Volume 1

CHAPTER 4

# Onboard Equipment

*Communications-Based Train Control*
A Comprehensive Guide for US Transit Professionals
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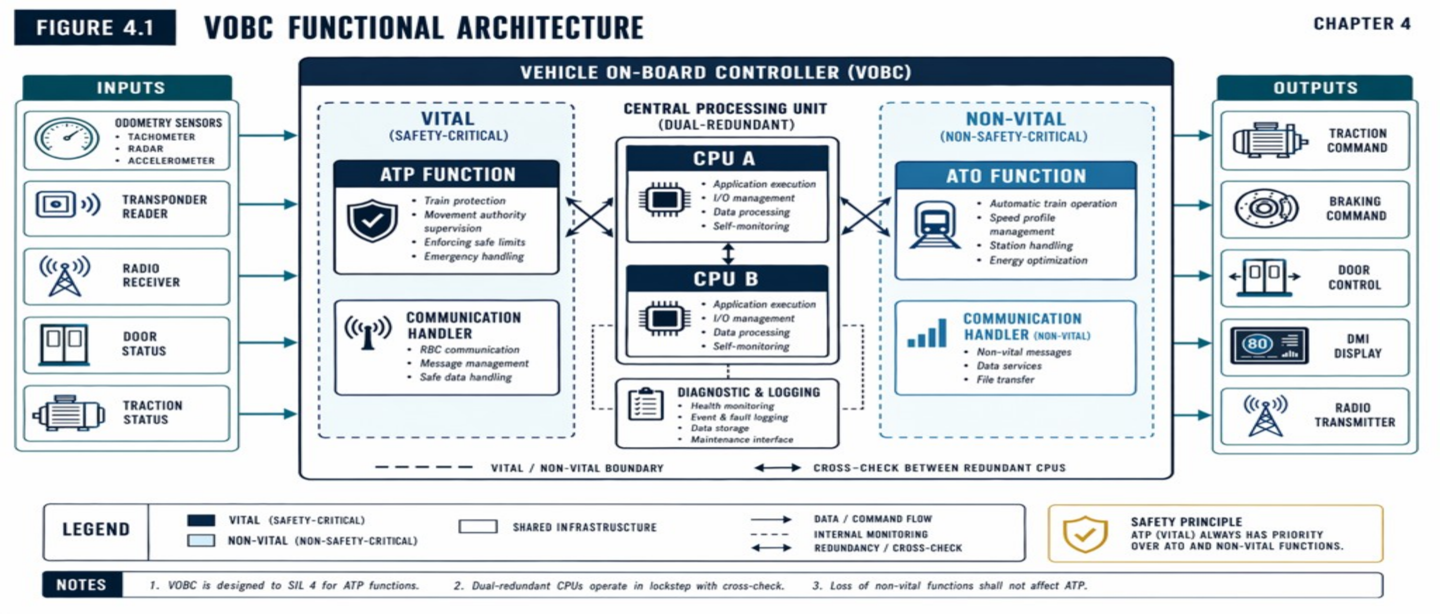
# Chapter Overview

- Vehicle On-Board Controller (VOBC): the safety-critical computing platform — hardware, software, redundancy
- Train Localization: odometry, sensor fusion, transponder correction, and map matching
- Speed Supervision and Braking Curves: ATP enforcement of safe speed profiles
- Driver Machine Interface (DMI): the human-facing display for situational awareness
- Automatic Train Operation (ATO): precision stopping, energy optimization, and schedule adherence

# 4.1

# Vehicle On-Board Controller (VOBC)

# VOBC Functional Architecture



ATP (VITAL) ALWAYS HAS PRIORITY OVER ATO AND NON-VITAL FUNCTIONS.

1. VOBC is designed to SIL 4 for ATP functions.
2. Dual-redundant CPUs operate in lockstep with cross-check.
3. Loss of non-vital functions shall not affect ATP.

*Figure 4.1 — VOBC functional architecture: safety processors, I/O modules, radio interface, and power supply.*

# VOBC: The Safety-Critical Brain

- Real-time, deterministic computing platform executing ATP (SIL 4) and ATO functions on every train
- Continuously: receives/validates MAs, monitors speed, manages propulsion/braking, detects faults
- A VOBC failure can cause: loss of ATO (manual operation) or safety-critical events (unintended acceleration)
- Consequence: design mandates redundancy, diversity, and continuous self-checking
- Cost: $200K–$400K per train; design life: 20–25 years with mid-life refresh at year 10–12

# Redundancy: 2oo2 vs. 2oo3 Architecture

- 2oo2 (Two-out-of-Two):
- Two independent processors (Channel A & B)
- Comparator validates matching outputs
- Disagreement → emergency brake + fault log
- Fault detection: high coverage
- Fault tolerance: none (single failure = shutdown)

- 2oo3 (Two-out-of-Three):
- Three independent processors with voting logic
- Majority result selected; outlier ignored
- Tolerates single processor failure
- Preferred for high-availability metro systems
- Higher cost and complexity vs. 2oo2

# VOBC Software: Layered Safety Architecture

- ATP Layer (SIL 4): speed enforcement, emergency braking, safe state machine, fault detection
- ATO Layer (SIL 1–2): speed profiles, station stopping, energy optimization — fault = manual mode, not safety loss
- Application Layer (non-safety): diagnostics, event logging, TMS integration, driver interface updates
- Cyclic execution: fixed 50–100ms cycle (input → compute → vote → output) with watchdog timers
- Diverse software: two independent teams, different languages (e.g., Ada + C++), cross-checked outputs

# VOBC by the Numbers

**50ms**

**cycle**

Typical VOBC computation cycle time

**SIL 4**

Safety integrity for ATP processors

**$300K**

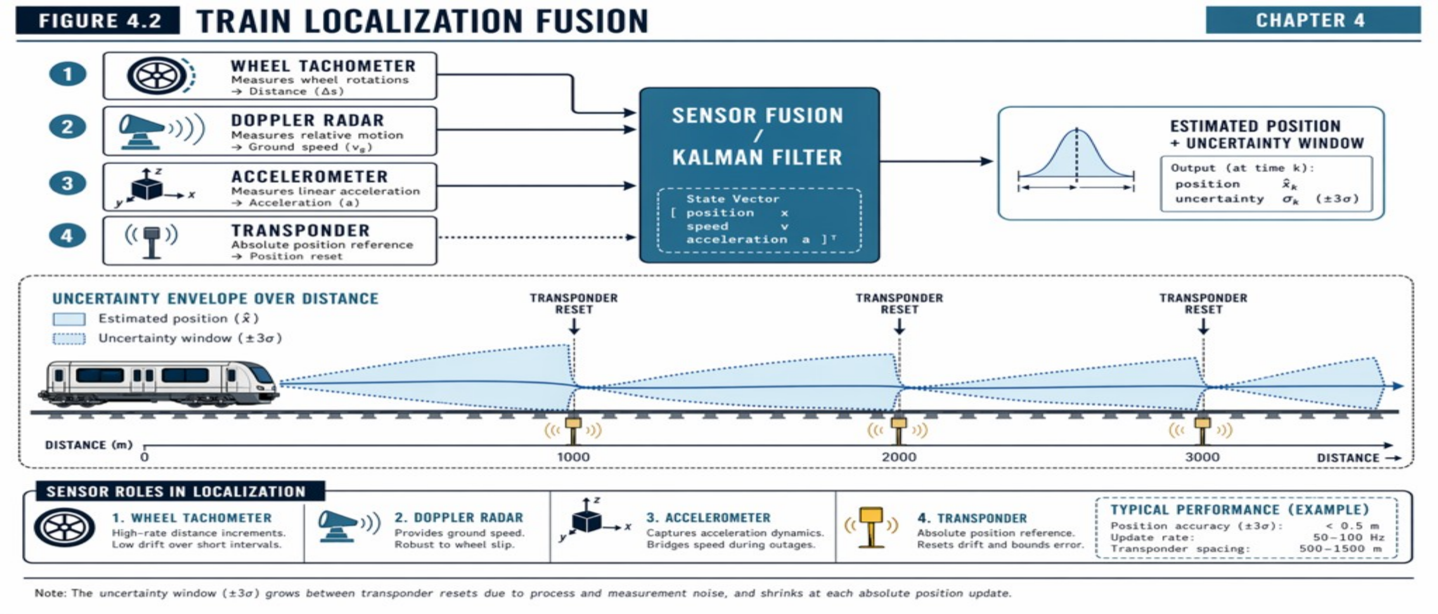
**per train**

Typical VOBC cost (NYC L Line, 2019)

# 4.2

# Train Localization Technologies

# Train Localization Architecture



**1. WHEEL TACHOMETER**
High-rate distance increments.
Low drift over short intervals.

**2. DOPPLER RADAR**
Provides ground speed.
Robust to wheel slip.

**3. ACCELEROMETER**
Captures acceleration dynamics.
Bridges speed during outages.

**4. TRANSPONDER**
Absolute position reference.
Resets drift and bounds error.

**TYPICAL PERFORMANCE (EXAMPLE)**

| | |
|---|---|
| Position accuracy (±3σ): | < 0.5 m |
| Update rate: | 50–100 Hz |
| Transponder spacing: | 500–1500 m |

Note: The *uncertainty window (±3σ) grows between transponder resets due to process and measurement noise, and shrinks at each absolute position update.*

*Figure 4.2 — Sensor fusion: tachometers + Doppler radar + IMU + transponder correction via Kalman filter.*

# Localization Sensors

- Wheel Tachometers ($200–$500):
- Counts wheel rotations → distance traveled
- Simple, proven, low cost
- Errors: wheel diameter wear, slip/slide
- 1mm diameter error → 300m drift over 100km

- Doppler Radar ($8K–$15K):
- Measures ground speed non-contact
- Slip-independent, no mechanical wear
- 100 Hz update rate, all-weather operation
- Becoming standard on new CBTC orders

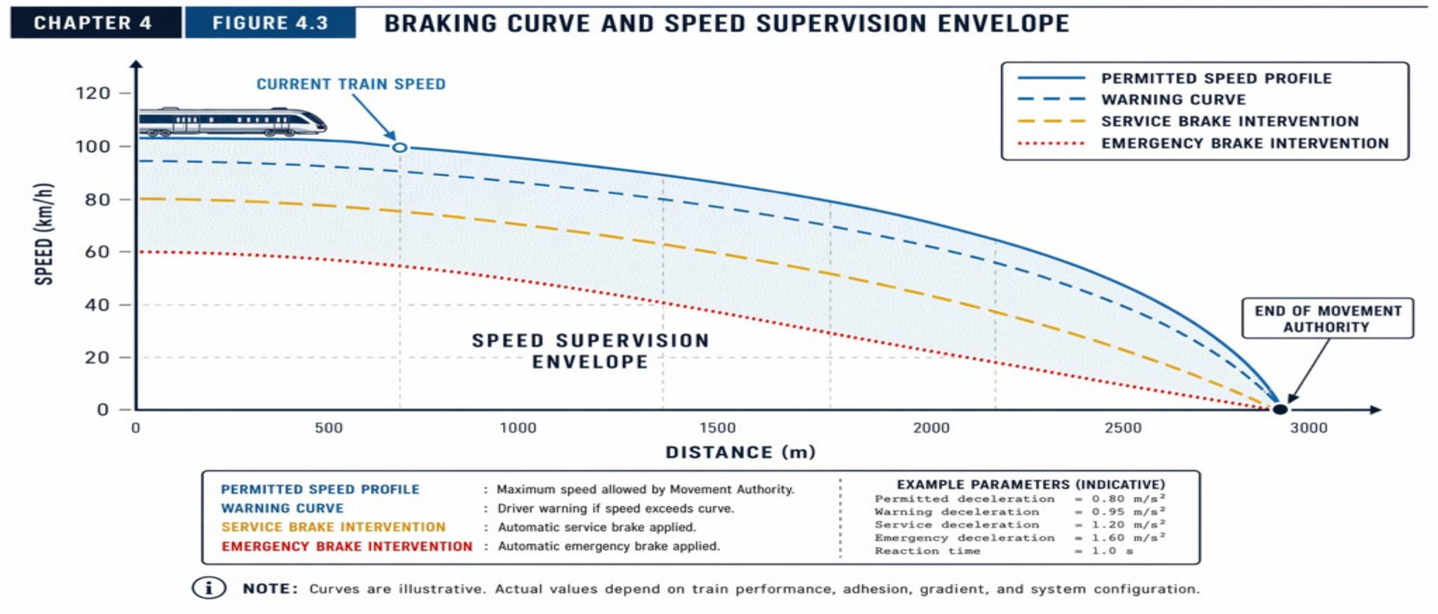
# Sensor Fusion and Transponder Correction

- Kalman filter: optimally blends tachometer + radar + IMU data; down-weights outlier sensors
- Achieves ±1–2m accuracy over 10–20km between transponder corrections
- Transponders (passive balises): absolute position references at 50–200m intervals; ±0.5m precision
- Cost: $200–$500 per passive transponder; 20+ year life with zero scheduled maintenance
- Track database + map matching: constrains position to known track geometry; resolves drift in tunnels

## 4.3

# Speed Supervision and Braking Curves

# ATP Braking Curve



**PERMITTED SPEED PROFILE** : Maximum speed allowed by Movement Authority.
**WARNING CURVE** : Driver warning if speed exceeds curve.
**SERVICE BRAKE INTERVENTION** : Automatic service brake applied.
**EMERGENCY BRAKE INTERVENTION** : Automatic emergency brake applied.

**EXAMPLE PARAMETERS (INDICATIVE)**

Permitted deceleration = $0.80\ m/s^2$
Warning deceleration = $0.95\ m/s^2$
Service deceleration = $1.20\ m/s^2$
Emergency deceleration = $1.60\ m/s^2$
Reaction time = 1.0 s

**NOTE:** Curves are illustrative. Actual values depend on train performance, adhesion, gradient, and system configuration.

*Figure 4.3 — ATP braking curve: speed-vs-distance envelope defining the maximum safe speed at each point.*

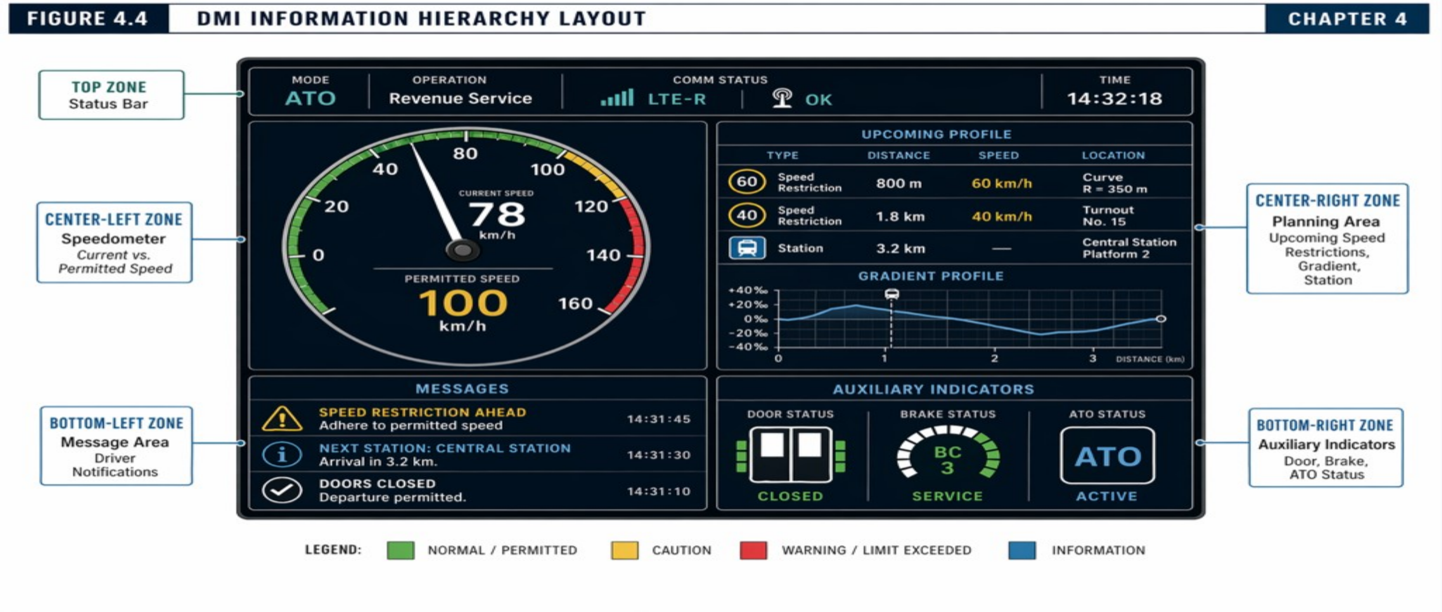
# Braking Curve Fundamentals

- ATP continuously computes the speed-vs-distance envelope based on MA endpoint, braking performance, and safety margin
- Three intervention levels: warning (alert driver), service brake (controlled deceleration), emergency brake (maximum rate)
- Inputs: current speed, train mass, track gradient, rail adhesion, MA endpoint distance
- Braking distance formula accounts for reaction time, brake build-up delay, and worst-case deceleration
- The curve is recalculated every VOBC cycle (50–100ms) as conditions change in real time

# 4.4

# Driver Machine Interface (DMI)

# DMI Display Layout



UPCOMING PROFILE

| TYPE | DISTANCE | SPEED | LOCATION |
|---|---|---|---|
| 60 Speed Restriction | 800 m | 60 km/h | Curve R = 350 m |
| 40 Speed Restriction | 1.8 km | 40 km/h | Turnout No. 15 |
| Station | 3.2 km | — | Central Station Platform 2 |

MESSAGES

| | | |
|---|---|---|
| ⚠ | SPEED RESTRICTION AHEAD<br>Adhere to permitted speed | 14:31:45 |
| ⓘ | NEXT STATION: CENTRAL STATION<br>Arrival in 3.2 km. | 14:31:30 |
| ✓ | DOORS CLOSED<br>Departure permitted. | 14:31:10 |

*Figure 4.4 — Typical DMI layout: speed gauge, MA distance, system status, alarms, and diagnostics.*

# DMI: The Driver's Window into CBTC

- 7–10" touchscreen displaying: current speed, target speed, MA distance, signal aspects, alarms
- Information hierarchy per IEEE 1474.2: speed and MA displayed prominently; faults cannot be overlooked
- Alarm management: audible/visual alerts for overspeed, brake faults, radio loss, VOBC channel mismatch
- Degraded mode support: allows driver to acknowledge faults and assume manual control
- NYC L Line example: 9" touchscreen integrated into cab console; critical for 3-minute headway operation

# 4.5

# Automatic Train Operation (ATO)

# ATO: Precision, Efficiency, Automation

- Speed regulation: optimal acceleration/deceleration profiles to meet timetable targets within ATP envelope
- Precision stopping: ±30cm accuracy at platforms — essential for PSD alignment and ADA compliance
- Energy optimization: coasting profiles reduce consumption by 10–20% across a busy line
- Control algorithms: PID (classical feedback), Fuzzy Logic (linguistic rules), MPC (optimization horizon)
- GoA dependency: absent at GoA 1, active with driver at GoA 2, mandatory and autonomous at GoA 3/4

# VOBC Vendor Landscape

| Vendor | Architecture | Key Deployments | Differentiator |
|---|---|---|---|
| Siemens Trainguard MT | 2oo3 voting | NYC L Line, Singapore | Seamless wayside integration |
| Thales/Hitachi SelTrac | 2oo2 comparison | WMATA, London Elizabeth | Open interfaces, multi-vendor |
| Alstom Urbalis | Modular, scalable | BART, Shanghai Metro | Metro to regional rail flexibility |

# Key Takeaways

1. The VOBC is a SIL 4, fault-tolerant computing platform on every train — redundant processors, diverse software, 50–100ms deterministic cycles with watchdog protection

1. Train localization combines odometry (tachometers + radar + IMU) with transponder correction and Kalman filtering to achieve ±1–2m accuracy required for moving-block operation

1. ATP braking curves define the safety envelope — recalculated every cycle, with three intervention levels (warning, service brake, emergency brake)

1. The DMI provides the driver's situational awareness window into CBTC, with strict information hierarchy and degraded-mode support per IEEE 1474.2

1. ATO delivers precision stopping (±30cm), energy savings (10–20%), and schedule adherence — mandatory at GoA 3/4, the enabler of driverless operation

# End of Chapter 4

Next: **Chapter 5: Wayside Equipment**

Questions & Discussion