INTERACTIVE CONTROL ENGINEERING
Principles and Applications

Volume 10 Control in Upstream and Midstream Oil and Gas

CHAPTER 13

Series Pump Stations, Batches and Surge on a Refined Products Pipeline

Pages 298–320

Edited by John D. Hedengren

How to cite this chapter. "Series Pump Stations, Batches and Surge on a Refined Products Pipeline," in *Control in Upstream and Midstream Oil and Gas*, John D. Hedengren, Ed., vol. 10 of *Interactive Control Engineering: Principles and Applications*. Advanced Process Solutions, LLC, 2026, ch. 13, pp. 298–320.

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

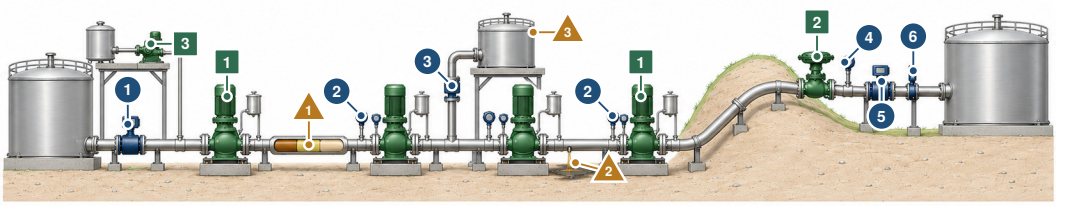
The app for this chapter
https://apmonitor.com/apps/products-pipeline/

The volume online: contents, other chapters and citation records
https://apmonitor.com/apps/books/v10-oil-gas/#products-pipeline

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

CHAPTER 13

Series Pump Stations, Batches and Surge on a Refined Products Pipeline



The controller moves 1 pump speed at the four stations 2 the far terminal's valve, holding back pressure 3 drag reducer dose

The controller reads 1 flow leaving the origin 2 pressures before and after each station 3 flow taken by the side terminal 4 pressure at the far terminal's valve 5 flow into the far terminal 6 fuel density at the far terminal

What disturbs it 1 a change of fuel 2 a leak 3 what the side terminal takes

The controller sets the flow at the first station on the left, the other three pass it on, and the valve at the far terminal on the right holds the pressure that keeps the hill full. Illustration, not to scale.

IN PLAIN TERMS **One Pipe, Four Pumps, Several Fuels**

The main idea. A long pipe carries gasoline, jet fuel and diesel one batch after another. Four pumping stations along the way push them. The same flow passes every station, so only the first may set it, and the others must pass on what arrives.

The challenge. If a valve at the far end shuts, a jump in pressure races back up the pipe in seconds. The pumps keep squeezing fuel in behind it. The leak alarm compares the fuel sent with the fuel received, and a change of fuel can fool it.

Why it matters. The line must stay below its pressure limit, keep each fuel clean and find a real leak fast.

THREE WAYS TO READ THIS CHAPTER

Explore	12 min	This page, the History boxes in Section 13.2, the Did you know? boxes in Sections 13.3 and 13.5, the Try it boxes in Section 13.5, and Key points in Section 13.8. No equations.
Study	50 min	The whole chapter in order, stopping at the three pause points, then Exercises 1 to 12.
Practice	20 min	This page, Section 13.5 with Figure 13.4, Section 13.6 and Section 13.7 with its Open challenge boxes.

The control question One flow passes every pump station of a refined products line, while its batches move at walking pace and its pressure news at the speed of sound. Which controller may set that flow, what must the other stations hold, and what protects the line when a valve closes, a station trips, a batch changes or a hill near the terminal runs slack?

Learning objectives

- Explain why only one station of a series line can set the flow, and how low selects of suction and discharge loops protect the rest.
- Compute the storage of a liquid line per bar, the drift of a suction under a flow mismatch and the Joukowsky rise of a closure.
- Tell the pressure front of a valve closure from the packing that follows it, and say which of the two the stroke time controls.
- Compute the friction gradient with and without a drag reducer, and explain why its gain in flow arrives over hours.
- Judge the settings of a volume-balance leak detector against false alarms at a batch change and the time to alarm a leak.

Prerequisites Sections 1.4.5 (line pack and water hammer), 1.4.8 (selectors in the external-reset form) and 1.4.9 (balance leak detection), with Section 1.6.2 for the terminal loop. Section 1.6.3 is needed only for the back-pressure MPC.

The app https://apmonitor.com/apps/products-pipeline/

See also Volume 4, Chapter 3 for min–max limiter selection on one fuel flow and Volume 4, Chapter 2 for a protective override. Volume 6, Chapter 7 for the choice of the loop that sets the throughput. Volume 8, Chapter 13 for a diversion valve that acts on what its instruments report.

13.1 Introduction

A products pipeline is a long column of nearly incompressible liquid moved by pumps that cannot see one another. In the generic line simulated here, 1000 m^3/h of diesel crosses 300 km of 16-inch pipe at 2.3 m/s, so a batch takes about 40 h to reach the far terminal while a pressure change arrives in 4.4 min. Shutting the terminal valve in 5 s raises the pressure there 18.5 bar in ten seconds, and the stations behind it go on packing the line until it sits at about 87 bar g, close to its maximum allowable operating pressure (MAOP). The hydraulics of such lines, from the friction gradient to the stations' heads, are textbook material [1], and the pressure wave of a sudden closure has been analyzed for more than a century [2].

Two common beliefs about such a line are wrong, and the simulator shows why. The first is that each pump station on a line can hold its own discharge pressure. One flow passes all four stations, so a station that holds its discharge pumps whatever its discharge demands, and the pipe upstream of it fills or empties. In case 3, with the override selectors off, a 10 % cut in the lead flow drains station 2's suction to the low-suction alarm in 4.6 min and trips all four stations within 10.2 min. The second belief is that a slow valve makes a closure safe. A stroke of 120 s instead of 5 s lowers the steepest ten-second rise from 17.0 to 8.3 bar, while the blocked-in line still ends near 87 bar g. Both corrections belong to a wider class, units in series that share one throughput and are protected by constraint overrides, which includes booster stations on water mains, compressor trains, cascades of reactors and canal pools. Override and selector control of constrained loops is treated in general form in [3], and the station, SCADA and monitoring layers of pipelines in particular in [4].

The published material divides this problem into pieces. Batch scheduling is posed as mixed-integer optimization of volumes and timing [5], interface mixing is estimated without control [6, 7], leak detection is reviewed method by method [8, 9], and slack flow is an operating topic of its own [10]. This chapter puts the pieces on one simulated line, on which the station overrides, the terminal valve, the batch cut, the drag reducer, the back pressure over a hill and a balance leak detector can be changed while the line runs and read against a scorecard. The lumped transient model, the

Darcy–Weisbach friction, the Austin–Palfrey mixing form, the override structure and the linear MPC are all established methods. The model has 70 states, and its volume balance closes to 2.3×10^{-13} of the throughput through batch changes, leaks and slack. A measurement boundary keeps every controller, the tracker and the detector away from the simulator's truth, so the detector's false alarm at a batch change can be split into a meter shift and an unmeasured change of line pack.

Section 13.2 follows the domain, from batch interfaces and water hammer to drag reducers and leak monitoring. Section 13.3 sets out the line as modeled: thirty lumped segments, friction and the drag reducer, the pump stations and terminals, the batches, the declared slack treatment and the instruments. Section 13.4 describes the control layers: the station overrides, the terminal back-pressure loop, the MPC that sets only that back pressure, the tracker, the cut and the leak detector. Section 13.5 reports the nine cases, each graded by a completion rule, from one flow through four pumps to a full day on the line. Section 13.6 sets the hardware of a real line beside the model, Section 13.7 states the limitations, Section 13.8 draws the conclusions, and the exercises of Section 13.9 put the cases to work.

13.2 Batches, Surge and Leak Monitoring on Liquid Lines

Refined products have long shared pipe. Instead of one line per fuel, a products line carries a sequence of batches, and every interface between two products leaves a mixed zone that must be cut out at the receiving terminal and sent to a transmix tank. How the length of that mixed zone came to be predicted is told in the History box below.

> **HISTORY 1954 to 1963: How Long Is a Mixed Zone?**
>
> Once several products shared one pipe, the length of the mixed zone between two batches became a design question. In 1954 G. I. Taylor treated dispersion in turbulent pipe flow with a virtual coefficient of diffusion and tested it on brine injected into a pipe of three-eighths of an inch. When one fluid is forced into a pipe full of another with which it can mix, his theory gave the length over which the interface spreads, and it agreed with tests made on long pipelines in America [11]. In 1963 Austin and Palfrey drew new formulae from pipes of one-eighth of an inch to 40 inches and from a few feet to hundreds of miles long. They found two regions of mixing in turbulent flow, with mixing growing fast below a critical Reynolds number, and offered the work for the design of products pipelines [6].

The pressure side of the problem has an older history. Joukowsky's water hammer relation, a rise of $\rho a \Delta V$ when a column moving at ΔV is stopped by a wave of speed a (Equation (1.9)), and the method-of-characteristics calculations that followed it are reviewed in [2]. Liquid lines over high ground meet the opposite extreme as well. Column separation, the vapor cavity that opens where a transient pulls the pressure down to the vapor pressure, has flow regimes of its own [12]. Its steady counterpart, slack flow downhill of a summit at low rates, is avoided in operation by holding back pressure [10].

Capacity came to be bought chemically, as the second History box tells.

Table 13.1 Variables and Their Roles, Valued at the Design Point

Variable	Role	Design	Range
Q_{in}	CV, lead flow (origin meter)	1000 m³/h	SP 200–1400
$p_{s,k}$	CV, suctions S2–S4	8 bar g	SP 2–40
$p_{d,k}$	CV (override), discharges	76.9–60.1 bar g	limit 85, 75
p_B	CV, Terminal B back pressure	5 bar g	SP 1–40
s_k	MV, pump speeds	99.8–83.7 %	0–105
x_B	MV, Terminal B valve	47.3 %	0–100
$p_{B,SP}$	MV of the MPC	5 bar g	3–40
c	MV, drag reducer dose	0 ppm	0–30
q_A	DV, Terminal A delivery	150 m³/h	0–300
ℓ	DV, leak at km 180	0	0–3 %
—	DV, product entering	diesel	3 products
—	DV, station 3 trip, B close	—	events
p_i, Q_j	states, 30 + 30	72.0–6.5 bar g	—
x_m	carried, interfaces	—	0–300 km
V_{slack}	carried, slack volume	0	—
r	output, leak residual	0	—

HISTORY 1979: Buying Flow With a Polymer

Dilute solutions of long, randomly coiling molecules reduce friction in turbulent pipe flow, and a 1975 review gathered the experimental evidence for the effect [13]. Drag reduction had been seen in the laboratory for almost 35 years, and its mechanism was still not well understood, when the first commercial use of a polymer additive to raise the flow of a crude oil pipeline began in 1979 on the trunk line across Alaska. Two experiments on that line led to the decision for full-scale use. The gain in pumpability was spent on more flow without exceeding the line's safe pressure limits, and until then drag reducers had not been used routinely in crude oil pipeline operations [14].

Automation moved the stations from local operators to a control center reached through SCADA, with station pressure control and leak detection among its functions [4]. Computational pipeline monitoring grew up in the same control rooms. Its simplest form is the compensated volume balance, metered inflow less metered outflow less the change of line pack over a window [8] (Section 1.4.9), while transient-model methods compare the measurements with a running hydraulic simulation [9, 15]. API Recommended Practice 1130 frames how such a detector's sensitivity, reliability and response time are stated together. Model predictive control entered process plants in the same decades [16], and on the simulated line of this chapter it sits above the station overrides rather than in place of them.

13.3 The Line as Modeled

The simulated line is generic and has no proprietary source. It runs 300 km from an origin tank farm to Terminal B, in NPS 16 steel of 392.1 mm inside diameter and 45 µm roughness, with pump stations S1 to S4 at km 0, 70, 140 and 210, as shown in Figure 13.1. Terminal A takes a delivery of 150 m³/h from station 3's suction header at km 140. The ground climbs from 20 m at the origin to 220 m at station 4, rises to a hill of 440 m at km 250, and falls to the terminal at 160 m. At 1000 m³/h of diesel with every intermediate suction at 8 bar g, the stations discharge at 76.9, 75.7, 59.6 and 60.1 bar g at speeds of 99.8, 96.2, 83.7 and 94.0 %, draw 7.98 MW, and deliver 851.8 m³/h to Terminal B at 5 bar g.

Each variable carries the role listed in Table 13.1. Seventy states are integrated: thirty segment pressures, thirty face flows, four pump speeds and six ledgers (the volumes through the origin, the two terminals, the leak and the relief valves, and the pumping energy) that let conservation be checked exactly. Batches, the drag reducer and any slack volume are carried beside the states and set the segment properties after each step. The clock is in minutes.

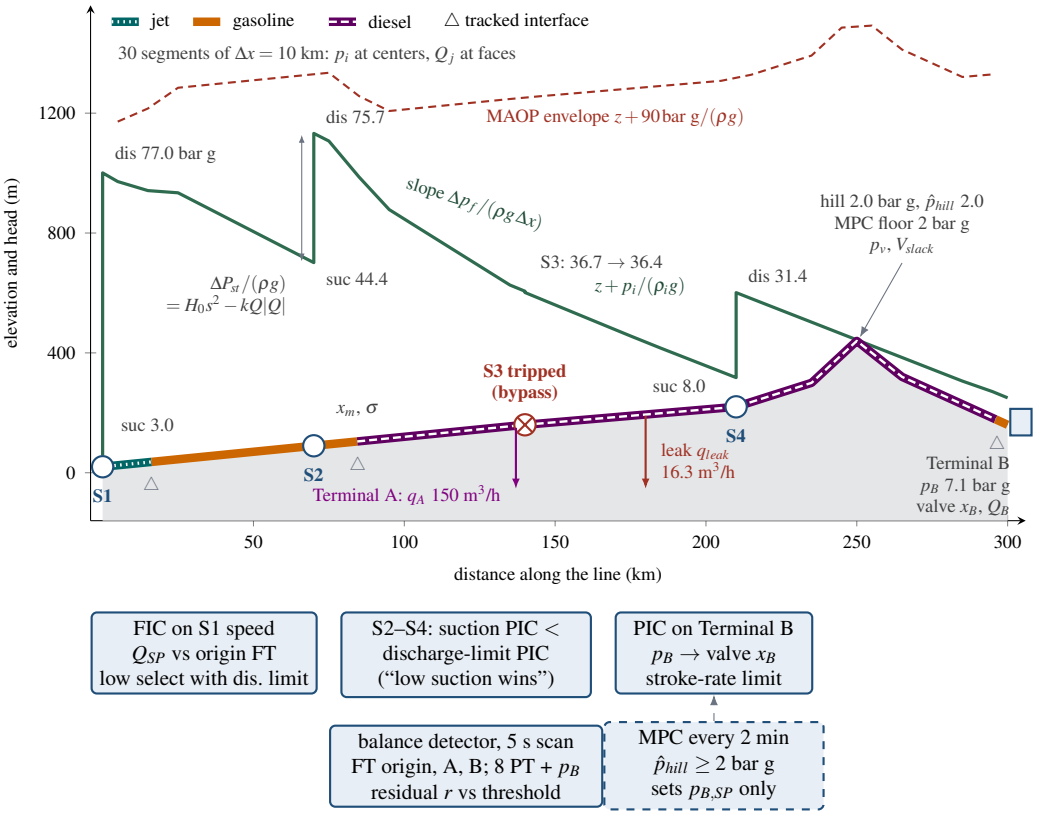


Figure 13.1 The line as modeled, redrawn from the Profile view of the challenge with the suggested settings at $t = 1000$ min. The ground $z(x)$ carries the pipe painted by batch, jet fuel (dotted band) entering behind gasoline (plain band), diesel (dashed band) and gasoline at Terminal B, with the tracked interfaces x_m marked by triangles. The very thick solid green hydraulic gradient $z + p_i/(\rho_i g)$ falls at the friction slope and jumps by the pump head at each running station. Station 3 has tripped and passes the flow through its bypass. The dashed MAOP envelope is the ground plus 90 bar g of head. Terminal A delivers q_A, the 2 % leak at km 180 loses q_{leak}, Terminal B holds the back pressure p_B with its valve x_B, and the hill holds 2.0 bar g against the MPC's 2 bar g floor. Station pressures are true values in bar g. The two rows below show the control layer, with the dashed MPC block setting only the setpoint of Terminal B's PIC. Not to scale across the pipe.

13.3.1 Thirty Lumped Segments

The line is divided into thirty segments of $\Delta x = 10$ km in the lumped inertia and compressibility form. Each segment holds a pressure at its center and each face between two segments carries a flow, as shown in Equation (13.1).

$$\begin{aligned} \frac{\mathrm{d}p_i}{\mathrm{d}t} &= \frac{\rho_i a_i^2}{A\,\Delta x}\left(Q_i - Q_{i+1} - q_{ext,i}\right) \\ \frac{\mathrm{d}Q_j}{\mathrm{d}t} &= \frac{A}{\rho_j\,\Delta x}\left(p_{j-1} - p_j - \Delta p_{f,j} - \rho_j g\,\Delta z_j + \Delta P_{st,j}\right) \end{aligned} \tag{13.1}$$

where A is the bore area, $\rho a^2 = K$ is the bulk modulus that the steel pipe presents to each product, q_{ext} collects Terminal A, the leak and the relief valves, Δz_j is the rise between neighboring centers, and ΔP_{st} is a pump's pressure rise on the face where a station sits. Face 0 is station 1, fed by the origin booster at 3 bar g through half a segment. Pressures are gauge throughout. A segment holding two

products averages ρ and $1/K$ by volume, and a face takes the geometric mean of the two viscosities. Each 10 km of diesel stores 0.113 m^3 per bar, so a 100 m^3/h mismatch between what station 1 sends and station 2 takes moves station 2's suction by 2.1 bar a minute. A liquid line stores almost nothing, as Section 1.4.5 shows for the oil line of the running example.

The scheme was timed on the app's own derivatives. On the line at rest a 0.1 bar step crosses from km 45 to km 245 at 1110.5 m/s in diesel against the declared 1130 m/s, 1093.5 m/s in jet fuel against 1110 and 1014.5 m/s in gasoline against 1030, the same at half and a quarter of the step. Friction is strong on this line. The front of a closure loses most of its height as it travels, so in case 2 only about 7.9 bar of the 18.6 bar front remain 75 km upstream.

13.3.2 Friction and the Drag Reducer

Friction follows Darcy–Weisbach with the Swamee–Jain explicit form of the Colebrook factor, laminar below a Reynolds number of 2300 and blended up to 4000. A polymer additive scales it down in turbulent flow, as shown in Equation (13.2).

$$\begin{aligned} \Delta p_f &= f(1-DR)\frac{\Delta x}{D}\frac{\rho V|V|}{2}, \quad DR = DR_{max}\frac{c}{c+c_{1/2}} \\ \frac{1}{\sqrt{f}} &= -2\log_{10}\!\left(\frac{\varepsilon}{3.7D}+\frac{5.74}{Re^{0.9}}\right) \end{aligned} \tag{13.2}$$

where $V = Q/A$ and c is the local additive concentration. Diesel at 1000 m^3/h runs at $Re = 257\,717$ with $f = 0.0159$ and loses 0.902 bar per km, about 11 m of head, against 0.596 bar/km at 800 m^3/h. The additive is injected at every running station at the dose c, carried with the flow at the liquid's speed, and sheared to nothing in the next station's pumps. At $DR_{max} = 60\,\%$ and $c_{1/2} = 8$ ppm, 10 ppm removes a third of the friction. Both constants are a declared teaching curve rather than a fit to an additive [13, 14].

13.3.3 Pump Stations, Terminals, the Leak and Relief

Each station is one variable-speed pump on a quadratic curve, with a check-valved bypass that carries the flow when the pump is stopped, as shown in Equation (13.3).

$$\begin{aligned} \Delta P_{st} &= \max\!\left(\rho g\,(H_0 s^2 - k\,Q|Q|),\; -K_{byp}Q^2\right) \\ \frac{\mathrm{d}s}{\mathrm{d}t} &= \frac{s_{cmd}-s}{\tau_s}, \qquad P = \sum_k \frac{Q_k\,\Delta P_{st,k}}{\eta} \end{aligned} \tag{13.3}$$

where s is the speed fraction, $H_0 = 1050$ m at stations 1 to 3 and 780 m at station 4, $\tau_s = 3$ s (20 s for a coast-down after a trip), the command ramps at 2 % per second, and $\eta = 0.8$. The bypass loses 1 bar at 1000 m^3/h, and check valves forbid reverse flow through any station. Terminal B's delivery valve is an orifice that passes 1200 m^3/h wide open across 2 bar into a tank at 0.5 bar g, so $Q_B = C_B x_B \sqrt{p_B - 0.5\,\mathrm{bar\,g}}$, with p_B the pressure at the valve inlet, extrapolated from the last segment center by half a segment of friction and the 23 m drop to the terminal. Terminal A delivers its nomination through its own flow controller, ramping 10 m^3/h per minute, and closes as its header falls from 2 to 1 bar g. A leak is a fixed opening split between the two nearest segment centers, $q_{leak} = \ell\,(1000\,\mathrm{m^3/h})\sqrt{p/30\,\mathrm{bar\,g}}$, so a 1 % leak at km 180 passes 10.0 m^3/h at the design pressure of 30.1 bar g there. Relief valves at each station discharge and at Terminal B open at the MAOP and pass 900 m^3/h at 4 % above it.

13.3.4 Batches and Their Mixed Zones

An interface moves with the local flow, and its mixed zone grows with the square root of the distance traveled, as shown in Equation (13.4).

$$\frac{\mathrm{d}x_m}{\mathrm{d}t} = \frac{Q(x_m)}{A}, \qquad c_{behind}(x) = \tfrac{1}{2}\,\mathrm{erfc}\!\left(\frac{x - x_m}{\sqrt{2}\,\sigma}\right)$$
$$4.65\,\sigma = C_m\sqrt{D\,(x_m - x_{m,0})}\,Re^{-0.1} \tag{13.4}$$

where $Q(x_m)$ is interpolated between faces, $C_m = 11.75$ is the turbulent-flow constant of the Austin–Palfrey form [6], and 4.65σ is the length from 1 to 99 %. For gasoline behind diesel at 850 m³/h the zone reaches 1079 m after 300 km, 130 m³ of line. The products are generic teaching values at 15 °C, given as density, viscosity and wave speed: gasoline 740 kg/m³, 0.6 cSt and 1030 m/s, jet fuel 800, 1.5 and 1110, and diesel 840, 3.5 and 1130. A segment whose product changes keeps its liquid volume referred to zero gauge, $A\Delta x(1 + p/K)$, so its pressure is scaled by K_{new}/K_{old} and the flows absorb the difference. Without that rule the line gained liquid wherever an interface moved under pressure, a defect that a technical review of the app found and removed.

13.3.5 Slack Line, a Declared Teaching Treatment

The hill at km 250 stands 280 m above Terminal B, 23.1 bar of diesel. At low flow the friction no longer holds its summit above the vapor pressure, and the treatment of Equation (13.5) applies after each step.

$$p_i < p_v \Rightarrow V_{slack,i} \mathrel{+}= \frac{(p_v - p_i)A\,\Delta x}{K_i}, \quad p_i = p_v$$
$$V_{slack,i} > 0 \Rightarrow Q_{i+1} \le Q_i \tag{13.5}$$

where p_v is the vapor pressure, −0.46 bar g for gasoline and −1.0 bar g for jet and diesel. Liquid arriving later fills the slack volume before the pressure rises. This is an outflow clamp, not a model of a partly full pipe [12], and its slack volume is a time-step artifact. In case 6 the volume grows by what the downhill pipe draws within one step before the clamp acts, 13.5 m³/h at the 1 s step, 6.8 at 0.5 s and 3.4 at 0.25 s, so the volume at 90 min falls from 15.3 to 7.7 to 3.9 m³ as the step halves. What does not depend on the step is when the hill reaches the vapor pressure (22.63, 22.62 and 22.60 min) and which back pressure refills it (15 bar g does at every step, 10 bar g does not). The app and this chapter therefore read the slack volume as a sign of slack, never as a prediction of how much vapor a real line would hold.

> **+ DID YOU KNOW? Slack Flow Over a Mountain**
>
> One liquid line of about 800 km, with six pump stations, crossed more than 1000 m of height between a mountain top and a river valley and ran slack there, which made its leak detection inaccurate. A pressure regulating station that kept the line full also made its leak detection more reliable [10].

13.3.6 Instruments

Pressure transmitters at each station's suction and discharge and at Terminal B have a 1 s lag and 0.03 bar of noise. The three flow meters, at the origin and at each terminal, have a 2 s lag, 0.1 % noise and a meter factor proved on diesel, so each reads gasoline high by the declared error of 0.25 % and jet fuel by half of it. A densitometer at Terminal B reads the composition at the valve through a 30 s sample delay with 0.3 kg/m³ of noise. The noise draws per execution are fixed in number, so two runs that differ in one setting see identical noise sequences.

13.3.7 Start-Up State and Integration

Table 13.2 collects the parameters. Each one is a generic teaching number for a 16-inch line, chosen to be self-consistent and taken from no pipeline. Every case opens on a steady line at its own settings,

Table 13.2 Parameters. A: Adjustable in the Parameters Panel. V: Fixed and Stated in the App. H: Fixed and Not Displayed

Symbol	Meaning	Value	Unit	
L, Δx, D	length, segment, bore	300, 10, 392.1	km, km, mm	V
ε	wall roughness	45	µm	A
a	wave speed scale	100	% of declared	A
MAOP	max. allowable pressure	90	bar g	A
—	high-high discharge trip	MAOP − 2	bar g, 2 s	A
—	low suction alarm, low-low trip	3, 1 (5 s)	bar g	A
—	Terminal B relief set	90	bar g	A
p_{tank}	origin booster	3	bar g	H
H_0	pump shutoff head	1050, 780	m	V
k	pump curve coefficient	1944, 1037	m s^2/m^6	H
K_{byp}	stopped-station bypass	1	bar at 1000 m^3/h	H
η	pump efficiency	0.8	—	V
τ_s	drive lag, coast-down	3, 20	s	V
C_B	Terminal B valve, wide open	1200	m^3/h at 2 bar	H
DR_{max}, $c_{1/2}$	drag reducer curve	60, 8	%, ppm	A
C_m	Austin–Palfrey constant	11.75	—	A
—	meter error on gasoline	0.25	%	A
—	densitometer delay	0.5	min	A
x_{leak}	leak location	180	km	A
ρ, ν, a	products, Section 13.3.4	—	—	V

found by marching from Terminal B's pressure back to the origin with every intermediate suction on its setpoint, and if the stations cannot carry the requested flow within their speed range and discharge limits a bisection lowers the flow until they can. Integration uses fourth-order Runge–Kutta steps of 1 s, inside the engine of Section 1.6.1. Halving the step moves the largest ten-second rise of case 2 from 16.89 to 16.53 bar (−2.1 %), because the valve's 5 s stroke from its 47 % opening is resolved in only a few steps. At half and a quarter of the step the shipped challenge still fails and the suggested one still passes. The truth volume balance closes to 2.3×10^{-13} of the volume pumped over the challenge's day.

13.3.8 Assumptions

The line is isothermal at 15 °C, with no exchange with the ground and no thermal expansion, which removes the largest source of false alarms on real lines. A wave front is spread over about one segment, so the model reproduces the wave speed and the Joukowsky rise but not the shape of a sharp front, and it says nothing about column separation during the front [12]. Each station is one pump at constant efficiency, with no multi-pump sequencing, start-up transient or cavitation below the suction trip. Products are constant in density, viscosity, bulk modulus and vapor pressure. The slack line is the treatment above. The safety numbers, the MAOP of 90 bar g, discharge limits of 85 and 75 bar g, the trips and the 3 bar g suction alarm, are teaching values. Real ones come from the pipe's design under ASME B31.4 and from the pumps' net positive suction head requirements, and real detector settings from API RP 1130 and the operator's own testing.

13.4 The Control Layers as Implemented

The controllers execute every 1 s of simulated time, the SCADA scan and the leak detector every 5 s, and the MPC every 2 min. Each physics step runs the controllers, the integrator, the post-step corrections (check valves, slack, interfaces, additive transport, trips, alarms) and the outputs. Everything the controllers, the tracker and the detector read passes through a measurement packet built from the instruments above, and the simulator's truth reaches only the scene's teaching overlay, the scorecard and the exported columns prefixed `truth_`.

13.4.1 Station Overrides

Station 1's flow loop (FIC) holds the origin meter at the line setpoint. At stations 2 to 4 a suction loop holds 8 bar g, and every station has a discharge-limit loop. With the selectors on, each pump takes the lower of its two speed requests, which is the arrangement known as "low suction wins" [3, 4]. With them off, station 1 runs on flow alone and stations 2 to 4 on discharge alone. The override loops are written in the external-reset form of Equation (13.6).

$$\begin{aligned} u_k &= K_c\, e_k + F_{k-1}, \qquad s_{cmd} = \min(u_{main},\, u_{dis}) \\ F_k &= F_{k-1} + \left(1 - \mathrm{e}^{-\Delta t/\tau_I}\right)\left(s_{applied} - F_{k-1}\right) \end{aligned} \tag{13.6}$$

where e is the error in the loop's own direction, u_{main} is the flow or suction request, $s_{applied}$ is the clamped speed the drive was given, and each loop's reset filter F follows that applied speed. This is the external-reset form of Equation (1.14), and Section 1.4.8 explains why neither loop winds up and why the transfer between them, or from Manual to Auto, is bumpless. In Manual each filter is reset to make its output match the operator's speed. The defaults are $K_c = 0.02\,\%$ per $\mathrm{m^3/h}$ with $\tau_I = 30\,\mathrm{s}$ for the flow loop, 1.0 % per bar with 60 s for the suction loops, and 4.0 % per bar with 15 s for the discharge loops, with speeds limited to 0 to 105 %. Two tracking PID objects in a low select were tried first and ratcheted the speed downward on measurement noise, which is why this form was chosen. The same selection of the most restrictive request, over a speed governor and its limiters on one fuel flow, protects the jet engine of Volume 4, Chapter 3. Choosing the one loop that sets the throughput is the plantwide question that Volume 6, Chapter 7 studies on a reactor and its recycle.

Pause. Try Exercise 13.1 before reading on.

13.4.2 Terminal B Back Pressure

The back-pressure loop (PIC) moves Terminal B's valve with the velocity-form PID of Section 1.6.2, with no derivative term and back-calculation on the integral with a tracking time equal to τ_I, as shown in Equation (13.7).

$$\begin{aligned} e_k &= -(p_{B,SP} - p_{B,k}), \qquad S_k = S_{k-1} + K_c(e_k - e_{k-1}) \\ \hat{x}_k &= x_0 + S_k + I_{k-1}, \qquad x_k^* = \min(100, \max(0, \hat{x}_k)) \\ I_k &= I_{k-1} + \left[\frac{K_c}{\tau_I} e_k + \frac{x_k^* - \hat{x}_k}{\tau_I}\right]\Delta t \\ x_{B,k} &= x_{B,k-1} + \mathrm{clip}\left(x_k^* - x_{B,k-1},\, \pm\tfrac{100\,\Delta t}{t_s}\right) \end{aligned} \tag{13.7}$$

where the minus sign makes a pressure above setpoint open the valve, S is the unclamped running sum of Equation (1.17), x_0 the output at the start, $K_c = 2\,\%$ per bar and $\tau_I = 60\,\mathrm{s}$. The stroke time t_s, 60 s by default, limits every move of the valve, an emergency close included.

13.4.3 Model Predictive Control of the Back Pressure

The MPC chooses one setpoint, Terminal B's back pressure, every 2 min. Its model is the control room's steady hydraulic profile on the tracked batches, rebuilt at each execution with any tripped station as a bypass. The profile uses the declared line of Table 13.2, with its 45 µm wall roughness, and never the plant's parameters, so a roughness changed in the app is model mismatch. In case 6 at 200 µm the MPC reads the hill 0.66 bar low at 120 min and holds 0.6 bar more back pressure than an MPC given the plant's roughness, and at 10 µm it reads the hill 0.07 bar high, which leaves the hill at 1.86 bar g, under its 2 bar g floor. From the measured terminal pressure it infers the lowest pressure $\hat{p}_{hill}$ over the five segment centers from km 235 to 275, and a finite difference of 1 bar gives the gain g of the hill on the back pressure. The profile is built at the smaller of the origin meter's flow and Terminal B's flow plus Terminal A's delivery, so a leak upstream of the hill cannot make the estimate

optimistic. The prediction model and the quadratic program, with a horizon of thirty 2-min steps grouped in graduated blocks, are given in Equation (13.8).

$$\begin{aligned} &\tau_h \dot{x} = g\,(u - u_0) - x, \qquad \hat{p}_{hill} = \hat{p}_{hill,0} + x \\ &\min \textstyle\sum_k w_E \frac{Q_{in}}{1000} u_k + w_{\Delta u} \Delta u_k^2 + 100 w_s s_k^2 + 10 w_s s_k \\ &\text{s.t. } \hat{p}_{hill,k} \geq 2 \text{ bar g} - s_k, \quad 3 \leq u_k \leq 40, \quad |\Delta u_k| \leq 4 \end{aligned} \tag{13.8}$$

where u is the back-pressure setpoint in bar g, $\tau_h = 3$ min, and $w_E = w_{\Delta u} = w_s = 1$. The linear cost prices back pressure in proportion to the flow that must be pumped against it, about 0.03 MW per bar at 1000 m³/h, paid by station 4 on the 850 m³/h past Terminal A. The shared linear MPC module of Section 1.6.3 solves it with the dual active-set algorithm of Goldfarb and Idnani [17] and sends only the first move to the loop below. A solve that is not optimal and finite is rejected and the setpoint stays where it was, with the station overrides running underneath in every case. Over the challenge's day the MPC solves 720 times with no rejection.

13.4.4 Tracker, Cut and Leak Detector

The tracker moves its own copy of each interface at the metered flow over the bore area, the origin meter upstream of km 140 and the origin meter less Terminal A's beyond it, with the line taken as rigid. It confirms and corrects an interface when the densitometer passes the midpoint of the density change. The cut sends the delivery from the ahead product's tank to a transmix tank when the density has moved a set share of the way, 10 % by default, and on to the next product's tank at a second share, 90 %. Like the flow diversion valve of Volume 8, Chapter 13, the cut acts on what its instrument reports, here a densitometer read through a sample delay. The leak detector is a compensated volume balance [8], as shown in Equation (13.9), the form of Equation (1.15) written in volumes.

$$\begin{aligned} r &= \frac{1}{W}\Big[\int_{t-W}^{t} (\hat{Q}_{in} - \hat{Q}_A - \hat{Q}_B)\,dt - \Delta \hat{V}_{pack}\Big] \\ \hat{V}_{pack} &= \textstyle\sum_i A\,\Delta x\,\big(1 + \hat{p}_i / \hat{K}_i\big) \end{aligned} \tag{13.9}$$

where $\hat{p}_i$ is interpolated along each leg in piezometric head from the eight station pressures and Terminal B's, and $\hat{K}_i$ comes from the tracked batches. An alarm is raised when r has stayed above the threshold for the persistence time, judged only once a full window has elapsed, and cleared below 80 % of the threshold. The defaults are 6 m³/h over a 15 min window with 2 min of persistence. Chapter 12 watches a gas transmission line with a detector of the same kind, where the pack is large and no instrument measures it.

13.4.5 Trips, Flags and Three Separate Models

Protection sits outside the controllers and reads the truth. It trips a station whose discharge stays within 2 bar of the MAOP for 2 s, or whose suction stays below 1 bar g for 5 s, and the trip latches until the operator restarts it. Status flags mark MAOP exceeded, low suction, slack line, an open relief and surge, defined as any segment rising more than 10 bar within 10 s. Three models are kept apart. The plant is Section 13.3. The identified model is what a learner reads from the trends, such as the friction gradient or the storage of a leg. The controller's model is the steady profile on the tracked batches, which knows neither the leak nor a meter's product shift nor the transient that follows a trip.

13.4.6 Design Choices

Six design choices shape the line and its control. First, the hill sits at km 250, in the last leg, and station 4 at km 210. An earlier layout placed the hill at km 190. A station cannot raise the pressure behind it, so a hill upstream of station 4 could not be held full from it, while in the last leg Terminal B's back pressure is a real handle. The leak stays at km 180. Second, the surge lesson states that a slower stroke removes the front but not the packing, which the measurements of Section 13.5 bear out. Third,

Table 13.3 The Nine Cases

#	Case and events	Teaching point
1	Manual at 800 m^3/h, diesel	the series line by hand
2	Terminal B emergency close at 3 min, 5 s stroke	Joukowsky front, packing
3	Selectors off; flow SP 1000 to 900 m^3/h at 10 min	low suction wins
4	Gasoline at B, diesel 12 km behind	tracking and the cut
5	Flow SP 1250 m^3/h, station 1 at top speed	drag reducer
6	Flow SP 1000 to 500 m^3/h at 10 min	slack line, back pressure
7	Gasoline behind diesel at 10, 1 % leak at 180 min; 3 m^3/h, 5 min, no persistence	detector tuning
8	Station 3 trips at 10 min	a trip under overrides
9	Challenge, 24 h: three batches, trip at 8 h, 2 % leak at 16 h	the whole line

Table 13.4 Case Outcomes Measured on the Engine

Case and condition	Result
1, S4 alone to 94 %	low-low suction trip at 2.32 min
1, origin downstream, 8 min apart	992 m^3/h at 60 min, suctions ≥ 8
2, stroke 5 s	+18.5 bar in 10 s, SURGE at 6 s
2, stroke 120 / 600 s	steepest 10 s rise 8.3 / 4.1 bar
2, end state, any stroke	87.0–87.4 bar g at B
3, selectors off	LOW SUCTION 14.6 min, S2 trip 15.9
3, selectors on	S2 lowest suction 7.05, 899 m^3/h
4, cut 10/90	transmix 73.4, off 2.01 / 0.74 m^3
4, cut 30/70	transmix 29.0, off 7.82 / 3.56 m^3
4, cut 5/95	transmix 92.6, off 1.05 / 0.30 m^3
5, no additive	1063 m^3/h, S1 at 105 %
5, 10 / 5 / 20 ppm at 2 min	1250 at 8 h / 1189 / 1251 at 4 h
6, 5 bar g	SLACK LINE at 25.05 min
6, 10 / 15 / 20 bar g at 40 min	not refilled / 44.2 / 42.0 min
6, MPC from Reset	never slack, 15.8 bar g at 90 min
7, as shipped	first alarm 11.4 min, 247 before the leak
7, persistence 5 min only	quiet, leak in 5.5 min
7, 4 / 6 m^3/h, 15 min, 2 min	quiet, leak in 3.7 / 7.0 min
8, after the trip	781 m^3/h, S1 and S2 at 85 bar g
8, restart at 70 min	above 990 m^3/h at 74.7 min

the MPC sets only the back pressure. In a series line of variable-speed stations the total head at a given flow is fixed by friction, elevation and the terminal pressure, and the suction setpoints only redistribute it, so the energy handles are the flow, the drag reducer, with a transport delay of 8.45 h a leg, and the back pressure the hill needs. Fourth, energy is reported but not judged in the challenge. Fifth, the stations use speed control only, without discharge throttle valves. Sixth, the slack line is the declared outflow clamp of Equation (13.5).

13.5 Nine Cases, Measured

The cases appear in Table 13.3 and the principal measurements in Table 13.4. All numbers come from the engine of Section 1.6.1 run without a browser on the default seed, advanced with the browser's own step, and any move the case's text asks the learner to make is made after the run begins. Seeds 1 to 3 were used to check the margins of cases 7 and 9. Every case loads identically when selected first, chosen after another case, or rerun with Reset.

13.5.1 One Flow Through Four Pumps

Case 1 starts lined out at 800 m^3/h in Manual, with speeds of 83.6, 79.3, 66.8 and 69.9 %. Raised alone to 94 %, station 4 takes its extra flow from the pipe just upstream before anything upstream can send more, and trips on low-low suction at 2.32 min. Raised alone to 96 %, station 2 pulls its own suction to −1.7 bar g and trips at 2.3 min while station 3's suction rises to 20.8 bar g. Raised from the

origin downstream, 8 min apart, to 99.8, 96.2, 83.7 and 94.0 %, the line reaches 992 m³/h by 60 min with no suction below 8 bar g, and the first leg's gradient steepens from 0.596 to 0.889 bar/km.

Case 3 ships the stations on discharge control at their design values and cuts the lead flow to 900 m³/h at 10 min. Station 2 keeps pumping what its discharge needs, the first leg empties at the storage rate above, LOW SUCTION appears at 14.6 min, and station 2 trips on low-low suction at 15.9 min. Stations 3 and 4 follow at 17.3 and 18.6 min as each leg empties, and station 1, pushing into a line that no longer moves, trips on high-high discharge at 88 bar g at 20.2 min. With the selectors on, each suction loop takes its pump as the suction falls below 8 bar g, station 2's lowest suction is 7.05 bar g and the line settles at 899 m³/h. In case 8 the same structure carries a trip of station 3. Stations 2 and then 1 reach their 85 bar g limits, their discharge loops take the pumps, and the line settles at 781 m³/h with station 4 still on its suction and no other trip. Restarted at 70 min, station 3 brings the flow back above 990 m³/h at 74.7 min.

> **TRY IT IN THE APP** **8 · Station 3 trips**
>
> Load the case and press Run. At 10 min station 3's drive trips. Watch the Flows trend: the line settles at about 781 m³/h with no other trip, while stations 1 and 2 hold their discharges at 85 bar g. Once it has settled, press Restart tripped stations, below the cards. Restarted at 70 min, station 3 brings the flow back above 990 m³/h at 74.7 min.

13.5.2 A Front That Wears Down, and Packing That Does Not

Case 2 closes Terminal B at 3 min with a 5 s stroke, as shown in Figure 13.2. Diesel at 840 kg/m³ stopping 1.96 m/s at 1130 m/s gives a Joukowsky rise of 18.6 bar, and the terminal rises 18.5 bar in the first 10 s. SURGE is flagged 6 s after the close begins. On the 5 s trends, Terminal B and station 4's discharge first stand 2 bar above their earlier values 5 s and 90 s after the close, an apparent 1060 m/s over the 90 km between them, slower than the declared speed because friction wears the front down as it travels [2]. Behind the front the stations go on pumping into a line that no longer delivers, and friction's head turns into pressure. The terminal is 38.4 bar above its start at 1 min and 80.3 bar at 5 min, peaks at 89.7 bar g about 9 min after the close, and sits near 87.4 bar g at 30 min once the discharge loops hold every station at its limit. A 120 s stroke lowers the steepest ten-second rise to 8.3 bar and a 600 s stroke to 4.1 bar, neither raising SURGE, and both end within 0.4 bar of the fast closure. These steepest rises are taken over every segment center, the measure behind the SURGE flag. The stroke time controls the front and not the packing, which is why a terminal closure on a real line is coordinated with the stations rather than left to the valve.

Pause. Try Exercise 13.2 before reading on.

13.5.3 Interfaces, Additive and the Hill

In case 4 the tracker predicts the interface at Terminal B at 102.3 min and the true interface arrives at 102.4 min. When the densitometer confirms it, the tracked position is 0.071 km, or 8.5 m³, off. The cut trades transmix against contamination, as Table 13.4 lists. Cutting at 10 and 90 % of the density change sends 73.4 m³ to transmix, with 2.01 m³ of diesel in the gasoline tank and 0.74 m³ of gasoline in the diesel tank, and 2 and 98 % raise the transmix to 115.7 m³ with 0.33 and 0.12 m³ off. The gasoline tank always receives more, because the 30 s sample delay, about 7.1 m³ of line at 850 m³/h, makes every switch late.

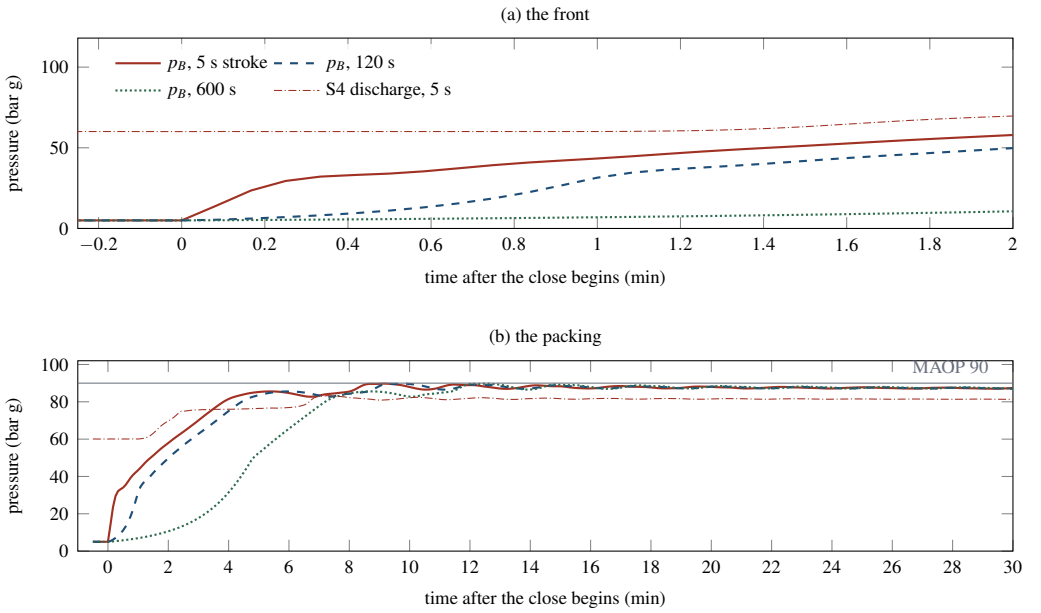


Figure 13.2 Terminal B's valve-inlet pressure after the emergency close of case 2 for three stroke times, 5 s (solid), 120 s (dashed) and 600 s (dotted), with station 4's discharge for the 5 s stroke (dash-dotted), logged every 5 s. The thin gray line is the MAOP. (a) The 5 s stroke raises 18.5 bar in 10 s, and the front reaches station 4 worn down. (b) All three strokes pack the line to the same end, near 87 bar g.

DID YOU KNOW? A Narrow Cut Is Not a Clean Cut

From the simulator (Table 13.4). Cutting case 4's interface at 30 and 70 % of the density change instead of 10 and 90 % sends only 29.0 m^3 to transmix instead of 73.4 m^3, but puts 7.82 m^3 of diesel into the gasoline tank instead of 2.01 m^3.

In case 5 the line delivers 1063 m^3/h with station 1 at its 105 % top speed. Dosed at 10 ppm at 2 min, the flow climbs leg by leg as treated diesel fills each one, to 1103 m^3/h after an hour, 1192 after four and the 1250 m^3/h setpoint after eight. Five ppm levels off near 1189 m^3/h, and 20 ppm reaches the setpoint after four hours. Used to save power at 1000 m^3/h instead, 10 ppm lowers the pumping power from 7.98 to 5.65 MW ten hours after the dose and toward 5.48 MW once every leg is treated.

TRY IT IN THE APP 5 · Drag reducer buys flow

Load the case and press Run. After the run starts, set Drag reducer dose on the Drag reducer card to 10 ppm, then run at 60 or 120 min/s. The line flow climbs leg by leg as treated diesel fills each one: about 1103 m^3/h after an hour, 1192 after four and the 1250 m^3/h setpoint after eight. Run again at 5 ppm: the flow levels off near 1189 m^3/h.

In case 6 the nomination falls to 500 m^3/h at 10 min. The hill reaches the vapor pressure at 22.6 min and SLACK LINE is flagged at 25.05 min. Raising the back pressure at 40 min to 10 bar g does not refill it by 120 min, 13 bar g refills it at 88.7 min, 15 bar g at 44.2 min and 20 bar g at 42.0 min. The MPC, from a Reset, holds the true hill at or above 1.74 bar g after 40 min with 15.8 bar g of back pressure and never lets it go slack, and at 1000 m^3/h it lowers the back pressure to its 3 bar g bound because friction keeps the hill full there. With 5 bar g at the terminal, a cut to 700 m^3/h leaves 1.7 m^3

of slack after two hours and a cut to 750 m³/h none. Those slack volumes carry the step artifact described in Section 13.3, while the onset does not.

13.5.4 What the Balance Can and Cannot Tell

Case 7 ships the detector at 3 m³/h over 5 min with no persistence, sends gasoline in behind the diesel at 10 min and opens a 1 % leak, 9.96 m³/h, at km 180 at 180 min. The first alarm comes at 11.4 min with no leak open, and the alarm comes and goes 247 times before the leak. Two causes add up. Once gasoline passes the origin meter, which is proved on diesel and reads gasoline 0.25 % high, the meters show 2.5 m³/h more entering than leaving. The line pack worked out from eight transmitters also misses part of the change as the lighter, more compressible gasoline fills the first leg, so from 30 min to 180 min the residual averages 3.08 m³/h with a standard deviation of 0.67, the remaining 0.6 m³/h of the mean coming from the unmeasured line pack. The residual sits on the threshold and the noise does the rest. With the meter error set to zero the same detector alarms twice, and without the batch change it stays quiet at all four seeds. Five minutes of persistence alone keeps it quiet at all four seeds and alarms the leak 5.5 min after it opens, and 6 m³/h over 15 min with 2 min of persistence alarms in 7.0 min. Two minutes of persistence at the shipped threshold is quiet at the default seed but not at seeds 1 and 3.

Pause. Try Exercise 13.3 before reading on.

The detector is more sensitive than a real one, because the model has no temperature and temperature is the largest source of false alarms on real lines. Its other false alarms come from transients nobody tells it about. With the default 6 m³/h, 15 min and 2 min, LEAK ALARM with no leak is raised from 20.1 to 28.7 min after case 2's closure, from 22.3 to 44.2 min while case 3's legs empty, from 17.0 to 25.1 min after case 6's rate cut and from 78.8 to 81.1 min after a restart at 60 min in case 8. A leak smaller than a meter's product shift can hide under it. On case 4's line, with gasoline arriving at Terminal B and diesel entering, the residual sits at −1.49 m³/h, and a 0.2 % leak of about 2 m³/h only brings it to +0.43 m³/h. Of 160 detector settings, with windows of 5 to 60 min, persistence of 0 to 5 min and thresholds of 1 to 6 m³/h, the 60 that stay quiet through case 7's batch change all miss that leak for an hour, the trade the monitoring literature describes [8, 9].

13.5.5 A Day on the Line

The challenge runs a day with jet fuel, gasoline and diesel in the line, gasoline entering at 4 h and jet fuel at 14 h, a trip of station 3 at 8 h and a 2 % leak at km 180 at 16 h. It is met with no MAOP exceedance, no suction below 3 bar g, no protective trip, every cut within 100 m³ of transmix and 2 m³ of the other product, and the leak alarmed within 10 min with no false alarm before it. The state of the suggested run at 1000 min is shown in Figure 13.3, and the configurations are compared in Table 13.5. As shipped, without selectors, the suctions run below their floor from 81.9 min, stations 4, 1 and 2 trip on protection after the drive fault at station 3, and the tight detector false-alarms 17 times. The selectors alone turn the trip into a lower flow and stop the protective trips, but at that flow the hill runs slack, up to 12.5 m³ by the app's measure, and with the shipped detector and cut the day carries 24 false alarms and 7.59 m³ off-product. The suggested configuration, selectors on, the MPC, 6 m³/h over 15 min with 2 min of persistence and a cut at 5 and 90 %, passes at the default seed and at seeds 1 to 3, alarming the leak in 8.6 to 8.75 min, and the line carries 727 to 729 m³/h between 600 and 900 min. The MPC's hill estimate is a steady inference and lags a fast transient. At 484 min, four minutes after the trip, it reads 4.51 bar g against a true −0.34 bar g, and the true hill touches −0.46 bar g, the gasoline vapor pressure, and holds at most 0.25 m³ of slack, under the 0.5 m³ that raises SLACK LINE. After the leak the estimate and the truth agree within 0.1 bar, 2.04 against 1.97 bar g at 1000 min. At the fastest playback speed of 300 min/s the day plays in about 5 s.

A fixed back pressure of 10 bar g also passes. Its day uses 102.3 MWh against the MPC's 107.9 MWh, but it pumps 19 324 m³ against 19 749 m³, because with the higher back pressure the line carries 880 to 955 m³/h in the hours before the trip against 942 to 989 m³/h under the MPC. The



Figure 13.3 The challenge with the suggested settings at $t = 1000$ min (16.67 h) on the Profile view, 40 min after the 2 % leak opened and eight hours after station 3 tripped, cropped to the plant view. The badges above the profile read 743 m^3/h on the origin meter, a lowest suction of 8.1 bar g, the next interface 42 min away by the tracker (50 min in truth, because the leak takes flow the tracker counts), a residual of 15.7 m^3/h and 3.18 MW. (1) Jet fuel entering behind gasoline, diesel and the gasoline reaching Terminal B, with the tracked interfaces marked by triangles. (2) Station 3 in red and with no jump in the gradient, which runs straight through its bypass. (3) The leak at km 180, losing 16.3 m^3/h. (4) The hill at 2.0 bar g with the MPC's estimate beside it (1.97 true and 2.04 inferred). (5) The status strip with LEAK ALARM, raised 8.75 min after the leak.

Table 13.5 Challenge Configurations Scored at 24 h

Configuration	False alarms	Leak (min)	Transmix (m^3)	Off (m^3)	Verdict
shipped	17	—	28	7.48	fails[a]
selectors on only	24	0.9	31	7.59	fails
suggested, shipped detector	13	0.7	84	1.03	fails
suggested, cut 10/90	0	8.75	74	2.08	fails
suggested, PID at 5 bar g[b]	1	8.4	86	0.98	fails
suggested, PID at 10 bar g	0	8.4	85	1.00	passes
suggested (MPC)	0	8.75	84	1.03	passes

[a] Suctions below the floor for 598 min and stations 1, 2 and 4 tripped by protection. [b] The hill's slack refill after the trip raises the false alarm. This row rests on the slack treatment and holds at the 1 and 0.5 s steps but not at 0.25 s, so it is not a converged result.

challenge does not hold the delivered volume fixed, so the energy totals of different configurations describe different days, which is why energy is reported on its tile and not judged. Figure 13.4 sets each configuration against the challenge's limits on alarms and off-product.

13.6 Technology in Practice

Figure 13.5 draws the station overrides, the back-pressure loop, the cut and the leak detector of Section 13.4 with the hardware of a liquid line in place of symbols.

What Measures It

The lead flow loop reads the meter at the origin, and every suction and discharge loop reads a pressure transmitter beside its own pump. The leak detector adds the meters at both terminals and the station

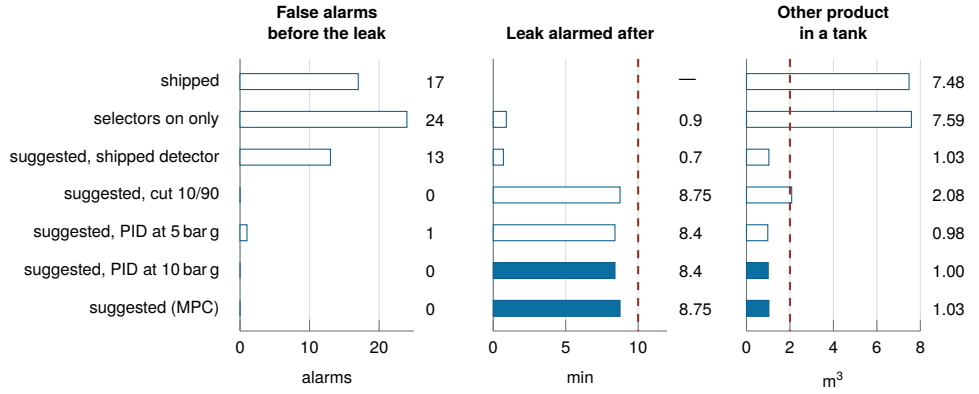


Figure 13.4 The configurations of Table 13.5: false alarms before the leak (left), minutes from the leak to its alarm (middle) and the other product put into a tank by the worst cut (right). Solid bars pass the challenge and open bars fail it. Dashed lines are the limits of 10 min and 2 m^3, a false alarm is not allowed, and the shipped row has no leak time. Notice that the suggested settings with the shipped detector alarm the leak fastest but fail on 13 false alarms, and that the cut at 10 and 90 % fails with 2.08 m^3 against the limit of 2.

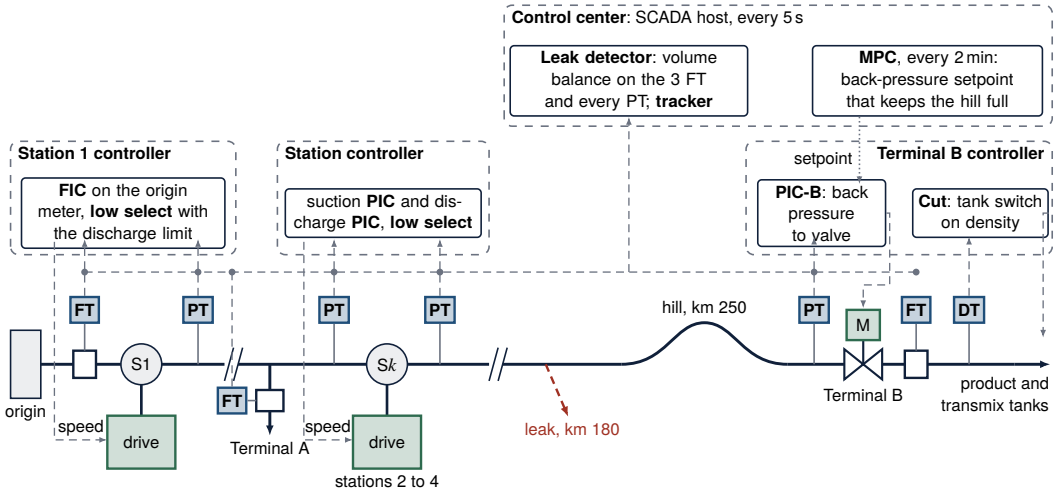


Figure 13.5 The loops of the line with their hardware. Blue boxes are sensing devices with the chapter's tags: the turbine meters (FT) at the origin and at both terminals, a suction and a discharge transmitter (PT) at each station, the transmitter at Terminal B's valve and the densitometer (DT). Green boxes are final elements: the pump drives and Terminal B's motor-operated valve. Dashed arrows are signals, the dotted arrow the back-pressure setpoint that the MPC writes. One station stands for stations 2 to 4. Notice that each pump takes the lower of two speed requests in its own station, while the leak detector in the control center reads the meters and transmitters of the whole line and moves nothing. Not to scale, and not a piping diagram.

and terminal pressures, and the cut reads the densitometer at Terminal B through its sample delay.

TECHNOLOGY Sensor: The Turbine Meter and Its Prover

A turbine meter measures flow with a free-spinning wheel in the stream, much like a small windmill. A pickup coil senses each passing blade, so the pulse frequency is proportional to the volumetric flow, and the turndown commonly exceeds 10 to 1. About 20 pipe diameters of straight pipe upstream and 5 downstream keep swirl away. For high accuracy the pulses per unit volume are found with a piston prover, best connected on site. Diesel lubricates the bearings, but viscosity slows the wheel, most at low flow, and a wheel that coasts after a sudden stop shows flow that is no longer there [18]. The model's meters are proved on diesel and read gasoline 0.25 % high, a declared error that stands for such a change of product.

What Moves It

Each station's loops move one pump's speed, and the back-pressure loop moves Terminal B's valve. The model's MAOP, its discharge trips and its relief valves stand for legal limits. A United States liquid line may not run above its maximum operating pressure, the lowest of limits that include the internal design pressure of the pipe and 80 % of its test pressure. A surge may not exceed 110 % of that limit, and the operator must provide the controls and protective equipment that hold it [19]. Relief valves and other pressure-limiting devices are inspected and tested every calendar year, at intervals of no more than 15 months [20].

TECHNOLOGY Final Element: The Terminal's Motor-Operated Valve

Electric motors have long driven large valves, first as shutoff valves and now in throttling service as well. A worm gear reduces the motor's fast rotation to the slow turn that moves a large valve. A throttling actuator needs a position sensor beside its limit switches, and a hand crank moves the valve if the motor or its power fails [18]. The model's stroke time, 60 s by default, limits every move of Terminal B's valve, an emergency close included, and case 2 shortens it to 5 s. The chapter's surge results turn on that one setting: it decides the front, while the stations decide the packing.

Where the Controller Runs

A pipeline is run through supervisory control and data acquisition: a control server at a control center gathers the field data, remote terminal units or programmable logic controllers at the field sites control the local process, and loops run with cycle times from milliseconds to minutes [21]. The app's controllers execute every 1 s, its SCADA scan and leak detector every 5 s and its MPC every 2 min. The chapter's structure maps onto standard blocks: two PI blocks in external-reset form and a low select in each station's controller, a velocity-form PI at Terminal B, and the tracker, the cut and the volume balance as applications on the control server, with the MPC above them. The server's performance is a safety matter. In June 1999 a 16-inch gasoline line leaked 237,000 gallons that ignited 1.5 hours later and killed three people, after a poorly performing supervisory system had kept the controllers from seeing the abnormal operation develop. The investigators asked for an offline system to test changes to the supervisory database [21].

IN PRACTICE What the Leak Detection Rule Asks

In the United States every hazardous liquid line that carries liquid in a single phase must have an effective leak detection system. The operator evaluates it against the length and size of the line, the product carried, the swiftness of detection, the location of the nearest response personnel and the leak history. A computational pipeline monitoring system must comply with API RP 1130 in its operation, maintenance, testing, record keeping and dispatcher training [22], and a new one is designed to section 4.2 of that practice [23]. Case 7's trade between a quiet detector and a fast alarm is what that evaluation weighs.

What Is Modernizing It

The first of three developments is the transient-model leak detector that the chapter's Conclusion names as the next step, which a 2019 review calls the most sensitive but also the most complex tech-

nique in use. It compares the measured values with those of a running hydraulic simulation [24]. The second is fiber-optic cable laid along the pipe. Leaking hydrocarbon changes the cable's temperature, small leaks can be found, and the timing of the scattered light locates them [24]. The third is security. In May 2021 a ransomware attack on the business systems of an operator of over 5,500 miles of products pipeline, carrying more than 100 million gallons a day, led it to shut the line down, with no evidence that the attack reached the control system [21].

13.7 Limitations

Every size, product property and limit is a generic teaching value, and none was fitted to an operating pipeline. The line is isothermal, so the detector is more sensitive than a real one, whose false-alarm band is set largely by temperature. Its false alarms here come from the meters' product shift and from the line pack that eight transmitters cannot measure at a batch change, and from transients no one reports to it. The lumped scheme smears a front over a segment and represents neither cavitation nor column separation during the front. The slack line is a declared teaching treatment, an outflow clamp whose slack volume is a time-step artifact of about 13.5 m^3/h of growth at the 1 s step that halves with the step. When the hill reaches the vapor pressure, and which back pressure refills it, do not depend on the step, but the slack volume must not be read as a physical prediction, and one row of Table 13.5 depends on it. A real slack line drains the downhill pipe much faster.

> **OPEN CHALLENGE** **How Friction Wears Down a Front**
>
> Hydraulic transients in pipes have been studied for more than a hundred years, yet a 2005 review found two questions still open: how the turbulence responds to a transient wave, and how the flow loses its symmetry about the pipe axis. Both matter for modeling how a transient dissipates its energy [2]. In case 2 friction takes most of the closure front's height before it reaches station 4. Progress would be a friction model, checked on real lines, that predicts how high a front still stands at the next station upstream.

The controllers carry simplifications of their own. The MPC moves only the terminal back pressure and infers the hill from a steady profile, so it lags a fast transient by several bar for a few minutes. Station setpoints, the flow and the additive remain the operator's. Stations are single pumps on speed control without throttle valves, sequencing or start-up. Pumping energy is reported but not judged, because the challenge does not fix the delivered volume.

> **OPEN CHALLENGE** **A Small Leak Under Temperature and Batch Changes**
>
> A 2019 review of leak detection counts temperature among the uncertainties that affect flow monitoring most, because it changes the density, viscosity and friction of the liquid. Temperature-dependent flow models had been limited to short lines, and the review asks for detectors that find the valid leaks with fewer false alarms. A volume balance, it notes, is sensitive to the dynamics of the line and cannot locate a leak [24]. On this isothermal line every detector setting that stayed quiet through a batch change missed a small leak for an hour. Progress would be a detector that follows temperature and batches along the whole line and still alarms a leak smaller than the meters' product shift.

13.8 Conclusion

A refined products line is a single flow shared by pumps in series, carrying batches that move at walking pace and pressure news that moves at 1110 m/s, and this chapter measured both on one simulated line. Without override selectors a 10 % flow cut trips all four stations within 10.2 min, while with them a station trip becomes a steady 781 m^3/h. A 5 s closure raises the terminal 18.5 bar in ten seconds, and slower strokes remove that front but end at the same packed pressure near 87 bar g. The densitometer's delay puts more of the following product into the leading tank at every cut, a drag reducer buys 187 m^3/h over eight hours, and a hill near the terminal needs about 15 bar g of back pressure at 500 m^3/h, where the MPC holds 15.8 bar g, and only its 3 bar g bound at full flow. A

balance detector tight enough to catch a 1 % leak in minutes also alarms on a meter's product shift at every batch change. The model is isothermal and lumped, and its slack treatment is declared rather than physical. A fuller model would add temperature to the line pack, a partly full pipe model for the hill, multi-pump stations with throttling, and a transient-model leak detector. The line is a compact setting for practicing override control on units in series.

KEY POINTS

- One flow passes every pump station, so only the lead station sets it and the others give way.
- Without override selectors a 10 % flow cut trips all four stations within 10.2 min. With them a station trip becomes a steady 781 m^3/h.
- A 5 s closure raises the terminal 18.5 bar in ten seconds. Slower strokes remove that front but end at the same packed pressure.
- A hill near the terminal needs about 15 bar g of back pressure at 500 m^3/h.
- A balance detector tight enough to catch a 1 % leak in minutes also alarms on a meter's product shift at every batch change.

Where else this applies. The Joukowsky rise of a fast closure also governs the penstock of Volume 1, Chapter 7, and an override that gives up throughput to hold a limit protects Volume 11, Chapter 3 as well.

References

[1] E. S. Menon, *Liquid Pipeline Hydraulics*. CRC Press, 2004.

[2] M. S. Ghidaoui, M. Zhao, D. A. McInnis, and D. H. Axworthy, "A review of water hammer theory and practice," *Applied Mechanics Reviews*, vol. 58, no. 1, pp. 49–76, 2005.

[3] A. H. Glattfelder and W. Schaufelberger, *Control Systems with Input and Output Constraints*, ser. Advanced Textbooks in Control and Signal Processing. London: Springer, 2003.

[4] M. S. Yoon, C. B. Warren, and S. Adam, Eds., *Pipeline System Automation and Control*. ASME Press, 2007.

[5] R. Rejowski and J. M. Pinto, "Scheduling of a multiproduct pipeline system," *Computers & Chemical Engineering*, vol. 27, no. 8–9, pp. 1229–1246, 2003.

[6] J. E. Austin and J. R. Palfrey, "Mixing of miscible but dissimilar liquids in serial flow in a pipeline," *Proceedings of the Institution of Mechanical Engineers*, vol. 178, no. 1, pp. 377–389, 1963.

[7] R. M. Baptista, F. B. de Freitas Rachid, and J. H. Carneiro de Araujo, "Estimating mixing volumes between batches in multiproduct pipelines," in *Proceedings of the 2000 International Pipeline Conference, Volume 2: Integrity and Corrosion; Offshore Issues; Pipeline Automation and Measurement; Rotating Equipment*. American Society of Mechanical Engineers, 2000, p. V002T08A008.

[8] M. Henrie, P. Carpenter, and R. E. Nicholas, "Mass balance leak detection," in *Pipeline Leak Detection Handbook*. Elsevier, 2016, pp. 41–55.

[9] A. F. Colombo, P. Lee, and B. W. Karney, "A selective literature review of transient-based leak detection methods," *Journal of Hydro-environment Research*, vol. 2, no. 4, pp. 212–227, 2009.

[10] T. Ma, O. O. Youzwishen, and M. Hylton, "Avoidance of slack flow in liquid pipelines," in *2004 International Pipeline Conference, Volumes 1, 2, and 3*. ASMEDC, 2004, pp. 491–497.

[11] G. I. Taylor, "The dispersion of matter in turbulent flow through a pipe," *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences*, vol. 223, no. 1155, pp. 446–468, 1954.

[12] A. Bergant and A. R. Simpson, "Pipeline column separation flow regimes," *Journal of Hydraulic Engineering*, vol. 125, no. 8, pp. 835–848, 1999.

[13] P. S. Virk, "Drag reduction fundamentals," *AIChE Journal*, vol. 21, no. 4, pp. 625–656, 1975.

[14] E. D. Burger, W. R. Munk, and H. A. Wahl, "Flow increase in the trans alaska pipeline through use of a polymeric drag-reducing additive," *Journal of Petroleum Technology*, vol. 34, no. 2, pp. 377–386, 1982.

[15] J. C. P. Liou and J. Tian, "Leak detection—transient flow simulation approaches," *Journal of Energy Resources Technology*, vol. 117, no. 3, pp. 243–248, 1995.

[16] 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.

[17] D. Goldfarb and A. Idnani, "A numerically stable dual method for solving strictly convex quadratic programs," *Mathematical Programming*, vol. 27, no. 1, pp. 1–33, 1983.

[18] 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.

[19] Pipeline and Hazardous Materials Safety Administration, "49 CFR 195.406, maximum operating pressure," Code of Federal Regulations, Title 49, Part 195, edition of October 1, 2025, govinfo.gov, 2025.

[20] ——, "49 CFR 195.428, overpressure safety devices and overfill protection systems," Code of Federal Regulations, Title 49, Part 195, edition of October 1, 2025, govinfo.gov, 2025.

[21] K. Stouffer, M. Pease, C. Tang, T. Zimmerman, V. Pillitteri, S. Lightman, A. Hahn, S. Saravia, A. Sherule, and M. Thompson, "Guide to operational technology (OT) security," National Institute of Standards and Technology, Gaithersburg, MD, Special Publication 800-82r3, 2023.

[22] Pipeline and Hazardous Materials Safety Administration, "49 CFR 195.444, leak detection," Code of Federal Regulations, Title 49, Part 195, edition of October 1, 2025, govinfo.gov, 2025.

[23] ——, "49 CFR 195.134, leak detection (design requirements)," Code of Federal Regulations, Title 49, Part 195, edition of October 1, 2025, govinfo.gov, 2025.

[24] M. A. Adegboye, W.-K. Fung, and A. Karnik, "Recent advances in pipeline monitoring and oil leakage detection technologies: Principles and approaches," *Sensors*, vol. 19, no. 11, p. 2548, 2019.

13.9 Exercises

13.1 Concept check · 2 min

The line runs at 1000 m^3/h of diesel with the override selectors On, and the shipper cuts the nomination to 900 m^3/h. Which loop makes the line carry 900 m^3/h, and what do the other stations do?

(a) Every station's discharge loop lowers its discharge in proportion, so the four pumps share the cut

(b) Station 4's suction loop slows its pump until Terminal B's meter reads 900 m^3/h

(c) Terminal B's back-pressure loop closes its valve until the delivery has fallen by the cut

(d) Station 1's flow loop alone sets the flow, and stations 2 to 4 hold their suctions under discharge limits

13.2 Concept check · 1 min

In case 2 the stroke time of Terminal B's valve is raised from 5 s to 600 s and the closure is run again. Which statement matches the measurements of Section 13.5?

(a) The steepest ten-second rise falls to about a quarter, and the terminal still ends near 87 bar g

(b) Both the steepest rise and the final pressure fall, because the stations see the closure coming

(c) The steepest rise is unchanged, because $\rho a \Delta V$ holds no time, while the final pressure falls

(d) Neither changes, because the line stops in either case and the same volume is packed

13.3 Concept check · 2 min

In case 7 the balance detector false-alarms after gasoline follows diesel into the line, with no leak open. What causes the false alarms on this line?

(a) The gasoline is warmer than the diesel, and the detector applies no temperature correction

(b) The origin meter, proved on diesel, reads gasoline high, and the line pack worked out from eight transmitters misses part of the change

(c) The leak at km 180 weeps before it opens, and a tight detector sees it early

(d) Transmitter noise alone, which a longer window would average away

13.4 Theory and calculation · 5 min

Use the diesel values of Section 13.3: inside diameter 392.1 mm, density 840 kg/m^3 and wave speed 1130 m/s.

(a) Compute the bore area, the bulk modulus $K = \rho a^2$, and the volume stored per bar of pressure by one 10 km segment and by the 70 km first leg. *Checkpoint:* 0.1207 m^2, 1.073 GPa, 0.113 m^3 and 0.788 m^3 per bar.

(b) Station 1 sends 100 m^3/h less than station 2 takes. How fast does station 2's suction fall? *Checkpoint:* 2.1 bar per minute.

(c) At that rate, how long does the suction take to fall from its 8 bar g setpoint to the 3 bar g low-suction alarm? Case 3 measures 4.6 min from the cut. Why is the measurement longer? *Checkpoint:* 2.4 min.

13.5 Theory and calculation · 6 min

Terminal B delivers 851.8 m^3/h of diesel at the design point when its valve is shut in 5 s.

(a) Compute the velocity stopped at the valve and the Joukowsky rise of Equation (1.9) with $a = 1130\,\mathrm{m/s}$. *Checkpoint:* 1.96 m/s and 18.6 bar.

(b) How long would a sharp front take to cover the 90 km back to station 4 at the declared 1130 m/s and at the 1110.5 m/s timed on the model? The trends show it about 85 s after the close. *Checkpoint:* 79.6 s and 81.0 s.

(c) Compare the time a pressure change takes to cross the 300 km line with the time a batch takes to reach Terminal B at 1000 m^3/h to km 140 and 850 m^3/h beyond. *Checkpoint:* 4.4 min and 39.6 h, a ratio of about 540.

13.6 Theory and calculation · 6 min

Use Equation (13.2) for diesel at 1000 m^3/h (kinematic viscosity 3.5 cSt, roughness 45 µm).

(a) Compute the velocity, the Reynolds number, the Swamee–Jain friction factor and the friction gradient in bar per km and in meters of diesel per km. *Checkpoint:* 2.30 m/s, 257 700, 0.0159, 0.902 bar/km and 10.9 m/km.

(b) Compute the drag reduction at 5, 10 and 20 ppm, and the gradient at 10 ppm if the whole leg is treated. *Checkpoint:* 23.1, 33.3 and 42.9 %. 0.601 bar/km.

(c) The additive moves with the liquid and is sheared to nothing at the next station. How long does it take to fill a 70 km leg at 1000 m^3/h, and what does that mean for using it on a nomination? *Checkpoint:* 8.45 h.

13.7 App challenge · 8 min

Load scenario 3, Low suction wins, with the default seed. Run at 5 min/s and export the CSV file after each run.

(a) Run as shipped, with Override selectors Off, to 30 min. Find the first row in which `truth_suc_min_barg` falls below the 3 bar g alarm, and list the order in which the stations trip, with the protection that trips each (status strip and station cards). *Checkpoint:* 14.58 min, within 0.1 min. Stations 2, 3 and 4 on low-low suction, then station 1 on high-high discharge.

(b) Set Override selectors to On, press Reset and run to 60 min. Read the Worst suction tile, the lowest value of `suc2_barg`, and `truth_flow_in_m3h` at 60 min. *Checkpoint:* 6.9 bar g. 7.0 bar g, within 0.1 bar. 899 m^3/h, within 2 m^3/h. No LOW SUCTION and no trip.

Explain the difference between the two runs in terms of who sets the flow.

13.8 App challenge · 8 min

Load scenario 2, A valve shut in five seconds, with the default seed. Each run goes to 30 min at 5 min/s. Export the CSV file after each run.

(a) Run as shipped, with the 5 s stroke. Read the largest value of `truth_surge_10s_bar`, `pB_meas_barg` at 30 min, and the Least MAOP margin tile. *Checkpoint:* 16.6 bar. 87.2 bar g, within 0.2 bar. 0.3 bar.

(b) Set Terminal B valve stroke time (PIC card) to 120 s, press Reset and repeat the three readings. Then do the same with 600 s. *Checkpoint:* 8.3 bar, 87.2 bar g, 0.3 bar, no SURGE. 4.1 bar, 87.3 bar g, 0.3 bar, no SURGE.

(c) Which of the three readings does the stroke time control, and why does the margin to the MAOP not improve?

13.9 App challenge · 9 min

Load scenario 6, Slack line over the hill, with the default seed. Run at 20 min/s and export the CSV file after each run.

(a) Run as shipped (back pressure 5 bar g) to 90 min. Find the first row with `truth_slack_m3` above 0.5 m^3, where SLACK LINE is raised, and the slack volume at 90 min. *Checkpoint:* 25.1 min, within 0.1 min. 15.3 m^3.

(b) Press the reload button, set Terminal B back pressure (PIC card) to 10 bar g before Run and run to 120 min. Then set it to 15 bar g, press Reset and run again. Is SLACK LINE raised in each run? *Checkpoint:* At 10 bar g, yes, from 26.7 min, with 11.8 m^3 at 120 min. At 15 bar g, no, the largest `truth_slack_m3` is 0.37 m^3.

(c) Press the reload button, choose MPC for Line control before Run, and run to 120 min. Read `pB_sp_barg` and `mpc_hill_est_barg` at 90 min. *Checkpoint:* 15.8 bar g and 2.1 bar g, each within 0.2 bar. No slack.

Why is the slack volume in (a) a sign of slack and not a prediction?

13.10 Application area · 3 min

The densitometer at Terminal B reads its sample 30 s late.

(a) How much line passes the valve during that delay at 850 m^3/h? *Checkpoint:* 7.1 m^3.

(b) In case 4 a cut at 10 and 90 % put 2.01 m^3 of diesel into the gasoline tank and 0.74 m^3 of gasoline into the diesel tank. Explain the asymmetry, and name two changes that would reduce the larger figure on a real line.

13.11 Application area · 4 min

Station 4 pays for Terminal B's back pressure on the 850 m^3/h that pass Terminal A, at a pump efficiency of 0.8.

(a) Compute the pumping power per bar of back pressure, and the energy a day of 10 bar g costs over the MPC's 3 bar g bound at full flow. *Checkpoint:* 0.0295 MW per bar, and about 5.0 MWh.

(b) Over the challenge's day the suggested settings use 107.9 MWh and pump 19 749 m^3 under the MPC, and 102.3 MWh and 19 324 m^3 with a fixed 10 bar g. Compute the energy per cubic meter of each, and explain why the challenge reports energy and does not judge it. *Checkpoint:* 5.46 kWh/m^3 and 5.29 kWh/m^3.

13.12 Review the agent · 5 min

An AI assistant proposes a tuning for the detector of case 7: "Set the leak alarm threshold to 2 m^3/h, the balance window to 60 min and the persistence to zero. A 60 min window averages away the

transmitter noise that causes the false alarms, so the detector will stay quiet through the batch change and catch leaks as small as 0.2 %.” Find the flaw, and say how you would check the proposal in the app.