📄 P7.2 — Rule-Based Detection

1. Introduction

Rule-based detection is the first operational layer of predictive maintenance. It transforms raw decoded signals into interpretable conditions, flags, and alerts. Unlike statistical models, rule-based logic:

- reacts immediately
- is deterministic
- is explainable
- is low compute
- is OTA-tunable (thresholds)
- is certifiable for safety-critical domains

In this system, rule-based detection targets early harness degradation using voltage asymmetry between nodes.

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2. Context: Harness as a Sensor

The three nodes (ECU_A, ECU_B, DCDC) create an electrical observing triangle:

```
ECU_A ---- HARNESS_A ---- DCDC ---- HARNESS_B ---- ECU_B
```

Each harness segment introduces resistance (R_A, R_B). As resistance increases due to corrosion, fretting, or mechanical stress, node voltages diverge:

> Resistance ↑ → Voltage drop ↑ → CAN-reported supply difference ↑

By measuring **relative voltage**, the harness becomes its own sensor with zero added hardware.

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3. Observables and Inference Basis

The system currently monitors:

Signal	Source	Units	Update
`ECUA_Supply_Voltage`	ECU_A	V	100ms
`ECUB_Supply_Voltage`	ECU_B	V	100ms
`DCDC_Output_Voltage`	DCDC	V	100ms

Derived deltas:

```
ΔA = DCDC - ECU_A
ΔB = DCDC - ECU_B
ΔAB = |ECU_A - ECU_B|
```

These deltas map to physical degradation:

- ΔA → HARNESS_A branch condition
- ΔB → HARNESS_B branch condition
- ΔAB → asymmetry indication
- Time correlation → progression detection

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4. Implemented Rule Classes (Current System)

The prototype uses three actionable rule outcomes:

Rule Class 1 – HARNESS_A Low

```
if ΔA > threshold_A and ΔB ≈ 0 → HARNESS_A degradation
```

Rule Class 2 – HARNESS_B Low

```
if ΔB > threshold_B and ΔA ≈ 0 → HARNESS_B degradation
```

Rule Class 3 – HARNESS_C Symmetric Low

```
if ΔA > threshold_A and ΔB > threshold_B → Global degradation
```

This corresponds to observed output:

```
HARNESS_A → ECU_A sag
HARNESS_B → ECU_B sag
HARNESS_C → Both sag (shared fault)
```

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5. Failure Mode Mapping (Physical → Rule)

Physical Cause	Rule Trigger	Notes
Connector corrosion (A branch)	HARNESS_A	gradual
Connector corrosion (B branch)	HARNESS_B	gradual
Shared ground degradation	HARNESS_C	symmetric
Partial open circuit	HARNESS_A / B / C	high Δ
Loose terminal	Intermittent	transient alerts
Fretting corrosion	Burst asymmetry	time-correlated
Temperature ↑	Resistance ↑	slow drift
Water ingress	Step-change	recovery after dry-out

This maps real physics to rule outputs — critical for PdM traceability.

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6. Tunable Parameters

Rule-based systems depend on parameters:

- Voltage thresholds (typ. 0.3–1.0 V)
- Time persistence (e.g., 3 consecutive samples)
- Reset hysteresis
- Rate-of-change triggers
- Dropout filters (anti-chatter)

These tunables allow calibration without modifying hardware or firmware.

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7. Time Dimension (Temporal Logic)

Predictive detection is not just **threshold detection**, but **trend and persistence**.

We introduce temporal layers:

Layer	Purpose
Instant	sudden anomalies
Short window (1–5s)	vibration/intermittent detection
Medium window (10–60s)	harness thermal effects
Long window (>1hr)	progressive corrosion

Future work can extend detection windows fleet-wide (Phase 8).

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8. Extendable Future Rule Domains

Although Phase 7 targets harness supply voltages, the architecture naturally extends to:

Category	Example
Temperature	ECU thermal throttling
Load current	Overcurrent due to resistance
Latency	CAN delivery jitter
DTCs	Early diagnostic correlation
Age + cycles	Vehicle usage hours
Ambient	Wet/dry + salt exposure
Fleet comparison	Cross-vehicle baselines

Predictive maintenance value increases as domains cross-correlate.

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9. Roadmap (Rule → Statistical → Fleet)

Rules form Stage 1 of the PdM progression:

```
Stage 1  → Rule-based detection (now)
Stage 2  → Statistical anomaly detection (7.3)
Stage 3  → Fleet-wide baselining (8.x)
Stage 4  → Prognostics (remaining useful life estimation)
Stage 5  → Automated service recommendation
```

OEMs typically commercialize PdM between Stages 2–4.

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10. Certification & Explainability

Rule-based detection is favored early in deployment because:

- OEM warranty requires root cause clarity
- Safety cases require determinism
- Fleet operators require explainability ("why did you flag ECU_B?")
- Regulatory mandates traceability

This positions rules as the correct foundation before ML or predictive modelling.

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11. Summary

Phase 7.2 solidifies predictive maintenance logic into deterministic, explainable rules that map CAN telemetry into physical harness degradation categories. Predictive value is achieved without new sensors, vehicle integration, or firmware changes.

From here, the system is ready to evolve into:

7.3 – Statistical anomaly detection

Which introduces:

- baselines
- variance
- drift
- hysteresis
- confidence scoring