CBTC Decoded. Advancing Rail Saftey Through Transparency and Technology

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- No proprietary information included.
- For CBTC educational purposes only.

Agenda

- Part I Intro and CBTC Proposal
- Part II Fundamentals and History
- Part III Architecture & Operation
- Part IV Development and Integration
- Part V Design Considerations + Future Trends.
- Part VI Q&A

Part 1

Introduction and Proposal

- Fixed block signaling issues.
- Why a new signaling approach is needed.

19th century: track circuits and colored wayside signals..

- 19th century: track circuits and colored wayside signals. Stop/Proceed.
- Key Innovation: **Track-circuit & fixed signals**
  Electric track circuits detect train presence
- Key Innovation: Colored wayside signals tell drivers “stop / proceed.”
- Why this Mattered: First step toward automated safety that prevented two trains from occupying the same block.

Fixed Block Signaling Constraints

Fixed blocks enforce rigid spacing.

Conservative safety margins slow trains.

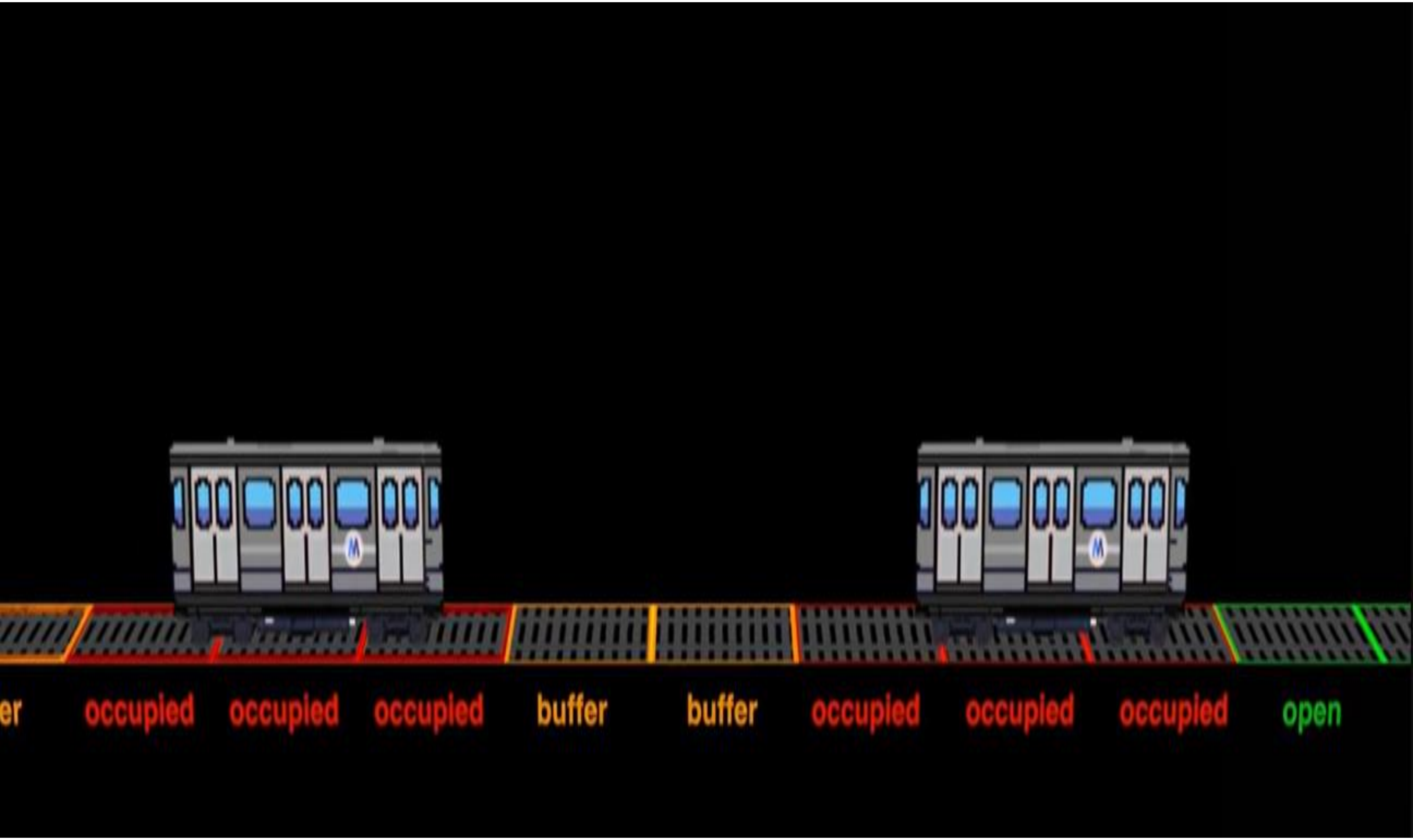
Limited real-time data sent to the train dispatcher.

Hardware (relays, track circuits) aging & failure-prone.

Three aspect Signaling System

- Green = 2+ blocks clear (≥2× SBD)
- Yellow = 1 block clear (≥1× SBD)
- Red = train ahead in next block
- Each signal is placed 1 safe braking distance (SBD) apart.
- Track circuits detect presence in fixed blocks.
- System knows train is “somewhere” in block — not exact location.
- This is the basis of fixed-block signaling.

Fixed Block Limitation Visualization



Fixed Block Limitation Visualization

Red blocks = occupied blocks.

Yellow Blocks = buffer zones. Trains cannot enter these zones neither.

Unused track between blocks wastes capacity.

More trains can't enter until block clears.


HOYT-SCHERMERHORN ST. INTERLOCKING
LINE A-E
NOSTRAND AVENUE
LOWER LEVEL
UPPER LEVEL
STATION
(212)712-4242
WARNING
HOYT STREET TOWER
1
2
3
4
5
6
7
8
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Fixed Block Signaling drawbacks.

Peak demand exceeds ~25–27 trains/hour limit. Ex. NYCT 7 Line.

Station crowding and longer wait times. Dangerous and unsanitary environment.

Building new tunnels for more trains costs billions & takes decades. We don’t have the space neither.

Fixed Block Signaling Drawbacks.

- The fixed block signaling system's requirement for a specific gap between trains constrained the track's maximum speed limit.
- Fixed block signaling system also relied on human operators, who could make mistakes and cause delays when deciding how to move trains.

CBTC (Moving block Signaling) Propoaal

GOAL: INCREASE CAPACITY ON EXISTING INFRASTRUCTURE.

ENHANCE SAFETY & RELIABILITY.

PROVIDE PRECISE TRAIN LOCATION DATA TO TRAIN DISPATCHER

ENABLE HIGHER AUTOMATION LEVELS.

Part 2

Fundamentals and History

Historical Advancements in Transit's signaling system leading to CBTC.

What Is CBTC?

CONTINUOUS AUTOMATIC TRAIN CONTROL VIA RADIO.

USES MOVING-BLOCK SEPARATION.

ENABLES ATP, ATO, ATS SUBSYSTEMS.

CBTC Benefits Overview

+20 – 50% capacity increase.

Automatic protection eliminates collisions.

Higher service reliability; fewer signal failures.

Foundation for driverless operation.

Evolution of Railway Signaling

- 19th century: track circuits and colored wayside signals. (Covered)
- Mid-20th: relay-based ATP (Automatic Train Protection) Relay based speed enforcement. Cab Signaling
- 1980s: first moving-block radio systems. Ex. SELTRAC on Scarborough RT Toronto Canada
- 1990s-2000s: digital CBTC lines open. Paris Line, L Canarsie Line, High Speed rail, PTC.

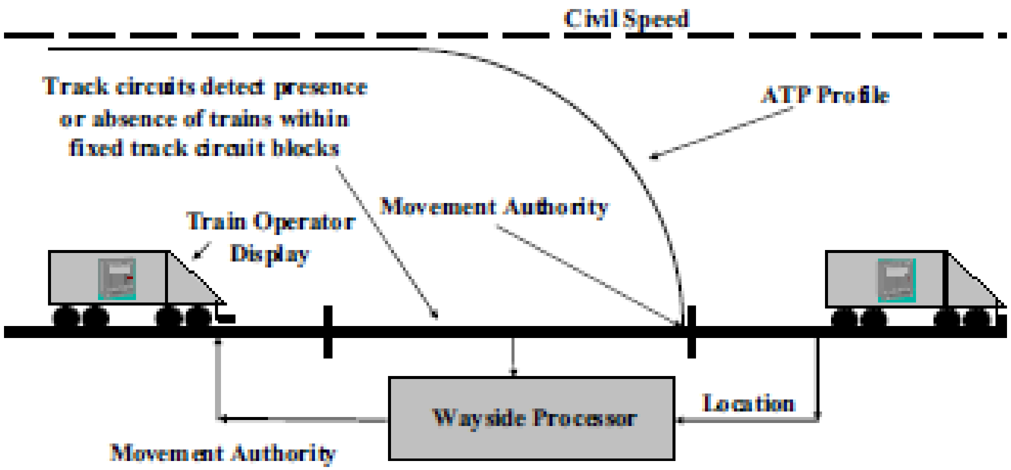
Mid-20th: relay-based ATP (Automatic Train Protection) Cab Signaling

- Cab signaling displays signal aspects in-cab via coded track circuits. (Speed codes)
- Added overspeed protection and richer information than simple red/green signals from wayside, boosting safety.
- Reduced human error and coded in-cab signals gave continuous movement authority.

Cab Signaling. How it works.

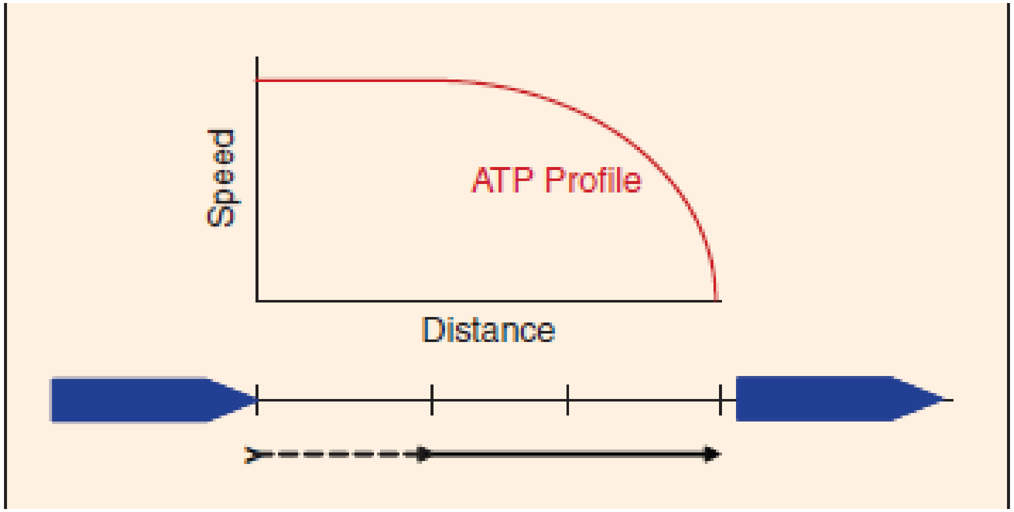
- Track circuit sends coded energy through the rails
- Pickup coils on train detect and convert the signal
- Cab equipment displays signal aspect in real time
- Driver must acknowledge restrictive aspects
- If not acknowledged: automatic braking in 8 seconds

Figure 2: Profile-Based Cab Signal System



Automatic Train Protection with Cab Signaling.

- Automatic train protection (ATP) with distance-to-go profile system.
- Train’s permitted speed gradually decreases as it approaches the end of its movement authority, ensuring a controlled and safe stop.



Cab signaling further advancments

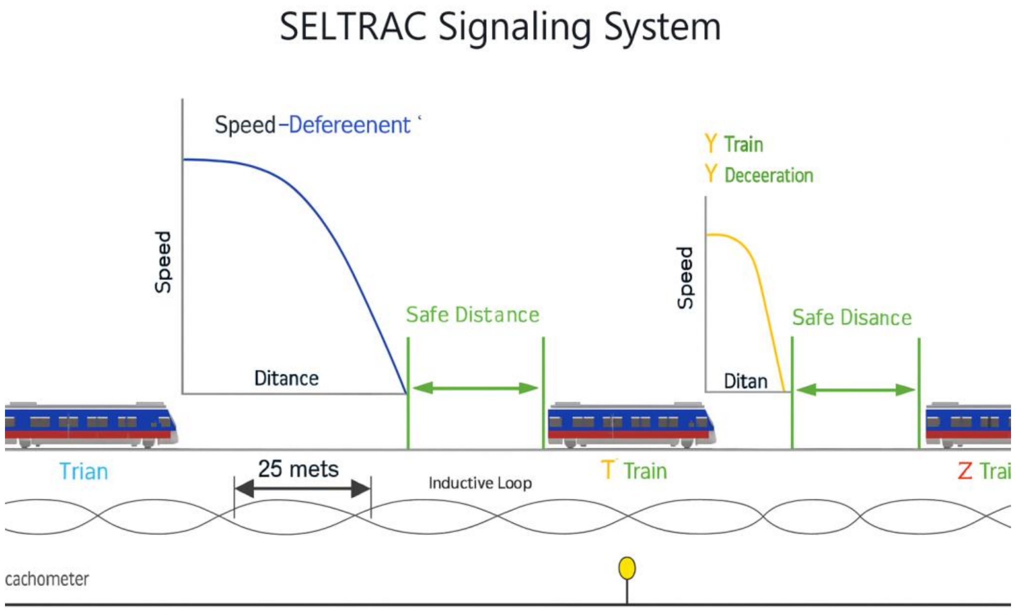
- Speed enforcement via onboard Brake Assurance (BA)
- BA device verified actual braking using motion of mercury tube
- Reduced need for wayside signals (ABS)
- Digital track circuits enabled Distance-to-Go (DtG) cab signaling
- Binary FSK modulation used to transmit speed + target info
- Train calculates its own braking profile using onboard data

1980s: Moving Block Radio Systems.

- 1980s: first moving-block radio systems. Ex. SELTRAC The **Vancouver SkyTrain** (1985). First moving-block CBTC system deployed
- SELTRAC installed on Toronto Scarborough RT (1985)
- Used radio communication and odometry instead of track circuits
- Enabled dynamic train separation and real-time movement authority
- Foundation for modern CBTC systems

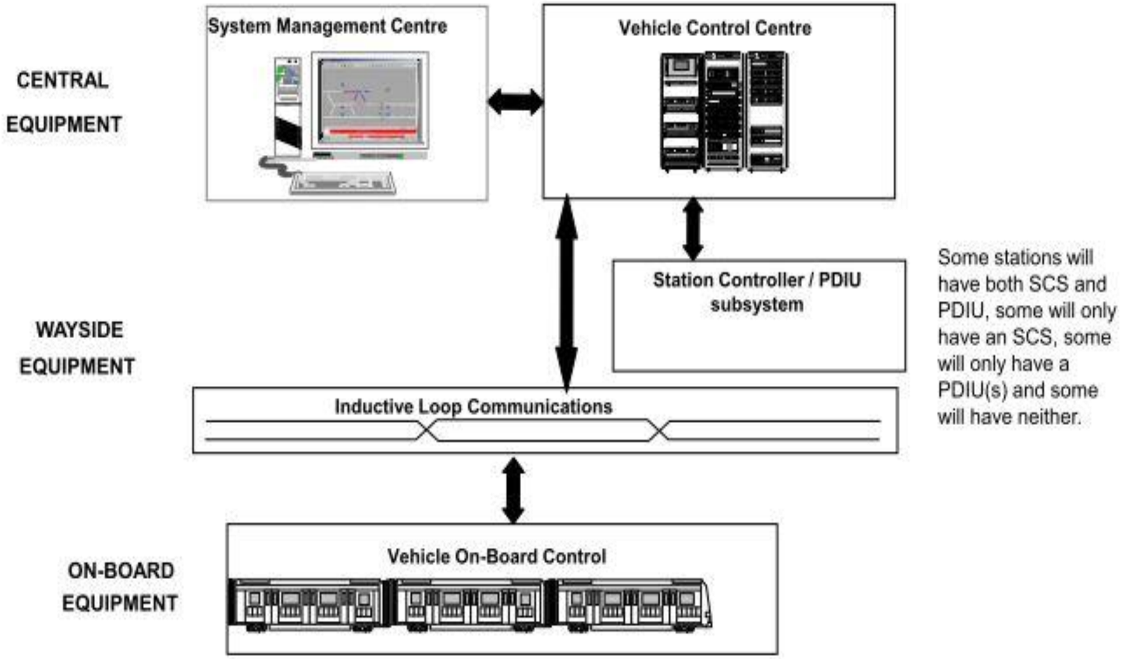
1985: SELTRAC

- SELTRAC introduced dynamic, moving-block signaling
- Train separation calculated in real time — no fixed blocks
- Continuous bi-directional communication via inductive loop
- Onboard ATP enforced braking curve from control center
- First deployed on Toronto Scarborough RT and Vancouver SkyTrain (mid-1980s)



SELTRAC Moving Block Architecture.

- • SELTRAC architecture: vehicle-based control + inductive loop communication
- • VOBC calculates location from odometry, transponders, and radio link
- • Zone Controller (VCC) sends movement authority via loops
- • No fixed blocks—continuous moving-block enforcement
- • Installed on Scarborough RT and Vancouver SkyTrain in mid-1980s



1990s-2000s:Paris Line 1998

- First full CBTC deployment: Paris Line 14 (1998), GoA4
- Onboard ATP: enforces speed limits and safe braking
- ATO: controls acceleration, cruising, and precise station stops
- ATS: manages schedule, dwell times, and passenger info
- Full radio-based, high-resolution train localization
- Eliminated trackside signals and enabled driverless operation

1990s-2000s: CBTC in NYCT

- First CBTC deployment in North America: NYC Subway L Line (2009)
- Siemens Trainguard MT system implemented
- Enabled 20% increase in train throughput
- Reduced signal-related delays and improved on-time performance
- ATO GoA2: Operator remains onboard for door and safety monitoring

1990s-2000s: CBTC in High-Speed rail and PTC

- • 2003: Shanghai Maglev launches with CBTC to support 430 km/h operation
- • 2018: Research proposes CBTC + PTC hybrid integration for U.S. rail
- • CBTC enables real-time control and speed commands
- • PTC ensures train stops if limits or signals are violated
- • Combined systems enhance safety and operational efficiency

Part 3 CBTC System Architecture and Operation

Deep dive into subsystems and moving block logic.

Grades of Automation (GoA) Overview

- GoA 1 Manual driving with ATP safeguard
- GoA 2 Semi-automatic – ATO drives, driver monitors
- GoA 3 Driverless – attendant on board
- GoA 4 Unattended – fully automated

IEEE 1474 Standard – Foundation for CBTC Automation

Establishes CBTC performance and functional standards (GoA 1-4).

Core principles: precise location, continuous communication, vital safety logic.

GoA 1 – Manual + ATP

Driver controls traction & braking.

ATP enforces speed & authority.

Common in legacy systems and during CBTC transition.

GoA 2 – Semi-Automatic

ATO handles speed profile & stops.

Driver supervises doors & emergencies.

Widely used on early CBTC upgrades.

GoA 3 – Driverless Operation

No driver; attendant may ride for passenger service.

System handles all driving functions.

Example: Vancouver SkyTrain (normal ops).

GoA 4 – Unattended Train Operation

Fully automated with platform screen doors.

Central control oversees multiple trains. Enable headways under 90 seconds.

Example: Paris Line 14, Copenhagen Metro.

CBTC System Architecture Key Components

- Train-borne subsystem: VOBC, odometry, ATP/ATO logic
- Wayside Zone Controller (ZC): assigns movement authority
- Operations Control Center (ATS): manages schedules and supervision
- Data Communication System (DCS): radio link + fiber backbone

CBTC System Architecture Block Diagram

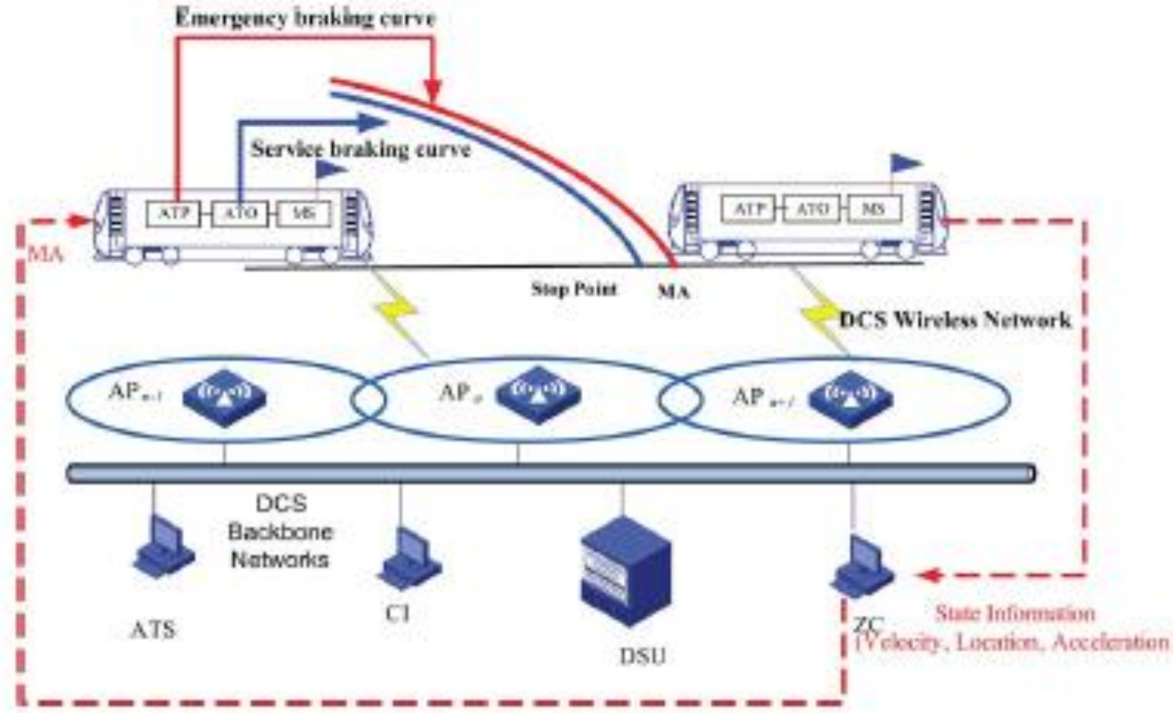


Fig. 1. CBTC systems.

Train-Borne Subsystem

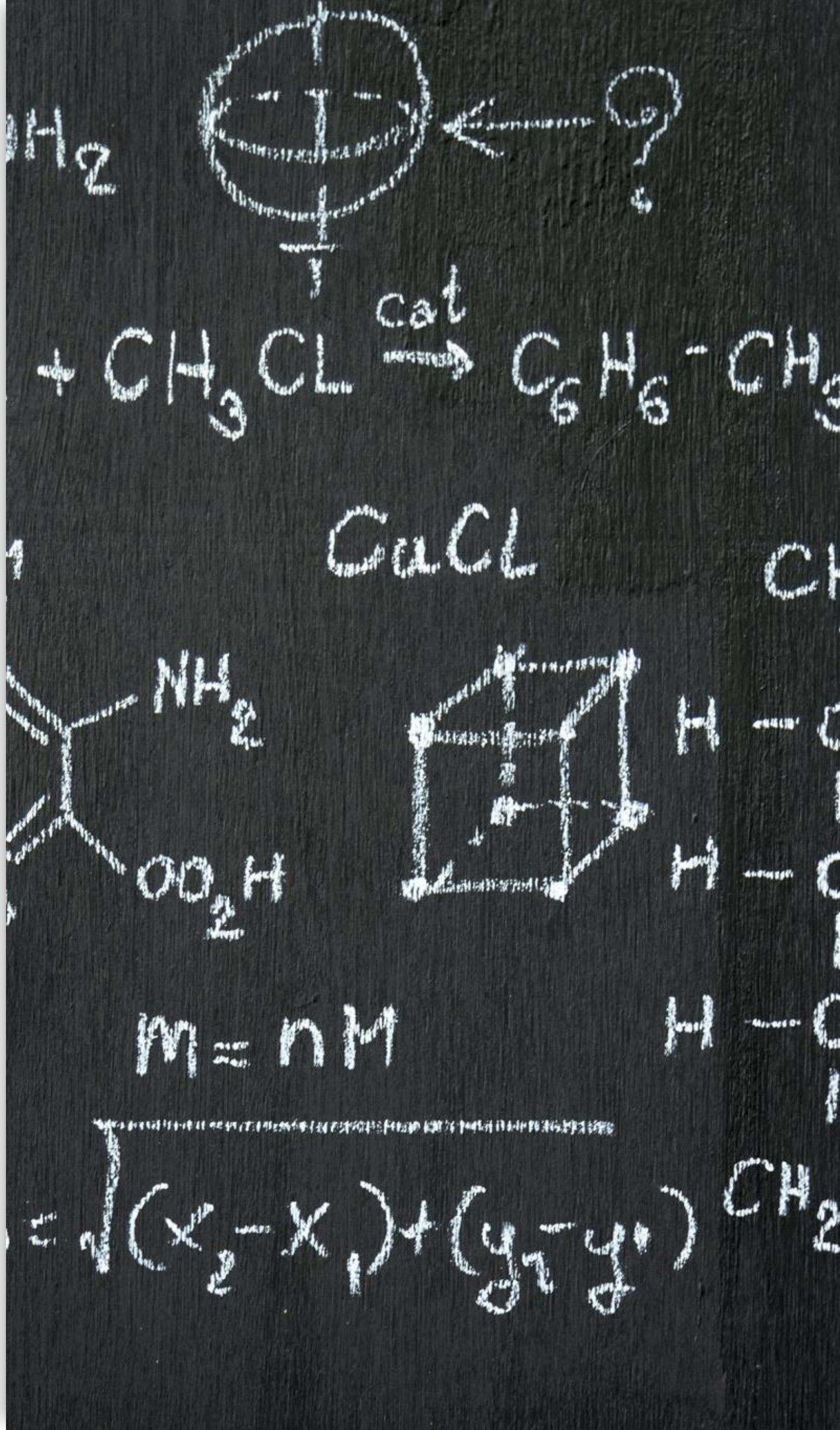
- Vehicle Onboard Controller (VOBC) – dual redundant
- Odometry Sensors – tachometer, IMU, Doppler radar
- Radio Transceiver – wireless link to wayside DCS
- • Human-Machine Interface (HMI) – for operator supervision
- • Safety-critical ATP/ATO logic onboard

Localization Accuracy and Spacing Margins

- Odometry drift corrected by transponders (beacons)
- Beacons placed ~300–400 m apart for ground truth reset
- Error between beacons may accumulate up to ±2 m
- Safety margin (SBD) includes worst-case error + brake distance
- Final spacing = SBD + localization margin + system tolerance

Localization Accuracy and Spacing Margins

- Spacing = SBD + localization error + system delay
- Example:
- Safe Braking Distance (SBD) = 110 m
- Worst-case odometry drift = ±2 m
- Delay margin = 1.5 m
- Required spacing = 110 + 2 + 1.5 = **113.5



Wayside Zone Controller (ZC)

- Computes safe Movement Authority (MA) for every train, 1–10 Hz
- Interfaces with Computer Interlocking (CI) to verify switch & route status
- Exchanges status with ATS/OCC for headway and dwell-time control
- Dual-computer, hot-standby design (SIL-4) for fail-safe redundancy

Computer Interlocking (CI) – Saftey Gatekeeper

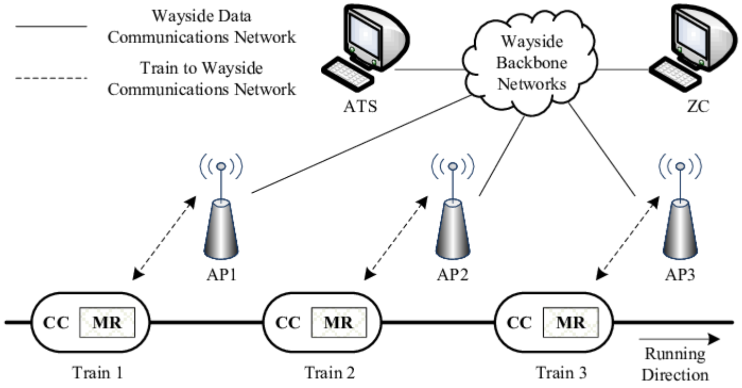
- Verifies switch & signal alignment before MA issued
- Locks conflicting routes, releases once train clears
- Independent SIL-4 logic (vital programmable controller)
- ZC requests → CI checks & grants “route proven” status

Thales Route control

- Redundant CPU cards (Upper shelves). Dual hot-standby logic; one falls -> the other takes over.
- Vital I/O modules (middle). Field contacts for point machines, signals, track circuits
- Relay / interface blocks (lower) Fail-safe output: de-energize-to-safe for points & signals
- Trackside cabinet + signal mast: Shows the CI located near the turnout it protects.

Data Communication System (DCS)

- Dual-band CBTC Wi-Fi (5 GHz + 2.4 GHz fallback) or LTE/5 G option
- Overlapping trackside APs – seamless hand-off < 50 ms (vital traffic)
- Redundant fiber ring backbone – self-heals in < 50 ms
- QoS: vital packets < 100 ms round-trip; non-vital best-effort
- MIMO / cooperative relaying boosts tunnel reliability

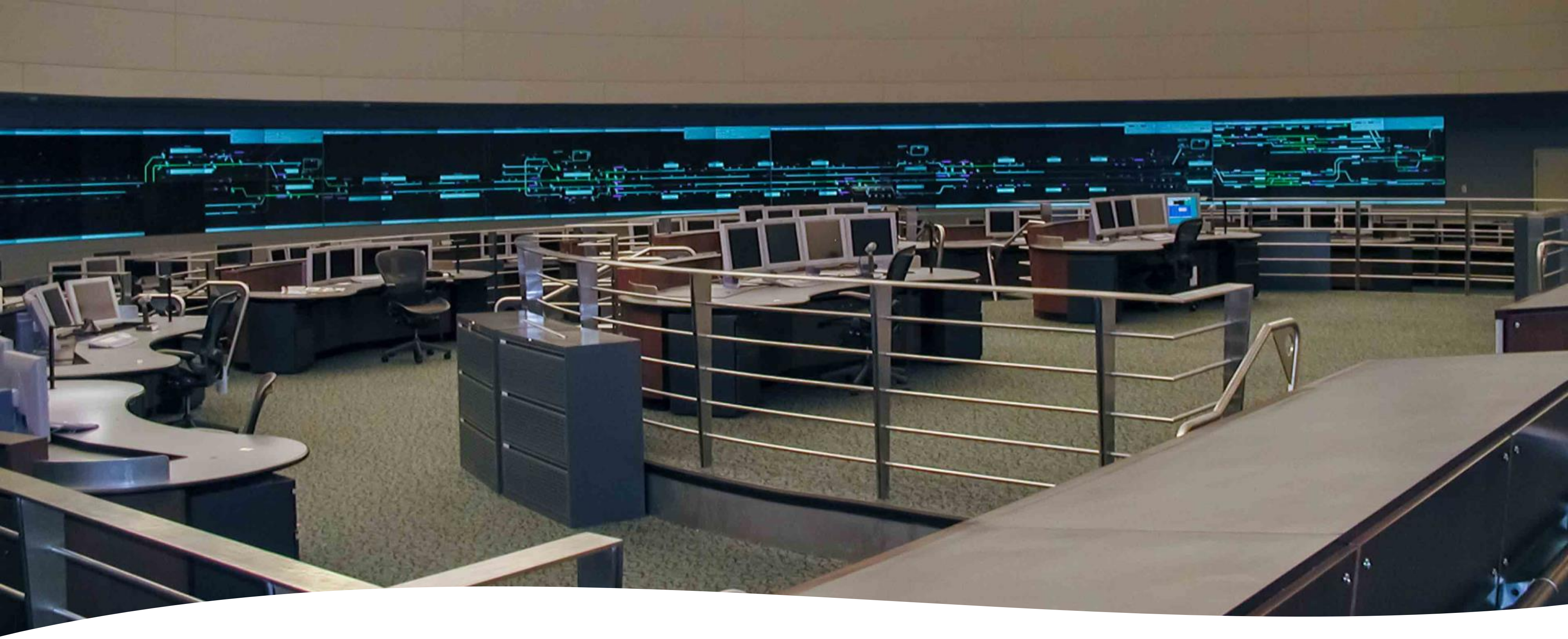


Operational Control Center (ATS)

- Real-time train map with predicted arrivals
- Regulates headways by sending speed/dwell commands
- Manages incident response & degraded-mode scenarios
- Interfaces to passenger information & CCTV systems
- Generates performance reports for service planning

ATS: Schedule Regulation Tools

- Live headway tracker flags gaps > ±10 s
- ATO speed offset (± 3 km/h) smooths the gap
- Dynamic dwell extension / hold at next station
- “Skip-and-fill” option during heavy disruption
- Results: 20 % reduction in bunching delays (NYC L-line data)



ATS: Incident Management in a CBTC world

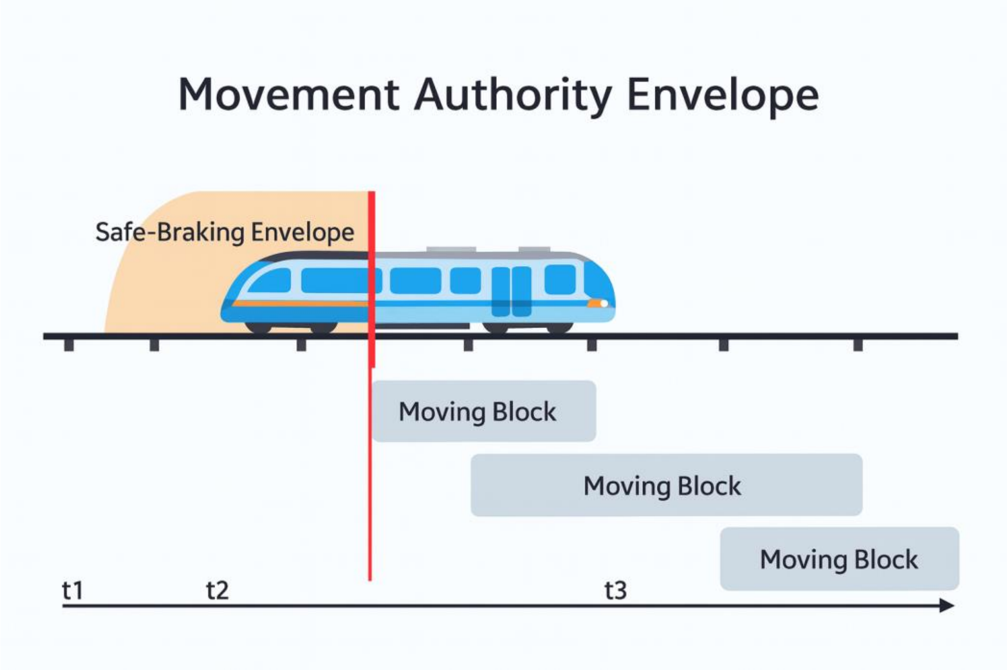
- Detects track-circuit failure → flags affected block in <5 s
- Automatically re-routes trains via crossover 17 / track 2
- Issues stop-and-proceed order to nearest train (safe speed 15 km/h)
- Short-turns trailing trains to prevent bunching at terminals
- Pushes realtime alerts to PIDS, staff tablets & maintenance crew

Automatic Train Protection (ATP) How the algorithm works.

- Computes safe-braking curve: $v^2 = v_0^2 - 2a(x - x_0)$
- Adds safety margin: MA = SBD + loc error + delay buffer
- Monitors distance-to-go each 100 ms ($\leq \pm 0.3$ m resolution)
- Cuts traction & applies service brake when curve touched
- Triggers emergency brake if MA is exceeded (fail-safe)

ATP: Movement Authority Logic

- MA = position of leading train – safe-braking envelope
- ATP updates curve 5–10 Hz; envelope “slides” with leader
- Following train sees shrinking distance-to-go in real time
- Loss of comms ⇒ MA frozen to restrictive value (fail-safe)



ATP: Overspeed Protection “Adaptive cruise control” for Trains.

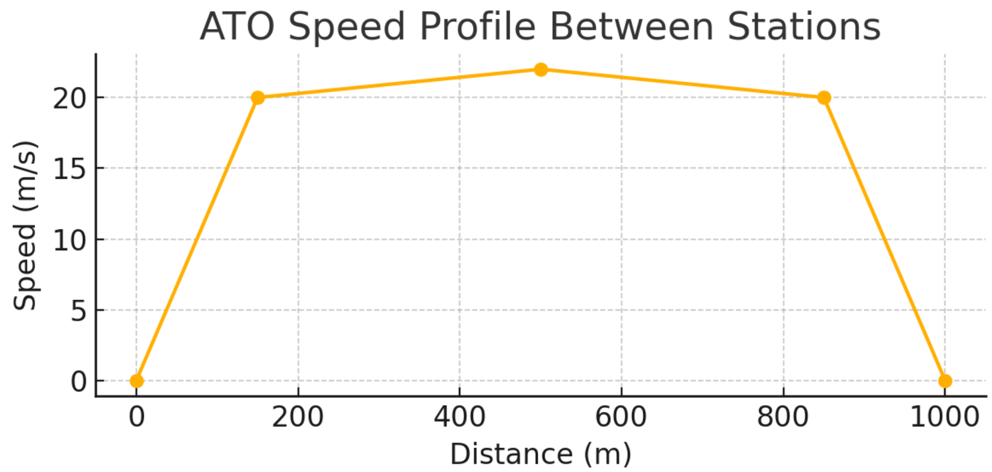
- Continuously compares actual speed to permitted curve
- 3-step response: audio-visual alert → service brake → emergency brake
- Curve adapts to gradient, mass, adhesion & MA length
- Conceptually like car ACC: maintains safe gap & enforces max speed

Automatic Train Operation (ATO) Precision Driving Benefits

- Executes target speed profile with ±0.1 m/s accuracy
- Uses coast phases & regen braking → 5-10 % energy savings
- Consistent station stops within ±30 cm of mark
- Reduces dwell-time variance → smoother headways
- Minimizes wear on brakes & wheels

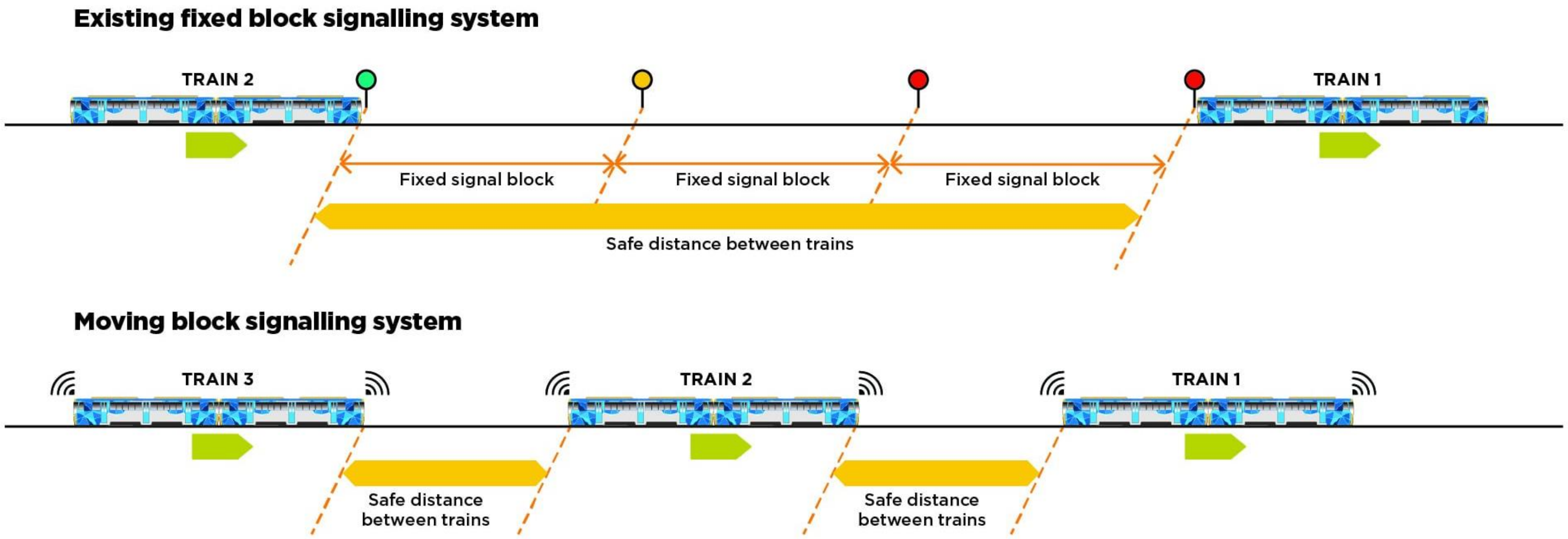
ATO: Comfort and Efficiency

- Smooth accel ≤ 1.3 m/s^2, decel ≤ 1.0 m/s^2
- Cruise-coast-brake profile saves 5-10 % energy
- Precision stop within ±30 cm enables PSDs
- Consistent ride → lower motion-sickness reports



ATO: Dynamic Dwell & Door Coordination

- Auto-aligns car doors with PSDs (±30 cm)
- Real-time passenger count adjusts dwell ±5 s
- ATS can hold or release doors to smooth headways
- Door status + crowd level reported instantly to OCC



Moving Block vs Fixed Block. Why CBTC Packs more trains.

- Fixed block = track divided into rigid 300-800 m sections
- Only one train per block → long empty gaps at low speed
- Moving block = “safety envelope” slides with each train
- Separation limited only by safe-braking curve, not block length
- Up to 30 % capacity gain on the same infrastructure

Moving vs Fixed Block Visualization

Figure 1: Diagram of a Conventional Fixed Block Signal System

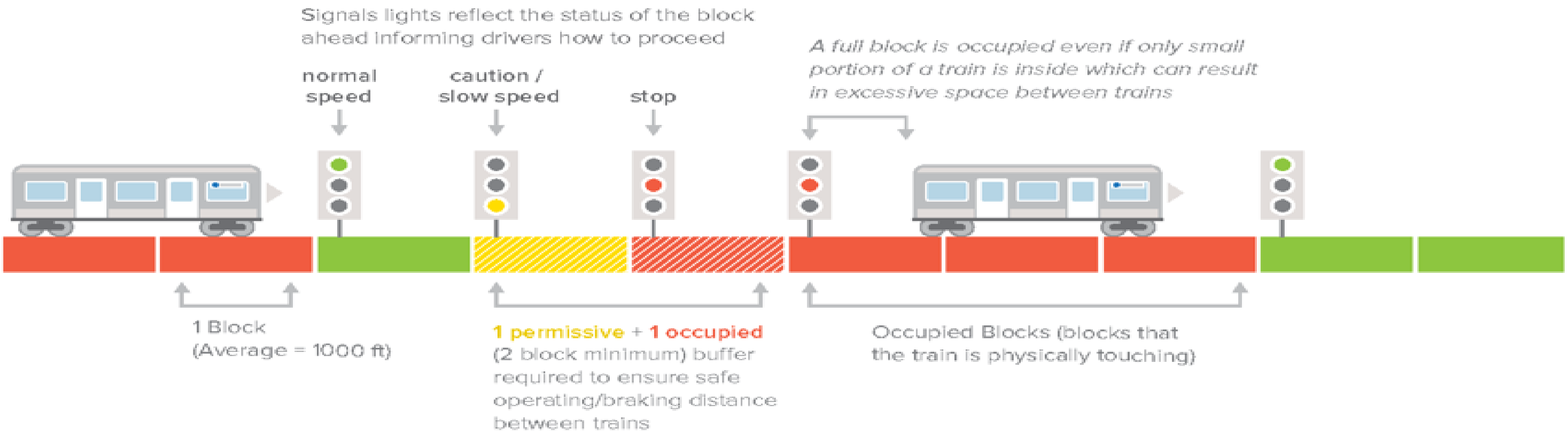
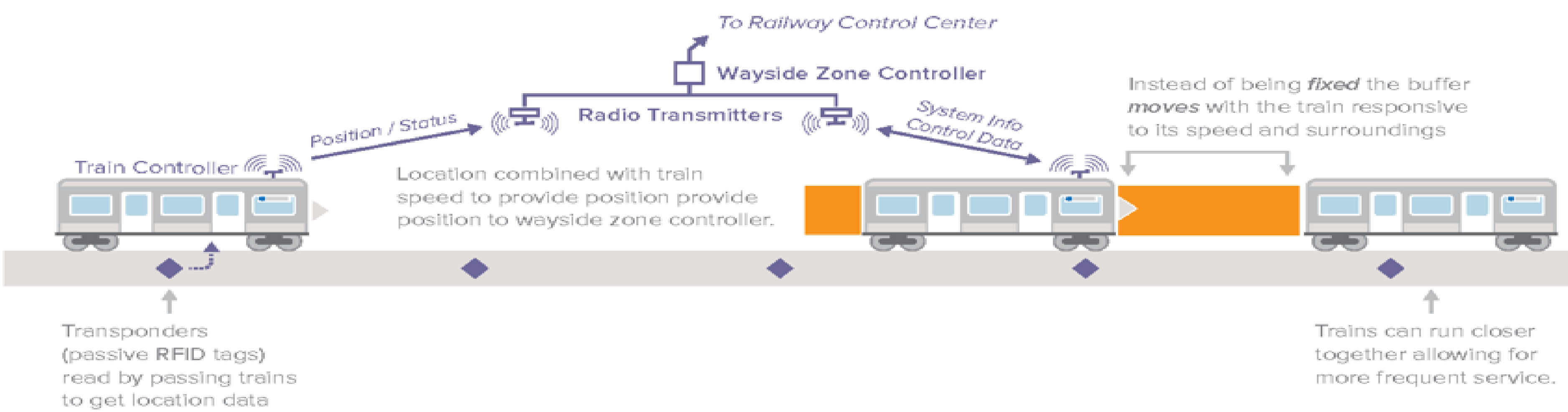
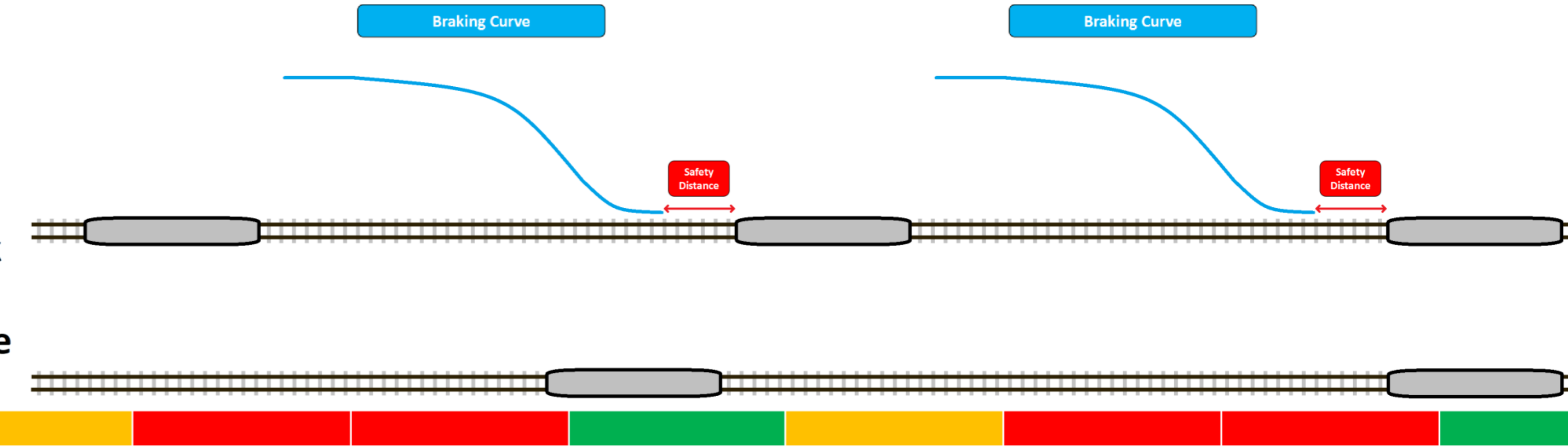


Figure 3: Diagram of a Moving Block (CBTC) Signal System



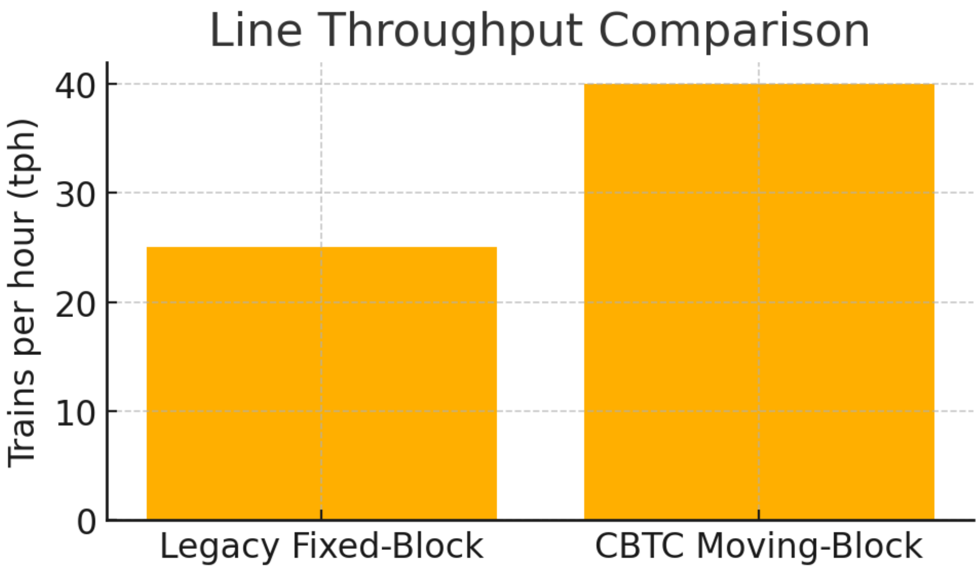


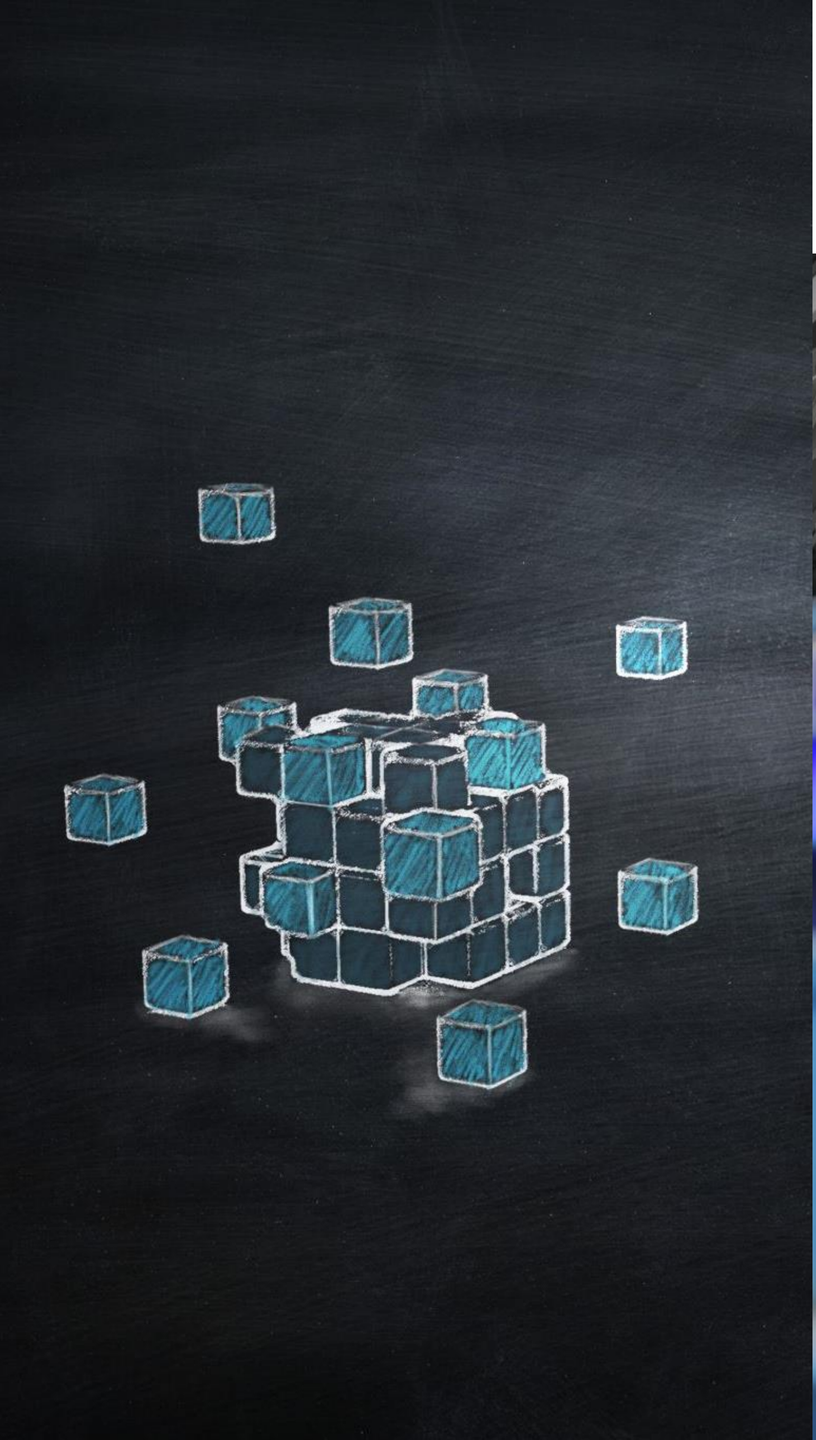
Safe Braking Distance Calculation

- Core physics: $d = v^2 / (2\, a_{serv}) + \text{margin}$
- Margin = odometry drift + comms delay + 5 % adhesion loss
- Gradient modifier: add / subtract $g \sin \theta$ term
- “Overlap” (5–10 m) appended for worst-case brake failure

Capacity Impact Example

- Legacy fixed-block (600 m) → 25 trains / h
- CBTC moving-block (120 m SBD) → 40 trains / h
- +60 % throughput on same two-track corridor





Part 4. Deployment and Intergration

Greenfield vs Brownfield CBTC Projects

Greenfield – Built from scratch; CBTC embedded day-1

- Typical timeline: 4-6 y design-build-commission
- Lower integration risk, single vendor stack
- Cap-ex ≈ US $30-40 M/km (incl. civil works)

Brownfield – Retrofit on an operating line

- Phased migration & dual signalling until cut-over
- Timeline 7-10 y (night/weekend outages)
- Higher O-pex during parallel run; cap-ex ≈ US $12-20 M/km

CBTC Overlay Strategy. Upgrade Without Shutting the Line

- New CBTC equipment installed while legacy signals stay live
- “Shadow running” 3-6 months – CBTC monitors but does not control
- Segment-by-segment weekend / overnight cut-over windows
- Legacy kept as fail-safe fallback until full line commissioned

Mixed Operations Challenges

- Legacy train = fixed-block mode; CBTC train = moving block
- Must apply least-common-denominator headway → capacity penalty
- Dual wayside beacons & overlay logic ⇒ ↑ maintenance & fault points
- Interlocking safety case doubles in complexity
- Agencies aim to limit mixed period to <12 months

“Big-Bang” Cut-Over – Paris Line 1 Case Study

- Entire fleet (MP 05) fitted; legacy drivers re-trained
- CBTC shadow-run 9 months with zero passenger impact
- Overnight switch-over 26 Jan 2013; legacy reached safe-state, CBTC became vital
- Achieved GoA 4 next morning – no fallback required

Testing & Commissioning- Staged Validation Path

- Factory Acceptance Test (FAT) – hardware & software bench-tested
- Site Acceptance Test (SAT) – power-up & static I/O checks on track
- Dynamic nighttime runs – no passengers, verify braking curves
- Shadow operation – CBTC calculates MA while legacy controls train
- Trial service – passengers aboard with safety staff riding, 30-90 days
- Safety Case approval by regulator → revenue GoA level granted

Training & Change Management. The "Soft" Success Factors.

- Up-skill drivers → attendants: simulator + GoA 2 in-cab drills
- 10-week maintainer programme: VOBC swap, ZC diagnostics, DCS RF survey
- Public-facing campaign: "Trains now run automatically—stand clear of doors"
- Emergency procedures rewritten for unattended operation (GoA 4)

NYC Subway CBTC Program. – Scale of the Retrofit

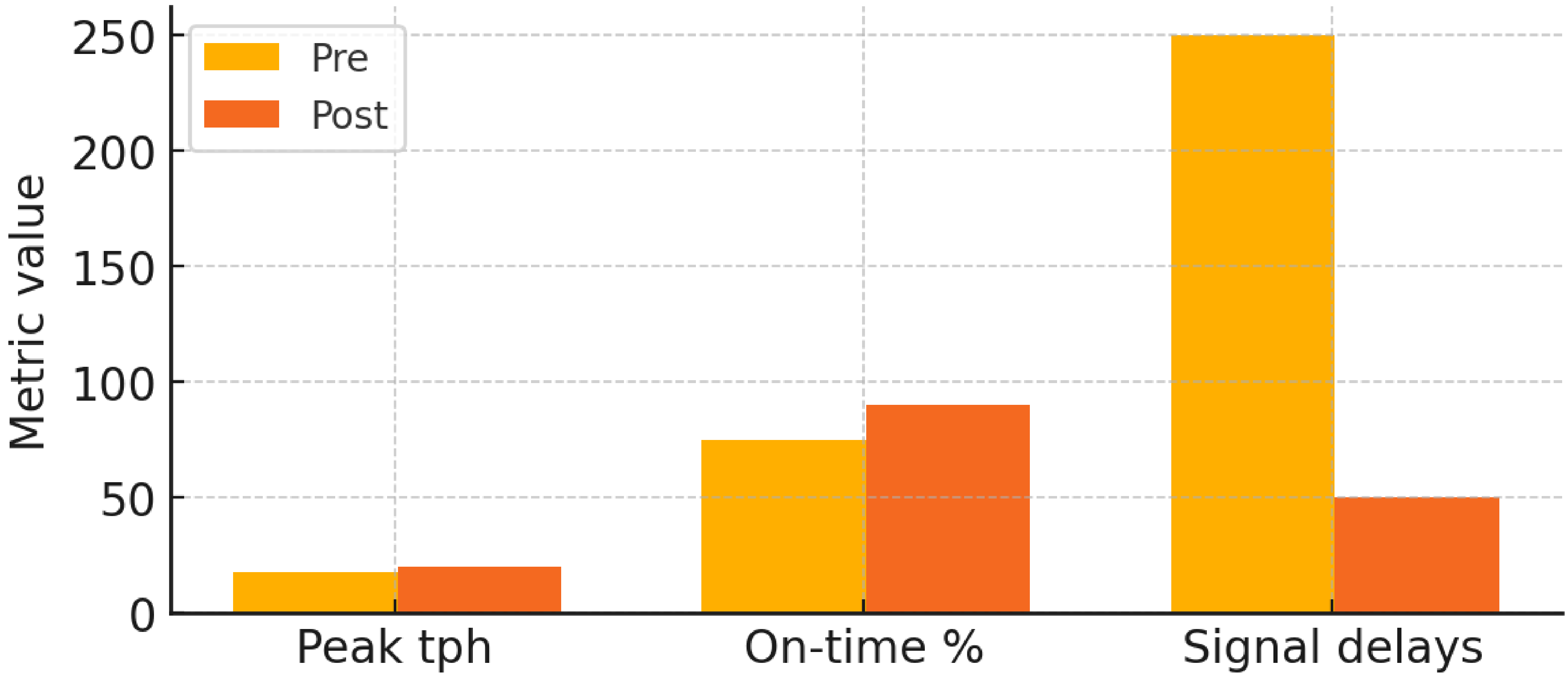
- World's oldest large metro (opened 1904); 1,000 km of track
- Completed: L (2009) & 7 (2018) – 40 tph and 32 tph peaks
- In progress: Queens Blvd, 8th Avenue Fulton Avenue, Astoria corridors
- $7 B in 2020-2024 & 2025-2029 capital plans; target full network by 2045
- Requires weekend outages + overlay; ~15 km commissioned per year

Canarsie Line (L) – Project Timeline & Milestones

- 1999 – Contract lent to Siemens for Trainguard MT CBTC
- 2000-2004 – Wayside install nights/weekends; VOBC retrofit on 212 cars
- Sept 2005 – First shadow-run segment (Rockaway Av–Broadway Jct)
- Sept 2006 – Full-line shadow complete, legacy coded-cab still vital
- 20 Sept 2009 – Weekend cut-over; revenue GoA 2 service begins Monday
- 2012 – Headway cut to 2 min 15 s (40 tph); on-time performance +12 %

Canarsie Line – CBTC Performance Gains

- Peak throughput +15 % (18 → 20 tph)
- On-time performance 75 % → 90 % (+15 pp)
- Signal-related delays cut 80 % (250 → 50 incidents / yr)



Flushing Line (7) – Lessons Learned from a tougher Retrofit.

- Different vendor (Thales) + dual-routed interlockings
- Integration & software-sign-off slipped 18 months (2016→2018)
- Added "countdown clocks" and real-time dwell-optimizer after go-live
- Reliability now rivals Canarsie: OTP 89 % vs 90 % on L

NYC CBTC – Interoperability Plan

Two supplier stacks today (Siemens + Thales) run on isolated corridors

2025 spec: “Train-Borne Controller Common Interface” for new fleets

RF band & message-format convergence planned for QBL / Culver overlap

Goal 2035: any CBTC-equipped consist can roam system-wide

Paris Metro. 25 years of GoA 4

1998

RATP twin-track strategy: build Line 14 as GoA 4 baseline

2012

Retrofit pilot: Line 1 big-bang conversion completed

Today

Lines 4 & 11 mid-upgrade; Line 18 automated from outset

2030

Network target: 20 % trains driverless by 2030

Paris Metro Line 14 – Greenfield Success

- Built GoA 4 from day 1; platform-screen doors integral
- Designed for 85–90 s headways ⇒ 42 tph theoretical
- MP14 eight-car sets add +30 % capacity vs MP05
- Success triggered north & south extensions (2020–2024)

Paris Line 1 – Brownfield Conversion

- 2010-2012: retrofit of 106-year-old line while carrying 725 k riders/day
- Entire MP05 fleet dual-fitted for CBTC + legacy SACEM during shadow run
- 01:00–05:00 weekend windows replaced 1500 balises & 5 interlockings
- Post-GoA 4: peak capacity 30 → 45 tph (+50 %), dwell-time variance −40 %

Paris Line 4 & Future Projects

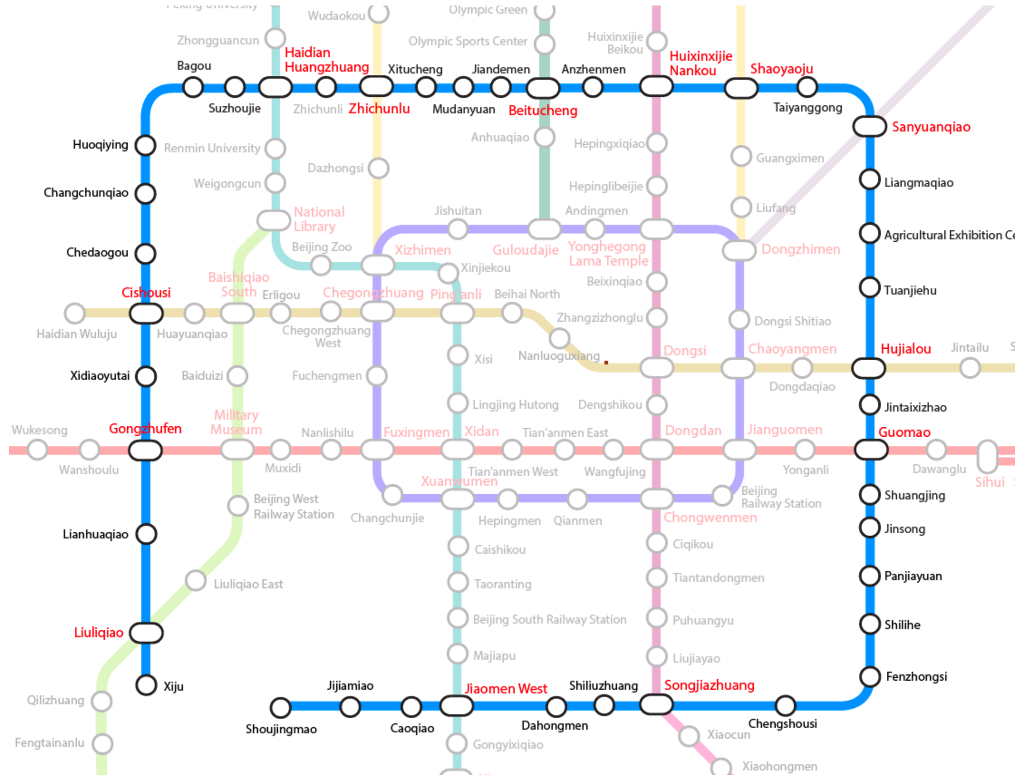
- Line 4 brownfield GoA 4 hand-over July 2022 (week-night cut-overs)
- Lines 6 & 11 mid-conversion; service maintained via dual-equipped MP89/MP14
- New Grand Paris Express Lines 15–18: all CBTC from day one
- RATP vision 2030: > 60 % of train-km in unattended operation

Beijing Metro Fast-Track CBTC Deployment

- First GoA 2 line (Airport Express) entered service 2008
- 2023 status: 17 of 27 lines now CBTC-equipped (Siemens, Thales, Bombardier)
- Network carries > 10 million trips / day; 840 km route length
- Typical brownfield corridor finished in < 36 months thanks to nightly block-hours

Beijing Line 10 – World's longest CBTC Loop

- 57 km ring with 45 stations; Siemens Trainguard MT (GoA 2)
- Peak headway 90 s; normal service 2 min even across junctions
- 2014 LTE roll-out caused 2.4 GHz radio drop-outs → migrated to 5.8 GHz & added directional antennas
- After spectrum fix: Radio failure rate ↓ 87 %, punctuality back above 96 %



China's CBTC Strategy

- Since 2015, every new Tier-1 metro line is specified at least GoA 2; most greenfields GoA 4
- "Multiple-vendor, local-license" policy keeps Siemens, Thales, Bombardier and CASCO competing
- Tech-transfer clauses require ≥ 70 % onboard & wayside hardware to be manufactured in-country
- Older fixed-block lines upgraded corridor-by-corridor to maintain 10-year capex cycles

Global CBTC Adoption Snapshot (2024)

- 85+ fully-automated (GoA ≥ 3) metro lines now in service worldwide
- > 1 500 route-km of CBTC commissioned since 2010; a further 900 km under construction
- CBTC is the **de-facto base-spec** for every green-field heavy-metro project approved after 2020
- Largest brown-field upgrades: New York (425 cars retro-fitted), Paris (Line 1 & 4), Beijing Line 1

Part 5 Design Considerations + Future Trends

Fail-Safe Design Philosophy

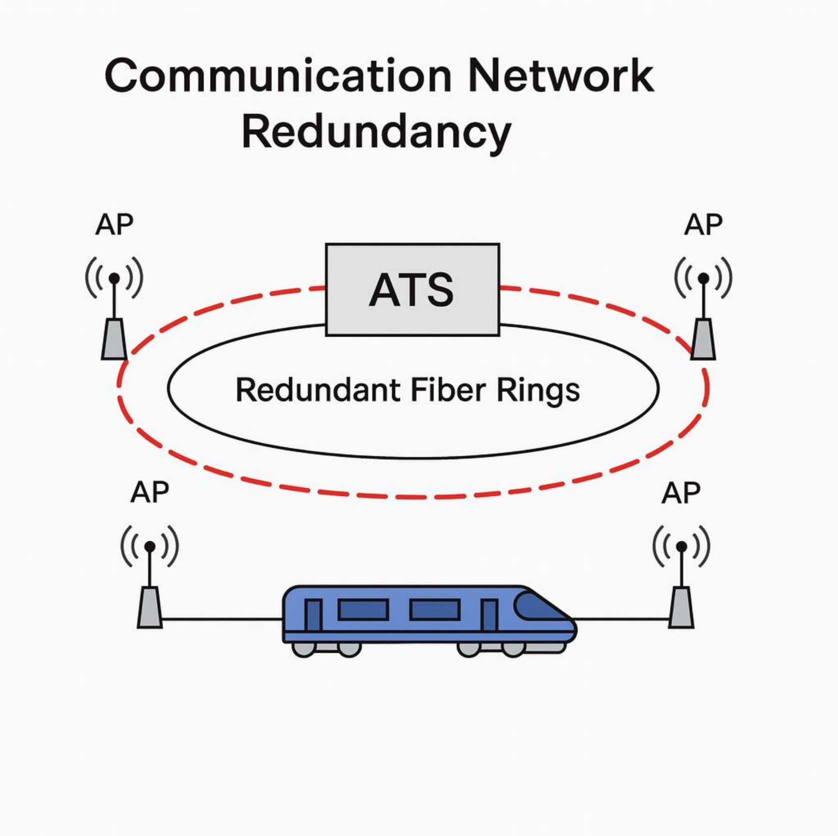
Failure mode	Likely cause	Detection / diagnostic	Automatic safe reaction	Dangerous failure rate (λ^d)
CPU-A clock stops	Component ageing, thermal stress	Hardware watchdog not stroked within 100 ms	Brake-apply relay de-energised, VOBC drops to "restricted"	1.2×10^{-10} h^{-1}
Channel A ⇔ B telegram CRC mismatch	Transient EMI on back-plane bus	16-bit CRC comparison every 50 ms	Both CPUs invalidate movement-authority; train coasts to stop	3.4×10^{-10} h^{-1}
Brake-release relay welded closed	Contact welding after high inrush	Dual-relay 1-out-of-2 vote disagrees	Second relay opens; pneumatic brakes remain applied	8.0×10^{-11} h^{-1}

CBTC Cybersecurity Standards

- IEC 62443 “zones & conduits” model segments wayside, radio and VOBC networks
- CENELEC TS 50701 adapts 62443 for rail-specific threats and ties security levels (SL) to SIL targets
- Layered defence-in-depth: trackside firewalls → DMZ → whitelisted VOBC endpoints
- Continuous risk assessment; patches validated like safety-critical software changes

Communication Network Redundancy

- Dual fiber rings (< 50 ms self-healing) keep the OCC⇄wayside backbone alive after any single break.
- Trackside Wi-Fi/LTE radios in A/B pairs give every train two simultaneous RF paths.
- Automatic “make-before-break” switchover is transparent to onboard VOBCs



Localization Error & Margin

600 m run — worst-case 400 m between beacons

Odometry drift ±0.1 % ⇒ ±0.6 m (0.001 × 600 m)

Fail-safe overlap adds 8 m buffer

Total clearance = 0.6 m + 8 m ≈ 8.6 m (≈ 9 m envelope)

Power & Environmental Hardening

- 30-min runtime UPS in every wayside cabinet (ride-through brown-outs)
- Components qualified –25 °C … +55 °C to EN 50155 T3 / IEC 60571
- Enclosures sealed ≥ IP54 (EU) / NEMA 4 (NA); conformal-coated PCBs
- Fans & heaters with thermostat-controlled duty cycle < 30 % (energy)

Zone Controller Redundancy

Dual redundant Zone-Controller pair (hot-standby 2oo2)

Physically separate, fire-rated racks

Automatic switchover < 50 ms on heartbeat loss

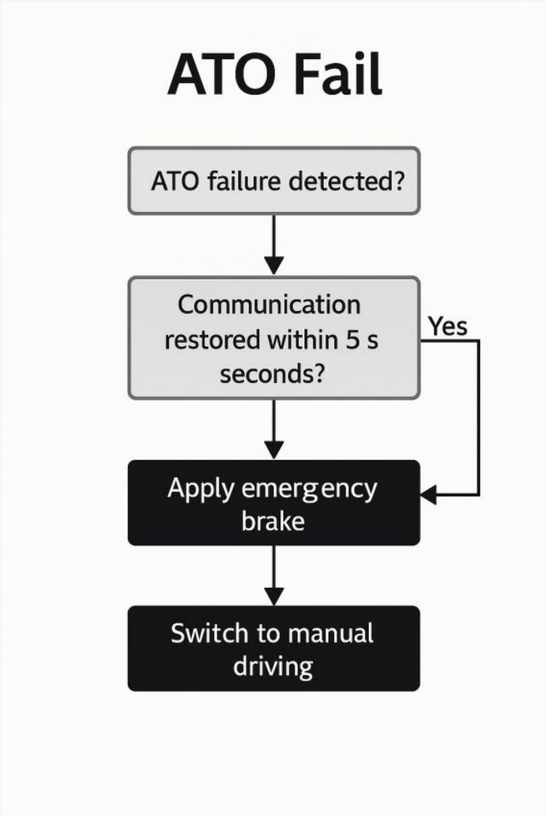
On-line self-test every 2 s; MTTR design target ≤ 4 h

Vital Onboard Controller Redundancy

- Dual VOBCs run 2-out-of-2 vital voting
- Separate tachometers, IMUs & A/B antennas
- Failed channel auto-isolates—train keeps authority
- Vital relay drop-out forces safe brake if disagreement >2 km/h

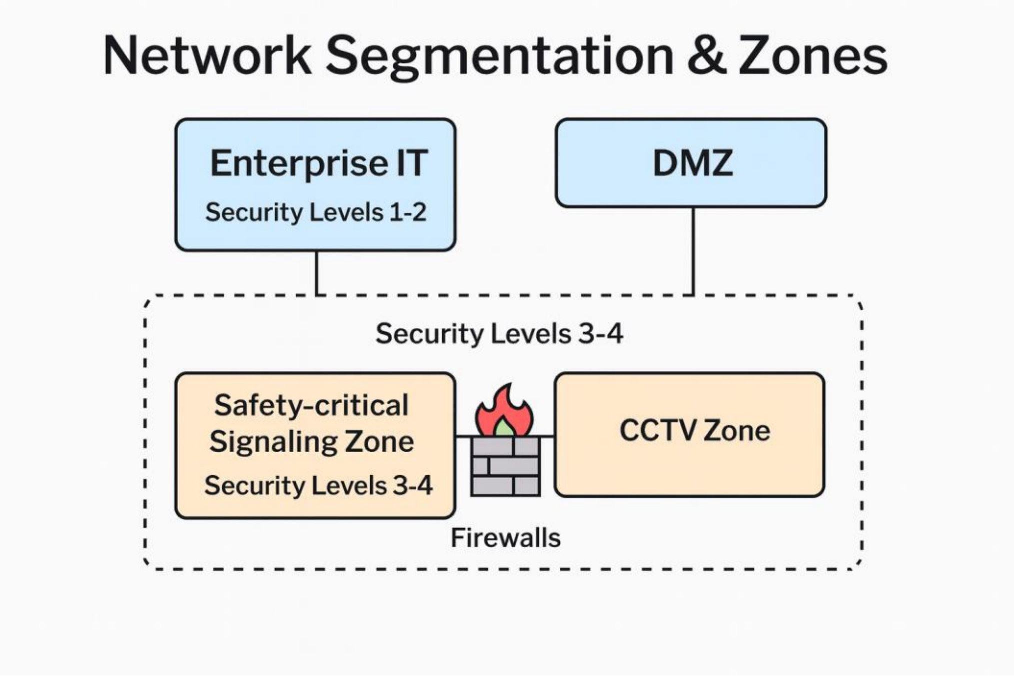
Graceful Degradation Mode

- ATO channel drops → driver takes over (ATP still vital)
- Radio link lost > 5 s → emergency brake, restrictive mode
- Zone-controller failure → adjacent ZC grants 25 km/h authority
- Manual fallback keeps ≤ 40 % service until fault cleared



Network Segmentation & Zones

- - Enterprise IT zone strictly separated from railway OT
- - Grey DMZ buffers traffic & applies deep-packet inspection
- - Blue safety-critical signalling zone accepts *only* vital protocols
- - CCTV / ancillary systems isolated in gold zone
- - Firewalls implement IEC 62443 “conduit” least-privilege rules



Access Control & Authentication

Unique operator & maintainer accounts — MFA required for every remote log-in

Least-privilege, role-based permissions enforced on ATS / zone controller

Secure-boot chain + signed firmware prevent rogue code on vital CPUs

Monitoring & Incident Response

- OT-aware IDS (e.g., Cisco Cyber Vision) baselines CBTC traffic and flags anomalies in <10 s
- Central SIEM (Splunk / QRadar) correlates logs from ZC, ATS & firewalls for Tier-1 SOC triage
- Pre-built IR playbook: isolate radio AP VLAN, switch to backup channel, verify ATP heartbeat
- 24 × 7 SOC drills quarterly tabletops using real events (e.g., MTA 2021 & SFMTA 2022 ransomware)
- NIST 800-82 and IEC 62443-3-3 both stress *continuous* monitoring.

AI/ML in Predictive Maintenance

Rail IoT gateway streams axle-box vibration & CBTC radio KPIs to cloud every 60 s

Gradient-boost ML model flags anomaly score > 0.85 ⇒ "AP-fail-in-7 days" ticket

Dashboard (Grafana-style) shows heat-map of AP MTBF & trend line of bearing RMS g

Pilot on 40 trains cut radio outages 40 % & saved ≈ 2 h mean-time-to-repair per event

AI/ML for Dynamic Scheduling

Cloud-based optimizer re-forecasts headway every 30 s using live APC counts & Bluetooth-probe demand heat-map

Algorithm elongates dwell ± 10 s at overloaded stations and simultaneously issues ±7 km/h cruise tweaks to trailing trains

Pilot on Hong Kong MTR Tuen Ma Line (Dec-22 → Mar-23) cut worst-case platform crowding by 18 % and saved 5 % traction energy

5G & FRMCS for CBTC

- **Release-18 FRMCS** on 700 MHz/1900 MHz gives < 10 ms URLLC + 99.999 % availability for CBTC traffic
- **Coverage economics** – 5 G small-cells @ ≈ 250 m spacing (-95 dBm) vs Wi-Fi 6 APs @ 70 m; 5 G needs ≈ 3 × fewer trackside sites
- **TCO snapshot (10 km guideway)** : Wi-Fi CAPEX ≈ US$ 1.9 M + OPEX $ 420 k/y; 5 G neutral-host lease ≈ $ 2.4 M upfront but OPEX drops to $ 240 k/y (-43 %)
- **Use-cases unlocked** : 4 K CCTV backhaul & edge AI, AR maintenance, broadband passenger Wi-Fi without a second network

Interoperability Initiatives

- **IEEE P1474.5 ‘Open CBTC Messages’** draft enables vendor-agnostic zone-to-train telegrams
- **UITP / ITxPT “Open CBTC Forum”** targets multi-vendor fleets before **2030** (first reference pilots in Copenhagen & Singapore)
- **EU-Shift2Rail X2Rail-1 / EULYNX** exports ETCS-style subsystem interfaces to metro CBTC to ease brownfield upgrades

Wrap-Up

Part 1 -Intro and proposal: Fixed block singaling limitations and CBTC = moving-block radio control; frees capacity & enables GoA.

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Part 2 – Fundamentals and History of CBTC and by SELTRAC ’80s → Paris 14 (1998) → NYC L (2009)

→

Part 3 – Architecture and Operation: Various pillars: VOBC, ZC, ATS, Data Comm, ETC.

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Part 4-Development and integration: Ex: Greenfield (built new) vs Brownfield (retrofit under traffic)

→

Part 5 – Design Considerations and Integration: Safety + Cyber + Redundancy; 5G next wave of CBTC.

Thank You.

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Track Circuit vs CBTC Diagram

- Visual: Schematic comparing track circuit block detection
- CBTC beacon + radio for continuous detection
- Highlights legacy vs modern hardware footprint

Beacon & Odometry Example

- Visual: Train passes beacon every 300 m
- Odometry measures intermediate distance
- Error reset at each beacon read

Network Topology Example

- Visual: Dual ring fiber with access switches
- Redundant radio APs every 250 m
- Core routers at OCC

Case Study – London Underground

- Jubilee Line upgrade to CBTC (2011)
- Headway improved from 24 to 30 tph
- Project lessons: staff training & staged testing

Capacity Math Worked Example

- Given $v=60$ km/h, $a=1$ m/s^2, EB dist = 50 m
- Add 5 m error, 10 m overlap → 65 m gap
- Compare with 300 m fixed block gap

System Availability Metrics

- Target: >99.99% service uptime
- MTBF & MTTR for critical components
- Redundancy strategy meets KPI

Safety Integrity Level (SIL) Table

- SIL 1–4 probabilities of dangerous failure/hr
- CBTC vital functions => SIL 4
- Design & test rigor grows with SIL