INTERACTIVE CONTROL ENGINEERING
Principles and Applications

Volume 4 Override, Split-Range, and Constraint Control

CHAPTER 3

Limiters That Vote on One Fuel Valve in a Turbofan Simulator

Pages 51–75

Edited by John D. Hedengren

How to cite this chapter. "Limiters That Vote on One Fuel Valve in a Turbofan Simulator," in *Override, Split-Range, and Constraint Control*, John D. Hedengren, Ed., vol. 4 of *Interactive Control Engineering: Principles and Applications*. Advanced Process Solutions, LLC, 2026, ch. 3, pp. 51–75.

The page numbers in this file are those of the printed volume.

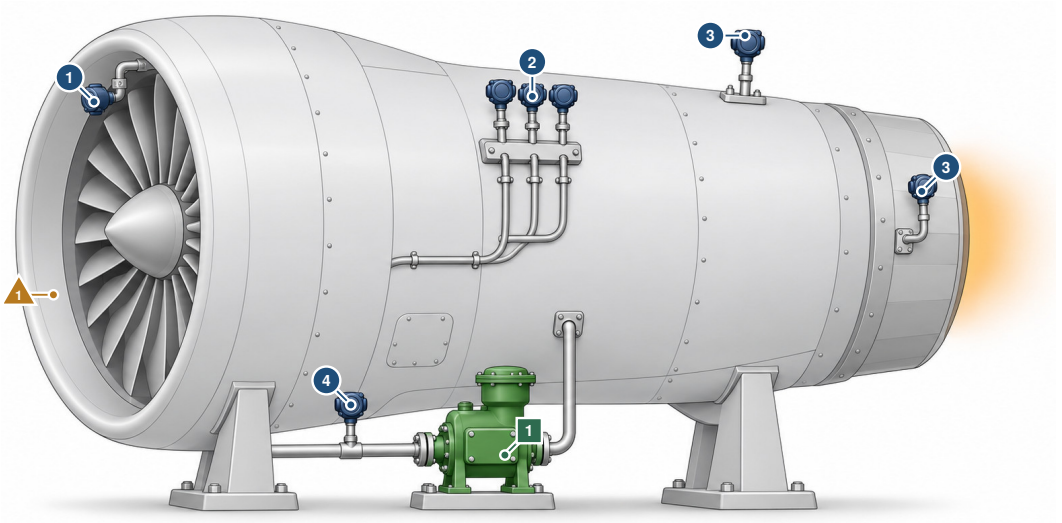
The app for this chapter
https://apmonitor.com/apps/turbofan-fadec/

The volume online: contents, other chapters and citation records
https://apmonitor.com/apps/books/v04-override-constraint/#turbofan-fadec

Copyright © 2026 Advanced Process Solutions, LLC. All rights reserved. Produced by Advanced Process Solutions, LLC.

CHAPTER 3

Limiters That Vote on One Fuel Valve in a Turbofan Simulator



The controller moves 1 valve that meters fuel to the flame

The controller reads 1 inlet air temperature and pressure 2 fan and core speeds, compressor pressure 3 exhaust temperature, read at several points 4 fuel flow

What disturbs it 1 a hot day or thin air at altitude

Notice that every head reads speed, pressure, temperature or fuel, and that none reads how close the compressor is to surge, so the one valve is moved by limits on what can be measured. Illustration, not to scale.

IN PLAIN TERMS One Fuel Valve and Many Guards

The main idea. A jet engine is steered by one fuel valve. Several small controllers each ask for an amount of fuel, and the valve follows the most cautious request.

The challenge. Fuel added faster than the spinning blades can speed up pushes the engine toward surge, a violent backflow of air that nothing on the engine measures. A guard not in charge must keep its running total matched to the real fuel flow, or it takes over late and with a jolt.

Why it matters. These rules decide whether an engine reaches takeoff power in seconds without surging, overheating or losing its flame.

THREE WAYS TO READ THIS CHAPTER

Explore	13 min	the first page, the fact on how controls grew (Section 3.1), the two history segments (Section 3.2), the two try-it segments and the fact on the challenge (Section 3.5) and the key points
Study	60 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 3.5), Technology in Practice (Section 3.6), Limitations (Section 3.7) and the open challenge

The control question A jet engine has one handle, its fuel flow, and the fuel the five-second thrust rule demands drives the compressor toward a surge line that nothing on the engine measures. How does a min/max selector of a speed governor, schedules and limiters share that one valve, and what must every loop that is not in charge do so that it can take over cleanly?

Learning objectives

- Explain why a fuel step moves the compressor toward surge before the spools can speed up.
- Trace which cap or floor holds the valve through a slam, a chop and a stall, and why the floors come after the caps.
- Derive the back-calculation trail of a loop that is not in charge and the distance from its limit at which it takes over.
- Trade an acceleration schedule's design margin against the time to 95 % thrust, on a new and on a worn engine.
- Use corrected quantities to compare the engine at altitude and on a hot day with the engine at sea level.

Prerequisites Sections 1.4.3 (selectors and override), 1.4.4 (external reset), 1.4.5 (saturation and rate limits), 1.4.2 (back-off) and 1.6.4 (scenarios and exported files); Chapter 2 for surge on a compressor map. Section 1.6.3 is needed only for the predictive governor.

The app https://apmonitor.com/apps/turbofan-fadec/

See also Volume 7, Chapter 3 for a gain schedule that keeps one linearized closed loop across operating points, and Volume 7, Chapter 4 for a back-calculation PI under an actuator limit. In this volume, Chapter 9 for an exhaust-temperature limit that derates a gas turbine on a hot day.

3.1 Introduction

At flight idle the simulated engine burns 0.164 kg/s of fuel and makes 12.0 kN, and ten times that thrust is a lever stroke away. Fuel delivered faster than the two spools can speed up heats the gas at once, and because the first turbine nozzle is choked the compressor has to deliver the same flow at a higher pressure. In case 1 of the simulator, takeoff fuel set in one move reaches the surge line 0.020 s after the move, at 0.51 kg/s of fuel on its way through the valve, while the core speed has risen from 60.6 to only 60.8 %. The same engine, slammed under an acceleration schedule designed for an 8 % margin, reaches 95 % of its rated thrust in 4.74 s with the surge margin never under 9.5 %.

The engine controller that makes the second run possible is not one loop. A fan-speed governor asks for fuel, an acceleration schedule caps it so that the compressor does not surge, a turbine temperature limiter caps it on a hot day, overspeed limiters cap it at the top, and a deceleration schedule floors it so that the combustor does not blow out. The lowest cap and then the highest floor win, and every loop that does not win must keep its integrator on the fuel actually commanded or its hand-over overshoots. This min/max architecture with integral wind-up protection is the structure of the public generic engine controller of a NASA study [1], and engine control texts and surveys treat it at length [2–4]. Selector and override control of the same shape appears in process plants wherever one actuator protects several limits [5] (Section 1.4.3), and anti-windup by back-calculation is the standard remedy for an integrator that is not in charge of its output [6] (Section 1.4.4).

+ DID YOU KNOW? From One Controlled Variable to Eleven

A jet engine flight-tested in 1942 had one controlled variable and three sensors. A large commercial turbofan of 1993 had three controlled variables and seven sensors, and a military engine of 1989 had eleven of each [7].

One belief this engine is meant to dislodge is that a controller protects a limit by measuring it. Nothing on an engine measures its surge margin. The schedule protects it by holding a ratio of measured fuel to measured compressor delivery pressure below a table drawn against corrected core

speed, and a student who tightens that table finds the margin spent by how fast fuel arrives rather than by how much arrives. A second belief, that gain scheduling is what makes an engine controller work across its envelope, is also tested. In this engine a fixed governor gain is stable at every point tried, and the scheduled gains buy uniform damping (overshoot of 0 to 8 % on 2 % lever steps at nine points, against 7 to 21 % fixed) without being what passes the graded challenge.

Teaching material usually separates these pieces. Compressor stability is taught on lumped surge models with a throttle and no fuel [8], the kind of model Chapter 2 works with, gas turbine performance on steady cycle calculations [9, 10], and the public component-level engine simulations that pair a turbofan with its controller, NASA's C-MAPSS40k and the T-MATS toolbox [11, 12], are research codes run inside a desktop modeling environment. This chapter works with a generic turbofan and its min/max fuel selector as a browser simulator runs them, and measures on that simulator where the surge margin, the turbine temperature, the flame and the five-second rule meet in one valve. The selector, the ratio-unit schedule, back-calculation and corrected-speed scheduling are established practice, and none of the results is a research result about engines. They are measurements on one teaching engine and one seed, among them that the graded re-slam can be bought from the chop as well as from the slam. The engine is a component-level model on declared maps, written for this application, whose controller reads only declared measurements, and the chapter states every equation and constant needed to build it again.

Section 3.2 follows the domain, from hydromechanical fuel controls to the five-second certification rule. Section 3.3 sets out the engine, its maps, spools, plenums, instruments and assumptions. Section 3.4 gives the controller as implemented: the governor and its gain schedule, the caps, floors and selector, integrator tracking, stall recognition and, in Section 3.4.6, an optional predictive fuel governor. Section 3.5 measures the ten cases of the simulator, the challenge, the verification of the code and the predictive governor against the selector. Section 3.6 sets the selector on engine hardware, Sections 3.7 and 3.8 state the limitations and conclude, and Section 3.9 holds the exercises.

3.2 Fuel Schedules, Limiters and the Five-Second Rule

The control problem of a jet engine was settled in its present shape before electronics could solve it. A pilot's lever had to be turned into a fuel flow that brought the engine to the requested speed without stalling the compressor, overheating the turbine or blowing out the combustor, and the early answer was a hydromechanical fuel control in which cams, levers and servo valves computed the governor and the limits mechanically. Surveys of the field follow that lineage from those fuel controls to the full-authority digital electronic engine control that replaced them [2, 3]. The acceleration and deceleration limits are statements of physics, a fuel flow allowed for a given compressor pressure and core speed, so they mean the same thing whether a cam or a processor computes them.

> ⧖ HISTORY **A Governor With a Stop and a Cap, 1942 to 1981**
>
> The first jet engine built in the United States, in 1942, had a hydromechanical governor that metered fuel in proportion to the difference between the set and the actual turbine speed. A minimum-flow stop on the metering valve kept the flame from going out, and a maximum-flow schedule kept the engine from overheating. The first full-authority electronic engine control entered service in 1972. It was a single analog channel that computed every schedule and limit, backed by a hydromechanical control with conservative, fixed fuel-ratio maximum and minimum schedules. Flight tests of the first full-authority digital control began in 1981, and between 1990 and 2002 dual-channel digital controls became the standard for jet engines [7]. The floor and the cap of this chapter's selector were there from the start.

Compressor surge entered the control problem as a stability question. A lumped compression-system model of 1976, a compressor feeding a duct, a plenum and a throttle, showed that whether an installation falls into rotating stall or into surge depends on one dimensionless group [8], and the engine's operating point, its steady line and its surge line became the vocabulary of every acceleration

schedule since. Engine performance texts give the corrected quantities that make one schedule serve every altitude and day, speed over $\sqrt{\theta}$, flow times $\sqrt{\theta}/\delta$ and fuel over $\delta\sqrt{\theta}$ [9], and the dynamic modeling of gas turbines for control has its own book-length treatment [10].

> ⧖ HISTORY **A Speed Loop That Cycled at Altitude, Before 1950**
>
> The first afterburning turbojet, tested in 1948, had a speed governor designed by frequency response alone. In altitude tests at the national aeronautics laboratory, noise in the speed sensor together with the governor's high gain made the engine behave like a limit cycle. Engineers of the maker and the laboratory turned to step-response analysis, and the fix was to reduce the control gain at altitude. In the same years corrected flows, speeds and pressure ratios, derived from dimensional similarity, cut the number of operating points that a calculation by slide rule had to cover. The corrected approach is still used because it simplifies the design and implementation of control laws [7]. A gain that changes across the envelope and tables written in corrected quantities are both part of this chapter's controller.

The certification requirement that makes the schedule tight is old and short. In the text in force, last amended in March 1971, 14 CFR 33.73 asks in paragraph (b) for an increase from the fixed minimum flight idle lever position, or from not more than 15 % of rated takeoff thrust, to 95 % of rated takeoff thrust in not over 5 s, from a stabilized static condition with only the bleed and accessory loads needed to run the engine. Paragraph (a) asks that a lever moved from minimum to maximum in not more than 1 s, with the most bleed and power extraction to be permitted, cause no overtemperature, surge or stall [13]. Neither paragraph names an altitude. A schedule wide enough to be safe on a worn engine has to be narrow enough to meet paragraph (b) on a new one.

Research on the controller itself moved to public generic engines. NASA's propulsion controls research has been reviewed in its own right [14]. Its non-proprietary C-MAPSS40k simulation of a generic 40,000 lbf two-spool high-bypass turbofan carries a controller built on common industry architecture [11], and the design of that controller, a gain-scheduled proportional-integral governor with logic that protects the engine's limits, was published with its acceleration schedule and its response to the Federal Aviation Administration's thrust requirement [1]. The open T-MATS toolbox later made the thermodynamic building blocks of such models available for reuse [12]. Advanced methods of turbofan control, among them alternatives to the min/max selector for limit protection, are collected in a monograph [4], while gain scheduling as a design method has general surveys of its own [15, 16]. Volume 7, Chapter 3 schedules a gain to preserve one linearized closed loop across operating points. The selector with tracking integrators is the structure this application implements.

3.3 The Engine as Modeled

The simulated engine is a component-level teaching model of a generic 120 kN-class two-spool high-bypass turbofan, on a test stand or in flight, as shown in Figure 3.1. It was written for this application from textbook relations on closed-form maps declared in its source. It is not a port of C-MAPSS40k, T-MATS or any licensed engine simulation, and no map, table or coefficient is taken from one or from any engine maker. The fan's outer stream passes a bypass duct to its own nozzle, while its root and a booster on the low spool feed the high-pressure compressor (HPC), the combustor, the high-pressure turbine (HPT) that drives the HPC on the high spool, and the low-pressure turbine (LPT) that drives the fan and booster. Five plenum volumes sit between the components. Station numbers follow the usual convention, 2 the fan face, 13 the bypass duct, 25 the HPC inlet, 3 its exit, 4 the combustor exit, 45 between the turbines and 5 the LPT exit.

The variables are classified in Table 3.1. Ten states are integrated, the two spool speeds, the five plenum pressures, the fuel actually flowing through the metering valve, the thermocouple's reading and the bleed valve's position. Units in the model are seconds, kilograms, pascals, kelvin, watts and radians per second, and the interface shows percent of gauge speed, bar, degrees Celsius and kilonewtons.

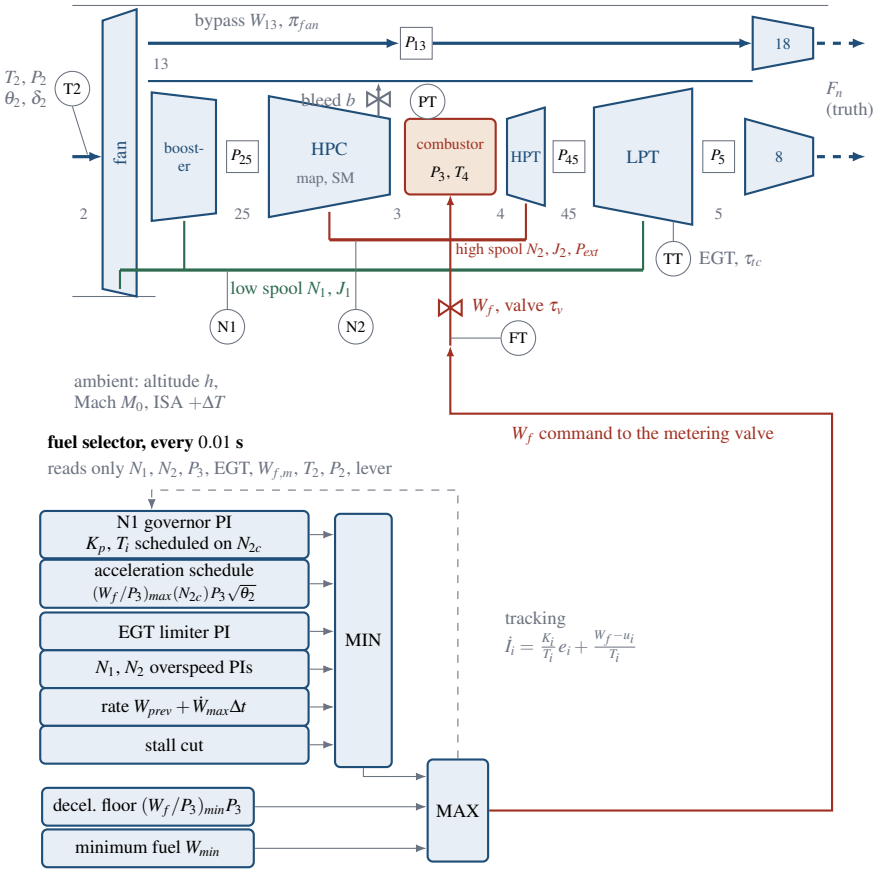


Figure 3.1 The engine as the Engine view draws it (top) and the fuel selector of the Ladder view (bottom). The fan and booster on the low spool (N_1, J_1) and the HPC on the high spool (N_2, J_2) feed five plenums, P_{13}, P_{25}, P_3, P_{45} and P_5. Fuel W_f through the metering valve sets T_4, the handling bleed b opens at the HPC exit, and the thrust F_n is truth. Circles are the measurement packet: speeds, P_3, the EGT thermocouple, the fuel flowmeter and the fan-face probes. Below, the minimum of six caps meets the maximum of two floors, the thick solid path is the fuel command to the valve, and the dashed path is integrator tracking. Process model only, not to scale.

3.3.1 Ambient Conditions and Corrected Quantities

The fan face sees the standard atmosphere shifted by the day offset ΔT at constant pressure, raised by the ram of the flight Mach number M_0 with a recovery of 0.995, as shown in Equation (3.1).

$$\begin{aligned} T_2 &= \left(T_{ISA}(h) + \Delta T\right)\left(1 + 0.2M_0^2\right) \\ P_2 &= 0.995\, p_{ISA}(h)\left(1 + 0.2M_0^2\right)^{3.5} \\ \theta_2 &= T_2/288.15\,\mathrm{K}, \qquad \delta_2 = P_2/101.325\,\mathrm{kPa} \end{aligned} \tag{3.1}$$

where T_{ISA} falls by 6.5 K/km to 11 km and is 216.65 K above it, and the flight velocity is $V_0 = M_0\sqrt{\gamma_a R T_0}$. Every map below is written in corrected speed $N/\sqrt{\theta}$ and corrected flow $W\sqrt{\theta}/\delta$ at its own inlet, so corrected similarity holds by construction except where a fixed offtake or the nozzles' exhaust to ambient pressure break it.

Table 3.1 Variables by Role, With Their Values at Flight Idle and Takeoff at Sea-Level Static ISA

Variable	Role	Idle, takeoff	Range
N_1	CV, fan speed[a]	34.5, 96.1 %	max 104
lever	SP, corrected N_1	0, 100 %	0–100
W_f	MV, fuel	0.164, 1.241 kg/s	0–1.6
N_2	state, core speed[a]	60.6, 97.2 %	max 105
EGT	limited, indicated	444, 872 °C	max 950
P_3	state, measured	5.8, 30.2 bar	—
SM	truth, HPC margin	22.8, 22.0 %	min 8
F_n	truth, net thrust	12.0, 120.2 kN	—
P_{13}, P_{25}, P_{45}, P_5	states, plenums	—	—
$W_{f,v}$, T_{tc}, b	states, valve, TC, bleed	—	—
h, M_0	DV, altitude, Mach	0, 0	12 km, 0.85
ΔT	DV, ISA offset	0 K	−30 to 40
d	DV, deterioration	0	0–100 %
W_{cust}	DV, customer bleed	0	0–8 %
events	DV, slam, chop, bodie, stall	—	—

[a] Percent of gauge speeds of 5100 and 14 500 rpm.

3.3.2 A Closed-Form Compressor Map

One closed form serves the fan's bypass stream, the fan root with the booster, and the HPC. With ψ the normalized pressure rise and n the corrected speed over its design value, the normalized corrected flow m is an explicit function of the pressure ratio, as shown in Equation (3.2).

$$\begin{aligned} \psi &= \frac{\pi - 1}{\pi_d - 1}, \qquad W_c = M_{ref}\, m \\ m &= n^a \left[1 - k\left(\frac{\psi}{S n^b}\right)^q\right], \qquad \psi_s(m) = S\left(\frac{m}{1-k}\right)^{b/a} \\ \mathrm{SM} &= \frac{1 + (\pi_d - 1)\psi_s(m)}{\pi} - 1 \end{aligned} \tag{3.2}$$

where each speed line runs from a choked top at $\psi = 0$ to its surge point $\big((1-k)n^a,\ Sn^b\big)$, so eliminating n gives the surge line ψ_s in closed form, and SM is the margin at constant corrected flow over the operating pressure ratio (some definitions divide by the surge line's ratio instead). For the HPC $a = 2.1$, $b = 2.9$, $k = 0.3$, $q = 3$ and $\pi_d = 12.5$, and $S = 1.0898$ is solved by bisection so that the design point has 22 % margin. At that point $m = 0.768$, the surge line sits at $\pi = 15.25$ and $M_{ref} = 35.33\,\mathrm{kg/s}$. The efficiency is a declared island, $\eta = \eta_{max} - e_1(n - n_e)^2 - e_2(r - 0.72)^2$ clipped to 0.30 to 0.95, with $r = \psi/(Sn^b)$ the fraction of the way up a speed line, shifted so that each component has its declared efficiency at design. Because the flow follows from the pressure ratio, the plenum pressures can be states and no map is ever inverted.

3.3.3 Compression, Combustion and Expansion

Each compression and expansion uses a constant-property isentropic relation with a map or turbine efficiency, and each shaft power is a flow times a temperature change, as shown in Equation (3.3).

$$\begin{aligned} T_{out} &= T_{in}\left[1 + \frac{\pi^{\kappa_a} - 1}{\eta_c}\right] \quad \text{(compressor)} \\ T_{out} &= T_{in}\left[1 - \eta_t\left(1 - \pi^{-\kappa_g}\right)\right] \quad \text{(turbine)} \\ P &= W c_p |T_{out} - T_{in}|, \qquad \eta_t = \eta_{t,d} - c_t(u-1)^2 \end{aligned} \tag{3.3}$$

where $\kappa_a = 0.2857$ for air with $c_{pa} = 1004.5\,\mathrm{J/(kg\,K)}$, $\kappa_g = 0.25$ for gas with $c_{pg} = 1148\,\mathrm{J/(kg\,K)}$, u is the blade-speed ratio $N/\sqrt{T_{in}}$ over its design value, and c_t is 0.35 for the HPT and 0.30 for the LPT. The combustor holds no gas. Its exit flow must pass the HPT, whose nozzle guide vanes are

choked above a pressure ratio of 2.2, and its exit temperature follows from an energy balance on one specific heat, as shown in Equation (3.4).

$$\begin{aligned} c_{pg} W_4 T_4 &= c_{pg} W_3 T_3 + \eta_b \,\mathrm{LHV}\, W_f, \qquad W_4 = W_3 + W_f \\ \frac{W_4\sqrt{T_4}}{P_4} &= \Phi_H\, g(\pi_H), \qquad g = \sqrt{1-x^2},\; x = \frac{2.2-\pi_H}{1.2} \\ \frac{W_L\sqrt{T_{45}}}{P_{45}} &= \Phi_L \sqrt{1-\pi_L^{-2}} \end{aligned} \tag{3.4}$$

where $P_4 = 0.95P_3$, $g = 1$ above $\pi_H = 2.2$, LHV is 43.0 MJ/kg, $\eta_b = 0.995$, and the LPT follows Stodola's ellipse law. With $G = \Phi_H P_4 g$ the first two lines close as one quadratic, $T_3 W_4^2 + (Q/c_{pg} - W_f T_3) W_4 - G^2 = 0$ with $Q = \eta_b \mathrm{LHV}\, W_f$, and then $T_4 = G^2/W_4^2$. This is the mechanism of the whole lesson. More fuel at the same core speed raises T_4, the choked HPT passes the same $W_4\sqrt{T_4}$ only at a higher P_4, and the HPC's point climbs its speed line. Fuel richer than a fuel-air ratio of 0.045 releases no more heat (a teaching cap that keeps T_4 in the flame range with a constant c_p). The exhaust gas temperature (EGT) is read a quarter of the way through the LPT's temperature drop, $T_{EGT} = T_{45} - 0.25(T_{45} - T_5)$, as many engines of the class measure it in the LPT's front stages, and the combustor blows out when W_f/P_3 falls under 9 g/s per bar.

🕮 **Pause.** Try Exercise 3.1 before reading on.

3.3.4 Spools, Plenums and Thrust

The two spools and the five plenums carry the dynamics, as shown in Equation (3.5).

$$\begin{aligned} J_1 N_1 \frac{\mathrm{d}N_1}{\mathrm{d}t} &= \eta_m P_{LPT} - P_{fan} - P_{boost} \\ J_2 N_2 \frac{\mathrm{d}N_2}{\mathrm{d}t} &= \eta_m P_{HPT} - P_{HPC} - P_{ext} \\ \frac{\mathrm{d}P_i}{\mathrm{d}t} &= \frac{RT_i}{V_i}\left(W_{in,i} - W_{out,i}\right),\; i \in \{13, 25, 3, 45, 5\} \\ F_n &= c_v \textstyle\sum_e A_e \left[\rho_e V_e^2 + p_e - p_0\right] - W_2 V_0 \end{aligned} \tag{3.5}$$

where N is in rad/s, e runs over the core and bypass nozzles, $W_2 = W_{13} + W_{25}$, $\eta_m = 0.99$, $P_{ext} = 150\,\mathrm{kW}$ is the accessory offtake, $R = 287.05\,\mathrm{J/(kg\,K)}$, and each volume V_i is sized to a 25 ms residence time at design (a real combustor is nearer 10 ms). The plenum outflows are the next component's map flow, and the HPC exit also loses the handling bleed $W_{bl} = bC_{bl}P_3/\sqrt{T_3}$ and the customer bleed on the same orifice law, sized so that the handling bleed passes 15 % of design core flow fully open. Both nozzles are convergent, choked or not, with $c_v = 0.985$ and pressure losses of 2 and 1 % upstream of them. The spool inertias $J_1 = 75\,\mathrm{kg\,m^2}$ and $J_2 = 10\,\mathrm{kg\,m^2}$ are geometric estimates for a 1.55 m fan, 24 blades and their disks on the low spool and nine HPC disks with one HPT stage on the high spool. The build's first guesses, 32 and 2.4 kg m^2, accelerated the engine from idle to takeoff in 1.2 to 1.5 s, faster than the class.

The metering valve, the thermocouple and the bleed valve are first-order lags, $\tau_v \dot{W}_{f,v} = W_f - W_{f,v}$, $\tau_{tc}\dot{T}_{tc} = T_{EGT} - T_{tc}$ and $\tau_b \dot{b} = b_{cmd} - b$, with $\tau_v = 0.05\,\mathrm{s}$, $\tau_{tc} = 1.0\,\mathrm{s}$ and $\tau_b = 0.3\,\mathrm{s}$.

3.3.5 Surge, Stall and Deterioration

A surge is the operating point reaching the surge line, SM ≤ 0, detected once at the end of a step. It starts a stall, and a stall started by an inlet distortion event behaves the same way. A stalled HPC delivers its flow only at a lower pressure rise, read from the map at $\psi/(1-d_s)$ with $d_s = 0.35$, its efficiency falls by $0.6d_s$, and the stall clears once the point has stayed below $r_u = 0.65$ of its speed line's height to surge for 0.2 s. These values were chosen from measured line positions: steady running sits at 0.90 to 0.92 of the way to surge, a stall held at constant fuel at 0.72, and fuel on the

Table 3.2 Declared Parameters. Fitted to the Class (F), Estimated (E) or a Teaching Value (T). All Below the Line Are Adjustable in the Parameters Panel

Symbol	Meaning	Value	Unit	
W_2, BPR	takeoff airflow, bypass ratio	355, 5.3	kg/s, —	F
π_{fan}, π_{bst}, π_{HPC}	design ratios	1.72, 2.40, 12.5	—	T
T_4	takeoff turbine inlet	1640	K	F
η fan, booster, HPC	design	0.89, 0.88, 0.85	—	T
η HPT, LPT	design	0.88, 0.90	—	T
$N_{1,d}$, $N_{2,d}$	design speeds	4900, 14,100	rpm	T
η_m, η_b, c_v	shaft, burner, nozzle	0.99, 0.995, 0.985	—	T
LHV, FAR_{max}	fuel, rich cap	43.0, 0.045	MJ/kg, —	T
fan a, b, k, q, SM_d	bypass map	1.05, 2.0, 0.3, 2.5, 18	—, %	T
booster, same	core map	1.30, 2.2, 0.3, 2.5, 20	—, %	T
HPC a, k, q	HPC map	2.1, 0.3, 3	—	T
π_{ch}, f_{EGT}	HPT choke, EGT plane	2.2, 0.25	—	T
τ_i	plenum residence	0.025	s	T
C_{bl}	bleed, fully open	15	% core	T
J_1, J_2	spool inertias	75, 10	kg m^2	E
P_{ext}	accessory offtake	150	kW	T
SM_d, b	HPC margin, exponent	22, 2.9	%, —	T
τ_v, τ_{tc}, τ_b	valve, TC, bleed lags	0.05, 1.0, 0.3	s	T
$(W_f/P_3)_{LBO}$	lean blow-out	9	g/s per bar	T
d_s, r_u	stall depth, clearing line	0.35, 0.65	—	T
wear, 100 %	HPC η, flow, surge, HPT η	3, 3, 4, 2	pt, %	T

deceleration floor with the bleed open at 0.64, so a hung stall and a recovered one are separated. Deterioration at 100 % removes 3 points of HPC efficiency, 3 % of its flow capacity, 4 % of its surge line's pressure rise and 2 points of HPT efficiency. The surge-line loss is a teaching value with no source. Without it, efficiency and flow loss alone moved the takeoff margin from 22.0 to 22.3 %, the wrong way for the lesson, and with it the margin falls to 17.8 % while the EGT rises 59.8 K at the same thrust. Variable stator vanes are folded into the HPC map on their nominal schedule, and an offset from it moves flow and the surge line by declared sensitivities of 1.2 and 1.0 % per degree.

3.3.6 Instruments

The controller receives a packet and nothing else. Speed pickups report N_1 and N_2 in percent with 0.02 % of colored noise, the thermocouple state carries 1.5 K, P_3 passes a 0.02 s lag with 0.2 % noise, the fuel flowmeter a 0.1 s lag, and the fan-face probes for T_2 and P_2 a 0.5 s lag. The noise is first-order filtered Gaussian, seeded from the case, so a run replays identically after Reset (Section 1.6.1). The surge margin, the thrust, T_4, the true EGT and the stall and flame states are truth, logged with a prefix and drawn dashed, and an automated check rejects any read of them in the controller's source.

3.3.7 Parameters, Initialization and Numerics

The declared values are collected in Table 3.2. A calibration at load sizes every flow capacity, nozzle area and volume so that the sea-level static takeoff point of the table is an exact steady state, and an independent hand calculation from the declared values reproduces the engine's 120.18 kN, 1.2405 kg/s of fuel, 10.322 g/(kN s), $T_3 = 855.6$ K, $T_{45} = 954.3$ °C and an EGT of 872.0 °C, with both nozzles unchoked at takeoff (core 525 m/s, bypass 307 m/s). Every run starts at a genuine steady state found by a damped Newton method on the seven gas-path derivatives with the fuel as an eighth unknown, for the lever's corrected N_1 in Auto, the hand-set fuel in Manual, or the EGT limit if it binds first. A start the corrected-similarity guess misses walks down the steady line from takeoff, and a start with no running steady state, or a step that turns non-finite, holds the run with a note saying it has left the model's range. The state then advances by fourth-order Runge-Kutta at $\Delta t = 0.005$ s, the controller runs every 0.01 s after a priming execution at $t = 0$, and a row is logged every 0.05 s, on the engine of Section 1.6.1.

Halving the step to 0.0025 s moves case 3's minimum surge margin at 8 % from 9.555 to 9.565 % and its time to 95 % from 4.745 to 4.750 s. Headless, a simulated second costs 1.0 ms, and the browser's fastest setting, five times real time, plays the 20 s challenge in 4.0 s.

3.3.8 Assumptions

The specific heats of air and gas are constant, the plenums isothermal and the combustor without volume or combustion delay, and there is no heat soak into casings and disks, no tip-clearance transient, no Reynolds-number effect at altitude and no cooling air. Each of these changes real transient margins by a point or more. The fan and booster have maps but no surge model, so only the HPC can stall. The stall is a declared loss of pressure rise, not a post-stall model of rotating stall or deep surge. The lever's flight idle is a corrected fan speed and the minimum fuel a fixed 0.06 kg/s, both sized for the low, slow part of the envelope, and there is no minimum core speed, so in fast, thin air at idle the core windmills and the run holds with a note. Every limit, the 8 % margin floor, the 950 °C EGT line, the overspeed limits of 104 and 105 % and the blow-out ratio, is a teaching value, and a real engine's come from its type certificate data sheet and its maker's operating limits.

3.4 The Controller as Implemented

The controller executes every $\Delta t_c = 0.01$ s from the measurement packet alone and emits one fuel command. Its loops are written in the application rather than taken from the shared velocity-form PID of Section 1.6.2, so that the tracking can be switched off and read. Each proportional-integral (PI) loop has no derivative term.

3.4.1 Power Management and the Governor

The lever sets a corrected fan-speed target from a table that makes sea-level static thrust linear in the lever, from 34.5 % corrected N_1 at flight idle to 96.08 % at takeoff, and the physical target is $N_{1t} = N_{1c}(\text{lever})\sqrt{\theta_2}$ with θ_2 from the fan-face probe. The governor's demand is $u_{gov} = Ke + I$ with $e = N_{1t} - N_{1,m}$. Its default gain is 0.2 kg/s of fuel per percent of N_1 with an integral time of 1.0 s. Scheduled on corrected core speed $N_{2c} = N_{2,m}/\sqrt{\theta_2}$, the gain becomes $K = K_p g_K(N_{2c})$ and the integral time $T = T_i g_T(N_{2c})\sqrt{\theta_2}/\delta_2$. The factors come from the eigenvalues of the seven-state Jacobian of the gas path along the steady line, g_K the design point's high-frequency gain $K_{ss}|\lambda_1|$ over its local value and g_T the local spool time constant $1/|\lambda_1|$ over the design one, with $K_{ss} = \mathrm{d}N_1/\mathrm{d}W_f$ and λ_1 the slowest eigenvalue. Over N_{2c} from 56 to 104 %, g_K runs from 0.55 to 1.11 and g_T from 7.48 down to 0.87. A first schedule built on the steady gain alone made the loop slower without damping it better, because K_{ss} varies sevenfold along the line while $K_{ss}|\lambda_1|$ varies only between 44 and 95.

3.4.2 Caps, Floors and the Selector

Each cap asks for at most a fuel and each floor for at least one, and the selector combines them as shown in Equation (3.6).

$$
\begin{aligned}
W_{acc} &= R_{acc}(N_{2c}, \mathrm{SM}_{acc})\, P_{3,m}\sqrt{\theta_2} \\
W_{dec} &= R_{dec} P_{3,m} \\
W_{rate} &= W_{f,k-1} + \dot{W}_{max}\Delta t_c \\
\bar{W} &= \min\left(u_{gov}, W_{acc}, u_{EGT}, u_{N1}, u_{N2}, W_{rate}, W_{stall}\right) \\
W_{f,k} &= \mathrm{clip}_{[0,\,1.6]}\left(\max(W_{dec}, W_{min}, \bar{W})\right)
\end{aligned}
\tag{3.6}
$$

where R_{acc} is the acceleration schedule's table of $W_f/(P_3\sqrt{\theta_2})$ against N_{2c} for a design surge margin SM_{acc} (interpolated between tables for 4 to 20 %), $R_{dec} = 13$ g/s per bar is 44 % above the blow-out ratio, $W_{min} = 0.06$ kg/s, $\dot{W}_{max} = 2$ kg/s per second, W_{stall} is $-\infty$ while a stall recovery cuts the fuel and $+\infty$ otherwise, and 1.6 kg/s is the valve's full flow. The EGT limiter is a PI on $950 - \mathrm{EGT}_m$ at

6 g/s per kelvin and 1.0 s, and the overspeed limiters are PIs on 104 and 105 % − N_m at 0.2 kg/s per percent and 0.5 s, scheduled with the governor. The floors come last, because keeping the flame lit outranks every limit a cap protects, the order of floors after caps of Section 1.4.3. The fuel rate limit is one of the caps, inside the selector where every PI loop sees it, one of the placements Section 1.4.5 compares. The loop whose demand wins holds the valve, and the Ladder view lights it.

The schedule's tables were designed on the nominal engine at sea-level static ISA, as the ratio that puts the HPC at the design margin with the spools held at their steady speeds and the pressures solved. At 8 % the ratio rises from 38.5 to 56.0 g/s per bar over N_{2c} from 54 to 104 %. The table is corrected as fuel over $\delta_2\sqrt{\theta_2}$ divided by pressure over δ_2, which is why $\sqrt{\theta_2}$ multiplies it. A usability review found the first, uncorrected form wanting. On W_f/P_3 alone, a 70 to 80 % lever step at 10 668 m and Mach 0.8 dipped the margin to 6.5 %, under the floor, and the corrected table keeps 10.1 to 10.3 % there. A technical review then confirmed θ_2 against θ_3, since at a corrected operating point every station's θ scales with θ_2, T_3 is not measured, and a θ_3 correction would loosen the cap by up to 1.0 % during case 3's slam, the wrong way.

3.4.3 Integrator Tracking

With tracking on, every PI's integrator is pulled toward the fuel actually commanded by back-calculation [6], with the tracking time equal to its integral time, as shown in Equation (3.7).

$$\begin{aligned} u_{i,k} &= K_i e_{i,k} + I_{i,k} \\ I_{i,k+1} &= I_{i,k} + \left[\frac{K_i}{T_i} e_{i,k} + \frac{W_{f,k} - u_{i,k}}{T_i}\right]\Delta t_c \end{aligned} \tag{3.7}$$

where i is the governor, the EGT limiter or an overspeed limiter. The loop that holds the valve has $u_i = W_f$ and sees no correction. For any other the $K_i e_i$ terms cancel, so its integrator follows the commanded fuel one integral time behind it, $\dot{I}_i = (W_f - I_i)/T_i$, and its demand rests at its proportional distance $K_i e_i$ above the fuel less that trail. A limiter therefore takes over from the fuel in the line, bumplessly, and only as it nears its limit. This is the external reset of Section 1.4.4 with $T_t = T_i$, Equation (1.4), applied to every loop of the selector, and Volume 7, Chapter 4 uses the same back-calculation on a slip loop under a torque limit. With tracking off each integral runs on its own error, $I_i \leftarrow \text{clip}_{[0,1.6]}(I_i + K_i e_i \Delta t_c / T_i)$, and a loop that does not hold the valve winds up against that clamp. At $t = 0$ and in Manual the governor's integrator is set to $W_f - Ke$ and every limiter's to W_f, so a return to Auto is bumpless. The plan of the application asked for every integrator to be reset each scan to the applied fuel, the one-scan limit of this law, but with that reset the EGT limiter won the valve on its rate of approach 215 K under its limit on a sea-level slam, while longer tracking times of 1.5 and 2 integral times let the challenge's EGT overshoot to 973 and 1012 °C.

3.4.4 Bleed, Stall Recognition and Recovery

The handling bleed opens fully below 55 % corrected core speed and shuts 5 % above it. A stall is recognized from measurements alone: $P_{3,m}$ down 6 % or more over the last five scans (50 ms) while the indicated EGT has not fallen by more than 1 K over the same window, with $N_{2,m}$ above 25 %. A stall drops P_3 and heats the gas, while a chop, a deceleration or a flameout drops P_3 because the gas cooled first. The recovery holds the fuel on the deceleration floor for 1 s and the bleed open for 3 s, a timed sequence that a second stall restarts and that never latches.

This rule replaced one that asked for the fuel command not to have been cut over the window. The earlier rule recognized 1 of 30 stalls injected during case 3's slam and left 29 still stalled 8 s later, because the ratio-unit schedule cuts the fuel with P_3, and it read case 5's chop without its floor as a stall 0.055 s after the chop. The present rule recognizes and clears all 30 mid-slam stalls and makes no false recognition in 936 ordinary maneuvers (four altitudes, three days, two Mach numbers, four schedule margins, both trackings, five lever moves). Its blind spot follows from the signature it uses. A stall within 0.3 s of a lever pull from 100 to 80 %, or within 0.7 s of a pull to 50 %, arrives while

the gas is still cooling, goes unrecognized and hangs. After a chop to idle such a stall is also missed but clears by itself as the operating point falls down its speed line.

3.4.5 Three Models

The plant is Section 3.3. The identified model is the linearization along the steady line that sets the gain schedule. The controller's model is its tables, designed once on the nominal engine at sea-level ISA, so a worn engine, a hot day or a changed map parameter meets schedules that do not know it.

3.4.6 Predictive Fuel Governor

The optional governor solves a fuel plan subject to the same current limiter votes, while the rate limiter, stall cut and flame floors still act every controller scan. This is receding-horizon optimization in the sense of industrial MPC [17], set up as in Section 1.6.3, not a replacement for the safety selector. Only the measured N_1, N_2 and indicated EGT enter the model. Three local fuel-to-output paths have the form

$$G_i(s) = \frac{K_i}{(1+\tau_{i1}s)(1+\tau_{i2}s)}. \tag{3.8}$$

At 0.6 kg/s, symmetric 0.003 kg/s steps on the nominal sea-level engine give $(K_i, \tau_{i1}, \tau_{i2}) = (53.725, 0.714, 0.200)$ for N_1, $(28.060, 0.433, 0.093)$ for N_2, and $(398.957, 0.347, 0.119)$ for EGT. Gains use percentage points or kelvin per kg/s, with times in seconds. After 30 seconds settling and 20 seconds observation, RMS fit residuals are 0.000635 and 0.000420 percentage points and 0.00987 K, respectively. The separate idle experiment has much larger gain and lag, so these paths are retained as one local nominal model rather than an envelope model.

Six states represent the two lags of each path, anchored at the first measured packet and known command. Each 0.01 second scan propagates the model and filters the measured-minus-predicted residual with gain 0.05 on each output. This bias adaptation is distinct from proving offset-free operation under general mismatch [18]. No true temperature, surge margin, thrust, plant state or changed kinetic or map parameter enters the prediction. Plans execute every 0.05 seconds with 40 predictions over 2 seconds and eight graduated fuel blocks. The cost is

$$\begin{aligned} J = {} & \sum_{k=1}^{40} (N_{1,k} - N_{1,\text{target}})^2 + 100 \sum_j (\Delta W_j)^2 \\ & + 10^3 (s_1^2 + s_2^2) + 0.1 s_E^2 + 10^3 (s_1 + s_2) + 10 s_E. \end{aligned} \tag{3.9}$$

Here $s_1, s_2, s_E \geq 0$ soften the predicted speed and indicated-EGT ceilings when their corresponding limiters are enabled. Each slack is shared over its full horizon. Current limiter votes form a hard fuel box, with the shipped floor precedence if a cap conflicts with a flame floor. The physical valve remains bounded between 0 and 1.6 kg/s. Fuel-block changes are bounded by the requested rate times 0.05 seconds, with the existing 0.01 second rate selector still above the result. The governor tracks applied fuel exactly. Limiter PIs retain their original back-calculation law, always enabled under MPC, because their proportional distance from a limit gives the safety vote its meaning. Failed, nonoptimal, nonfinite, malformed or out-of-box plans restore the tracked classical governor.

3.5 Ten Cases, Measured

The figures of this section are headless runs at seed 20261027, the default, stepped exactly as the browser steps the engine, each case following its own instructions. Settings named in a row are entered before Run, so they are part of the starting state, and a slam is the lever moved to 100 % at the time named. The time to 95 % runs from the slam to 95 % of the rated thrust at that condition, the nominal engine's steady takeoff thrust or, if its EGT would pass 950 °C first, its thrust at that line. The minimum surge margin is the truth's, with stalled steps left out because a stall is counted instead. Each case runs the same whether it is opened first, picked from the menu with another case

Table 3.3 Ten Scenario Comparisons and Their Completion Criteria

#	Case and setting	Outcome as measured	Required to complete (kind)
1	Manual at flight idle, fuel by hand	1.2 kg/s in one move surges 0.020 s later, ramps of 0.1 and 0.2 kg/s per second dip to 8.7 and 2.0 %, 0.3 surges	set the fuel to 0.8 kg/s or more in one move, watch until SURGE, confirm (demonstration)
2	Governor, schedule off, slam	surge 0.125 s after the slam, 9 surges in the next 10 s, N_1 down to 19.5 %	slam with the schedule off, watch until SURGE, confirm the governor's demand (demonstration)
3	Schedule at 10 %, slam	5.37 s at 11.3 %, at 8 % 4.74 s at 9.5 %, tracking off N_1 peaks at 97.98 %	slam at 10, then at 8 % within 5 s above 8 %, then with tracking off see N_1 pass its target (experiment)
4	ISA + 30 K, slam	EGT limiter from 3.94 s, 111.3 kN against 120.2 kN at ISA	slam, watch the EGT limiter hold the valve 3 s, confirm the thrust (experiment)
5	Takeoff, chop, floor off	flameout 0.105 s after the chop, with the floor N_1 near idle at 3.26 s	see FLAMEOUT, then with the floor on chop to within 2 points of idle lit (experiment)
6	10 668 m, Mach 0.8, lever 70, gains fixed	N_1 77.6 % against 83.9 at sea level, 14.6 kN against 87.7, 70 to 80 % overshoots 0.26 points fixed, 0.01 scheduled	step 70 to 80 % fixed and read the Overshoot tile, repeat scheduled (experiment)
7	Takeoff, inlet stall	recognized 0.025 s, cleared 0.39 s, back to 95 % in 4.88 s, recovery off hung at 89.5 kN	press Stall, see it clear and the thrust back to 95 %, then with the recovery off see it hang 5 s (experiment)
8	ISA + 15 K, wear 100 % at 2 s	EGT limiter 0.59 s later, 110.0 kN, 91.5 % of the rating, SM 21.9 to 18.4 %, at ISA + 30 K 86.6 %	set wear to 100 %, watch the limiter trim the thrust under 95 % for 5 s, confirm (demonstration)
9	Predictive fuel governor, sea-level slam	MPC 5.21 s at 9.69 % margin, peak EGT 884.3 °C	select PI selector once, return to MPC, run the 15 s comparison (experiment)
10	Challenge: bodie at 3048 m, ISA + 30 K	shipped fails (8.49 s, 996 °C), suggested passes (5.86 s, 9.4 %, 938 °C)	meet the target of Table 3.5 at 20 s with the parameters and disturbances as given (challenge)

Table 3.4 Measured Slams. Time to 95 % of the Rating, Smallest True Surge Margin, and Peak Indicated (True) EGT

Case	Setting	t_{95} (s)	SM (%)	EGT (°C)
2	schedule off	—	surge	709 (1525)
3	6 %	4.30	7.8	902 (1027)
	8 %	4.74	9.5	899 (1022)
	8 %, tracking off	4.66	9.5	927 (1060)
	10 % (shipped)	5.37	11.3	896 (1011)
	12 %	6.27	13.0	889 (1005)
	14 %	7.55	14.8	879 (985)
4	ISA + 30, tracking on	6.25	9.3	955 (1020)
	ISA + 30, tracking off	4.75	9.3	996 (1140)
7	stall at takeoff, recovery on	4.88[a]	12.7	905 (1080)

[a] From the stall, not a slam. Case 2's figures are over the 10 s after its first surge.

already loaded, or restarted by Reset. The cases are listed in Table 3.3 and the measured comparisons in Table 3.4, which Figure 3.2 redraws as bars against the three limits.

3.5.1 Fuel Faster Than the Spools

Case 1 is the plant without a controller. Takeoff fuel in one move surges the compressor 0.020 s after the move (0.018 to 0.027 s over 20 instants of the move), and the path on the map climbs nearly straight up its speed line. In case 2's slam the corrected flow even falls, from 12.9 to 11.7 kg/s, while the pressure ratio rises from 4.98 to 5.48, as shown in Figure 3.3. Added slowly, 0.1 kg/s each second, the fuel lets the spools keep up and the margin dips only to 8.7 %, while 0.2 kg/s each second dips it to 2.0 % and 0.3 kg/s surges. The margin is spent by the rate of fuel. Case 2 gives the same engine its governor and no schedule. At the slam the governor's error is 62 points of N_1, so only the 2 kg/s-per-second rate limit stands between its demand and the valve, and 0.33 kg/s has passed the valve when the path reaches the surge line 0.125 s after the slam (0.123 to 0.132 s over 20 instants). Run on, the stall recovery ends each surge and the governor causes the next, 9 in 10 s, while N_1 falls to 19.5 % because each recovery puts the fuel on the floor.

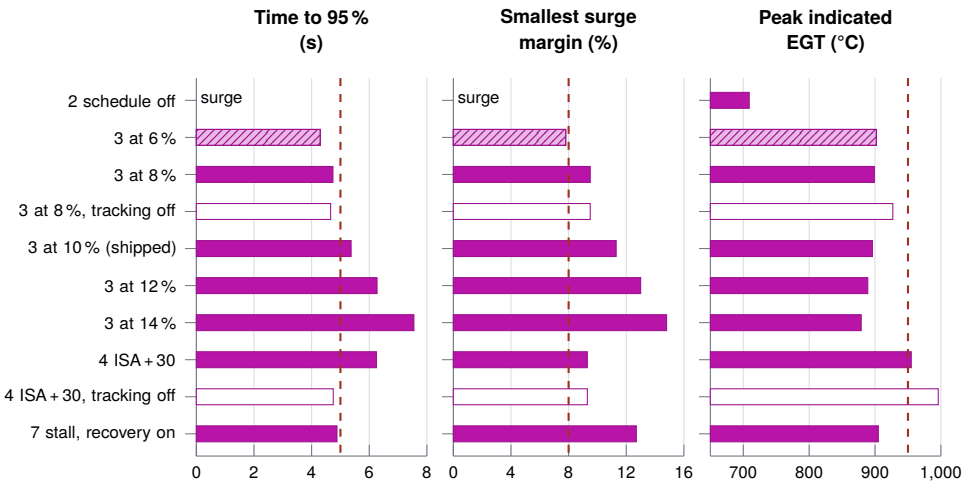


Figure 3.2 Table 3.4 redrawn. Dashed lines mark the 5 s of paragraph (b), the 8 % margin floor and the 950 °C indicated limit, and case 7 is timed from its stall. White bars are runs with integrator tracking off, and the hatched bar is the 6 % schedule, under the floor. Notice that the design margin trades time for margin row by row, that only the 8 % schedule meets both lines of a sea-level slam, and that switching tracking off shortens the time but raises the peak indicated temperature, to 996 °C on the hot day.

> **TRY IT IN THE APP** **1 · Fuel by Hand: Slam It (Start Here)**
>
> Load the scenario, press Run on the Map view and find the operating point below the surge line. Set Fuel flow to 1.2 kg/s in one move and watch the dashed path. It climbs nearly straight up its speed line and reaches the surge line 0.020 s after the move, while the core speed has hardly changed.

3.5.2 The Schedule Against the Five Seconds

Case 3 ships with the schedule designed for 10 %. The path hugs the margin line, the schedule holds the valve for 5.18 s, and 95 % comes 5.37 s after the slam (5.36 to 5.39 s over the slam instant and three seeds), too late for paragraph (b). At 8 % the schedule holds for 4.40 s, 95 % comes at 4.74 s, and the margin never falls under 9.5 %, a little above the line because the low spool lags the high one, as shown in Figure 3.3. Over 40 slam instants the time stays between 4.735 and 4.760 s. A 6 % schedule would take 4.30 s but dip to 7.8 %, under the floor, while 12 and 14 % take 6.27 and 7.55 s, as listed in Table 3.4. The hand-overs are continuous. In the 8 % slam the valve passes from the governor to the rate limit, the schedule, the EGT limiter and back to the governor, and the largest step in the command at any hand-over is 0.020 kg/s, one scan of the rate limit.

Near the top of that slam the EGT limiter holds the valve for 0.43 s, taking it 4.43 s after the slam with the gauge at 861 °C, 89 K under its line. This looks like a fault and is not one. The gauge is climbing 136 K/s on the EGT card and lags the gas by 1 s, and the true EGT is already 1021 °C. With tracking the limiter's integrator trails the rising fuel by about one integral time, and the limiter's demand meets the fuel when its proportional term has shrunk to that trail, 0.539 kg/s against a trail of 0.534 kg/s at the takeover. The limiter is protective by rate through the back-calculation trail, and it slows the last of the acceleration. With tracking off, the same 8 % slam reaches 95 % sooner, at 4.66 s, but N_1 overshoots to 97.98 % against its 96.08 % target, because the governor's integrator wound up while the schedule held the valve. With tracking on it peaks at 96.10 %. Figure 3.4 shows the application at the 95 % pause of the 8 % slam with tracking on.

Pause. Try Exercise 3.2 before reading on.

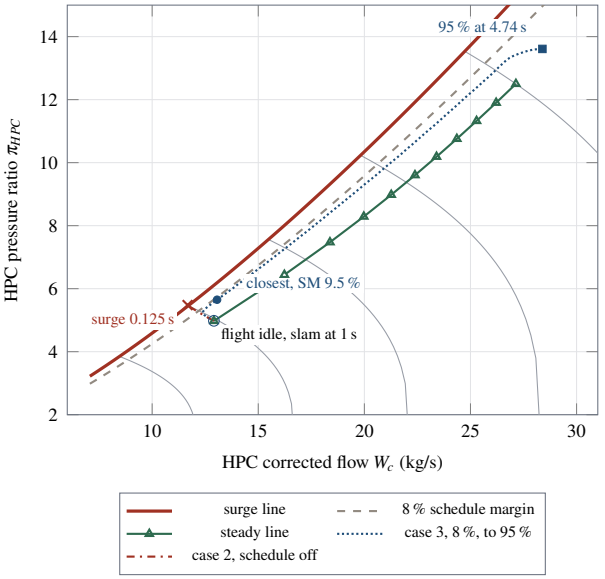


Figure 3.3 HPC map from the application's own map functions, with two runs at the default seed. Speed lines at $n = 0.6$ to 1.0 (thin gray), the surge line (very thick solid), the 8 % schedule-margin line (dashed) and the steady line at sea-level ISA (solid with triangles). Case 2 (schedule off, dash-dotted, its surge marked by a cross) climbs its speed line to the surge line 0.125 s after the slam, and case 3 (schedule at 8 %, dotted) runs along the margin line to 95 % thrust.

3.5.3 Heat, Chop, Altitude, Stall and Wear

On an ISA + 30 K day at sea level the rating is EGT-limited at 111.2 kN. In case 4 the EGT limiter first holds the valve 3.94 s after the slam and keeps it, and 20 s after the slam the engine makes 111.3 kN against 120.2 kN at ISA, 7.4 % less, with N_1 at 97.7 % short of its 101.0 % target. The indicated EGT peaks at 955 °C while the gas reaches 1020 °C, and with tracking off the limiter's wound-up integrator lets the indication overshoot to 996 °C. The flat rating ends where the takeoff lever's EGT reaches the line, at ISA + 20.0 K. Chapter 9 meets the same exhaust-temperature limit and ambient derating on a constant-speed gas turbine.

> **TRY IT IN THE APP** **4 · A Hot Day: The EGT Limiter**
>
> Run the scenario, slam the Thrust lever to 100 % and watch the Ladder view. The EGT limiter first holds the valve 3.94 s after the slam and keeps it, and the engine makes 111.3 kN instead of 120.2 kN. Then set the lever back to 0 %, set Integrator tracking Off, press Reset, Run and slam again: the indicated EGT now overshoots to 996 °C.

In case 5 the governor answers a chop from takeoff by cutting to the 0.06 kg/s minimum, which is 2 g/s per bar at takeoff pressure. With the floor off, the ratio crosses the blow-out line 0.105 s after the chop (0.103 to 0.112 s over 20 instants). With the floor on, the fuel follows P_3 down at 13 g/s per bar, the ratio never falls under 13.2, and N_1 is within 2 points of idle 3.26 s after the chop.

Case 6 flies the lever at 70 % at 10 668 m and Mach 0.8. The lever asks for the same corrected speed, 83.9 %, and the cold fan face ($\theta_2 = 0.86$) brings the physical N_1 down to 77.6 %. The thrust is 14.6 kN against 87.7 kN at sea level, the EGT 588 against 748 °C and the fuel 0.267 against 0.848 kg/s. At the same corrected N_1 of 95 % every corrected quantity matches sea level within 0.32 % at 3048 m and 0.19 % on an ISA + 30 K day, and within 2.06 % at 10 668 m, mostly because the fixed 150 kW offtake is a larger share of the smaller core power there (0.41 % without it). A step from 70 to 80 %

Table 3.5 The Challenge Over 20 s. Target: 95 % Within 7.0 s, SM at Least 8 %, Indicated EGT at Most 950 °C

Settings	t_{95} (s)	SM (%)	EGT (°C)	Verdict
shipped (fixed, 14 %, tracking off)	8.49	14.8	996	fails
8 % schedule alone	5.17	9.4	1019	fails
tracking on alone	8.55	14.8	934	fails
8 % + tracking, scheduled (suggested)	5.86	9.4	938	passes
8 % + tracking, fixed gains	5.86	9.4	936	passes
6 % + tracking	5.44	7.7	936	fails
10 % + tracking	6.46	11.2	935	passes
12 % + tracking	7.30	13.0	935	fails
shipped + tracking + floor 20 g/s per bar	6.09	15.0	935	passes

overshoots by 0.26 points of N_1 with fixed gains, 6 to 7 % of the step, and by 0.01 points scheduled. Both are stable. At the shipped gain, 2 % lever steps at nine points from sea level to cruise overshoot 7 to 21 % fixed and 0 to 8 % scheduled, so what the schedule buys is uniform damping. The corrected schedule keeps the margin of lever steps at 8.84 % or more over 7 altitudes, 3 Mach numbers and 5 days, and of slams from flight idle at 8.1 % or more up to 9144 m. Above that the envelope has a corner. At 10 668 m and higher with Mach 0 to 0.4, slams from idle fall to 0 to 7.3 % or surge, identically with and without $\sqrt{\theta_2}$ at Mach 0, because the 0.06 kg/s minimum fuel there exceeds the flight-idle fuel and, as a floor, outranks the schedule. That corner is a test-cell condition outside every case, and it shows that a floor outranks every cap. In the same sweep the uncorrected table took 115 of 236 transients under 8 %.

🕮 **Pause.** Try Exercise 3.3 before reading on.

In case 7 an inlet distortion stalls the HPC at takeoff. The controller recognizes it 0.025 s later, the fuel goes to the floor and the bleed opens, the stall clears 0.39 s after it began, the thrust dips to 38.1 kN, and the schedule brings it back to 95 % of the rating 4.88 s after the stall. With the recovery off the EGT limiter holds the indication at 951 °C but the compressor stays stalled, and 20 s later the engine makes only 89.5 kN with N_1 at 85.5 %.

Case 8 wears the engine fully at 2 s on an ISA + 15 K day. The EGT limiter takes the valve 0.59 s later and trims the thrust to 110.0 kN, 91.5 % of the rating, while the margin falls from 21.9 to 18.4 %, and nothing on the flight deck but a lower N_1 says so. On an ISA + 30 K day the worn engine settles at 96.3 kN, 86.6 % of its 111.2 kN rating, and that variant is infeasible by design. A pass would hold 95 % of the rating for 2 s with the indicated EGT never over 950 °C in 25 s. None of 65 logged settings in the application's tests (16 automatic, 13 hand-set fuels, 36 hand pulses) passes, nor do 1,581 more drawn over the controller's settings and hand-set fuels, and the closest reaches 86.5 % of the rating.

3.5.4 The Challenge

The challenge starts at takeoff at 3048 m on an ISA + 30 K day, chops the lever at 2 s and slams it back 3 s later (a bodie). Over 20 s it asks for 95 % of the 82.6 kN rating within 7.0 s of the second slam, the true margin never under 8 %, no surge or flameout, and the indicated EGT never over 950 °C. It ships with fixed gains at the scheduled gains' idle values (0.16 kg/s per percent, 5.5 s), a 14 % schedule and tracking off. Table 3.5 gives the verdicts, whose verdicts repeat at seeds 1 and 2 with every figure within 0.04 s, 0.1 % and 4 K.

Two settings pass it together and neither alone. The 8 % schedule alone makes 5.17 s but lets the indication reach 1019 °C, because the EGT limiter's integrator wound up while the engine was cold, and tracking alone holds 934 °C but takes 8.55 s. The gain schedule makes no difference here (5.86 s either way), because the acceleration schedule holds the valve until 95 %. There is a second way through. Tracking with the deceleration floor raised to 20 g/s per bar passes on the shipped 14 % schedule in 6.09 s, because the floor keeps fuel in through the chop and the re-slam starts from 28.5 %

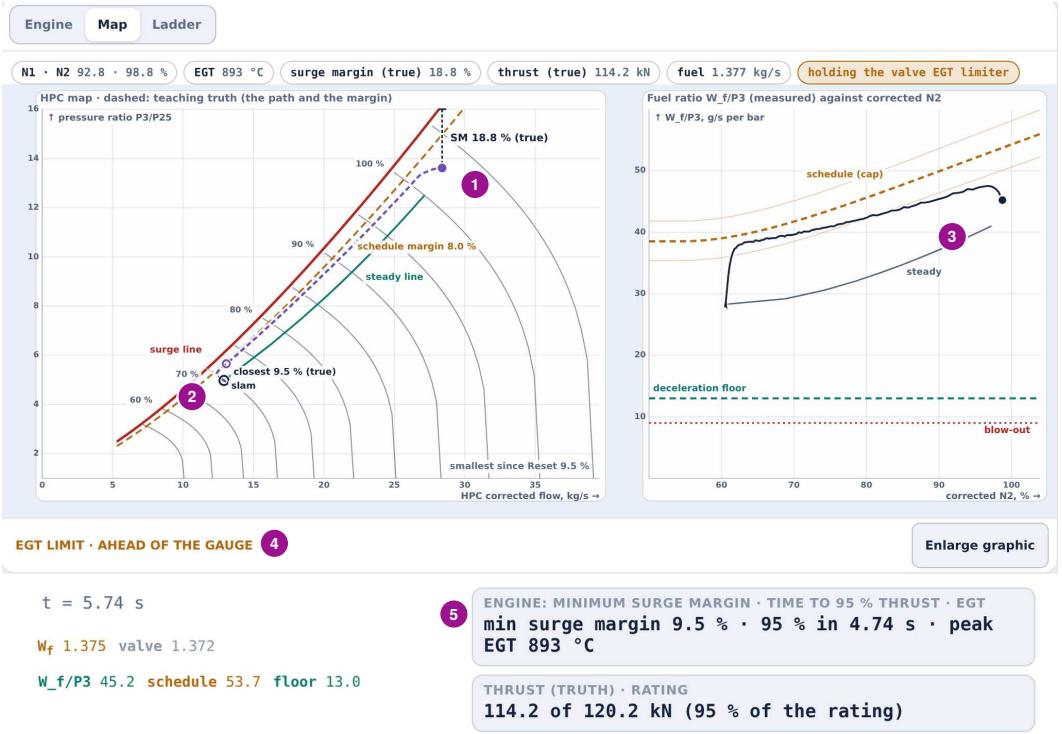


Figure 3.4 Case 3 with the schedule designed for an 8 % margin, at its 95 % pause on the Map view, $t = 5.74$ s after a slam at 1.0 s, in a composite of the application window: the plant view, with the run clock, two trend labels and two scorecard tiles set below it. On the HPC map the dashed violet path runs from the slam ring along the amber dashed 8 % line, with its closest approach marked at 9.5 % (2), and the operating point now sits at 18.8 % true margin (1). Beside it the measured W_f/P_3 of 45.2 rides under the schedule's ceiling of 53.7 g/s per bar, above the 13 g/s-per-bar floor (3), as the trend label below reads. The EGT limiter holds the valve at 1.375 kg/s with the gauge at 893 °C (status EGT LIMIT, AHEAD OF THE GAUGE (4)). The scorecard reads 95 % in 4.74 s, a minimum margin of 9.5 % and 114.2 kN of 120.2 kN (5).

of the rating instead of 20.2 %. It buys the time from the chop, not from the slam, and the verdict does not grade that.

> **DID YOU KNOW? Two Settings Pass Together, Neither Alone**
>
> From the simulator: in the challenge, the 8 % schedule alone reaches 95 % thrust in 5.17 s but lets the indicated exhaust temperature reach 1019 °C, and integrator tracking alone holds 934 °C but takes 8.55 s. Together they pass, in 5.86 s at 938 °C (Table 3.5).

The 7.0 s is a teaching value, not paragraph (b)'s 5 s, which times a slam from a stabilized idle. With the shipped floor and governor no schedule margin from 4 to 8 % gets the bodie to 95 % within 5 s with 8 % of margin, the fastest being 5.63 s at a 7 % design margin. A sweep of 3,300 settings over every control found 907 that do reach 5 s with the margin and EGT kept, as fast as 2.87 s, all by holding fuel through the chop with a higher floor or minimum fuel. With the floor and minimum fuel as shipped, 2 of 4,450 settings reach it, through a governor at a quarter of its gain with a 5 s integral time. From a stabilized idle in this air the 8 % schedule takes 7.64 s, against 4.74 s at sea level.

Table 3.6 Matched Fuel-Governor Comparisons

Case	Governor	t_{95} s	Min SM %	Peak EGT °C	Travel kg/s
Sea-level slam	PI	4.74	9.51	899.3	4.50
	MPC	5.21	9.69	884.3	1.81
Hot-day slam	PI	6.25	9.26	954.6	4.38
	MPC	6.32	9.43	954.4	3.24
Bodie, suggested	PI	5.86	9.45	938.3	4.17
	MPC	5.71	9.66	938.7	2.11
Bodie, shipped	PI	8.49	14.78	996.4	3.44
	MPC	8.34	14.89	936.1	1.93

Travel sums absolute fuel-command changes, not fuel mass burned. Surge margin and thrust are evaluated after the run, never supplied to MPC.

3.5.5 Verification and Comparison With the Class

The following checks concern the code, not the quality of control. The takeoff design point and flight idle are exact steady states, with no derivative above 1.6×10^{-14} and 1.4×10^{-13} of its state per second. At takeoff the air in equals the air out of both nozzles and the bleeds to 9.7×10^{-14}. Over a slam each spool’s kinetic energy change equals the integral of its net shaft power to 2×10^{-5} on the low spool and 4×10^{-5} on the high spool, by the trapezoid rule on the 0.005 s step. The engine’s design point equals an independent hand calculation from the declared values to the last digit quoted, and the combustor’s convention of one specific heat on both sides of the burner needs 1.6 % less fuel than air-table enthalpies would, against 13.6 % more for a balance with c_{pa} on the inlet side. The surge line in closed form reproduces each speed line’s surge point at $n = 0.6$, 0.8 and 1.0. The selector hands over without a step larger than one scan of the rate limit in every case except the commanded cut of a chop, and switching to Manual and back at 40 instants of a slam moves the valve by at most 0.014 kg/s beyond one scan of the rate limit. Across 384 corners of the sliders at the default controls no state goes non-finite, and 18 starts, all at idle in fast, thin air, hold the run as outside the model’s range, where 10 had gone non-finite before that hold was added. All 46 of the application’s checks and all 10 completion walks pass.

Agreement with published data is a narrower claim. The takeoff point, 355 kg/s of air, a bypass ratio of 5.30, an overall pressure ratio of 30.0, 120.2 kN and 10.32 g/(kN s), and the flight idle at 10.0 % of takeoff thrust with N_2 at 60.6 %, were fitted inside ranges that the build collected for this thrust class from an airworthiness type-certificate data sheet and public specification tables, which are not cited here so that no engine maker is named. Flight idle at 10 % is inside paragraph (b)’s 15 % [13], and the NASA generic engine’s controller reached 95 % from 15 % in 4.07 s on a larger engine [1], against 4.74 s here from 10 %. The maps are teaching shapes, no transient has been compared with an engine’s, and no learner study has been made.

3.5.6 Predictive Governor Comparison

Table 3.6 compares complete 20 second runs at the same seed and settings, changing only the governor. Case 9 slams at 1 second with an 8% acceleration schedule. The hot-day case also slams at 1 second. Wear is applied at 2 seconds and the warmer day at 10 seconds in the wear comparison. The bodie rows use the challenge’s suggested settings of Table 3.5 and, separately, its shipped settings.

The sea-level loss is explicit: 0.47 seconds more to reach 95% thrust in exchange for 2.68 kg/s less accumulated command movement. The suggested bodie passes under both laws, with MPC gaining 0.15 seconds but adding 0.4 K to peak indicated EGT. The hot-day test exceeds the 950 °C indicated-EGT limit under both laws, by 4.6 and 4.4 K. Prediction does not make the protection a hard guarantee. The wear-and-warmer-day test reaches minimum margins of 0.37% with PI and 0.36% with MPC, without a modeled surge. A fixed local model is not a margin estimator.

Thirty comparison rows include four schedule margins, six hindsight PI gain settings and half-step refinement. The latter keeps the sea-level ordering at 4.758 versus 5.220 seconds and the movement

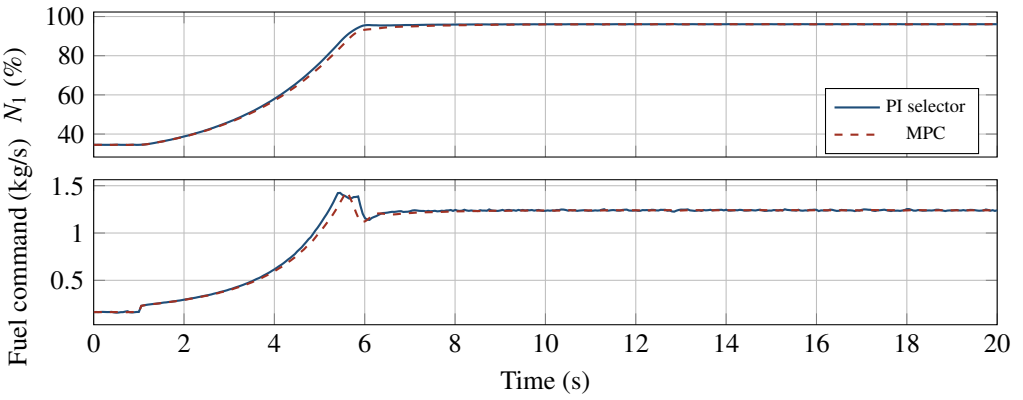


Figure 3.5 Same sea-level slam and protection settings, PI selector solid and MPC dashed. MPC suppresses fuel movement but reaches the thrust criterion 0.47 seconds later. The plotted speed is measured, while the thrust criterion is scored on teaching truth.

ordering at 4.53 versus 1.79 kg/s. Independent exact second-order responses agree with the sampled model within 3.0×10^{-11}, and an independent stepping harness reproduces both nominal travel totals exactly. Eight injected solver faults are rejected. Chrome averages 201 microseconds per plan over 400 plans, 0.402% of one core at unit playback and 2.01% at the maximum fivefold speed. Figure 3.5 shows the command tradeoff.

3.6 Technology in Practice

An engine control on a real turbofan reads the same kinds of measurement and moves the same valve as the selector of Section 3.4. Figure 3.6 draws that loop with engine hardware in place of the schematic's symbols.

What Measures It

Thrust cannot be measured in flight, so engines are controlled on shaft speed or on engine pressure ratio, both good indicators of it [7]. Many newer engines read shaft speed with a magnetic pickup that counts passing gear-tooth edges as pulses, which needs little maintenance beyond setting its gap to the teeth, and a maintenance check compares the speed indicator with an analyzer that reads engine speed within 0.1 %. The fuel control also senses compressor inlet pressure and temperature, burner pressure and compressor discharge pressure [19]. The model gives the speed pickups 0.02 % of colored noise and the discharge pressure P_3 a 0.02 s lag, and the ratio schedule divides the fuel by that P_3.

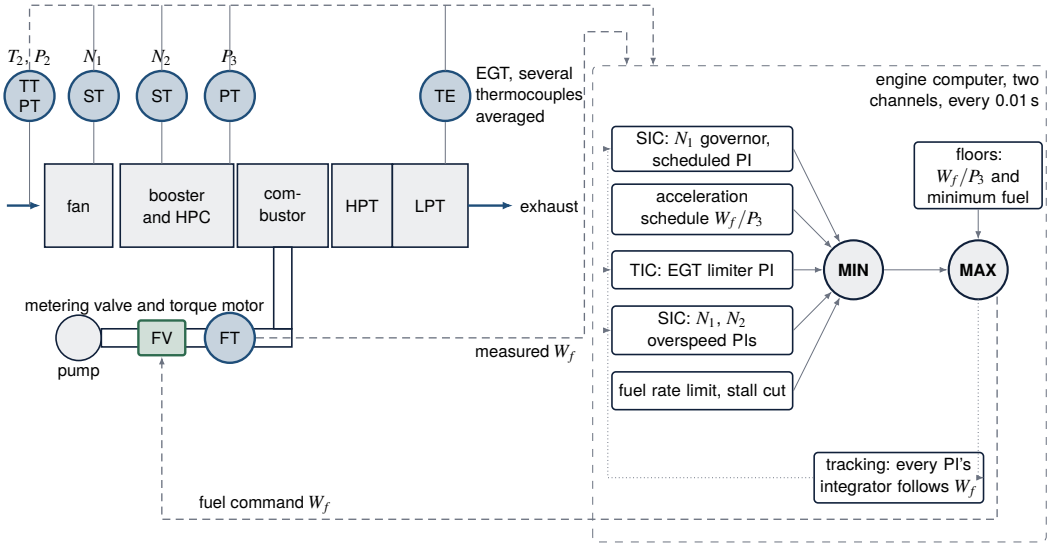


Figure 3.6 The selector of Figure 3.1 on engine hardware. Speed pickups (ST) on both spools, the discharge pressure (PT), thermocouples spaced around the exhaust and averaged (TE), the fan-face probes (TT, PT) and the fuel flowmeter (FT) feed the engine computer. There the governor (SIC) and the limiters (TIC, SIC) vote: the least of the caps, then the greatest of the floors, goes to the metering valve (FV). Notice that no sensor reads surge margin or thrust, and that the dotted tracking path returns the selected fuel to every loop that does not hold the valve.

> **TECHNOLOGY** **Sensor: Exhaust Thermocouples Averaged Around the Duct**
>
> The gas entering the first turbine is the most critical engine variable, but in most engines it is impractical to measure. Thermocouples at the turbine discharge give a relative indication of it instead: several are spaced around the exhaust duct near the turbine exit, the gauge shows their average, and they are made of chromel and alumel [19], the type K pair, usable to about 2300 °F [20]. In the oxidizing exhaust they drift from calibration, and a harness whose resistance has risen reads low, which the handbook calls dangerous because the engine then runs hot behind a normal gauge [19]. No open source read gives the probe's speed. The model reads the gas a quarter of the way through the low-pressure turbine's temperature drop, behind a 1.0 s lag.

What Moves It

The fuel metering unit sits on the front of the accessory gearbox, attached to the fuel pump, and the engine computer commands both its metering valve and the minimum-pressure and shutoff valve that starts and stops the flow [19]. A generic engine simulation of the kind this chapter cites models three actuators, the fuel metering valve, the variable stator vanes and the variable bleed valve [1]. The model has the first and the last, and folds the vanes into the compressor map on their schedule.

> **TECHNOLOGY** **Final Element: A Metering Valve Behind a Fixed Pressure Drop**
>
> In a full-authority control the computer decides the fuel flow and the metering valve only meters it. A differential pressure valve holds a constant drop across the metering valve by returning surplus pump flow to the pump inlet, so the metered flow is proportional to the valve's open area, and a torque motor driven by the control's current sets that area. In a hybrid control with a hydromechanical backup, an electrical failure, or the pilot's choice, puts the engine in manual mode: the torque motor current is zero, which sets a fixed ratio of fuel to compressor discharge pressure, and the engine runs at reduced power [19]. The handbook gives no stroke time or accuracy. The model's valve is a 0.05 s lag with a full flow of 1.6 kg/s.

Where the Controller Runs

The engine computer of a large turbofan has two channels, each an independent computer that can control the engine completely, and cross-talk logic picks the better channel for each bank of output drivers [19]. On commercial engines it is mounted on the fan casing and cooled by air [21]. The NASA generic controller samples every 0.015 s, beside the application's 0.01 s, and it uses the min/max structure that is common in commercial engines. Its designers rejected zeroing a deselected integrator's error, which steps the fuel at the hand-over and slows the response, and fed back instead the difference between the selected command and each loop's own output through an integral feedback gain tuned empirically. Too high a gain makes the loop act like a proportional controller or even destabilizes it, and too low a gain leaves windup in place [1]. Equation (3.7) is that scheme with the gain set by $T_t = T_i$.

> **IN PRACTICE** **Hand-Overs That Certification Asks For**
>
> The United States rule for engine control systems, 14 CFR 33.28, asks that the control keep the engine within its approved limits as conditions change. When a fault moves the engine from one control mode, channel or backup system to another, the engine must not exceed a limit, surge or stall, and the size and duration of the thrust change must be stated in the instructions. The full system must tolerate any single electrical or electronic failure without losing thrust control, an electronic overspeed protection must be tested once per start and stop cycle, and the software must be verified by an approved method [22]. The bumpless return from Manual in this chapter answers the first of these in miniature.

What Is Modernizing It

Three developments bear on the selector. The first is the onboard model: a flight program that estimated engine parameters with a Kalman filter led to a self-tuning engine model implemented in the engine computer of a military engine [7]. The second is distributed control. Today's architecture wires every sensor and actuator to one hardened box, because commercial electronics cannot survive the heat around the engine, and it suffers from parts obsolescence and heavy harnesses. A distributed architecture would replace them with nodes on a standard digital network, for less weight, better reliability and room for new functions [21]. The third is electric actuation: electromechanical actuators have joined stepper motors on engines [7].

3.7 Limitations

The engine is a teaching model of a class, with declared maps, constant properties, isothermal plenums of a declared residence time and a combustor without volume, and its transient margins are plausible for the class rather than predicted for any engine. The stall is a declared loss of pressure rise that clears low on its speed line, so neither rotating stall nor deep surge is represented, and only the HPC can stall. The schedules were designed on the model itself, so they fit it better than a real schedule fits a real engine, and the deterioration's surge-line loss has no source. The stall recognition has a stated blind spot after lever pulls, the controller has no minimum core speed, no thrust rating schedule against the ambient, no duplicated sensors and no fault accommodation, and the protection it provides is an educational guardrail, not certified logic. A pass of the challenge is not compliance with 14 CFR 33.73 or any other requirement.

The MPC's single local fuel model omits nonlinear gas-path transients, ambient scheduling and wear. Its soft speed and indicated-temperature ceilings do not constrain true EGT or actual surge margin. In particular, the 954.4 °C hot-day peak stands as a counterexample to an unconditional protection claim.

OPEN CHALLENGE **Closing the Loop on What No Sensor Reads**

Thrust, the variable an engine is flown by, cannot be measured, and neither can turbine inlet temperature or stall margin, two of the limits that matter, while the components degrade with use. Model-based control would run an onboard engine model, tuned to the individual engine by a tracking filter, and close loops on its estimates of thrust and stall margin. The difficulty is that the health parameters to be estimated generally outnumber the sensors, so the unmeasured outputs can carry significant errors [21], and any model used inside a control loop will itself need to be certified [23]. Progress would be estimates good enough on a worn engine to replace fixed schedules designed once on the nominal engine.

3.8 Conclusion

This chapter studied a browser simulator of a generic 120 kN-class two-spool turbofan with its min/max fuel selector. Takeoff fuel in one move surges its compressor 0.020 s later, and the governor alone surges 0.125 s after a slam. An acceleration schedule on the corrected ratio $W_f/(P_3\sqrt{\theta_2})$ trades margin for time, 5.37 s at a 10 % design margin and 4.74 s at 8 % with the margin never under 9.5 %, and it keeps 8.1 % or more on slams up to 9144 m except where the minimum fuel outranks it. With integrator tracking by back-calculation each limiter takes the valve from the fuel in the line, the EGT limiter 89 K under its line while the gas is already at 1021 °C, and without it the governor overshoots by 1.9 points and the challenge's EGT reaches 1019 °C. The challenge passes with the schedule tightened and tracking on, in 5.86 s, whatever the gain schedule, or with tracking and a higher floor that buys the time from the chop. The model's maps are teaching shapes and its limits teaching values. A fuller model would add a minimum core speed, a thrust rating schedule against the ambient, heat soak and tip clearance, a fan stall model, and a model predictive limit protection for comparison with the selector. The simulator shows that an engine controller is a set of limits voting on one valve before it is a speed loop.

The predictive fuel governor reduces the nominal fuel-command travel from 4.50 to 1.81 kg/s while slowing 95% acquisition from 4.74 to 5.21 seconds.

KEY POINTS

- An engine controller is a set of limits voting on one fuel valve before it is a speed loop: the lowest cap and then the highest floor win.
- Takeoff fuel in one move surges the compressor 0.020 s later, because the margin is spent by the rate of fuel rather than its amount.
- The acceleration schedule trades margin for time, 5.37 s at a 10 % design margin and 4.74 s at 8 % with the margin never under 9.5 %.
- With integrator tracking by back-calculation each limiter takes the valve from the fuel in the line, and without it the challenge's indicated EGT reaches 1019 °C.

Where else this applies. Chapter 9 meets the same exhaust-temperature limit on a constant-speed gas turbine, and Volume 7, Chapter 4 uses the same back-calculation on a slip loop under a torque limit.

References

[1] J. Csank, R. May, J. Litt, and T.-H. Guo, "Control design for a generic commercial aircraft engine," in *46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*. American Institute of Aeronautics and Astronautics, 2010, paper AIAA 2010-6629.

[2] H. A. Spang, III and H. Brown, "Control of jet engines," *Control Engineering Practice*, vol. 7, no. 9, pp. 1043–1059, 1999.

[3] L. C. Jaw and J. D. Mattingly, *Aircraft Engine Controls: Design, System Analysis, and Health Monitoring*. Reston, Virginia: American Institute of Aeronautics and Astronautics, 2009.

[4] H. Richter, *Advanced Control of Turbofan Engines*. New York: Springer, 2012.

[5] D. E. Seborg, T. F. Edgar, D. A. Mellichamp, and F. J. Doyle, III, *Process Dynamics and Control*, 4th ed. Hoboken, NJ: John Wiley & Sons, 2016.

[6] K. J. Åström and T. Hägglund, *Advanced PID Control*. Research Triangle Park, NC: ISA – The Instrumentation, Systems, and Automation Society, 2006.

[7] L. C. Jaw and S. Garg, "Propulsion control technology development in the United States: A historical perspective," NASA Glenn Research Center, Cleveland, OH, Technical Memorandum NASA/TM-2005-213978, 2005, nTRS 20050238468.

[8] E. M. Greitzer, "Surge and rotating stall in axial flow compressors, Part I: Theoretical compression system model," *Journal of Engineering for Power*, vol. 98, no. 2, pp. 190–198, 1976.

[9] P. P. Walsh and P. Fletcher, *Gas Turbine Performance*. Wiley, 2004.

[10] G. G. Kulikov and H. A. Thompson, Eds., *Dynamic Modelling of Gas Turbines*, ser. Advances in Industrial Control. London: Springer, 2004.

[11] R. May, J. Csank, T. Lavelle, J. Litt, and T.-H. Guo, "A high-fidelity simulation of a generic commercial aircraft engine and controller," in *46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*. American Institute of Aeronautics and Astronautics, 2010, paper AIAA 2010-6630.

[12] J. W. Chapman, T. M. Lavelle, R. May, J. S. Litt, and T.-H. Guo, "Propulsion system simulation using the Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS)," in *50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*. American Institute of Aeronautics and Astronautics, 2014, paper AIAA 2014-3929.

[13] U.S. Code of Federal Regulations, "Title 14, Part 33, Section 33.73: Power or thrust response," Electronic Code of Federal Regulations, https://www.ecfr.gov/current/title-14/part-33/section-33.73, 2026, amdt. 33-1, 36 FR 5493, Mar. 24, 1971; text as in force on 2026-10-01.

[14] S. Garg, "Aircraft turbine engine control research at NASA Glenn Research Center," *Journal of Aerospace Engineering*, vol. 26, no. 2, pp. 422–438, 2013.

[15] W. J. Rugh and J. S. Shamma, "Research on gain scheduling," *Automatica*, vol. 36, no. 10, pp. 1401–1425, 2000.

[16] D. J. Leith and W. E. Leithead, "Survey of gain-scheduling analysis and design," *International Journal of Control*, vol. 73, no. 11, pp. 1001–1025, 2000.

[17] S. J. Qin and T. A. Badgwell, "A survey of industrial model predictive control technology," *Control Engineering Practice*, vol. 11, no. 7, pp. 733–764, 2003.

[18] G. Pannocchia and J. B. Rawlings, "Disturbance models for offset-free model-predictive control," *AIChE Journal*, vol. 49, no. 2, pp. 426–437, 2003.

[19] Federal Aviation Administration, *Aviation Maintenance Technician Handbook–Powerplant*. U.S. Department of Transportation, Federal Aviation Administration, 2023, no. FAA-H-8083-32B.

[20] T. R. Kuphaldt, *Lessons in Industrial Instrumentation*, version 2.33 ed. Open textbook, Creative Commons Attribution 4.0 license, ibiblio.org/kuphaldt/socratic/sinst, 2024.

[21] S. Garg, "Aircraft turbine engine control research at NASA Glenn Research Center," NASA Glenn Research Center, Cleveland, OH, Technical Memorandum NASA/TM-2013-217821, 2013, nTRS 20130013439.

[22] "Title 14, Part 33, Section 33.28: Engine control systems," Code of Federal Regulations, 14 CFR Ch. I (1–1–25 Edition), govinfo.gov, 2025, amdt. 33–26, 73 FR 48284, Aug. 19, 2008.

[23] S. Garg, K. Schadow, W. Horn, H. Pfoertner, and I. Stiharu, "Sensor and actuator needs for more intelligent gas turbine engines," NASA Glenn Research Center, Cleveland, OH, Technical Memorandum NASA/TM-2010-216746, 2010, also ASME paper GT2010-22685; NTRS 20100029602.

3.9 Exercises

3.1 ○ Concept check · 2 min

In scenario 1, Fuel by hand, the fuel at flight idle is raised from 0.164 to 1.2 kg/s in one move. The HPC operating point reaches the surge line 0.020 s later, while the core speed has moved only from 60.6 to 60.8 %. Why does the point climb its speed line before the spools speed up?

(a) The governor raises the core speed first, and the pressure ratio follows it along the steady line

(b) The hotter gas must pass the choked HPT nozzle at the same flow, which takes a higher P_3

(c) The handling bleed shuts as the fuel rises, so the air at the HPC exit has nowhere to go

(d) The fan speeds up first and forces more air into the HPC than its speed line can pass

3.2 Concept check · 2 min

In scenario 3 with the schedule designed for 8 % and integrator tracking on, the EGT limiter takes the valve 4.43 s after the slam with the gauge at 861 °C, 89 K under its line. What makes it take over that far from its limit?

(a) Thermocouple noise now and then carries the gauge over the limiter's setpoint

(b) The limiter's setpoint is lowered by a fixed margin while the schedule holds the valve

(c) Its integrator trails the rising fuel, and its demand meets the fuel when $K_E e$ equals that trail

(d) The selector gives the valve to the limiter whose error is falling fastest

3.3 Concept check · 2 min

At 10 668 m and Mach 0 to 0.4, slams from flight idle fall to 0 to 7.3 % of surge margin or surge, and they do so identically with and without the $\sqrt{\theta_2}$ correction at Mach 0. Which property of the selector, Equation (3.6), explains it?

(a) The $\sqrt{\theta_2}$ correction loosens the schedule too far in cold, thin air

(b) The fuel rate limit of 2 kg/s per second is too fast for the thin air

(c) The gain schedule raises the governor's gain at low corrected core speed

(d) The 0.06 kg/s minimum fuel exceeds the idle fuel there and, as a floor, outranks the schedule

3.4 Theory and calculation · 5 min

Scenario 6 flies the lever at 70 % at 10 668 m and Mach 0.8 on a standard day. The lever asks for a corrected fan speed of 83.9 %.

(a) From Equation (3.1), with the standard atmosphere falling 6.5 K/km from 288.15 K, find T_0, T_2 and θ_2. *Checkpoint:* $\theta_2 = 0.857$

(b) Find the physical fan-speed target N_{1t}. *Checkpoint:* 77.6 %

(c) The acceleration cap is $W_{acc} = R_{acc} P_{3,m} \sqrt{\theta_2}$. By what fraction is it lower here than a cap on the uncorrected ratio W_f/P_3 with the same table value and P_3, and which way does that move the surge margin? *Checkpoint:* 7.4 % lower, more margin

3.5 Theory and calculation · 5 min

Integrator tracking, Equation (3.7), for a loop i that does not hold the valve.

(a) Substitute $u_{i,k} = K_i e_{i,k} + I_{i,k}$ into the integrator update and show that I_i is a first-order lag of the commanded fuel with time constant T_i. *Checkpoint:* $\dot{I}_i = (W_f - I_i)/T_i$

(b) The fuel rises at a steady rate ρ. Show that the trail $W_f - I_i$ settles at ρT_i, and find the error e_i at which the loop's demand meets the fuel. Evaluate it for the EGT limiter in the 8 % slam of scenario 3, with $K_E = 6\,\mathrm{g/s}$ per kelvin, $T_E = 1.0\,\mathrm{s}$ and a trail of 0.534 kg/s. *Checkpoint:* $e = \rho T_i / K_i$, about 89 K

(c) Estimate the distance from the limit at takeover if the EGT limiter's gain were doubled to 12 g/s per kelvin with the same trail, and say what the limiter's integrator does instead with tracking off. *Checkpoint:* about 45 K

3.6 Theory and calculation · 6 min

The HPC map of Equation (3.2) has $a = 2.1$, $b = 2.9$, $k = 0.3$, $\pi_d = 12.5$ and $S = 1.0898$, and the design point sits at $m = 0.768$ with $\pi = 12.5$.

(a) Find the normalized pressure rise ψ_s on the surge line at $m = 0.768$ and the surge pressure ratio. *Checkpoint:* $\psi_s = 1.239$, $\pi_s = 15.24$

(b) Find the design surge margin by the chapter's definition, and by the other common definition that divides by the surge line's ratio. *Checkpoint:* 22.0 % and 18.0 %

(c) At the same corrected flow, at what pressure ratio does the margin fall to the 8 % floor? *Checkpoint:* 14.12

3.7 App challenge · 8 min

Scenario 3, The acceleration schedule, default seed. In each run press *Run* and, about 1 s later, move *Thrust lever* to 100 % (or press *Throttle slam*). The run pauses at 95 % of the rated thrust.

(a) As shipped (*Schedule design margin* 10 %), read the time to 95 % and the minimum surge margin on the scorecard at the pause. *Checkpoint:* 5.37 s, 11.3 %

(b) Reload the case, set *Schedule design margin* to 8 % before Run, and slam again. Read the same two values and the *Holding the valve* tile at the pause. *Checkpoint:* 4.74 s, 9.5 %, EGT limiter

(c) Reload the case, set the margin to 8 % and *Integrator tracking* to Off before Run, and slam again. Read the time to 95 %, then press Run at the pause and read the *Peak N1* tile about 15 s later. Explain the difference from (b). *Checkpoint:* 4.66 s, 98.0 %

Tolerance: 0.03 s on the times, which move that much with the instant of the slam, and 0.1 point on the percentages.

3.8 App challenge · 8 min

Scenario 4, A hot day: the EGT limiter (ISA + 30 K at sea level), default seed. Press *Run*, move *Thrust lever* to 100 % about 1 s later, press Run again at the 95 % pause, and let the run end at 21 s.

(a) Export the CSV file. Take the time of the first row with `lever_pct` at 100 and of the first row whose `active` column reads `egt`. How long after the slam does the EGT limiter first hold the valve? *Checkpoint:* about 3.9 s

(b) At the end of the run read the thrust and the rating on the *Thrust (truth)* tile, the peak indicated EGT on the scorecard, and the largest `truth_egt_c` in the file. *Checkpoint:* 111.3 kN of 111.2 kN, 955 °C, about 1020 °C

(c) Set the lever back to 0 %, set *Integrator tracking* Off, press Reset and repeat the run. Read the peak indicated EGT. *Checkpoint:* 996 °C

Tolerance: 0.1 s on (a), 0.2 kN on the thrust, 2 K on the indicated EGT and 3 K on the true one.

3.9 App challenge · 8 min

The challenge, *the bodie at 10,000 ft on a hot day*, default seed. Run each setting for the full 20 s, then change it, press Reset and run again. Leave every parameter and disturbance as shipped.

(a) Run as shipped and read the verdict: time to 95 %, minimum surge margin, peak indicated EGT, and which limits are missed. *Checkpoint:* 8.49 s, 14.8 %, 996 °C; time and EGT

(b) Run with only *Schedule design margin* at 8 %, then with only *Integrator tracking* On. *Checkpoint:* 5.17 s and 1019 °C; 8.55 s and 934 °C

(c) Run with both changes and the shipped fixed gains, then with *Gain schedule* On N2c, governor gain 200 g/s per percent and integral time 1.0 s. Does the gain schedule pass the challenge? *Checkpoint:* 5.86 s both times

Tolerance: 0.02 s, 0.1 point and 2 K.

3.10 Application area · 4 min

14 CFR 33.73(b) asks for 95 % of rated takeoff thrust within 5 s of a slam. The schedules of this engine were designed on the nominal engine. On the sea-level slam of scenario 3 they give 4.74 s and a minimum margin of 9.5 % at an 8 % design margin, 5.37 s and 11.3 % at 10, 6.27 s and 13.0 % at 12, and 7.55 s and 14.8 % at 14. Full deterioration lowers the steady takeoff margin from 22.0 to 17.8 %.

(a) Suppose a worn engine's slam loses the same 4.2 points as its steady takeoff point. Which design margins keep a worn engine's slam above the 8 % floor, and which of those meet the 5 s? *Checkpoint:* 12 and 14; neither

(b) Why is that supposition optimistic, and what would an engineer do before choosing the design margin?

3.11 Application area · 4 min

At sea-level ISA the new engine's takeoff EGT is 872.0 °C, its rating is flat to ISA + 20.0 K, and full deterioration raises the EGT by 59.8 K at the same thrust. The indicated limit is 950 °C.

(a) What is the new engine's EGT margin at sea-level ISA, and about how many kelvin of EGT does each kelvin of day temperature add at takeoff? *Checkpoint:* 78 K, about 3.9 K per kelvin

(b) Estimate the day temperature at which the fully worn engine's rating stops being flat, and compare with scenario 8. *Checkpoint:* about ISA + 5 K

3.12 Review the agent · 5 min

An AI assistant reviews the trends of scenario 3 and writes: "The EGT limiter takes the valve at 861 °C, 89 K under its 950 °C limit, which shows it is tuned too aggressively. Lengthen its tracking time to two integral times, or switch integrator tracking off, so that it acts only at the limit. The slam then reaches 95 % sooner, which is what the five-second rule asks for." Find the flaw and say how you would check it in the application.