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CHAPTER 12

Stored Ammonia and a Sensor That Reads Both Ways in Diesel Urea Dosing

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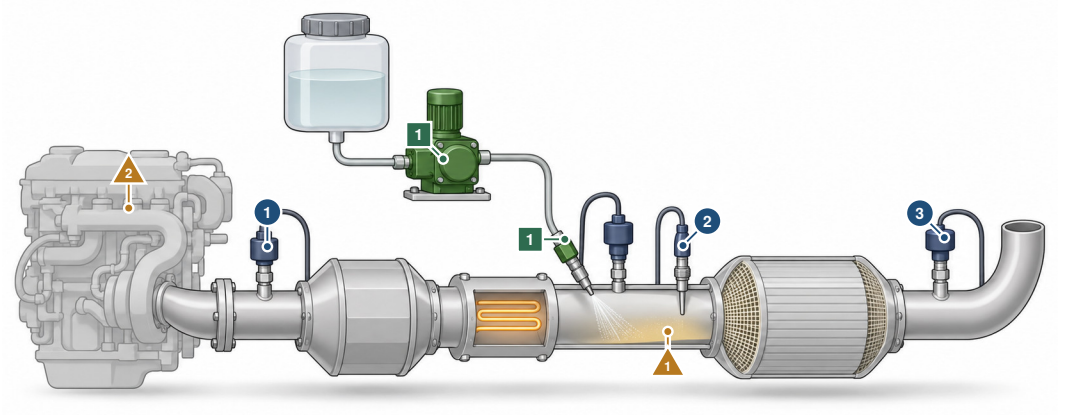
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CHAPTER 12

Stored Ammonia and a Sensor That Reads Both Ways in Diesel Urea Dosing



The controller moves 1 urea pump and injector

The controller reads 1 nitrogen oxides leaving the engine 2 gas temperature at the catalyst inlet 3 tailpipe sensor, which also counts ammonia

What disturbs it 1 urea deposits when the gas is too cool 2 engine load: exhaust flow, heat and nitrogen oxides

The ammonia stored in the catalyst brick sets the cleaning but has no instrument, so the controller must infer it from readings (1 to 3) while the tailpipe sensor (3) cannot tell nitrogen oxides from ammonia. Illustration, not to scale.

IN PLAIN TERMS Dosing a Catalyst That Hides What It Holds

The main idea. A diesel truck sprays urea in water into its hot exhaust, where it turns into ammonia. A catalyst then uses the ammonia to turn harmful nitrogen oxides into nitrogen. The catalyst soaks up the ammonia first, like a sponge holding water, and the amount it holds does the cleaning.

The challenge. No gauge reads that amount, and a hot catalyst holds less, so a climb can push the extra out. The one sensor at the tailpipe counts this ammonia as if it were nitrogen oxides. A high reading can mean too little urea or too much.

Why it matters. A controller that trusts that reading alone can keep adding urea while ammonia pours out.

THREE WAYS TO READ THIS CHAPTER

Explore	12 min	the first page, the fact on the limits (Section 12.1), the history at the end of Section 12.2, the try-it on the heat-up release and the try-it on the trim loop, the fact on the challenge (Section 12.5) and the key points
Study	50 min	the whole chapter with its three pause points and the twelve exercises at its end
Practice	20 min	the first page, the results (Section 12.5), Technology in Practice (Section 12.7), Limitations (Section 12.8) and the two open challenges

The control question An SCR catalyst converts nitrogen oxides with ammonia it has stored, a store that no instrument measures and whose capacity falls as the brick heats, while the tailpipe sensor reads ammonia as nitrogen oxides. How can a doser hold a cycle's NO_x limit under an ammonia cap when a high reading may mean too little urea or too much?

Learning objectives

- Relate the dose ratio to the stored ammonia and the conversion, and explain why the conversion takes minutes to follow a dose.
- Split a tailpipe sensor reading into its NO_x and ammonia parts, and locate the bottom of the sensor's V.
- Predict a heat-up release from the store and the capacity, and explain why a storage setpoint read at the inlet lowers it.
- Explain why a trim loop on the tailpipe sensor runs away past the bottom of the V, and how an observer's gradient settles the sign.
- Compare feedforward, trim, storage control and MPC on cycle NO_x, slip peak and DEF, and say what each verdict depends on.

Prerequisites Sections 1.4.6 and 1.4.7 (observers and bias updates), 1.6.2 (the trim and fill loops) and 1.6.4 (cases and the challenge), with 1.6.3 for case 9. Chapter 13 is the companion chapter on estimators.

The app https://apmonitor.com/apps/diesel-scr/

See also Volume 7, Chapter 4 for a loop whose process gain reverses at the peak of the plant's curve, Volume 7, Chapter 2 for Arrhenius kinetics that change a plant's character within a few kelvin, and Volume 7, Chapter 3 for a plant whose linearization moves with the operating point.

12.1 Introduction

Ten minutes of city crawl leave the catalyst of the simulated truck near 220 °C with 11.75 g of ammonia stored on it. At 10:00 the truck pulls onto a 2.5 % grade, the inlet thermocouple passes 350 °C 35 s later, and the heating brick can no longer hold what it stored. At 705 s the ammonia leaving the tailpipe peaks at 384.5 ppm while the nitrogen oxides there have fallen to 0.1 ppm. The tailpipe sensor reads 267.5 ppm, which a controller would read as a conversion of only 47.6 % and answer with more urea. The plant has too much ammonia and the measurement says it has too little.

Urea selective catalytic reduction (SCR) was proposed for automotive diesel engines from a technique long established on power plant stacks [1–3], and heavy-duty regulation has since tightened the nitrogen oxide (NO_x) limits again [4, 5]. The control problem it poses belongs to a wider class, in which a reactant held on a surface sets the conversion, the inventory is inferred rather than measured, and the capacity to hold it depends on the operating condition. The three-way catalyst of a gasoline engine, whose conversion depends on the air-to-fuel ratio, the exhaust velocity and the catalyst temperature, is the older automotive member of the class [6]. The SCR case adds a measurement whose sign is ambiguous, because the NO_x sensor at the tailpipe also responds to ammonia [3, 7].

+ DID YOU KNOW? A Limit Cut Again for 2027

From model year 2027 a heavy-duty compression-ignition engine may emit 35 mg of NO_x per horsepower-hour over the transient Federal Test Procedure and the Supplemental Emission Test, and 50 mg over the new Low Load Cycle [8]. The standard set in 2001 was 0.20 g/bhp–hr [9].

This chapter sets out to dislodge two beliefs. The first is that a dosing ratio is a conversion. In the model the conversion follows the stored ammonia, which takes 11.8 minutes to reach 94 % conversion after the dose is raised from 0.8 to 1.0 ammonia per NO_x on a steady highway. The second is that a high tailpipe reading calls for more urea. The sensor's reading against the dose is a V with its bottom near one ammonia per NO_x, and a feedback loop on it pushes the right way only on the left side. A block diagram with a gain and a lag shows neither the stored inventory nor the sign that changes with the state.

The published work treats these elements one at a time. Control-oriented models establish the storage state and its observability [10, 11], kinetic studies model the catalyst [12], and control studies compare open loop, sensor feedback and coverage control [3, 7, 13]. This chapter works with a browser model of a whole SCR line on a transient cycle, in which the true stored ammonia, the true tailpipe NO_x and ammonia and the sensor reading are logged side by side, and measures on it how a feedforward, a sensor trim and a storage controller on an observer meet a cycle limit with an ammonia cap. The sign ambiguity and its resolution by a model are documented in the literature [7, 14, 15], and the observer used here, a model copy corrected along the gradient of its own predicted reading, is a simple member of that family. The model has nineteen states, its ammonia, urea and NO_x ledgers close to round-off, and every parameter is stated so that it can be rebuilt.

Section 12.2 traces the technology from power plant stacks to trucks. Section 12.3 sets out the exhaust line: the engine maps, the urea and its decomposition floor, the three cells of stored ammonia and the tailpipe sensor that reads ammonia as NO_x. Section 12.4 describes the doser: the feedforward, the trim on the tailpipe sensor, the observer of the stored ammonia, the storage loop on its temperature schedule and the added predictive controller. Section 12.5 measures the nine cases and the graded cycle, Section 12.6 sorts the evidence behind the model, Section 12.7 sets the real sensors, dosing hardware and control units beside the model, Section 12.8 states the limitations, Section 12.9 draws the conclusions, and the exercises of Section 12.10 work through the cases.

12.2 From Power Plant Stacks to Truck Tailpipes

Selective reduction of nitric oxide by ammonia over a catalyst was first a technology for power plants [3], and the present status and perspectives of its catalysis were reviewed in 2001 [2]. A vehicle carries the reagent instead as an aqueous urea solution that decomposes in the hot exhaust, a route presented in 2000 as a promising technique to reduce NO_x from automotive diesel engines [1]. In 2006 a control study for a mobile heavy-duty application observed that SCR was well known for power plants and would soon be introduced on European heavy-duty diesels, and that the dynamic operation of a vehicle demanded advanced control [3]. By 2014 the automotive technology had an edited book of its own [16].

The catalysts moved toward copper zeolites. A kinetic model of ammonia SCR over Cu-ZSM-5 was published in 2008 [12], and a copper chabazite, Cu-SSZ-13, was reported in 2010 with excellent activity and selectivity for the reaction [17]. Such catalysts hold ammonia that leaves as they heat. On one commercial Cu-chabazite monolith the total uptake fell from 4.6 to 1.6 g/L as the adsorption temperature rose from 50 to 300 °C, with three desorption peaks centered near 147, 266 and 447 °C [18].

Control followed the stored state. A three-state lumped model of a urea SCR plant was analyzed for controllability and observability in 2006, with an observer for the gas-phase slip and a sliding-mode design [10]. The heavy-duty study of the same year combined a model-based feedforward with feedback on a NO_x sensor cross-sensitive to ammonia, possible only with a procedure that

separated the two signals [3]. A comparison published in 2007 found that open loop can reach high conversion with acceptable slip, that closed loop is needed for robustness to dosing error, aging and engine-out variation, and that an adaptive surface-coverage strategy outperformed sensor feedback with cross-sensitivity compensation over simulated test cycles [13]. Control-oriented models were developed and tested on a two-catalyst system in 2011 [11]. The ambiguity itself became a subject. A closed loop on the cross-sensitive sensor was shown to have spurious equilibria besides the point of interest, to which it nevertheless converges [7], a robust separation of the mixed signal's domain was published [14], and the cross-sensitivity factor itself was estimated by an observer [15].

The limits that frame the problem come from type approval. Euro VI, proposed for about 2013 to harmonize with US and Japanese rules [4], allows 460 mg/kWh of NO_x on the world-harmonized transient cycle (WHTC) of a compression-ignition engine and 10 ppm of ammonia [5]. Its implementing regulation takes the ammonia result as the average concentration over the cycle, weights the WHTC 0.14 cold and 0.86 hot, and sets a NO_x threshold of 1200 mg/kWh for on-board diagnostics (OBD) [19].

> ⧖ HISTORY **2001: A Regulator Doubts the Urea Tank**
>
> In January 2001 the United States Environmental Protection Agency set a heavy-duty standard of 0.20 g/bhp–hr of nitrogen oxides, phased in for diesel engines between 2007 and 2010. The rule noted that selective catalytic reduction was first developed for stationary applications, with a urea solution injected upstream of the catalyst and broken down into ammonia and carbon dioxide, and it did not base the new standard on that technology. Urea would have to be sold at the diesel fuel pump, and because an empty urea tank would not normally affect driveability, operators would have an incentive not to refill it. One commenter proposed a NO_x sensor that would detect the lost control and cut engine power gradually until half of it was gone [9].

12.3 The Exhaust Line as Modeled

The simulated line belongs to a loaded 30 t truck and runs from the turbine outlet to the tailpipe, drawn left to right as the application's Exhaust view draws it, in Figure 12.1(a). An oxidation catalyst heats or cools the gas without chemistry, an injector sprays diesel exhaust fluid (DEF, 32.5 % urea) at its outlet, a mixer leads to a 32 L SCR brick represented by three cells, an optional slip catalyst follows, and a zirconia NO_x sensor sits at the tailpipe. The engine-out NO_x sensor upstream sees no ammonia. The engine integrates in seconds with a step of $\Delta t = 50$ ms, the doser runs every 0.1 s and the log records every 0.5 s, the three clocks of Section 1.6.1.

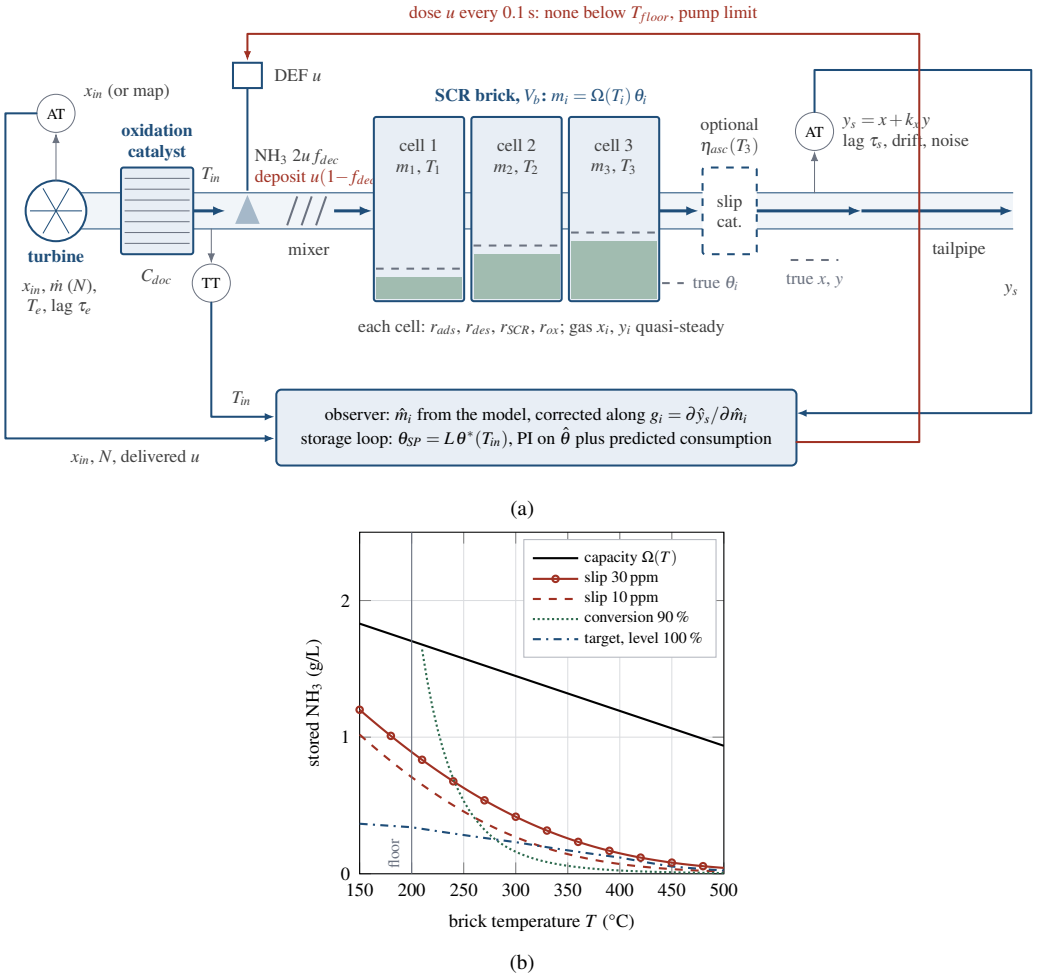
The variables are classified in Table 12.1. Nineteen states are integrated. Eight are physical, the turbine-out and oxidation-catalyst temperatures and the stored ammonia and temperature of each of the three cells. Eleven are ledgers of ammonia released, reacted, oxidized and slipped, NO_x in and out, tailpipe NO_x and ammonia, engine work, urea and deposit, which make every balance exact.

12.3.1 Engine Maps and the Drive Cycle

The engine is a map, not a combustion model. The road load of a cycle table of speed v and grade β gives the brake power, and three declared functions of power and speed give the exhaust, as shown in Equation (12.1).

$$\begin{aligned} P &= \frac{\left(m_v g(C_{rr}+\beta)+\tfrac{1}{2}\rho C_d A\, v^2 + m_v a\right) v}{\eta_d} + P_{acc} \\ \dot{m} &= 0.045 + 0.0055\, v + 0.00095\, P \\ T_{e,ss} &= 130 + 1.9\,P - 0.0022\,P^2, \qquad x_{in} = 120 + 1.6\,P \end{aligned} \tag{12.1}$$

where $\dot{m}$ is in kg/s, v in m/s, P in kW (capped at 340 kW), the temperature in °C and x_{in} in ppm. At a standstill the engine idles at P_{acc}, and a negative wheel power while rolling cuts the fuel, with $P = 0$, $x_{in} = 0$ and 100 °C at the turbine. The turbine-out temperature follows its map through a



(a)

(b)

Figure 12.1 The SCR line as modeled, and its operating window. (a) The engine maps give the engine-out NO_x x_{in}, the exhaust flow $\dot{m}$ (molar flow N) and the turbine-out temperature T_e. The oxidation catalyst (C_{doc}) sets the inlet temperature T_{in} read by the thermocouple TT. The dose u releases $2u\,f_{dec}(T_{in})$ of ammonia and leaves the rest as deposit. Each cell stores $m_i = \Omega(T_i)\theta_i$ at temperature T_i through four rates, the gas x_i, y_i passing in closed form. The tailpipe sensor AT reads $y_s = x + k_x y$ through a lag τ_s. The observer and storage loop read y_s, T_{in}, x_{in}, N and the delivered urea, and set u. Truth is dashed, the cells filled to the observer's estimate. (b) At the highway point (0.278 kg/s, 294 ppm), from the application's own cell model on a uniform brick: the capacity (solid), the stores at which the gas leaving the brick carries 10 (dashed) and 30 ppm (solid with circles) of ammonia, the store that converts 90 % (dotted), and the storage target at level 100 % (dash-dotted). Not to scale.

lag, $\tau_e\,\dot{T}_e = T_{e,ss} - T_e$ with $\tau_e = 4$ s. On the 85 km/h highway the engine gives 108.8 kW, 0.278 kg/s, 310.7 °C and 294.1 ppm, a gas hourly space velocity of about 24 000 h^{-1}. On the climb at 72 km/h it gives 244.0 kW, 0.387 kg/s, 462.6 °C and 510.4 ppm. The cycle is a synthetic table, not a regulatory cycle: eight stop-and-go blocks of 75 s, an on-ramp to 85 km/h, three minutes of flat highway, six minutes at 72 km/h on 2.5 %, 90 s of descent at -3 % with the fuel cut, and highway to a stop at 1800 s. Its engine-out NO_x is 4.39 g/kWh, counted as NO_2. A severity factor s scales the truck's mass by $1 + 0.35(s-1)$ and the climb's grade by s.

Table 12.1 Variables by Role, With Values at the Screenshot Instant (Case 4, $t = 705\,\mathrm{s}$)

Symbol	Role	705 s	Unit
x	CV, tailpipe NO_x (truth)	0.087	ppm
y	constraint, tailpipe ammonia slip (truth)	384.5	ppm
y_s	measured, tailpipe sensor	267.4	ppm
$\hat{\theta}$, θ_{SP}	CV of the storage loop, its setpoint	0.270, 0.046	—
u	MV, DEF dosing	2280	g/h
x_{in}	DV, measured engine-out NO_x	510.4	ppm
$\dot{m}$, P	DV, exhaust flow and brake power	0.387, 244.0	kg/s, kW
T_{in}	DV, inlet thermocouple	459.0	°C
m_i	states, stored ammonia (total)	8.91	g
θ_i	coverages $m_i/\Omega(T_i)$	0.12, 0.29, 0.35	—
T_i	states, cell temperatures	460, 447, 422	°C
—	DVs: severity, NO_x map bias, aging, sensor drift, noise, failure	—	—

12.3.2 Oxidation Catalyst, Urea and Deposits

The oxidation catalyst is one thermal node that sets the SCR inlet, and the urea gives two ammonia per molecule once it decomposes, as shown in Equation (12.2).

$$\begin{aligned} C_{doc}\,\dot{T}_{in} &= N c_p\,(T_e - T_{in}) \\ \dot{n}_{NH_3} &= 2\,u\,f_{dec}(T_{in}), \qquad \dot{D} = u\,\big(1 - f_{dec}(T_{in})\big) \\ f_{dec} &= \min\!\Big(1,\ \max\!\Big(0,\ \frac{T_{in} - 170\,^\circ\mathrm{C}}{50\,\mathrm{K}}\Big)\Big) \end{aligned} \tag{12.2}$$

where T_{in} is the true gas temperature at the mixer, $N = \dot{m}/M_{ex}$ is the molar exhaust flow, u the urea delivered in mol/s, and D the deposit index. The doser delivers nothing while the inlet thermocouple, a 2 s lag of T_{in}, reads below the floor $T_{floor} = 200\,^\circ$C, and at most 6000 g/h of DEF. One mole per second of urea is 665 280 g/h of DEF, so a dose ratio $\alpha = 1$ (one ammonia per engine-out NO_x) takes 945 g/h on the highway. A ramp from 180 to 250 °C, considered when the model was designed, left the passing controller depositing 15.6 g of urea per cycle at the same floor, against 2.95 g with the ramp used.

12.3.3 Three Cells of Stored Ammonia

The state of each cell is the stored amount per catalyst volume, m_i in mol/m^3, rather than its coverage. A rise in temperature that lowers the capacity then raises the coverage and pushes ammonia out through desorption, instead of making it vanish from the balance. The capacity and the four rates are shown in Equation (12.3).

$$\begin{aligned} \Omega(T) &= A\,\Omega_0\,\max\!\big(0.02,\ 1 - a(T - T_0)\big), \qquad \theta = m/\Omega \\ r_{ads} &= k_a\,C_{NH_3}\,(1-\theta)^{+}\,\Omega \\ r_{des} &= k_d\,\mathrm{e}^{-E_d(1-\alpha_T\theta)/RT}\,\theta\,\Omega \\ r_{SCR} &= A\,k_s\,\mathrm{e}^{-E_s/RT}\,C_{NO}\,\theta \\ r_{ox} &= k_o\,\mathrm{e}^{-E_o/RT}\,\theta\,\Omega \\ \frac{\mathrm{d}m_i}{\mathrm{d}t} &= r_{ads} - r_{des} - r_{SCR} - r_{ox} \end{aligned} \tag{12.3}$$

where C are gas concentrations in mol/m^3, $A = 1$ for a fresh brick and 0.7 for an aged one, and every rate is in mol/(m^3 s) of catalyst. The rates are adsorption on free sites, a Temkin desorption that weakens with coverage, standard SCR ($4\,NH_3 + 4\,NO + O_2$) by NO reacting with stored ammonia, and oxidation of stored ammonia to nitrogen, a lumped coverage description of the kind reduced for control in the cited studies [7, 10].

The gas crosses a 10.7 L cell in 23 ms on the highway and 13 ms on the climb, below the step, so each cell's gas balances are quasi-steady. Both are linear in the outlet at a given coverage and are solved exactly, as shown in Equation (12.4).

$$\begin{aligned} x_i &= \frac{x_{i-1}}{1 + V_c A k_s \mathrm{e}^{-E_s/RT_i}\, \theta_i\, P_{ex}/(RT_i N)} \\ y_i &= \frac{N y_{i-1} + V_c\, r_{des,i}}{N + V_c\, k_a (P_{ex}/RT_i)(1-\theta_i)^{+}\, \Omega_i} \end{aligned} \tag{12.4}$$

where x_i and y_i are the NO and ammonia mole fractions leaving cell i, $x_0 = x_{in}$, $y_0 = \dot{n}_{NH_3}/N$, $V_c = V_b/3$ and $P_{ex} = 101\,325$ Pa. Each cell's ammonia then closes by construction, $N(y_{i-1} - y_i) = V_c(\dot{m}_i + r_{SCR} + r_{ox})$. The cell temperatures follow the gas and the heats of reaction, as shown in Equation (12.5).

$$C_c \frac{\mathrm{d}T_i}{\mathrm{d}t} = N c_p\,(T_{i-1} - T_i) - V_c\left(\Delta H_{SCR}\, r_{SCR} + \Delta H_{ox}\, r_{ox}\right) \tag{12.5}$$

with $C_c = (\rho c)_b V_b/3$, $T_0 = T_{in}$, $\Delta H_{SCR} = -407$ kJ and $\Delta H_{ox} = -317$ kJ per mole of ammonia. No heat is lost to the surroundings. Figure 12.1(b) shows the consequence at the highway flow for a brick of uniform temperature and store. Below about 210 °C no store converts 90 %, and only above 260 °C does a store that converts 90 % leave less than 10 ppm of ammonia in the gas. The window opens as the brick heats, but the capacity that a cool brick filled shrinks at the same time.

12.3.4 Slip Catalyst and Instruments

The optional slip catalyst oxidizes a share η_{asc} of the ammonia leaving the brick, zero below 200 °C and rising linearly to 0.9 at 275 °C of the last cell, and turns 15 % of what it oxidizes into NO. The tailpipe sensor reads NO_x and a share of the ammonia, as shown in Equation (12.6).

$$\tau_s\, \dot{y}_s = x_{tail} + k_x\, y_{tail} + \delta + n(t) - y_s \tag{12.6}$$

where $k_x = 0.7$ is a teaching value (a published control study used 0.8 for a commercial sensor [7]), $\tau_s = 1.5$ s, δ is a drift and n is colored noise of 1 ppm with a 0.5 s correlation time, drawn from the case's seed. The lag is applied in exact zero-order-hold form at each step. The engine-out sensor has the same lag and no noise, and when it fails the controller receives the engine's NO_x map at the measured power instead. The inlet and outlet thermocouples have a 2 s lag. The exhaust flow and the delivered urea are passed to the controller as the engine control unit knows them. The scorecard counts tailpipe NO_x as NO_2 over the engine's positive work, both from the truth and from the sensor's own reading, and the slip peak and time average from the truth.

12.3.5 Parameters, Initialization and Numerics

Table 12.2 lists the parameters. The kinetic constants are teaching values fitted to two declared targets: a storage curve holding 1.09 g/L at 200 °C and 0.28 g/L at 400 °C with 100 ppm of ammonia in the gas, and 97.1 % conversion lined out at $\alpha = 1$ on the highway. The curve is compared with a measured one in Table 12.3, as a comparison rather than a validation. At 500 ppm it holds 1.60, 1.34 and 0.86 g/L at 150, 200 and 300 °C. The measured total uptake on one commercial Cu-chabazite monolith falls to 1.6 g/L at 300 °C [18], and values read from that source's figure place the declared curve at 0.61 to 0.79 of the total uptake and 0.94 to 1.22 of the strongly bound part. From 200 to 300 °C the curve falls to 0.64 of its value, faster than the total uptake (0.82 with water in the feed) and slower than the strongly bound part (0.50), so the heat-up release it predicts is likely generous.

Each case starts at its own declared condition. The warm cases start the line at 220 °C with a fifth of the capacity stored, the cold start at 40 °C with none, and the highway cases lined out at a stated dose ratio, where a bisection on each cell's storage rate gives the steady store and temperature cell by cell from the inlet, with derivatives below 10^{-6}. The observer starts from the true store unless a case says otherwise. The integrator is the framework's classical fourth-order Runge-Kutta method

Table 12.2 Parameters. A: Adjustable in the Model Dialog or the Advanced Controls. F: Fitted Teaching Value

Symbol	Meaning	Value	
m_v, C_dA, C_{rr}	truck mass, drag area, rolling resistance	30 t, 6 m^2, 0.0065	—
η_d, P_{acc}	driveline efficiency, accessories	0.90, 6 kW	—
τ_e, C_{doc}	turbine-out lag, oxidation catalyst	4 s, 10 kJ/K	A
V_b, $(\rho c)_b$	brick volume, heat capacity	32 L, 0.6 MJ/(m^3 K)	A
c_p, M_{ex}	exhaust heat capacity, molar mass	31.5 J/(mol K), 28.8 g/mol	—
Ω_0, T_0, a	sites at T_0, reference, capacity slope	100 mol/m^3, 200 °C, 0.0015 K^{-1}	A, F
k_a	adsorption	5.0 m^3/(mol s)	F
k_d, E_d, α_T	desorption, Temkin	330 s^{-1}, 57.7 kJ/mol, 0.42	F
k_s, E_s	standard SCR	1.3×10^8 s^{-1}, 60 kJ/mol	F
k_o, E_o	ammonia oxidation	2.4×10^7 s^{-1}, 130 kJ/mol	F
ΔH_{SCR}, ΔH_{ox}	reaction heats per mol NH_3	−407, −317 kJ	—
f_{dec}	decomposition ramp	170 to 220 °C	F
T_{floor}, u_{max}	dosing floor, pump	200 °C, 6000 g/h	A, —
k_x, τ_s	cross-sensitivity, sensor lag	0.7, 1.5 s	A
σ_n	sensor noise	1 ppm	A
—	thermocouple lag	2 s	—
η_{asc}	slip catalyst, share to NO	0.9 above 275 °C, 0.15	on/off
A	aging factor (sites, activity)	1 or 0.7	on/off

Table 12.3 The Declared Storage Curve Against a Measured Cu-Chabazite Monolith [18], in g/L

T (°C)	Ω	100 ppm	500 ppm	total, wet[a]	strong[a]
150	1.83	1.39	1.60	2.5	1.7
200	1.70	1.09	1.34	1.7	1.4
300	1.45	0.60	0.86	1.4	0.7
400	1.19	0.28	0.49	—	—

[a] Measured at 500 ppm, read from the source's figure, so approximate. The source's text gives a dry total of 1.6 g/L at 300 °C.

(Section 1.6.1). Halving the step moves the cycle's NO_x by 0.15 % as shipped, 0.07 % under the suggested control and 0.06 % under the feedforward, and moves no verdict. The 1800 s cycle takes 154 ms without a browser, in Node on the build machine, and about 9 s of real time in a browser run 200 times faster than the plant.

12.3.6 Assumptions

The engine and the cycle are declared maps and a synthetic table, so nothing here is a regulatory cycle or an engine's data. Only standard SCR is modeled. The oxidation catalyst makes no NO_2, so the fast SCR reaction, nitrate chemistry and N_2O are absent, which overstates the low-temperature penalty a real system pays. The gas is quasi-steady and the brick is three stirred cells. The three cells are part of the fitted model, not a grid refined to convergence, because the storage curve and k_s were fitted with three, and Section 12.5.9 shows that the challenge verdict depends on that choice. The urea decomposes at the mixer with no droplet evaporation time or wall film, and deposits never decompose again. No heat is lost and no particulate filter sits upstream, so every heat-up reaches the brick faster than it would on a truck with a filter. The cross-sensitivity is a constant. Aging removes 30 % of storage and reaction sites together and nothing else. The 0.46 g/kWh limit, the 10 and 30 ppm ammonia caps and the 0.55 g/kWh OBD threshold are teaching values, discussed with their sources in Section 12.5.

12.4 The Doser as Implemented

Every strategy computes an ammonia request every 0.1 s from one packet of measurements, the engine-out NO_x (or the map), the tailpipe sensor, the inlet thermocouple, the molar flow and the urea delivered at the previous call, and a test in the application fails if the controller or the observer reads any truth field. The request in g/h of DEF then passes the floor (zero while $T_{in} < T_{floor}$) and

the pump's maximum. In Manual the reader sets the DEF rate directly. The feedforward doses $\dot{n}_{NH_3} = \alpha\, x_{in} N$ with $\alpha = 1$ as shipped, where α is the dose ratio.

12.4.1 The Trim on the Tailpipe Sensor

The trim multiplies the feedforward by $1 + u_{trim}$, where u_{trim} is the output of the shared velocity-form PID of Section 1.6.2 on the conversion the sensor implies, as shown in Equation (12.7).

$$\begin{aligned} \eta_s &= 1 - y_s / x_{in}, \qquad & e_k &= \eta_{SP} - \eta_{s,k} \\ P_k &= K_{c,t}\, e_k, & s_k &= s_{k-1} + P_k - P_{k-1} \\ \hat{u}_k &= s_k + I_{k-1}, & u_{trim,k} &= \min\!\big(1,\ \max(-0.5,\ \hat{u}_k)\big) \\ I_k &= I_{k-1} + \Big[\frac{K_{c,t}}{\tau_{I,t}} e_k + \frac{u_{trim,k} - \hat{u}_k}{\tau_{I,t}}\Big]\Delta t_c \end{aligned} \tag{12.7}$$

with $\eta_{SP} = 95\,\%$, $K_{c,t} = 0.5$, $\tau_{I,t} = 30\,\mathrm{s}$, no derivative and $\Delta t_c = 0.1\,\mathrm{s}$. In the symbols of Equations (1.16) to (1.18), s_k is S_k and $\hat{u}_k$ is v_k, and the tracking time is $\tau_{I,t}$. When the pump saturates, the back-calculation drives the integral toward the trim that the applied dose implies. The trim holds by tracking while the floor shuts the doser or the measured engine-out NO_x is below 20 ppm, where no conversion is defined. A low apparent conversion raises the dose, a correct move on an underdosed brick and a wrong one past the bottom of the V. The process gain of the loop changes sign at that bottom, as the gain of a braking wheel does at the friction peak in Volume 7, Chapter 4.

12.4.2 The Stored-Ammonia Observer

The observer runs a copy of the three cells of Equations (12.3) to (12.5) on the measured inputs, with the cell temperatures driven by the inlet thermocouple, and corrects each cell's store along the gradient of its own predicted sensor reading, as shown in Equation (12.8).

$$\begin{aligned} \hat{y}_{s,raw} &= \big(\hat{x}_3 + \hat{k}_x \hat{y}_3\big)10^6, \qquad & \tau_s\, \dot{\hat{y}}_s &= \hat{y}_{s,raw} - \hat{y}_s \\ g_i &= \partial \hat{y}_{s,raw} / \partial \hat{m}_i \\ \dot{\hat{m}}_i &= f_i(\hat{m}, \hat{T}) + \frac{1}{\tau_o} \frac{g_i\,(y_s - \hat{y}_s)}{\sum_j g_j^2 + g_0^2} \end{aligned} \tag{12.8}$$

where f_i is the model's storage rate, $\hat{k}_x = 0.7$ is the datasheet value the observer assumes, $\tau_o = 20\,\mathrm{s}$, $g_0 = 0.5\,\mathrm{ppm\,m^3/mol}$, and the gradient is a forward difference of $\max(0.05,\ 0.02\hat{m}_i)$. The observer integrates in two explicit substeps per control period and clips each store at zero. Its capacity assumption κ multiplies Ω_0, with $\kappa = 1$ the right value. The sign of g_i is the model's answer to the ambiguity. Where a larger store would lower the predicted reading (NO_x coming through) g_i is negative, where it would raise it (slip) g_i is positive, and near the bottom of the V both terms cancel and the observer runs on its model alone. In the terms of Section 1.4.6, the stores are observable through the sensor only where its sensitivity to them is not zero. The correction is a fixed-gain relative of the extended Kalman filter of Section 1.4.7, which Chapter 13 runs in full on a vehicle whose position no instrument aboard measures.

12.4.3 Storage Control on a Schedule

The storage loop holds the observer's coverage $\hat{\theta} = \sum \hat{m}_i V_c / \sum \hat{\Omega}_i V_c$ on a setpoint scheduled on temperature, and adds the ammonia the model predicts the reactions consume, as shown in Equation (12.9).

$$\begin{aligned} \theta_{SP} &= \min\!\big(0.95,\ L\,\theta^*(T_s)\big) \\ \dot{n}_{NH_3} &= \underbrace{\hat{r}_{SCR} + \hat{r}_{ox}}_{\text{consumption}} + \hat{C}\,\mathrm{PI}_s(\theta_{SP} - \hat{\theta}) \end{aligned} \tag{12.9}$$

where θ^* is linear between 0.20, 0.16, 0.10, 0.05 and 0.025 of the capacity at 200, 300, 400, 450 and 500 °C, T_s is the inlet thermocouple (or, as an option, the observer's brick temperature), L is the storage level, and $\hat{C}$ is the observer's capacity in moles, so the fill loop's output is a share of the capacity per second. The fill loop is the same shared PI with gain $K_{c,s}/60$ for $K_{c,s} = 4\,\mathrm{min}^{-1}$ and $\tau_{I,s} = 60\,\mathrm{s}$, its limits set every call so that the total request stays between zero and the pump's maximum. In the classical strategies, every loop that is not in charge tracks the dose actually applied, so a change of mode or strategy is bumpless (Section 1.6.2).

The schedule is high when the brick is cool, for conversion, and low when it is hot, to leave room for a heat-up release. Reading it at the inlet lowers the setpoint as soon as a climb heats the gas. In case 4 the inlet thermocouple reaches 350 °C at 635.4 s, the brick's mean at 660.8 s and its last cell at 676.6 s.

🕮 **Pause.** Try Exercise 12.2 before reading on.

12.4.4 Model Predictive Control

The option and its general form are described in Section 1.6.3. At a fixed store of 10 mol/m^3 the ammonia in equilibrium with the surface rises from 0.225 to 96.6 ppm between 200 and 450 °C, about 430-fold, so one fixed linear storage model misplaces the slip cap across the cycle. The binding constraint is a release from storage already present when the climb begins, which the scheduled loop meets in the original comparison. The resulting feedback policy depends nonlinearly on the state even though each optimization uses a linear model. The added MPC therefore linearizes Equations (12.3) and (12.4) at each decision rather than using one linear model throughout the cycle [20]. Fresh kinetics, 32 L volume and 0.6 MJ/(m^3 K) heat capacity are frozen at their declared values. A separate instance of Equation (12.8) propagates in every mode from the existing instrument packet and applied dose. It receives the same declared opening prior as Storage, which may match the initial true store. Known service loading updates its nominal prior using its own capacity, without copying the post-event plant store. No storage instrument is added.

The linear representation has eight states, three stores $\hat{m}_i/100$, the previous dose, a constant and three affine output offsets. Central differences of 0.01 mol/m^3 and 0.001 kg/h give the chemical and dose Jacobians. Exact zero-order hold gives a 1 s discrete model. An independent Taylor-exponential calculation differs by at most 5.72×10^{-9} at 200, 300 and 450 °C. The largest tested one-step local output residual is 0.001679 in scaled units. This does not validate a 60 s forecast. The current Jacobians remain fixed over the horizon, with affine offsets for forecast flow, inlet NOx and temperature. The observer includes reaction heat, while the future thermal transport forecast omits it.

The normalized outputs are $z = (\hat{\theta}_f, x/100, y/30)$, with x, y in ppm and $\hat{\theta}_f$ estimated moles divided by fresh nominal capacity. The observer's κ fraction is a separate diagnostic. A residual bias b supplies offset correction [21],

$$b^+ = \mathrm{clip}_{[-100,100]}\left[b + (1 - \mathrm{e}^{-\Delta t_c/30})(y_s - \hat{y}_s - b)\right]. \tag{12.10}$$

Here b is in ppm and adds to predicted NOx. The update has the form of the bias filter of Equation (1.12) with a fixed weight. It cannot separate NOx, ammonia and sensor drift uniquely, as two constant errors seen through one measurement never can (Section 1.4.6). No Kalman gain is used, whereas Volume 9, Chapter 4 carries its unmeasured fuel bias as a state of a Kalman estimator.

The MPC decides every 1 s, holds its first move between decisions and plans 60 samples with the move-block lengths $[1,1,2,3,4,6,8,10,12,13]$ in seconds. For dose v in kg/h, target $r = (\theta_{SP}, 0, 0)$ and nonnegative horizon-wide slacks $s = (s_\theta, s_x, s_y)$, its quadratic objective is

$$\begin{aligned} J = \sum_{k=1}^{60} \left[400(z_{1,k} - r_{1,k})^2 + 2z_{2,k}^2 + 0.01 v_k^2\right] \\ + 0.15 \sum_{j=1}^{10} (\Delta v_j)^2 + 10^4 s_\theta^2 + 20 s_x^2 + 10^3 s_y^2. \end{aligned} \tag{12.11}$$

Table 12.4 The Cases and the Challenge

#	Setting	Teaching point
1	Highway, Manual, lined out at $\alpha = 0.8$	conversion against dose
2	Highway, Manual, lined out at $\alpha = 1.3$	the ambiguous sensor
3	Highway, $\alpha = 1.1$; dosing stops at 120 s	the stored buffer
4	Warm crawl, climb at 600 s; feedforward	the heat-up release
5	Cold start at 40 °C, urban crawl	the floor and deposits
6	Cycle to 15:00, storage control	storage against feedforward
7	Cycle, aged brick, storage control	aging, OBD, infeasibility
8	Highway, lined out at $\alpha = 1.3$, trim	a loop that runs away
9	Full cycle, MPC or Storage, preview Off	constrained dosing and forecast error
ch	Full cycle from 220 °C, trim as shipped	the whole problem

There is zero direct slip tracking weight and no terminal multiplier. Hard constraints impose $0 \le v_k \le 6$, $|\Delta v_j| \le 1.5$ between blocks, nonnegative predicted stores, NOx and slip, and zero dose throughout a block containing any forecast inlet below the selected floor. The first difference uses the applied dose. The measured floor remains a hard actuation backstop. The soft bands are

$$\begin{aligned} \max(0, \theta_{SP,k} - .04) - s_\theta &\le z_{1,k}, \\ z_{1,k} &\le \theta_{SP,k} + .04 + s_\theta, \\ z_{2,k} &\le \frac{.46 \max(0, P_k) 10^6}{3600(46.0055) \max(.1, N_k) 100} + s_x, \\ z_{3,k} &\le 1 + s_y. \end{aligned} \tag{12.12}$$

The NOx ceiling is an instantaneous power-based equivalent of 0.46 g/kWh, not a cycle-integral guarantee. Each output uses one slack for all 60 samples. The shared solver's plans are accepted only when they also satisfy every hard bound over the whole horizon (Section 1.6.3). A rejected first scan holds the previous applied dose, then the tracked Storage loop acts until a valid plan returns. Cold priming solves in the zero-dose box before reporting floor protection. Trim tracking inverts applied dose divided by feedforward only when the latter is nonzero. Its zero-feedforward stand-in cannot represent a positive dose. Storage inversion requires positive estimated capacity, and Manual follows the requested station separately.

The inlet thermocouple is current upstream information, not a future climb announcement. Preview is Off by default and holds current measured inlet, flow and NOx. On uses an explicitly selected public synthetic cycle through nominal thermal lags, with a declared clock error. Storage receives the same forecast and can lower its target using the maximum forecast inlet temperature. Neither law reads the actual future profile or scripted events.

12.4.5 Three Models

Section 12.3 is the plant. From case 1 a reader identifies a conversion against dose ratio and a filling time of minutes. The classical Storage controller's model is the observer's copy, which knows the declared kinetics, V_b and $(\rho c)_b$ exactly, assumes a fresh capacity scaled by κ and $\hat{k}_x = 0.7$, and knows neither the aging, the sensor drift nor the engine's departure from its NO_x map.

12.5 Ten Cases, Measured

The cases appear in Table 12.4. The figures below come from headless runs that advance the engine one step at a time as the browser does, on the default seed, and a setting named in a sentence is applied at the moment that sentence gives. The three ways into a case (opening the page on it, switching to it from another case, pressing Reset) give runs equal to the last bit, as Section 1.6.1 leads a reader to expect.

12.5.1 A Dose Ratio Is Not a Conversion

Lined out on the highway, the brick converts 79.4, 97.1 and 99.6 % of the NO_x at α of 0.8, 1.0 and 1.3, storing 3.0, 7.9 and 16.7 g of ammonia, while the slip rises from 0.5 to 5.3 to 82.8 ppm. Raised from 756 to 945 g/h at 30 s in case 1, the conversion reaches 94 % at 739 s, 11.8 minutes later, because the extra dose first raises the store toward its new level. At 1229 g/h the slip passes 30 ppm at 817 s. Figure 12.2(a) shows the lined-out sensor reading against the dose ratio. It falls with the NO_x to 12.1 ppm at $\alpha = 1.0$ and rises again with the ammonia, reading 60.8 ppm at 0.8 and 59.3 ppm at 1.3. Case 2 walks across it. At $\alpha = 1.3$ the sensor reads 60.0 ppm with 1.3 ppm of NO_x and 82.8 ppm of ammonia. Lowered to $\alpha = 0.8$, the store drains, the slip falls below 2 ppm at 1020 s with the sensor at 36.2 ppm, and by 30:00 the sensor reads 60.4 ppm again, now with 60.4 ppm of NO_x and 0.5 ppm of ammonia. Two doses that differ by 60 % give one reading.

Pause. Try Exercise 12.1 before reading on.

12.5.2 The Buffer and the Heat-Up Release

The store is a buffer of minutes. Lined out at $\alpha = 1.1$ in case 3 the brick holds 12.3 g ($\theta = 0.272$) against the 2.9 g of ammonia a minute that the highway's NO_x consumes at full conversion. When the urea stops at 120 s, the conversion stays above 90, 80 and 50 % for 154, 191 and 247 s. A store lined out at $\alpha = 1.0$ holds 7.9 g and keeps 90 % for 86 s, and one at 1.2 holds 14.9 g for 187 s.

The same store becomes the hazard when the brick heats. In case 4 the feedforward at $\alpha = 1.0$ leaves 11.75 g stored at 600 s, when the climb begins, and the climb produces the two humps of Figure 12.2(b). First the NO_x rises faster than the cool brick converts it, and the sensor reads 296.7 ppm at 627.5 s with 291.5 ppm of NO_x and 3.0 ppm of ammonia. Then the capacity falls under the store, the slip peaks at 384.5 ppm at 705 s, and the sensor reads 267.5 ppm with 0.1 ppm of NO_x. Both readings say dose more, and only the first is right. Storage control on the same seed stores 10.1 g by 600 s, not much less, but its setpoint falls with the inlet temperature and the doser stops, so the NO_x uses the store up instead of fresh urea joining it. Its slip peaks at 32.2 ppm at 692 s. With the schedule read on the brick estimate instead of the inlet, the same loop peaks at 43.1 ppm, and the trim loop, which stores 16.4 g by 600 s, peaks at 1537 ppm.

> **TRY IT IN THE APP** **4 · The Heat-Up Release**
>
> Load the scenario, press Run on the Exhaust view and watch the tailpipe sensor and the ammonia slip as the climb starts at 10:00. Near 705 s the slip peaks at 384.5 ppm while the sensor reads 267.5 ppm, a reading a controller would take for unconverted NO_x.

12.5.3 The Floor and the Cold Start

From 40 °C on the urban crawl of case 5 the doser waits for its floor. At 200 °C the first urea flows at 185 s, and at 10:00 the tailpipe has 3.03 g/kWh with a deposit index of 1.00 g of urea. Lowered to 150 °C, the floor lets urea flow at 104 s into a brick too cold to use it, for 2.93 g/kWh, 3 % less, and 3.04 g of deposit. At 220 °C nothing deposits and the doser waits until 264 s, for 3.26 g/kWh. Every choice leaves more than six times the 0.46 g/kWh limit at 10:00, so the cold start is lost whatever the floor, and the floor trades deposits, not NO_x.

12.5.4 The Trim Loop That Runs Away

Case 8 starts lined out at $\alpha = 1.3$ with the trim on. The sensor's apparent conversion is 80.1 % against a target of 95 %, so the trim adds urea, the slip grows, the reading rises and the trim adds more. The slip passes 100 ppm at 151 s and 300 ppm at 305 s, the trim reaches its +100 % limit at 256 s, and at 10:00 the doser delivers 2458 g/h ($\alpha = 2.60$) with 461 ppm of ammonia and 0.5 ppm of NO_x. Storage control on the same seed drains the overfull brick to its schedule and doses 918 g/h ($\alpha = 0.97$) at 10:00 with 6.3 ppm of ammonia and 11.0 ppm of NO_x. Started lined out at $\alpha = 1.0$ instead, the trim never saturates in 900 s, which is why the case starts on the right side of the V.

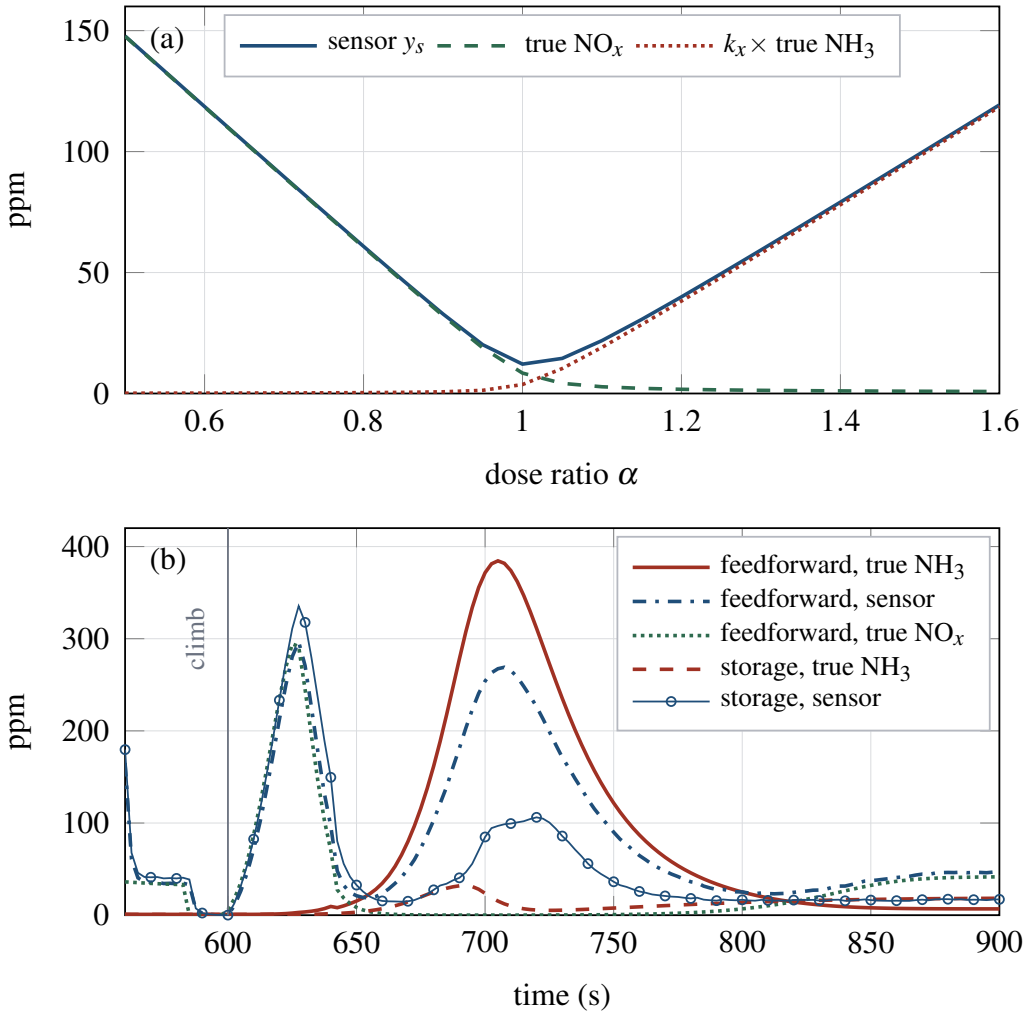


Figure 12.2 Two faces of the ambiguity, from the application's own functions. (a) The lined-out highway point at each dose ratio: the sensor reading (solid), the true NO_x (dashed) and k_x times the true ammonia (dotted). (b) Case 4, the climb from 600 s: under the feedforward (true ammonia solid, sensor dash-dotted, true NO_x dotted) the sensor reads high twice, first on NO_x (296.7 ppm at 627.5 s) and then on released ammonia (267.5 ppm against 384.5 ppm of slip at 705 s). Storage control on the same seed (true ammonia dashed, sensor thin with circles) peaks at 32.2 ppm of slip.

> **TRY IT IN THE APP** **8 · The Trim Loop Runs the Wrong Way**
>
> Press Run and watch the trim and the slip. The trim reaches its +100 % limit at 256 s, and at 10:00 the slip is 461 ppm. Then set Dosing strategy to Storage, press Reset and run ten minutes on the same seed. At 10:00 the slip is 6.3 ppm.

12.5.5 The Observer

From a zero initial estimate with the right capacity on the highway, the coverage error falls from -0.175 to -0.0058 in 120 s and is 0.0019 at 1200 s. Started on the other side of the V at $\hat{\theta}_0 = 0.6$, it falls from 0.527 to 0.126 in 120 s and to 0.021 at 1200 s, more slowly. A wrong capacity assumption biases the stored mass far more than the coverage, +27.0 and −22.3 % at κ of 1.3 and 0.7 against -2.3

Table 12.5 The Challenge Over 1800 s, Default Seed. Limits 0.46 g/kWh, Mean 10 ppm, Peak 30 ppm

Configuration	g/kWh	Peak (ppm)	Mean (ppm)	DEF (g)	Verdict
trim, $\alpha = 1.0$ (shipped)	0.293	1301.9	108.3	893	fails
feedforward, $\alpha = 1.0$	0.564	228.2	17.5	455	fails
feedforward, $\alpha = 0.7$	1.145	40.1	4.8	318	fails
feedforward, $\alpha = 0.6$	1.466	32.3	3.2	273	fails
storage, level 100 % (suggested)	0.423	23.5	5.75	470	passes
schedule on the brick	0.429	32.4	6.1	457	fails
no consumption feedforward	0.448	22.7	5.4	468	passes
both of the above	0.450	23.0	5.2	452	passes
level 90 %	0.470	19.8	5.0	453	fails
level 95 %	0.446	21.6	5.4	462	passes
level 115 %	0.362	29.96	7.2	496	passes
level 120 %	0.344	32.5	7.7	504	fails

and +11.0 %, because the sensor correction holds the coverage that matches the tailpipe. Perturbing every truth field before a control call leaves the dose identical to the last bit.

🕮 **Pause.** Try Exercise 12.3 before reading on.

12.5.6 Storage Control, Aging and the OBD

Over the first 15 minutes of the cycle in case 6, storage control leaves 0.68 g/kWh with a slip peak of 23.5 ppm on the on-ramp, against 0.54 g/kWh and 94.9 ppm for the feedforward. It gives up crawl conversion to keep the on-ramp release under 30 ppm, and over the whole cycle it leads on both, 0.423 g/kWh and 23.5 ppm against 0.564 g/kWh and 228 ppm.

On the aged brick of case 7 the same settings pass the NO_x at 0.428 g/kWh but slip 53.8 ppm at 1231 s, the end of the climb, with a 13.0 ppm mean. Telling the observer the right capacity ($\kappa = 0.7$) gives 0.414 g/kWh and 59.0 ppm, because the schedule is a share of the capacity, and lowering the level to 70 % trades the slip for NO_x, 0.569 g/kWh and 36.0 ppm. The sensor's own cycle number is 0.586 g/kWh aged against 0.490 g/kWh fresh, on either side of the teaching OBD threshold of 0.55 g/kWh, but the fresh brick under the plain feedforward reads 0.792 g/kWh, because its slip reads as NO_x. The threshold is set below the regulation's 1.2 g/kWh [19], but the shipped challenge reads 1.689 g/kWh and case 8 reads 2.876 g/kWh, so some sensor values exceed that threshold. On the severe cycle (severity 1.3, 10.5 % more mass and a 3.25 % grade) the aged brick meets the three limits at none of 19 settings, seven feedforward ratios from 0.6 to 1.2 and twelve storage settings with κ of 1 and 0.7. The lowest peak among them is 38.3 ppm at 1.18 g/kWh, so the case is reported as infeasible.

12.5.7 The Challenge

The challenge runs the whole cycle from a warm start and grades the truth over 1800 s against 0.46 g/kWh of NO_x, a 10 ppm ammonia average and a 30 ppm peak, with the plant as shipped. The NO_x limit is Euro VI's WHTC value and the average its ammonia form [5, 19], here applied to one warm run rather than the weighted cold and hot pair. The peak is the target of a published control study [7]. A 10 ppm peak was considered first. Measured, a peak of 10 ppm or less needs a storage level of 40 % or less, and the least NO_x with it is 0.93 g/kWh (0.92 g/kWh with the true store handed to the controller, a teaching bound), twice the limit, so the regulation's average and the published peak were adopted. Table 12.5 lists the configurations, and Figure 12.3 draws them as a chart.

The shipped trim meets the NO_x by overdosing. Every release reads as NO_x, the trim answers with urea, and the slip peaks at 1302 ppm on the climb. No feedforward ratio passes. At $\alpha = 0.6$ the on-ramp release still peaks at 32.3 ppm and the NO_x is 1.466 g/kWh. Storage control passes with 0.423 g/kWh, a 23.5 ppm peak on the on-ramp and a 5.75 ppm mean, and on five other seeds of the sensor noise it gives 0.422 to 0.424 g/kWh and 23.5 to 23.7 ppm, while the shipped trim fails on

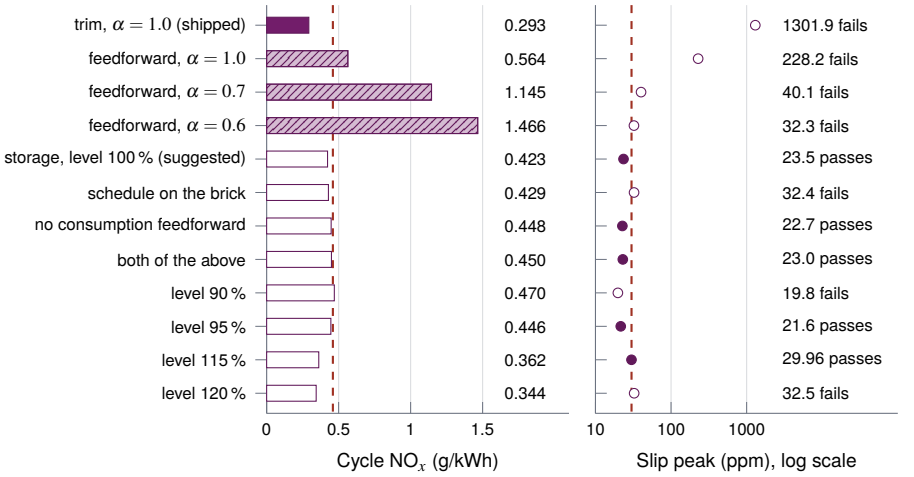


Figure 12.3 The challenge of Table 12.5: the cycle NO_x (left, dashed line at the 0.46 g/kWh limit) and the ammonia slip peak (right, log scale, dashed line at the 30 ppm cap) with the verdict. The dark bar is the shipped trim, hatched bars the feedforward and white bars the storage loop and its variants. Filled dots pass all three limits and open dots fail. Notice that the configuration with the least NO_x has the highest peak, and that the passing storage settings sit in a narrow band just under both lines.

every seed. Levels from 95 to 115 % pass, and every fill gain from 2 to 10 min^{-1} and integral time from 20 to 600 s passes at level 100 %. The inlet lead and the consumption feedforward work as a pair. With the schedule read on the brick estimate and the feedforward on, the loop doses 41.4 g of DEF between 860 and 960 s against 29.6 g as suggested and 35.0 g with both removed, because the feedforward keeps feeding what the hot brick consumes while the late setpoint still sits high, and the peak reaches 32.4 ppm at 958 s. With both removed the cycle passes again. What passes the cycle is the storage loop on the observer, and the lead is what makes the consumption feedforward safe on a climb. With the sensor's cross-sensitivity at 0.8 instead of 0.7 the suggested settings still pass (0.425 g/kWh, 23.5 ppm) and the shipped trim still fails.

> **+ DID YOU KNOW? The Lowest Nitrogen Oxides and the Worst Slip**
>
> From the simulator: the shipped trim leaves 0.293 g/kWh of NO_x over the challenge cycle, the lowest of the twelve configurations of Table 12.5, and still fails, with a slip peak of 1301.9 ppm and a mean of 108.3 ppm. The sensor it trusts reads the released ammonia as NO_x.

12.5.8 MPC and the Information Available to the Doser

Table 12.6 compares full 1800 s runs at the default seed 20261026, 0.05 s physics step and unchanged instruments. One MPC tuning serves every case. A faster Storage rule is frozen before the comparisons: $d\theta/dt \simeq$ fill with repeated closed-loop poles at $-1/\tau$, $\tau = 60/6 = 10$ s, gives $K_{c,s} = 12\,\text{min}^{-1}$ and $\tau_{I,s} = 20$ s. All its other settings equal the original Storage row. No shipped or suggested setting changes. The new comparison case records two full runs separated by Reset, not an emissions pass. Physical criteria here are 0.46 g/kWh, 10 ppm mean and 30 ppm peak. The actual challenge also requires full duration and unchanged parameters and non-event disturbances.

Without preview the MPC reduces NOx but fails the slip peak, while both Storage tunings pass. Its peak exceeds 30 ppm for 35.3 s, with an excess integral of 108.270 ppm s. These are time and cumulative excess, not peak depth. The physical release persists despite a soft predicted cap, as shown in Figure 12.4. With equal public preview the MPC passes while both Storage tunings miss NOx. The

Table 12.6 Full-Cycle Comparison, With One Frozen Tuning per Law. O: Preview Off, P: Public Preview On, E: On With +90 s Clock Error

Preview	Law	NOx (g/kWh)	Peak (ppm)	Mean (ppm)	DEF (g)	Slip integral (ppm s)	Rejected/solves	Fallback (s)	Criteria
O	Storage	.423342	23.505	5.754	470.379	10357.3	0/0	0	pass
O	Fixed Storage	.412347	24.133	6.242	478.419	11235.1	0/0	0	pass
O	MPC	.365405	34.631	7.038	477.686	12668.4	274/1735	273.4	fail
P	Storage	.473256	21.354	5.629	463.382	10132.0	0/0	0	fail
P	Fixed Storage	.467040	22.923	6.027	468.193	10848.8	0/0	0	fail
P	MPC	.395184	26.273	6.459	473.265	11626.2	392/1735	391.8	pass
E	Storage	.529614	21.269	5.353	458.461	9635.8	0/0	0	fail
E	Fixed Storage	.513025	22.124	5.618	464.593	10112.8	0/0	0	fail
E	MPC	.400146	28.644	6.500	476.418	11700.1	510/1735	510.0	pass

+90 s error still passes this fresh case but needs 510 s of fallback. This is an information-dependent comparison.

The aged case without preview gives MPC 0.409 652 g/kWh and 76.937 ppm peak against Storage 0.427 789 g/kWh and 53.757 ppm. The crawl/climb gives 0.136412 and 83.737 ppm against 0.186772 and 32.161 ppm. Sensor drift worsens MPC NOx (0.515580 versus 0.456 280 g/kWh), and failed engine-out sensing plus a map change worsens both NOx and peak (0.548224, 33.836 ppm versus 0.506747, 22.697 ppm). In the high-store ambiguity case both begin above the cap (81.728 versus 82.584 ppm). A 50 L volume mismatch reverses the NOx ranking (MPC 0.346 versus Storage 0.281 g/kWh). No case is retuned to remove these losses.

The matrix contains 134 primary and 66 fixed-rule runs, checking 10.764 million physics steps, plus ten mismatch runs and eight independent integral checks. No finite-value, applied-dose or measured-floor violation occurs. Halving the step retains all physical grades and the 33 original MPC-minus-Storage signs for NOx, peak, DEF and integrated slip. The largest relative changes are 1.09, 3.43 and 0.69 % for NOx, peak and DEF. Fixed Storage has one cold-start/preview-On integrated-slip near-tie reversal, from MPC minus fixed +0.0281 to −0.595 85 ppm s. This is sensitivity evidence, not convergence. The acting observer/reference coverage IAE is 17.933 versus 37.881 s times fractional coverage for Storage and MPC, with 2 Hz dose travel 42071 versus 93 275 g/h and MPC saturation 0.389 %. Fallback changes the observer underlying this metric.

Rendered Chrome at 1× uses 0.276 % of one core for all controller work, with mean solve 642 µs over 12 decisions. At 200× it reaches 201.2 s/s and 60.1 frames/s with 17.92 % controller core share. A separate synchronous full cycle averages 218 µs per solve over 1735 attempts. The 25 ms frame guard has no natural stops in these measurements. Forced stops preserve all 36000 physics steps and 1735 attempts, with identical non-wall-clock CSV data in Chrome. These host timings do not imply a pacing benefit.

12.5.9 The Cell Count Decides the Verdict

The three cells are a declared structure. An independent harness rebuilt the line on the application's own cell functions. It reproduces the application at three cells (feedforward cycle 0.564 g/kWh and 231 ppm against the application's 0.564 and 228), and ran it with the same constants on more cells, with the storage law given the true store as a labeled bound. Table 12.7 gives the result. More cells convert more and release a sharper front, so at level 100 % the peak rises from 24.9 to 42.2 and 66.8 ppm at 3, 6 and 12 cells, and the passing window of levels narrows to 70 % alone at six cells and closes at twelve. The ranking holds at every count, storage control below the feedforward on NO_x and on peak. A six-cell brick with these constants is a different, unfitted catalyst, so the verdict belongs to the three-cell model and the lesson does not.

The heat-up release at its peak is shown in Figure 12.5, the instant case 4 is built around.

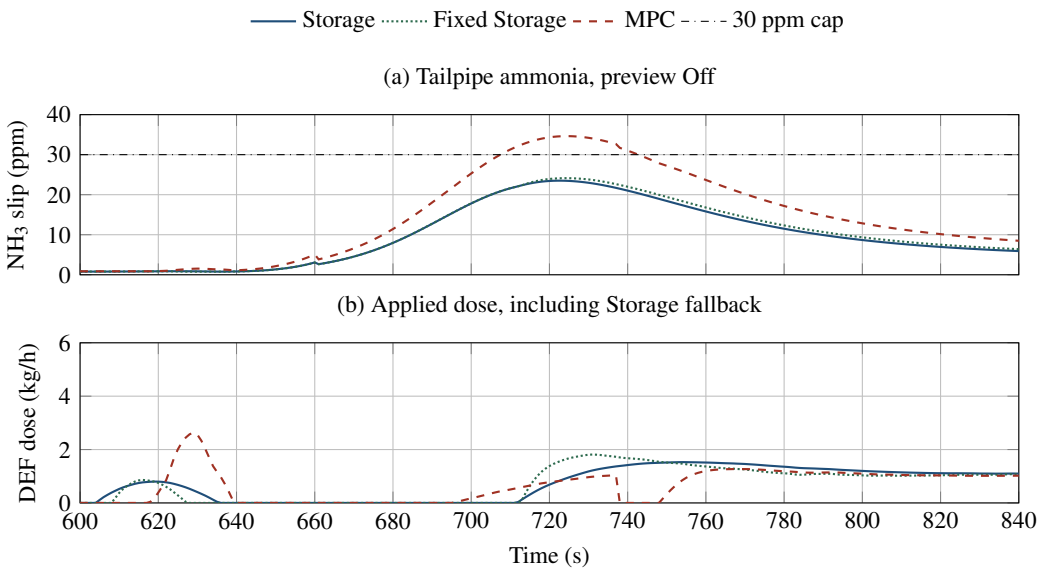


Figure 12.4 The on-ramp release with preview Off on the full-cycle comparison. (a) True ammonia slip and its physical cap (dash-dotted). (b) Applied DEF dose. Common time axes and the same seed show the original Storage settings (solid) beside the fixed rule (dotted) and the MPC (dashed), the MPC run including its Storage fallback. The MPC peak is 34.631 ppm at 724.45 s, during fallback, against original Storage's 23.505 ppm peak at 722.55 s.

Table 12.7 Cell Count With the Same Constants (Independent Harness, Storage Law on the True Store)

Cells	Feedforward cycle	Storage, level 100 %	Case 4 feedforward
3	0.564, 231 ppm	0.406, 24.9 ppm, passes	388 ppm
6	0.487, 225 ppm	0.315, 42.2 ppm, fails	500 ppm
12	0.440, 261 ppm	0.265, 66.8 ppm, fails	598 ppm

12.6 Evidence of Three Kinds

Code verification, agreement with published data and educational evaluation are reported separately. Code verification covers the ledgers, where on a disturbed run of case 4 with the slip catalyst fitted, an aging step and a sensor drift the ammonia closes to a relative 8.7×10^{-16}, the urea to 1.2×10^{-15}, the NO consumed equals the ammonia reacted to 1.7×10^{-14}, and the slip catalyst makes exactly 0.150 of what it oxidizes into NO. The brick's energy balance over 1200 s closes to 0.003 % with a trapezoid on the step values, and the two heats agree with the formation enthalpies. Limiting cases hold, among them a sensor that reads the true NO_x at $k_x = 0$, zero conversion at $\theta = 0$, a store lined out at $\alpha = 1$ that empties to 0 % conversion without urea, and no urea delivered below the floor. The application runs 50 checks, 31 of its own and 19 common to every framework app, among them the step halving above. Agreement with published data is limited to the storage curve of Table 12.3, which lies within one source's band for one catalyst, and to the regulatory numbers taken as teaching values. No engine, catalyst or sensor was fitted to plant data. Educational evaluation consists only of trial runs made while the application was reviewed. The conversion of case 1 reached 94 % after 35 s of wall time and the challenge was passed through the interface in 41.6 s. No learning study has been made.

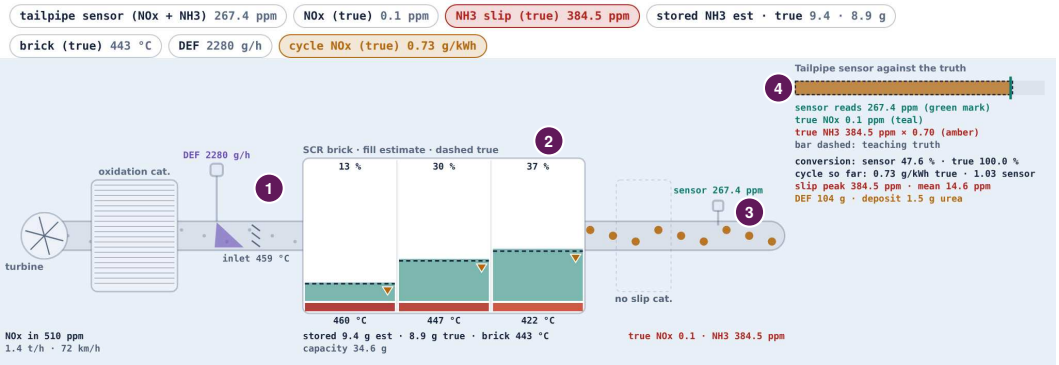


Figure 12.5 The heat-up release of case 4 at its peak, $t = 705\,\mathrm{s}$, on the Exhaust view, as shipped with the feedforward at $\alpha = 1.0$, cropped from the full screen. Callouts: (1) the urea injector with its dose, (2) the three cells of the brick, (3) the tailpipe sensor and (4) the bar of the sensor against the truth. The truck climbs at 72 km/h with 510 ppm of engine-out NO_x, the inlet reads 459 °C and the cells 460, 447 and 422 °C. Each cell is filled to the observer's coverage (13, 30 and 37 %) with the true coverage dashed, and its amber marker shows a store emptying. The tailpipe sensor reads 267.4 ppm against 0.1 ppm of true NO_x and 384.5 ppm of true ammonia, a sensor conversion of 47.6 % against a true 100.0 %, and the status strip, cropped from this view, reads HEAT-UP RELEASE. The observer estimates 9.4 g stored against a true 8.9 g. The trend panels of the full screen, cropped from this view, show over the ten-minute window the crawl's dosing pulses, the storage loop tracking in the background with its setpoint fallen to 4.6 % (0.046 in Table 12.1), and the slip and sensor rising together after the climb.

12.7 Technology in Practice

What Measures It

The doser reads three things in the exhaust: the NO_x leaving the engine, the gas temperature at the inlet of the brick and the tailpipe sensor. The first two are honest. The third is the instrument the whole chapter turns on, because it answers to ammonia as well as to NO_x.

> **TECHNOLOGY** **Sensor: A Tailpipe NO_x Sensor That Also Sees Ammonia**
>
> Exhaust gas sensors are solid-state electrochemical cells, most built on yttria-stabilized zirconia, a ceramic that conducts oxygen ions. Read in the amperometric mode, the cell gives a current of nanoamperes at parts per million of NO_x, and in 2012 only one type of NO_x sensor was sold commercially [22]. In engine tests, when the ammonia in the exhaust rose from about 10 to 30 ppm with no change in nitric oxide, the reading of that commercial sensor rose too [23]. An open circuit in a NO_x sensor is one of the faults on which a heavy-duty engine must derate [8]. The chapter's sensor counts the ammonia with $k_x = 0.7$ behind a 1.5 s lag.

The model keeps that sensor simple, a fixed cross-sensitivity, a lag, a drift and colored noise, so that the ambiguity is the only thing that can mislead the doser. A real sensor's cross-sensitivity varies with the sensor and the gas, which the Limitations section notes and which an observer can estimate.

What Moves It

The single manipulated variable is the dose of diesel exhaust fluid. The pump and the valve that inject it decide what reaches the exhaust, and the temperature of the gas decides how much of it becomes ammonia.

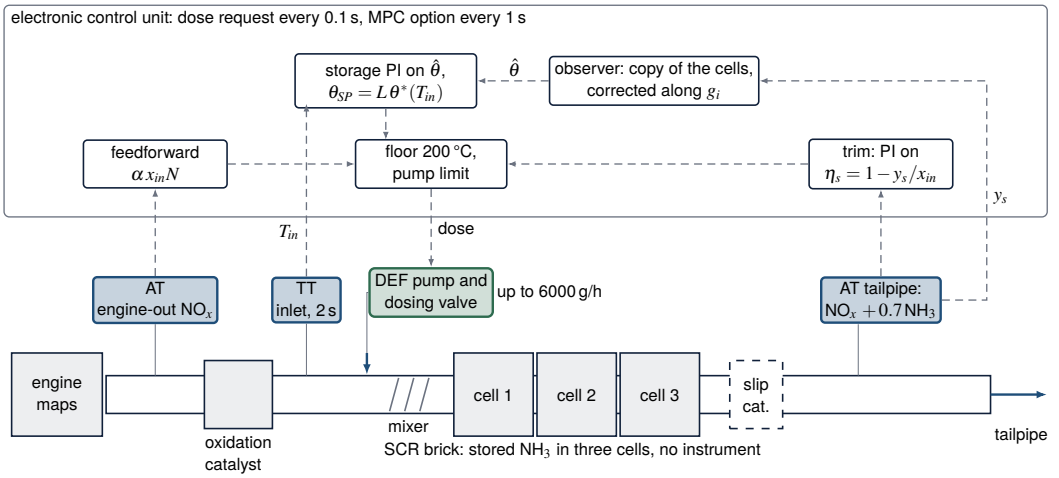


Figure 12.6 The dosing loop on vehicle hardware. The engine-out NO_x sensor AT, which sees no ammonia, feeds the feedforward. The inlet thermocouple TT sets the storage schedule and the dosing floor. The tailpipe sensor AT, which reads $x + k_x y$ with $k_x = 0.7$, feeds the trim and corrects the observer. The observer also reads the engine-out NO_x, the inlet temperature, the flow and the delivered urea (lines not drawn), and the MPC option is not drawn. One electronic control unit computes every strategy every 0.1 s, the request passes the floor and the pump limit, and the pump and dosing valve inject the fluid ahead of the mixer. Notice that no line leaves the three cells of the brick: the store that sets the conversion reaches the controller only through the observer.

> **TECHNOLOGY** **Final Element: The DEF Pump and Dosing Valve**
>
> Diesel exhaust fluid is a water solution of 32.5 % urea [24], generally understood to conform to ISO 22241 [8]. A pump and a dosing valve deliver it, and a tank heater and a tank temperature sensor let the system watch for freezing. A blocked line or dosing valve can be caused by crystallized fluid [24], and dosing may stop through faulty sensors, faults in the delivery system or frozen reductant. Among the data an on-board diagnostic system stores at a fault are the dosing quantity commanded and the quantity actually delivered [24]. The model's doser delivers what it is asked up to 6000 g/h, and nothing while the inlet reads below its floor.

Where the Controller Runs

In a vehicle, control runs in electronic control units, microprocessors with input and output interfaces. A modern car has more than 100 of them, and computer control entered cars in the late 1970s to meet stringent emission requirements [25]. The heavy-duty rules name an aftertreatment control module among the parts whose open circuit must trigger a derate [24]. The sources opened for this section give no scan period for such a module. The chapter's doser computes a request every 0.1 s, and the added MPC decides every 1 s. Every strategy runs in that one controller on one packet of measurements, the loops not in charge tracking the applied dose, and the observer runs its copy of the three cells beside the PI blocks. Figure 12.6 draws the loop on that hardware.

What Is Modernizing It

Three developments bear on this doser. The first is the regulation. The 2027 heavy-duty standards were shown to be achievable with cylinder deactivation, a dual-SCR arrangement and heated dosing of the fluid for low power and cold starts, and with better catalyst formulation, sizing and mixing of the fluid with the exhaust at higher power [24]. Each of these changes the plant the doser sees. The second is the sensor. Work on impedance-based NO_x sensors, read with an alternating current instead of a direct one, aimed at higher sensitivity to NO_x, better long-term stability and the ability to

subtract background interference [22]. In the model a sensor with $k_x = 0$ reads the true NO_x, and the V is gone. The third is a direct reading of the store, the subject of the second open challenge. If it holds up in service, the observer of Section 12.4 would be corrected by a measurement of the very state it now has to infer.

> **IN PRACTICE** **When the Fluid Runs Out, the Truck Slows Down**
>
> Engines that use selective catalytic reduction depend on a constant supply of the fluid. From model year 2027 a heavy-duty engine must derate when the supply falls to 2.5 % of tank capacity or to three hours of operation, when the fluid fails its concentration specification, when a catalyst appears to be missing, or on an open circuit in the tank level sensor, pump, quality sensor, NO_x sensors, dosing valve, tank heater or aftertreatment control module. The derate takes away 1 mile per hour of top speed every five minutes until the scheduled limit is reached [8]. Without the fluid, NO_x could rise to levels comparable to having no NO_x control at all [24].

12.8 Limitations

The engine and the cycle are declared maps, and the kinetics, the storage curve and the decomposition ramp are teaching values fitted to declared targets. The curve sits inside the band of one measured catalyst but is not a fit to it, and its fall with temperature makes the release likely generous. The challenge verdict depends on the declared three cells, since the same constants on six or twelve cells peak at 42 and 67 ppm at level 100 %. Only standard SCR is present, with no NO_2, N_2O, poisoning, heat loss or filter, and urea decomposition is instantaneous. The sensor's cross-sensitivity is a constant, whereas a real one varies with the sensor and the gas and can be estimated [15]. The cycle is one warm run, while type approval weights a cold and a hot one, and the OBD threshold is set below the regulation's so that a short cycle can cross it. A climb announced by a step at 10:00 and an aged brick that loses 30 % of its sites at once are not how a truck behaves, though each isolates one mechanism. The observer knows the plant's structure and kinetics exactly, so it meets model error only through κ, the thermocouple lag, the sensor noise and the ambiguity. A simulated pass is not type approval, and none of these numbers predicts the emissions of a real truck.

> **OPEN CHALLENGE** **Clean Exhaust Before the Catalyst Is Warm**
>
> In stop-and-go traffic or at idle the exhaust can cool until the catalyst system becomes less effective or stops working, and test data indicate that such low-load operation could account for more than half of a truck's NO_x in a typical workday [24]. A 2013 workshop of laboratories and industry noted that most catalyst systems began to work near 200 °C, set a goal of 90 % conversion at 150 °C, and called that lowering extremely difficult [26]. Case 5 meets the same wall: whatever the floor, the cold start is lost. Progress would be a catalyst and a dosing method that convert in the first minutes after a start.

The MPC uses frozen fresh geometry and kinetics, local Jacobians held for 60 s, an approximate thermal forecast without future reaction heat and three horizon-wide soft slacks. It has no future event access or robustness guarantee. Its opening truth-shaped teaching prior, ambiguous residual bias and missing installed slip-catalyst model restrict interpretation. The statement above about the classical observer does not imply that the MPC adapts to changed geometry or chemistry.

> **OPEN CHALLENGE** **A Gauge for the Stored Ammonia**
>
> The NO_x and ammonia sensors around a catalyst give only an inference of how much ammonia it holds, often confounded by the NO_x sensor's cross-sensitivity to ammonia. A radio-frequency method uses the catalyst housing as a microwave resonant cavity and reads the stored ammonia from the change in its dielectric properties. On one engine its readings correlated closely with the inventory estimated from gas measurements, and studies showed its potential as the feedback of closed-loop dosing [27]. A measurement that holds up in service would give this chapter's observer a reading of the very state it infers.

12.9 Conclusion

This chapter studied a diesel SCR line as a plant whose conversion is set by an unmeasured store, whose capacity falls as it heats, and whose tailpipe sensor rises on both sides of the right dose. In the model the conversion takes 11.8 minutes to follow a dose change, the sensor reads 60 ppm at doses 60 % apart, and a climb after a city crawl releases 384.5 ppm of ammonia that the sensor reports as NO_x. A trim on that sensor runs to its limit and slips 461 ppm, while storage control on an observer holds 6.3 ppm on the same seed. Over the graded cycle the storage loop passes at 0.423 g/kWh and a 23.5 ppm peak where no feedforward ratio passes, and the aged brick on a severe cycle passes at none of 19 settings. The verdict belongs to a fitted three-cell model. A fuller model would add NO_2 and the fast reaction, a particulate filter's thermal mass, a sensor cross-sensitivity that varies, a cold and hot weighted cycle, and a storage curve fitted to a measured catalyst. The simulator shows that a doser has to know how much ammonia is stored before it can read its own sensor.

The added MPC lowers cycle NOx from 0.423 to 0.365 g/kWh with preview Off but fails its 34.6 ppm peak, while its public-preview result passes at 0.395 g/kWh and 26.3 ppm.

KEY POINTS

- The catalyst stores the ammonia first, and the stored amount, which no instrument measures, sets how much of the nitrogen oxides is cleaned.
- The tailpipe sensor reads ammonia as NO_x, so two doses 60 % apart give one reading.
- A climb after a city crawl releases 384.5 ppm of ammonia that the sensor reports as NO_x.
- A trim on that sensor runs to its limit, while storage control on an observer passes the graded cycle at 0.423 g/kWh and a 23.5 ppm peak.
- The challenge verdict belongs to the fitted three-cell model.

Where else this applies. Volume 7, Chapter 4 meets a process gain that reverses at the peak of its curve, and Chapter 13 runs a full extended Kalman filter on a state that no instrument aboard measures.

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12.10 Exercises

12.1 ⌕ Concept check · 2 min

Case 2 starts lined out on the highway at a dose ratio of 1.3, where the tailpipe sensor reads about 60 ppm. The dose is lowered to $\alpha = 0.8$ and the brick is left to settle. What does the sensor read then, and why?

(a) About 12 ppm, because the lower dose sits at the bottom of the V where NO_x and slip are both small

(b) About 60 ppm again, because the reading is now made of NO_x that the lower dose leaves unconverted

(c) About 120 ppm, because the NO_x left by the lower dose adds to the ammonia still slipping from the store

(d) About 25 ppm, because the reading falls with the slip while the tailpipe NO_x stays small

12.2 Concept check · 2 min

The storage loop reads its setpoint schedule $\theta^*(T_s)$ at the inlet thermocouple, not at the observer's brick temperature. Why does that choice matter on the climb of case 4?

(a) The inlet thermocouple is quieter than the brick estimate, so the setpoint moves less with noise

(b) The brick temperature is not available to the controller, so the schedule could not be read on it

(c) The inlet passes 350 °C about 25 s before the brick mean, so the setpoint falls and dosing stops first

(d) The inlet is hotter than the brick, so the schedule gives a higher setpoint and keeps the conversion up

12.3 Concept check · 2 min

On the highway the observer is told a capacity 30 % too high ($\kappa = 1.3$) for a fresh brick. Which result does the chapter report, and why?

(a) The coverage and the stored mass are both about 30 % high, since one scales the other

(b) The estimate diverges, because a wrong capacity flips the sign of every gradient g_i of the correction

(c) The coverage is 27 % high and the stored mass only 2 % low, since the sensor fixes the mass

(d) The stored mass is 27 % high and the coverage only 2.3 % low, since the sensor fixes the coverage

12.4 Theory and calculation · 6 min

On the 85 km/h highway ($v = 23.61\,\mathrm{m/s}$) the engine delivers $P = 108.8\,\mathrm{kW}$. Use the maps of Equation (12.1), an exhaust molar mass of 28.8 g/mol, 17.03 g/mol for ammonia and the conversion of 665 280 g/h of DEF per mole per second of urea.

(a) Find the exhaust flow, the engine-out NO_x and the molar exhaust flow N. *Checkpoint:* 0.278 kg/s, 294.1 ppm and 9.66 mol/s.

(b) Find the DEF rate for dose ratios of 1.0, 0.8 and 1.3. *Checkpoint:* 945, 756 and 1229 g/h.

(c) At full conversion, how many grams of stored ammonia does the NO_x use per minute? The store lined out at $\alpha = 1.1$ holds 12.3 g. Compare the time it would last at that rate with the 154 s for which case 3 keeps 90 % conversion after the urea stops. *Checkpoint:* 2.90 g/min, so about 4.2 min, against 2.6 min above 90 %.

12.5 Theory and calculation · 6 min

The highway point lined out at dose ratios of 0.8, 1.0 and 1.3 converts 79.4, 97.1 and 99.6 % of 294.1 ppm of engine-out NO_x and slips 0.5, 5.3 and 82.8 ppm of ammonia. The tailpipe sensor follows Equation (12.6) with $k_x = 0.7$, no drift and no noise.

(a) Find the steady sensor reading at each dose. *Checkpoint:* About 60.9, 12.2 and 59.1 ppm.

(b) Find the conversion η_s that the trim of Equation (12.7) computes at 0.8 and at 1.3, and the sign of its error against $\eta_{SP} = 95\,\%$ in each case. *Checkpoint:* 79.3 and 79.9 %, both below the target, so the trim raises the dose at both.

(c) At 705 s of case 4 the tailpipe carries 0.087 ppm of NO_x and 384.5 ppm of ammonia, the engine-out NO_x is 510.4 ppm and the sensor reads 267.4 ppm. Find the steady value the sensor is heading for, and the conversion a loop computes from the present reading. *Checkpoint:* 269.2 ppm and 47.6 %.

12.6 Theory and calculation · 7 min

The brick holds $\Omega(T)$ of Equation (12.3) with $A = 1$, $\Omega_0 = 100\,\mathrm{mol/m^3}$, $T_0 = 200\,^\circ\mathrm{C}$ and $a = 0.0015\,\mathrm{K^{-1}}$, over $V_b = 32\,\mathrm{L}$. Treat the brick as uniform in temperature and use 17.03 g/mol for ammonia.

(a) Find the capacity in grams at 220 °C, the crawl, and at 459 °C, the inlet on the climb. *Checkpoint:* 52.9 g and 33.3 g.

(b) The crawl of case 4 leaves 11.75 g stored. Find its coverage at both temperatures, and say what the rise means for the desorption rate. *Checkpoint:* 0.222 and 0.353.

(c) Find the storage loop's target in grams at both temperatures for level $L = 100\,\%$, from the schedule θ^* given below Equation (12.9). *Checkpoint:* 10.1 g and 1.52 g.

12.7 App challenge · 9 min

Load scenario 4, The heat-up release, with the default seed, and run at 20× (36 s of wall time per run).

(a) Run the feedforward as loaded past 12:00 and export the CSV. Read the slip peak on the scorecard, and from the columns `truth_nh3_slip_ppm`, `sens_nox_tail_ppm` and `truth_nox_tail_ppm` the time of the peak and the sensor and true NO_x at that row. *Checkpoint:* 384.5 ppm at 705 s (within 1 s), sensor 267.4 ppm, true NO_x 0.1 ppm.

(b) Set Dosing strategy to Storage, press Reset, and run past 12:00 again. Read the slip peak and its time, and the true stored ammonia (`truth_stored_g`) at 600 s in both runs. *Checkpoint:* 32.2 ppm at 692 s. 11.75 g under the feedforward and 10.1 g under storage control.

(c) In Advanced, set Schedule on to Brick, press Reset, and run past 12:00. Read the slip peak and explain the difference from (b). *Checkpoint:* 43.1 ppm, within 0.1 ppm.

12.8 App challenge · 8 min

Load scenario 8, The trim loop runs the wrong way, with the default seed, and run at 20× (30 s of wall time per run). Export the CSV after each run.

(a) Run the trim as loaded past 10:00. From the column `trim_pct`, find when the trim reaches its +100 % limit, and from the row at 600 s read `def_gph`, `alpha_applied` and `truth_nh3_slip_ppm`. *Checkpoint:* About 256 s (within 1 s); 2458 g/h, $\alpha = 2.60$, 461 ppm.

(b) Set Dosing strategy to Storage, press Reset, and run past 10:00. Read the same three columns and `truth_nox_tail_ppm` at 600 s. *Checkpoint:* 918 g/h, $\alpha = 0.97$, 6.3 ppm of ammonia and 11.0 ppm of NO_x.

(c) Explain from the sensor's V why the same tailpipe sensor drives one loop to its limit while the observer, which reads that sensor too, brings the dose back near $\alpha = 1$. *Checkpoint:* The trim's gain has the wrong sign right of the V's bottom; the observer's model knows the side.

12.9 App challenge · 9 min

Load the Challenge, the 30 min cycle, with the default seed. Each run pauses at 30:00 with its verdict; run at 200× (9 s of wall time per run). Read the challenge tile.

(a) Run as shipped (feedforward with the trim). Read the cycle NO_x, the slip mean and peak, the DEF and which limit fails. *Checkpoint:* 0.293 g/kWh, mean 108.3 ppm, peak 1301.9 ppm, 893 g; the ammonia mean and peak fail.

(b) Set Dosing strategy to Storage, leave its settings, press Reset and run. Read the same four numbers and the verdict. *Checkpoint:* 0.423 g/kWh, mean 5.8 ppm, peak 23.5 ppm, 470 g; met.

(c) Set Storage level to 115 %, press Reset and run, then repeat at 120 %. Explain the trade the level makes. *Checkpoint:* 115 %: 0.362 g/kWh, peak 30.0 ppm on the tile, met. 120 %: 0.344 g/kWh, peak 32.5 ppm, not met.

12.10 Application area · 4 min

Euro VI weights the transient cycle 0.14 cold and 0.86 hot and allows 0.46 g/kWh of NO_x on the weighted result.

(a) Storage control leaves 0.423 g/kWh on the warm cycle of the challenge. Taking that as the hot result, find the most the cold run may leave. *Checkpoint:* 0.687 g/kWh.

(b) Case 5 leaves 3.03 g/kWh over the first 10 min of a cold start at a 200 °C floor. If a whole cold run left that much, what hot result would be needed? What does case 5 say about lowering the floor as the remedy? *Checkpoint:* 0.042 g/kWh. Lowering the floor to 150 °C gains 3 % for three times the deposits.

12.11 Application area · 4 min

The on-board diagnostic of the app flags a run when the tailpipe sensor's own cycle number exceeds a teaching threshold of 0.55 g/kWh. Over the full cycle the sensor's number is 0.586 g/kWh for the aged brick under storage control, 0.490 g/kWh for the fresh brick under storage control and 0.792 g/kWh for the fresh brick under the plain feedforward, whose true NO_x is 0.564 g/kWh.

(a) Which runs are flagged, and which of them has a failing catalyst? *Checkpoint:* Two flagged; one failing catalyst.

(b) Why does the fresh brick on the feedforward read higher than its true NO_x, and by how much? What must a diagnostic know to tell aging from overdosing? *Checkpoint:* About 40 % high, from slip read as NO_x.

12.12 Review the agent · 5 min

An AI assistant compares the two strategies of case 9 for a calibration team: "With Drive preview Off, the MPC leaves 0.365 g/kWh of NO_x against 0.423 g/kWh for Storage, for nearly the same DEF, 478 g against 470 g. The MPC is therefore the better doser on this cycle, and switching to it would pass the challenge with a wider NO_x margin." Find the flaw, and say how you would check it in the app.