Volume 2

CHAPTER 13

Performance Criteria and Capacity Analysis

Communications-Based Train Control
A Comprehensive Guide for US Transit Professionals
Francisco Wang

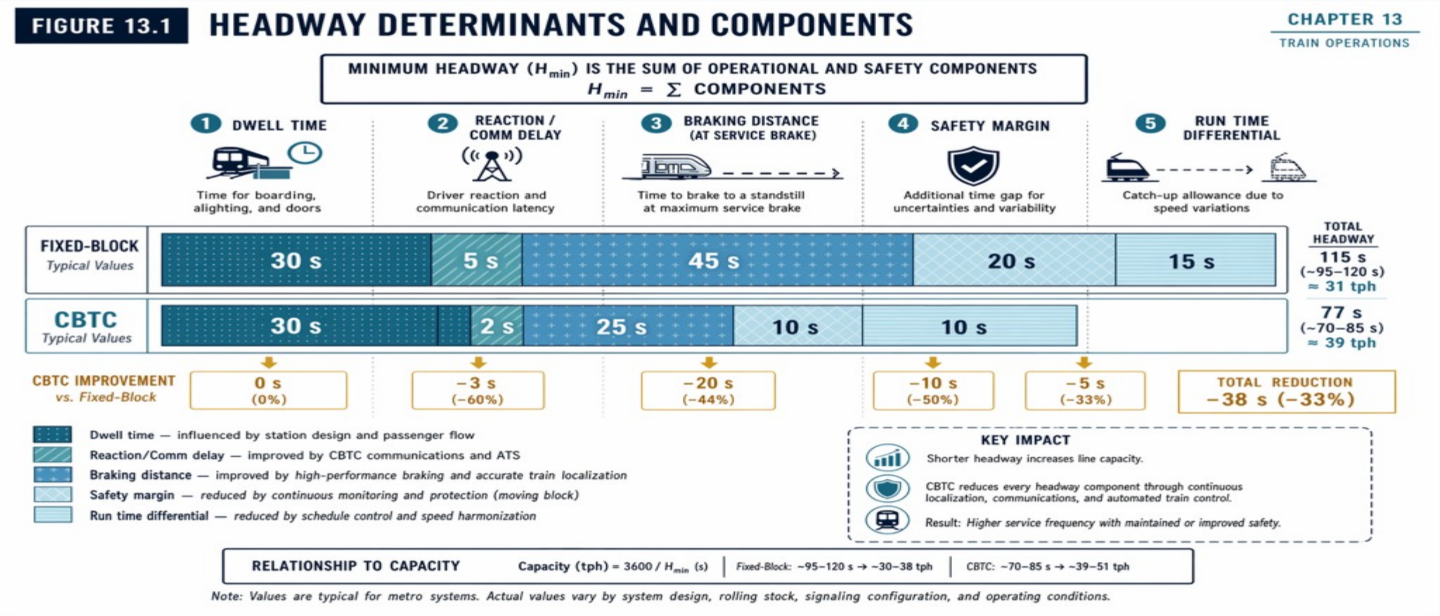
Chapter Overview

- Performance is a portfolio, not a single metric — agencies must specify targets in all four domains
- Four interdependent domains: Capacity (headway/tph), Availability (RAM), Energy Efficiency, Passenger Experience
- Excellence in three of four leaves the deployment incomplete
- Practical tools, benchmarks, and case studies for specifying, measuring, and optimizing all four
- The most successful deployments (MTA L Line, BART TCMP, RATP Line 14) optimize all four simultaneously

13.1

Headway and Throughput Analysis

Headway Determinants and Components



▦ **Dwell time** — influenced by station design and passenger flow

▨ **Reaction/Comm delay** — improved by CBTC communications and ATS

▦ **Braking distance** — improved by *high-performance braking and accurate train localization*

▨ **Safety margin** — *reduced by continuous monitoring and protection (moving block)*

▤ **Run time differential** — *reduced by schedule control and speed harmonization*

KEY IMPACT

Shorter headway increases line capacity.

CBTC reduces every headway component through continuous localization, communications, and automated train control.

Result: *Higher service frequency with maintained or improved safety.*

RELATIONSHIP TO CAPACITY Capacity (tph) = 3600 / H_{min} (s) | Fixed-Block: ~95–120 s → ~30–38 tph | CBTC: ~70–85 s → ~39–51 tph

Note: Values are typical for metro systems. Actual values vary by system design, rolling stock, signaling configuration, and operating conditions.

Figure 13.1 — Five additive components of theoretical minimum headway.

Theoretical Minimum Headway

- h_min = braking distance + safety margin + controller delay + train length + dwell time
- At 55 mph: braking 20–30 sec, margin 3–6 sec, delay 2–4 sec, train length 8–12 sec, dwell 25–40 sec
- Achievable tph = 3600 / headway (seconds) — 90 sec = 40 tph, 120 sec = 30 tph
- Moving-block CBTC eliminates fixed-block quantization penalty — saves 10–20 sec per train
- Practical headway is 75–85% of theoretical minimum; systems hitting 80% are considered excellent

Constraints: Dwell, Terminals, Junctions

- Dwell time: 25–60 sec — the single largest variable, least influenced by CBTC
- PSDs + level boarding + wider doors can save 15–30 sec system-wide
- CBTC alone does not reduce dwell — passenger physics governs

- Single-track terminals: 5–6 min turnback — catastrophic headway constraint
- Double-track with pocket tracks: 2.5–3 min turnback achievable
- Flat junctions: 2–3 min per train — can halve capacity of both lines
- Flying junctions eliminate conflict but cost $50–100M each

US CBTC Headway Benchmarks

System	Headway	tph	Speed	Year	Notes
MTA L Line	2:05–2:30	24–29	55 mph	2018	Moving-block; dense dwell
BART TCMP	2:30	24→30	80 mph	2026 plan	Terminal bottleneck
CTA Red	3:00–4:00	15–20	60 mph	2024	Aging infrastructure
Honolulu	3:00–4:00	15–20	70 mph	2023	Demand-limited, not physics

13.2

System Availability and Reliability (RAM)

RAM: The Availability Equation

99.5%+

target

System availability for vital functions

35-45%

of failures

Radio/communication dropouts — #1 bottleneck

<4 hrs

MTTR

Required for redundancy to improve availability

MTBF and Availability Analysis

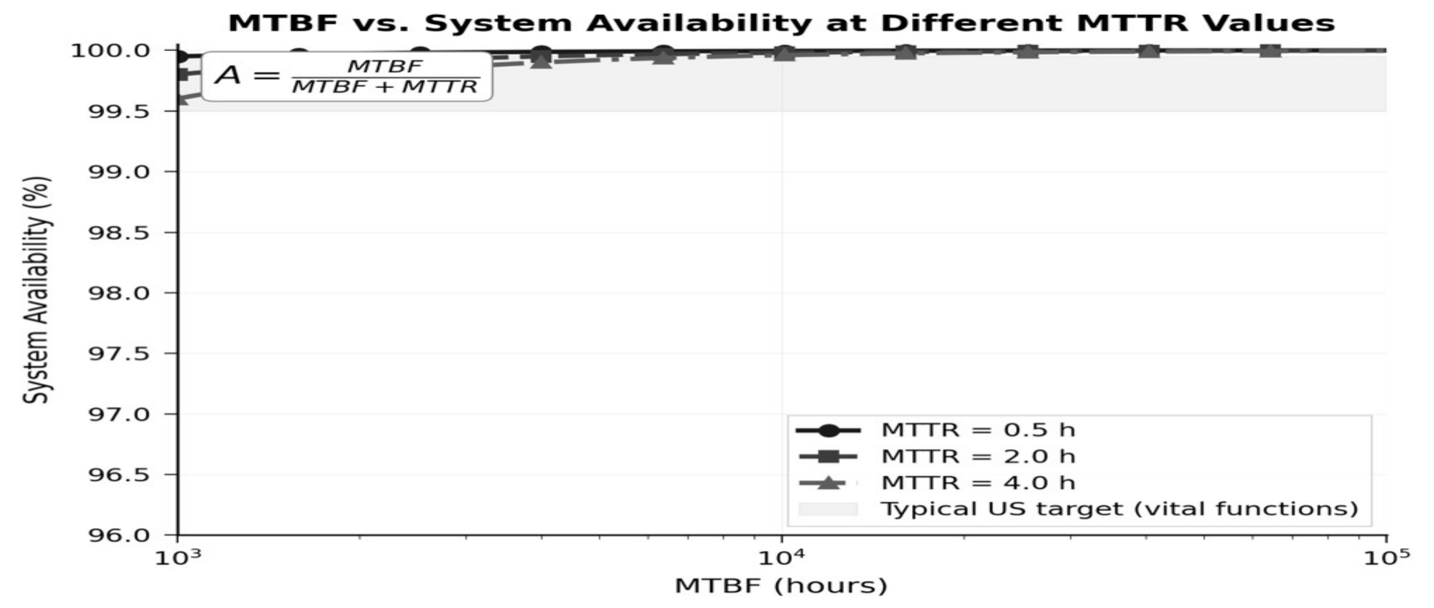
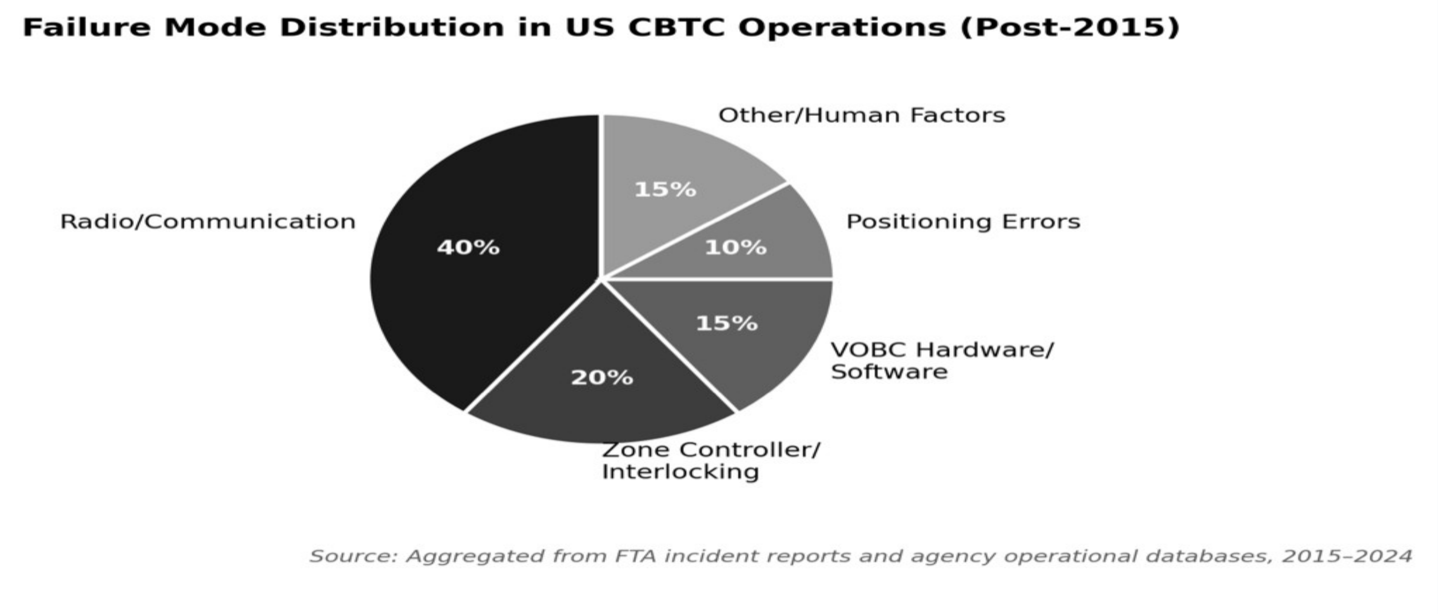


Figure 13.3 — Relationship between MTBF, MTTR, and system availability.

Failure Mode Distribution



Failure Mode Distribution in US CBTC Operations (Post-2015)

Source: Aggregated from FTA incident reports and agency operational databases, 2015–2024

Figure 13.4 — Distribution of service-affecting failure modes in US CBTC systems.

N+1 Redundancy Failover Impact

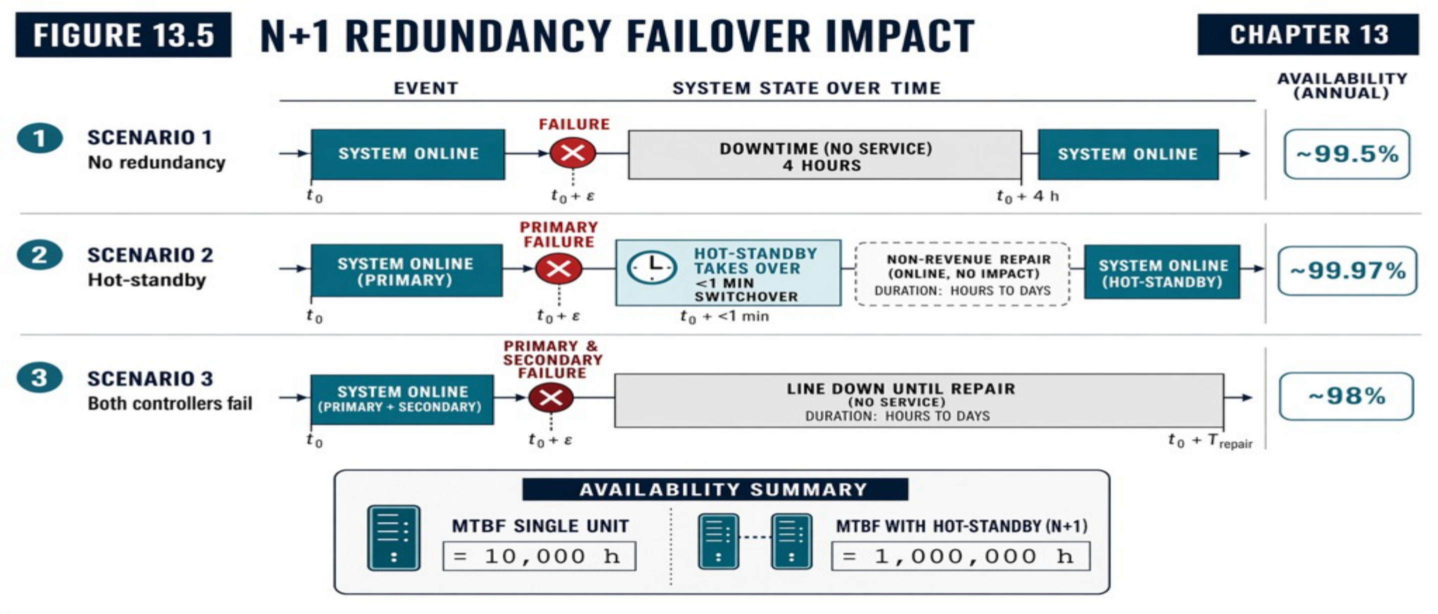


Figure 13.5 — N+1 redundancy failover impact on system availability.

RAM Contract Mechanics

- Performance Acceptance Period: 12–24 months post-commissioning with monthly MTBF/MTTR reports
- Failure classification: Category 1 (line-down), Cat 2 (degraded mode), Cat 3 (redundant path used)
- Liquidated damages: $50K–$500K/day for missing Revenue Service Ready date, capped at 5–10%
- N+1 hot-standby: wayside zone controllers failover in <500 ms; improves availability ~2 orders of magnitude
- Maintenance strategy: preventive on safety-critical + condition-based on non-vital; spares pre-positioning is critical

13.3

Energy Efficiency and Eco-Driving

Energy Consumption Breakdown

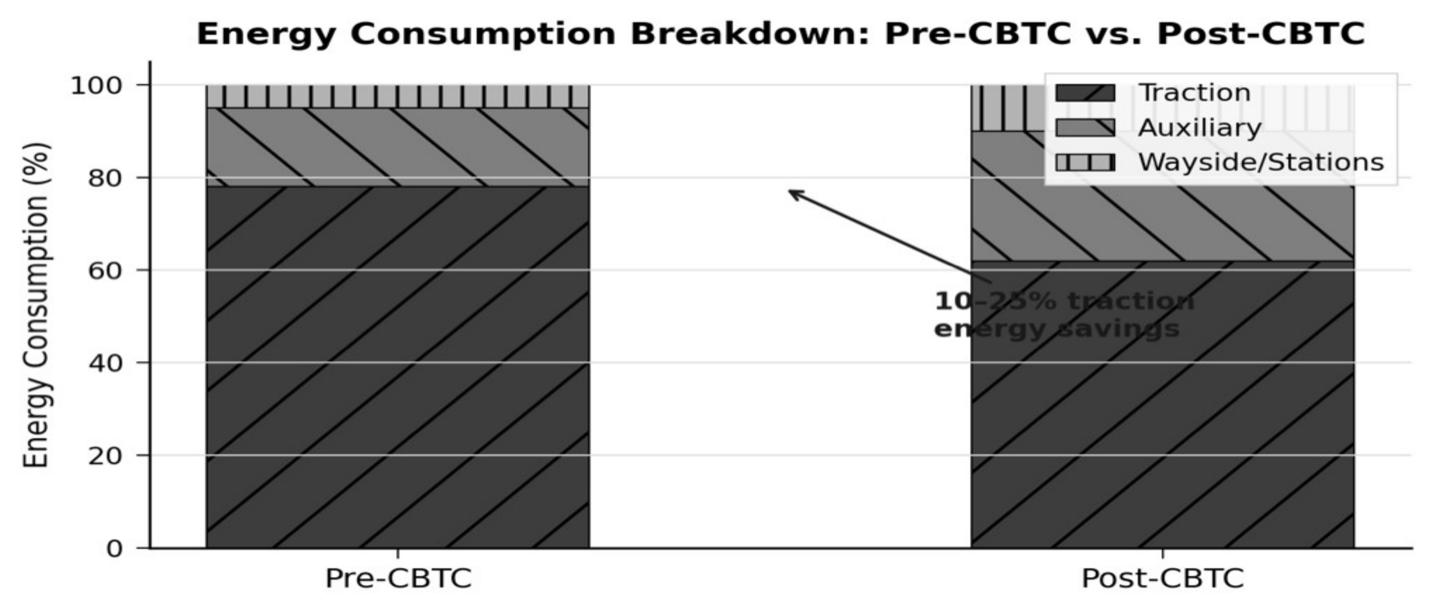


Figure 13.6 — Transit system energy consumption breakdown: traction, auxiliary, and station.

Eco-Driving Speed Profiles

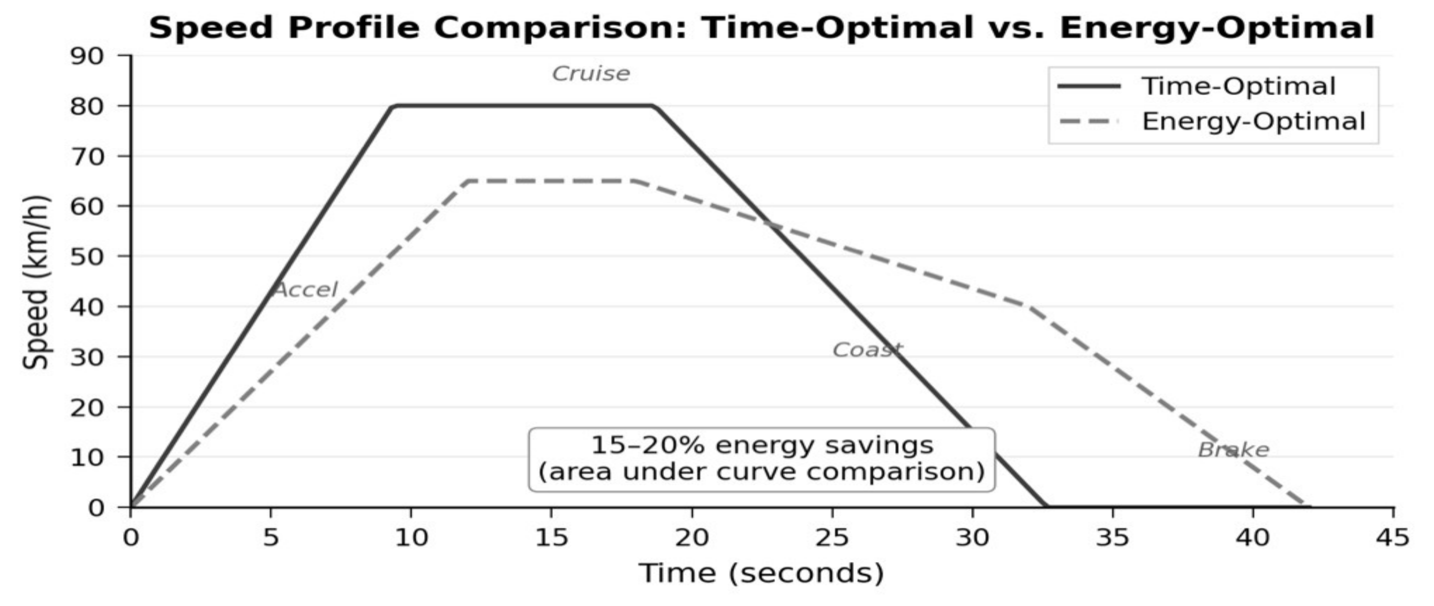


Figure 13.7 — ATO eco-driving profiles: accelerate, coast, late-brake vs. conventional.

Energy Savings Mechanisms

- Eco-driving and coasting optimization: 12–20% traction reduction (dominant mechanism)
- Regenerative braking coordination: ATS aligns braking/acceleration timing for energy reuse
- Speed smoothing: eliminates unnecessary decel-accel cycles

- Headway optimization: 8–12% off-peak savings through precise scheduling
- Wayside Energy Storage (Li-ion, supercapacitor): regen recovery 30–50% → 70%+
- Payback: 8–12 years at $0.12/kWh; SEPTA Letterkenny: 2-MW, 8-MWh system

Regenerative Braking & Wayside Storage

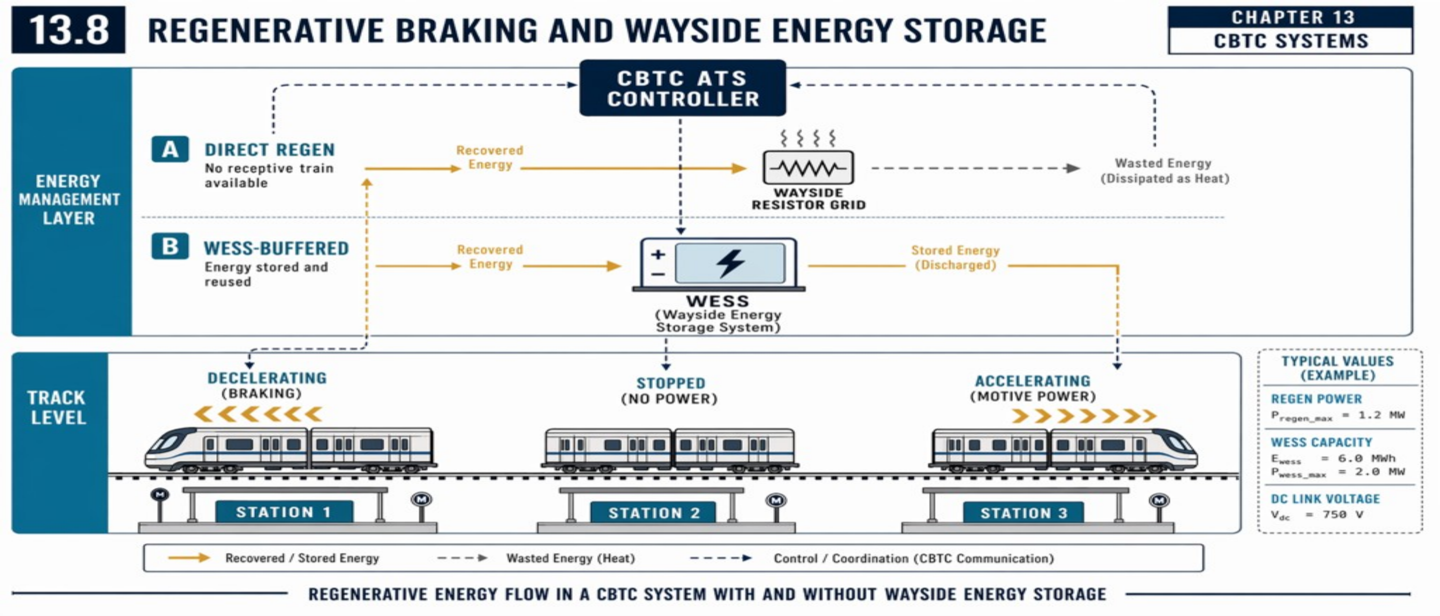


Figure 13.8 — Regenerative braking coordination and wayside energy storage architecture.

Energy Savings by System

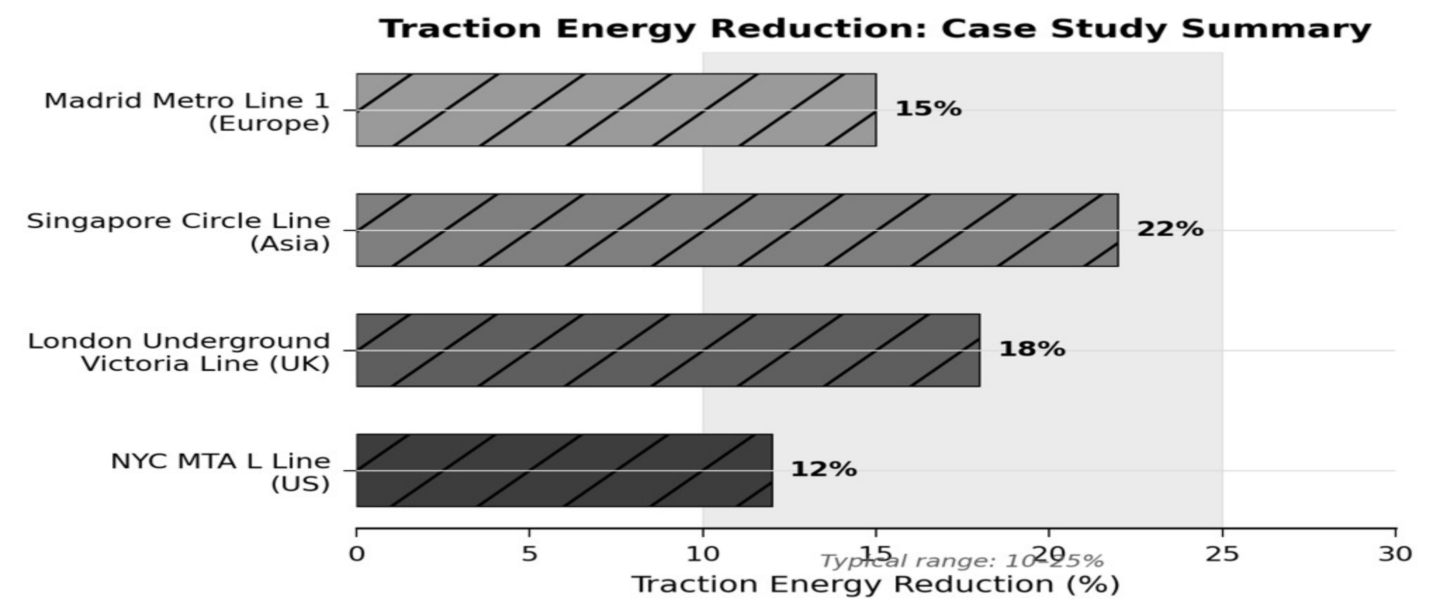


Figure 13.9 — Documented energy savings from major CBTC deployments worldwide.

13.4

Passenger Experience Metrics

Passenger-Centric Performance

- Journey time = access + platform wait + in-vehicle + transfer + egress — CBTC improves three of five
- Platform wait: headway/2 for random arrivals; 5→3 min headway saves 1 min/trip (~540K person-hours/year)
- GTFS-RT prediction accuracy: ±10–15 sec (vs. legacy ±2–3 min) — reduces perceived wait 20–30%
- Stopping precision: ±10–35 cm (vs. manual ±1–2 m) — enables level boarding, ADA compliance 70% → 96%
- Denied boarding drops from ~8% to ~1% with capacity gains — top rider frustration eliminated

Journey Time Decomposition

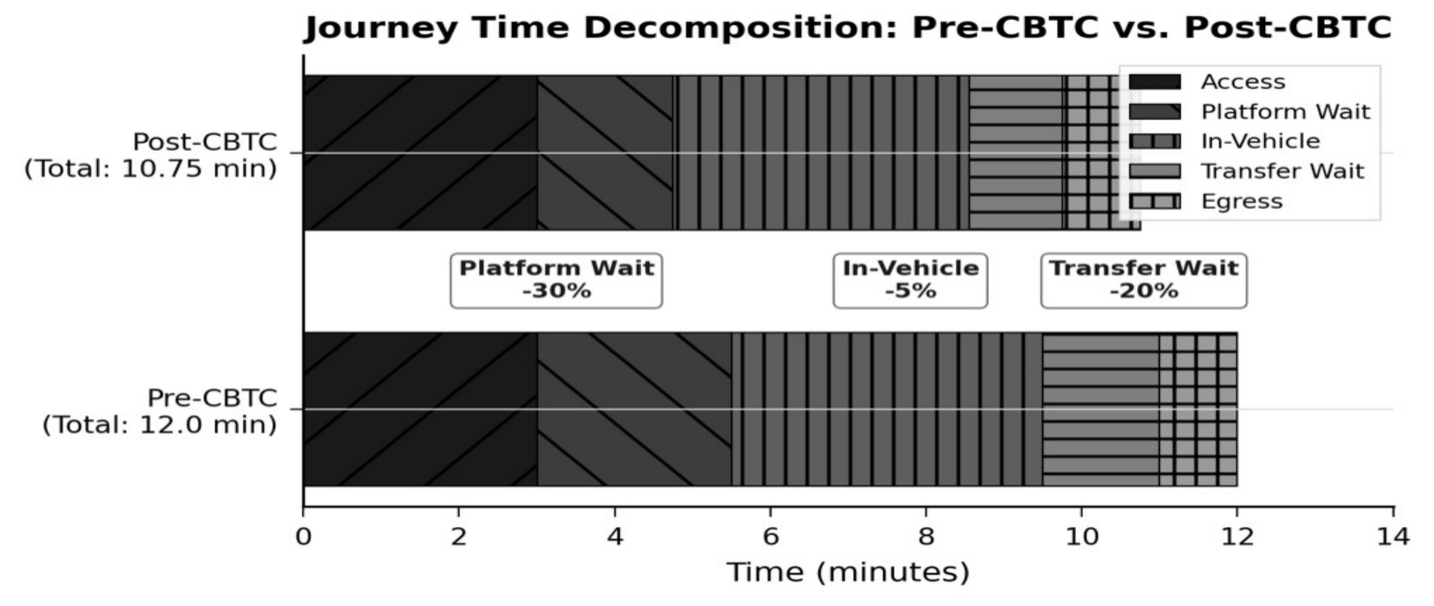


Figure 13.10 — Journey time decomposition: CBTC impact on each component.

13.5

The Performance Quadrant: Integration and Synthesis

Performance Quadrant (KPI Synthesis)

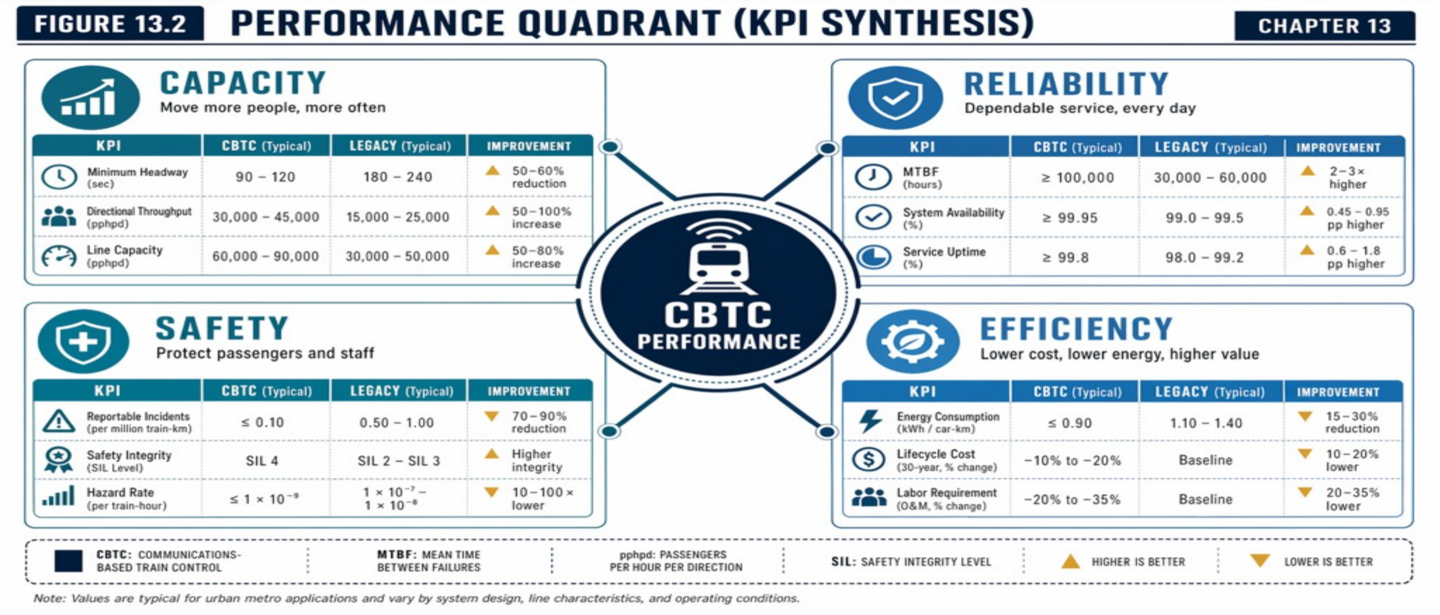


FIGURE 13.2 PERFORMANCE QUADRANT (KPI SYNTHESIS) **CHAPTER 13**

CAPACITY

Move more people, more often

KPI	CBTC (Typical)	LEGACY (Typical)	IMPROVEMENT
Minimum Headway (sec)	90 – 120	180 – 240	▲ 50–60% reduction
Directional Throughput (pphpd)	30,000 – 45,000	15,000 – 25,000	▲ 50–100% increase
Line Capacity (pphpd)	60,000 – 90,000	30,000 – 50,000	▲ 50–80% increase

RELIABILITY

Dependable service, every day

KPI	CBTC (Typical)	LEGACY (Typical)	IMPROVEMENT
MTBF (hours)	≥ 100,000	30,000 – 60,000	▲ 2–3× higher
System Availability (%)	≥ 99.95	99.0 – 99.5	▲ 0.45 – 0.95 pp higher
Service Uptime (%)	≥ 99.8	98.0 – 99.2	▲ 0.6 – 1.8 pp higher

CBTC PERFORMANCE

SAFETY

Protect passengers and staff

KPI	CBTC (Typical)	LEGACY (Typical)	IMPROVEMENT
Reportable Incidents (per million train-km)	≤ 0.10	0.50 – 1.00	▼ 70–90% reduction
Safety Integrity (SIL Level)	SIL 4	SIL 2 – SIL 3	▲ Higher integrity
Hazard Rate (per train-hour)	$\le 1 \times 10^{-9}$	1×10^{-7} – 1×10^{-8}	▼ 10–100× lower

EFFICIENCY

Lower cost, lower energy, higher value

KPI	CBTC (Typical)	LEGACY (Typical)	IMPROVEMENT
Energy Consumption (kWh / car-km)	≤ 0.90	1.10 – 1.40	▼ 15–30% reduction
Lifecycle Cost (30-year, % change)	−10% to −20%	Baseline	▼ 10–20% lower
Labor Requirement (O&M, % change)	−20% to −35%	Baseline	▼ 20–35% lower

■ **CBTC:** COMMUNICATIONS-BASED TRAIN CONTROL
MTBF: MEAN TIME BETWEEN FAILURES
pphpd: PASSENGERS PER HOUR PER DIRECTION
SIL: SAFETY INTEGRITY LEVEL
▲ HIGHER IS BETTER
▼ LOWER IS BETTER

Note: Values are typical for urban metro applications and vary by system design, line characteristics, and operating conditions.

Figure 13.2 — The Performance Quadrant: Capacity, Availability, Energy, Passenger Experience.

The Performance Quadrant Framework

- Headway/Throughput sets the capacity ceiling — max tph given track, dwell, terminal constraints
- Availability ensures headway is delivered — without ≥99.5%, theoretical capacity dissolves
- Energy Efficiency constrains operational cost — 30-tph at poor efficiency is financially unsustainable
- Passenger Experience converts gains into ridership — improved headway attracts riders only if perceived
- A 30-tph system at 92% availability delivers only 27.6 tph in practice — all four domains must be optimized

Key Takeaways

1. Headway is capacity: tph = 3600/headway; controlling constraint is at stations, terminals, or junctions — not open track
1. Moving-block CBTC saves 10–20 sec per train vs. fixed-block; practical achievable headway is 75–85% of theoretical minimum
1. System availability must be ≥99.5% for capacity gains to matter; radio failures (35–45%) are the current US bottleneck
1. CBTC unlocks 10–25% energy savings through eco-driving, regen coordination, and headway optimization — but requires intentional implementation
1. Performance is a portfolio: agencies must specify, measure, and enforce targets in all four quadrant domains simultaneously

End of Chapter 13

Next: **Chapter 14: Lifecycle Costs and Return on Investment**

Questions & Discussion