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CHAPTER 4

Feed Rate, Grain Loss and a Rain Deadline in a Combine Harvester Simulator

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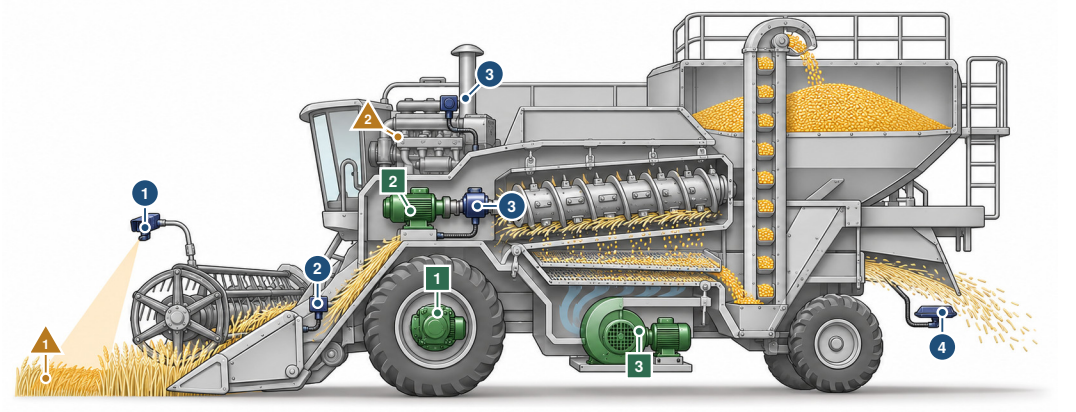
The app for this chapter
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CHAPTER 4

Feed Rate, Grain Loss and a Rain Deadline in a Combine Harvester Simulator



The controller moves 1 ground speed, set through the hydrostatic drive 2 rotor speed 3 cleaning fan speed

The controller reads 1 crop ahead of the header 2 crop flow into the feeder 3 engine load and rotor torque 4 grain lost behind the machine

What disturbs it 1 denser, wetter or flattened crop 2 engine power lost

Notice that the scanner reads the crop meters ahead of the header, while the loss pad reads grain only after it has passed through the whole machine. Illustration, not to scale.

IN PLAIN TERMS **Driving at the Pace the Machine Can Take**

The main idea. A combine cuts, threshes and cleans grain as it drives across a field. Its speed sets how much crop goes in. A controller holds that intake steady by changing the speed.

The challenge. The intake reading cannot show what really limits the machine: wet straw that clogs the spinning drum, an engine running out of power, or grain thrown out the back with the straw. Guard controllers watch those limits and may slow the machine, while the reading of lost grain arrives late and can be wrong.

Why it matters. Drive too slowly and the rain finds crop still standing, drive too fast and grain is lost or the machine jams.

THREE WAYS TO READ THIS CHAPTER

Explore	13 min	the first page, the fact on overload (Section 4.1), the two history segments (Section 4.2), the two try-it segments (Sections 4.6.3 and 4.6.6), the fact on the challenge (Section 4.6.7) and the key points
Study	65 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 4.6), Technology in Practice (Section 4.7), Limitations (Section 4.8) and the open challenge

The control question A combine's ground speed sets its feed, but grain loss, a plugging rotor and the engine's power limit do not show in the feed rate and are measured late or not at all. Which layers of override, preview and supervisory control keep the machine and the grain safe, and what does each one cost in grain brought in before the rain?

Learning objectives

- Compute the process gain and the delay budget of the feed loop, and predict when a later feed signal makes it hunt.
- Explain how a low selector with external reset lets the engine and rotor overrides take the ground speed without a bump.
- Size the range of a crop preview from its braking curve and the drive lag.
- Tell which disturbances the feed loop, the preview and the loss supervisor can each see, and judge a supervisor that trusts a biased monitor.
- Choose and defend a configuration that meets a grain target under loss, plug and overload limits.

Prerequisites Sections 1.4.2 (constraints as objectives), 1.4.3 (selectors and override), 1.4.4 (external reset), 1.4.5 (rate limits), 1.6.2 (velocity form) and 1.6.4 (scenarios and exported files). Section 1.6.3 is needed only for the predictive controller.

The app https://apmonitor.com/apps/combine-harvester/

See also Volume 5, Chapter 3 for a fixed tuning eroded by a slow analyzer, and Volume 5, Chapter 2 for control through a transport delay. Volume 3, Chapter 2 for matching a cascade to where a disturbance enters, and Volume 3, Chapter 6 for feedforward from an upstream measurement with feedback demoted to a slow trim.

4.1 Introduction

The combine harvester cuts a swath of crop, threshes the grain out of the heads, separates it from the straw and cleans it from the chaff, all while it drives across the field. The ground speed is the only handle on how much material enters, because the header takes whatever crop stands in its path. The rotor and the sieves can pass only so much straw and chaff, and the grain that leaves with them rises steeply as the feed approaches that capacity [1, 2]. The harvest window is short as well, and crop still standing when the weather turns carries a cost of its own, so studies of automatic combine control have treated the forward speed as a balance between the grain the machine loses and the grain that time loses [3, 4].

> ✦ DID YOU KNOW? **Five Bushels an Acre to a Slug of Straw**
>
> Combines were designed for wheat, and the first was built in 1838. An extension guide on harvesting wheat warns that many growers forfeit as much as 5 bushels per acre in the heaviest-yielding parts of a field when the header is not raised for tall straw and the straw overloads the combine for a moment [5].

The loop that sets the speed is not difficult by itself. Feed rate is crop density times header width times speed, so the process gain is known, and the dynamics are a drive lag and a transport delay. The difficulty is that the constraints that matter do not appear in the feed rate. Wet crop loses more grain at the same feed, a rotor fed faster than its capacity fills until it plugs, an engine asked for more power than it has slows everything it drives, and the loss monitor reports the result seconds late through a calibration that may be wrong. The simulator of this chapter is built to correct the belief that a throughput loop on its setpoint is protecting the machine and the grain. Section 4.6 measures a feed loop holding 70 t/h while the loss rises from 1.00 to 2.69 %, and one holding 80 t/h while the rotor plugs 27 s into a patch of lodged crop.

The same structure appears wherever a throughput loop feeds equipment whose limit it cannot see. Grinding mills are fed ore against the load and the power they can take, and the choice of controlled and manipulated variables around them has been surveyed across 68 circuits [6]. Volume 15, Chapter 3 treats one such mill, with the ore feed moved against the bearing pressure. Crusher feeders are

regulated to keep the crushing chamber full while the crusher power stays inside a safe margin [7]. The established answer has several parts. Override controllers on the equipment limits share the manipulated variable with the throughput loop through a selector [8], and the controllers that lose the selector need anti-windup so that they can take over without delay [9] (Sections 1.4.3 and 1.4.4). A slower loop on a quality measurement moves the throughput setpoint as the outer loop of a cascade, and a measurement of the incoming material, where one exists, supplies feedforward [10, 11]. The combine carries every one of these parts.

This chapter weighs, on one simulated combine, what each layer of that structure contributes, using patches of crop that each defeat a different layer and a rain deadline that prices every lost minute. The strategies are established practice. The model integrates the feed exactly from a mapped field, has a rotor whose capacity falls with moisture and with engine lugging and a plug with a real cost, and carries a measurement chain in which every signal is late, noisy or biased. Nine case studies and a graded challenge take the feed loop, its transport delay, the preview, the overrides and the supervisor one at a time before setting them together against the weather.

Section 4.2 reviews the automation of combines. Section 4.3 sets out the field, the machine, its instruments and the assumptions, and Section 4.4 derives the characteristics that shape the control problem: the loss curve, a process gain set by the crop and the delay budget of the feed loop. Section 4.5 gives the speed selector, the preview, external reset, the loss supervisor and the trims as implemented, and in Section 4.5.7 the optional predictive controller. Section 4.6 reports the measured scenarios, from the uniform field through the dense patch, the wet strip, the delayed and the biased signals and the engine and rotor limits to the harvest against the rain and the predictive comparison. Sections 4.8 and 4.9 state the limitations and conclude after Section 4.7 has set the loop on real machine hardware, and Section 4.10 holds the exercises.

4.2 Automation of the Combine Harvester

The capacity a combine works against is set inside the machine. Grain must be detached from the heads and must then find its way through a moving mat of straw to the concave. Stochastic models of threshing and separation along the rotor express the unthreshed and unseparated grain, which become the losses, as functions of the operating and design parameters, and they have been validated on extensive tests of axial and tangential threshing units [2]. The theory, modeling and design of the machine from the header to the cleaning shoe have been collected in one monograph [1].

Automatic control of the forward speed was first weighed by simulation in a 1983 thesis, whose findings the history segment below gives. Timeliness costs vary less from year to year for machinery with a high daily capacity, and they respond nonlinearly to a loss of capacity because more fields are then left partly or wholly unfinished [4].

> ⧖ HISTORY **Holding the Loss or the Feed Constant, 1983**
>
> By 1983 a doctoral thesis on combine automation could survey several automatic controls that had been built and tested. Each varied the ground speed to keep either the grain loss or the straw feed rate constant as the crop density changed across the field. The thesis simulated five ways of setting the forward speed and the threshing cylinder speed, from the driver alone through loss control and combined loss and feed-rate control to two schemes that also set the cylinder. Following the slowly varying crop brought the main savings, following its rapid variations brought none, and timeliness losses mattered greatly to the optimum. The disturbances could not be measured accurately while the machine worked, and the effect of control was seen only after a delay. A reliable loss measurement was a necessary condition, and the meters of the day were not accurate enough [3].

A quarter century later, model-based predictive control was applied to the same problem. A cruise controller set the hydrostatic pump and the engine speed from a nonlinear model of the propulsion system and was validated on a production machine [12], and a throughput controller regulated the

Table 4.1 Variables at the Uniform-Field Operating Point

Symbol	Role	Nominal	Range
Q_m	CV, feed rate as measured	70 t/h	SP 20–115
λ_m	CV (override), engine load	71 %	SP 60–100
T_m	CV (override), rotor torque	38 %	SP 40–95
L_m	CV (supervisor), loss monitor	1.02 %	SP 0.5–3
v_{cmd}	MV, ground speed command	7.56 km/h	0–10
Q_{SP}	MV (supervisor), feed setpoint	70 t/h	14.4–115.2
ω_{set}	MV (trim), rotor speed	950 rpm	700–1200
n_{set}	MV (trim), fan speed	1000 rpm	700–1300
ρ, m	DV, crop density, moisture	1.045, 14 %	patches
δ	DV, engine power available	100 %	50–100
b, b_p	DV, loss, preview calibration	0, 0	±60, ±30 %
m_{off}, $\dot{m}_d$	DV, moisture offset, drift	0, 0	−4 to 6, ±0.5/min
σ_Q	DV, feed-signal noise	3 %	0–10
s, v	states, route position, speed	0, 7.40 km/h	—
n_e	state, engine speed of rated	0.986	0.5–1
M_r, G_r	states, rotor straw, grain	26.5, 29.4 kg	—
Ψ_r	state, rotor straw times moisture	369 kg %	—
G_s, C_s	states, shoe grain, chaff	15.2, 2.77 kg	—
G_t, G_d	states, tank grain, cracked grain	0, 0	—
G_{ls}, G_{lc}, V_f	states, lost grain, fuel	0, 0, 0	—

Density in kg/m^2. Engine load is a share of the power available, and rotor torque a share of the plug torque.

ground speed from measurements of feed rate, engine load and grain mass flow so that the capacity of the machine was used at all times [13]. Loss measurements entered the loop in the same years. A fuzzy controller built on expert knowledge adjusted the cylinder speed, the concave clearance, the fan speed and the forward speed from the losses measured at the straw walkers and the sieve [14], and a fuzzy controller for the cleaning section set the fan speed from the grain loss sensors and a differential air pressure that expresses the working load, and lost less grain than a sub-optimal fixed fan speed [15].

The second history segment follows the sensors that have tried to measure the crop before the header reaches it. LiDAR has been shown to estimate the crop density of small grains [16]. Control that uses such future information is preview control, whose optimal continuous-time form was derived in 1975 [11].

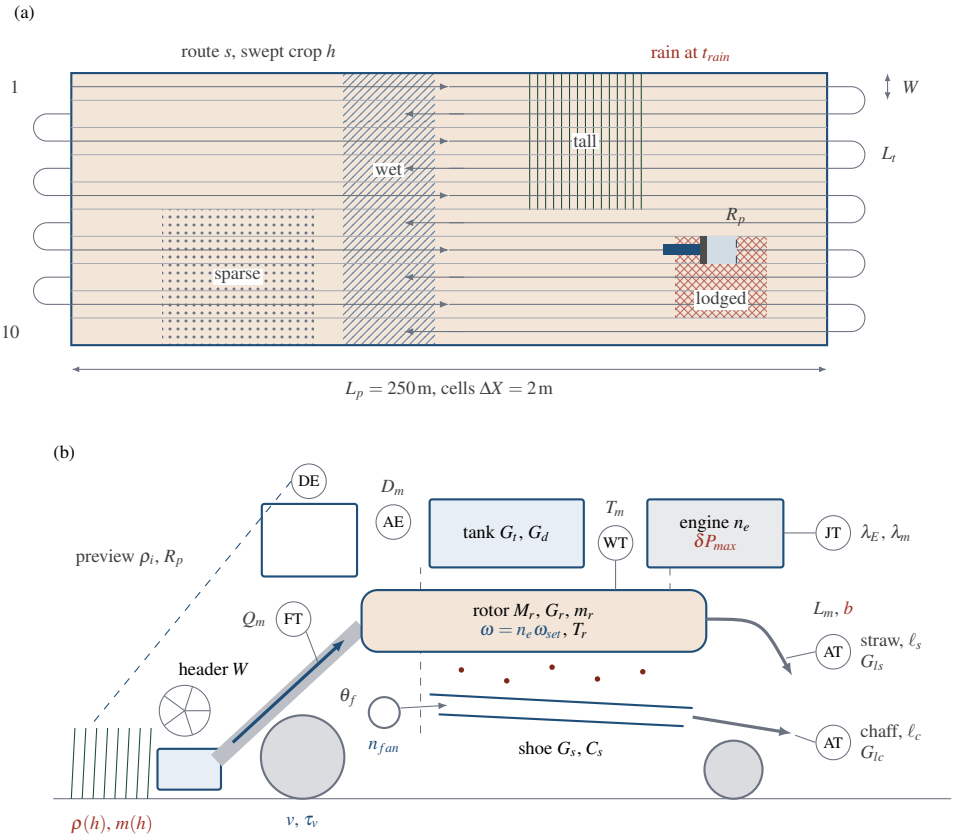


Figure 4.1 The simulated field and machine. (a) The challenge field in plan view, ten passes of width W and length L_p joined by headland turns of length L_t, with the tall, sparse, wet and lodged patches and the combine on pass 7 with its preview range R_p ahead. The route position is s and the crop swept so far is h. (b) The machine in side view. Crop of density $\rho(h)$ and moisture $m(h)$ is cut by the header and reaches the rotor after θ_f. The rotor holds straw M_r, grain G_r and moisture m_r and turns at ω, the shoe holds grain G_s and chaff C_s under the fan at n_{fan}, and the clean grain rises to the tank. Straw and chaff leave with the separation and cleaning losses. One engine at speed n_e drives the wheels at v, the rotor and the fan. The instruments are the feed-rate signal FT, the rotor torque WT, the engine load JT, the loss sensors AT with calibration error b, the damage camera AE and the forward crop sensor DE. The disturbances ρ, m, δP_{max}, b and the rain are printed in red, and the manipulated quantities v, ω and n_{fan} in blue.

HISTORY Seeing the Crop Before the Header, 1980 to 2020

A feed-rate control that weighs the crop on its way through the header and the feeder measures crop already inside the machine. With no time to anticipate a sudden change, it keeps a safety margin and leaves part of the capacity unused. Researchers therefore moved the measurement forward. An ultrasonic beam across the header, tried in 1980, did not follow the crop density closely enough. A laser beam ahead of the header followed in 1986, capacitance plates on the header table in 1994, and in 1996 a pendulum bar pushed by the crop, whose reading a speed change of 0.5 km/h shifted by up to 2 %. Laser scanners came next, and by 2020 crop height and density estimation ahead of the combine had been studied for 30 years and remained a challenge [17].

4.3 Machine and Field Model

The combine carries a 9 m header along a fixed serpentine route of ten 250 m passes, 2.25 ha of wheat yielding 5.5 t/ha of grain with 0.9 kg of straw and chaff for every kilogram of grain. The field, the machine and its instruments are shown in Figure 4.1. Thirteen states are integrated, and they are listed with the other variables in Table 4.1.

4.3.1 Route, Field and Feed

Because the route is fixed, the position s along it is the only coordinate, and the harvest coordinate h counts the meters of crop the header has swept, as shown in Equation (4.1).

$$\dot{s} = \max(0, v), \qquad h = kL_p + \min(u, L_p) \tag{4.1}$$

Here $k = \lfloor s/(L_p + L_t) \rfloor$ is the pass index, $u = s - k(L_p + L_t)$, $L_p = 250\,\mathrm{m}$ is the pass length and $L_t = 2 \times 8\,\mathrm{m} + \pi W/2 = 30.1\,\mathrm{m}$ is the headland turn. The coordinate h stops during a turn, after the last pass and once the rain has come, so nothing is cut then.

The field is stored in the order the header meets it, in cells $\Delta X = 2\,\mathrm{m}$ long and one header width wide. Cell i carries grain $\rho_{g,i} = Y f_{g,i}$, straw and chaff (material other than grain, MOG) $\rho_{m,i} = Y r_M f_{m,i}$ and moisture $m_i = m_0 + \Delta m_i$, with $Y = 0.55\,\mathrm{kg/m^2}$, $r_M = 0.9$ and $m_0 = 14\,\%$ on a wet basis. A smooth texture $f_g = 1 + a\xi$, $f_m = 1 + 1.3a\xi$ and $\Delta m = 0.3\zeta$ comes from bilinear interpolation of standard normal deviates ξ and ζ drawn by the seeded generator on a grid 25 m long and one pass wide, with $a = 0.03$, or 0.02 in case 1. A patch multiplies f_g and f_m and adds to Δm by $(1.25, 1.9, 0)$ for tall crop, $(0.55, 0.5, 0)$ for sparse crop, $(1.0, 1.1, 6)$ for a wet strip and $(1.1, 1.4, 7)$ for lodged crop. Uniform crop therefore stands at $\rho = \rho_g + \rho_m = 1.045\,\mathrm{kg/m^2}$, and the four patches at 1.56, 0.53, 1.05 and 1.24 times that density.

The crop enters the header at $Q_c = W\rho(h)v$, and the mass cut in each physics step is taken exactly from cumulative sums along the route, as shown in Equation (4.2).

$$\Delta G_c = W\left[C_g(h_{k+1}) - C_g(h_k)\right], \qquad C_g(h) = \int_0^h \rho_g \,\mathrm{d}h' \tag{4.2}$$

The MOG and the MOG weighted by its moisture are cut the same way, so what leaves the field is exactly what enters the machine. A moisture offset and a moisture drift, both disturbances, are added to the crop as it is cut. The header auger and the feeder chain carry the crop to the rotor through a ring buffer of $\theta_f/\Delta t = 30$ physics steps, with $\theta_f = 1.5\,\mathrm{s}$ and $\Delta t = 0.05\,\mathrm{s}$. The cell leaving the buffer is fed to the rotor over the following step, so the applied delay is one step longer, and the rotor inflow $Q_i(t) = Q_c(t - \theta_f - \Delta t)$, 1.55 s late, holds for grain, MOG and moisture alike.

4.3.2 Rotor and Plugging

The rotor is one well-mixed inventory of straw M_r, grain G_r and moisture-weighted straw $\Psi_r = M_r m_r$, emptied at the specific rate r, as shown in Equation (4.3).

$$\begin{gathered}
\dot{M}_r = Q_{i,m} - rM_r, \qquad \dot{G}_r = Q_{i,g} - rG_r \\
\dot{\Psi}_r = Q_{i,w} - r\Psi_r, \qquad rM_r = \bar{Q}\tanh\frac{M_r}{\bar{Q}\,\bar{\tau}_r} \\
\bar{Q} = Q_{cap}\left(\frac{\omega}{\omega_{ref}}\right)^{0.8} \mathrm{e}^{-0.04(m_r - 14)}, \qquad \bar{\tau}_r = \tau_r\left(\frac{\omega_{ref}}{\omega}\right)^{1/2}
\end{gathered} \tag{4.3}$$

Here $\tau_r = 2.5\,\mathrm{s}$, $Q_{cap} = 16\,\mathrm{kg/s}$, $\omega = n_e\omega_{set}$ is the rotor speed, $\omega_{ref} = 950\,\mathrm{rpm}$, and $m_r = \Psi_r/M_r$ is in percent. Lightly loaded, the straw leaves in $\bar{\tau}_r$. Near capacity the outflow saturates at $\bar{Q}$, and any faster feed piles up. The capacity is 16.0 kg/s of straw at 14 % moisture, 12.6 kg/s at 20 and 12.1 kg/s at 21 %.

The rotor torque grows with the straw mat and with its moisture, as shown in Equation (4.4).

$$T_r = T_0 \frac{\omega}{\omega_{ref}} + k_T M_r \max\left[0.7,\ 1 + 0.06(m_r - 14)\right] \tag{4.4}$$

with $T_0 = 200\,\mathrm{N\,m}$ and $k_T = 26.8\,\mathrm{N\,m/kg}$. At 70 t/h of dry crop the rotor holds 26.5 kg of straw at 908 N m, which is 38 % of the plug torque $T_{plug} = 2.4\,\mathrm{kN\,m}$. The plug is reached at 82 kg of dry straw and at 58 kg at 21 % moisture, and it is a hard event. When $T_r \geq T_{plug}$ the drive command drops to zero at once, the rotor and shoe flows stop, the crop still arriving piles onto the conveyor, and after $t_{clear} = 120\,\mathrm{s}$ the grain in the rotor is pulled out onto the ground as dumped grain G_p and the rotor restarts empty.

4.3.3 Losses, Cleaning and Damage

Grain leaves the rotor at the same specific rate as the straw, and a fraction ℓ_s of it goes out of the back with the straw as separation loss, as shown in Equation (4.5).

$$\ell_s = \min\left[0.5,\ 0.0065\,\mathrm{e}^{2(\lambda_r - 1)}\,\mathrm{e}^{0.10(m_r - 14)}\,\frac{\omega_{ref}}{\omega}\right] \tag{4.5}$$

Here $\lambda_r = M_r / M_{ref}$ is the rotor load, and the reference inventory $M_{ref} = 25.5\,\mathrm{kg}$ is what the rotor holds at 9 kg/s of dry straw and 950 rpm. The loss rises exponentially with the rotor load and with moisture and falls with rotor speed, which are the directions reported for threshing and separating units [1]. Its constants were chosen so that dry crop reaches 2 % of loss at a plausible feed rate, and they are not calibrated to any machine.

The rest of the grain falls through the concave onto the cleaning shoe with a share $\chi = 0.2$ of the straw as chaff, and the fan lifts the chaff away, as shown in Equations (4.6) and (4.7).

$$\dot{G}_s = (1 - \ell_s) r G_r - \frac{G_s}{\tau_s}, \qquad \dot{C}_s = \chi r M_r - \frac{C_s}{\tau_s} \tag{4.6}$$

$$\ell_c = \min\left[0.5,\ 0.003\max(0.2, \lambda_s) + 0.008\,\varepsilon_f^2\right] \tag{4.7}$$

$$n_{opt} = 1000\left[1 + 0.1(\lambda_s - 1) + 0.012(m_r - 14)\right]$$

Here $\tau_s = 1.5\,\mathrm{s}$, $\lambda_s = C_s / C_{ref}$ with $C_{ref} = 2.7\,\mathrm{kg}$ the chaff at the reference straw rate, $\varepsilon_f = (n_{fan} - n_{opt})/150$ with $n_{fan} = n_e n_{set}$, and n_{opt} is the fan speed in rpm at which the shoe loses least. Too little air leaves grain in a chaff mat that rides off the sieve, and too much blows it out. At 70 t/h of dry crop the shoe loses 0.31 % of the grain leaving the machine at 1000 rpm, 1.26 at 850 and 0.91 % at 1150 rpm.

Clean grain reaches the tank, and a fraction D of it is cracked, as shown in Equation (4.8).

$$\begin{aligned} \dot{G}_t &= (1 - \ell_c)\frac{G_s}{\tau_s}, \qquad \dot{G}_d = D\dot{G}_t \\ \dot{G}_{ls} &= \ell_s r G_r, \qquad \dot{G}_{lc} = \ell_c \frac{G_s}{\tau_s} \\ D &= \min\left[0.2,\ 0.008\,\mathrm{e}^{4(\omega/\omega_{ref} - 1)}\,\mathrm{e}^{0.15(14 - m_r)}\right] \end{aligned} \tag{4.8}$$

The damage is 0.80 % at 950 rpm and 14 % moisture, 1.50 % at 1100 rpm and 1.08 % at 12 % moisture, because a faster rotor threshes harder and dry grain is brittle. The grain balance of Equation (4.9) holds at every step,

$$G_{cut} = G_{conv} + G_r + G_s + G_t + G_{ls} + G_{lc} + G_p \tag{4.9}$$

where G_{conv} is the grain on the conveyor. The verification suite checks it through turns and two plugs, and the largest imbalance over the whole challenge as shipped is 6.0×10^{-11} kg.

4.3.4 Engine and Drive

One engine drives the wheels, the rotor and the fan, which all turn in proportion to its speed n_e, a fraction of rated. The power drawn is the sum in Equation (4.10).

$$\begin{aligned} P = {} & \frac{(m_{mc} + G_t)\, g\, c_{rr}\, v}{\eta_h} + T_r \omega + e_{ch}(1-\chi) r M_r \\ & + P_h n_e + e_h Q_c + P_f \left(\frac{n_e n_{set}}{1000} \right)^3 + P_a n_e \end{aligned} \tag{4.10}$$

The machine mass is $m_{mc} = 18\,\text{t}$, the rolling resistance $c_{rr} = 0.08$, the drive efficiency $\eta_h = 0.75$, the chopper energy $e_{ch} = 3\,\text{kJ/kg}$ of straw, the header power $P_h = 8\,\text{kW}$ plus $e_h = 600\,\text{J/kg}$ of crop, the fan power $P_f = 12\,\text{kW}$ at 1000 rpm and the auxiliaries $P_a = 55\,\text{kW}$. At 70 t/h of dry crop the machine draws 235 kW of its 330 kW, of which 39 go to the drive, 89 to the rotor, 22 to the chopper, 20 to the header, 11 to the fan and 54 to the rest.

The governor holds the engine within 2 % of rated speed up to full power, and beyond it the engine lugs down 1.5 % of speed per percent of overload, as shown in Equation (4.11).

$$\begin{aligned} \tau_e \dot{n}_e &= n_{ss} - n_e \\ n_{ss} &= \begin{cases} 1 - 0.02\lambda_E, & \lambda_E \le 1 \\ \max\left[0.5,\ 0.98 - 1.5(\lambda_E - 1)\right], & \lambda_E > 1 \end{cases} \end{aligned} \tag{4.11}$$

Here $\lambda_E = P/(\delta P_{max})$ is the engine load, $P_{max} = 330\,\text{kW}$, δ is the share of power available and $\tau_e = 0.8\,\text{s}$. A 10 % overload lugs the engine 17 % below rated speed, and the rotor slows with it.

The hydrostatic drive follows the applied command v_a through a lag, and the command is limited in acceleration and deceleration at every control step $\Delta t_c = 0.2\,\text{s}$, as shown in Equation (4.12).

$$\begin{aligned} \tau_v \dot{v} &= n_e v_a - v \\ \Delta v_k &= \text{clamp}\left(v_{cmd,k} - v_{a,k-1},\ -d_{max}\Delta t_c,\ a_{max}\Delta t_c\right) \\ v_{a,k} &= \text{clamp}\left(v_{a,k-1} + \Delta v_k,\ 0,\ v_{max}\right) \end{aligned} \tag{4.12}$$

with $\tau_v = 1.2\,\text{s}$, $a_{max} = 0.25\,\text{m/s}^2$, $d_{max} = 1.0\,\text{m/s}^2$ and $v_{max} = 11.5\,\text{km/h}$. A plug sets v_a to zero at once. Fuel follows the power at 220 g/kWh of diesel at 0.84 kg/L.

4.3.5 Measurements

The feed-rate signal comes from the feeder house. The mean feed cut over each control interval, $\bar{Q}_c$, is delayed by $\theta_m = 1.5\,\text{s}$, multiplied by $1 + \sigma_Q \nu_Q$ with $\sigma_Q = 3\,\%$ and passed through a first-order filter of 0.4 s. The loss monitor divides delayed, averaged loss flows, scaled by a calibration gain $1 + b$, by the flow of grain leaving the machine, as shown in Equation (4.13).

$$\begin{aligned} Q_m &= F_{0.4}\left[(1 + \sigma_Q \nu_Q)\, \bar{Q}_c(t - \theta_m)\right] \\ L_m &= 100\, \frac{\hat{S} + \hat{C}}{\hat{S} + \hat{C} + \hat{T}} \\ \hat{S} &= F_{\tau_L}\left[(1+b)(1 + 0.05\nu_s)\, \dot{G}_{ls}(t - \theta_L)\right] \end{aligned} \tag{4.13}$$

Here $\hat{C}$ is formed like $\hat{S}$ from $\dot{G}_{lc}$ with its own noise, $\hat{T} = F_{\tau_L}[\dot{G}_t(t - 2\,\text{s})]$ is the yield sensor at the top of the clean grain elevator, $\theta_L = 1\,\text{s}$, $\tau_L = 4\,\text{s}$, F_τ is a first-order filter of time constant τ in its exact discrete form, and each ν is unit-variance Gaussian noise passed through a first-order filter, correlated over 0.5 s on the feed and over 1.5 s on the losses. The rotor torque T_m is measured with 1.5 % noise and a 0.3 s filter, the engine load λ_m with a 0.3 s filter, and a camera reports the cracked share of the grain, D_m, 3 s after it passes, filtered over 6 s. With the preview on, a forward sensor reports the density of each 2 m cell ahead of the header averaged over two cells, with a calibration gain $1 + b_p$ and 2 % of noise. The true loss share L that the trends show is $100(\dot{G}_{ls} + \dot{G}_{lc})/(\dot{G}_{ls} + \dot{G}_{lc} + \dot{G}_t)$, held at its last value through turns and stops.

Table 4.2 Machine and Field Parameters, With Hidden Ones Marked

Symbol	Parameter	Value	Class
Y, r_M	grain yield, MOG per kg grain	5.5 t/ha, 0.9	adjustable
m_0	base grain moisture	14 %	adjustable
W	header width	9 m	hidden
L_p, N_p	pass length, passes	250 m, 10	hidden
v_{max}	drive speed limit	11.5 km/h	adjustable
a_{max}, d_{max}	acceleration, deceleration	0.25, 1.0 m/s^2	adjustable
τ_v	hydrostatic drive lag	1.2 s	adjustable
v_{turn}	headland turn speed	5.4 km/h	adjustable
θ_f	cutter bar to rotor	1.5 s	hidden
m_{mc}, c_{rr}	empty mass, rolling resistance	18 t, 0.08	hidden
τ_r, Q_{cap}	rotor residence, straw capacity	2.5 s, 16 kg/s	adjustable
T_{plug}, t_{clear}	plug torque, time to clear	2.4 kN m, 120 s	adjustable
k_T, T_0	torque per kg, empty torque	26.8, 200 N m	hidden
τ_s	shoe residence time	1.5 s	adjustable
χ	MOG share reaching the shoe	0.2	hidden
P_{max}, τ_e	rated power, speed response	330 kW, 0.8 s	adj., hidden
θ_m	feed-rate signal delay	1.5 s	adjustable
θ_L, τ_L	loss sensor delay, averaging	1.0, 4 s	adjustable
t_{rain}	rain arrives	20 min	adjustable
ω_{ref}, M_{ref}, C_{ref}	reference speed, straw, chaff	950, 25.5, 2.7	fixed
η_h, e_{ch}, e_h	drive efficiency, chopper, header	0.75, 3, 0.6 kJ/kg	fixed
P_h, P_f, P_a	header, fan, auxiliary power	8, 12, 55 kW	fixed

The references are in rpm and kg. Fixed constants are not in the panel.

4.3.6 Parameters, Initialization and Numerics

The parameters are listed in Table 4.2. Those marked adjustable are sliders in the model panel, those marked hidden are part of the model but not offered there, and the constants of Equations (4.3) to (4.10) are fixed in the code. Each scenario starts at the head of pass 1, already harvesting steadily at the speed that meets the feed setpoint in the mean crop of the first 12 m, or at the manual speed. The rotor, the shoe and the engine start at the equilibrium of Equations (4.3) to (4.11), found by iterating the engine speed, with the conveyor full and the tank empty. The states are integrated by the classical fourth-order Runge-Kutta method with $\Delta t = 0.05$ s. The harvest, the conveyor, the plug and the pass bookkeeping run after each step, and the historian logs at 4 Hz. Halving Δt changes the tank at 200 s in case 2 by 0.0003 %. The texture and the noise come from the framework's seeded generator (Section 1.6.1).

4.3.7 Assumptions

One well-mixed inventory stands for the whole rotor and another for the shoe. A real axial rotor threshes at the front and separates along its length, and the grain spends less time in it than the straw does [2]. The lumped model keeps the capacity, the load dependence and the transport delay, which are what the control problem is made of.

The separation, cleaning and damage relationships are illustrative. Their shapes, exponential in the rotor load, a U in fan speed and rising with rotor speed and dryness, follow published combine behavior, while their constants were chosen [1]. They are not calibrated to any machine or crop variety.

One moisture stands for both the grain and the straw. Real straw is usually wetter than the grain, green weeds add moisture without grain, and dew wets the straw first.

The route is fixed and the field flat. The combine does not steer, the header height is constant, the reel and the header add no losses of their own, and the tank is never unloaded. No scenario field carries more than 12.9 t of grain, less than the 13 t the scene draws as a full tank.

The engine is a quasi-static governor with a first-order speed response, with no turbocharger lag and no fuel map, and the hydrostatic drive is a first-order lag with separate acceleration and

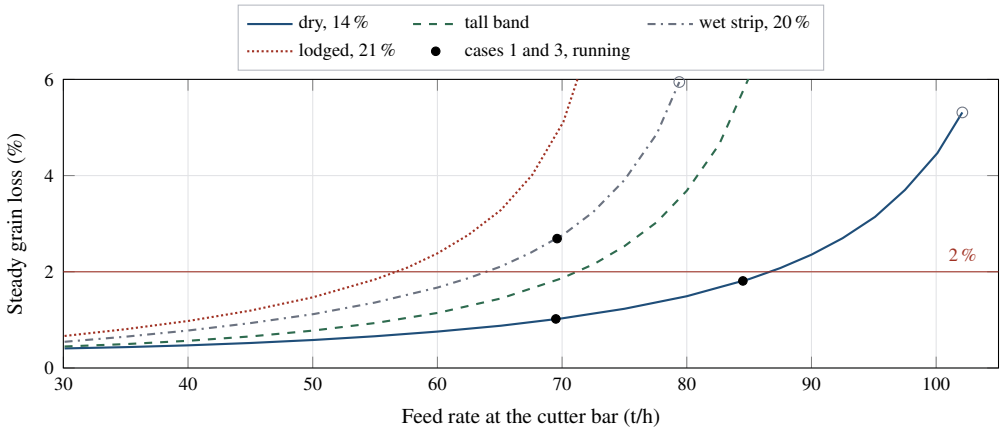


Figure 4.2 Steady loss against feed rate at 950 rpm of rotor and 1000 rpm of fan for the four crops of the scenarios: dry crop solid, the tall band dashed, the wet strip dash-dotted and lodged crop dotted, with the 2 % level as a thin line. Each curve is drawn to the feed at which the engine reaches its rated 330 kW (open circles) or to 6 %. The filled points are the running machine, case 1 at 70 and 85 t/h and the peak of case 3 in the wet strip at the mean feed of the crossing.

deceleration limits. On a real machine the speed depends nonlinearly on the pump setting and the engine speed [12].

The loss monitor is a delayed, averaged ratio of flows with a steady calibration error, and the preview measures mass with 2 % of noise. Real impact sensors count kernels and saturate at high loss rates, and real forward sensors see height and volume and remain hard to calibrate [17].

4.4 What Shapes the Control Problem

4.4.1 Throughput Against Loss

Setting every derivative of Equations (4.3) to (4.11) to zero at a fixed drive command gives the steady loss against feed, the curve on which every choice of speed sits, as shown in Figure 4.2. In dry crop at 950 rpm with the fan at 1000 rpm, the loss is 1.03 % at 70 t/h, 1.49 % at 80 and 2.36 % at 90 t/h, so a 21 % rise from 70 to 85 t/h costs 79 % more loss (1.03 to 1.85 %). The same 70 t/h loses 1.87 % in the tall band, whose crop carries 1.37 kg of straw for every kilogram of grain, 2.77 % in the wet strip and 5.11 % in lodged crop. The loss reaches 2 % at 86.7 t/h in dry crop, 71.2 in the tall band, 64.0 in the wet strip and 56.7 t/h in lodged crop. At a given feed the feed-rate signal is the same in all four crops, so nothing the feed loop measures tells them apart.

Each curve ends where the engine reaches its rated power, at 102.1, 89.0, 79.4 and 72.6 t/h, with the rotor at about 65, 75, 75 and 80 % of its plug torque. Past that point the engine lugs. In lodged crop the feed then rises to no more than 72.8 t/h, at a command of 6.5 km/h, and it falls as the command rises further while the slower rotor fills. At a command of 6.9 km/h the lugging steady state already puts the rotor above its plug torque, so in lodged crop an engine overload is the first stage of a plug.

4.4.2 A Process Gain Set by the Crop

The process gain of the feed loop is $\partial Q_c / \partial v = W \rho$, which is 9.4 t/h per km/h in uniform crop. It is 14.9 in the tall band of case 2, 1.59 times the uniform value, 11.7 in lodged crop and 4.95 in the sparse stretch of the challenge. A tuning chosen in average crop is therefore hotter in heavy crop and more sluggish in thin crop, by a factor of three between the extremes.

4.4.3 The Delay Budget

Around the uniform operating point the feed loop is a PI controller acting through the drive lag, the feed-signal filter and the transport delay, as shown in Equation (4.14).

$$L(s) = K_c \left(1 + \frac{1}{\tau_I s}\right) \frac{n_e W \rho \, \mathrm{e}^{-\theta_m s}}{(\tau_v s + 1)(\tau_f s + 1)} \tag{4.14}$$

Here $n_e = 0.986$ and $\tau_f = 0.4\,\mathrm{s}$, and the rate limits, the 0.2 s sampling and the averaging of the signal are neglected. With the shipped tuning, $K_c = 0.08$ km/h per t/h and $\tau_I = 2\,\mathrm{s}$, the loop gain $K_c n_e W \rho$ is 0.74. With the signal 1.5 s late the gain margin is 1.95 and the phase margin 57°. The gain margin falls to one at a delay of 3.82 s, and at 4 s the loop gain at the phase crossover is 1.04, with a crossover period of 15.3 s. Halving K_c restores a gain margin of 1.93 at 4 s, and lengthening τ_I to 5 s restores 1.50. In the tall band of case 2 the shipped tuning keeps a gain margin of only 1.23 and a phase margin of 23° at the nominal 1.5 s of delay. Section 4.6.4 compares these figures with the running loop.

4.5 Implemented Controller

Control executes every 0.2 s, once every four physics steps and before the integration, and the loss supervisor and the trims run on slower clocks within it. Four PI controllers share the ground speed and the feed setpoint, as shown in Figure 4.3, and their settings are listed in Table 4.3.

4.5.1 Discrete PI Algorithm

All four PI loops use the velocity-form PID of the framework (Section 1.6.2). The running sum S_k of the proportional and derivative increments, Equation (1.13), is never clamped, the output before limiting is $c_k = u_{bias} + S_k + I_{k-1}$, Equation (1.14), with the bias u_{bias} written u_b and c_k written v_k in Chapter 1, and the integral I_k is unwound by back-calculation, Equation (1.15), with $T_t = \tau_I$. The derivative term is zero here because $\tau_D = 0$ in all four loops. The acceleration and deceleration limits of Equation (4.12) act after the selector in PI operation, and no PI loop sees them, so the loop in charge keeps integrating while the drive is rate limited. In MANUAL, and whenever a schedule rather than the selector sets the speed, each speed controller tracks the command with $I_k = v_{cmd,k} - u_{bias} - S_k$, so its output equals that command exactly and the return to automatic is bumpless. All four loops set $a = +1$ because every process gain is positive. More speed means more feed, more engine load and more torque, and more feed means more loss. Each output therefore falls as its measurement rises, which is reverse action in the usual process-control convention [10].

4.5.2 The Speed Selector

Under PI control the ground speed command is the lowest of five demands, as shown in Equation (4.15).

$$v_{cmd} = \min\left(v_{feed},\ 1.1\,v_{ff},\ v_{eng},\ v_{rot},\ v_{hi}\right) \tag{4.15}$$

The feed PI acts on $Q_{\mathrm{SP}} - Q_m$, the engine PI on $E_{\mathrm{SP}} - \lambda_m$ with $E_{\mathrm{SP}} = 95\,\%$, and the rotor PI on $T_{\mathrm{SP}} - T_m$ with $T_{\mathrm{SP}} = 70\,\%$ of the plug torque. The preview speed v_{ff} is that of Section 4.5.3, and $v_{hi} = \min(v_{lim}, v_{max}) = 10\,\mathrm{km/h}$. Every PI is limited to $[0, v_{hi}]$. The incumbent keeps the drive until another demand undercuts it by 0.072 km/h (0.02 m/s), so noise cannot make two nearly equal demands trade it back and forth, except that the speed limit takes over as soon as it is lower. This incumbent margin is the one of Section 1.4.3, and Volume 19, Chapter 6 shares a belt speed between two limits through the same low selector with external reset. With the overrides off the engine and rotor controllers still run under external reset, but they are not candidates, and with the preview off neither is its cap.

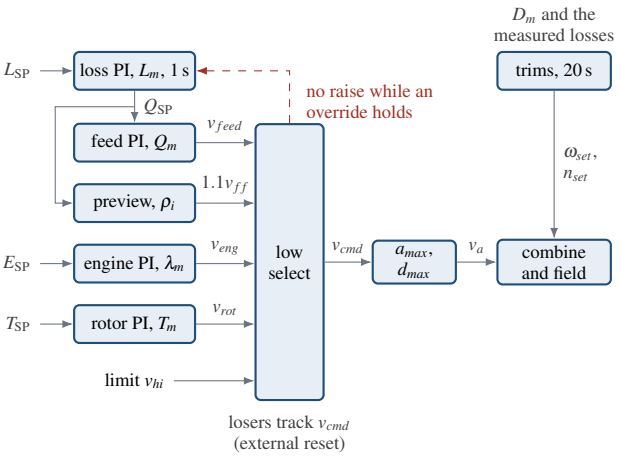


Figure 4.3 Control structure. Five speed demands meet in a low selector, and the controllers that lose track the applied command through external reset. The loss PI sets the feed setpoint once a second as the outer loop of a cascade and may not raise it while the engine limit, the rotor limit or the speed limit holds the drive. The trims step the rotor and fan speeds every 20 s.

4.5.3 Preview Braking Curve

With the preview on, the forward sensor scans the crop from the header to the range $R_p = 10\,\text{m}$ or the end of the pass. For each cell i in view, at distance d_i ahead, the speed that would meet the feed setpoint there is $v_i = Q_{SP}/(\rho_i W)$, and the preview speed is the fastest one from which the drive could still slow to every v_i in time, as shown in Equation (4.16).

$$v_{ff} = \min_i \sqrt{v_i^2 + 2d_{max}\max\left(0,\ d_i - 2.5\,v\,\tau_v\right)} \tag{4.16}$$

The term $2.5v\tau_v$ is the distance the header covers while the drive lag settles, and the square root is the braking curve at the deceleration limit. The selector sees $1.1v_{ff}$, a 10 % margin that keeps the cap clear in crop that suits the present speed, and at each pass start the uncapped v_{ff} is the entry speed. The preview is therefore feedforward that acts as a moving limit rather than as an additive bias. Placed in the selector, it slows the machine while the feed PI, which cannot yet see the heavier crop, is held on external reset instead of fighting the slowdown.

Pause. Try Exercise 4.2 before reading on.

4.5.4 External Reset

Each losing controller, after its own update, has its integral pulled toward the applied command through a first-order lag, as shown in Equation (4.17).

$$I \leftarrow I + \left(1 - \mathrm{e}^{-\Delta t_c/\tau_I}\right)\left(v_{cmd} - u_{bias} - I\right) \tag{4.17}$$

This is the lag of the applied output of Equation (1.4), with $T_t = \tau_I$, executed in its exact discrete form. Its output therefore settles at the applied speed plus its own proportional term. An override whose constraint is comfortable asks for more than the applied speed and stays out of the way, and one whose constraint is threatened drops below it at once and takes the drive without a bump [8, 9]. The feed PI is treated the same way whenever any other demand holds the drive.

4.5.5 Loss Supervisor and Trims

The loss controller is the outer loop of a cascade. Once a second it moves the feed setpoint Q_{SP} with a PI on $L_{SP} - L_m$, with $K_L = 7$ t/h per percent and $\tau_{I,L} = 20\,\text{s}$, within 14.4 t/h to 115.2 t/h and at no

Table 4.3 Controller Settings as Shipped

Loop	Measurement, SP	Gain, τ_I	Output and limits
feed	Q_m, 70 t/h	0.08 km/h per t/h, 2 s	v_{feed}, 0–10 km/h
engine	λ_m, 95 %	0.1 km/h per %, 2 s	v_{eng}, 0–10 km/h
rotor	T_m, 70 %	0.1 km/h per %, 2 s	v_{rot}, 0–10 km/h
loss	L_m, 1.5 %	7 t/h per %, 20 s	Q_{SP}, 14.4–115.2
rotor trim	D_m, ℓ_s	25 rpm per 20 s	ω_{set}, 700–1200
fan trim	ℓ_c	30 rpm per 20 s	n_{set}, 700–1300

Periods 0.2, 1 and 20 s. Selector margin 0.072 km/h, preview margin 1.1, range 10 m. Overrides on, preview, loss controller and trims off, except where a scenario sets them.

more than 0.54 t/h per second. It acts only while the machine is harvesting and more than 25 s after a pass has started, so that the rotor has refilled after the turn, and otherwise it tracks the setpoint in force. The first pass starts with the rotor full. The priming call tracks the starting feed setpoint, and the first update occurs after one simulated second. Paused pre-Run selections therefore cannot ratchet the setpoint. While the engine limit, the rotor limit or the speed limit holds the drive the feed loop is not delivering its setpoint, and the supervisor may then lower Q_{SP} but not raise it. A raise is refused by tracking the previous value, which is conditional integration in the outer loop of the cascade. The preview cap does not count as a hold, because it lets go as soon as the heavier crop is under the header.

🕮 **Pause.** Try Exercise 4.3 before reading on.

Every 20 s of settled harvesting a rule steps the rotor speed ω_{set} by 25 rpm and a perturb-and-observe search steps the fan n_{set} by 30 rpm. The rotor steps down when the damage camera reads above the damage limit $D_{max} = 1.5\,\%$, and it steps up when the measured separation loss exceeds half the loss setpoint while the damage is below 85 % of its limit, within 700 rpm to 1200 rpm. The fan reverses its direction of search whenever the cleaning loss averaged over the last 12 s of a window exceeds that of the previous window, within 700 rpm to 1300 rpm. The variator and the fan follow at no more than 8 and 15 rpm/s.

4.5.6 Speed Outside Automatic Harvesting

Outside automatic harvesting a schedule or the operator sets the speed, and every speed controller tracks it. Through a headland turn the command is 5.4 km/h. For $\theta_m + 0.6\,\mathrm{s} = 2.1\,\mathrm{s}$ after a pass starts, until the feed signal carries crop again, the command stays at the turn speed or, with the preview on, at v_{ff}. A plug stops the drive at once, and the rain or the end of the field brings it to rest at the deceleration limit. In MANUAL the operator sets the speed from 0 to 11.5 km/h with a slider, or in 0.5 km/h steps from the keyboard or two buttons. The supervisor and the trims then stop, and the drive limits of Equation (4.12) still apply.

4.5.7 Model Predictive Ground-Speed Control

The optional model predictive controller (MPC) replaces the normal speed request, applying the first planned command [18], as the framework's MPC option does (Section 1.6.3). It replans at initialization and every 1 s over 30 samples in ten blocks of lengths $(1,1,1,2,2,3,4,4,6,6)$. Integration, control and recording remain 0.05 s, 0.2 s and 4 Hz.

The ten-state predictor approximates the nominal dry machine at 950 rpm rotor and 1000 rpm fan

speed, with exact zero-order-hold discretization of Equation (4.18).

$$\begin{gathered} 1.2\dot{\hat{v}} = 0.985739u - \hat{v}, f = 9\rho\hat{v} + w \\ 0.75\dot{z}_1 = f - z_1, 0.75\dot{z}_2 = z_1 - z_2 \\ 0.4\dot{\hat{q}} = z_2 + b_q - \hat{q}, 0.775\dot{z}_3 = f - z_3 \\ 0.775\dot{z}_4 = z_3 - z_4, 1.5\dot{z}_5 = z_4 - z_5 \\ 4.038075\dot{\hat{T}} = 2.022643z_4 - 1.496689 + b_T - \hat{T} \\ 1.1\dot{\hat{E}} = 2.546671z_4 + 21.799254 + b_E - \hat{E} \\ \dot{\hat{G}} = 0.521053z_5 \end{gathered} \tag{4.18}$$

Units are m/s for $u, \hat{v}$, kg/s for $z_1, \ldots, z_5, \hat{q}$, percentage points for $\hat{T}, \hat{E}$, kg for $\hat{G}$ and seconds for lags. Nominal $\rho = 1.045\,\mathrm{kg/m^2}$ gives feed gain 9.270876 kg/s per m/s. Load slopes use steady balances. The rotor lag approximates capacity-dependent residence and instrument lag, 1.72 % below the 4.108 870 s operating-speed value. Texture-free $\pm 0.15\,\mathrm{m/s}$ steps give feed RMSE 0.0417/0.0566 kg/s, engine 0.427/0.339 points and torque 0.376/0.457 points, with feed noise off but 1.5 % torque noise retained.

Instruments and applied-command history drive the observer. Each scan, propagation gives x^- and residuals $e_i = y_{m,i} - x_i^-$ update $b_i^+ = \mathrm{clip}(b_i + 0.012\Delta t_c e_i)$, and the observed feed, engine and torque states receive $(1 - \exp(-\Delta t_c/0.6))e_i$. The integration gain is $0.012\,\mathrm{s^{-1}}$. Bias limits are $\pm 8\,\mathrm{kg/s}$ for feed and ± 60 points for each load. Integrating disturbances address constant offsets [19], without a guarantee of zero error for this nonlinear machine. Measured speed replaces $\hat{v}$, and measured yield integrates $\hat{G}$. Density comes from the scanner's first sample, or $Q_m/[9\max(0.3, v_{old})]$, bounded to 0.2–3 $\mathrm{kg/m^2}$, with v_{old} about 2 s old to align the delayed feed. Propagation uses density rounded to 0.01 $\mathrm{kg/m^2}$. Observation continues under PI and Manual. Initial flows, speed and loads equal measurements, with zero tank integral and biases.

The scanner model, range, calibration and seeded noise mechanism match. Each run's profile and braking cap share one scan without extra draws. With v_m the measured speed, the last scanner sample before distance $\max(0.25, v_m)j$ supplies ρ_j, held beyond range, with $w_j = 9(\rho_j - \rho)v_m$ in kg/s. A 10 m range covers about 4.8 s at nominal speed. After estimated arrival at a visible pass end, reference, reward and w_j become zero. The current density gain remains, so this is not an exact zero-crop or turn model.

The shared active-set quadratic solver minimizes Equation (4.19) with ten speed decisions, three slacks and a 600-iteration ceiling.

$$\begin{aligned} J = &\sum_{j=1}^{30}[(\hat{q}_j - r_j)^2 - 0.5\chi_j\hat{q}_j] + 8\sum_{b=1}^{10}(\Delta u_b)^2 \\ &+ 20s_q^2 + 10s_E^2 + 10s_T^2 \\ 0 \le u_b \le \bar{u}, &\quad -d_{max}T_s \le \Delta u_b \le a_{max}T_s \\ \hat{q}_j \le Q_{\mathrm{SP}} + 1 + s_q, &\quad \hat{E}_j \le E_{\mathrm{SP}} + s_E, \quad \hat{T}_j \le T_{\mathrm{SP}} + s_T \end{aligned} \tag{4.19}$$

Here $T_s = 1\,\mathrm{s}$, $r_j = Q_{\mathrm{SP}}$ in kg/s and $\chi_j = 1$ except after the visible end, where both are zero. The hard command ceiling $\bar{u}$ is v_{hi}, reduced by $1.1v_{ff}$ when preview is on. Rate bounds apply at block transitions from the previous applied command. The three nonnegative slacks span the horizon. Tank and terminal weights are zero. Weights use numerical SI values: $(\mathrm{kg/s})^{-2}$ for feed, $(\mathrm{kg/s})^{-1}$ for reward, $(\mathrm{m/s})^{-2}$ for moves and point^{-2} for load slacks. A 10^{-7} Hessian ridge regularizes all 13 variables. Nominal gains remain frozen when plant parameters or power change.

Loss supervision, trims, stops, turns, pass-start hold and slew remain. Armed load PIs override when measured limits are breached and all speed PIs track post-slew applied command. Nonoptimal,

Table 4.4 Headline Measurements by Case

Case, setting	Measured result
1, 70 t/h, 20 s to 100 s	7.43 km/h, loss 1.02 %
1, 85 t/h	9.03 km/h, loss 1.81 %
1, 300 s, 70 / 85 t/h	2.61 / 3.13 t, harvest loss 0.99 / 1.73 %
2, reactive	feed peak 107.8 t/h, speed down to 2.55 km/h
2, preview 10 m	feed peak 78.8 t/h, speed down to 4.12 km/h
2, range 2 / 3–4 / 5–6 / ≥7 m	feed peak 101.8 / 86.2 / 79.8 / 78.8 t/h
3, 70 t/h	loss 1.00 to 2.69 %, torque 37 to 57 %
3, preview / loss controller	peak 2.88 / 3.04 %
3, 60 t/h / 1050 rpm	peak 1.71 / 2.10 %
4, loss controller	Q_{SP} 76.3 to 65.7 t/h, loss 1.37–1.76 %
4, Manual / trims on	loss to 1.92 % / 8.74 against 8.10 t
5, $\theta_m = 4$ s	speed 6.40–8.75 km/h, period 15.8 s
5, K_c 0.04 / τ_I 5 s / θ_m 1.5 s	7.08–7.75 / 7.10–7.75 / 7.07–7.75 km/h
6, $b = -40$ %, 250 s to 500 s	monitor 1.44 %, true 2.40 %
6, Q_{SP} biased / calibrated	91.3 / 79.6 t/h
7, overrides on, 80 s to 120 s	feed 55.1 t/h, engine 95 %, loss 0.67 %
7, overrides off	engine 105 %, rotor 854 rpm, loss 1.64 %
8, overrides off	plugs at 53.15 and 203 s, 1.29 t at 400 s
8, overrides on	no plug, torque peak 88 %, 3.55 t at 400 s

malformed, nonfinite, out-of-bounds or rate-violating plans, negative feed and decreasing tank reject. First failure holds applied speed for one 0.2 s scan under current caps, then tracked PI selection acts until recovery. Noise-free first-failure command jump is zero.

4.5.8 Plant, Analysis and Controller Models

The plant as simulated is Equations (4.1) to (4.13). No model is identified in the application, and the control model used for analysis is the linearization of Equation (4.14). The classical controller model is the preview, which uses the static feed relation $Q = \rho W v$, the deceleration limit and a settling distance of $2.5 v \tau_v$, and knows nothing of moisture. The PI controllers and the supervisor are model-free. The MPC model is Equation (4.18), distinct from the nonlinear plant and the pure-delay model used for loop analysis.

4.6 Measured Scenarios

The ten scenarios are the uniform field (case 1), a dense patch (2), a wet strip (3), a moisture drift (4), a sensor delay (5), a biased loss sensor (6), a power reduction (7), a plugging threat (8), the predictive controller against the preview and the overrides (9) and the challenge against the rain (10). Each carries a completion rule (Section 1.6.4). The challenge is judged on the case as given, so a changed model parameter or disturbance voids the attempt. Table 4.4 collects the measured results. Every value was read from headless runs of the application's engine at its default seed, with each setting made after the case is loaded and before the run starts unless a time is named, over the window stated with it. The scorecard's harvest loss is the grain lost at separation, at cleaning and in plugs as a share of all the grain that has left the machine. The worst pass is the largest share lost on any one pass, counted from its start to the start of the next pass so that the turn after it, where the rotor empties, belongs to it. The pass in progress counts with its share so far, which can still fall as the pass goes on. Engine overload is the total time with $\lambda_E > 1$.

4.6.1 Throughput Against Loss

In the uniform field at the default 70 t/h, the combine drives 7.43 km/h over 20 s to 100 s, takes in 69.5 t/h at the cutter bar, draws 71 % of its engine power, runs its rotor at 38 % of the plug torque and loses 1.02 % of its grain. The first pass takes 121 s and the headland turn 19.7 s. At 85 t/h the speed is 9.03 km/h and the loss 1.81 %, so 21 % more feed costs 78 % more loss. Over 300 s the faster machine puts 3.13 t in the tank and cuts 0.58 ha, against 2.61 t and 0.48 ha, at a harvest loss of 1.73 %

against 0.99 %. Whether the extra half tonne is worth the extra loss depends on the price of grain and on how soon the rain comes, which is the decision the challenge poses. It is the trade of Section 1.4.2, where better control is paid out in throughput.

4.6.2 A Dense Patch Seen Late and Seen Early

In case 2 a 40 m band of tall wheat, 1.56 times as dense as the crop just before it, crosses every pass. The header enters it at 53.70 s. The feed at the cutter bar jumps at once and peaks at 107.8 t/h at 55.20 s, while the measured feed still reads near 70, because the feeder-house signal is 1.5 s late and filtered. By the time the loop answers, its process gain is 1.59 times the one it was tuned in, which leaves the gain margin of 1.23 found in Section 4.4.3, and it overcorrects, taking the speed down to 2.55 km/h before it settles near 4.8 km/h in the band. The rotor torque peaks at 55 % of the plug torque and the loss at 2.90 %. With the 10 m preview the machine is already slowing as the header reaches the band. The feed then peaks at 78.8 t/h, the speed bottoms at 4.12 km/h, the torque at 49 % and the loss at 2.06 %. Inside the band the loss averages 2.05 % without the preview and 1.89 % with it over 65 s to 82 s, because tall crop brings more straw per tonne whatever the speed. The preview removes the surge, not the heavier crop. The same division of labor, feedforward from a measurement upstream with feedback left to trim, is the subject of Volume 3, Chapter 6.

The range the preview needs is set by the drive. At 7.4 km/h the header covers $2.5 v \tau_v = 6.2$ m while the drive lag settles and another 1.3 m while the drive brakes at 1 m/s^2 to the 4.7 km/h the band needs, and with the 10 % margin the cap starts to bind about 7 m before the band. The feed peaks at 101.8 t/h with a 2 m range, 86.2 with 3 or 4 m, 79.8 with 5 or 6 m and 78.8 from 7 m on. The peaks change in pairs of ranges because the sensor resolves the crop in 2 m cells.

4.6.3 Moisture That No Sensor Sees

Case 3 crosses a 50 m strip that is 6 points wetter than the rest and carries 10 % more straw. At a constant 70 t/h the rotor torque rises from 37 to 57 % of the plug torque, the engine load from 71 to 85 % and the true loss from 1.00 to 2.69 %, while the feed trend shows nothing. The preview cannot help, because the strip is only 5 % denser, and the peak is 2.88 % with it. The loss controller makes the peak worse, 3.04 %. It enters the strip at 46.85 s with the setpoint already raised to 75.6 t/h by the dry crop before it, its monitor peaks at the scan at 65.25 s, 5.25 s after the true loss, and the setpoint bottoms at 62.6 t/h at the scan at 75.05 s, 2.95 s after the header has left the strip at 72.10 s. A strip that passes under the header in about 25 s is gone before a loop with a 5 s measurement lag and a 20 s integral time has finished answering it. What works is a decision made before the strip. A feed of 60 t/h holds the peak to 1.71 %, and a rotor at 1050 rpm holds it to 2.10 % while cracking 0.56 % of the grain that reaches the tank during the crossing against 0.37 %.

> **TRY IT IN THE APP** **3 · Wet Strip**
>
> Load the scenario and press Run. Watch the Feed rate trend and the Grain loss trend as the header crosses the wet strip. The feed stays at 70 t/h while the true loss climbs from 1.00 to 2.69 % and the rotor load rises from 37 to 57 % of the plug torque.

Case 4 is the disturbance the supervisor is for. Dew wets the crop by 0.3 points a minute, and the loss controller lowers the feed setpoint from 76.3 t/h at 60 s to 65.7 t/h at 880 s while the moisture at the header rises from 14.4 to 18.5 %. From 300 s on, the settled true loss stays within 1.37 % to 1.76 % and averages 1.58 % over the last 200 s against its 1.5 % setpoint. With the supervisor in Manual the setpoint stays at the 70.0 t/h it held when the case was loaded, which the switch to Manual copies into the setpoint and Reset keeps, and the loss creeps from 1.05 % at 60 s to 1.92 % at 900 s. With the trims on as well, the rotor steps up to its 1200 rpm limit, turning at 1178 rpm by 600 s because wet grain cracks less, and the machine brings in 8.74 t in 15 min against 8.10 t, over 1.61 ha against 1.50 ha.

🕮 **Pause.** Try Exercise 4.1 before reading on.

4.6.4 Hunting on a Later Signal

Case 5 infers the feed from the rotor drive pressure, 4 s after the crop is cut instead of 1.5 s, with the tuning unchanged. Over 55 s to 115 s the speed hunts between 6.40 and 8.75 km/h with a period of 15.8 s, and the feed between 60 and 81 t/h, where the linearization of Equation (4.14) gives a loop gain of 1.04 at a phase crossover period of 15.3 s. Halving the gain to 0.04 keeps the speed within 7.08 km/h to 7.75 km/h, a 5 s integral time keeps it within 7.10 km/h to 7.75 km/h, and with the signal back at 1.5 s the shipped gains give 7.07 km/h to 7.75 km/h. The limit of the running loop was located in a counterfactual run with the crop texture removed, the feed noise off and the pass lengthened to 1000 m, from the oscillation left by a 2 t/h setpoint step. Its amplitude falls by 4.4 % per cycle at a delay of 3.7 s and grows by 2.0 % per cycle at 3.8 s, so the running loop reaches its limit at 3.77 s, with a period of 15.1 s, close to the linear estimate of 3.82 s. Volume 5, Chapter 3 measures the same erosion of a fixed tuning as an analyzer lag grows.

4.6.5 A Monitor That Reads Low

In case 6 the loss monitor reads 40 % low and the supervisor is in Auto at a 1.5 % setpoint. Over 250 s to 500 s of settled harvesting the monitor reads 1.44 % while the true loss is 2.40 %, as the calibration says it must be, and the supervisor has raised the feed setpoint to 91.3 t/h, against 79.6 t/h with a calibrated monitor. By 500 s the harvest loss is 1.97 % and the worst pass has lost 2.23 %. A kernel count behind the machine at 300 s, which is the recalibration event, brings the setpoint back down to 80.3 t/h at 436 s and 80.7 t/h at 500 s, with the true loss at 1.56 % over 430 s to 500 s. The loop held its measurement on setpoint throughout, and the measurement was wrong.

4.6.6 The Engine and the Rotor as Constraints

At 60 s in case 7 the engine derates to 65 % of its 330 kW. With the overrides on, the engine limit takes the drive 0.8 s later and holds the engine at 95 %. Over 80 s to 120 s the feed is 55.1 t/h against 69.5 t/h before the derate, the speed 5.99 km/h and the loss 0.67 %, because the rotor is lightly loaded, and on the way down the engine is over its available power for 6.05 s. Without the overrides the feed loop holds 70.4 t/h by demanding power the engine does not have. The engine runs at 105 % and lugs to 89.9 % of rated speed, the rotor slows from 937 to 854 rpm with it, the loss rises to 1.64 %, and the engine is still at 106 % of its available power at 180 s.

Case 8 feeds 80 t/h into 140 m of lodged crop across the first two passes with the overrides off, beyond the 72.6 t/h at which the engine reaches full power in that crop. The header enters it at 25.75 s with the rotor at 45 % of its plug torque. The feed loop holds a mean of 80.2 t/h, the engine is overloaded from 36.80 s and lugs, the rotor slows from 935 to 847 rpm and loses capacity, and the torque climbs to the plug at 53.15 s, 27 s into the patch, with 51 kg of grain in the rotor. The machine stands for 120 s, restarts in the same crop and plugs again at 203 s, and at 400 s the tank holds 1.29 t. The preview alone does not help, because lodged crop is only 1.24 times as dense, and the rotor plugs at 53.80 s. With the overrides on, the rotor limit holds the drive for 156 s of the first 300 s, the torque overshoots its 70 % limit to 88 % before the override catches it, because the crop already on the feeder must still pass, and the machine never stops. The feed in the lodged crop averages 68.4 t/h and the tank holds 3.55 t at 400 s. The override protects the rotor, not the grain. After 300 s the harvest loss is 3.49 %, because a torque limit of 70 % admits a steady loss of about 4.5 % in lodged crop.

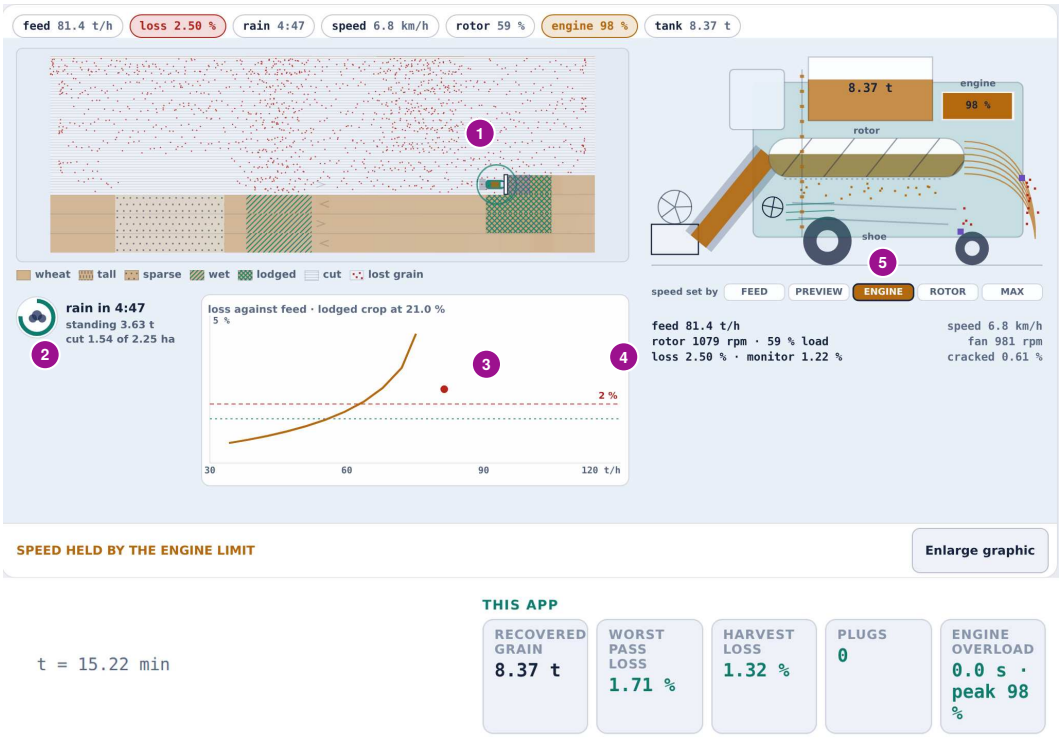


Figure 4.4 The combine harvester application 913 s into the challenge (the clock reads 15.22 min) after the suggested configuration was revealed, with the loss controller in Auto, the overrides armed at an engine limit of 90 % and the preview and the trims on. The figure is a composite: the plant view of the window and, enlarged below it, the run clock and the scorecard tiles. (1) The field is 1.54 of 2.25 ha cut, with red dots of lost grain on the stubble, and the combine is 210 m into pass 7, just inside the cross-hatched lodged patch, with the violet preview wedge ahead and the dotted sparse, hatched wet and cross-hatched lodged crop still standing in the last passes. (2) Below the field the weather clock shows the rain 4 min 47 s away with 3.63 t standing. (3) The steady loss curve is drawn for the lodged crop at 21.0 % moisture, and the operating point, at 81.4 t/h and 2.50 %, lies above the 2 % line but below that curve, because the rotor still holds crop cut before the patch, at 19.4 % moisture. (4) The readout gives the true loss against the lagging monitor (2.50 % against 1.22 %), and the cutaway shows 8.37 t in the tank and the engine at 98 %. (5) The ENGINE chip says that the engine override has the speed. The worst pass so far has lost 1.71 %.

> **TRY IT IN THE APP** **8 · Plugging Threat**
>
> Run the scenario with the Overrides off and watch the rotor load after the header enters the lodged crop. The rotor plugs at 53.15 s, 27 s into the patch. Press Reset, set Overrides to On before pressing Run, and repeat: the torque overshoots to 88 % of the plug torque, the machine never stops, and at 400 s the tank holds 3.55 t against 1.29 t.

4.6.7 The Harvest Against the Rain

The challenge field carries a tall band across passes 1 to 5, a sparse stretch in passes 6 to 10, a wet strip across every pass and a lodged patch in passes 7 to 9, 12.10 t of grain in all, with the rain at 20 min. The target is at least 10.5 t in the tank, no pass above 2 % of loss, no plug and at most 10 s of engine overload, and the run stops itself 12 s after the rain. The shipped configuration drives

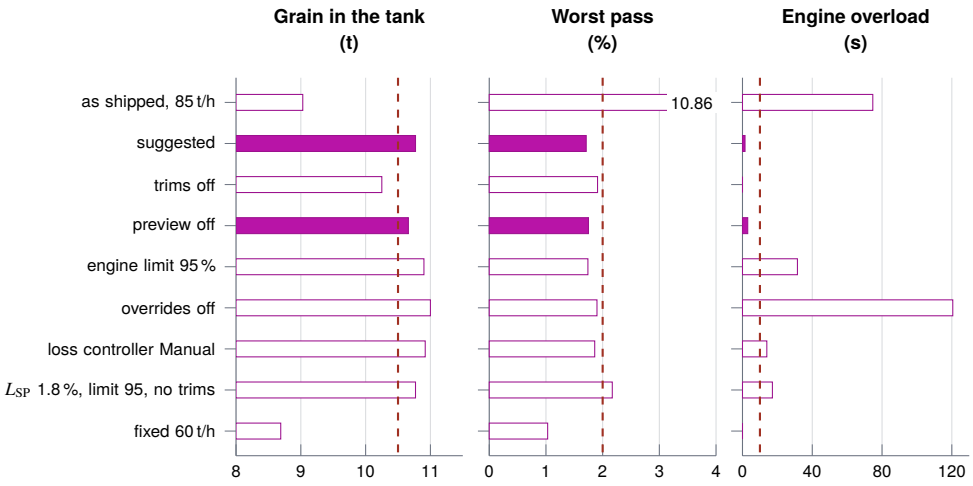


Figure 4.5 Table 4.5 redrawn against the three limits of the target, dashed: at least 10.5 t, no pass above 2 % and at most 10 s of engine overload. Solid bars meet the whole target and white bars do not. The shipped configuration's worst pass, 10.86 %, runs off its axis. Notice that each of the three configurations that bring in more grain than the suggested one fails on overload, and that the clean fixed feed fails on grain.

Table 4.5 Challenge Configurations, Read When the Run Stops Itself

Configuration	Grain (t)	Worst pass (%)	Plugs	Overload (s)	Met
as shipped, 85 t/h, overrides off	9.03	10.86	2	74.70	no
suggested	10.77	1.71	0	1.45	yes
trims off	10.25	1.91	0	0.00	no
preview off	10.66	1.75	0	3.00	yes
engine limit 95 %	10.90	1.74	0	31.50	no
overrides off	11.00	1.90	0	120.55	no
loss controller Manual	10.92	1.86	0	13.95	no
L_{SP} 1.8 %, limit 95 %, trims off	10.77	2.17	0	17.15	no
fixed 60 t/h, overrides, preview	8.69	1.03	0	0.00	no

85 t/h with the overrides off. It plugs twice in the lodged patch, at 865.5 s and 1044.8 s, losing 240 s and 104 kg of grain dumped from the rotor. It overloads the engine for 74.7 s with a peak of 109 % and brings in 9.03 t with 2.78 t still standing, as shown in Table 4.5 and drawn against the target in Figure 4.5. Its worst pass reads 10.86 % when the run stops, and that figure belongs to pass 8, still in progress and carrying the second plug, while the worst completed pass lost 7.20 %.

The suggested configuration puts the loss controller in Auto, arms the overrides with the engine limit at 90 %, and turns on the preview and the trims. It brings in 10.77 t from 2.00 ha, loses at most 1.71 % on any pass and 1.36 % over the harvest, never plugs and overloads the engine for 1.45 s, at 2.13 L/t with 1.24 % cracked grain. It passes with 0.27 t of margin on the grain, 0.29 points on the worst pass and 8.1 s on the overload. Its worst pass is the first, driven while the supervisor brings the setpoint down from the shipped 85 t/h (to 72.4 t/h by 90 s) and the trims raise the rotor from 950 to 1075 rpm. Removing the trims leaves 10.25 t, short of the target, and removing the preview still passes at 10.66 t. The default engine limit of 95 % brings in 10.90 t but overloads the engine for 31.50 s, because the load overshoots the limit its override holds in every transient, and removing the overrides reaches 11.00 t with 120.55 s of overload, although its worst pass, 1.90 %, stays inside

Table 4.6 Matched 1260 s Comparison. Paired Entries Give PI / MPC

Case, setting	Tank (t)	Loss (%)	Plugs	Overload (s)	Feed IAE (10^3 t/h s)	Travel (km/h)	Sat. (%)	Attempts/ rejects	Solve (μs)
Dense, scan On	10.150 / 10.576	1.134 / 1.328	0 / 0	0.00 / 0.00	17.06 / 20.35	342 / 306	4.76 / 4.76	1260/91	104
Dense, scan Off	10.193 / 10.229	1.190 / 1.277	0 / 0	0.00 / 0.00	19.43 / 19.88	446 / 415	4.76 / 4.76	1260/56	80
Dense, scan −30%	10.211 / 10.682	1.206 / 1.961	0 / 0	0.00 / 0.00	19.96 / 31.89	479 / 453	4.76 / 5.63	1260/0	75
Dense, power 65%	8.111 / 8.917	0.708 / 0.898	0 / 0	55.85 / 705.45	30.55 / 24.45	119 / 134	4.76 / 4.76	1260/91	109
Plug threat, scan On	11.247 / 11.890	1.877 / 2.247	0 / 0	19.90 / 24.85	23.13 / 25.34	378 / 352	4.76 / 4.76	1260/89	89
Plug threat, scan Off	11.122 / 11.474	1.903 / 2.028	0 / 0	24.45 / 3.50	24.60 / 23.64	378 / 381	4.76 / 4.76	1260/55	72
Plug threat, scan −30%	11.252 / 11.292	1.888 / 2.882	0 / 0	17.65 / 41.45	23.75 / 36.09	383 / 360	4.76 / 5.71	1260/0	87
Plug threat, power 65%	8.051 / 9.054	0.934 / 1.633	0 / 0	58.75 / 937.10	44.50 / 37.05	112 / 101	4.76 / 4.76	1260/92	118
Challenge, scan On	11.209 / 11.444	2.336 / 2.843	0 / 0	32.65 / 106.80	28.45 / 29.82	410 / 373	4.76 / 4.84	1260/84	90
Challenge, scan Off	11.120 / 11.239	2.404 / 2.538	0 / 0	16.75 / 62.95	31.11 / 30.59	446 / 467	4.76 / 4.76	1260/55	81
Challenge, scan −30%	11.266 / 10.661	2.445 / 3.720	0 / 0	22.50 / 173.00	29.63 / 37.92	429 / 394	4.76 / 6.67	1260/0	95
Challenge, power 65%	8.058 / 8.909	0.893 / 1.422	0 / 0	109.50 / 807.85	49.77 / 43.32	172 / 162	4.76 / 4.76	1260/95	116
Challenge, suggested	10.770 / 10.913	1.362 / 1.405	0 / 0	1.45 / 48.60	23.37 / 25.39	360 / 309	4.76 / 4.84	1260/88	90
Challenge, SIMC suggested	10.833 / –	1.382 / –	0 / –	0.00 / –	23.41 / –	300 / –	4.76 / –	–	–

PI / MPC entries share settings, seed and the same 10 m scan, or both turn it Off. Wrong scan has −30% calibration bias. Power falls unannounced to 65% at 60 s. PI uses shipped feed tuning. The fixed SIMC row has no paired MPC entry. Overload counts actual engine load above 100%. Scorecard IAE, travel and command saturation include stops and turns. MPC attempts/rejects include physical sequences. Solve is the mean QP time in Node.js on the measuring host, excluding observation and model construction. The dense rows are case 9, whose physics duplicates the dense case.

the limit. A fixed 60 t/h with the overrides and the preview is clean and brings in only 8.69 t. The verdict does not depend on the seed. Over five other seeds of the texture and the noise, the suggested configuration brings in 10.78 to 10.85 t with a worst pass of 1.688 to 1.692 %, and the shipped one fails every time. It plugs twice at four of the seeds, bringing in 9.01 to 9.05 t, and once at the fifth, which brings in 10.11 t but overloads the engine for 126.1 s and loses 7.47 % on its worst pass.

> **+ DID YOU KNOW? The Most Grain, and a Failed Harvest**
>
> From the simulator: against the rain, the suggested configuration with its overrides switched off brings in the most grain of any configuration, 11.00 t, yet it fails on 120.55 s of engine overload. A fixed 60 t/h with the overrides and the preview is clean and brings in only 8.69 t (Table 4.5).

With the rest of the suggested configuration fixed, the loss setpoint sets the trade. The grain rises from 9.93 t at 1.0 % to 10.45 at 1.2, 10.75 at 1.4, 10.77 at 1.5 and 10.90 at 1.6 %, and it stays between 10.89 and 10.90 t from 1.7 to 2.0 %, while the worst pass rises from 1.47 to 1.93 %. The target is met at every setpoint tested from 1.3 to 2.0 %, with 10.57 t at 1.3, and missed at 1.2 and 1.0 %. Above about 1.7 % the loss is no longer what limits the machine. The engine limit holds the drive for 264 s of the run at 1.5 %, 22 % of it, for 428 s at 1.8 % and for 524 s at 2.0 %, against only 84 s without the trims. The trims let the rotor separate better at the same feed, the supervisor spends that margin on feed, and the engine becomes the active constraint, which is how the trims earn their 0.52 t. The machine at 913 s of the suggested run, with the engine override holding the drive as the header enters the lodged patch, is shown in Figure 4.4.

4.6.8 Predictive Control with the Same Crop Scanner

Case 9 repeats case 2's tall band. Table 4.6 uses 1260 s, seed 20261009, matched instruments and protections, original suggested settings and frozen MPC tuning. A fixed SIMC feed PI [20] uses the nominal half-rule values $\tau = 1.4$ s, $\theta = \lambda = 1.7$ s and $k = 9.270876$: $K_c = \tau/[k(\lambda + \theta)] = 0.044415$ m/s per kg/s, $\tau_I = \min(\tau, 4(\lambda + \theta)) = 1.4$ s. Only feed tuning changes, with the rule frozen before comparison.

Case 9's real tank holds 1786.038 versus 1743.042 kg at 200 s, and 10576.485 versus 10 150.144 kg at 1260 s, for MPC versus PI. Harvest loss rises from 1.134 to 1.328 %. Feed

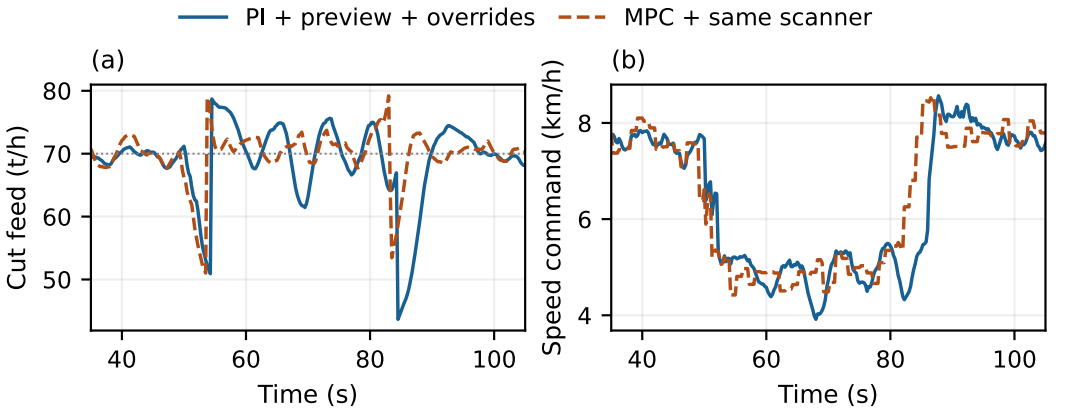


Figure 4.6 Dense-band passage with the same scanner model and range, PI with preview and overrides solid and MPC dashed. Feed rate and commanded speed over the first band show the local tracking improvement, with the whole-run throughput and loss trade reported in Table 4.6.

IAE over 45 s to 95 s falls from 262.88 to 147.57 t/h s, while whole-run IAE, including turns and stops, rises from 17060.39 to 20 354.86 t/h s. Figure 4.6 shows the local improvement.

In the plug case both protected laws avoid plugging, but MPC raises overload duration from 19.90 to 24.85 s, depth from 0.767 to 1.715 points and area from 7.624 to 16.792 point seconds. Suggested-challenge MPC collects 10912.76 versus 10 769.84 kg, with worst-pass losses 1.724 versus 1.709 %, yet fails with 48.60 s overload against PI's 1.45 s and the 10 s allowance. Fixed SIMC PI passes with 10 832.90 kg and zero overload. With unannounced power loss, dense-case MPC overloads for 705.45 versus 55.85 s.

The 76 primary, 52 zero-sensor-noise and 34 classical rows include half-step repeats. No paired ranking or challenge grade reverses, but suggested MPC overload becomes 27.45 s, without numerical convergence. Four independent grain ledgers close within 1.7×10^{-10} kg. Case 9's 1260 attempts reject 91 plans (36 visible-end, 55 after rain). The 91 s fallback flag includes 57.2 s of physical sequences and 33.8 s automatic harvesting, distinct from 992.4 s of actual MPC actuation. Chrome's full control callback averages 418.3 μs at real time (0.209% core at five scans/s). Requested 50× reaches 50.33× at 60.16 frames/s. Both guard settings have zero stops, with no observed pacing benefit. The 25 ms wrapper preserves reached steps and decisions. Four browser playback variants produce 961 identical non-wall rows, with zero Node/Chrome numerical difference in this test. Timing is host dependent.

4.7 Technology in Practice

A real combine reads the same kinds of signal and moves the same drive as the selector of Section 4.5.2. Figure 4.7 draws that loop with machine hardware in place of the schematic's symbols.

What Measures It

The automatic feed-rate controls built into combines rely on a sensor of the crop intake. The drive torque of the conveyors that carry the crop, the header auger and the feeder, gives the throughput of biomass [17]. The model's feed signal stands for such a measurement at the feeder house, 1.5 s after the cut and filtered over 0.4 s, and case 5 moves it to the rotor drive pressure, 4 s late. Grain loss is read behind the rotor and the sieves, by the pads of the next segment.

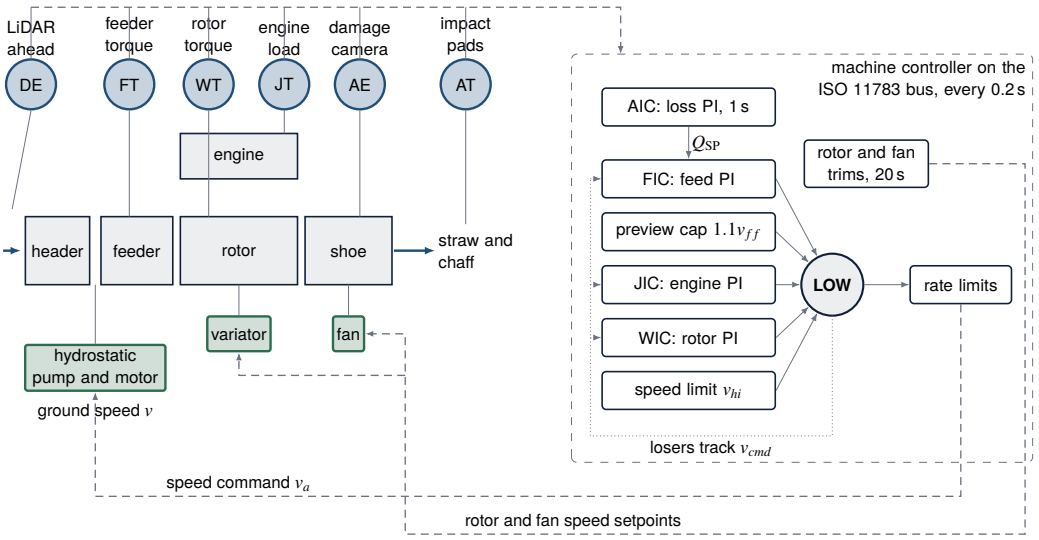


Figure 4.7 The feed loop and its overrides on machine hardware. Sensors (blue circles): DE, a LiDAR or other forward crop sensor; FT, the feed rate from the feeder drive torque; WT, the rotor torque; JT, the engine load; AE, the damage camera on the clean grain; AT, the kernel-impact loss pads behind the rotor and the sieves. Final elements (green): the hydrostatic pump and motor of the ground drive, the rotor variator and the fan. Five speed demands meet in the low selector, the losers track the applied command (dotted), and the loss PI moves the feed setpoint. Notice that only DE sees the crop before it enters, and only AT sees the grain that leaves.

TECHNOLOGY **Sensor: Kernel-Impact Loss Pads**

Grain loss sensors are plates or films of piezoelectric material that turn the impact of material into an electrical signal, which is amplified, filtered and rectified before the impacts are counted [21]. They sit where the straw and the chaff leave the machine. An extension guide asks that the sensitivity be set so that grain, not pieces of straw, triggers them, that the monitor be calibrated for the crop, and that the operator check now and then that the losses on the ground follow the signal in the cab [5]. Once the losses have been counted and the machine adjusted, the monitor serves as an early warning of change [22]. The model's monitor is a delayed ratio of flows, and its calibration error b stands for a pad that is set wrong.

What Moves It

The selector's output is a ground-speed command, and the drive that follows it is hydrostatic. A wheat guide asks the operator to use the slowest rotor speed and the widest concave spacing that still thresh the crop, and to judge threshing by the damaged kernels, the kernels left in the heads and how finely the straw is broken [5].

> **TECHNOLOGY** **Final Element: A Hydrostatic Ground Drive**
>
> The operator sets a combine's ground speed with the hydrostat, the speed control of its hydrostatic drive [22]. The heart of such a drive is a variable-displacement pump. It delivers a set volume of oil per shaft revolution, and moving a part inside the pump changes that volume. Coupled closely to a hydraulic motor, such a pump works as a continuously variable transmission between a diesel engine and a drive axle [23]. No open source read gives the drive's speed of response. The model draws it as a 1.2 s lag on the command scaled by the engine speed, behind acceleration and deceleration limits.

Where the Controller Runs

Agricultural machines share an electronic communication bus [22]. Its standard, the 14 parts of ISO 11783, builds on a controller area network at 250 kbit/s. One of its functions, Tractor-Implement Management, lets an implement set the tractor's speed and steering [24]. Such control loops run with cycle times from milliseconds to minutes and are often nested, the setpoint of one taken from the measurement of another [25]. In the application the speed loops run every 0.2 s, the loss supervisor every 1 s and the trims every 20 s. The low selector itself is textbook override control. An instrumentation text explains it with a truck driver who holds the speed limit until the exhaust temperature nears its limit on a mountain pass: whichever demand calls for less engine power wins. The same text warns that a deselected controller must not wind up [23], and external reset is this chapter's answer to that warning.

> **IN PRACTICE** **Counting Kernels Behind the Machine**
>
> Extension guides check a combine by counting the kernels on the ground behind it. In wheat, 20 to 22 kernels in one square foot are a loss of one bushel per acre [22]. The combine's own losses should not exceed one bushel per acre, and one adjustment is made at a time, each followed by a check under normal load of the losses in the field, the bin sample and the tailings [5]. The loss monitor is put to use only after such a count, as an early warning of changes in the crop or in the load [22]. The recalibration event of case 6, a kernel count behind the machine, is this check.

What Is Modernizing It

Three developments bear on the selector. The first is forward sensing. A scanning LiDAR ahead of the header estimated crop height with a root mean squared error of 0.082 m, and crop density with a coefficient of determination of 0.77, and its mounting height mattered more than its angle [17]. The second is predictive throughput control, which sets the ground speed from the feed rate, the engine load and the grain mass flow so that the capacity of the machine is used at all times [13]. The third is the bus itself. A high-speed version built on gigabit single-pair Ethernet is being developed, and functional safety is named as one factor holding back automation in agriculture [24].

4.8 Limitations

The rotor is one well-mixed inventory, so the distribution of threshing and separation along its length, which stochastic separation models resolve [2], is absent, and grain and straw share one residence time.

The loss, cleaning and damage constants are chosen rather than calibrated. Their shapes follow published behavior of rotors and shoes, but the numbers in Tables 4.4 and 4.5 belong to a teaching model and should be read as trends and ratios rather than as a machine's performance.

One moisture describes the grain and the straw, the preview sees only mass, and the loss monitor is a ratio of flows with a steady bias. The route is fixed and flat, and the engine and the drive are first-order models without the nonlinear pump and engine relation of a real propulsion system [12].

The MPC omits moisture, nonlinear capacity, power changes, losses, turns and the rain deadline. Its 30 s horizon extrapolates beyond 4.8 s of density information. Its nominal tank fraction differs from the physical ledger, and soft bands permit the suggested challenge's 48.60 s overload.

OPEN CHALLENGE **A Loss Signal Good Enough to Close a Loop On**

A 1983 study found a reliable loss measurement necessary for cheaper harvests and called better meters a pressing need [3]. A 2022 review of loss sensing still lists low resolution, impact signals that overlap when material arrives densely, interference from machine vibration, grain taken for straw and straw for grain, and changes with grain moisture. Most of the systems it reviewed had been tested in the laboratory and only a few in field harvesting, and it notes that readings in units of absolute grain loss would help operators decide [21]. Progress would be a field-proven monitor whose calibration holds across crops and moisture, so that a supervisor like that of case 6 could trust it.

4.9 Conclusion

A combine's ground speed sets its feed, and the simulator of this chapter shows how little the feed rate says about the constraints that decide a harvest. In dry crop 21 % more feed costs 78 % more loss, the same 70 t/h loses 2.69 % instead of 1.00 % in a wet strip that no sensor on the machine detects, and a loss supervisor that corrects late makes that strip worse, at 3.04 %. A dense patch seen 1.5 s late drives the feed to 107.8 t/h, and a preview that sees 7 m ahead, as far as the machine travels while its drive settles and brakes, holds it to 78.8 t/h. Moving the feed signal to 4 s makes the shipped tuning hunt between 6.40 and 8.75 km/h, and the running loop reaches its stability limit at 3.77 s, close to the 3.82 s of a linearization.

A monitor reading 40 % low lets the true loss run to 2.40 %, and a feed loop holding its setpoint in lodged crop plugs the rotor 27 s after entering it, which the rotor override prevents. Against the rain, the supervisor, the overrides with a 90 % engine limit, the preview and the trims together bring in 10.77 t with no pass above 1.71 %, against 9.03 t and two plugs as shipped. The optional MPC gains 426 kg on the dense-field comparison but fails the suggested challenge with 48.60 s of overload, while a fixed model-derived PI passes with zero overload.

The constants of the losses are chosen rather than calibrated, and the rotor is one mixed inventory. A fuller model would add a distributed rotor, separate grain and straw moisture, an impact-sensor loss monitor and a predictive controller that also plans against the time left before the rain. Within those limits the simulator poses throughput control against limits that the throughput measurement cannot see.

KEY POINTS

- A combine's ground speed sets its feed, but the feed rate says little about the limits that decide a harvest.
- In a wet strip the same 70 t/h loses 2.69 % instead of 1.00 %, and a loss supervisor that corrects late makes it worse, at 3.04 %.
- Five speed demands meet in a low selector, and the controllers that lose track the applied command through external reset, so an override takes the drive without a bump.
- Against the rain, the supervisor, the overrides, the preview and the trims together bring in 10.77 t with no pass above 1.71 %, against 9.03 t and two plugs as shipped.

Where else this applies. Volume 15, Chapter 3 moves an ore feed against the bearing pressure of a mill, and Volume 19, Chapter 6 shares a belt speed between two limits through the same low selector with external reset.

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4.10 Exercises

4.1 Concept check · 2 min

In scenario 3, Wet strip, the feed trend stays at 70 t/h while the true loss climbs from 1.00 to 2.69 %, and no controller moves the ground speed. Why does the feed loop not react?

(a) The feed signal arrives 1.5 s late, so the strip has passed before the loop can see it

(b) At a given feed the feed signal reads the same in dry and wet crop, so nothing it measures changes

(c) The speed command sits at its 10 km/h limit in the strip, so the loop has no room to slow down

(d) The rotor override holds the drive in the strip and keeps the ground speed constant

4.2 Concept check · 2 min

The crop preview enters the low selector of Equation (4.15) as a cap $1.1\,v_{ff}$ instead of being added to the feed PI's output as a bias. What does the cap gain?

(a) Selector inputs bypass the acceleration and deceleration limits, so the cap slows the machine faster

(b) The cap can use the crop moisture, which an additive bias on the feed loop could not use

(c) While the cap slows the machine, the feed PI tracks the applied speed instead of fighting the slowdown

(d) The cap leaves the feed setpoint to the loss supervisor, while a bias would have to move the setpoint

4.3 Concept check · 1 min

While the engine override holds the drive, the loss supervisor may lower the feed setpoint Q_{SP} but not raise it. Why is a raise refused?

(a) A raise would lift the engine load limit E_{SP} above 95 %

(b) The loss monitor reads low while an override holds, so a raise would rest on a false reading

(c) The supervisor executes once a second, too slowly to act while the override holds

(d) The feed loop is not delivering its setpoint, so a raise would wind up the outer loop without moving the feed

4.4 Theory and calculation · 6 min

Use Equations (4.3) and (4.4) with $\omega = \omega_{ref}$, so the rotor turns at 950 rpm.

(a) Find the straw capacity $\bar{Q}$ at a rotor moisture of 14, 20 and 21 %. *Checkpoint:* 16.0, 12.6 and 12.1 kg/s.

(b) Find the straw inventory M_r at which the torque reaches the plug torque $T_{plug} = 2.4\,\mathrm{kN\,m}$ in dry crop and at 21 % moisture. *Checkpoint:* 82.1 and 57.8 kg.

(c) In dry crop the steady inventory solves $rM_r = Q$. Show that 9 kg/s of straw gives the reference inventory M_{ref}, then find M_r at 12 kg/s and the factor by which Equation (4.5) raises the separation loss share. *Checkpoint:* 25.5 and 38.9 kg, $\lambda_r = 1.53$, a factor of 2.88.

4.5 Theory and calculation · 7 min

Take the feed loop of Equation (4.14) with the shipped tuning, $K_c = 0.08$ km/h per t/h, $\tau_I = 2\,\mathrm{s}$, $n_e = 0.986$, $W = 9\,\mathrm{m}$, $\tau_v = 1.2\,\mathrm{s}$ and $\tau_f = 0.4\,\mathrm{s}$.

(a) Find the process gain $W\rho$ in t/h per km/h for uniform crop, $\rho = 1.045\,\mathrm{kg/m^2}$, and for the tall band at its entry, $\rho = 1.657\,\mathrm{kg/m^2}$, and the loop gain $K_c n_e W \rho$ in uniform crop. *Checkpoint:* 9.41 and 14.9, a ratio of 1.59. Loop gain 0.742.

(b) With the signal delay moved to $\theta_m = 4\,\mathrm{s}$, evaluate the phase and the magnitude of $L(j\omega)$ at $\omega = 0.4095\,\mathrm{rad/s}$. *Checkpoint:* -50.7, -26.2, -9.3 and -93.9 degrees, about -180 in all, and $|L| = 1.04$.

(c) What gain margin does halving K_c give at $\theta_m = 4\,\mathrm{s}$? Why does lengthening τ_I not have so simple an answer? *Checkpoint:* 1.93.

4.6 Theory and calculation · 5 min

In case 2 the header approaches the tall band at $v = 7.43\,\mathrm{km/h}$ with $Q_{\mathrm{SP}} = 70\,\mathrm{t/h}$, $W = 9\,\mathrm{m}$, $\tau_v = 1.2\,\mathrm{s}$ and $d_{max} = 1\,\mathrm{m/s^2}$. The forward sensor reads $\rho_i = 1.657\,\mathrm{kg/m^2}$ in the band.

(a) Find the speed v_i that meets the setpoint in the band. *Checkpoint:* 1.304 m/s, or 4.69 km/h.

(b) Find the settling distance $2.5v\tau_v$ and the distance needed to brake from v to v_i at d_{max}. *Checkpoint:* 6.19 and 1.28 m.

(c) From Equation (4.16), at what distance ahead of the band does $1.1\,v_{ff}$ fall below the present speed, so that the cap takes the drive? Compare with the measured feed peaks for preview ranges of 2 and 7 m. *Checkpoint:* About 7.1 m.

4.7 App challenge · 8 min

Load scenario 1, Uniform field, at the default seed. Run at 50× until the run stops itself, shortly after the rain at 20 min, and read the Recovered grain, Harvest loss and Standing at the rain tiles. Reload the scenario with the reload button, set the Feed-rate setpoint to 85 t/h before Run and repeat.

(a) Report the three tiles for both runs. *Checkpoint:* At 70 t/h: 10.48 t, 1.00 % and 1.84 t. At 85 t/h: 12.23 t, 1.73 % and 0.00 t, within 0.01.

(b) Find the grain lost behind the machine in each run, $G_t L/(100 - L)$ with G_t the tank and L the harvest loss in percent, and compare the extra loss with the extra grain in the tank. *Checkpoint:* 0.106 and 0.215 t. About 0.11 t more lost for 1.75 t more in the tank.

4.8 App challenge · 8 min

Load scenario 8, Plugging threat (80 t/h, overrides off), at the default seed.

(a) Run to 400 s at 20×, read the Plugs and Recovered grain tiles, export the CSV file and find the first row with `plugged` equal to 1. *Checkpoint:* 2 plugs, 240 s lost, and 1.29 t. First plugged row at 53.25 s, within 0.1.

(b) Press Reset, set Overrides to On, run to 300 s and read the Plugs and Harvest loss tiles. In a new CSV file find the largest `rotor_torque_pct`. Then run on to 400 s and read Recovered grain. *Checkpoint:* No plug, 3.49 %, torque peak 88.2 % within 0.5, and 3.55 t.

Why does the torque overshoot a limit of 70 % by 18 points, and what does the override protect?

4.9 App challenge · 9 min

Load the challenge, Beat the rain, at the default seed. For each run below, run at 50× until the run stops itself and read the Recovered grain, Worst pass loss, Plugs and Engine overload tiles.

(a) Run the challenge as loaded (85 t/h, overrides off). *Checkpoint:* 9.03 t, 10.86 %, 2 plugs and 74.7 s.

(b) Press Reveal suggested tuning, then Reset, and run again. *Checkpoint:* 10.77 t, 1.71 %, no plug and 1.5 s.

(c) Set Rotor and fan trims to Off, press Reset and run again. *Checkpoint:* 10.25 t, 1.91 %, no plug and 0.0 s.

Which target does run (c) miss, and how do the trims earn the difference?

4.10 Application area · 3 min

In scenario 6 the loss sensors read 40 % low, $b = -0.4$, and the monitor of Equation (4.13) forms $L_m = 100\,(1+b)X/[(1+b)X+T]$ from the loss flow X and the tank flow T.

(a) What true loss does a supervisor see as its 1.5 % setpoint? What does the monitor read when the true loss is 2.40 %? *Checkpoint:* 2.48 %, and 1.45 %.

(b) How would you keep a loss-limited speed controller honest on a real machine?

4.11 Application area · 4 min

In scenario 7 the engine derates at 60 s to 65 % of its 330 kW. At 70 t/h the machine draws 235 kW: 39 to the drive, 89 to the rotor, 22 to the chopper, 20 to the header, 11 to the fan and 54 to the rest.

(a) Treat the fan, the rest, the 8 kW header base and the empty-rotor term $T_0(\omega/\omega_{ref})\,\omega \approx 19\,\mathrm{kW}$ as fixed, and the remainder as proportional to the feed. Estimate the feed at which the engine override holds the engine at 95 % of its available power. *Checkpoint:* Available 214.5 and limit 203.8 kW. Fixed 92 kW, 2.04 kW per t/h, about 55 t/h.

(b) With the overrides off the engine runs at 105 %. What engine and rotor speeds does Equation (4.11) give, and what does a slower rotor do to the grain? *Checkpoint:* 90.5 % and about 860 rpm.

4.12 Review the agent · 5 min

An AI assistant reviews scenario 3, Wet strip, run with the Loss controller in Auto, where the true loss peaks at 3.04 %, and replies: “The loss controller is too slow for a strip that lasts 25 s. Cut the Loss controller integral time from 20 to 5 s and it will catch the strip and hold the loss near 1.5 %.” Find the flaw and say how you would check it.