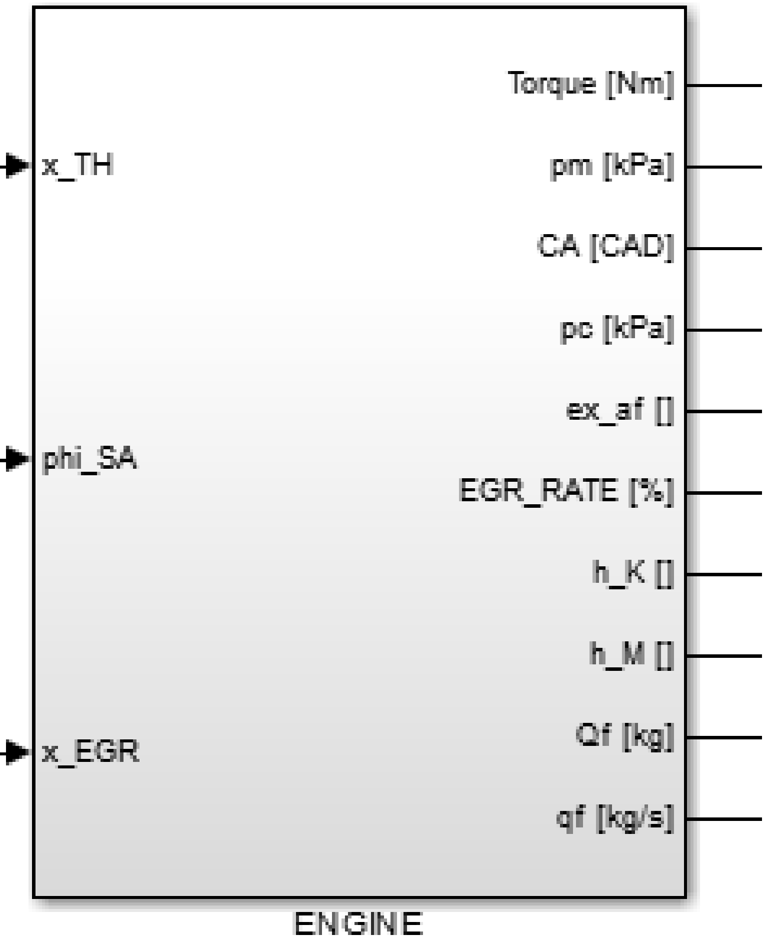
1. Linearization of the provided model (Toyota model)
2. Defining horizons options.
3. Define input and output constraints.
4. Adjusting output and input weights, and input rate weight to accommodate the non linear plant to the desired output.

Identification

Type	Min	Max	Seed
PRBS	14	90	0.1

Type	Min	Max	Seed
PRBS	50	60	0.1111

Type	Amplitude
Constant	10



Output

Identification: Result

- Cylinders 1 and 2 have been selected as basis for an MPC controller design.
  - They have the highest fit values.

output	cylinder 1	cylinder 2	cylinder 3	cylinder 4
torque	76.88	79.51	-	72.96
knocking	46.73	64.29	-	51.95
misfiring	24.33	37.19	-	21.41
fuel consumption	76.38	78.28	-	69.79
system order	2	5	-	2

MPC Controller Design: Controller $MPC_{c1,basic}$

- $MPC_{c1,basic}$: designed based on **Cylinder 1**.

Name	Weight	Rate Weight
Throttle	0	8.8674
Spark Advance	0	5.5116
EGR position	0	13.2278

Table 8: Inputs Weights for nonlinear model

[mi]

Name	Weight
Torque	0.22679
Knocking	0.49895
Misfiring	0.63503
Fuel consumption	0.0028804

Table 9: Outputs Weights for nonlinear model

[mo]

MPC Controller Design: Controller $MPC_{c1,advanced}$

- $MPC_{c1,advanced}$: based on **Cylinder 1** with error adjustment.

Name	Weight	Rate Weight
Throttle	0	8.8674
Spark Advance	0	5.5116
EGR position	0	13.2278

Table 8: Inputs Weights for nonlinear model

mi

Name	Weight
Torque	0.22679
Knocking	0.49895
Misfiring	0.63503
Fuel consumption	0.0028804

Table 9: Outputs Weights for nonlinear model

mo

signal name	output disturbances type	output disturbances magnitude	Measurement Noise type	Measurement Noise magnitude
Torque	step	10	white	1
Knocking	step	0.01	white	1
Misfire	step	0.01	white	1
Fuel consumption	step	$1e^{-5}$	white	1

Table 10: Type and magnitude of the error signals.

MPC Controller Design: Controller $MPC_{c2,advanced}$

- $MPC_{c2,advanced}$: based on **Cylinder 2** with error adjustment.

Name	Weight	Rate Weight
Throttle	0	48.3416
Spark Advance	0.15386	148.6233
EGR position	0.0017311	3.4684

Table 11: Inputs Weights for nonlinear model

mi

Name	Weight
Torque	0.74961
Knocking	0.029526
Misfiring	0.12397
Fuel consumption	0.025704

Table 12: Outputs Weights for nonlinear model

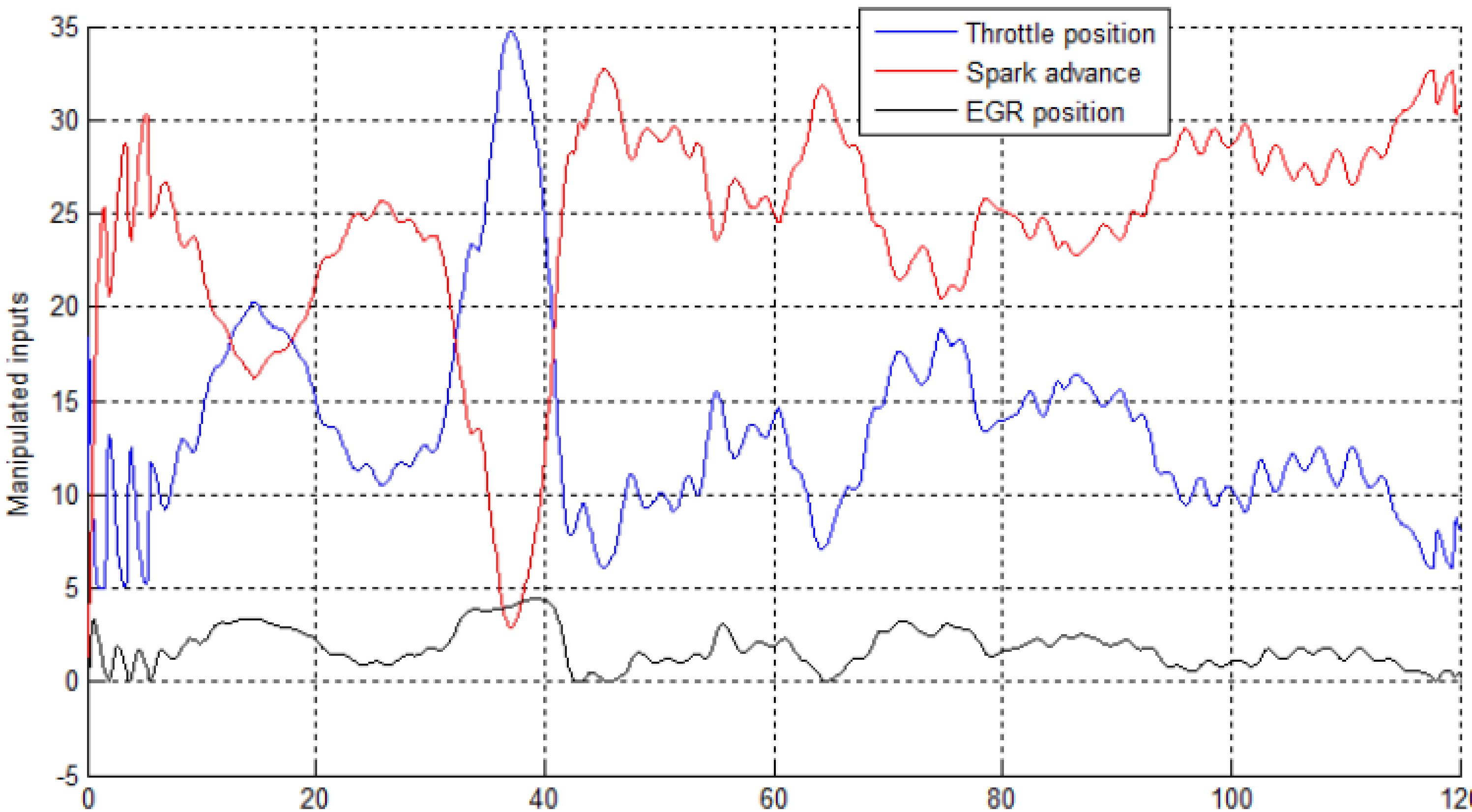
mo

signal name	output disturbances type	output disturbances magnitude	Measurement Noise type	Measurement Noise magnitude
Torque	step	10	white	1
Knocking	step	0.01	white	1
Misfire	step	0.01	white	1
Fuel consumption	step	$1e^{-5}$	white	1

Table 10: Type and magnitude of the error signals.

MPC Controller Design: Evaluation of $MPC_{c1,basic}$

- Input



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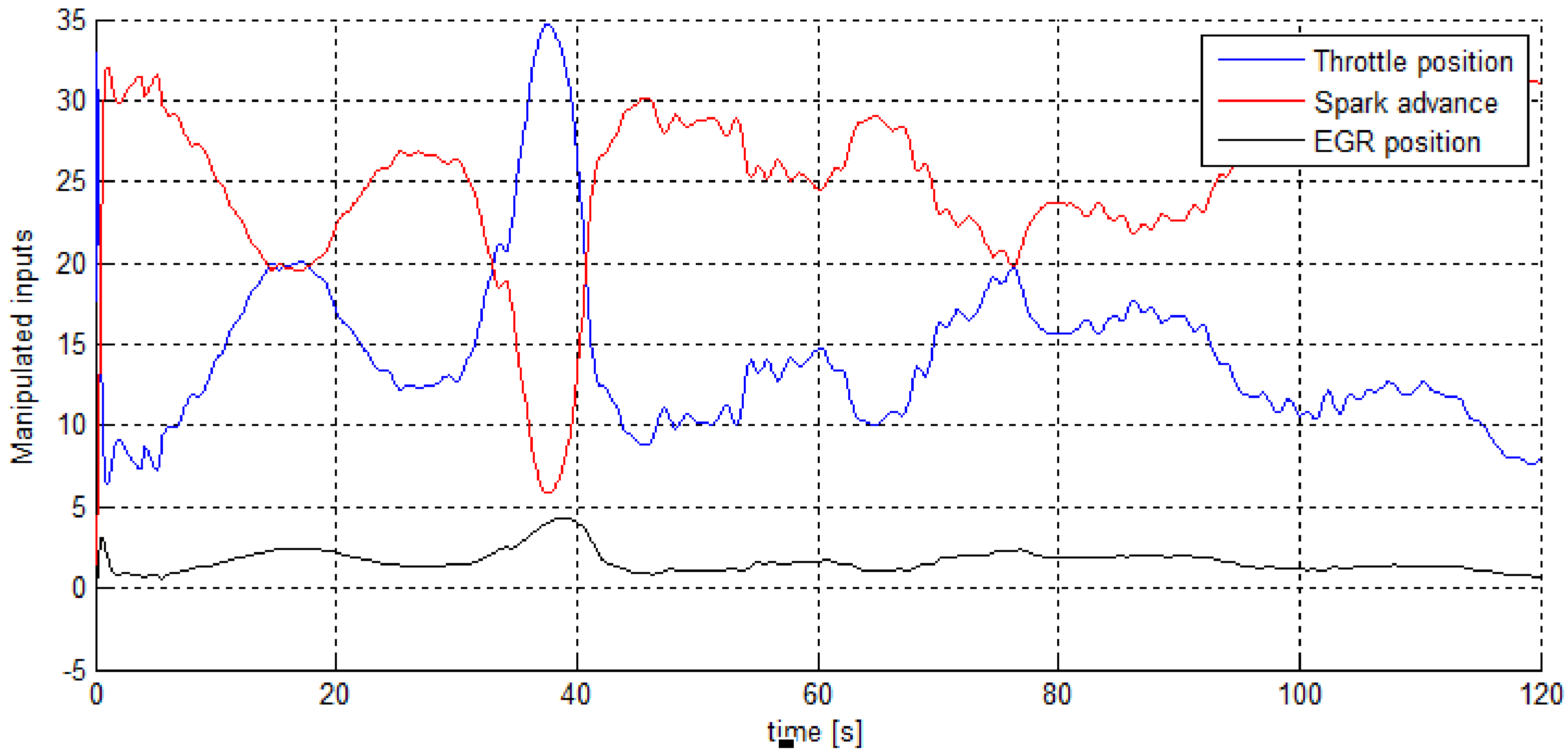
MPC Controller Design: Evaluation of $MPC_{c1,advanced}$

- Input



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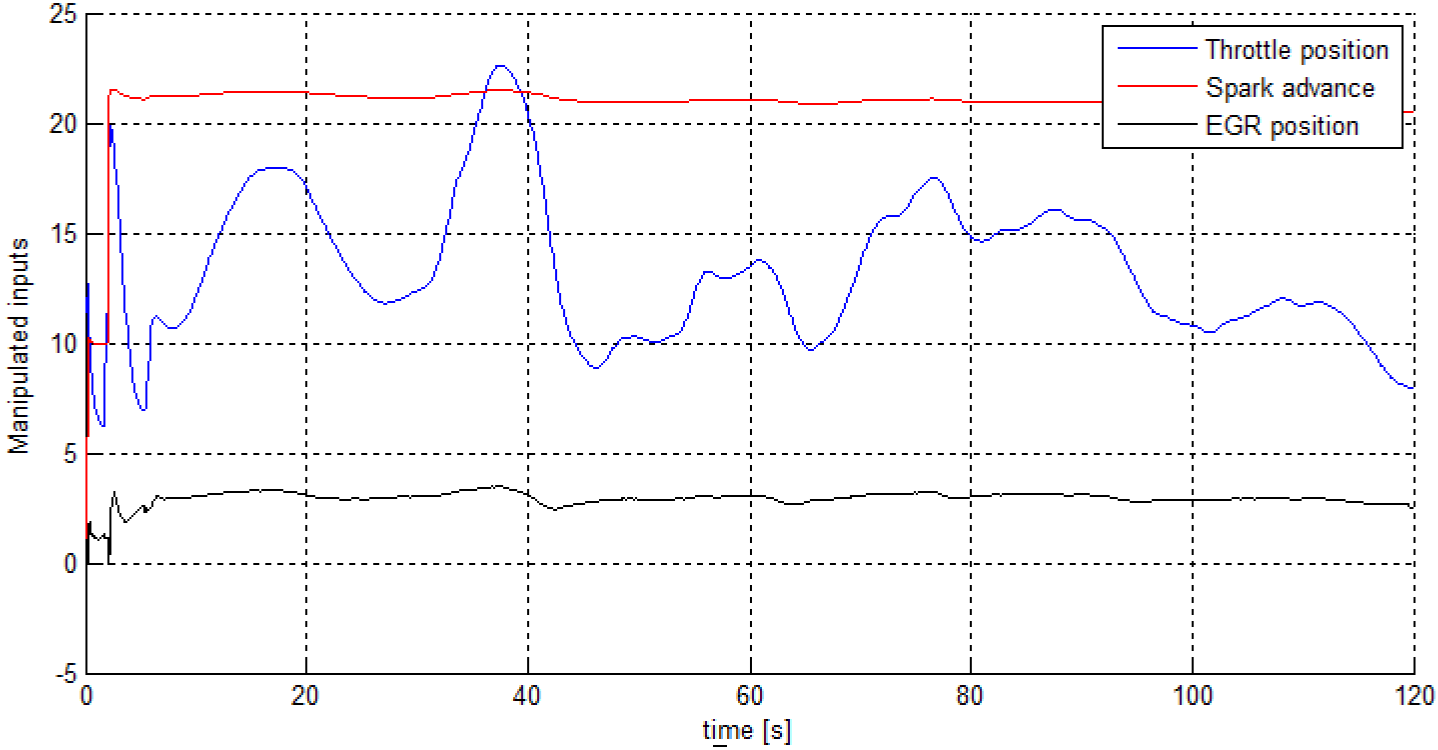
MPC Controller Design: Evaluation of $MPC_{c2,advanced}$

- Input



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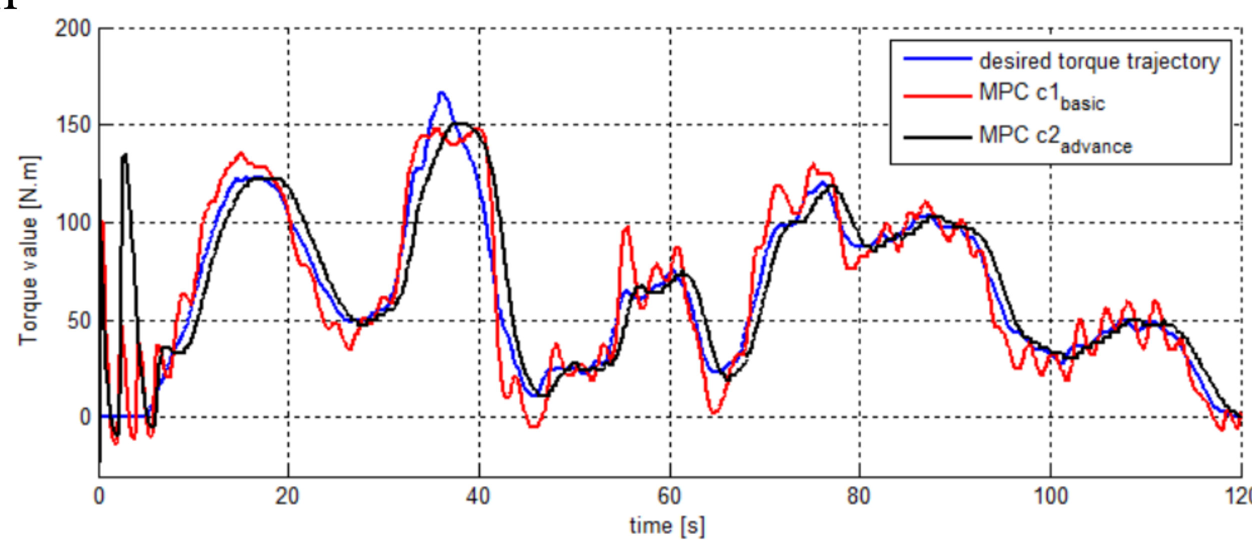
Conclusion

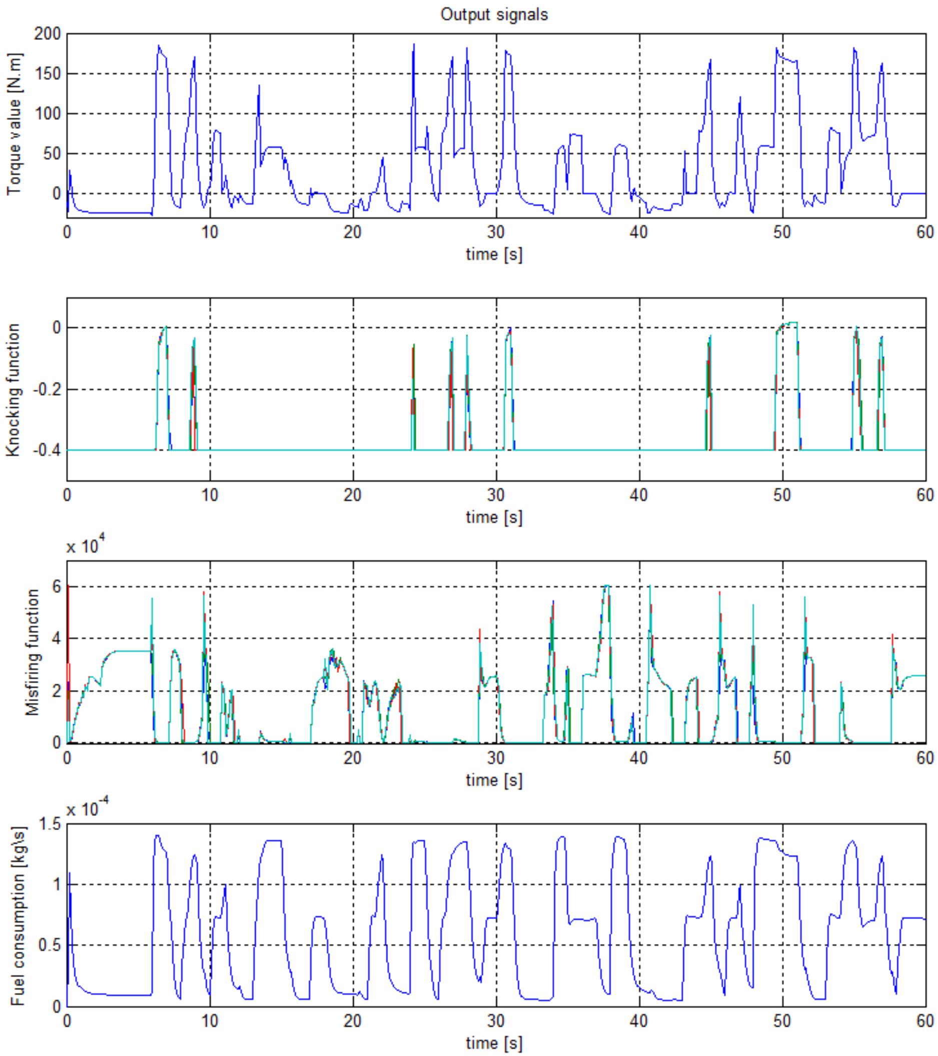
- We have selected **MPC$_{c2,advanced}$** because it has the highest efficiency while having a smooth torque trajectory.

Signals	$MPC_{c1\ basic}$	$MPC_{c1\ advanced}$	$MPC_{c2\ advanced}$
torque	126.0657	28.025	138.1639
knocking	0	0	0
misfire	0.2681	0	9.7705
fuel consumption	$4.2256 * 10^{-9}$	$8.1545 * 10^{-9}$	$4.1255 * 10^{-9}$
throttle	205.8399	226.5927	182.9434
spark advance	606.4382	606.2328	424.0316
EGR value	4.2121	3.1248	8.5438
$\overline{\mu}_{engine}$	28.84	12.20	30.77



Questions !

Scenario ONE: output



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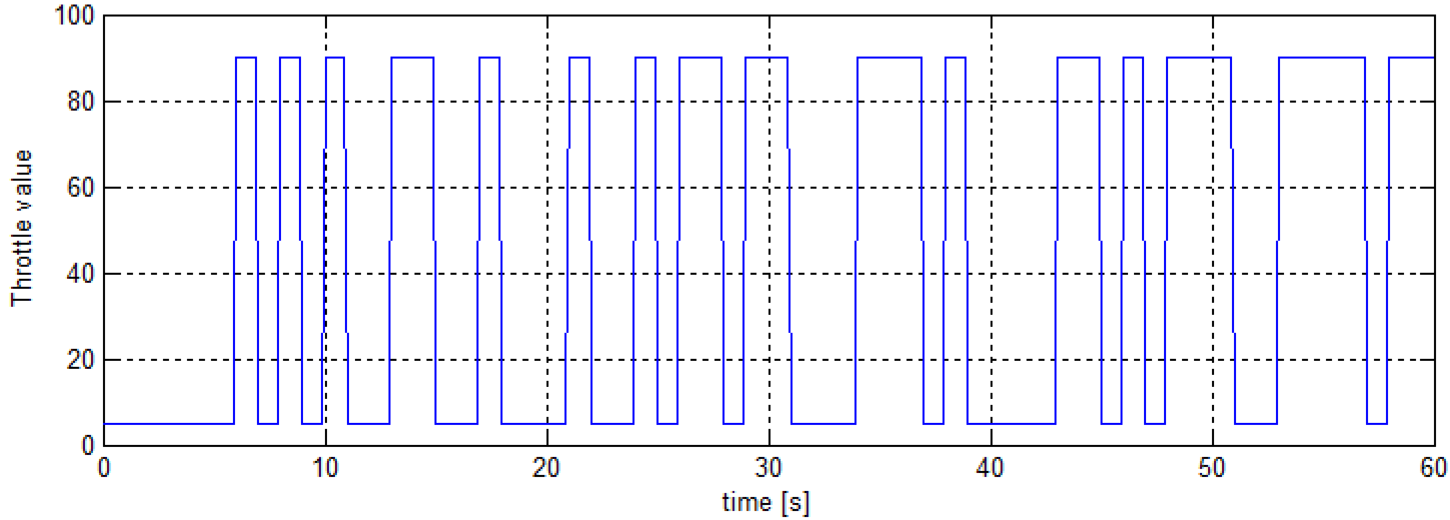
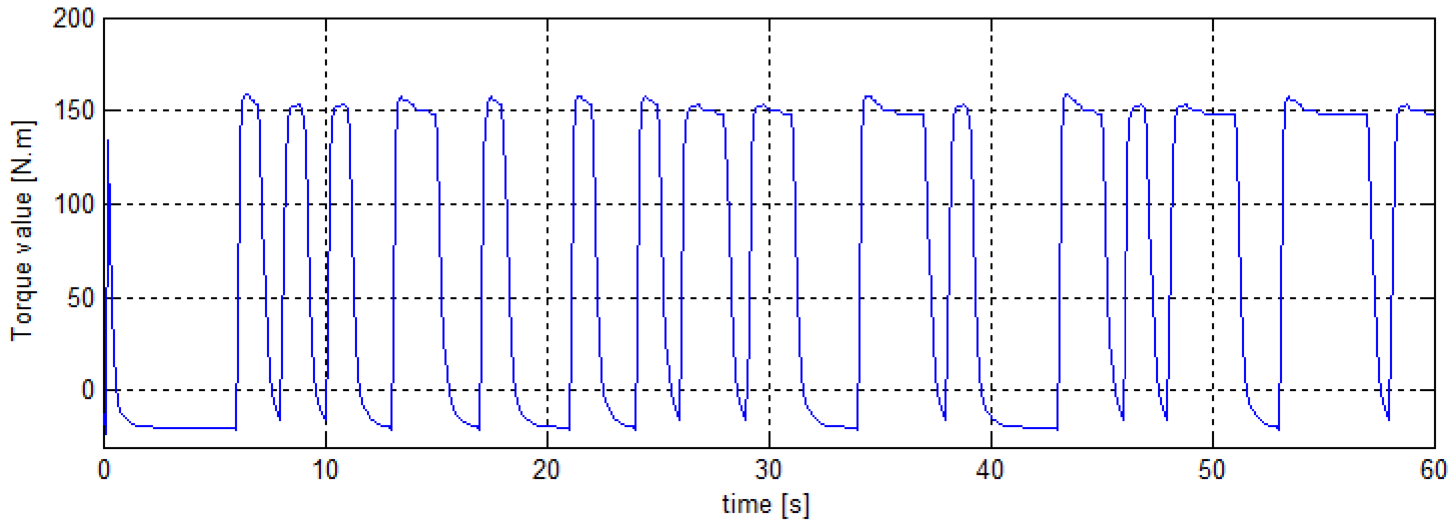
Scenario TWO: output





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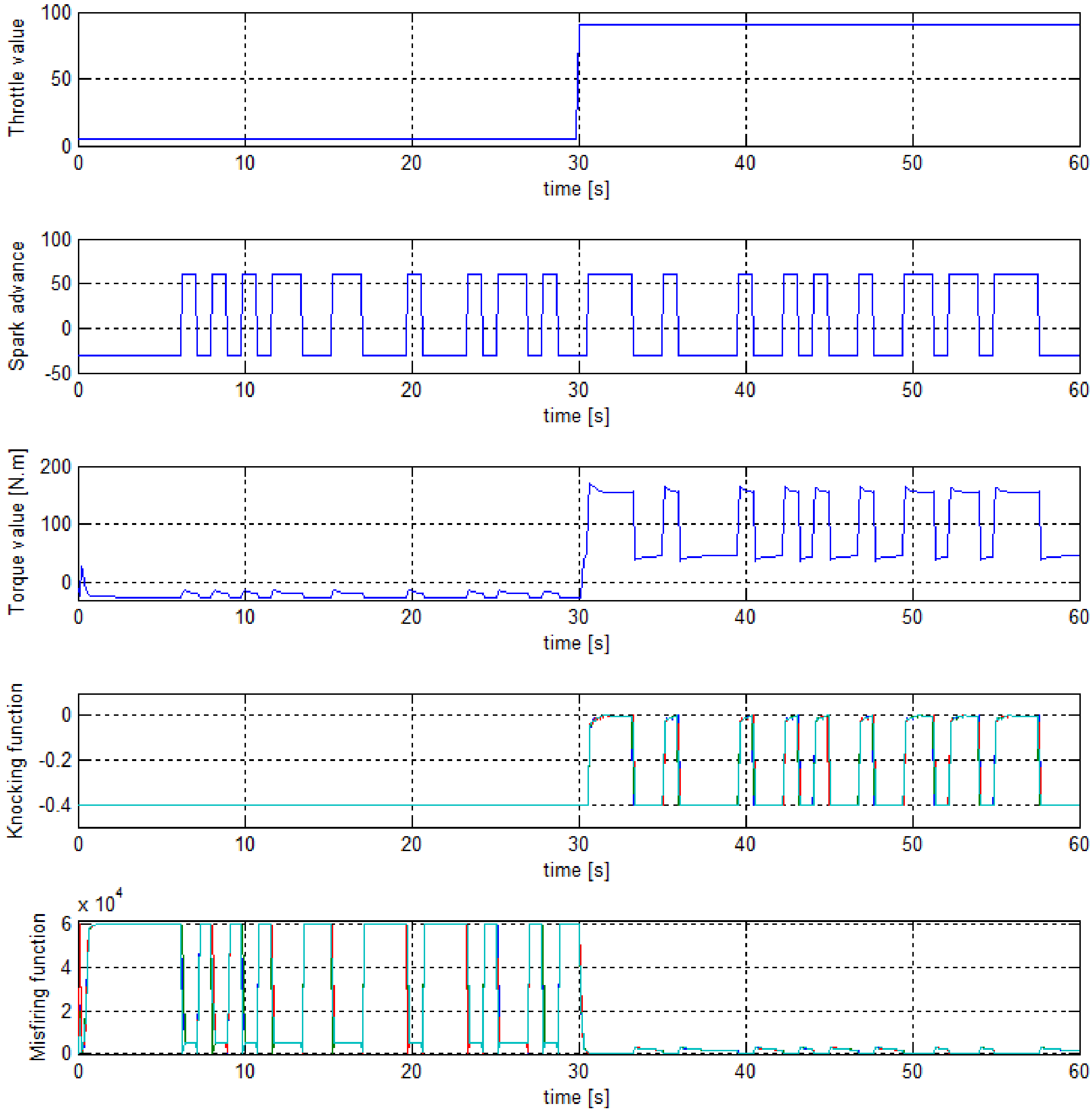
Scenario THREE: output



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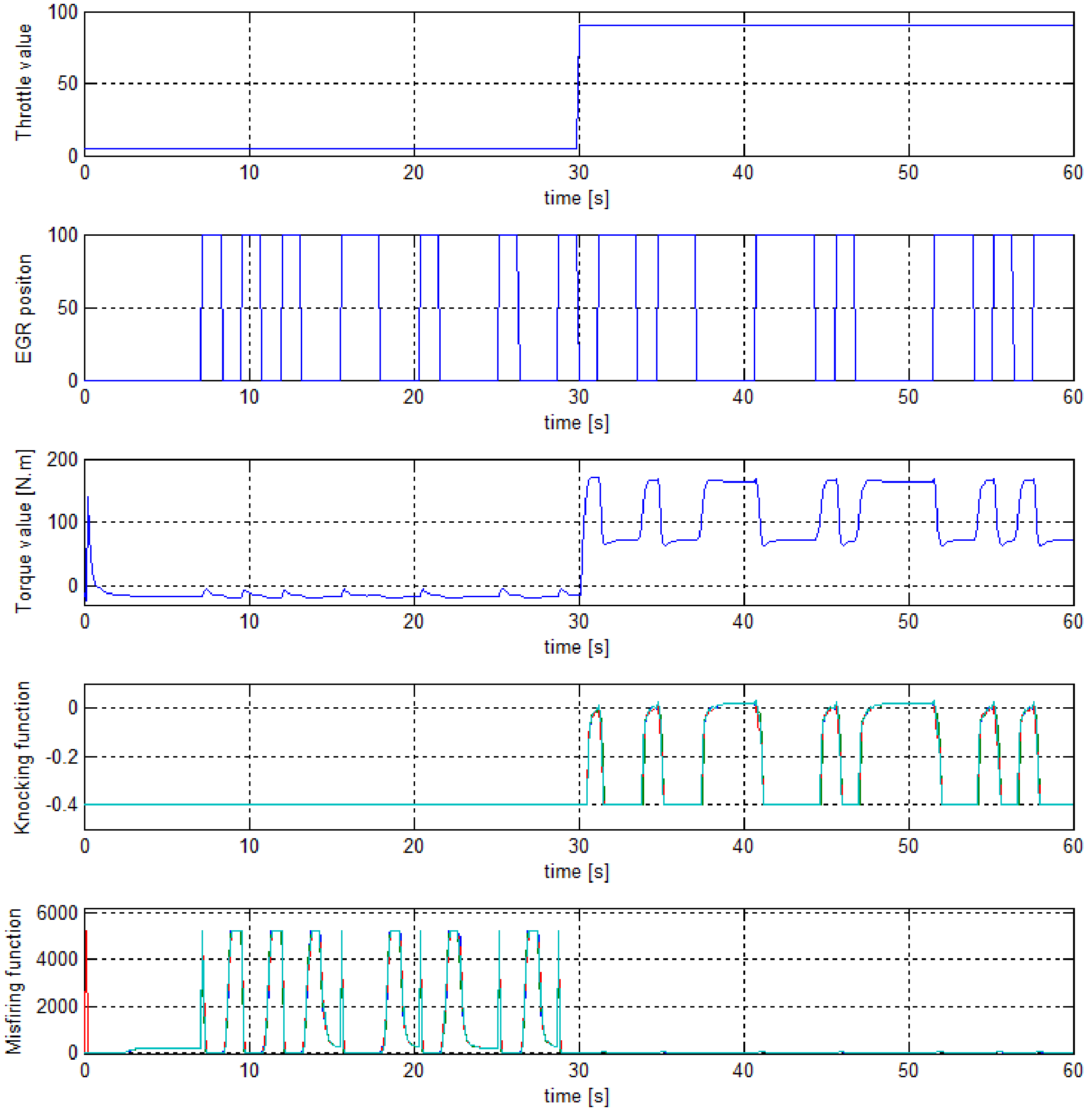
Scenario FOUR: output



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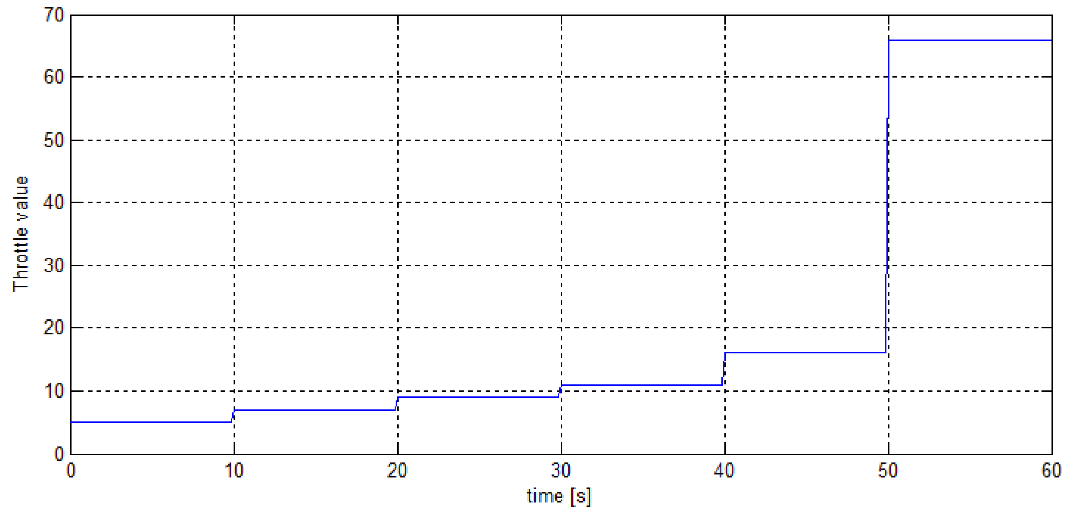
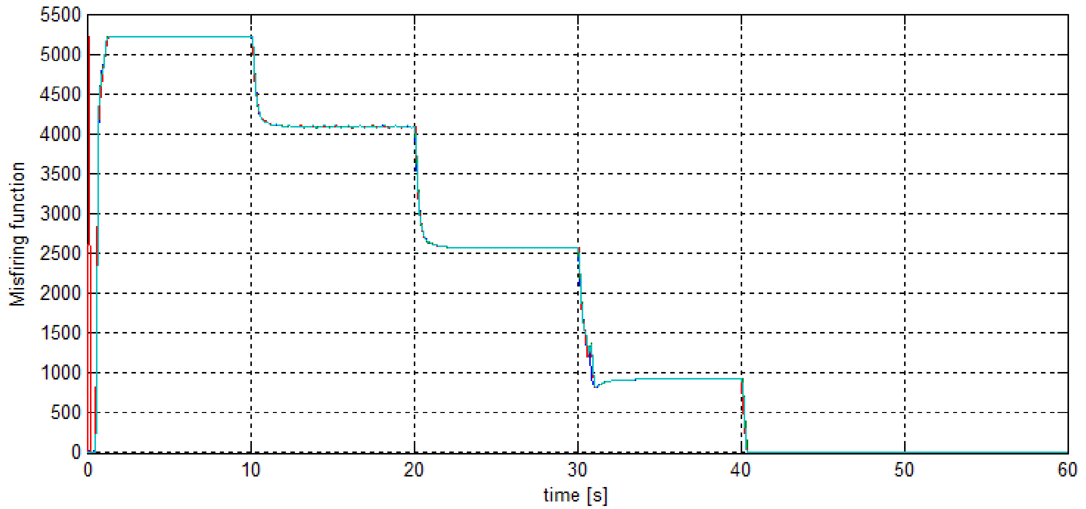
Scenario FIVE: output





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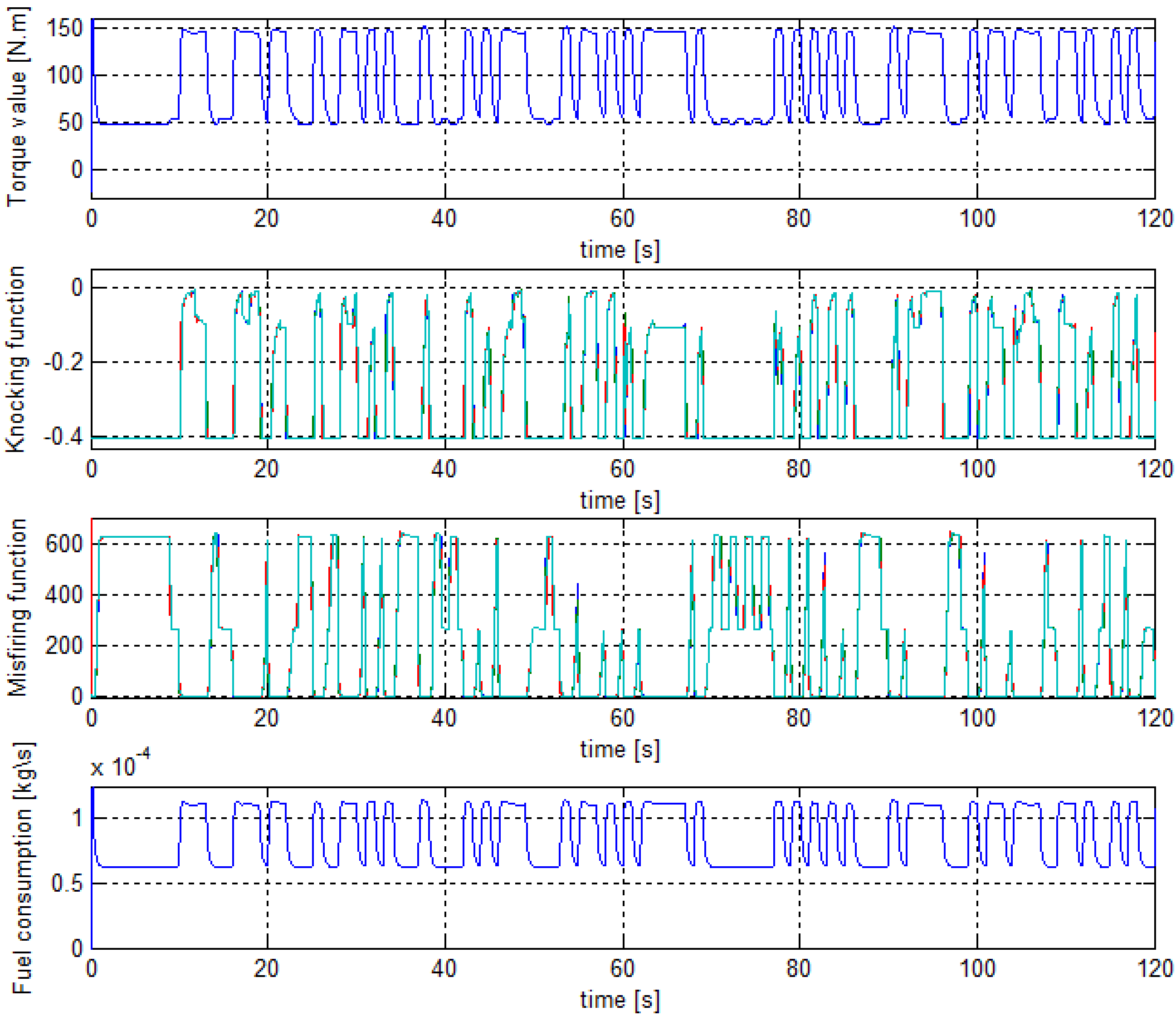
Identification Scenario: output



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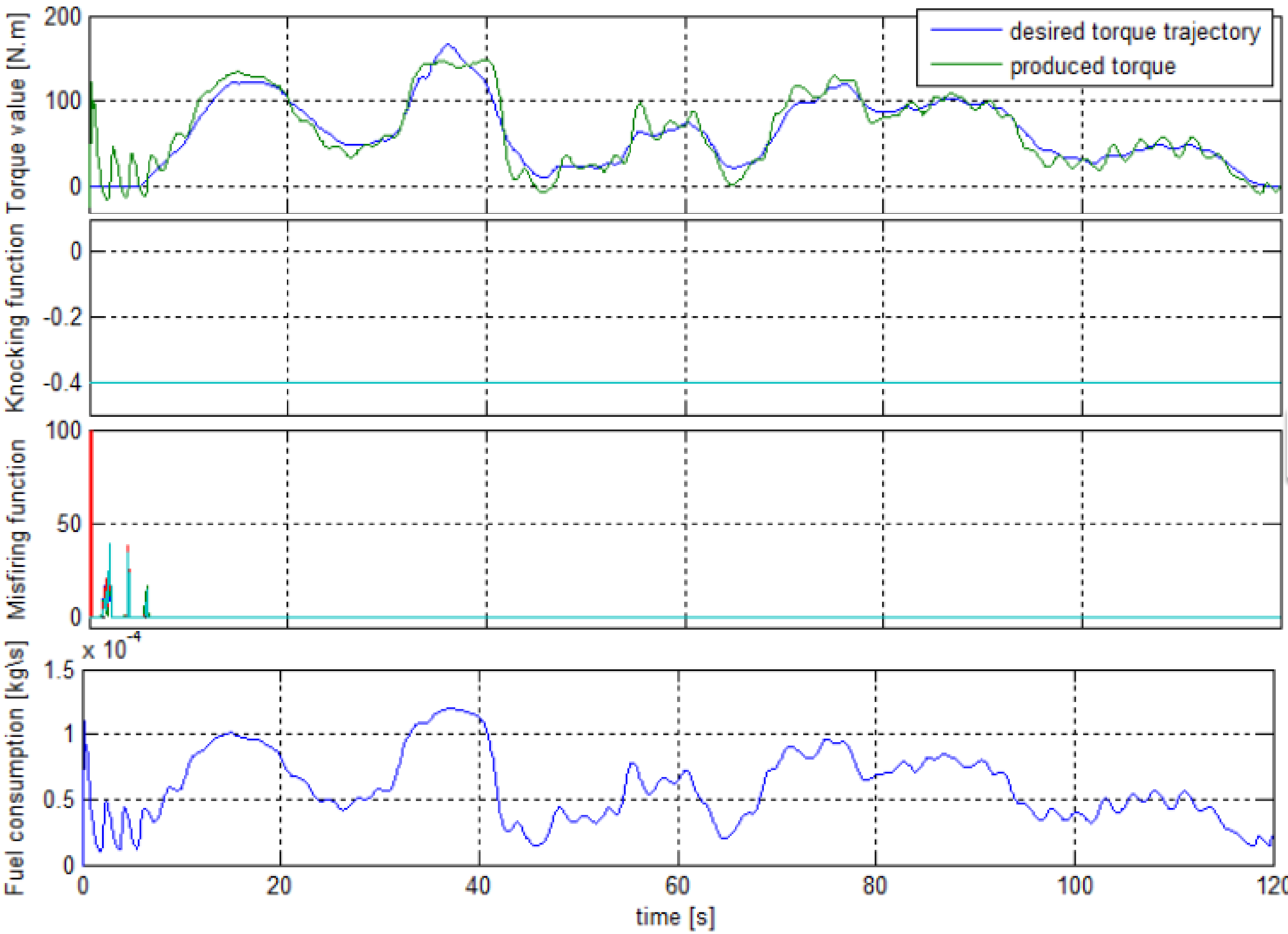
MPC$_{c1,basic}$ Scenario: output



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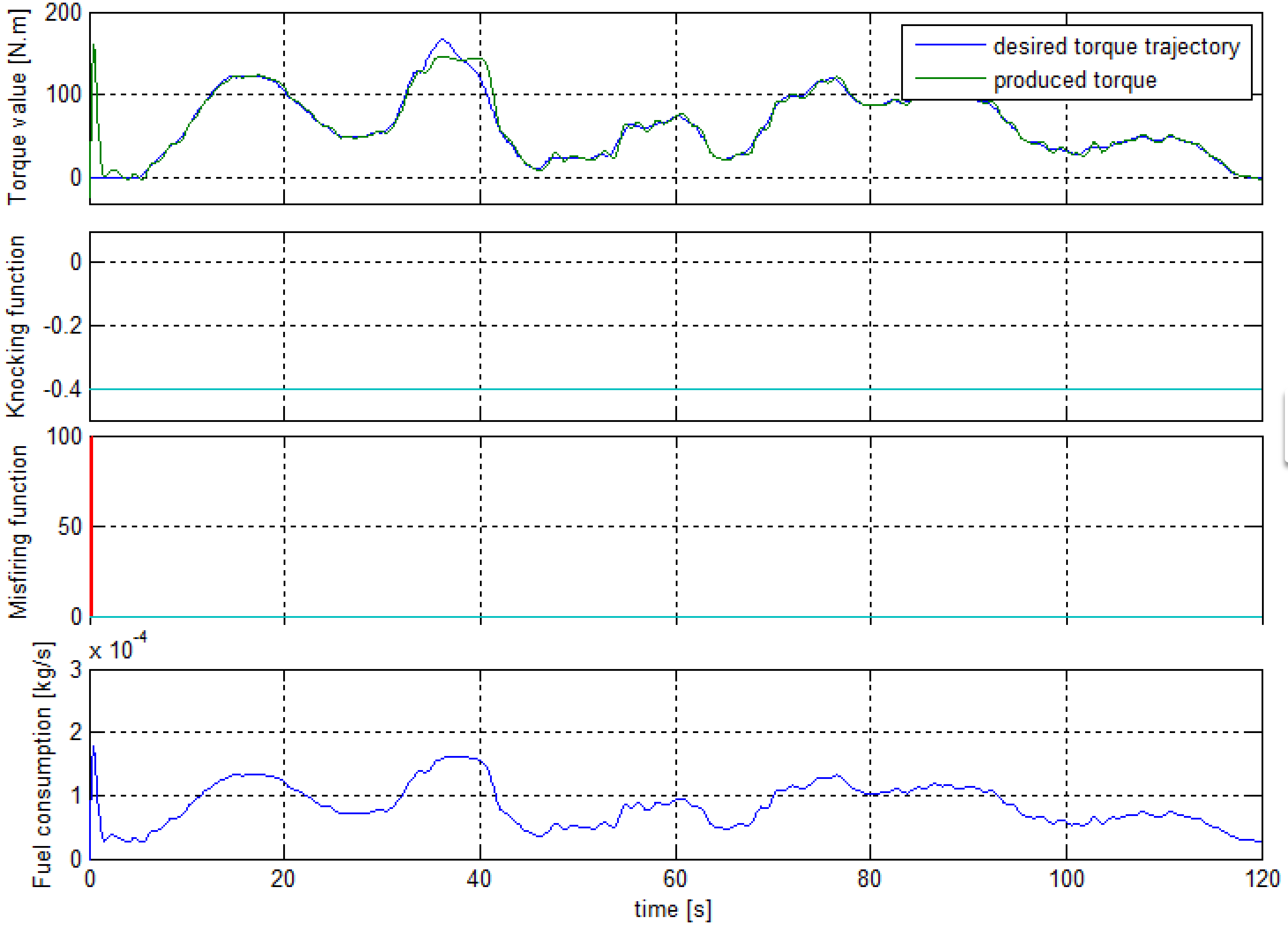
$MPC_{c1,advanced}$ Scenario: output



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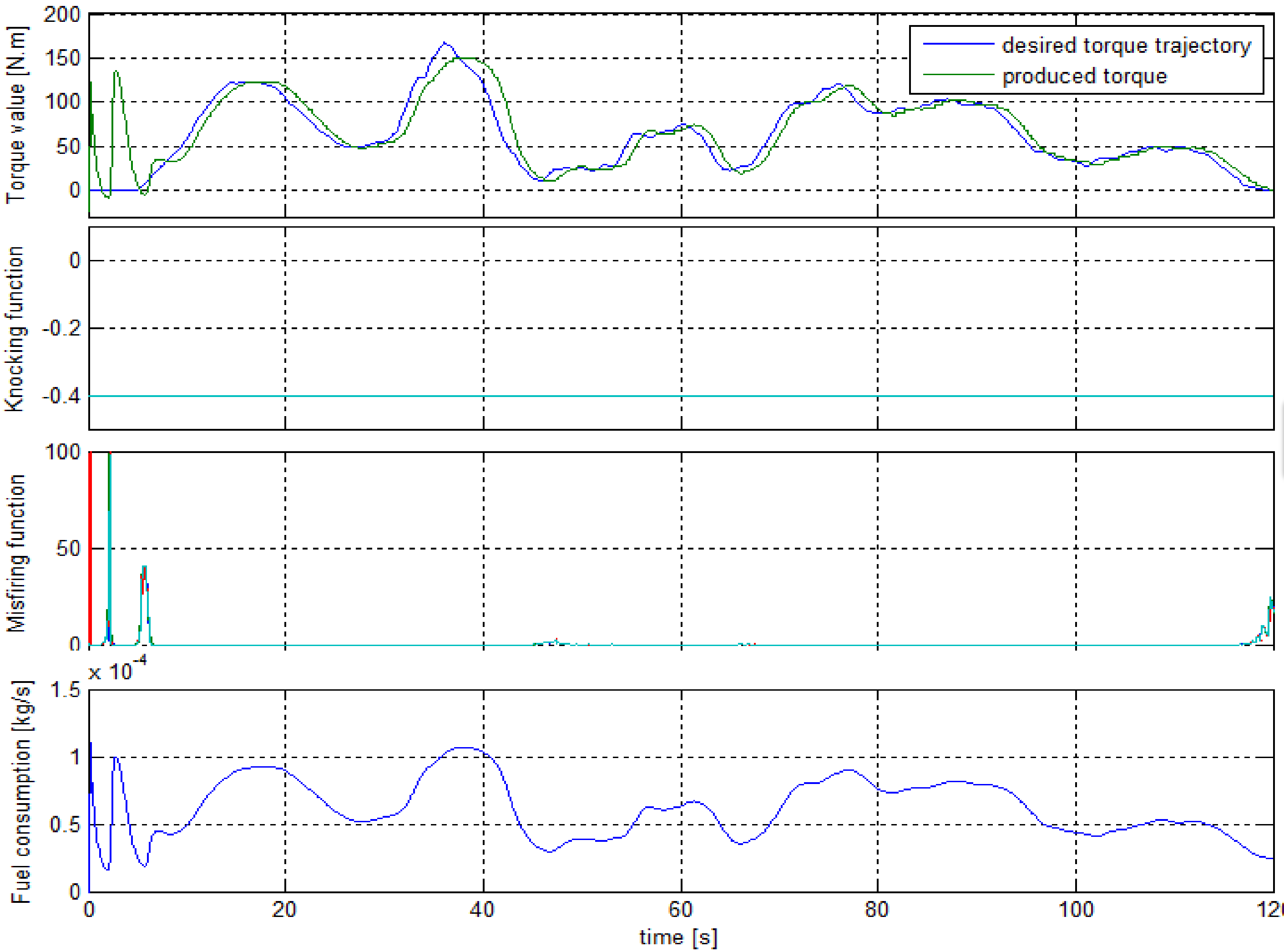
MPC$_{c2,advanced}$ Scenario: output



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MATLAB MPC Cost Function

$$\begin{aligned}
J(z_k) &= J_y(z_k) + J_u(z_k) + J_{\Delta u}(z_k) + J_\epsilon(z_k) \\
J_y(z_k) &= \Sigma_{j=1}^{n_y} \Sigma_{i=1}^{p} \left\{ \frac{w_{i,j}^y}{s_j^y} [r_j(k+i|k) - y_j(k+i|k)] \right\}^2 \\
J_u(z_k) &= \Sigma_{j=1}^{n_u} \Sigma_{i=0}^{p} \left\{ \frac{w_{i,j}^u}{s_j^u} [u_j(k+i|k) - u_{j,target}(k+i|k)] \right\}^2 \\
J_{\Delta u}(z_k) &= \Sigma_{j=1}^{n_u} \Sigma_{i=0}^{p-1} \left\{ \frac{w_{i,j}^{\Delta u}}{s_j^u} [u_j(k+i|k) - u_j(k+i-1|k)] \right\}^2 \\
J_\epsilon(z_k) &= \rho_\epsilon \epsilon_k^2
\end{aligned}$$

$$u = \begin{bmatrix} x_{th} & 0 & 0 \\ 0 & \varphi_{SA} & 0 \\ 0 & 0 & x_{EGR} \end{bmatrix}$$

$$\Delta u = \begin{bmatrix} \Delta x_{th} & 0 & 0 \\ 0 & \Delta\varphi_{SA} & 0 \\ 0 & 0 & \Delta x_{EGR} \end{bmatrix}$$

$$r = \begin{bmatrix} T_r & 0 & 0 & 0 \\ 0 & h_{K,r} & 0 & 0 \\ 0 & 0 & h_{M,r} & 0 \\ 0 & 0 & 0 & qf_r \end{bmatrix}$$

$$y = \begin{bmatrix} T & 0 & 0 & 0 \\ 0 & h_K & 0 & 0 \\ 0 & 0 & h_M & 0 \\ 0 & 0 & 0 & qf \end{bmatrix}$$