LANE ONE Directional Vehicle Detection → LED Board Control System

> **Application Scenario**: A single-lane work-zone section is controlled by **two photoelectric beam locations**, **A** (entry) and **B** (exit), spaced apart to form a detection zone. Traffic is **one car at a time**. When a vehicle travels in the **forward direction** (passes **A first, then B**), the **LED Board** turns ON the moment the car passes **A**, stays ON while the car is in the zone, and remains ON for an additional **10 seconds after the car passes B**, then turns OFF. A vehicle travelling in the **reverse direction** (passes **B first, then A**) does **NOT** activate the LED Board.

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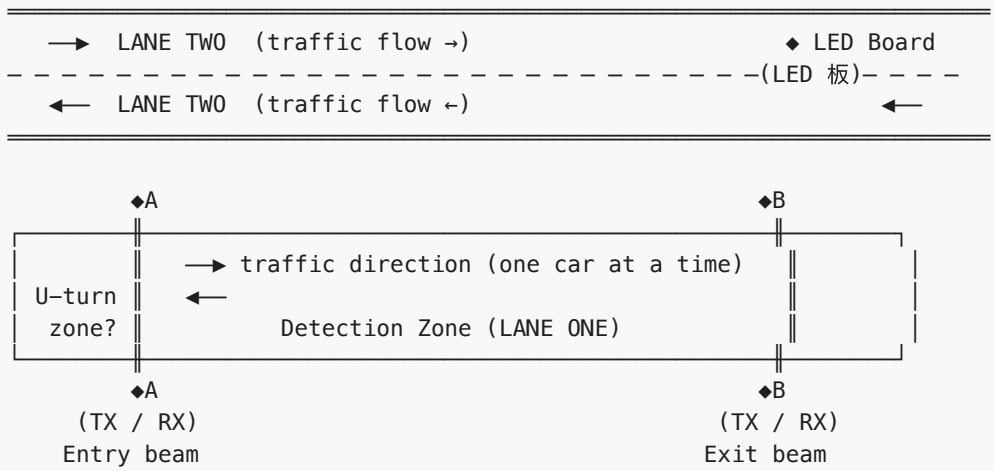
1. System Overview

1.1 Physical Scene



Forward (A → B): LED Board ON when passing A; hold 10 s after passing B.
Reverse (B → A): LED Board stays OFF.

⚠ Concern: sensor group A may be affected by U-turning vehicles
near the entry side → see §7.5 mitigation.

1.2 Control Objective

Condition	LED Board	Description
Vehicle passes **A first** (forward entry)	**ON**	Turns on immediately at A
Vehicle inside the zone (between A and B, forward)	**ON**	Zone occupied
Vehicle has just passed **B** (forward exit)	**ON for 10 more seconds**	Hold timer — safety buffer
10 s hold expired after passing B	**OFF**	Zone clear
Vehicle passes **B first, then A** (reverse)	**No action (stays OFF)**	Reverse traffic does not activate the board
System fault / communication loss	**ON (fail-safe)**	Default deny — avoid hazard

1.3 Key Design Rules (per supervisor's plan)

1. **Two beam locations only**: `A` (TX/RX pair, entry) and `B` (TX/RX pair, exit). The "4 photoelectric sensors" are the 2 emitters + 2 receivers of these two beams.
2. **One car at a time** — the lane geometry limits traffic to single-file passage, so a single direction-aware state machine suffices (no multi-vehicle counter).
3. **Direction is decided by which beam is broken first**:
   - **A before B** → forward (rightward) → activate LED.
   - **B before A** → reverse (leftward) → do NOT activate LED.
4. **Requirement 1**: car passes A → LED ON; after car passes B → LED stays ON for **10 s** (configurable `T_HOLD`), then OFF.
5. **Requirement 2**: car passes B then A → LED does not display.
6. **U-turn consideration**: sensor group A may be tripped by a U-turning vehicle that never reaches B. A **transit timeout** (`T_TRANSIT_MAX`) prevents the LED from being stuck ON in this case (see §7.5).
7. **Fail-Safe**: on sensor wire break or PLC fault, the default is LED = ON.

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2. System Requirements Specification (SRS)

2.1 Functional Requirements (FR)

- **FR-1** The system shall turn the LED Board ON the instant a vehicle breaks beam **A** as the **first** event of a passage (A broken while B is clear).
- **FR-2** The LED Board shall remain ON while the vehicle is in the zone (from breaking A until it has fully passed B).
- **FR-3** After the vehicle has fully passed **B**, the LED Board shall remain ON for an additional **10 seconds** (configurable `T_HOLD`, default 10 s) and then turn OFF.
- **FR-4** A vehicle that breaks beam **B** as the **first** event (i.e. travelling reverse, B then A) shall **not** activate the LED Board.
- **FR-5** The system shall determine direction from the order of beam events:
  - A-first-then-B → **forward** passage.
  - B-first-then-A → **reverse** passage (ignored for LED activation).
- **FR-6** If a forward passage starts (A broken) but **B is not reached within** `T_TRANSIT_MAX` (default 60 s), the system shall assume the vehicle left or U-turned and shall clear the LED (return to idle) to prevent a stuck-ON condition.
- **FR-7** If a new forward vehicle breaks A during the 10 s hold, the hold shall be cancelled and the LED shall stay ON for the new passage.
- **FR-8** If any photoelectric beam remains continuously broken for longer than `T_SENSOR_FAULT` (default 5 min), the system shall enter `S_FAULT` and output `FAULT_LAMP = ON`, LED = ON.
- **FR-9** A manual RESET pushbutton shall force the system back to idle (LED OFF) for maintenance.

2.2 Non-Functional Requirements (NFR)

- **NFR-1** PLC scan cycle ≤ 20 ms.
- **NFR-2** Photoelectric beam response time ≤ 2 ms (recommended: Omron E3Z-T or Keyence PR-G series).
- **NFR-3** Fail-safe: on beam power loss (cable break) → LED = ON (PNP NO output + wire-break detection).
- **NFR-4** LED Board service life ≥ 50,000 h (LED matrix type).

2.3 Nomenclature

Abbreviation	Full name	Description
`A`	Beam **A** (entry, left)	Through-beam pair (TX + RX) at the entry boundary of the zone
`B`	Beam **B** (exit, right)	Through-beam pair (TX + RX) at the exit boundary of the zone
`LED_BOARD`	—	LED Board output facing LANE TWO traffic
`T_HOLD`	—	Hold time after the vehicle passes B (default 10 s)
`T_TRANSIT_MAX`	—	Max expected A→B transit time; U-turn / lost-vehicle timeout (default 60 s)

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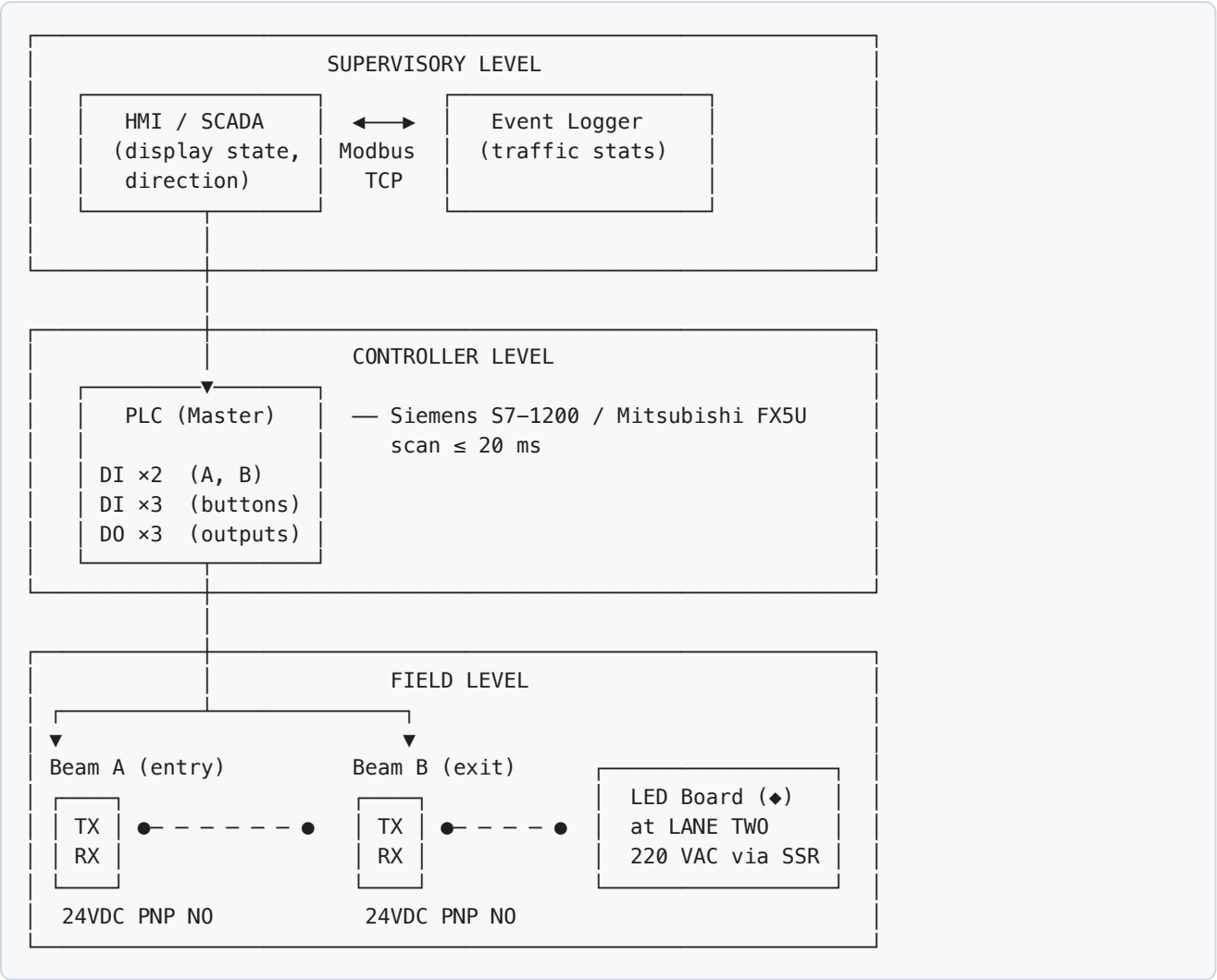
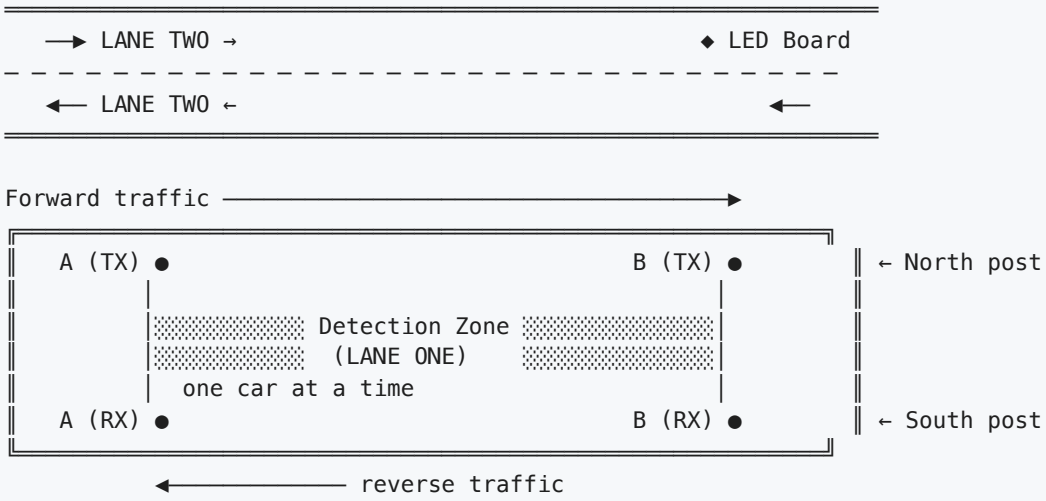
3. System Design Diagrams

3.1 Overall System Architecture



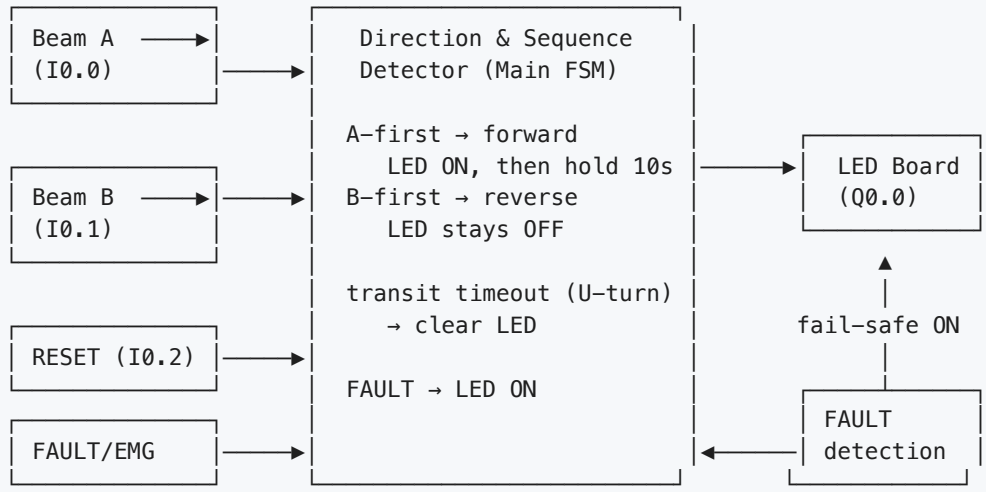
3.2 LANE ONE Plan View (Beam A and Beam B)



Beam separation (A↔B) = detection zone length (site-dependent, 30–200 m)
Gate width: 3.0 ~ 3.5 m (full width of LANE ONE)

⚠ U-turn zone is near beam A (entry side) — see §7.5.

3.3 Control Block Diagram

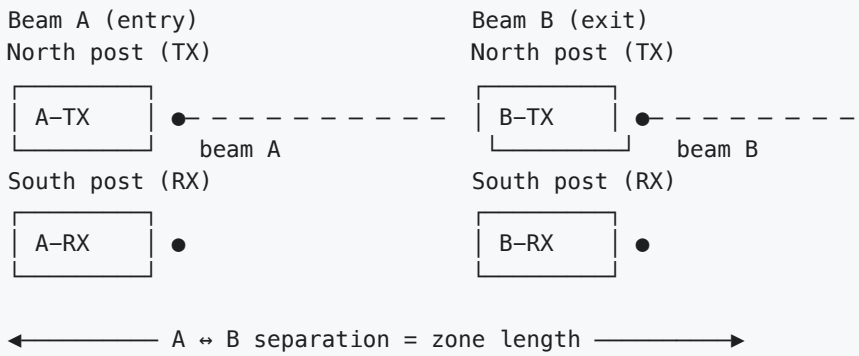


4. Hardware Layout and Sensor Design

4.1 Photoelectric Beam Selection

Item	Specification
Type	Through-beam photoelectric (2 sets: A and B, each = TX + RX)
Recommended part	Omron E3Z-T81 / Keyence PR-G51N3
Sensing distance	0 — 15 m (lane is only 3 m, so plenty of margin)
Light source	Infrared LED, modulated, ambient-light immune
Response time	≤ 1 ms
Output	PNP NO (normally open), 24 VDC, 100 mA
Protection	IP67
Operating temperature	−25 °C to +55 °C
Wiring	3-wire (V+, GND, OUT) + shield
Mounting	Stainless-steel posts, TX/RX paired, beam height ≈ 50 cm

4.2 Posts and Beam Arrangement

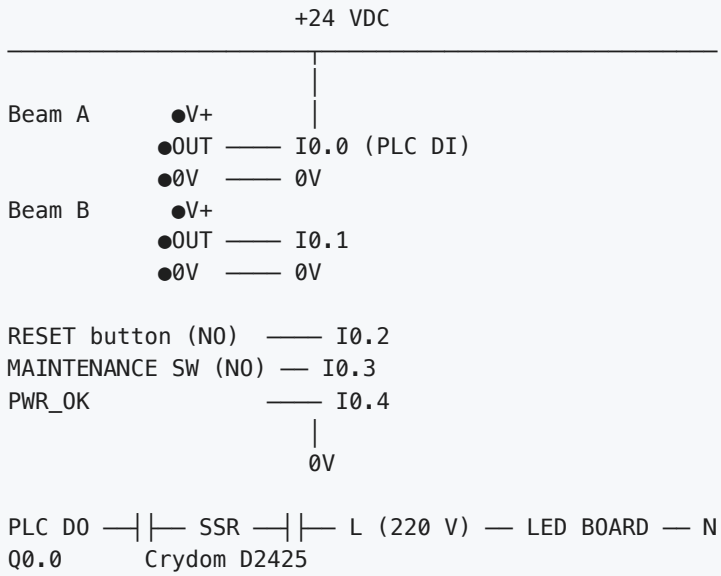


- Beam **A** sits at the entry boundary, beam **B** at the exit boundary. Their separation defines the detection zone.
- Direction is obtained from the **temporal order** of A and B being broken (see §6) — no second beam per location is required.
- Each beam should use a **different modulation frequency** to avoid cross-talk (use the sensor's Mutual Interference Prevention feature).

4.3 LED Board

Item	Specification
Type	LED matrix board; graphics: red octagon + "STOP" / arrow text
Size	800 × 800 mm (incl. housing)
Power	AC 220 V, 30 W
Control	Through SSR (Crydom D2425) switched by PLC DO
Protection	IP65
Mounting	≥ 2.5 m above ground, in LANE TWO facing the traffic to be warned
Accessory	Current transformer (CT) wired to PLC AI for bulb-fault detection

4.4 Electrical Connection Overview



> **Note**: With PNP wiring, the beam output = 24 V means "beam is broken" (NO logic), which is compatible with the active-high PLC DI input.

5. I/O List

5.1 Digital Inputs (DI)

Address	Tag	Description	Contact	Note
I0.0	`A`	Beam A (entry) broken = 1	PNP NO	Through-beam
I0.1	`B`	Beam B (exit) broken = 1	PNP NO	Through-beam
I0.2	`PB_RESET`	Reset to idle pushbutton	NO	Pressed = 1
I0.3	`SW_MAINT`	Maintenance-mode selector	NO	ON = maintenance
I0.4	`PWR_OK`	24 V power-OK feedback	NO	—

5.2 Digital Outputs (DO)

Address	Tag	Description
Q0.0	`LED_BOARD`	LED Board facing LANE TWO (lit = do not proceed)
Q0.1	`FAULT_LAMP`	Fault indicator lamp
Q0.2	`BUZZER`	Alarm buzzer (sounds on fault)

5.3 Internal Variables (Memory)

Address	Tag	Type	Description
M30.0	`A_Rise`	BOOL	Beam A rising edge (just broken)
M30.1	`A_Fall`	BOOL	Beam A falling edge (just cleared)
M30.2	`B_Rise`	BOOL	Beam B rising edge (just broken)
M30.3	`B_Fall`	BOOL	Beam B falling edge (just cleared)
MW40	`SysState`	INT	Main FSM state
M50.0	`FaultLatch`	BOOL	Fault latch
M50.1	`SensorStuck`	BOOL	Beam continuously broken
M50.2	`HoldActive`	BOOL	10 s hold timer is running
MD60	`TotalFwdCnt`	DINT	Cumulative forward passages (statistics)
MD64	`TotalRevCnt`	DINT	Cumulative reverse passages

5.4 Modbus Registers (to HMI / SCADA)

Address	Tag	Type	R/W	Description
10001	`STA_A`	BOOL	R	Current state of beam A
10002	`STA_B`	BOOL	R	Current state of beam B
10010	`STA_LED`	BOOL	R	LED Board state
10011	`STA_FAULT`	BOOL	R	Fault flag
10012	`STA_HOLD`	BOOL	R	Hold timer active
30001	`SYS_STATE`	UINT16	R	Current FSM state code
30002	`TOTAL_FWD`	UINT32	R	Cumulative forward passages
30004	`TOTAL_REV`	UINT32	R	Cumulative reverse passages
30006	`HOLD_REMAIN_MS`	UINT16	R	Hold timer remaining (ms)
40001	`T_HOLD_CFG`	UINT16	RW	Hold time (s), default 10
40002	`T_TRANSIT_CFG`	UINT16	RW	Transit timeout (s), default 60
00001	`CMD_RESET`	BOOL	RW	Write 1 = reset to idle
00002	`CMD_ACK_FAULT`	BOOL	RW	Write 1 = acknowledge fault

---

6. Direction Detection Principle (A–then–B vs B–then–A)

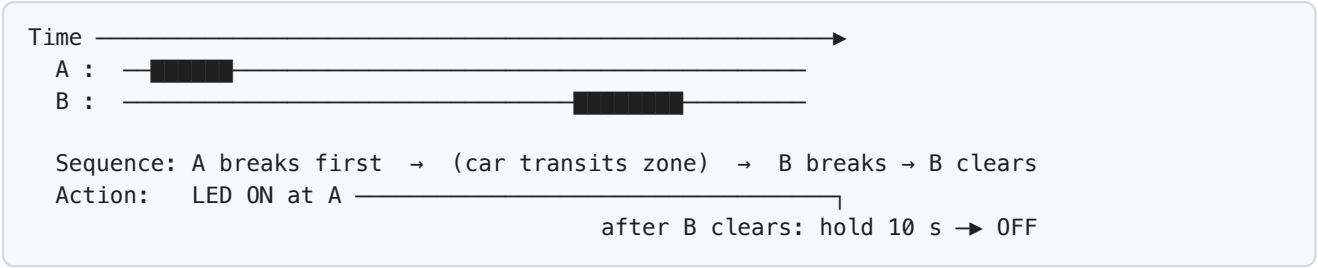
6.1 Why Two Beam Locations?

A single beam can only tell you "**something is there**", not which way it is moving. By placing **two beams (A and B) at the two ends of the zone**, the **order in which they are broken** reveals the direction of travel:

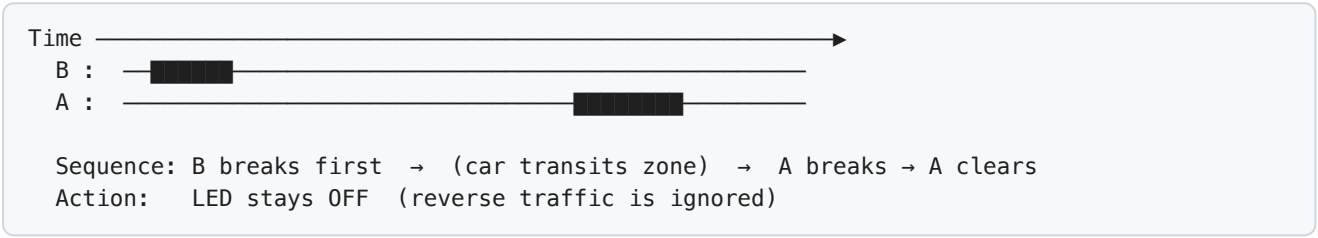
- **A broken first, then B** → vehicle moving from entry to exit → **forward**.
- **B broken first, then A** → vehicle moving from exit to entry → **reverse**.

This is exactly what the supervisor's two requirements describe.

6.2 Forward Passage (A → B, LED ON)



6.3 Reverse Passage (B → A, LED OFF)



6.4 Summary Table

First beam broken	Second beam broken	Direction	LED Board action
A	B	**Forward**	ON at A; hold 10 s after B; then OFF
B	A	**Reverse**	Stays OFF (ignored)
A	(B never reached, A clears)	**U-turn / lost**	ON at A; cleared by `T_TRANSIT_MAX` timeout

To reject momentary flickers, beam edges are debounced with a minimum-break filter (`T_MIN_BLOCK`, e.g. 100 ms) before being treated as a valid event.

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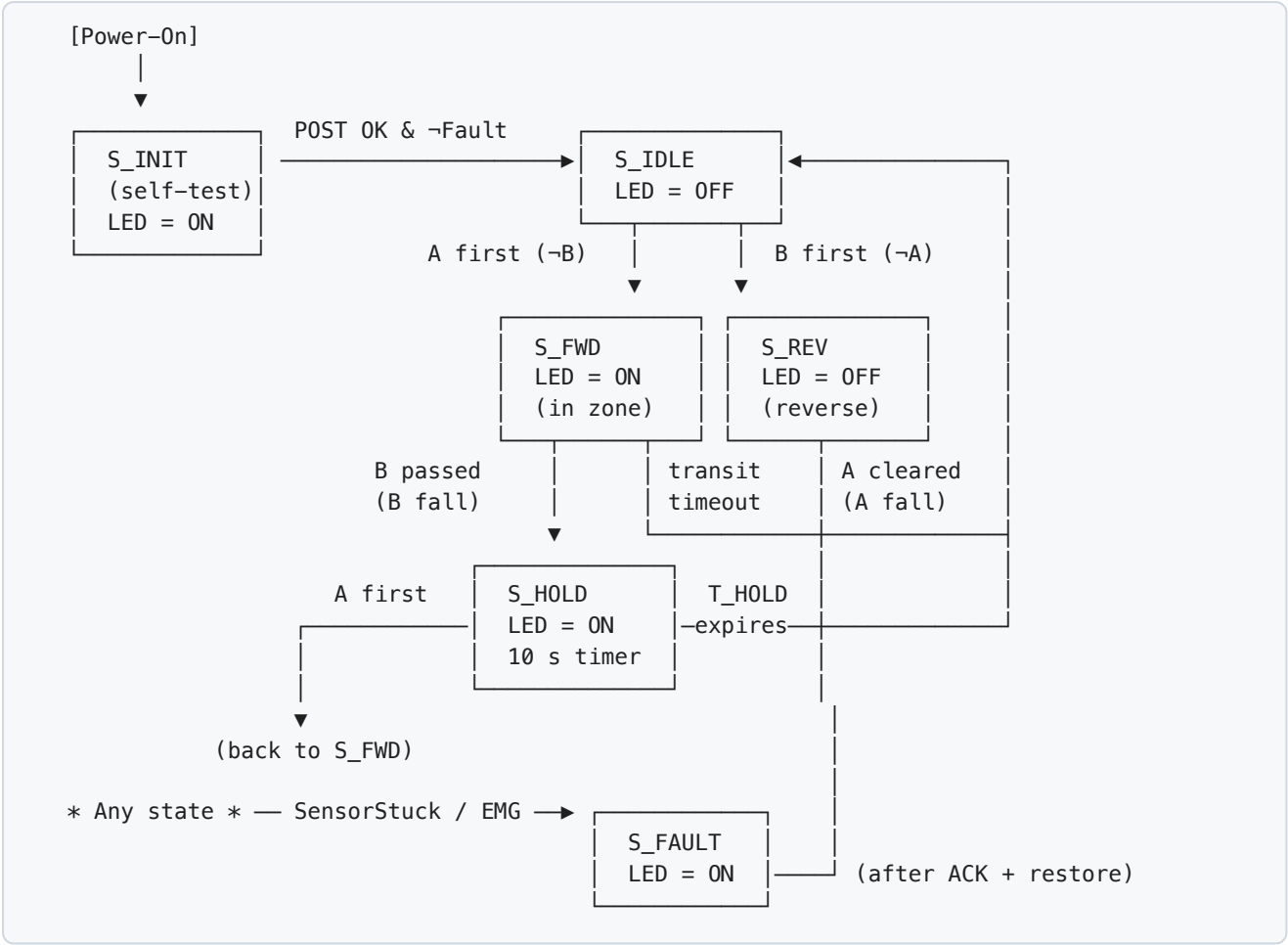
7. State Machine Design

Because traffic is **one car at a time**, a single direction-aware main FSM is sufficient — no multi-vehicle counter is needed.

7.1 Main FSM Overview



7.2 State Table

State	Entry condition	Action	Exit condition
`S_INIT`	Power-up / reset	Self-test, LED = ON (safe default)	Self-test OK → `S_IDLE`
`S_IDLE`	No vehicle, hold expired	LED = OFF	`A↑` while B clear → `S_FWD` ; `B↑` while A clear → `S_REV`
`S_FWD`	Forward car detected at A	LED = ON	`B↓` (car passed B) → `S_HOLD` ; transit timeout → `S_IDLE`
`S_HOLD`	Car just passed B	LED = ON, start 10 s timer	timer expires → `S_IDLE` ; `A↑` (new forward car) → `S_FWD`
`S_REV`	Reverse car detected at B	LED = OFF	`A↓` (car cleared A, exited) → `S_IDLE` ; transit timeout → `S_IDLE`
`S_FAULT`	Beam stuck / comm. error	LED = ON, FAULT_LAMP = ON, BUZZER = ON	Reset + fault cleared → `S_IDLE`

7.3 Requirement 1 Trace (forward A→B with 10 s hold)

```
S_IDLE ──A↑──► S_FWD (LED ON) ──B↑──► still S_FWD ──B↓──► S_HOLD (LED ON, 10 s) ──timeout──► S_
```

7.4 Requirement 2 Trace (reverse B→A, LED off)

```
S_IDLE ──B↑──► S_REV (LED OFF) ──A↑──► still S_REV (LED OFF) ──A↓──► S_IDLE (LED OFF)
```

The LED never turns on, because the passage entered through `S_REV` (B–first), not `S_FWD` (A–first).

7.5 U–Turn / Lost–Vehicle Mitigation (sensor A concern)

The supervisor noted that **sensor group A may be tripped by U–turning vehicles** near the entry side. Because the LED turns ON the instant A is broken (FR–1), a U–turning car that breaks A but never reaches B would otherwise leave the LED stuck ON.

Mitigation — a transit timeout in `S_FWD`:

- When entering `S_FWD`, start `TransitTimer (PT := T_TRANSIT_MAX, default 60 s)`.
- If B is reached first (`B↓`) → normal flow → `S_HOLD`.
- If `TransitTimer.Q` fires before B is reached → assume the vehicle U–turned / left → clear LED → `S_IDLE` and increment a diagnostic counter.
- Optionally, also treat "A re–broken and cleared without B" as an immediate back–out (configurable).

This bounds the worst–case false–ON time to `T_TRANSIT_MAX`.

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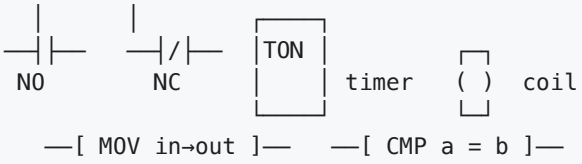
8. Ladder Diagram (LD, IEC 61131–3)

> The LD shown below maps directly to TIA Portal / GX Works3 / Studio 5000. Timers use the IEC standard `TON`.

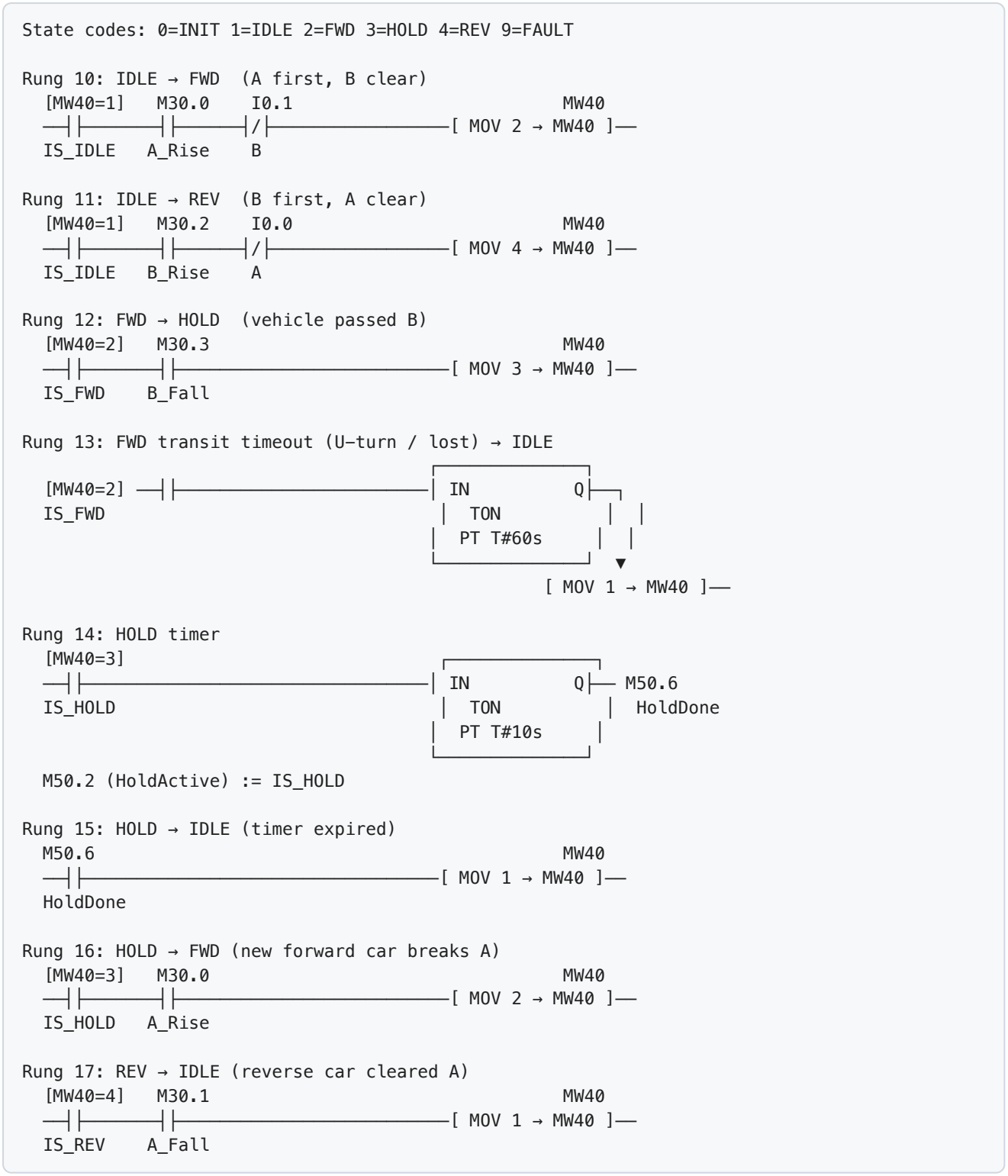
8.1 Symbol Recap



8.2 LD-01: Edge Detection (A, B)

```
Rung 1: Beam A rising / falling edge
  I0.0      M30.4                                   M30.0
  ──┤├──────┤/├──────────────────────────────────( )──   A_Rise
  A         A_LAST

  M30.4     I0.0                                    M30.1
  ──┤├──────┤/├──────────────────────────────────( )──   A_Fall
  A_LAST    A

  I0.0                                              M30.4
  ──┤├──────────────────────────────────────────( )──   A_LAST

Rung 2: Beam B rising / falling edge
  I0.1      M30.5                                   M30.2
  ──┤├──────┤/├──────────────────────────────────( )──   B_Rise
  B         B_LAST

  M30.5     I0.1                                    M30.3
  ──┤├──────┤/├──────────────────────────────────( )──   B_Fall
  B_LAST    B

  I0.1                                              M30.5
  ──┤├──────────────────────────────────────────( )──   B_LAST
```

8.3 LD-02: Main FSM (state in MW40)



8.4 LD-03: LED Board Output

```
Rung 20: LED_BOARD ON  (FWD OR HOLD OR Fault)
  [MW40=2]                                              Q0.0
  ──┤├──────┐──────────────────────────────────────────( )──
  IS_FWD     │                                        LED_BOARD
  [MW40=3]   │
  ──┤├──────┤
  IS_HOLD    │
  M50.0      │
  ──┤├──────┘
  FaultLatch

   (Note: in S_IDLE and S_REV the LED stays OFF.
          On OB100 startup, default Q0.0 = 1 until self-test ends.)

Rung 21: FAULT_LAMP
  M50.0   ──┤├──────────────────────────────────────( )──   Q0.1

Rung 22: BUZZER (1 Hz beep on fault)
  M50.0   ──┤├──────┤ M0.5 (1 Hz) ├──────────────────( )──   Q0.2
```

8.5 LD-04: Fault Detection

```
Rung 30: Stuck beam (A or B broken continuously > 5 min)

                                          ┌──────────────┐
  I0.0   ──┤├──────────────────────────►| IN          Q├─┐
  A                                      |  TON  T#5m   |  |
                                         └──────────────┘  |
                                                           |
                                          ┌──────────────┐ |  ├─► M50.1
  I0.1   ──┤├──────────────────────────►| IN          Q├─┘   SensorStuck
  B                                      |  TON  T#5m   |
                                         └──────────────┘


Rung 31: Fault latch + enter FAULT state
  M50.1   ──┬──────────────────────────────────────────[S]── M50.0 (FaultLatch)
  I0.4=0    |                                           [ MOV 9 → MW40 ]
  PWR_OK 0  |
  CMD_ACK_FAULT (Modbus 00002 / RESET)
  ──┤├──────────────────────────────────────[R]── M50.0
            ── if ¬stuck & PWR_OK: [ MOV 1 → MW40 ]
```

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9. Structured Text (ST, IEC 61131-3)

> Structured Text expresses this FSM most clearly. The code below compiles in TIA Portal, Codesys and Beckhoff TwinCAT.

9.1 Type Declarations

```
TYPE
    E_SysState : (
        SS_INIT     := 0,
        SS_IDLE     := 1,
        SS_FWD      := 2,   // forward car in zone (A first) — LED ON
        SS_HOLD     := 3,   // car passed B — 10 s hold, LED ON
        SS_REV      := 4,   // reverse car (B first) — LED OFF
        SS_FAULT    := 9
    );
END_TYPE
```

9.2 Main Program

```
PROGRAM LaneOne_LedBoard
VAR_INPUT
    A              : BOOL;  // I0.0  beam A (entry)
    B              : BOOL;  // I0.1  beam B (exit)
    PB_RESET       : BOOL;  // I0.2
    SW_MAINT       : BOOL;  // I0.3
    PWR_OK         : BOOL;  // I0.4
    CMD_RESET      : BOOL;  // Modbus coil 00001
    CMD_ACK_FAULT  : BOOL;  // Modbus coil 00002
END_VAR

VAR_OUTPUT
    LED_BOARD      : BOOL;  // Q0.0
    FAULT_LAMP     : BOOL;  // Q0.1
    BUZZER         : BOOL;  // Q0.2
END_VAR

VAR
    SysState     : E_SysState := SS_INIT;

    A_Prev, B_Prev : BOOL;
    A_Rise, A_Fall : BOOL;
    B_Rise, B_Fall : BOOL;

    InitTimer    : TON;
    HoldTimer    : TON;
    TransitTimer : TON;
    StuckA       : TON;
    StuckB       : TON;
    BuzzerClock  : TON;
    BuzzerPulse  : BOOL;

    FaultLatch   : BOOL := FALSE;
    SensorStuck  : BOOL := FALSE;

    TotalFwdCnt  : DINT := 0;
    TotalRevCnt  : DINT := 0;
    LostCnt      : DINT := 0;   // U-turn / lost-vehicle timeouts

    // — Configurable parameters (Modbus holding) —
    T_HOLD        : TIME := T#10s;
    T_TRANSIT_MAX : TIME := T#60s;
    C_StuckTime   : TIME := T#5m;
END_VAR
```

9.3 Edge Detection and Fault Aggregation

```
// === 1. Edge detection ===
A_Rise :=     A AND NOT A_Prev;
A_Fall := NOT A AND     A_Prev;
B_Rise :=     B AND NOT B_Prev;
B_Fall := NOT B AND     B_Prev;
A_Prev := A;
B_Prev := B;

// === 2. Stuck-beam detection ===
StuckA(IN := A, PT := C_StuckTime);
StuckB(IN := B, PT := C_StuckTime);
SensorStuck := StuckA.Q OR StuckB.Q;

IF SensorStuck OR (NOT PWR_OK) THEN
    FaultLatch := TRUE;
END_IF;
IF CMD_ACK_FAULT AND NOT SensorStuck AND PWR_OK THEN
    FaultLatch := FALSE;
END_IF;

// === 3. Manual reset ===
IF PB_RESET OR CMD_RESET THEN
    SysState := SS_IDLE;
END_IF;
```

9.4 Main FSM

```
// === 4. Global fault override ===
IF FaultLatch THEN
    SysState := SS_FAULT;
END_IF;

CASE SysState OF

    SS_INIT:
        LED_BOARD := TRUE;                      // fail-safe default ON
        InitTimer(IN := TRUE, PT := T#2s);
        IF InitTimer.Q AND NOT FaultLatch THEN
            InitTimer(IN := FALSE);
            SysState := SS_IDLE;
        END_IF;

    SS_IDLE:
        LED_BOARD := FALSE;
        HoldTimer(IN := FALSE);
        TransitTimer(IN := FALSE);
        // Direction decided by which beam breaks first
        IF A_Rise AND NOT B THEN
            SysState := SS_FWD;                 // forward: A first
        ELSIF B_Rise AND NOT A THEN
            SysState := SS_REV;                 // reverse: B first
        END_IF;

    SS_FWD:
        LED_BOARD := TRUE;                       // Req-1: LED ON at A
        TransitTimer(IN := TRUE, PT := T_TRANSIT_MAX);
        IF B_Fall THEN                           // vehicle has passed B
            TransitTimer(IN := FALSE);
            SysState := SS_HOLD;
        ELSIF TransitTimer.Q THEN                // §7.5 U-turn / lost vehicle
            TransitTimer(IN := FALSE);
            LostCnt := LostCnt + 1;
            SysState := SS_IDLE;
        END_IF;

    SS_HOLD:
        LED_BOARD := TRUE;                       // Req-1: hold 10 s after B
        HoldTimer(IN := TRUE, PT := T_HOLD);
        IF A_Rise AND NOT B THEN                 // new forward car during hold
            HoldTimer(IN := FALSE);
            SysState := SS_FWD;
        ELSIF HoldTimer.Q THEN
            HoldTimer(IN := FALSE);
            TotalFwdCnt := TotalFwdCnt + 1;      // completed forward passage
            SysState := SS_IDLE;
        END_IF;

    SS_REV:
        LED_BOARD := FALSE;                      // Req-2: reverse → LED OFF
        TransitTimer(IN := TRUE, PT := T_TRANSIT_MAX);
        IF A_Fall THEN                           // reverse car cleared A → exited
            TransitTimer(IN := FALSE);
            TotalRevCnt := TotalRevCnt + 1;
            SysState := SS_IDLE;
        ELSIF TransitTimer.Q THEN
```

```
            TransitTimer(IN := FALSE);
            SysState := SS_IDLE;
        END_IF;

    SS_FAULT:
        LED_BOARD := TRUE;                          // fail-safe ON
        IF NOT FaultLatch THEN
            SysState := SS_IDLE;
        END_IF;

END_CASE;

// === 5. Annunciators ===
FAULT_LAMP := FaultLatch;
BuzzerClock(IN := NOT BuzzerClock.Q AND FaultLatch, PT := T#500ms);
IF BuzzerClock.Q THEN
    BuzzerPulse := NOT BuzzerPulse;
END_IF;
BUZZER := FaultLatch AND BuzzerPulse;
```

9.5 Modbus Mapping for SCADA / HMI

```
FUNCTION_BLOCK FB_ModbusMap
VAR_INPUT
    SysState     : E_SysState;
    Led, Fault   : BOOL;
    HoldActive   : BOOL;
    HoldRemainMs : UINT;
    TotalFwd     : DINT;
    TotalRev     : DINT;
    A, B         : BOOL;
END_VAR
VAR_OUTPUT
    DiscreteIn   : ARRAY[0..15] OF BOOL;     // 1xxxx
    InputReg     : ARRAY[0..15] OF UINT;     // 3xxxx
END_VAR

DiscreteIn[0]  := A;
DiscreteIn[1]  := B;
DiscreteIn[9]  := Led;
DiscreteIn[10] := Fault;
DiscreteIn[11] := HoldActive;

InputReg[0]    := UINT(SysState);
InputReg[1]    := UINT(SHR(TotalFwd, 16));        // high word
InputReg[2]    := UINT(TotalFwd AND 16#FFFF);     // low  word
InputReg[3]    := UINT(SHR(TotalRev, 16));
InputReg[4]    := UINT(TotalRev AND 16#FFFF);
InputReg[5]    := HoldRemainMs;
```

---

10. Sequential Function Chart (SFC, IEC 61131–3)

> SFC (also called a Sequential Function Diagram, IEC 61131–3 / Grafcet) expresses the control sequence as **steps** (boxes) linked by **transitions** (horizontal bars with a Boolean condition). Exactly one branch of a selection divergence is taken, based on which transition fires first. This SFC is the supervisor–supplied sequence reference; the executable logic in §7—§9 is the validated implementation of the same behaviour.

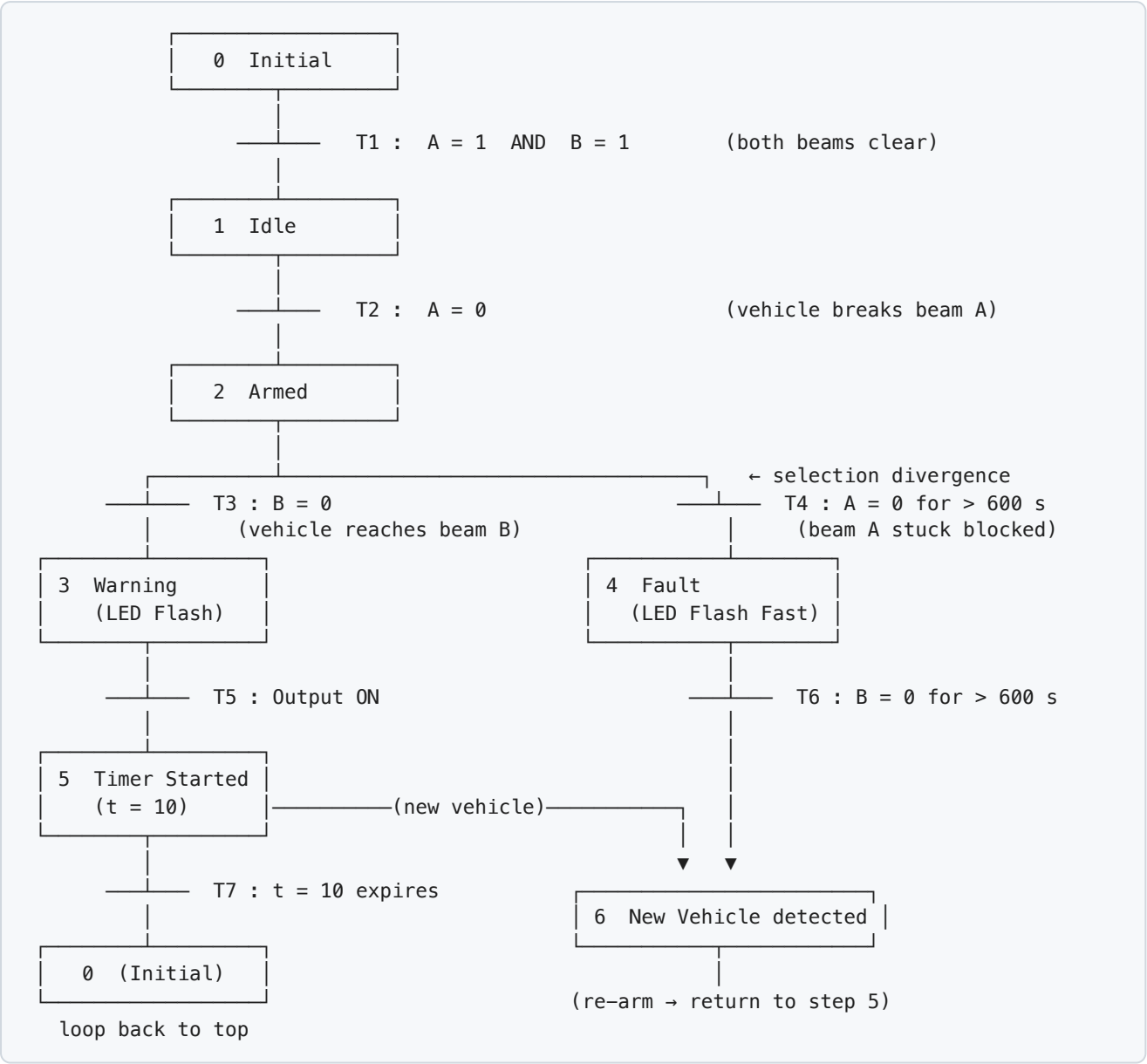
10.1 Polarity Convention Used in This SFC

In this SFC the beam variables follow the **light–received** convention:

Symbol	Meaning in SFC
`A = 1` / `B = 1`	beam **clear** (light received, no vehicle)
`A = 0` / `B = 0`	beam **blocked** (vehicle interrupting the beam)

> This is the logical complement of the raw PNP–NO wiring used elsewhere in this document (where *broken = 1*). In code, simply map `A := NOT A_broken_DI` (or select light–operate sensors), so `A = 0` here = "vehicle present at A".

10.2 SFC Diagram



10.3 Step Table

Step	Name	Action / output
0	Initial	Power-up state; outputs reset, self-test
1	Idle	Both beams clear, LED OFF, waiting for a vehicle
2	Armed	Beam A broken — forward candidate detected, waiting for B
3	Warning (LED Flash)	Vehicle reached beam B — LED Board flashes (warning)
4	Fault (LED Flash Fast)	Beam A stuck blocked > 600 s — fault, LED flashes fast
5	Timer Started (t = 40)	Output ON; hold timer running (preset t = 40, see §10.5)
6	New Vehicle detected	A further vehicle arrived during hold/fault — re-arm sequence

10.4 Transition Table

Transition	Condition	From → To
T1	`A = 1 AND B = 1` (both clear)	0 → 1
T2	`A = 0` (vehicle breaks A)	1 → 2
T3	`B = 0` (vehicle reaches B)	2 → 3
T4	`A = 0` for > 600 s (A stuck)	2 → 4
T5	`Output ON` (LED energised)	3 → 5
T6	`B = 0` for > 600 s (B stuck)	4 → 6
T7	`t = 40` expires (hold elapsed)	5 → 0
—	New vehicle detected (during hold)	5 → 6

10.5 Mapping to the Validated Main FSM (§7)

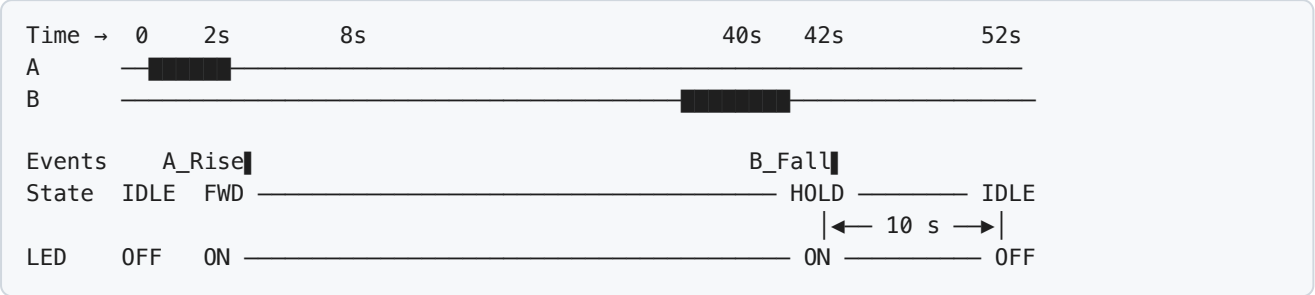
SFC step	§7 main FSM state	Notes
0 Initial	`S_INIT`	self-test, fail-safe LED ON
1 Idle	`S_IDLE`	LED OFF
2 Armed	`S_FWD` (entry)	A-first confirms forward direction
3 Warning	`S_FWD` (in zone)	LED ON/flashing while car transits to B
5 Timer Started	`S_HOLD`	hold after passing B
4 Fault	`S_FAULT`	stuck-beam fault (> 600 s)
6 New Vehicle	`S_FWD` (re-entry)	new car during hold cancels timer

> **Timer preset note**: the SFC labels the hold timer `t = 40`. To realise the **10 s hold** required by FR-3, set the timebase so that `40 × 250 ms = 10 s` (or set the preset directly to `T#10s` as in the ST code, where `T_HOLD := T#10s`). The `> 600 s` stuck-beam thresholds map to the `T_SENSOR_FAULT` (5 min) / configurable fault timers — adjust to site preference.
>
> **Reverse traffic**: the SFC arms only on `A = 0` first (T2). A reverse vehicle breaks B first, so T2 never fires and the sequence stays in **Idle** — i.e. the LED never turns on, satisfying Requirement 2.

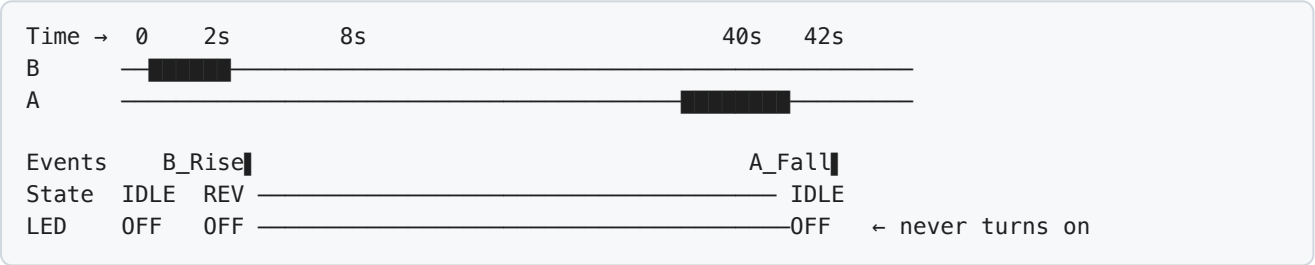
---

11. Timing Diagrams

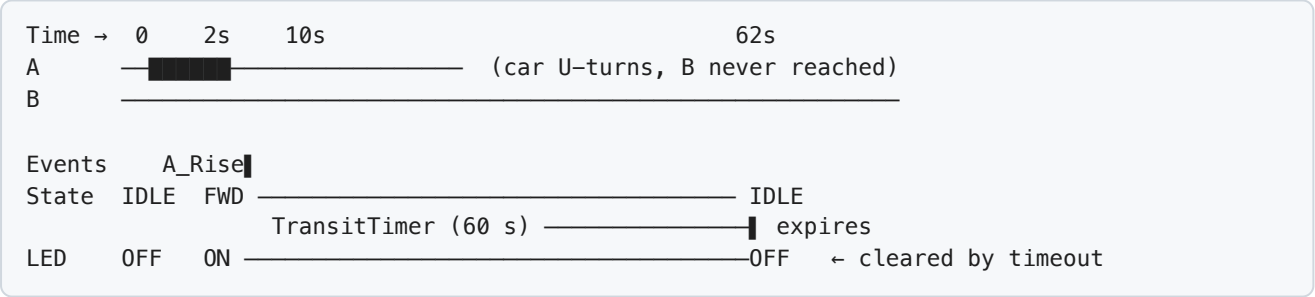
11.1 Requirement 1 — Forward (A → B) with 10 s Hold



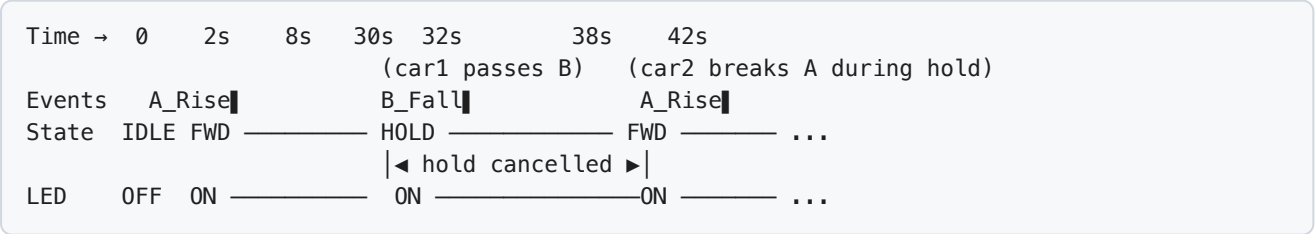
11.2 Requirement 2 — Reverse (B → A), LED stays OFF



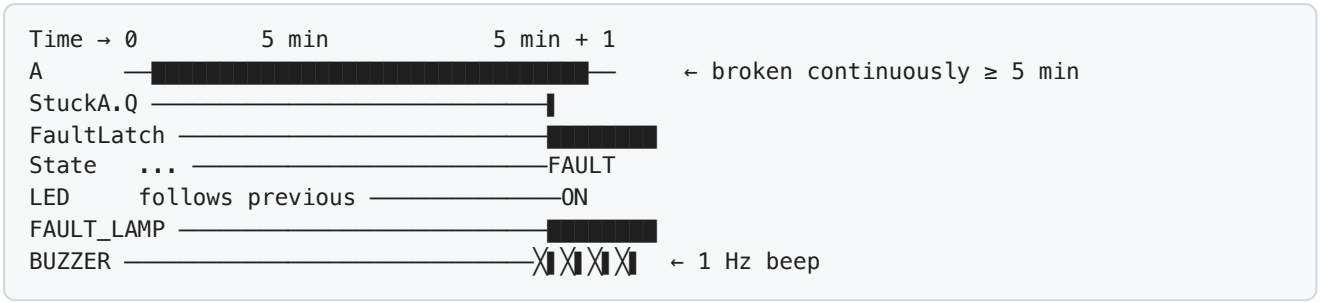
11.3 U-Turn at A (sensor A concern, §7.5)



11.4 New Forward Car During the 10 s Hold



11.5 Stuck Sensor (fault transition)



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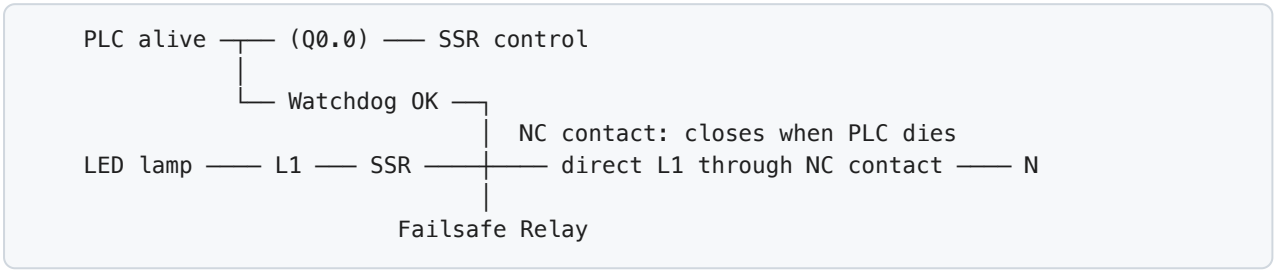
12. Safety Design and Failure Modes

12.1 FMEA (Failure Mode and Effects Analysis)

Failure	Cause	Effect	Detection	Response
Dirty beam lens	Dust, rain	Weak / intermittent trigger	StuckTimer + scheduled cleaning	`S_FAULT`, LED = ON
Beam wire break	Mechanical damage, ageing	Signal stuck at 0 (never triggers)	Wire-break detection (NAMUR) or loop-back test	`S_FAULT`, LED = ON
24 V power loss	UPS exhausted	Full system loss	`PWR_OK` signal	UPS + LED held ON via hard-wired NC contact
PLC failure	CPU stop	No control	Watchdog timer	DO defaults OFF; LED uses "lit on failure" wiring (see below)
U-turn vehicle trips A	Vehicle reversing near entry	False LED ON	A broken but B never reached	`T_TRANSIT_MAX` timeout clears LED (§7.5)
Slow vehicle crossing	Truck, traffic jam	Transit timeout misfires	Tune `T_TRANSIT_MAX` to site	Maintenance mode can extend timeout
Two vehicles at once	Violates "one car at a time"	Sequence ambiguity	Geometric single-file enforcement	Narrow lane / barriers; optional counter upgrade
Pedestrians / animals	Non-vehicle objects	False trigger	Minimum-break filter (`T_MIN_BLOCK` , 100 ms)	Filter out short pulses

12.2 Fail-Safe Design Principles

1. **LED Board uses "positive logic stop"**: lamp on = danger signal, therefore **it must remain lit when power is lost**. Solution: drive the LED Board via a **dual power source** or **independent battery backup** sharing the PLC UPS. If the PLC fails, the SSR drops out through the watchdog and a **relay-based lockout** takes over:



2. **PNP NO beams with wire-break detection**: choose sensors with IO-Link or NAMUR signalling to detect cable disconnection.
3. **Watchdog**: the PLC toggles a `WD_BIT` every scan; if the external watchdog relay sees no toggle for 200 ms it forces the LED ON.
4. **Battery backup**: size the UPS for ≥ 30 min.

12.3 SIL Assessment (Recommended SIL 2)

- Target **PFD (Average Probability of Failure on Demand)** in the range 1e-3 to 1e-2.
- A second independent direction check (or redundant beams) can raise integrity toward SIL 2.
- For SIL 3, introduce a second independent PLC arranged in a 1oo2D voting architecture.

---

13. Test Cases

13.1 Unit Tests (simulated inputs)

TC#	Event sequence	Expected LED	Expected State
TC–01	Power–up → self–test OK	OFF	S_IDLE
TC–02	Forward: A↑ → A↓ → B↑ (LED on at A)	ON	S_FWD
TC–03	Continue: B↓ (car passed B)	ON (hold)	S_HOLD
TC–04	Wait 10 s after TC–03	OFF	S_IDLE
TC–05	Reverse: B↑ → A↑ → A↓ (B first)	OFF throughout	S_REV → S_IDLE
TC–06	U–turn: A↑ then A↓, B never reached, wait 60 s	ON then OFF (timeout)	S_FWD → S_IDLE
TC–07	New car: in S_HOLD at t = 5 s, A↑	ON (hold cancelled)	S_HOLD → S_FWD
TC–08	Press PB_RESET while LED ON	OFF	S_IDLE
TC–09	A broken continuously for 5 min	ON	S_FAULT
TC–10	Press CMD_ACK_FAULT after beam recovers	OFF	S_IDLE
TC–11	Momentary 50 ms flicker on A (< T_MIN_BLOCK)	OFF (filtered)	S_IDLE

13.2 Integration Tests

TC#	Scenario	Expected result
IT–01	100 forward vehicles within 1 hour at 20 km/h	`TotalFwd = 100`, LED correctly ON during each passage + 10 s hold
IT–02	Brief raindrop streak across the lens (< 50 ms jitter)	No state change, with `T_MIN_BLOCK = 100 ms` filtering
IT–03	Disconnect beam B cable	Transition to `S_FAULT` within 1 s, LED = ON
IT–04	PLC restart	On power–up LED = ON for ≈ 2 s (INIT), then OFF if idle
IT–05	UPS cutover (mains lost)	LED remains ON for ≥ 30 min
IT–06	10× reverse vehicles (B→A)	LED never turns on; `TotalRev = 10`
IT–07	5× U–turn vehicles at A (no B)	LED clears within `T_TRANSIT_MAX` each time; `LostCnt = 5`

13.3 Acceptance Criteria

- **Direction accuracy**: 100 % correct forward/reverse classification over a 100-vehicle test.
- **Response time**: from vehicle breaking A to LED turning ON ≤ 200 ms.
- **Hold timer accuracy**: 10 s ± 0.5 s.
- **Availability**: MTBF ≥ 1000 h over 30 days of continuous 7×24 operation.
- **EMC**: compliant with CNS 13438 Class A.

Appendix A: Integration with the Existing 4-Phase Signal System (File 01)

This subsystem can be plugged into 01_PLC_Modbus_SCADA.md as a **sub-program**:

- Shares the same S7-1200 PLC (only 2 DI + 1 DO are required, well within the existing modules).
- Shares the same SCADA / HMI; LED state and direction counters are exposed via Modbus.
- Add a "LANE ONE Direction Monitor" panel to the SCADA screen showing the FSM state, beam A/B states, forward/reverse totals and hold-timer status.

```
PROGRAM OB1
BEGIN
    TrafficLight_Main(...);    // existing intersection controller
    LaneOne_LedBoard(...);     // new sub-program
END_PROGRAM
```

Appendix B: Incremental BOM

Item	Specification	Qty	Note
Through-beam photoelectric beam	Omron E3Z-T81 (TX/RX pair)	2 pairs	Beam A + Beam B (= 4 sensors: 2 TX + 2 RX)
Stainless-steel sensor post	H = 1 m, with base	4 pcs	A: TX+RX posts, B: TX+RX posts
LED display board	800 × 800 mm, 220 VAC, IP65	1 set	In LANE TWO facing traffic
SSR	Crydom D2425 (25 A)	1 pc	For LED Board switching
Current transformer (CT)	5 A : 5 mA	1 pc	LED Board bulb-fault detection
4–20 mA transmitter	—	1 pc	CT → AI
MCB	6 A, C-curve	1 pc	LED Board circuit
Fail-safe relay	Omron MY2N 24 VDC	1 pc	Fail-safe interlock
Cable (3C × 0.75 mm^2 shielded)	—	≈ 150 m	Site-dependent
Waterproof junction box	IP66	4 pcs	One per post

> **Document version**: v3.0 **Standards referenced**: IEC 61131-3 (LD, ST, FBD), IEC 61508 SIL 2 (recommended), CNS 13438 (EMC)