THE ULTIMATE DEVELOPER GUIDE

CAN Bus

TECHNICAL GUIDE

Comprehensive Technical Reference and Application Guide

Controller Area Network Protocols, Implementation, and Diagnostics

- CAN 2.0 & FD & XL
- SAE J1939 / CANopen
- UDS / ISO 14229
- OBD-II
- Common Faults
- EMC & Harness

17 Chapters · 66 Diagrams · 90 Tables · 30+ ISO/SAE Standards

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Chapter 1: Introduction to CAN Bus

The Controller Area Network (CAN) is a robust vehicle bus standard designed to allow microcontrollers and devices to communicate with each other without a host computer. Originally developed by Robert Bosch GmbH in 1986, CAN has become the de facto standard for in-vehicle communications and is widely used in industrial automation, medical equipment, and other embedded systems.

1.1 History and Evolution

The development of CAN was driven by the need for a reliable, cost-effective communication protocol for automotive applications. In the early 1980s, automotive wiring harnesses were becoming increasingly complex and heavy due to the growing number of electronic control units (ECUs) in vehicles. Point-to-point wiring between ECUs was no longer practical.

Table 1-1 CAN Protocol Evolution Timeline

Year	Milestone	Description
1986	CAN Birth	Bosch introduces CAN at SAE Congress in Detroit
1991	Mercedes W140	First production vehicle with CAN bus
1993	ISO 11898	CAN standardized as ISO 11898
2003	ISO 11898-2	High-speed CAN physical layer standard
2012	CAN FD	Bosch releases CAN FD specification
2015	ISO 11898-1:2015	CAN FD included in ISO standard
2018	CAN XL	CAN XL specification for 10+ Mbps

The original CAN protocol, now referred to as Classical CAN or CAN 2.0, supported data rates up to 1 Mbps with a maximum payload of 8 bytes per frame. While sufficient for many applications, the increasing data bandwidth requirements of modern vehicles led to the development of CAN FD (Flexible Data-rate) in 2012, which increased the payload to 64 bytes and introduced dual bit-rate capability.

1.2 OSI Model Mapping

The CAN protocol implements layers of the OSI (Open Systems Interconnection) reference model. Understanding this mapping is essential for comprehending how CAN integrates with higher-level protocols and applications.

Table 1-2 CAN Protocol OSI Layer Mapping

OSI Layer	CAN Implementation	Function
7 - Application	SAE J1939, CANopen, DeviceNet	Application-specific protocols and services
6 - Presentation	Not implemented	Data format translation
5 - Session	Not implemented	Session management
4 - Transport	J1939 TP, ISO-TP	Multi-packet message transport
3 - Network	Not implemented	Routing and addressing
2 - Data Link	CAN Controller (LLC + MAC)	Framing, arbitration, error detection
1 - Physical	ISO 11898-2 Transceiver	Electrical signaling, bit encoding

The Data Link Layer in CAN is divided into two sublayers:

- **Logical Link Control (LLC):** Handles message filtering, overload notification, and error recovery
- **Medium Access Control (MAC):** Manages message framing, arbitration, acknowledgment, and error signaling

1.3 CAN Standards Overview

The CAN protocol is governed by several international standards that define different aspects of the technology:

Table 1-3 Key CAN Standards

Standard	Title	Scope
ISO 11898-1	Data Link Layer and Physical Signaling	CAN protocol, frame formats, error handling
ISO 11898-2	High-Speed Medium Access Unit	Physical layer for up to 1 Mbps
ISO 11898-3	Low-Speed, Fault-Tolerant MAU	Physical layer for up to 125 kbps
ISO 11898-4	Time-Triggered CAN (TTCAN)	Time-triggered communication
ISO 16845	CAN Conformance Test Plan	Conformance testing for CAN controllers
SAE J2284	High-Speed CAN for Vehicles	Vehicle-specific CAN implementation
SAE J1939	Recommended Practice	Heavy-duty vehicle application layer

> **Key Insight: CAN vs. Other Protocols**
>
> Unlike master-slave protocols (such as SPI or I2C), CAN uses a multi-master architecture where any node can initiate communication when the bus is idle. This peer-to-peer approach, combined with non-destructive arbitration, makes CAN highly efficient for distributed systems.

Chapter 2: Physical Layer (ISO 11898-2)

The physical layer of CAN, defined in ISO 11898-2, specifies the electrical characteristics of the bus, including voltage levels, signaling rates, cable requirements, and transceiver specifications. This layer is responsible for converting the digital bits from the CAN controller into electrical signals on the bus medium.

2.1 Differential Signaling

CAN uses differential signaling on a two-wire bus, consisting of CAN High (CAN_H) and CAN Low (CAN_L). This differential approach provides excellent noise immunity, as any common-mode noise affects both wires equally and is rejected by the differential receiver.

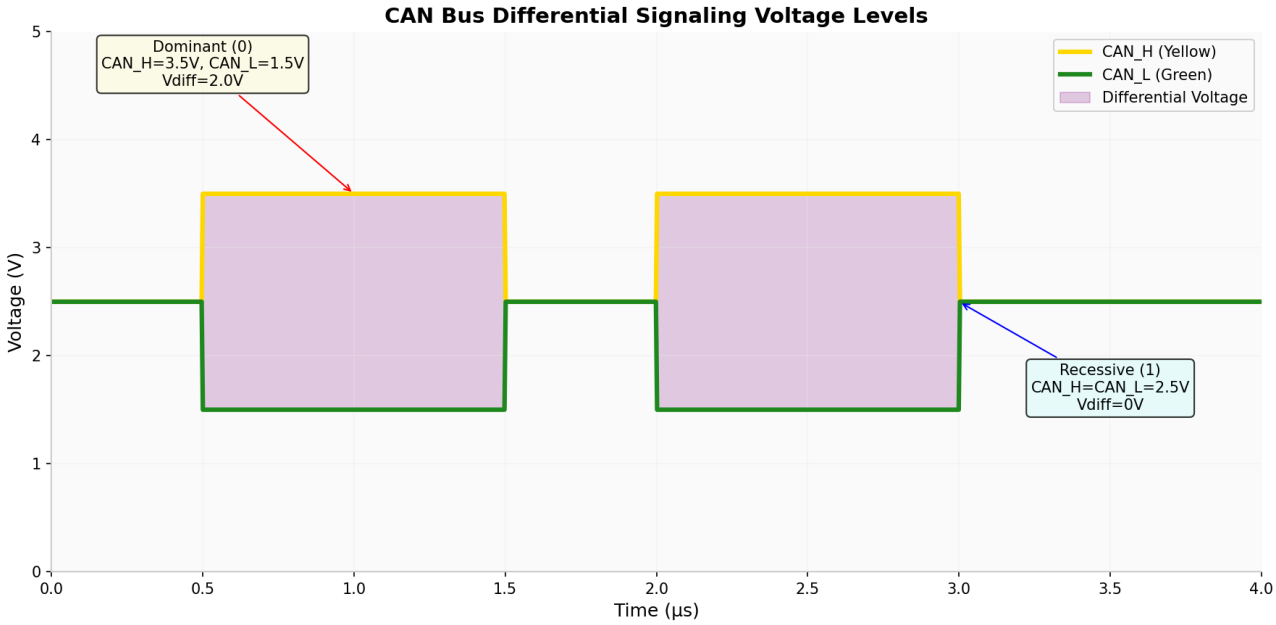


Figure 2-1 *CAN Bus Differential Signaling Voltage Levels*

The two logical states are defined as follows:

Table 2-1 CAN Bus Voltage Levels (ISO 11898-2)

State	CAN_H	CAN_L	Differential Voltage	Logical Value
Dominant	3.5V (typical)	1.5V (typical)	2.0V (typical)	0
Recessive	2.5V (typical)	2.5V (typical)	0V (typical)	1

Differential Voltage Calculation

$$V_{diff} = V_{CAN_H} - V_{CAN_L}$$

Dominant state recognized when: $V_{diff} > 0.9V$ (minimum)

Recessive state recognized when: $V_{diff} < 0.5V$ (maximum)

The dominant state (logic 0) will always override the recessive state (logic 1) when multiple nodes transmit simultaneously. This property is fundamental to CAN's non-destructive arbitration mechanism.

2.2 Bus Termination

Proper termination is critical for signal integrity in CAN networks. The termination resistors serve two primary purposes:

1. **Impedance matching:** Prevents signal reflections at the bus ends
2. **Recessive state biasing:** Ensures the bus returns to recessive state when idle

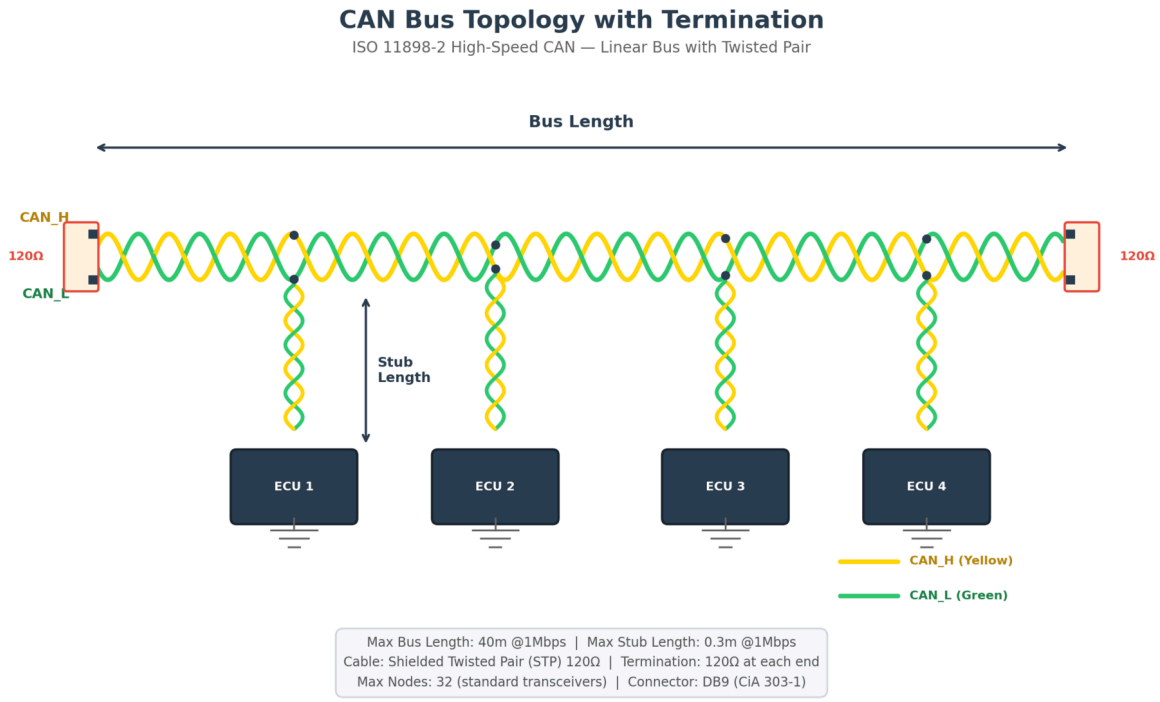


Figure 2-2 *CAN Bus Network Topology with Termination*

Termination Resistance

$$R_T = Z_0 = 120\Omega$$

Where Z_0 is the characteristic impedance of the cable (typically 120Ω for twisted pair)

Critical Warning: Termination Requirements

Both ends of the CAN bus MUST be terminated with 120Ω resistors. Missing or incorrect termination will cause signal reflections, leading to communication errors. The total bus resistance measured between CAN_H and CAN_L with all nodes disconnected should be approximately 60Ω (two 120Ω resistors in parallel).

Termination placement options include:

- **Standard termination:** 120Ω resistor at each end of the bus
- **Split termination:** Two 60Ω resistors with center tap to ground via capacitor (improves EMI)
- **Node-integrated termination:** Some ECUs include switchable termination

2.3 Transceiver Characteristics

The CAN transceiver is the interface between the CAN controller and the physical bus. It converts the logic-level signals from the controller to the differential bus signals and vice versa.

Table 2-2 Common CAN Transceivers

Transceiver	Manufacturer	Speed	Features
TJA1040	NXP	1 Mbps	Standby mode, excellent EMI
TJA1042	NXP	5 Mbps (CAN FD)	CAN FD capable, low power
TJA1051	NXP	5 Mbps (CAN FD)	Silent mode, VIO pin
TCAN1042	Texas Instruments	5 Mbps (CAN FD)	Automotive grade, CAN FD
MAX3051	Maxim	1 Mbps	+80V fault protection
ADM3050	Analog Devices	1 Mbps	Isolated transceiver

Key Transceiver Specifications

- **Supply voltage:** Typically 5V ±10%
- **Common-mode range:** -2V to +7V (for robust applications)
- **Differential output:** 1.5V to 3.0V (dominant)
- **Propagation delay:** Typically < 100 ns
- **Standby current:** < 50 µA typical

> **Design Note: Transceiver Selection**
>
> When selecting a CAN transceiver, consider the maximum data rate required, EMI requirements, fault protection needs, and power consumption constraints. For CAN FD applications, ensure the transceiver supports the higher data rates (up to 8 Mbps).

Chapter 3: Data Link Layer

The Data Link Layer in CAN is responsible for message framing, arbitration, acknowledgment, and error detection. This layer is implemented in the CAN controller hardware and operates autonomously once configured by the host microcontroller.

3.1 Frame Formats

CAN defines four different frame types for communication:

- **Data Frame:** Carries actual data from transmitter to receivers
- **Remote Frame:** Requests the transmission of a specific identifier
- **Error Frame:** Transmitted when a node detects an error
- **Overload Frame:** Provides extra delay between data/remote frames

CAN supports two identifier formats:

Table 3-1 CAN 2.0A vs CAN 2.0B Comparison

Feature	CAN 2.0A (Standard)	CAN 2.0B (Extended)
Identifier Length	11 bits	29 bits
Maximum Identifiers	2,048	536,870,912
IDE Bit Value	Dominant (0)	Recessive (1)
Frame Length (max data)	108 bits	128 bits
Compatibility	CAN 2.0A only	CAN 2.0A and 2.0B
Common Use	Industrial CANopen	Automotive J1939

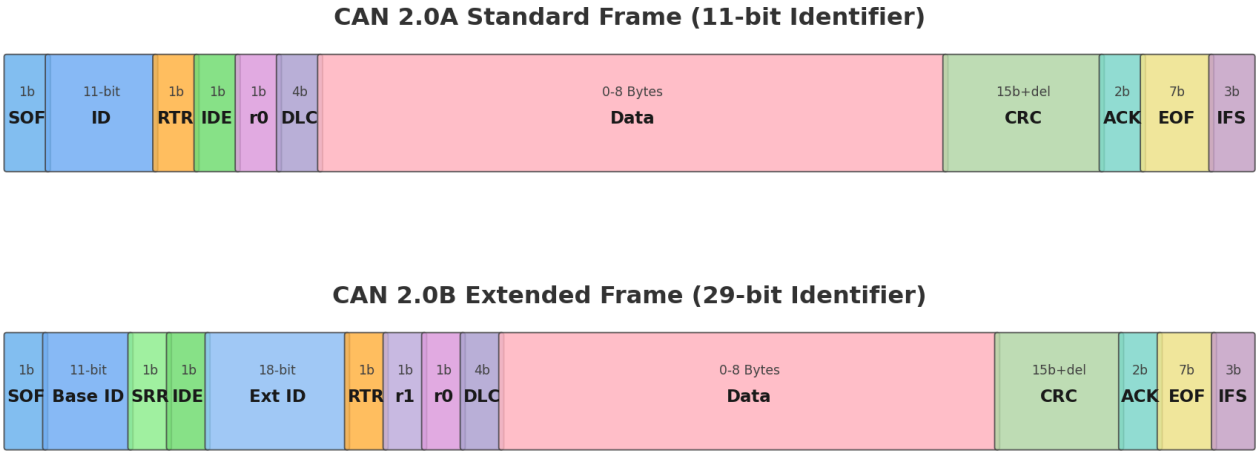


Figure 3-1 *CAN 2.0A Standard and CAN 2.0B Extended Frame Formats*

Standard CAN 2.0A Data Frame Fields

Table 3-2 CAN 2.0A Data Frame Field Descriptions

Field	Bits	Description
SOF	1	Start of Frame - dominant bit marks frame start
Identifier	11	Unique message identifier (determines priority)
RTR	1	Remote Transmission Request (dominant for data frame)
IDE	1	Identifier Extension (dominant for standard frame)
r0	1	Reserved bit (must be dominant)
DLC	4	Data Length Code (0-8 bytes)
Data Field	0-64	Actual data payload (0-8 bytes)
CRC	15	Cyclic Redundancy Check
CRC Delimiter	1	Recessive bit
ACK Slot	1	Receiver overwrites with dominant if CRC OK
ACK Delimiter	1	Recessive bit
EOF	7	End of Frame (7 recessive bits)
IFS	3	Interframe Space (minimum 3 recessive bits)

3.2 Bit Timing

CAN bit timing is crucial for proper synchronization and reliable communication. Each bit time is divided into segments to allow for sampling and synchronization.

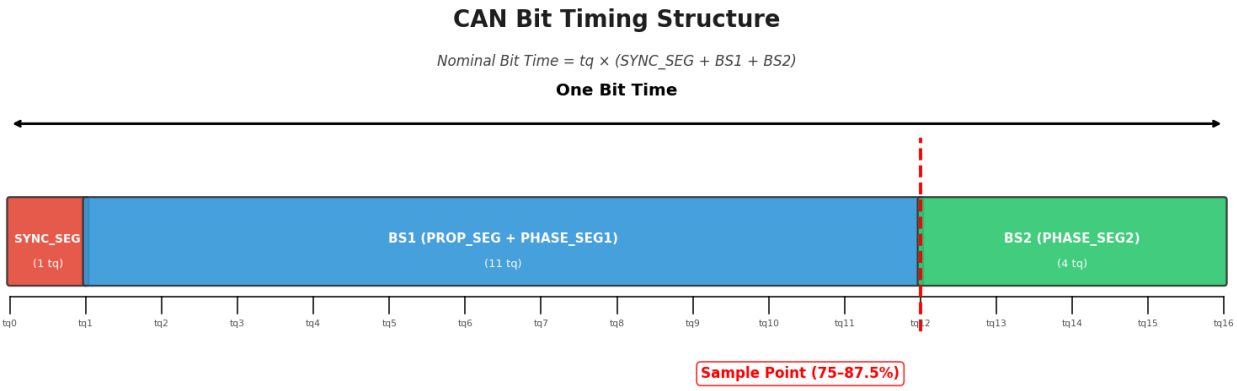


Figure 3-2 *CAN Bit Timing Structure*

The bit time consists of the following segments:

- **SYNC_SEG:** Synchronization segment (1 Time Quantum) - used for edge alignment
- **BS1 (Bit Segment 1):** Includes PROP_SEG and PHASE_SEG1 - defines sample point location
- **BS2 (Bit Segment 2):** PHASE_SEG2 - provides phase buffer after sample point

Bit Time Calculation

$$T_{bit} = t_q \times (SYNC\_SEG + BS1 + BS2)$$

Where t_q (Time Quantum) = $2 \times (BRP + 1) / f_{CAN\_CLK}$

Baud Rate Calculation

$$Baud\ Rate = \frac{f_{CAN\_CLK}}{2 \times (BRP + 1) \times (SYNC\_SEG + BS1 + BS2)}$$

Table 3-3 Recommended Bit Timing Parameters

Baud Rate	Total TQ	Sample Point	SJW
125 kbps	16	75-87.5%	1-2 TQ
250 kbps	16	75-87.5%	1-2 TQ
500 kbps	16	80-87.5%	1-2 TQ
1 Mbps	8-16	80-87.5%	1 TQ

> **Sample Point Recommendation**
>
> The sample point should be positioned at 75-87.5% of the bit time. A later sample point (closer to 87.5%) provides better tolerance for propagation delays, while an earlier sample point (closer to 75%) provides better tolerance for phase errors.

3.3 Synchronization

CAN uses two types of synchronization to maintain bit timing across all nodes:

Hard Synchronization

Occurs once at the start of frame (SOF). All nodes restart their internal bit timing when the recessive-to-dominant edge of SOF is detected.

Resynchronization

Occurs during the frame when an edge is detected outside the SYNC_SEG. The PHASE_SEG1 is lengthened or PHASE_SEG2 is shortened by up to SJW (Synchronization Jump Width) time quanta.

Synchronization Jump Width

$$SJW \leq min(PHASE\_SEG1, PHASE\_SEG2)$$

Typical SJW value: 1-2 Time Quanta

The resynchronization mechanism allows CAN to compensate for clock drift between nodes. With proper configuration, CAN can tolerate oscillator tolerances of up to 1.58% for a bit time of 10 TQ.

Chapter 4: Error Handling

CAN incorporates comprehensive error detection and handling mechanisms that contribute to its high reliability. The protocol achieves a residual error probability of less than 4.7×10^{-11}, making it suitable for safety-critical applications.

4.1 Error Types

CAN defines five types of errors that can be detected:

Table 4-1 CAN Error Types

Error Type	Detection Method	Description
Bit Error	Transmitter monitoring	Transmitter monitors bus level and compares with sent bit
Stuff Error	Bit stuffing rule	More than 5 consecutive bits of same polarity detected
CRC Error	CRC check	Calculated CRC doesn't match received CRC
Form Error	Fixed-form bit fields	Violation in CRC delimiter, ACK delimiter, or EOF
Acknowledgment Error	ACK slot check	No dominant bit detected in ACK slot

Bit Stuffing

Bit stuffing is used to ensure enough edges for synchronization. After 5 consecutive bits of the same polarity, an opposite polarity bit is inserted by the transmitter and removed by the receiver.

> **Stuff Bit Calculation**
>
> For a standard CAN frame with 8 data bytes, the maximum number of stuff bits is 24. This results in a maximum frame size of 132 bits (108 + 24 stuff bits).

4.2 TEC and REC Counters

Each CAN node maintains two error counters to track its error status:

- **Transmit Error Counter (TEC):** Tracks errors during message transmission
- **Receive Error Counter (REC):** Tracks errors during message reception

Table 4-2 Error Counter Update Rules

Event	TEC Update	REC Update
Transmitter detects error	+8	-
Receiver detects error	-	+1
Successful transmission	-1 (if TEC > 0)	-
Successful reception	-	-1 (if REC > 0)
Error flag after dominant ACK error	+8	-

4.3 Bus States

Based on the TEC and REC values, a CAN node can be in one of three states:

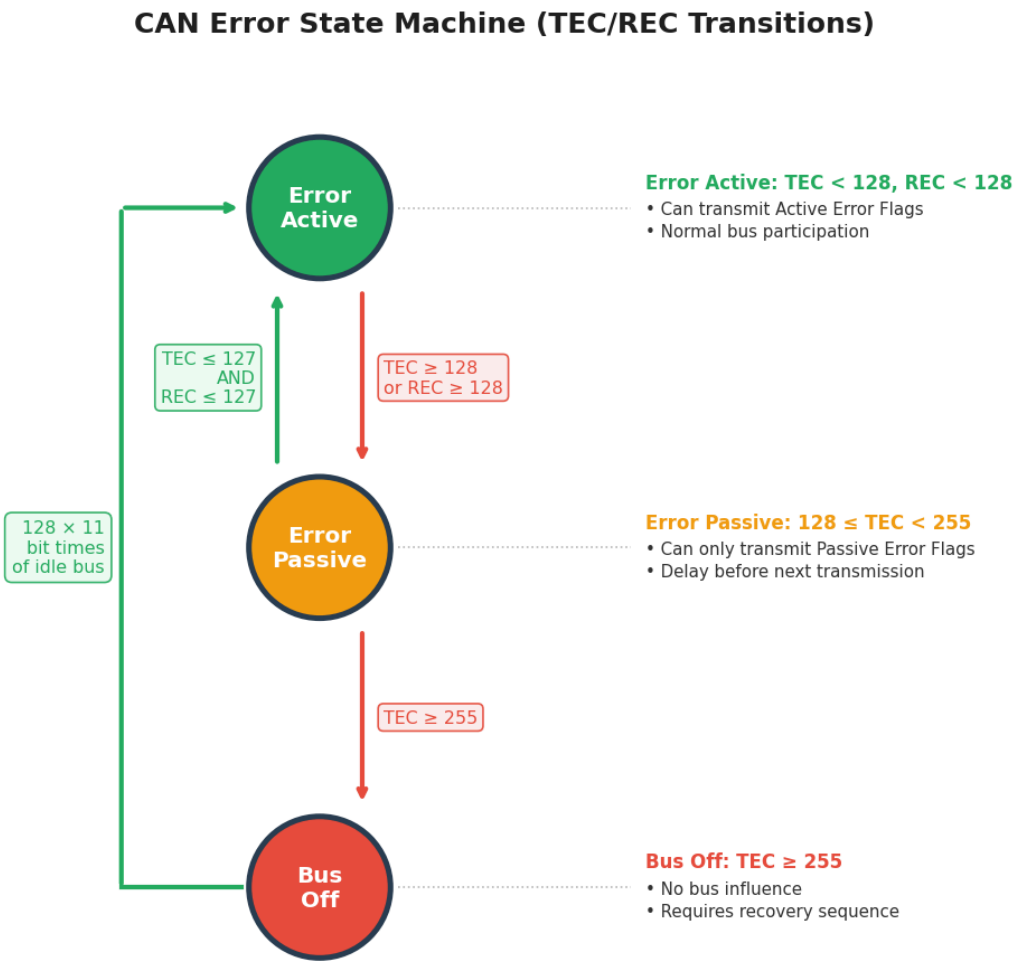


Figure 4-1 *CAN Error State Machine (TEC/REC Transitions)*

Table 4-3 CAN Node Error States

State	Condition	Behavior
Error Active	TEC < 128 AND REC < 128	Normal operation, transmits Active Error Flags
Error Passive	128 ≤ TEC < 255 OR REC ≥ 128	Transmits Passive Error Flags, 8-bit delay after transmission
Bus Off	TEC = 255	No bus participation, requires recovery sequence

Bus Off Recovery

When a node enters Bus Off state, it must undergo a recovery sequence before returning to Error Active state:

1. Node detects 128 occurrences of 11 consecutive recessive bits (128 × 11 bit times)
2. TEC and REC are reset to 0
3. Node returns to Error Active state

> **Bus Off Critical Condition**
>
> A node entering Bus Off state indicates a serious problem - either a hardware fault, incorrect bit timing configuration, or severe bus disturbances. In automotive applications, this typically triggers a diagnostic trouble code (DTC) and may illuminate the MIL (Malfunction Indicator Lamp).

4.4 Fault Confinement & Bus-Off Recovery

ISO 11898 defines **fault confinement** as the mechanism that prevents a malfunctioning node from permanently disrupting the bus. The protocol uses TEC/REC counters (Section 4.2) to progressively isolate a faulty node through three states: Error Active → Error Passive → Bus Off. This graduated response ensures that a single defective node cannot lock out the entire network.

Recovery Time Calculation

When a node enters Bus Off state, it must wait for 128 occurrences of 11 consecutive recessive bits before returning to Error Active. The minimum recovery time depends on the bus data rate:

Table 4-4 Bus-Off Recovery Time by Data Rate

Data Rate	Bit Time	Recovery Bits (128 × 11)	Minimum Recovery Time
125 kbit/s	8 µs	1,408	11.26 ms
250 kbit/s	4 µs	1,408	5.63 ms
500 kbit/s	2 µs	1,408	2.82 ms
1 Mbit/s	1 µs	1,408	1.41 ms

The formula is: **Recovery Time = 128 × 11 × Bit Time**. During recovery, the node remains silent and only monitors bus activity.

Auto Bus-On vs. Manual Recovery

After completing the 128 × 11 bit recovery sequence, the node can re-join the bus either automatically or through explicit software intervention:

Table 4-5 Auto Bus-On vs. Manual Recovery Comparison

Aspect	Auto Bus-On (ABOM)	Manual Recovery
Recovery Trigger	Automatic after 128 × 11 bit times	Software must explicitly reinitialize the CAN peripheral
Downtime	Minimal (1.4–11.3 ms depending on baud rate)	Depends on application polling interval
Root Cause Analysis	May mask recurring faults if not logged	Forces application to handle and log the event
Typical Use Case	Production ECUs, safety-critical systems	Development/debugging, bench testing
Risk	Rapid re-entry may cause repeated bus-off cycles	Extended communication loss if recovery is delayed

Driver / HAL Configuration

Most CAN controllers provide a hardware register bit to enable automatic bus-off recovery. Below are common configuration examples:

STM32 HAL (bxCAN / FDCAN)

```
/* Enable Automatic Bus-Off Management */
hcan.Init.AutoBusOff = ENABLE;
HAL_CAN_Init(&hcan);

/* For FDCAN peripherals: */
hfdcan.Init.AutoRetransmission = ENABLE;
hfdcan.Init.TransmitPause = ENABLE;
HAL_FDCAN_Init(&hfdcan);
```

Linux SocketCAN

```
# Enable automatic restart after 100 ms delay
ip link set can0 type can restart-ms 100

# Manual one-shot restart
ip link set can0 type can restart
```

AUTOSAR CanSM (CAN State Manager)

In AUTOSAR-based ECUs, the **CanSM** module manages CAN controller state transitions. When bus-off is detected, CanSM follows a configurable recovery strategy:

1. **Level 1 (L1):** Fast recovery — attempts `CanSMBorCounterL1ToL2` restarts with `CanSMBorTimeL1` interval (typically 10–50 ms)
2. **Level 2 (L2):** Slow recovery — if L1 fails, switches to `CanSMBorTimeL2` interval (typically 100–500 ms)
3. Recovery counters and timings are defined in the CanSM configuration container

> **Recurring Bus-Off Condition**
>
> If a node repeatedly enters Bus Off state shortly after recovery, this indicates a persistent fault — typically a wiring short, termination mismatch, or baud rate misconfiguration. Enabling auto bus-on without monitoring creates a rapid bus-off / recovery cycle that floods the bus with error frames and degrades communication for all nodes.

Best Practice

Enable auto bus-on (ABOM) in production, but always log bus-off events as a diagnostic trouble code (DTC). Implement a bus-off counter with a cooldown window — if bus-off occurs more than 3 times within 1 second, disable auto-recovery and escalate via diagnostic services (e.g., UDS DTC 0x600110).

Chapter 5: Network Topology

Proper network topology design is essential for reliable CAN communication. The physical layout of the bus, including wiring practices, stub lengths, and termination, directly impacts signal integrity and system robustness.

5.1 Bus Wiring

CAN uses a linear bus topology where all nodes connect to a single transmission line. The bus consists of two wires (CAN_H and CAN_L) that should be routed as a twisted pair to minimize electromagnetic interference.

Key wiring guidelines:

- Use twisted pair cable with characteristic impedance of 120Ω
- Maintain consistent wire gauge throughout the bus (typically 0.25-0.5 mm² / 22-24 AWG)
- Route CAN wires away from high-current power lines
- Use shielded cable in high-EMI environments
- Ground the shield at one end only (typically at the diagnostic connector)

Table 5-1 Bus Length vs. Data Rate

Data Rate	Maximum Bus Length	Maximum Stub Length
1 Mbps	40 meters	0.3 meters
500 kbps	100 meters	0.6 meters
250 kbps	250 meters	1.5 meters
125 kbps	500 meters	3.0 meters
50 kbps	1000 meters	6.0 meters
20 kbps	2500 meters	15.0 meters

Maximum Bus Length Approximation

$$L_{max} \approx \frac{50 \times 10^6}{Baud\ Rate}$$

Where L_{max} is in meters and Baud Rate is in bits per second

5.2 Stub Lengths

Stubs are the connections from the main bus to individual nodes. Long stubs create impedance mismatches that cause signal reflections, degrading signal quality.

> **Stub Length Limitation**
>
> Stub lengths should be kept as short as possible. As a general rule, the stub length should not exceed 0.3 meters at 1 Mbps. The maximum stub length increases proportionally as the data rate decreases.

For applications requiring longer stubs or drop-line topology, consider:

- **Low-speed CAN (ISO 11898-3):** Supports star topology with longer stubs
- **CAN repeaters:** Extend bus length and isolate segments
- **Optical isolation:** Provides galvanic isolation between segments

5.3 Cable Specifications

Table 5-2 Recommended CAN Cable Specifications

Parameter	Specification	Notes
Characteristic Impedance	120Ω ± 12Ω	At 1 MHz
Conductor Cross-section	0.25-0.5 mm² (22-24 AWG)	Based on current requirements
Twist Rate	20-50 twists per meter	Higher twist rate = better EMI immunity
Propagation Delay	< 5 ns/m	For high-speed applications
Capacitance	< 60 pF/m	Between conductors
Insulation Resistance	> 1 MΩ/km	At 500V DC

Common cable types for CAN applications:

- **UTP (Unshielded Twisted Pair):** Cost-effective, suitable for controlled environments
- **STP (Shielded Twisted Pair):** Better EMI protection, recommended for automotive
- **Double-shielded:** Maximum EMI protection for harsh environments

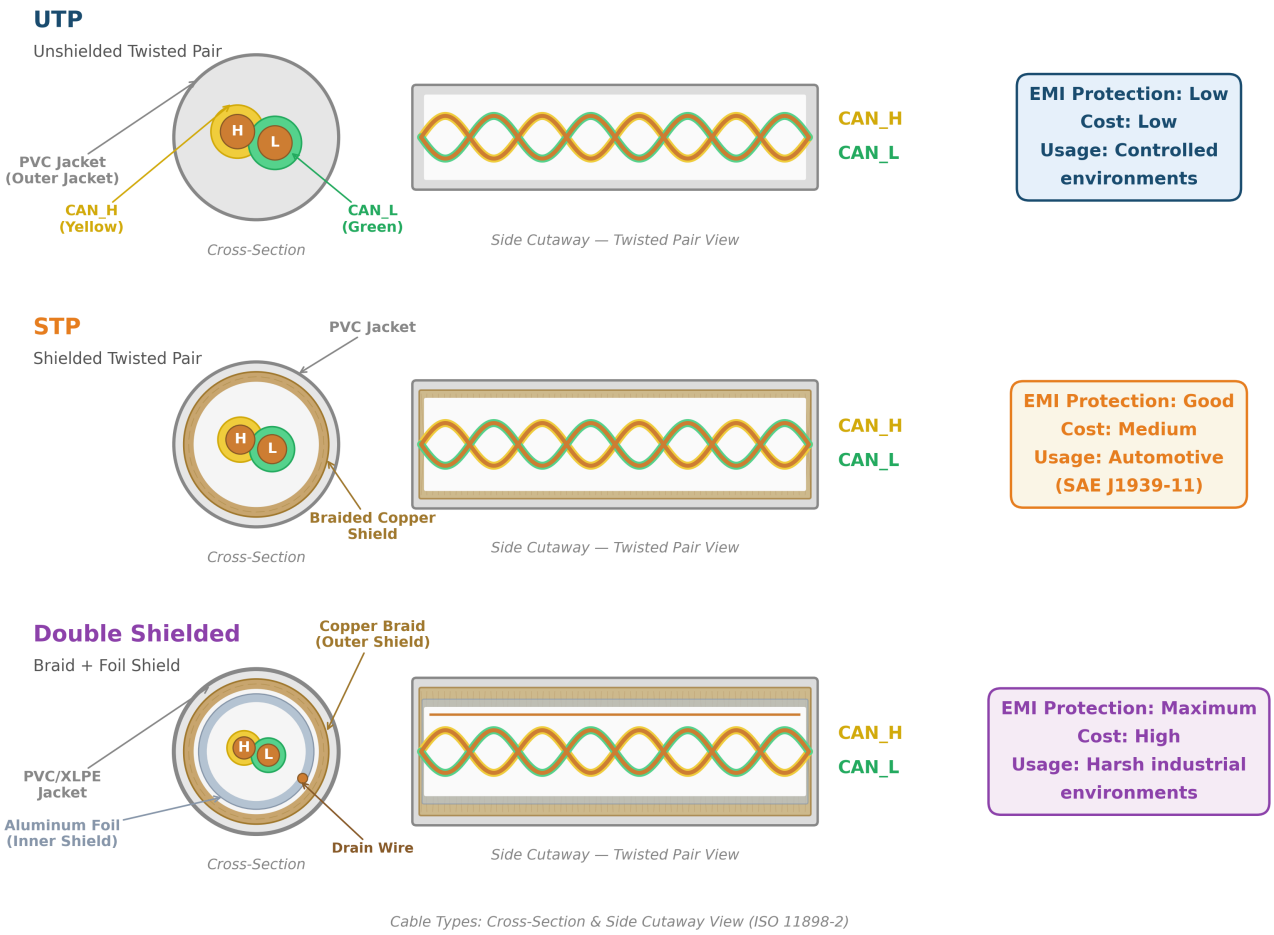


Figure 5-1 *CAN Bus Cable Types — Cross-Section View (UTP, STP, Double-Shielded)*

Automotive Cable Standards

Automotive applications typically use cables meeting SAE J1939/11 or SAE J2284 specifications. These specify twisted pair with 120Ω characteristic impedance and PVC or XLPE insulation, designed for the automotive temperature range of -40°C to +125°C.

Chapter 6: SAE J1939 Protocol Stack

SAE J1939 is the standard communication protocol for commercial vehicles (trucks, buses, agricultural machinery, construction equipment). Built on CAN 2.0B, J1939 defines a complete application layer with standardized message formats, network management, and diagnostic procedures.

6.1 29-bit Identifier Structure

J1939 exclusively uses the CAN 2.0B extended frame format with a 29-bit identifier. This identifier is structured to provide priority, parameter group identification, and source addressing.

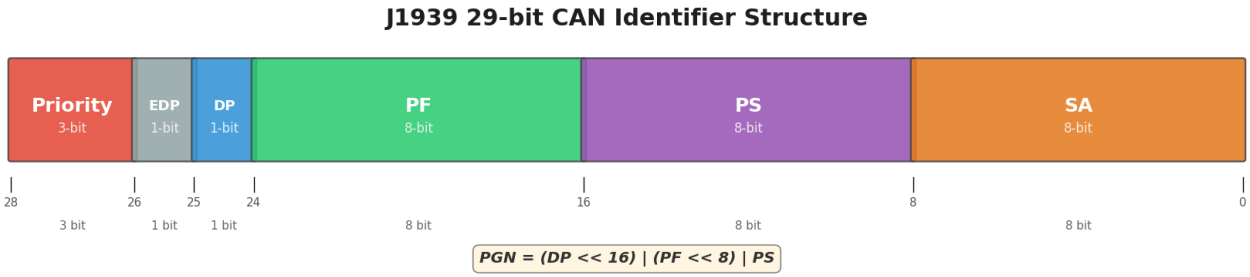


Figure 6-1 *J1939 29-bit CAN Identifier Structure*

Table 6-1 J1939 Identifier Field Descriptions

Field	Bits	Description
Priority (P)	3	Message priority (0=highest, 7=lowest)
Extended Data Page (EDP)	1	Reserved (must be 0)
Data Page (DP)	1	Expands PGN range (0 or 1)
PDU Format (PF)	8	Determines PDU type (PDU1 or PDU2)
PDU Specific (PS)	8	Destination address (PDU1) or Group Extension (PDU2)
Source Address (SA)	8	Address of transmitting node (0-253)

Complete 29-bit Identifier Calculation

$$ID = (P \ll 26) | (EDP \ll 25) | (DP \ll 24) | (PF \ll 16) | (PS \ll 8) | SA$$

6.2 PGN Structure

The Parameter Group Number (PGN) uniquely identifies a group of related parameters. PGNs are 18-bit values derived from the DP, PF, and PS fields.

PGN Calculation

$$PGN = (DP \ll 16) | (PF \ll 8) | PS$$

There are two PDU types in J1939:

Table 6-2 PDU Types in J1939

Type	PF Range	PS Field	Communication
PDU1 (Destination Specific)	0-239 (0x00-0xEF)	Destination Address	Point-to-point
PDU2 (Global)	240-255 (0xF0-0xFF)	Group Extension	Broadcast

PGN Range Allocation

The complete PGN address space is divided between SAE-defined and manufacturer-assignable ranges, organized by Data Page (DP) bit and PDU format:

Table 6-3 J1939 PGN Range Allocation

DP	PGN Range (hex)	Number of PGNs	SAE or Manufacturer Assigned	Communication Type
0	000000 – 00EE00	239	SAE	PDU1: Peer-to-Peer
0	00EF00	1	MF	PDU1: Peer-to-Peer
0	00F000 – 00FEFF	3840	SAE	PDU2: Broadcast
0	00FF00 – 00FFFF	256	MF	PDU2: Broadcast
1	010000 – 01EE00	239	SAE	PDU1: Peer-to-Peer
1	01EF00	1	MF	PDU1: Peer-to-Peer
1	01F000 – 01FEFF	3840	SAE	PDU2: Broadcast
1	01FF00 – 01FFFF	256	MF	PDU2: Broadcast

SAE vs Manufacturer (MF) PGNs

SAE-assigned PGNs are defined in SAE J1939-71 and have standardized meanings across all J1939 networks. Manufacturer-specific (MF) PGNs (PGN 0xEF00 and range 0xFF00–0xFFFF for each Data Page) are available for proprietary use. OEMs and ECU manufacturers can use MF PGNs for custom parameters without conflicting with standardized PGNs. The total address space provides 8,672 PGNs across both Data Pages.

Common J1939 PGNs include:

Table 6-4 Common J1939 PGNs

PGN	Name	Description	Rate
61444 (0x00F004)	Electronic Engine Controller 1 (EEC1)	Engine speed, torque	10 ms
61443 (0x00F003)	Electronic Engine Controller 2 (EEC2)	Accelerator pedal, road speed	50 ms
65248 (0x00FF00)	Vehicle Distance	Odometer, trip distance	1 s
65265 (0x00FF07)	Cruise Control/Vehicle Speed	Cruise control status	100 ms
65262 (0x00FF04)	Engine Temperature 1	Coolant, fuel temperatures	1 s
65263 (0x00FF05)	Engine Fluid Level/Pressure 1	Oil pressure, coolant level	500 ms
59904 (0x00EA00)	Request PGN	Request for specific PGN	On demand

SPN — Suspect Parameter Number

Each PGN contains one or more **Suspect Parameter Numbers (SPNs)** — individual signals within the 8-byte data field. SPNs define the start position, length, resolution, offset, and unit for each parameter. The physical value is calculated from the raw data bytes using:

SPN Physical Value Calculation

$$\text{Physical Value} = (\text{Raw Value} \times \text{Resolution}) + \text{Offset}$$

Example — Engine Speed (SPN 190 in PGN 61444 / EEC1):

Table 6-5 SPN 190 — Engine Speed Decoding

Property	Value
PGN	61444 (0x00F004) — Electronic Engine Controller 1
SPN	190 — Engine Speed
Start Byte.Bit	4.1 (byte 4, bit 1 — zero-indexed)
Length	16 bits (2 bytes)
Resolution	0.125 rpm/bit
Offset	0 rpm
Range	0 – 8031.875 rpm

For raw bytes `FF FF FF 68 13 FF FF FF` (hex), extract bytes 4–5: `0x1368` = 4968 decimal. Physical value: 4968 × 0.125 = **621 rpm**.

> **J1939 Data Validity Convention**
>
> In J1939, data bytes set to `0xFF` (all ones) indicate "Not Available" or invalid data. When decoding SPNs, any raw value that consists entirely of 0xFF bytes should be excluded from analysis. For 2-byte SPNs, `0xFFFF` means the parameter is not available; for 1-byte SPNs, `0xFF` means invalid.

J1939 Request Messages

Not all PGNs are broadcast periodically. Some parameters must be explicitly requested using **PGN 59904 (0xEA00)** — the Request PGN. The requesting node sends a 3-byte data field containing the PGN it wants to receive:

Table 6-6 Request PGN Message Format

Byte	Content	Description
1	PGN[7:0]	Least significant byte of requested PGN
2	PGN[15:8]	Middle byte of requested PGN
3	PGN[23:16]	Most significant byte of requested PGN

6.3 Address Claiming

J1939 uses a dynamic address claiming procedure to resolve address conflicts on the network. Each node has a preferred NAME and address.

The 64-bit NAME structure:

Table 6-7 J1939 NAME Structure (64-bit)

Field	Bits	Description
Arbitrary Address Capable	1	Node can use arbitrary address
Industry Group	3	Industry classification (0-7)
Vehicle System Instance	4	Instance of vehicle system
Vehicle System	7	Vehicle system classification
Reserved	1	Reserved (0)
Function	8	Function code (e.g., engine, transmission)
Function Instance	5	Instance of function
ECU Instance	3	ECU instance within function
Manufacturer Code	11	SAE-assigned manufacturer ID
Identity Number	21	Unique serial number

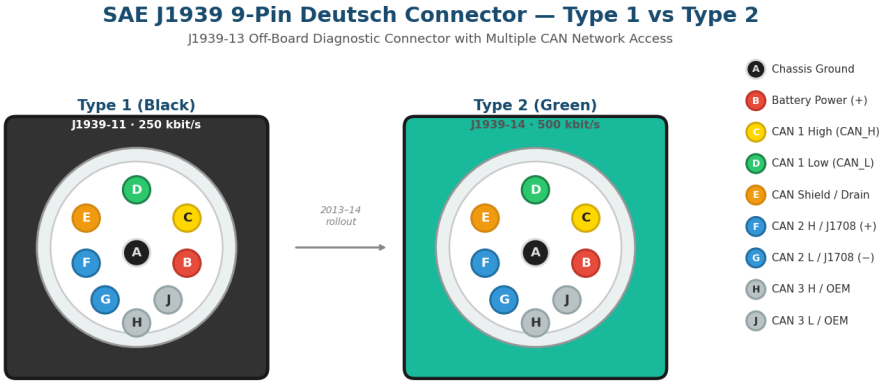
Address Claiming Flow:

1. Power On → Send Address Claimed
2. Check for Address Conflict
    - No Conflict → Normal Operation
    - Conflict Detected → Compare NAME values
        - Higher NAME wins → Claim Address
        - Lower NAME loses → Send Cannot Claim, Wait for Command

> **Address Claiming Priority**
>
> When two nodes attempt to claim the same address, the node with the higher NAME (numerically greater) wins the arbitration. The losing node must either claim a different address or enter the "Cannot Claim" state.

6.4 Physical Layer and Connector Specifications

The J1939 physical layer defines the electrical and mechanical characteristics for connecting ECUs on the CAN bus. The SAE J1939-13 standard specifies the **9-pin Deutsch HD10-9-1939** off-board diagnostic connector — the primary standardized interface for accessing J1939 networks in heavy-duty vehicles.



Multiple CAN Networks via Single J1939 Connector

Network	CAN_H Pin	CAN_L Pin	Typical Use
CAN 1 (Primary J1939)	**C**	**D**	Engine, transmission, brakes — main vehicle bus
CAN 2 (Secondary)	**F**	**G**	Body electronics, ISOBUS, or J1708 legacy
CAN 3 (OEM-specific)	**H**	**J**	OEM proprietary network (manufacturer-defined)

Physical Layer Comparison

Parameter	J1939-11	J1939-14	J1939-15
Connector Type	Type 1 (Black)	Type 2 (Green)	Type 1 (Black)
Bit Rate	250 kbit/s	500 kbit/s	250 kbit/s
Cable Type	Shielded TP	Shielded or Unshielded	Unshielded TP
Max ECUs	30	30	10
Max Bus Length	40 m	40–56.4 m	40 m
Max Stub Length	1 m	1.67 m	3 m

Figure 6-2 *J1939 9-Pin Deutsch Connector: Type 1 (Black) vs Type 2 (Green) with Multiple CAN Network Access and Physical Layer Comparison*

Type 1 (Black) vs Type 2 (Green) Connectors

The J1939 Deutsch connector comes in two variants:

- **Type 1 (Black housing):** The original connector defined by J1939-11, operating at **250 kbit/s**. This has been the standard connector in heavy-duty vehicles since the mid-1990s.
- **Type 2 (Green housing):** Introduced around 2013–14 for the J1939-14 standard, supporting **500 kbit/s** networks. The green color provides visual differentiation.

Connector Backwards Compatibility

Type 2 **female** connectors are physically backwards compatible — they fit both Type 1 and Type 2 male sockets. However, Type 1 female connectors **only fit Type 1** male sockets. The physical blocking mechanism is a smaller hole for **Pin F** in Type 2 male connectors, preventing older 250K hardware from being connected to 500K networks.

Multiple J1939 Networks

Many modern heavy-duty vehicles have 2 or more parallel CAN bus networks. The 9-pin Deutsch connector can provide access to up to three separate CAN networks through different pin pairs:

Table 6-8 CAN Network Access via J1939 Connector

Network	CAN_H	CAN_L	Typical Use
CAN 1 (Primary)	Pin C	Pin D	Main J1939 vehicle bus — engine, transmission, brakes
CAN 2 (Secondary)	Pin F	Pin G	Body electronics, ISOBUS, or legacy J1708 serial
CAN 3 (OEM)	Pin H	Pin J	OEM-proprietary network (manufacturer-defined)

Accessing All Available Data

Connecting only to Pin C and Pin D (the standard pair) does not guarantee access to all available J1939 data. If the vehicle uses multiple CAN networks, critical parameters may only be available on the secondary (F/G) or OEM-specific (H/J) bus. When logging data, use a dual-channel CAN logger with a DB9-to-J1939 adapter cable to capture data from both networks simultaneously.

Physical Layer Standards

Three key SAE standards specify different physical layer configurations optimized for various vehicle environments:

J1939-11 is the original physical layer standard, specifying a shielded twisted pair cable with 120 Ω termination resistors at each end of the bus. It supports up to 30 ECUs at 250 kbit/s with a maximum bus length of 40 m and stub lengths up to 1 m.

J1939-15 provides a reduced-cost alternative for lighter-duty applications. It uses unshielded twisted pair cabling and allows longer stub lengths (up to 3 m), but limits the network to 10 ECUs due to reduced noise immunity.

J1939-14 targets higher bandwidth applications with a 500 kbit/s data rate. It accepts both shielded and unshielded wiring, supports up to 30 ECUs, and allows bus lengths between 40 m and 56.4 m depending on the cable type used.

6.5 J1939 Document Structure and Related Standards

The SAE J1939 standard suite is organized into numbered documents, each covering a specific aspect of the protocol. The following figure shows the complete document family organized by protocol layer:

Figure 6-3 *SAE J1939 Document Family — Standards Hierarchy Organized by Protocol Layer*

Standards Based on J1939

The J1939 protocol serves as the foundation for several industry-specific communication standards through SAE's consortium approach:

Table 6-9 Standards Derived from SAE J1939

Standard	Industry	Relationship to J1939
ISO 11783 (ISOBUS)	Agriculture	Extends J1939 for tractors and implements; adds task controller, virtual ECU
NMEA 2000	Marine	Adapts J1939 for marine electronics with device class definitions
ISO 11992	Truck-Trailer	J1939-based communication between truck and trailer via ISO 7638 connector
FMS Standard	Fleet Management	Subset of J1939 PGNs exposed via a standard gateway interface for telematics
MilCAN	Military	Military adaptation with deterministic scheduling requirements

SAE J1939 Consortium Model

SAE licenses the J1939 base standard to industry organizations who then extend it for their specific domains. This consortium approach ensures that developments in the base J1939 standard (e.g., CAN FD support via J1939-22) can propagate to all derived standards while allowing each industry to define domain-specific PGNs, device types, and application profiles.

6.6 J1939 Request Mechanism

J1939 provides a general-purpose request mechanism using **PGN 59904 (0xEA00)** — the Request PGN. Any node can request any PGN from a specific ECU (destination-specific) or from all ECUs on the bus (global request). This is essential for retrieving parameters that are not broadcast periodically.

Request vs Broadcast Model

J1939 uses two communication models:

Table 6-10 J1939 Communication Models

Model	Mechanism	Examples
Periodic Broadcast	ECU sends PGN at fixed intervals (10 ms – 10 s)	EEC1 (Engine Speed, 10 ms), CCVS1 (Vehicle Speed, 100 ms)
On-Request	PGN sent only when explicitly requested via PGN 59904	Software Identification, Component ID, ECU Identification
Event-Driven	PGN sent when a specific condition occurs	DM1 (active DTC detected), Address Claimed

Request Message Structure

The Request PGN uses a 3-byte data field containing the PGN being requested, sent in little-endian byte order:

```
Request PGN (0xEA00) — CAN ID: 0x18EAFF[SA] (global) or 0x18EA[DA][SA] (destination-
specific)

CAN ID breakdown:
  Priority: 6 (0x18 = 0b110...)
  PGN:      0xEA00 (59904) — Request PGN
  DA:       0xFF (global) or specific destination address
  SA:       Source address of requester

Data (3 bytes):
  Byte 1:   PGN[7:0]   — LSB of requested PGN
  Byte 2:   PGN[15:8]  — Middle byte
  Byte 3:   PGN[23:16] — MSB of requested PGN
```

Request/Response Example: Request Engine Speed (EEC1)

```
Step 1 — Service Tool (SA=0xF9) requests PGN 61444 from Engine ECU (DA=0x00):
  CAN ID: 0x18EA00F9    Data: [04 F0 00]
                              │  │  └─ PGN MSB = 0x00
                              │  └──── PGN mid = 0xF0
                              └─────── PGN LSB = 0x04  → PGN = 0x00F004 = 61444

Step 2 — Engine ECU (SA=0x00) responds with EEC1:
  CAN ID: 0x0CF00400    Data: [FF FF FF 68 13 FF FF FF]
                                        │  └─ Byte 5 = 0x13
                                        └──── Byte 4 = 0x68
  Engine Speed (SPN 190) = 0x1368 × 0.125 = 621.0 rpm
```

> **Global vs Destination-Specific Request**
>
> When DA = `0xFF`, the request is global — all ECUs that support the requested PGN will respond. This is useful for discovery (e.g., requesting Address Claimed from all nodes). When DA is a specific address, only that ECU responds. For Transport Protocol messages (>8 bytes), the responding ECU initiates a TP.CM_RTS/CTS or BAM sequence to deliver the multi-packet response.

6.7 Identification Requests

J1939 defines several standard PGNs for ECU identification. These are typically on-request PGNs that provide software version, hardware identity, and component information. They are essential for fleet management, diagnostics, and regulatory compliance.

Software Identification (PGN 65242 / 0xFEDA)

Reports the software version(s) installed on the ECU. This PGN is used by diagnostic tools and fleet management systems to verify ECU firmware versions across a vehicle fleet.

Table 6-11 PGN 65242 — Software Identification

Byte	SPN	Description
1	SPN 965	Number of software identification fields
2–n	SPN 234	Software identification (ASCII string, `*` delimited for multiple versions)

```
Example — Request Software ID from Body Controller:
  Request:  CAN ID: 0x18EA21F9  Data: [DA FE 00]  ← PGN 65242 (0xFEDA)
  Response: via BAM (broadcast, because PGN 0xFEDA is PDU2 format — PF ≥ 0xF0)
    TP.CM_BAM: CAN ID: 0x18ECFF21  Data: [20 12 00 03 FF DA FE 00]
    TP.DT.1:   CAN ID: 0x18EBFF21  Data: [01 02 42 43 4D 5F 41 50]
    TP.DT.2:   CAN ID: 0x18EBFF21  Data: [02 50 5F 76 32 2E 31 2E]
    TP.DT.3:   CAN ID: 0x18EBFF21  Data: [03 30 2A 42 43 4D 5F 49]

    Decoded: Count=2, "BCM_APP_v2.1.0*BCM_IO_v1.3"
```

Component Identification (PGN 65259 / 0xFEEB)

Provides the ECU manufacturer, model, and serial number as ASCII strings. Each field is delimited by `*` (asterisk).

Table 6-12 PGN 65259 — Component Identification

Field	SPN	Description
Make	SPN 586	Component manufacturer name (ASCII)
Model	SPN 587	Component model designation (ASCII)
Serial Number	SPN 588	Component serial number (ASCII)
Unit Number	SPN 233	Unit/asset number assigned by owner (ASCII)

```
Decoded Component ID example:
  "BOSCH*EDC17C46*0281020567*FLEET-4821"
   │      │          │             └─ Unit Number (SPN 233)
   │      │          └───────────── Serial Number (SPN 588)
   │      └──────────────────────── Model (SPN 587)
   └─────────────────────────────── Make (SPN 586)
```

ECU Identification (PGN 64965 / 0xFDC5)

Provides the ECU part number and ECU type information. Unlike Component Identification which describes the physical component, ECU Identification provides the manufacturer's part and type codes used for service and replacement.

Table 6-13 PGN 64965 — ECU Identification

Field	SPN	Description
ECU Part Number	SPN 2901	Manufacturer's part number for the ECU (ASCII)
ECU Serial Number	SPN 2902	Unique serial number for the ECU unit (ASCII)
ECU Location	SPN 2903	Physical installation location description (ASCII)
ECU Type	SPN 2904	Functional type of ECU (ASCII)

Vehicle Identification (PGN 65260 / 0xFEEC)

Broadcasts the Vehicle Identification Number (VIN) — a 17-character ASCII string. This PGN is broadcast by the vehicle gateway or body controller and is used to identify the vehicle in diagnostic and fleet management contexts.

```
PGN 65260 (0xFEEC) — Vehicle Identification:
  SPN 237: Vehicle Identification Number (VIN)
  Data: 17-byte ASCII string (e.g., "WDB9634031L123456")
  Transmitted via BAM (requires 3 TP.DT packets)
```

Summary: Common Identification PGNs

Table 6-14 J1939 Identification PGN Summary

PGN	Hex	Name	Key SPNs	Typical Size
65242	0xFEDA	Software Identification	SPN 234, 965	Variable (BAM)
65259	0xFEEB	Component Identification	SPN 586, 587, 588, 233	Variable (BAM)
64965	0xFDC5	ECU Identification	SPN 2901–2904	Variable (BAM)
65260	0xFEEC	Vehicle Identification	SPN 237 (VIN)	17 bytes (BAM)
65243	0xFEDB	Calibration Identification	SPN 1634, 1635	Variable (BAM)

> **Multi-Packet Identification Responses**
>
> All identification PGNs contain variable-length ASCII data and typically exceed 8 bytes. When responding to a request, the ECU uses the **BAM** (Broadcast Announce Message) transport protocol for global responses, or **RTS/CTS** for destination-specific responses. Diagnostic tools must implement the J1939 Transport Protocol (see Chapter 7) to receive these multi-packet responses.

Chapter 7: J1939 Transport Protocol

Since CAN frames are limited to 8 data bytes, J1939 defines a Transport Protocol (TP) for transmitting larger messages. The transport protocol supports two modes: Connection Mode (CM) for point-to-point communication and Broadcast Announce Message (BAM) for global broadcasts.

7.1 TP.CM and TP.DT

The Connection Mode transport protocol uses two PGNs:

- **TP.CM (PGN 60416):** Transport Protocol Connection Management - controls connection setup
- **TP.DT (PGN 60160):** Transport Protocol Data Transfer - carries actual data packets

TP.CM Control Bytes

Table 7-1 TP.CM Control Byte Values

Value	Name	Description
16 (0x10)	RTS	Request to Send - initiates connection
17 (0x11)	CTS	Clear to Send - acknowledges RTS
19 (0x13)	End of Message ACK	Acknowledges complete reception
255 (0xFF)	Abort	Aborts connection
32 (0x20)	BAM	Broadcast Announce Message

RTS Message Format (TP.CM)

```
Byte 0: Control Byte = 0x10 (RTS)
Byte 1-2: Total message size (bytes) - LSB first
Byte 3: Total number of packets
Byte 4: Reserved (0xFF)
Byte 5-7: PGN of requested message - LSB first
```

CTS Message Format (TP.CM)

```
Byte 0: Control Byte = 0x11 (CTS)
Byte 1: Number of packets that can be sent
Byte 2: Next packet number to be sent
Byte 3-4: Reserved (0xFFFF)
Byte 5-7: PGN - LSB first
```

TP.DT Data Packet Format

```
Byte 0: Sequence number (1-255)
Byte 1-7: Data (up to 7 bytes per packet)
```

7.2 BAM Protocol

The Broadcast Announce Message (BAM) protocol is used for global broadcasts where no connection management is required. The transmitting node announces the message and then broadcasts all data packets.

BAM Message Format (TP.CM)

```
Byte 0: Control Byte = 0x20 (BAM)
Byte 1-2: Total message size (bytes) - LSB first
Byte 3: Total number of packets
Byte 4: Reserved (0xFF)
Byte 5-7: PGN of broadcast message - LSB first
```

> **BAM Limitations**
>
> BAM does not provide flow control or acknowledgment. The transmitter sends all packets at 50-200 ms intervals regardless of receiver capability. BAM is limited to 1785 bytes (255 packets × 7 bytes).

7.3 Multi-packet Messages

The transport protocol can handle messages up to 1785 bytes using up to 255 data packets. Each TP.DT frame carries a sequence number and up to 7 data bytes.

Number of Packets Calculation

$$N_{packets} = \lceil \frac{Message\ Size}{7} \rceil$$

Maximum message size: 255 × 7 = 1785 bytes

Example: Transmitting a 100-byte message

```
1. Send TP.CM RTS:
   - Total size: 100 bytes
   - Number of packets: ceil(100/7) = 15
   - PGN: 0x00FF00 (example)

2. Receive TP.CM CTS:
   - Number of packets allowed: 1-255
   - Next packet: 1

3. Send TP.DT packets 1-15:
   - Each packet: 7 bytes (except last may have less)
   - Packet 15: only 2 bytes (100 - 14×7 = 2)

4. Receive TP.CM End of Message ACK
```

Connection Mode Transport Protocol Sequence:

1. Sender → Receiver: TP.CM RTS (Request to Send)
2. Receiver → Sender: TP.CM CTS (Clear to Send)
3. Sender → Receiver: TP.DT #1 (Data Transfer Packet 1)
4. Sender → Receiver: TP.DT #2 (Data Transfer Packet 2)
5. Continue until all packets sent...
6. Receiver → Sender: TP.CM EOM (End of Message ACK)

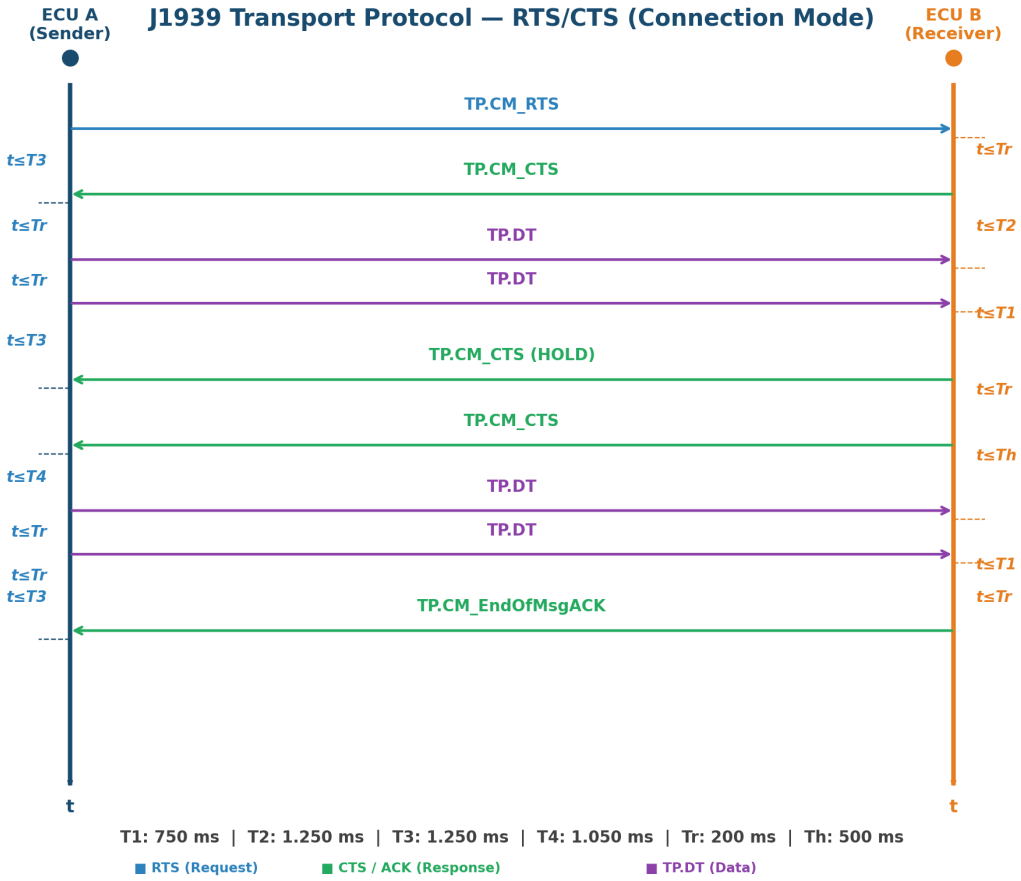


Figure 7-1 *J1939 RTS/CTS Connection Mode — Complete Sequence with Timeout Values*

RTS/CTS Timeout Parameters

The J1939-21 standard defines strict timeout values for each phase of the RTS/CTS handshake. Violating these timeouts results in connection abort:

Table 7-2 J1939 Transport Protocol Timeout Values

Timeout	Value	Monitored By	Description
T1	750 ms	Receiver	Maximum wait between consecutive TP.DT packets
T2	1250 ms	Receiver	Maximum wait after sending CTS before first TP.DT arrives
T3	1250 ms	Sender	Maximum wait for CTS response after sending RTS or last TP.DT
T4	1050 ms	Sender	Maximum wait for CTS after receiving CTS(HOLD)
Tr	200 ms	Both	Maximum response time for protocol messages
Th	500 ms	Receiver	Hold timeout — time receiver may request sender to wait

CTS HOLD Mechanism

The receiver can temporarily pause data transfer by sending a CTS with "number of packets = 0" (CTS HOLD). This signals the sender to wait without aborting the connection. The receiver uses this when its internal buffers are full or processing is temporarily blocked. The sender waits up to T4 (1050 ms) for a new CTS before aborting.

BAM Sequence Diagram

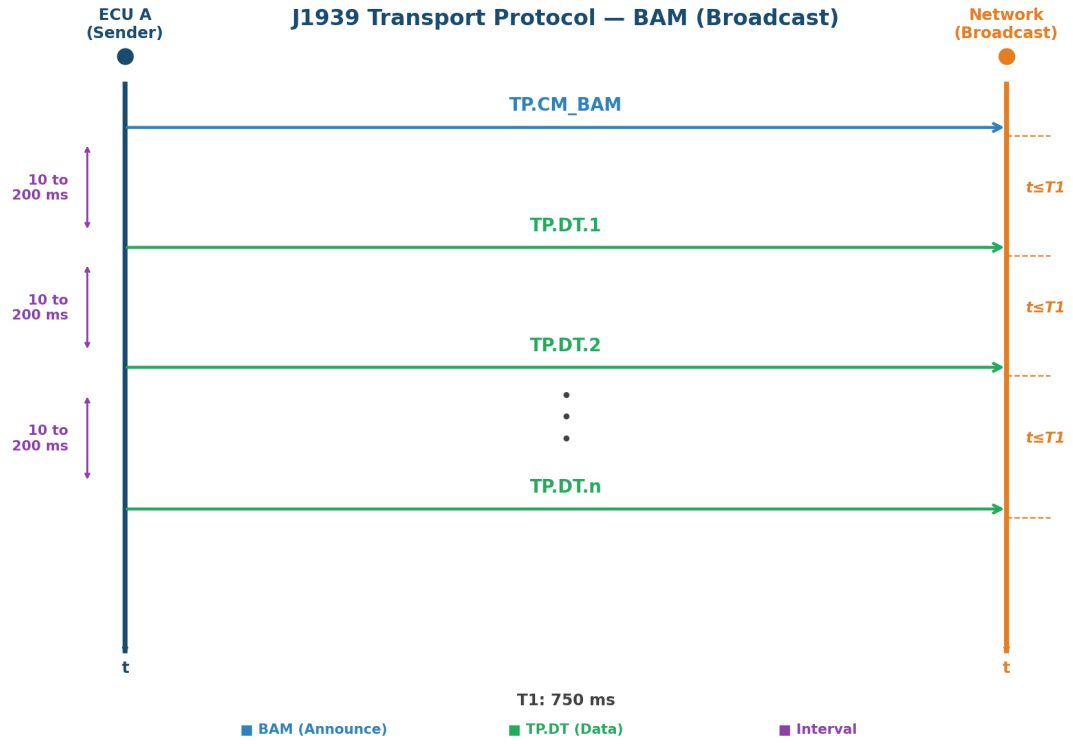


Figure 7-2 *J1939 BAM (Broadcast Announce Message) — Sequence with Timing*

> **Transport Protocol Timing**
>
> In BAM mode, the transmitter sends TP.DT packets at intervals of 10 to 200 ms. The receiver monitors T1 (750 ms) between consecutive packets — if no packet arrives within T1, the transfer is considered failed. In RTS/CTS mode, the sender monitors T3 (1250 ms) waiting for CTS, and the receiver monitors T1 (750 ms) between TP.DT packets and T2 (1250 ms) after sending CTS before receiving the first TP.DT.

Chapter 8: J1939 Diagnostics

J1939 provides comprehensive diagnostic capabilities through standardized Diagnostic Message (DM) PGNs and a structured Diagnostic Trouble Code (DTC) format. The diagnostic system enables fault detection, reporting, and clearing across all vehicle systems.

8.1 DTC Structure

J1939 Diagnostic Trouble Codes follow a standardized format that provides detailed information about detected faults.

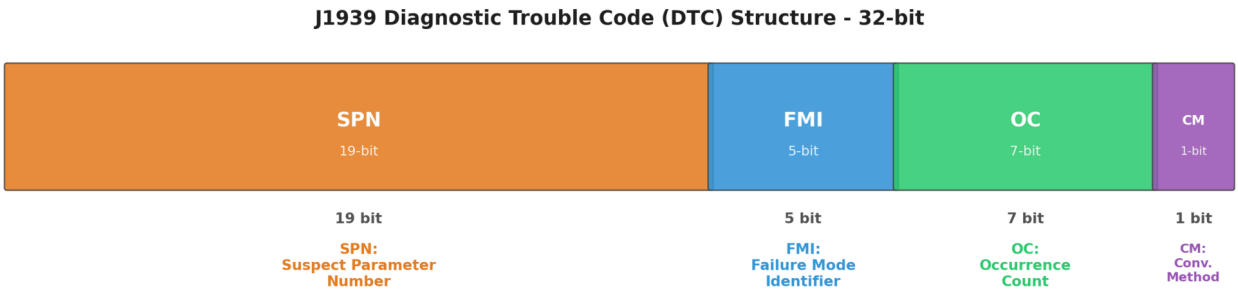


Figure 8-1 *J1939 Diagnostic Trouble Code (DTC) Structure - 32-bit*

8.2 SPN-FMI-OC-CM

The DTC consists of four fields:

Table 8-1 DTC Field Descriptions

Field	Bits	Description
SPN (Suspect Parameter Number)	19	Identifies the specific parameter with fault (0-524287)
FMI (Failure Mode Identifier)	5	Type of failure detected (0-31)
OC (Occurrence Count)	7	Number of fault occurrences (0-126, 127=not available)
CM (Conversion Method)	1	SPN conversion method (0=method 1, 1=method 2)

DTC Encoding

$$DTC = (SPN \ll 13) | (FMI \ll 8) | (OC \ll 1) | CM$$

Common FMI Values

Table 8-2 Common Failure Mode Identifiers (FMI)

FMI	Description	Typical Cause
0	Data Valid But Above Normal Range	Sensor reading too high
1	Data Valid But Below Normal Range	Sensor reading too low
2	Data Erratic, Intermittent, or Incorrect	Unstable signal
3	Voltage Above Normal or Shorted High	Short to power
4	Voltage Below Normal or Shorted Low	Short to ground
5	Current Below Normal or Open Circuit	Open circuit, broken wire
6	Current Above Normal or Grounded Circuit	Short circuit
7	Mechanical System Not Responding	Actuator failure
8	Abnormal Frequency or Pulse Width	Signal interference
9	Abnormal Update Rate	Communication failure
10	Abnormal Rate of Change	Rapid signal change
11	Root Cause Not Known	Unknown failure
12	Bad Intelligent Device or Component	Component malfunction
13	Out of Calibration	Calibration required
14	Special Instructions	See service manual
15	Data Valid But Above Normal Range (Least Severe)	Warning threshold
16	Data Valid But Above Normal Range (Moderately Severe)	Critical threshold
17	Data Valid But Below Normal Range (Least Severe)	Warning threshold
18	Data Valid But Below Normal Range (Moderately Severe)	Critical threshold
31	Condition Exists	General condition

8.3 DM Messages

Diagnostic Messages (DM) are PGNs used for diagnostic communication. They enable reading DTCs, clearing faults, and accessing diagnostic data.

Table 8-3 Common J1939 Diagnostic Messages (DM)

DM	PGN	Name	Description
DM1	65226 (0x00FECA)	Active Diagnostic Trouble Codes	Broadcasts active DTCs
DM2	65227 (0x00FECB)	Previously Active DTCs	DTCs that are now inactive
DM3	65228 (0x00FECC)	Clear Previously Active DTCs	Command to clear DM2 DTCs
DM4	65229 (0x00FECD)	Freeze Frame Parameters	Snapshots of parameters at fault
DM5	65230 (0x00FECE)	Diagnostic Readiness	Monitor readiness status
DM6	65231 (0x00FECF)	Pending DTCs	Intermittent faults
DM11	65235 (0x00FED3)	Clear Active DTCs	Command to clear DM1 DTCs
DM19	54016 (0x00D300)	Calibration Information	ECU calibration details
DM21	49408 (0x00C100)	MIL Status	Malfunction Indicator Lamp

DM1 Active DTCs Format

```
Byte 0: Protect Lamp Status / Amber Warning Lamp
Byte 1: Red Stop Lamp / Malfunction Indicator Lamp
Byte 2-5: DTC #1 (SPN-FMI-OC-CM)
Byte 6-9: DTC #2 (SPN-FMI-OC-CM)
Byte 10-13: DTC #3 (SPN-FMI-OC-CM)
Byte 14-17: DTC #4 (SPN-FMI-OC-CM)
Byte 18-21: DTC #5 (SPN-FMI-OC-CM)
```

> **DM1 Broadcast Rate**
>
> DM1 is broadcast every 1 second when active DTCs exist. When no DTCs are active, DM1 is broadcast every 10 seconds with a lamp status of 0x00 and no DTCs.

Chapter 9: Automotive Diagnostics — OBD-II and UDS

On-Board Diagnostics (OBD) and Unified Diagnostic Services (UDS) are the two primary diagnostic protocols used in automotive applications. OBD-II is mandated for emissions-related diagnostics, while UDS (ISO 14229) provides a comprehensive framework for all manufacturer-specific diagnostic, programming, and calibration functions.

9.1 OBD-II Protocol

OBD-II (On-Board Diagnostics II) is a standardized system mandated by regulations in the United States (EPA), European Union (EOBD), and other regions. It provides access to emissions-related diagnostic information.

OBD-II Connector (J1962)

The OBD-II system uses the **SAE J1962** 16-pin diagnostic link connector (DLC), located under the dashboard within reach of the driver's seat. Key CAN bus pins:

Table 9-1 OBD-II (J1962) Connector CAN-Related Pins

Pin	Function	Notes
4	Chassis Ground	Vehicle chassis ground reference
5	Signal Ground	Signal reference ground
6	CAN High (CAN_H)	High-speed CAN bus — yellow wire
14	CAN Low (CAN_L)	High-speed CAN bus — green wire
16	Battery Positive (+12V)	Permanent battery power, always on

> **OBD-II Vehicle Compatibility**
>
> OBD-II over CAN (ISO 15765-4) is mandatory for: **USA** — all vehicles from model year 2008+; **EU** — gasoline cars from 2001+ (EOBD) and diesel cars from 2004+. Older vehicles may use other OBD-II transport protocols (ISO 9141-2, SAE J1850 VPW/PWM, ISO 14230 KWP2000) which use different DLC pins. CAN bus uses pins 6 and 14 exclusively.

OBD-II Diagnostic Modes (Services)

Table 9-2 OBD-II Diagnostic Modes

Mode	Hex	Description
01	0x01	Current Powertrain Diagnostic Data (PID 00-FF)
02	0x02	Powertrain Freeze Frame Data
03	0x03	Emission-Related Diagnostic Trouble Codes
04	0x04	Clear/Reset Emission-Related Diagnostic Information
05	0x05	Oxygen Sensor Monitoring Test Results
06	0x06	On-Board Monitoring Test Results
07	0x07	Pending DTCs (Detected During Current Drive Cycle)
08	0x08	Control of On-Board System/Test
09	0x09	Vehicle Information (VIN, Calibration IDs)
0A	0x0A	Permanent DTCs (Emissions-related, cannot be cleared)

OBD-II DTC Format

OBD-II DTCs are 2-byte codes following a standardized format:

```
P0XXX - Powertrain (ISO/SAE controlled)
P1XXX - Powertrain (Manufacturer controlled)
B0XXX - Body (ISO/SAE controlled)
B1XXX - Body (Manufacturer controlled)
C0XXX - Chassis (ISO/SAE controlled)
C1XXX - Chassis (Manufacturer controlled)
U0XXX - Network (ISO/SAE controlled)
U1XXX - Network (Manufacturer controlled)
```

9.2 UDS Protocol

Unified Diagnostic Services (ISO 14229) is a comprehensive diagnostic protocol that supersedes the manufacturer-specific protocols used with OBD-II. UDS provides a standardized framework for all diagnostic, programming, and calibration functions.

UDS Protocol Stack

Table 9-3 UDS Protocol Stack

Layer	Standard	Description
Application	ISO 14229 (UDS)	Diagnostic services and functions
Transport	ISO 15765-2 (ISO-TP)	Multi-frame message transport
Network	ISO 15765-3	Network layer services
Data Link	ISO 11898-1 (CAN)	CAN frame transmission
Physical	ISO 11898-2 (CAN)	Physical signaling

ISO-TP Transport Layer (ISO 15765-2)

UDS messages that exceed 8 bytes (Classical CAN) or 64 bytes (CAN FD) must be segmented using the ISO-TP (ISO 15765-2) transport protocol. ISO-TP defines four frame types for multi-frame communication:

Table 9-3a ISO-TP Frame Types

Frame Type	PCI Byte	Description	Max Payload
Single Frame (SF)	0x0N (N = data length)	Complete message in one frame	7 bytes (CAN) / 62 bytes (CAN FD)
First Frame (FF)	0x1N NN (12-bit length)	First segment of a multi-frame message	6 bytes (CAN) / 61 bytes (CAN FD)
Consecutive Frame (CF)	0x2N (N = sequence number)	Subsequent segments (SN wraps 0–F)	7 bytes (CAN) / 63 bytes (CAN FD)
Flow Control (FC)	0x30 [FS] [BS] [STmin]	Receiver controls sender's transmission rate	N/A

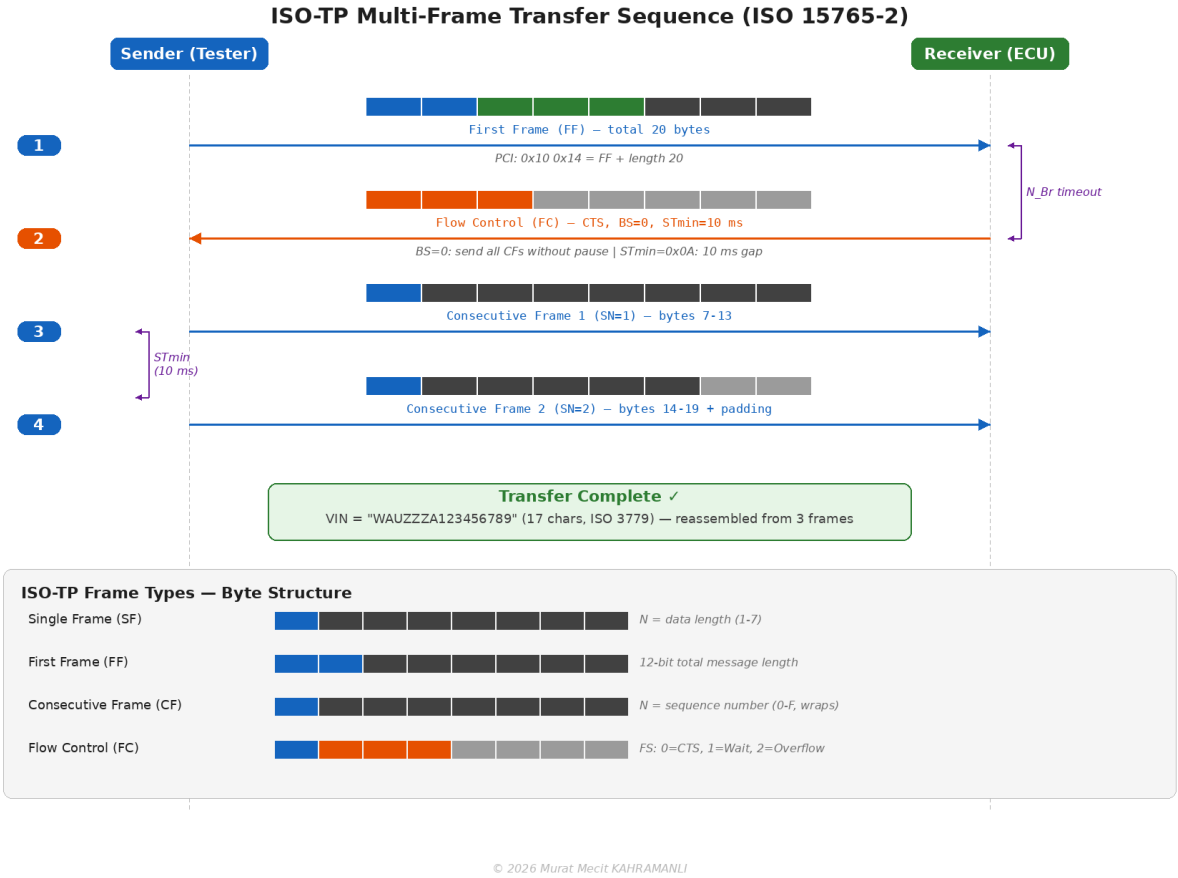


Figure 9-1 *ISO-TP Multi-Frame Transfer Sequence (ISO 15765-2)*

Flow Control Parameters

Block Size (BS): Number of consecutive frames the sender can transmit before waiting for the next FC. BS = 0 means no limit (send all CFs without pause).

STmin: Minimum separation time between consecutive frames. Values 0x00–0x7F represent 0–127 ms; values 0xF1–0xF9 represent 100–900 µs. STmin = 0 means send as fast as possible.

Flow Status (FS): 0 = Continue To Send (CTS), 1 = Wait, 2 = Overflow (abort).

UDS Timing Parameters

ISO 14229 and ISO 15765-3 define strict timing constraints that govern UDS communication. Correct implementation of these timers is critical for reliable diagnostic behavior:

Table 9-3b UDS Timing Parameters (ISO 14229 / ISO 15765-3)

Parameter	Description	Default Value	Extended Value
$P2_{server}$	Maximum time for ECU to start a response after receiving a request	50 ms	—
$P2^*_{server}$	Maximum time for ECU to start a response after sending NRC 0x78 (Response Pending)	5000 ms	—
$P2_{client}$	Tester timeout waiting for a response from ECU	50 ms + tolerance	—
$P2^*_{client}$	Tester timeout after receiving NRC 0x78	5000 ms + tolerance	—
$S3_{server}$	Session timeout — ECU reverts to Default Session if no request received	5000 ms	—
$S3_{client}$	Tester must send TesterPresent before this timer expires	< $S3_{server}$ (e.g., 4000 ms)	—

> **P2* Timeout Chain**
>
> When an ECU sends NRC 0x78 (Response Pending), the tester must reset its timeout to P2* and continue waiting — **not retry**. The ECU may send multiple NRC 0x78 responses before the final positive or negative response. Each NRC 0x78 resets the P2* timer. A common implementation error is to treat NRC 0x78 as a failure and retry the request, which causes duplicate requests and potential data corruption during flash programming.

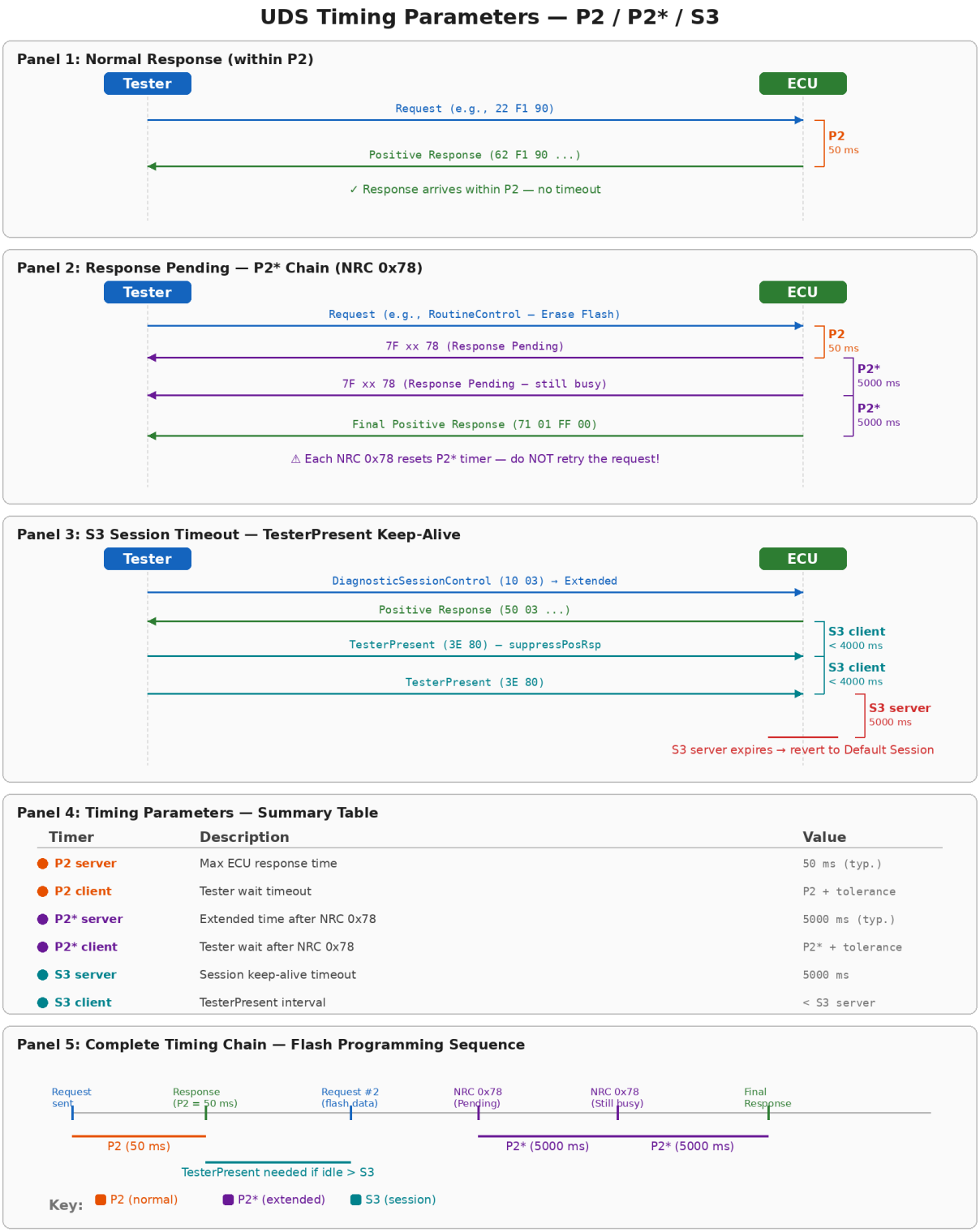


Figure 9-2 *UDS Timing Parameters — P2, P2*, and S3 Scenarios*

UDS Error Handling and Retry Strategy

Robust UDS implementations must distinguish between recoverable and non-recoverable errors. The retry behavior depends entirely on the Negative Response Code (NRC) received — or the absence of any response:

Table 9-3c UDS Error Handling — NRC-Based Retry Strategy

Condition	NRC / Behavior	Tester Action	Max Attempts
No response (timeout)	P2 expires, no frame received	Retry the same request	3
Response Pending	0x78	**Wait** (reset timer to P2*), do NOT retry	N/A (wait until final response)
Busy — Repeat Request	0x21	Wait briefly, then retry	3
Conditions Not Correct	0x22	Check pre-conditions, fix, then retry	1 (manual)
Service Not Supported	0x11	**Abort** — ECU does not support this service	0
Sub-function Not Supported	0x12	**Abort** — invalid sub-function	0
Security Access Denied	0x33	**Abort** — security locked, wait for delay timer	0
Invalid Key	0x35	Retry with correct key (decrement attempt counter)	Typically 3 before lockout
Request Sequence Error	0x24	**Abort** — restart sequence from beginning	0
General Reject	0x10	**Abort** — unrecoverable	0
Wrong Session	0x7E (serviceNotSupportedInActiveSession)	Switch session first (0x10), then retry	1 (after session change)

```
UDS Retry Logic — Pseudocode:

function uds_request(service, data, max_retries=3):
    for attempt in 1..max_retries:
        send(service, data)
        response = wait_response(timeout=P2)

        if response == TIMEOUT:
            continue                    // retry

        if response == POSITIVE:
            return response             // success

        nrc = response.nrc
        if nrc == 0x78:                 // Response Pending
            while True:
                response = wait_response(timeout=P2_star)
                if response != NRC_0x78:
                    return response     // final answer

        if nrc == 0x21:                 // Busy — Repeat Request
            wait(100 ms)
            continue                    // retry

        if nrc in [0x10, 0x11, 0x12, 0x24, 0x33]:
            return ERROR(nrc)           // non-recoverable → abort

        if nrc == 0x7E:                 // Wrong session
            switch_session(required_session)
            continue                    // retry once

    return ERROR(MAX_RETRIES_EXCEEDED)
```

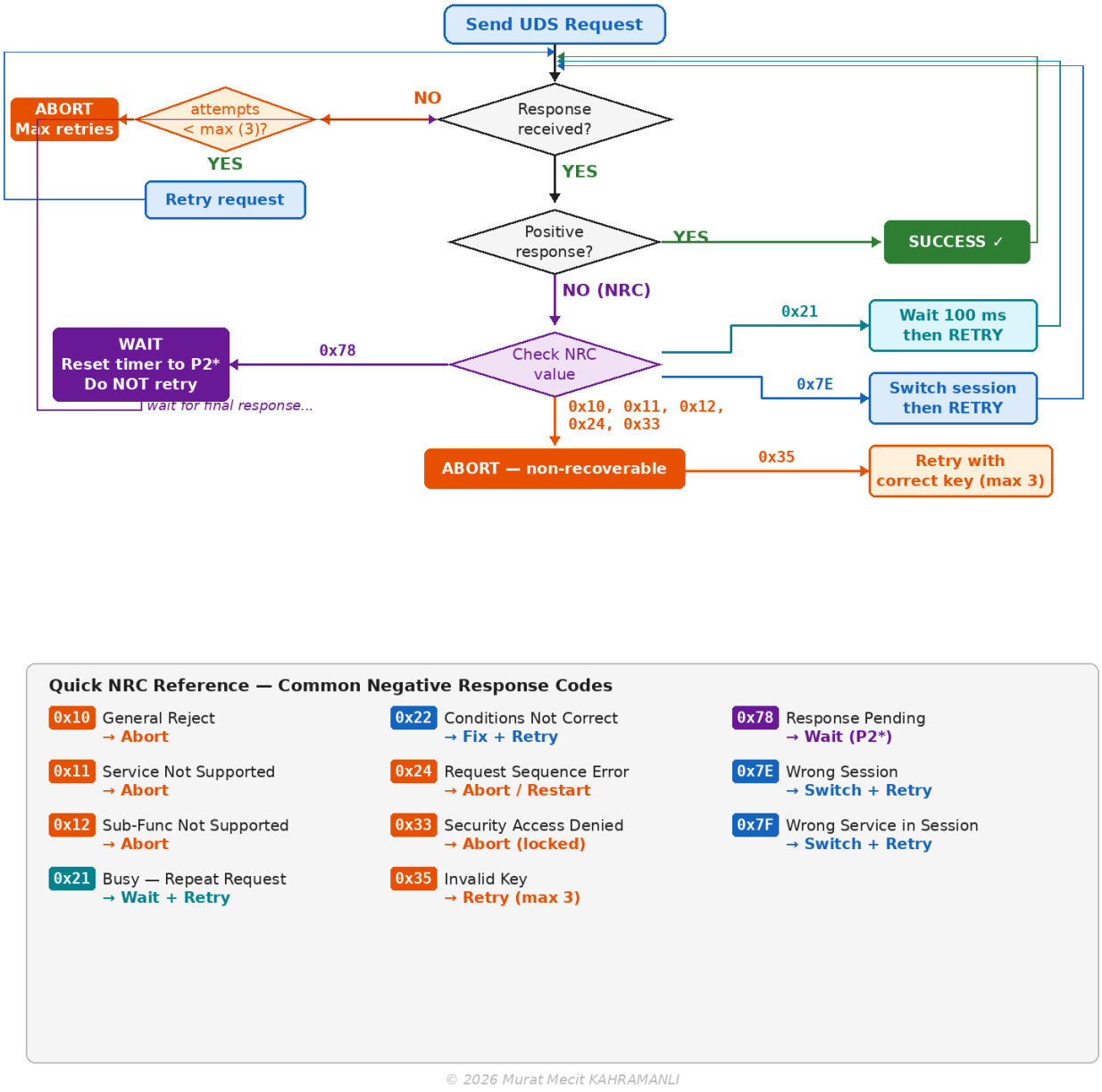


Figure 9-3 *UDS Error Handling — NRC-Based Retry Strategy Flowchart*

9.3 Protocol Comparison

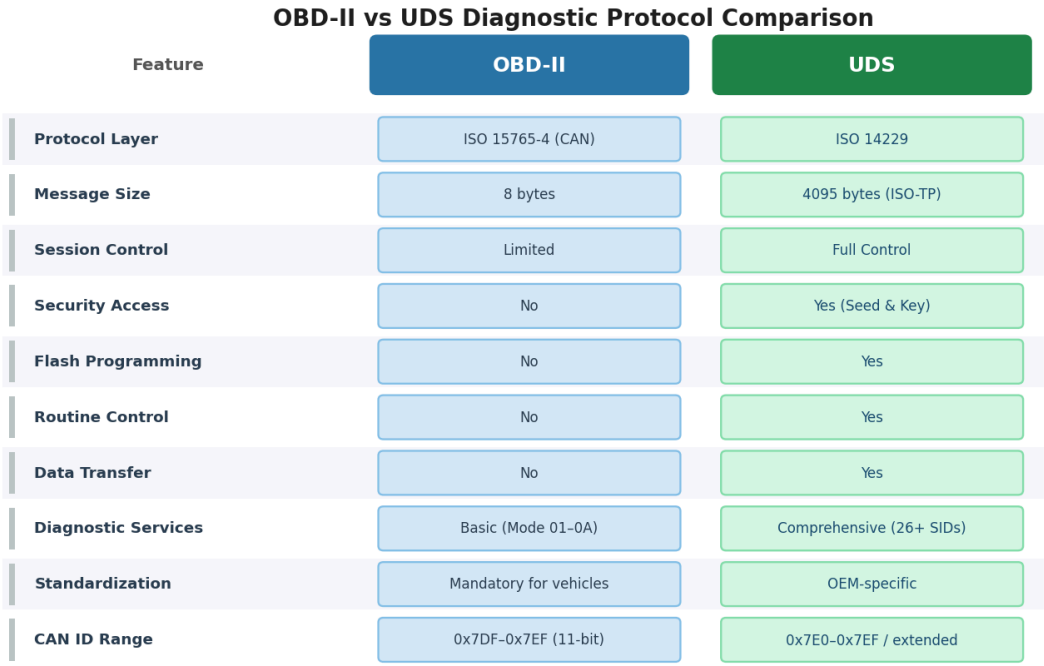


Figure 9-4 *OBD-II vs UDS Diagnostic Protocol Comparison*

Table 9-4 Detailed OBD-II vs UDS Comparison

Feature	OBD-II	UDS
Standard	SAE J1979, ISO 15031-5	ISO 14229
Mandatory	Yes (emissions-related)	No (manufacturer-specific)
Physical Layer	ISO 15765-4 (CAN), ISO 9141-2, SAE J1850	CAN, LIN, FlexRay, Ethernet
Max Data Length	7 bytes per frame (255 with TP)	4095 bytes (ISO-TP)
Session Control	Limited	Full session management
Security Access	Not defined	Seed/Key authentication
Flash Programming	Not supported	Full support
Number of Services	10 modes	26+ services
Manufacturer Extensions	Limited	Extensive

Regulatory Context

OBD-II is legally mandated for emissions-related diagnostics and must be supported by all vehicles sold in regulated markets. UDS is not mandated but has become the de facto standard for manufacturer-specific diagnostics and is required for vehicle type approval in Europe under the UNECE WP.29 regulations.

9.4 Diagnostic Protocol Standards — OSI Layer Mapping

All CAN-based diagnostic protocols share the same Physical (ISO 11898-2) and Data Link (ISO 11898-1) layers but diverge at higher OSI layers depending on the protocol family. The following diagram and table show how five major diagnostic standards map onto the 7-layer OSI model:

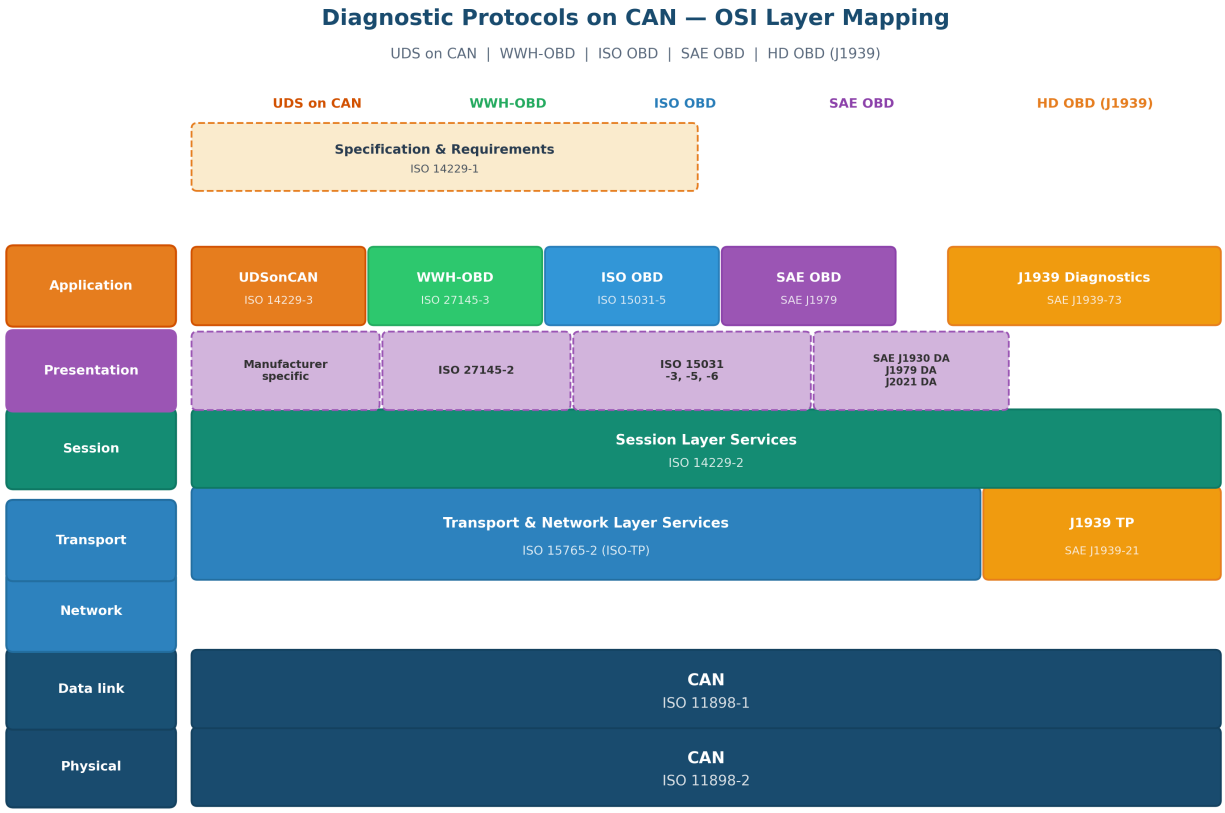


Figure 9-5 *Diagnostic Protocols on CAN — OSI Layer Mapping (UDS, WWH-OBD, ISO OBD, SAE OBD, HD OBD)*

Key specification — **ISO 14229-1** defines the common UDS service specification and requirements that sit above all application-layer variants. All five diagnostic families converge at ISO-TP (ISO 15765-2) for transport, except **HD OBD (J1939)** which uses its own transport protocol defined in SAE J1939-21.

UDS on CAN vs OBD-II: Which Standard When?

OBD-II / EOBD (ISO 15031-5 / SAE J1979) is mandatory for emissions-related diagnostics — legally required for all vehicles. **UDS** (ISO 14229) handles everything else: manufacturer diagnostics, ECU programming, flash updates, calibration. In practice, modern vehicles support *both* simultaneously — OBD-II services mapped to UDS SIDs 0x01–0x0A and full UDS services via manufacturer-specific extended sessions.

9.5 OBDonUDS and WWH-OBD — Diagnostic Protocol Evolution

The automotive industry is transitioning from legacy OBD-II (SAE J1979 / ISO 15031-5) to UDS-based emissions diagnostics. Two parallel paths exist: **OBDonUDS** (SAE J1979-2) for the US market and **WWH-OBD** (ISO 27145) for the EU market. Both leverage UDS (ISO 14229) as their foundation, replacing the proprietary Mode/PID structure of legacy OBD-II with standard UDS services (ReadDataByIdentifier, ReadDTCInformation, etc.).

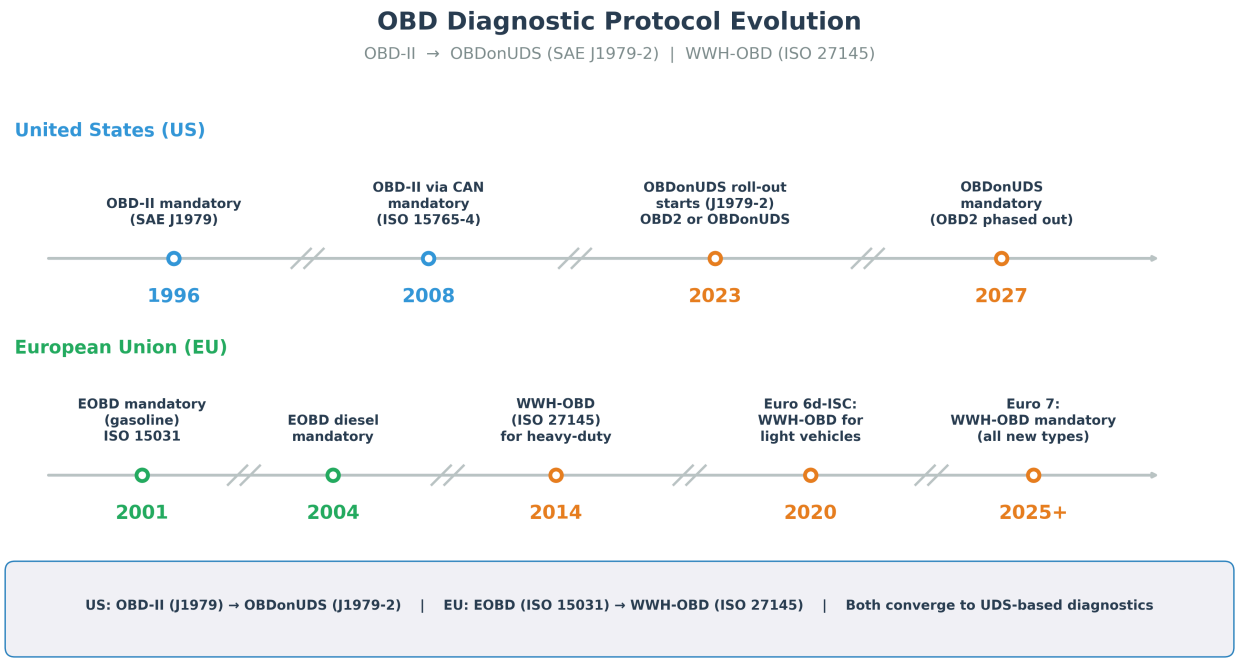


Figure 9-6 *OBD Diagnostic Protocol Evolution — US (OBDonUDS) and EU (WWH-OBD) Timelines*

US Market: OBD-II → OBDonUDS (SAE J1979-2)

EU Market: EOBD → WWH-OBD (ISO 27145)

OBDonUDS vs WWH-OBD vs Legacy OBD-II Comparison

Table 9-5 Legacy OBD-II vs OBDonUDS vs WWH-OBD

Feature	OBD-II (Legacy)	OBDonUDS (J1979-2)	WWH-OBD (ISO 27145)
Region	US / EU (legacy)	United States	European Union
Application Standard	SAE J1979 / ISO 15031-5	SAE J1979-2	ISO 27145-3
Base Protocol	Proprietary Mode/PID	UDS (ISO 14229)	UDS (ISO 14229)
Transport Layer	ISO 15765-4	ISO 15765-2	ISO 15765-2
Data Access	Mode + PID (e.g., Mode 01, PID 0x0C)	UDS SID + DID (e.g., 0x22 + DID)	UDS SID + DID (e.g., 0x22 + DID)
DTC Access	Mode 03 (stored), Mode 07 (pending)	SID 0x19 (ReadDTCInformation)	SID 0x19 (ReadDTCInformation)
Session Management	Not defined	Full UDS session control	Full UDS session control
Physical Layer	CAN only (ISO 15765-4)	CAN, CAN FD, DoIP	CAN, CAN FD, DoIP
Backward Compatible	—	Yes (legacy scan tools supported)	Yes (legacy scan tools supported)

> **Industry Convergence**
>
> Both OBDonUDS and WWH-OBD are built on UDS (ISO 14229), which means the automotive industry is converging to a **single diagnostic framework**. The key difference is the regulatory scope: OBDonUDS follows EPA/CARB regulations (US), while WWH-OBD follows UNECE WP.29 / Euro 7 regulations (EU). For engineers, this means UDS expertise covers both emissions and manufacturer diagnostics across all markets.

9.6 OBD-II Messaging Scenarios

OBD-II on CAN (ISO 15765-4) uses standardized 11-bit CAN message IDs. The diagnostic tester sends requests using either the functional address `0x7DF` (broadcast to all ECUs) or physical addresses `0x7E0` – `0x7E7` (targeted to specific ECUs). Each ECU responds on its assigned response ID (`0x7E8` – `0x7EF`).

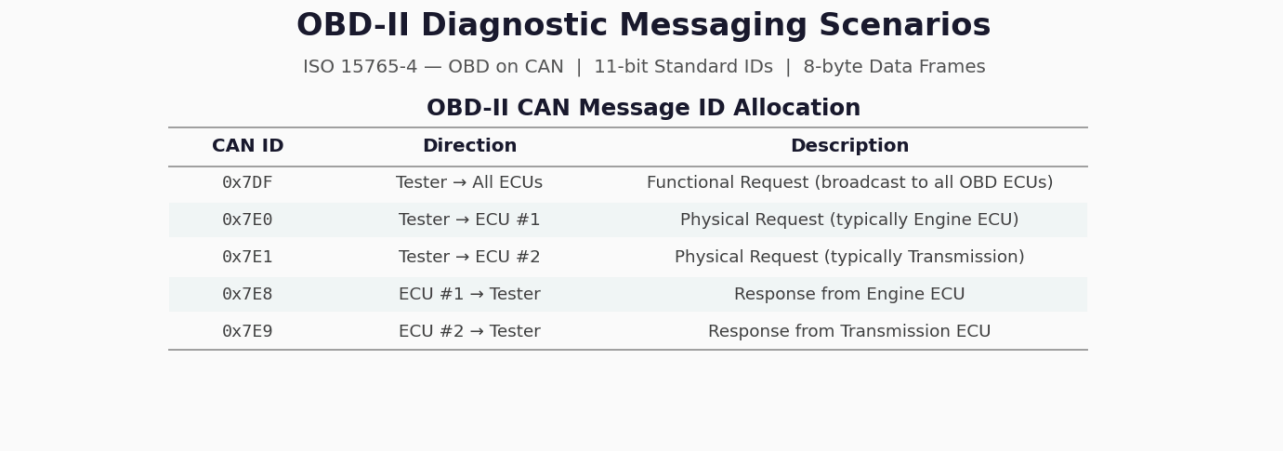


Figure 9-7 *OBD-II CAN Message ID Allocation (ISO 15765-4)*

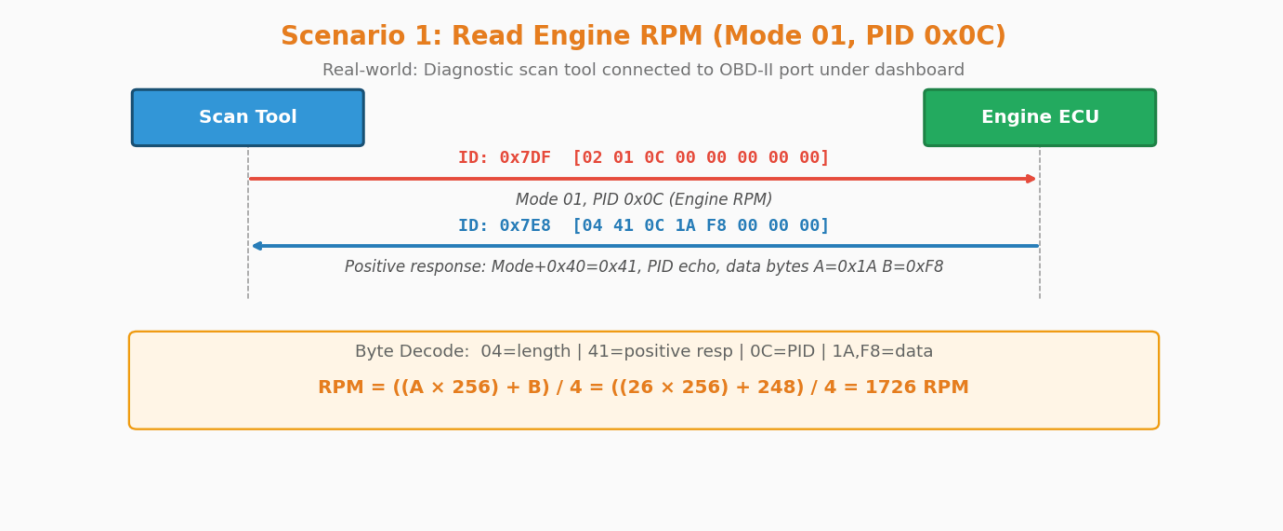


Figure 9-8 *Scenario 1: Read Engine RPM — Mode 01, PID 0x0C*

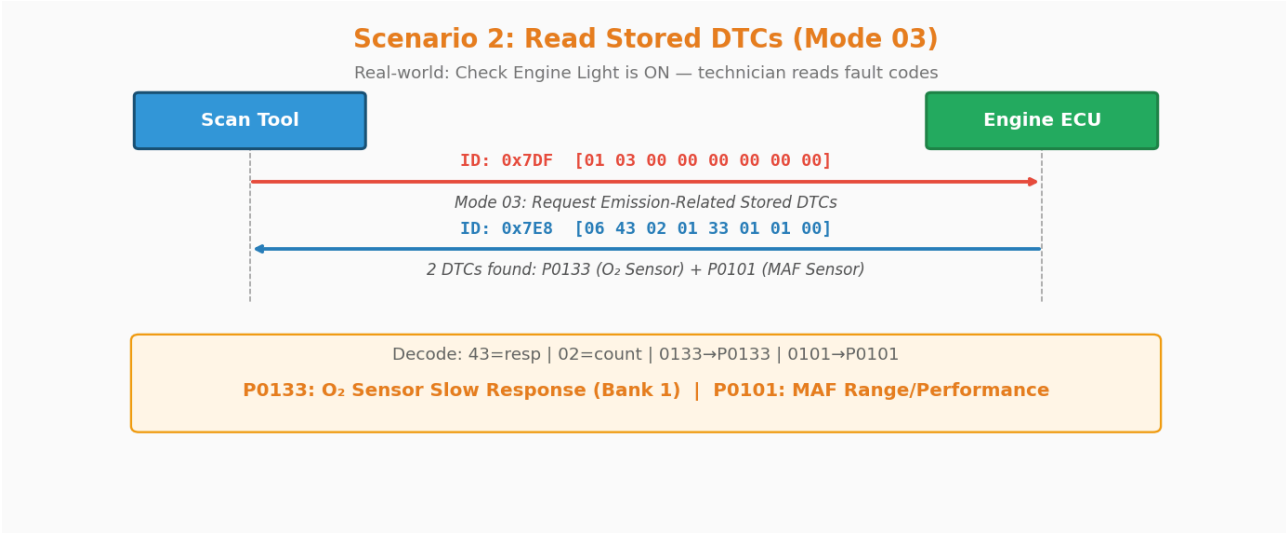


Figure 9-9 *Scenario 2: Read Stored DTCs — Mode 03*

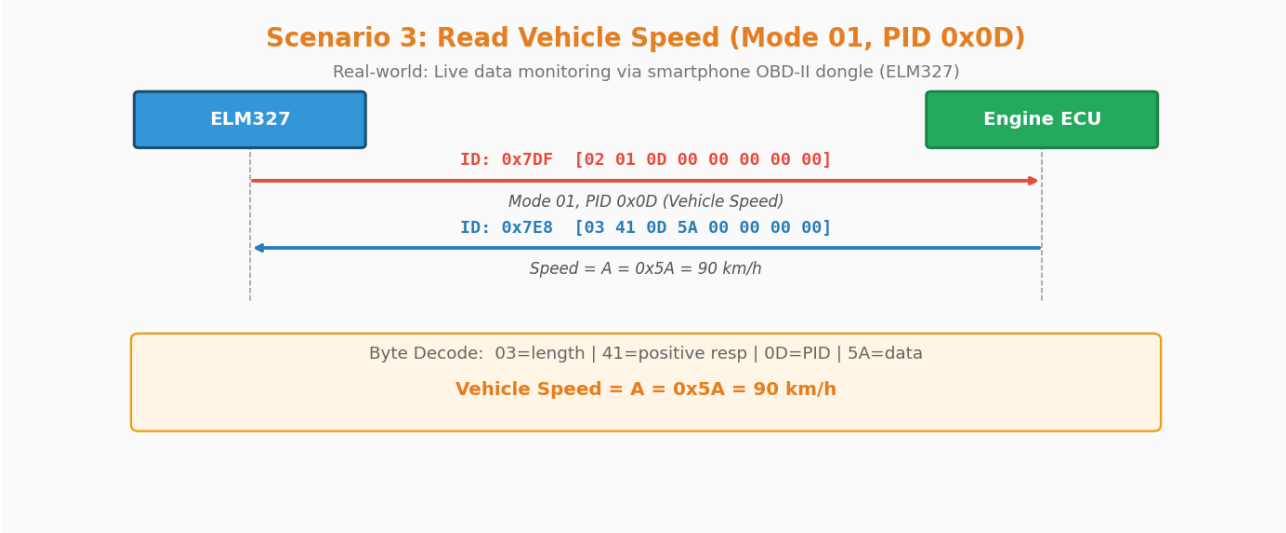


Figure 9-10 *Scenario 3: Read Vehicle Speed — Mode 01, PID 0x0D*

Commonly Used OBD-II PIDs (Mode 01)

PID	Parameter	Formula	Unit	Bytes
0x04	Engine Load	A × 100 / 255	%	1
0x05	Coolant Temperature	A − 40	°C	1
0x0C	Engine RPM	(A×256 + B) / 4	RPM	2
0x0D	Vehicle Speed	A	km/h	1
0x0F	Intake Air Temperature	A − 40	°C	1
0x10	MAF Air Flow Rate	(A×256 + B) / 100	g/s	2
0x11	Throttle Position	A × 100 / 255	%	1
0x2F	Fuel Tank Level	A × 100 / 255	%	1

Figure 9-11 *Commonly Used OBD-II PIDs (Mode 01) Reference Table*

Real-World Example: Reading Engine RPM at a Workshop

A technician connects an OBD-II scan tool to the 16-pin DLC connector under the dashboard. The tool sends a Mode 01 request for PID 0x0C (Engine RPM):

```
Tester Request (CAN ID: 0x7DF):
  [02] [01] [0C] [00] [00] [00] [00] [00]
   |    |    |
   |    |    └── PID: 0x0C (Engine RPM)
   |    └─────── Mode: 0x01 (Current Data)
   └──────────── Data Length: 2 bytes

ECU Response (CAN ID: 0x7E8):
  [04] [41] [0C] [1A] [F8] [00] [00] [00]
   |    |    |    |    |
   |    |    |    └────┘── Data bytes A=0x1A, B=0xF8
   |    |    └──────────── PID echo: 0x0C
   |    └───────────────── Positive response: 0x41 (Mode + 0x40)
   └────────────────────── Data Length: 4 bytes

RPM Calculation: ((A × 256) + B) / 4 = ((26 × 256) + 248) / 4 = 1726 RPM
```

Real-World Example: Reading Fault Codes After Check Engine Light

When the MIL (Check Engine Light) illuminates, a technician uses Mode 03 to retrieve stored DTCs:

```
Tester Request (CAN ID: 0x7DF):
  [01] [03] [00] [00] [00] [00] [00] [00]
   |    └── Mode 03: Request Emission-Related DTCs
   └─────── Length: 1 byte

ECU Response (CAN ID: 0x7E8):
  [06] [43] [02] [01] [33] [01] [01] [00]
   |    |    |    |         |
   |    |    |    └─────────┘── DTC 1: 0x0133 → P0133
   |    |    └── DTC count: 2  |       DTC 2: 0x0101 → P0101
   |    └─────── Positive response (Mode + 0x40)
   └──────────── Length: 6 bytes

P0133 → O₂ Sensor Circuit Slow Response (Bank 1, Sensor 1)
P0101 → Mass Air Flow (MAF) Circuit Range/Performance
```

9.7 J1939 OBD-II Diagnostics (Extended 29-bit IDs)

In heavy-duty vehicles (trucks, buses, construction equipment), diagnostics follow the **SAE J1939-73** standard instead of ISO 15765-4. J1939 uses **29-bit extended CAN identifiers** where the Parameter Group Number (PGN) is embedded directly in the CAN ID. Unlike standard OBD-II's request/response model, J1939 ECUs *broadcast* most parameters periodically (typically at 1 Hz), with specific diagnostic messages (DM1–DM4) carrying active and stored fault codes.

The 29-bit identifier encodes priority (3 bits), PGN/PDU format (18 bits), and source address (8 bits). For example, the Engine ECU (SA=0x00) broadcasting DM1 active DTCs uses CAN ID `0x18FECA00`, where PGN 65226 = DM1. Fault codes use the **SPN + FMI** format (Suspect Parameter Number + Failure Mode Identifier) rather than the P/C/B/U DTC codes of standard OBD-II.

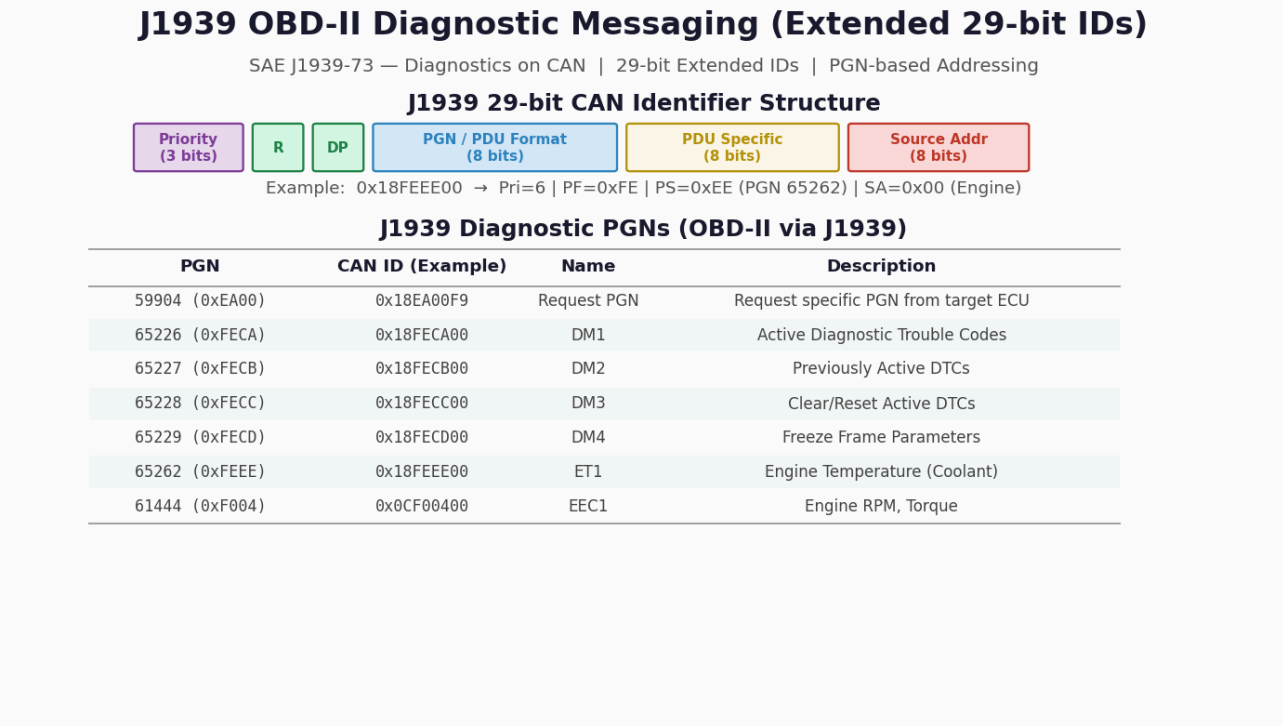


Figure 9-12 *J1939 29-bit CAN Identifier Structure and Diagnostic PGNs*

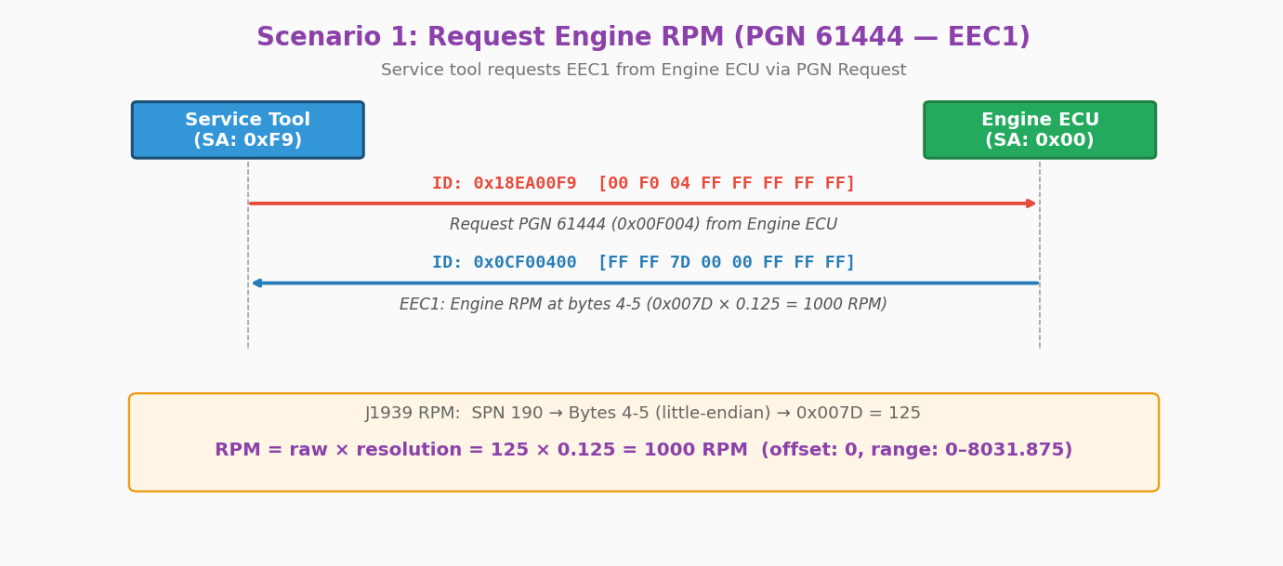


Figure 9-13 *Scenario 1: Request Engine RPM via PGN 61444 (EEC1)*

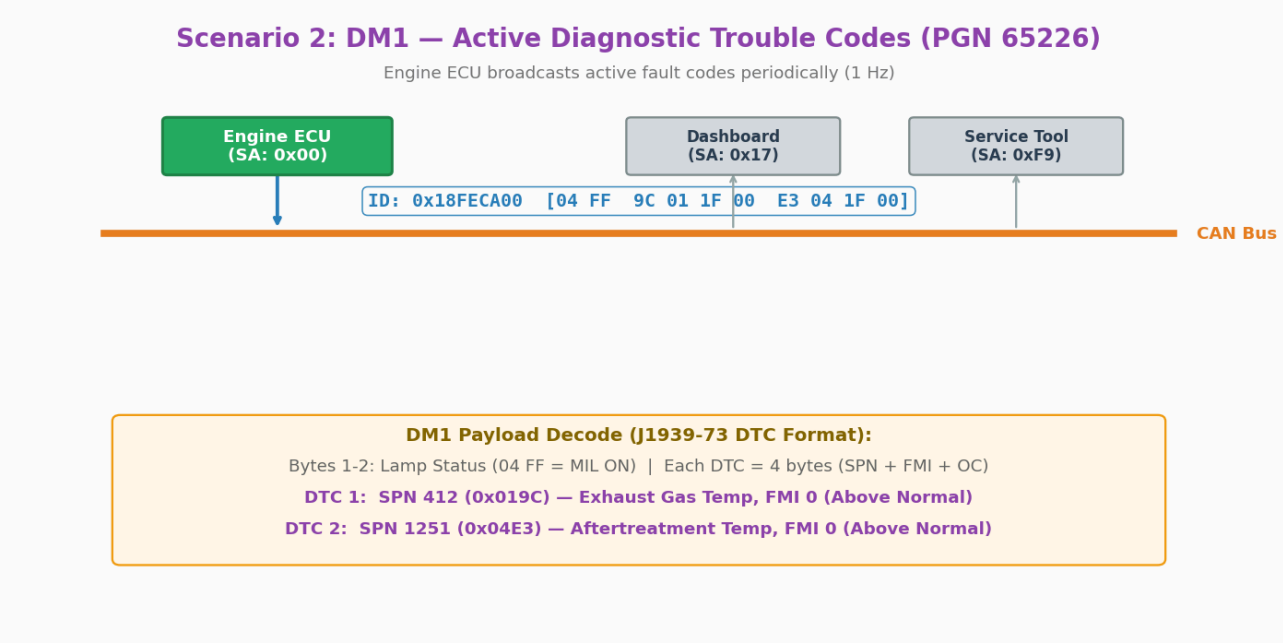


Figure 9-14 *Scenario 2: DM1 Active Diagnostic Trouble Codes (PGN 65226)*

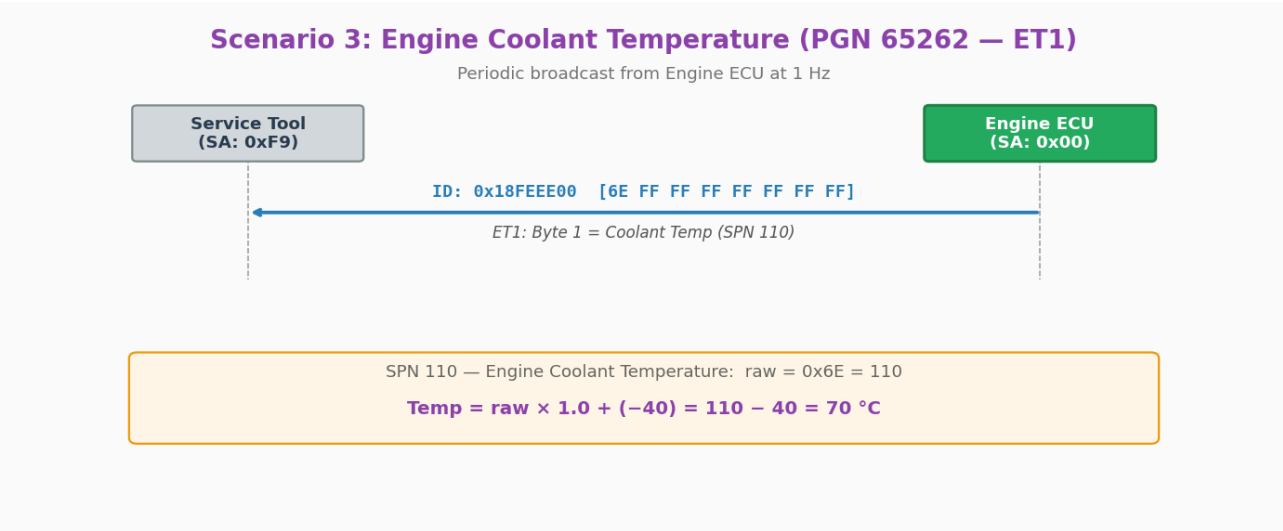


Figure 9-15 *Scenario 3: Engine Coolant Temperature (PGN 65262 — ET1)*

Key Differences: Standard OBD-II vs J1939 Diagnostics

Feature	Standard OBD-II (ISO 15765-4)	J1939 Diagnostics (SAE J1939-73)
CAN ID Length	11-bit standard	29-bit extended
Addressing	Fixed IDs (0x7DF, 0x7E0–0x7EF)	PGN-based (embedded in 29-bit ID)
Communication Model	Request/Response	Periodic Broadcast + Request/Response
Fault Code Format	P/C/B/U DTCs (e.g., P0133)	SPN + FMI (e.g., SPN 412, FMI 0)
Vehicle Type	Passenger cars, light trucks	Heavy-duty trucks, buses, off-highway
Diagnostic Messages	Modes 01–0A	DM1–DM50+ (Diagnostic Messages)

9.8 UDS Messaging Scenarios

UDS (ISO 14229) uses the same CAN ID range as OBD-II (`0x7E0` – `0x7EF`) but provides a far richer set of diagnostic services. UDS messages longer than 8 bytes are segmented using ISO-TP (ISO 15765-2) multi-frame transport protocol.

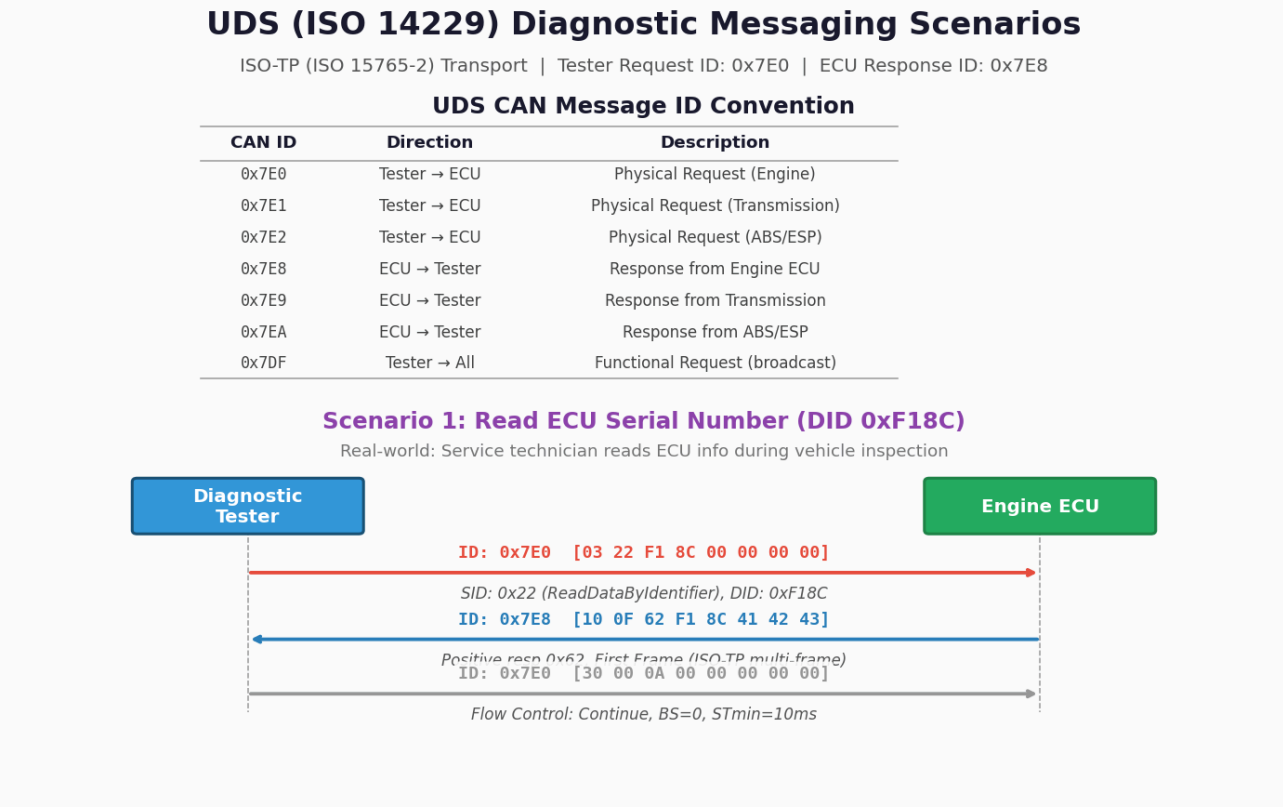


Figure 9-16 *UDS CAN Message IDs and Scenario 1: Read ECU Serial Number (DID 0xF18C)*

Figure 9-17 *Scenario 2: ECU Firmware Update — Complete Flash Programming Sequence*

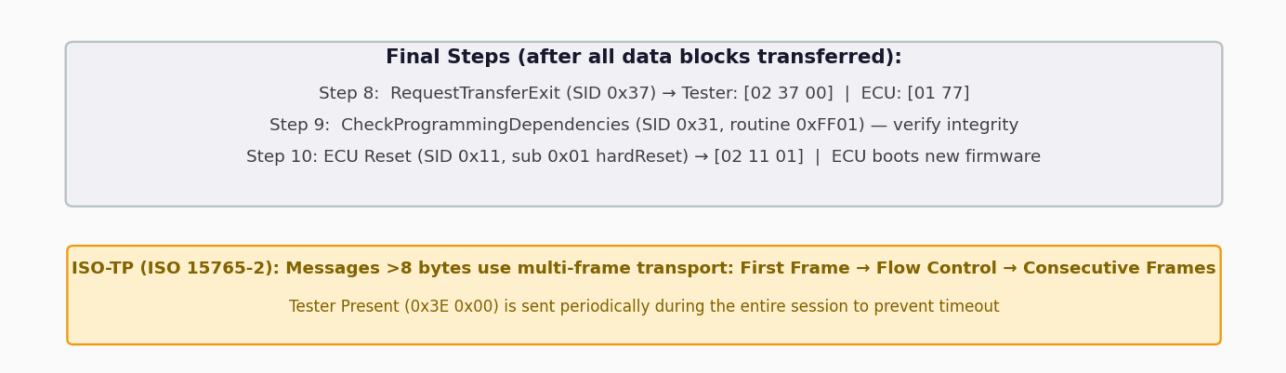


Figure 9-18 *Final Flash Programming Steps and ISO-TP Transport Note*

Real-World Example: ECU Firmware Update at Dealer Workshop

During an OEM recall campaign, the dealer workshop uses a VCI (Vehicle Communication Interface) to update the engine ECU firmware. The complete flash programming sequence follows these steps:

```
Step 1: Enter Extended Diagnostic Session
  Tester → ECU (0x7E0): [02 10 03]     DiagnosticSessionControl(ExtendedDiag)
  ECU → Tester (0x7E8): [02 50 03]     Positive Response

Step 2: Security Access — Request Seed
  Tester → ECU (0x7E0): [02 27 05]     SecurityAccess(Level 5 Seed Request)
  ECU → Tester (0x7E8): [06 67 05 A3 B2 C1 D0]  Seed = A3B2C1D0

Step 3: Security Access — Send Key
  Tester → ECU (0x7E0): [06 27 06 7C 4D 3E 2F]  Key = f(Seed, Secret)
  ECU → Tester (0x7E8): [02 67 06]     Security Unlocked ✓

Step 4: Enter Programming Session
  Tester → ECU (0x7E0): [02 10 02]     DiagnosticSessionControl(Programming)
  ECU → Tester (0x7E8): [02 50 02]     Positive Response

Step 5: Erase Flash Memory
  Tester → ECU (0x7E0): [10 0B 31 01 FF 00 ...]  RoutineControl(Erase)
  ECU → Tester (0x7E8): [03 7F 31 78]  NRC 0x78: Response Pending
  ECU → Tester (0x7E8): [04 71 01 FF 00]  Erase Complete ✓

Step 6: Request Download
  Tester → ECU (0x7E0): [10 0B 34 00 44 ...]  RequestDownload(addr, size)
  ECU → Tester (0x7E8): [04 74 20 10 02]  Max block = 4098 bytes

Step 7: Transfer Data (repeated for each block)
  Tester → ECU (0x7E0): [10 xx 36 01 <data>]  TransferData(block 1)
  ECU → Tester (0x7E8): [02 76 01]     Block Accepted

Step 8: Exit Transfer
  Tester → ECU (0x7E0): [02 37 00]     RequestTransferExit
  ECU → Tester (0x7E8): [01 77]        Exit OK

Step 9: Verify Programming
  Tester → ECU (0x7E0): [06 31 01 FF 01 ...]  RoutineControl(CheckDependencies)
  ECU → Tester (0x7E8): [06 71 01 FF 01 00]   Verification OK ✓

Step 10: ECU Hard Reset
  Tester → ECU (0x7E0): [02 11 01]     ECUReset(hardReset)
  ECU → Tester (0x7E8): [02 51 01]     ECU reboots with new firmware
```

> **Tester Present — Session Keep-Alive**
>
> During the entire programming sequence, the tester periodically sends `0x3E 0x00` (TesterPresent) to prevent the ECU from timing out and reverting to Default Session. The S3 timer is typically 5 seconds — if no diagnostic activity occurs within this period, the ECU automatically drops back to Default Session, aborting the programming process.

> **NRC 0x78 — Response Pending**
>
> When the ECU needs more time to process a request (e.g., erasing flash memory), it responds with Negative Response Code 0x78 (Response Pending). The tester must wait for the final positive or negative response. The ECU may send multiple 0x78 responses before the operation completes.

Practical Debug Scenarios

The following real-world CAN log examples demonstrate common UDS communication patterns and error conditions encountered during diagnostic development and field debugging.

Scenario 1 — VIN Read via ISO-TP Multi-Frame

```
TX: 7E0  [03 22 F1 90 00 00 00 00]     ReadDataByIdentifier(DID=0xF190)

RX: 7E8  [10 14 62 F1 90 57 41 55]     First Frame: total 20 bytes
TX: 7E0  [30 00 00 00 00 00 00 00]     Flow Control: BS=0, STmin=0 (send all)
RX: 7E8  [21 5A 5A 5A 31 32 33 34]     CF SN=1: "ZZZA1234"
RX: 7E8  [22 35 36 37 38 39 00 00]     CF SN=2: "56789"

Result: VIN = "WAUZZZA123456789" (17 characters, ISO 3779)
```

Analysis: The response exceeds 7 bytes, so ISO-TP segments it across 3 frames. Byte `0x10 0x14` = First Frame with total length 20 bytes. The tester responds with Flow Control (BS=0 = no limit). Two Consecutive Frames complete the transfer.

Scenario 2 — Response Pending (NRC 0x78)

```
TX: 7E0  [10 0B 31 01 FF 00 ...]       RoutineControl(Erase Flash)

RX: 7E8  [03 7F 31 78]                 NRC 0x78 — Response Pending
                                        ↳ Reset timer to P2* (5000 ms)
... (ECU erasing, 3.2 seconds later) ...
RX: 7E8  [03 7F 31 78]                 NRC 0x78 — Still processing
                                        ↳ Reset timer to P2* again
... (1.8 seconds later) ...
RX: 7E8  [04 71 01 FF 00]              Positive Response — Erase Complete ✓
```

Analysis: The ECU sends multiple NRC 0x78 while erasing flash. Each 0x78 resets the P2* timer. The tester must **not** retry — just wait.

Scenario 3 — Timeout (No Response)

```
TX: 7E0  [03 22 F1 90 00 00 00 00]     ReadDataByIdentifier(VIN)
RX: ---  (no response within P2=50 ms)

Retry 1:
TX: 7E0  [03 22 F1 90 00 00 00 00]     Retry
RX: ---  (no response)

Retry 2:
TX: 7E0  [03 22 F1 90 00 00 00 00]     Retry
RX: ---  (no response)

Result: FAIL — ECU unreachable after 3 attempts
```

Root causes: ECU not powered, wrong CAN bus, incorrect baud rate, ECU in sleep mode, physical layer fault (broken termination, CAN_H/CAN_L short).

Scenario 4 — Wrong Session (NRC 0x7E)

```
TX: 7E0  [04 2E F1 90 41]              WriteDataByIdentifier (in Default Session)
RX: 7E8  [03 7F 2E 7E]                NRC 0x7E — serviceNotSupportedInActiveSession

Fix: Switch to Extended Diagnostic session first
TX: 7E0  [02 10 03]                    DiagnosticSessionControl(ExtendedDiag)
RX: 7E8  [06 50 03 00 19 01 F4]       Positive: P2=25 ms, P2*=5000 ms

TX: 7E0  [04 2E F1 90 41]              Retry WriteDataByIdentifier
RX: 7E8  [02 6E F1]                    Positive Response ✓
```

Analysis: Many UDS services require Extended Diagnostic or Programming session. The positive response to `0x10` includes P2 and P2* timing values — the tester should update its timers accordingly.

Scenario 5 — Security Access Failure (NRC 0x35)

```
TX: 7E0  [02 27 01]                    SecurityAccess — Request Seed (Level 1)
RX: 7E8  [06 67 01 A3 B2 C1 D0]       Seed = 0xA3B2C1D0

TX: 7E0  [06 27 02 FF FF FF FF]        Send Key (WRONG key!)
RX: 7E8  [03 7F 27 35]                 NRC 0x35 — invalidKey

TX: 7E0  [02 27 01]                    Request new seed
RX: 7E8  [06 67 01 5E 7A 1C 9F]       New seed (different each time)

TX: 7E0  [06 27 02 XX XX XX XX]        Send correct key
RX: 7E8  [02 67 02]                    Access Granted ✓
```

Analysis: After an invalid key, the ECU generates a new seed on the next request. After 3 consecutive failures, the ECU activates a delay timer (typically 10–60 s) before accepting further seed requests.

Scenario 6 — ISO-TP Flow Control Failure

```
TX: 7E0  [10 14 62 F1 90 57 41 55]     ECU sends First Frame
RX: ---  (tester fails to send Flow Control)

Result: Transfer aborted — ECU timeout on FC
        No Consecutive Frames are sent
```

Root causes: Tester software bug (FC not implemented), CAN bus congestion preventing FC transmission, receive buffer overflow at tester side.

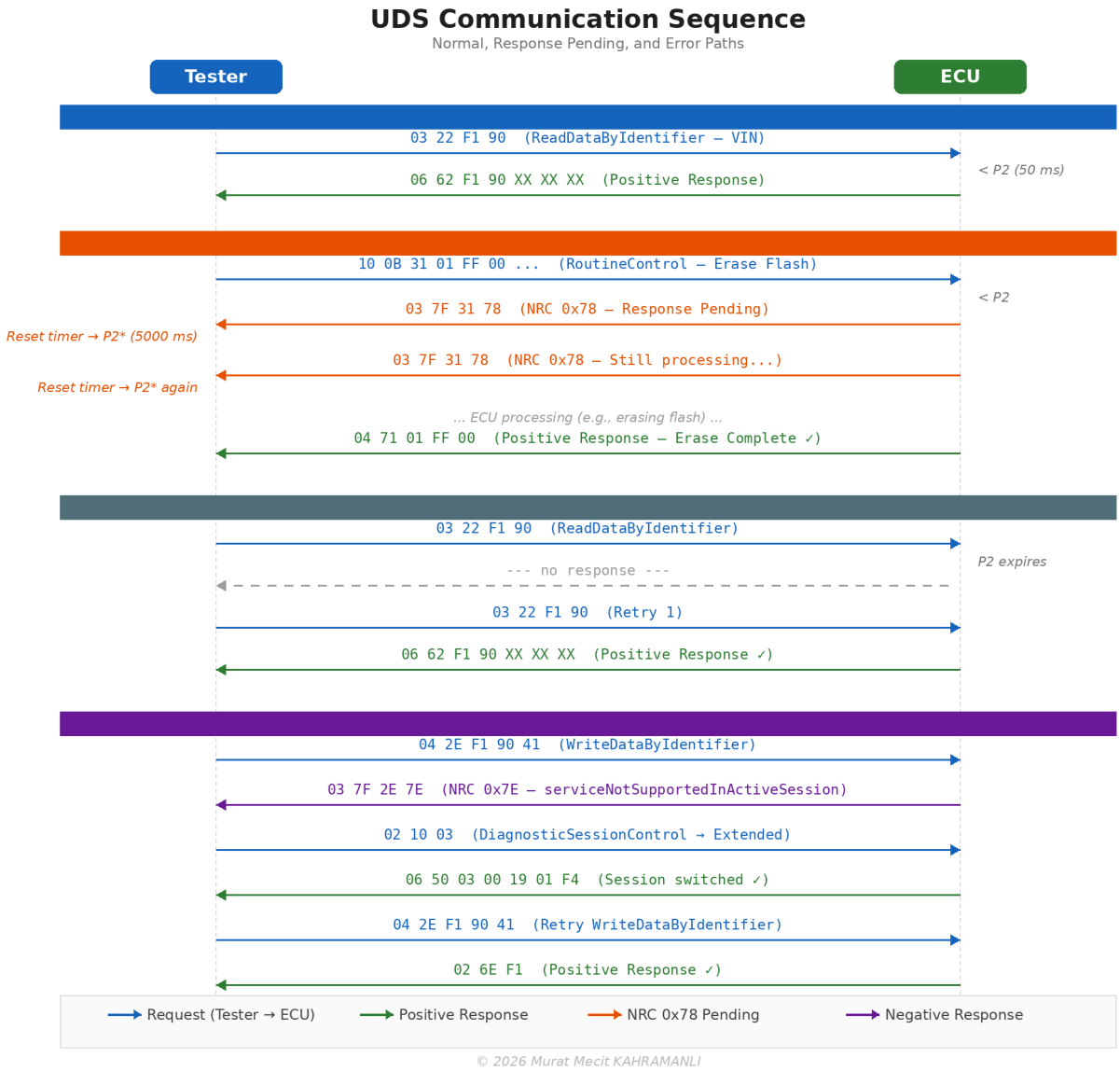


Figure 9-19 *UDS Communication Sequence — Normal, Response Pending, and Error Paths*

9.9 UDS Services

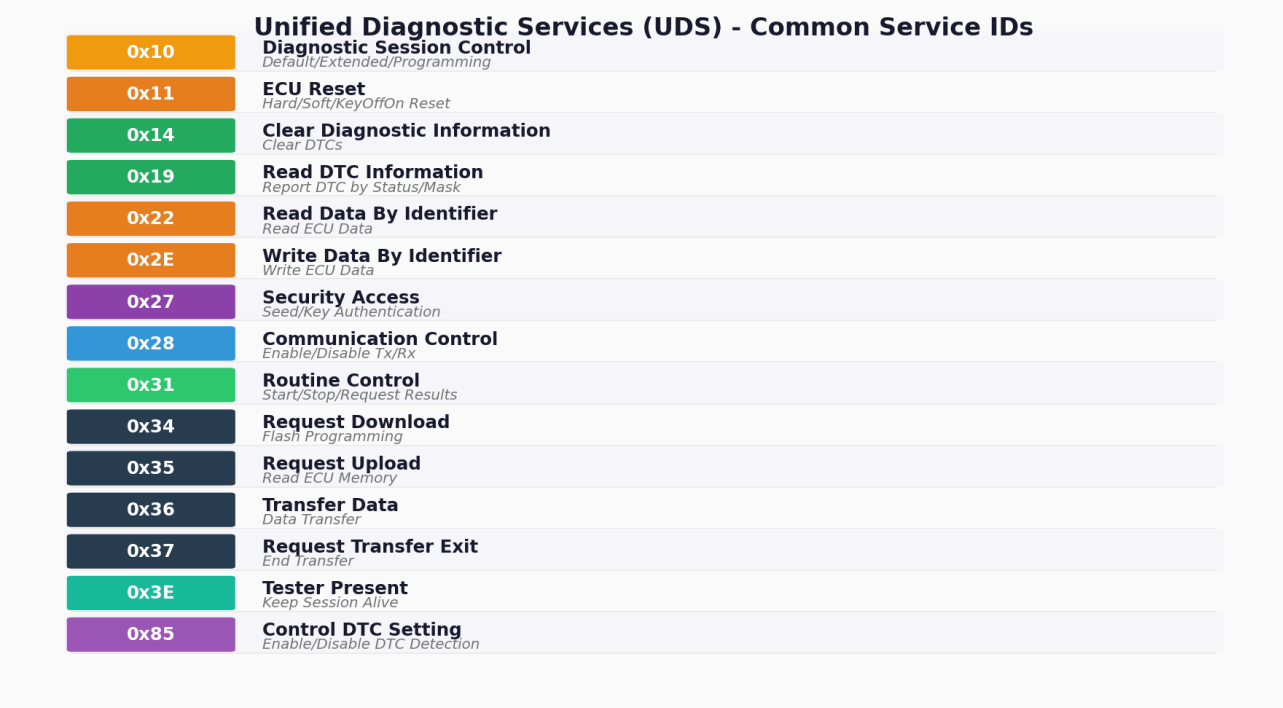


Figure 9-20 *Unified Diagnostic Services (UDS) - Common Service IDs*

UDS services are identified by a 1-byte Service Identifier (SID), as shown in Figure 9-20.

UDS Request/Response Format

```
Request Format:
[SID] [Sub-function/Data] [...]

Positive Response:
[SID + 0x40] [Sub-function/Data] [...]

Negative Response:
0x7F [SID] [Response Code]
```

Common Negative Response Codes

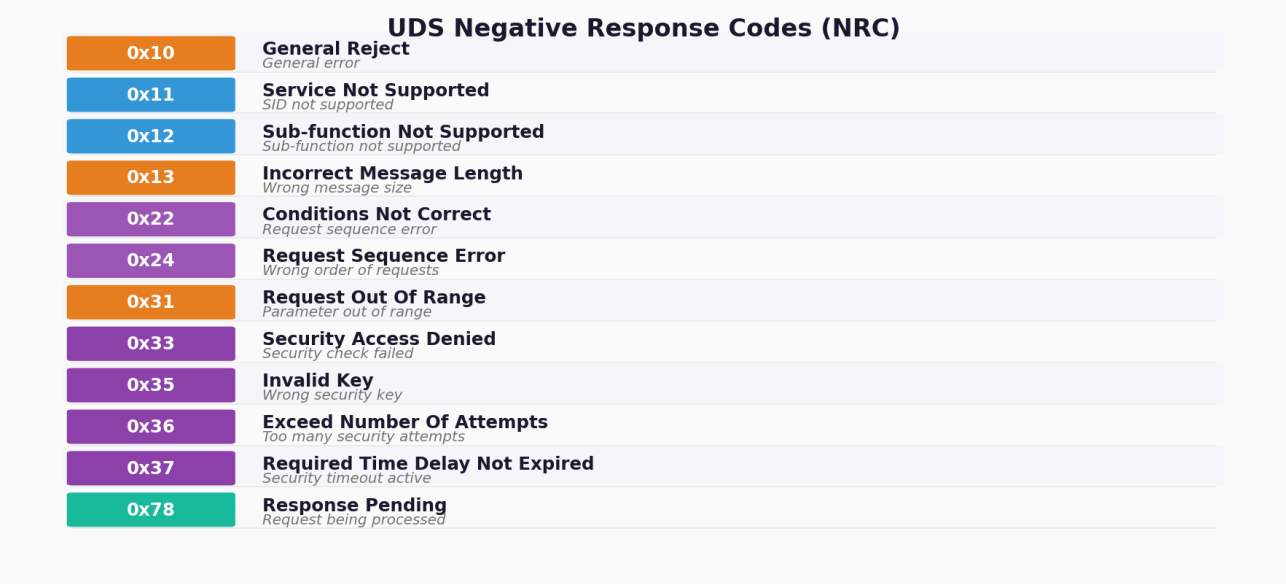


Figure 9-21 *UDS Negative Response Codes (NRC)*

9.10 Session Control

UDS defines multiple diagnostic sessions that control the level of access to ECU services:

Table 9-6 UDS Diagnostic Sessions

Session	ID	Description	Timeout
Default Session	0x01	Normal operation, limited services	N/A
Programming Session	0x02	Software download/upload	5s
Extended Diagnostic	0x03	Full diagnostic access	5s
Safety System Diagnostic	0x04	Airbag, ABS diagnostics	5s

Session Transition Diagram:

- Default Session → (0x10 0x02) → Programming Session
- Default Session → (0x10 0x03) → Extended Diagnostic
- Programming Session → (0x10 0x01) → Default Session
- Extended Diagnostic → (0x10 0x01) → Default Session
- Any Session → (Timeout) → Default Session

Session Timeout (S3)

Diagnostic sessions (except Default) have a timeout period. If no diagnostic activity occurs within this period, the ECU automatically returns to Default Session.

```
S3 Timeout: Typically 5000 ms (5 seconds)
Tester Present (0x3E): Used to keep session alive
```

9.11 Security Access

Security Access (SID 0x27) protects sensitive ECU functions from unauthorized access. The seed/key authentication mechanism ensures only authorized diagnostic tools can perform critical operations.

Security Access Sequence

```
Step 1: Request Seed
Tester -> ECU: 0x27 0x01 (Request Seed, Security Level 1)
ECU -> Tester: 0x67 0x01 [Seed 4 bytes]

Step 2: Send Key
Tester -> ECU: 0x27 0x02 [Key 4 bytes]
ECU -> Tester: 0x67 0x02 (Positive Response)

If Key Invalid:
ECU -> Tester: 0x7F 0x27 0x35 (Invalid Key)
```

Key Calculation

$$Key = f(Seed, Secret)$$

Where f() is a manufacturer-specific algorithm (typically AES, RSA, or proprietary)

Table 9-7 Security Access Levels

Level	Sub-function	Access
Level 1	0x01 (Seed), 0x02 (Key)	Standard diagnostic functions
Level 3	0x03 (Seed), 0x04 (Key)	Extended diagnostic functions
Level 5	0x05 (Seed), 0x06 (Key)	Flash programming
Level 7	0x07 (Seed), 0x08 (Key)	Development/Engineering

Security Lockout

After a configurable number of failed security access attempts (typically 3), the ECU enters a lockout state. The delay timer (typically 10-60 seconds) must expire before further attempts are allowed. This prevents brute-force attacks on the security mechanism.

Chapter 10: CAN FD and CAN XL Evolution

As automotive systems generate increasing amounts of data, Classical CAN's limitations of 1 Mbps and 8-byte payloads became restrictive. CAN FD (Flexible Data-rate) and CAN XL address these limitations while maintaining compatibility with the CAN protocol.

10.1 CAN FD Features

CAN FD, introduced by Bosch in 2012 and standardized in ISO 11898-1:2015, provides two major improvements over Classical CAN:

- **Higher Data Rates:** Up to 8 Mbps in the data phase (arbitration remains at 1 Mbps)
- **Larger Payloads:** Up to 64 bytes of data per frame

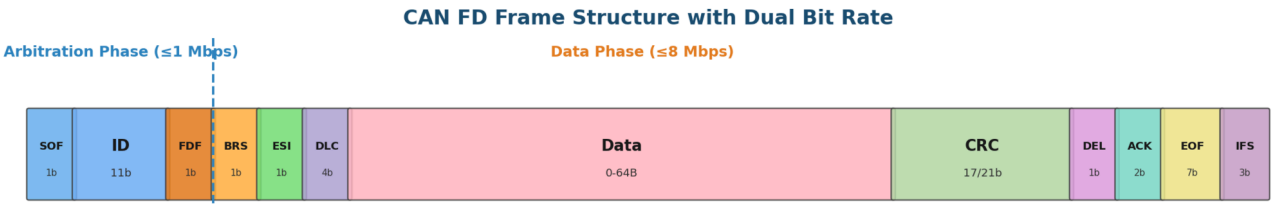


Figure 10-1 *CAN FD Frame Structure with Dual Bit Rate*

CAN FD Frame Differences

Table 10-1 CAN FD vs Classical CAN Frame Differences

Feature	Classical CAN	CAN FD
Data Length	0-8 bytes	0-8, 12, 16, 20, 24, 32, 48, 64 bytes
Arbitration Bit Rate	Up to 1 Mbps	Up to 1 Mbps
Data Bit Rate	Same as arbitration	Up to 8 Mbps
FDF Bit	Reserved (dominant)	FD Format (recessive)
BRS Bit	Not present	Bit Rate Switch
ESI Bit	Reserved (dominant)	Error State Indicator
CRC Length	15 bits	17 bits (≤16 bytes) or 21 bits (>16 bytes)
Stuff Bits in CRC	Fixed form	Dynamic (stuff count + parity)

CAN FD DLC Encoding

Table 10-2 CAN FD Data Length Code Mapping

DLC	Classical CAN Data Bytes	CAN FD Data Bytes
0-8	0-8	0-8
9	8	12
10	8	16
11	8	20
12	8	24
13	8	32
14	8	48
15	8	64

CAN FD Overhead and Data Efficiency

A significant advantage of CAN FD is improved protocol efficiency. In Classical CAN, the overhead (SOF, arbitration, control, CRC, ACK, EOF, IFS) consumes a large percentage of each frame, especially for small payloads. CAN FD dramatically improves the data-to-overhead ratio by supporting larger payloads at higher data rates:

Table 10-3 CAN FD vs Classical CAN — Data Efficiency Comparison

Payload (bytes)	Classical CAN Efficiency	CAN FD Efficiency	Throughput Gain
8	~47% (8 / ~17 bytes total)	~53% (+ BRS speedup)	Up to 3.5×
12	N/A (max 8 in CAN)	~60%	—
32	N/A	~80%	—
64	N/A	~91%	Up to 8×

When CAN FD Matters Most

The greatest throughput improvement occurs when using the **Bit Rate Switch (BRS)**. With BRS active and a 2 Mbps data phase (vs 500 kbps arbitration), a 64-byte CAN FD frame achieves approximately 8× the effective throughput of a Classical CAN frame carrying 8 bytes. Even without BRS, the larger payload alone reduces the number of frames needed — e.g., transmitting 64 bytes requires 1 CAN FD frame vs. 8 Classical CAN frames, reducing arbitration overhead by ~87%.

10.2 CAN XL Features

CAN XL (Extra Long), standardized in CiA 610-1, further extends CAN capabilities to meet the demands of modern automotive networks:

- **Data Length:** Up to 2048 bytes per frame
- **Data Rate:** Up to 10 Mbps or higher
- **SDU Type Field:** Indicates the type of data carried (IP, J1939, etc.)

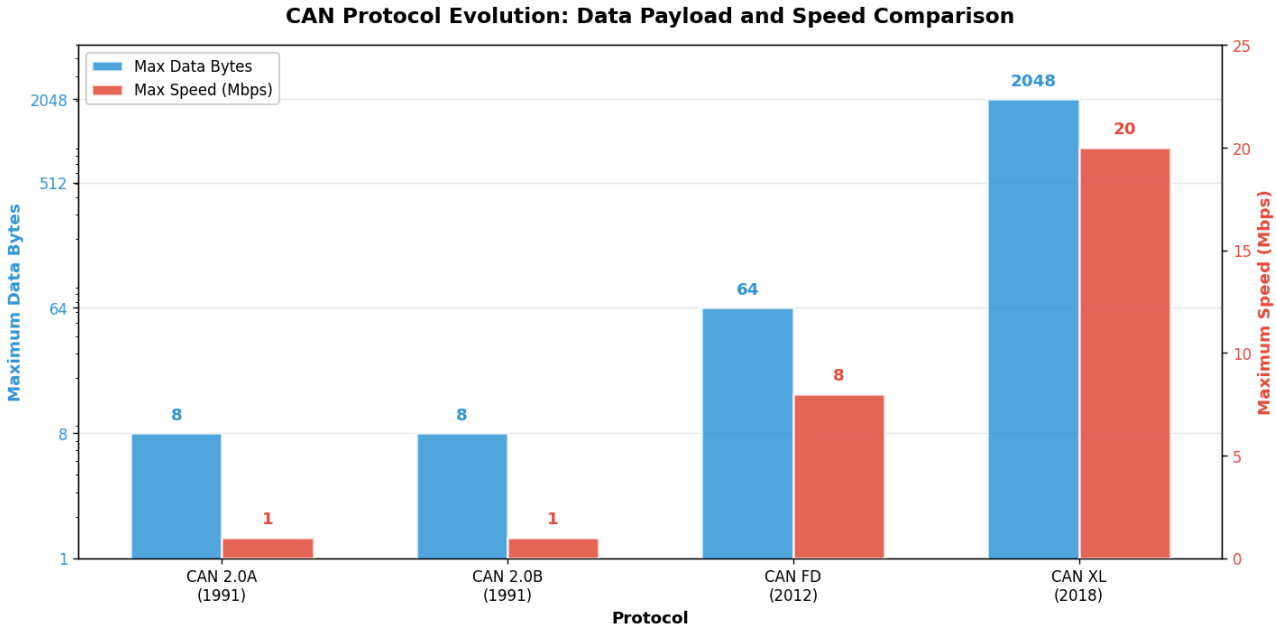


Figure 10-2 *CAN Protocol Evolution: Data Payload and Speed Comparison*

CAN XL Frame Structure

CAN XL introduces several new fields:

- **XLF (CAN XL Format):** Distinguishes CAN XL from CAN FD
- **SEC (Simple Extended Content):** Indicates SDU type field presence
- **SDT (SDU Type):** Identifies the service data unit type
- **SBC (Stuff Bit Count):** Extended stuff bit counter
- **VCID (Virtual CAN ID):** For network virtualization

CAN XL and IP Cooperation

A key design goal of CAN XL is native support for Internet Protocol (IP) communication. With payloads up to 2048 bytes and the SDU Type field, CAN XL frames can directly carry Ethernet/IP packets without fragmentation in many use cases. This enables:

- **TCP/IP over CAN XL:** Small TCP/IP packets can be tunneled directly within CAN XL data frames, enabling IP-based diagnostics and over-the-air updates via the CAN XL backbone
- **Multi-Protocol Bridging:** The SDU Type field allows a single CAN XL network to carry mixed traffic — J1939 PGNs, CANopen objects, and IP packets simultaneously, identified by different SDT values
- **Gateway Simplification:** CAN XL to Ethernet gateways become simpler since the SDU type explicitly identifies the payload format, avoiding complex protocol detection heuristics

SIC Transceiver (Signal Improvement Capability)

CAN XL requires a new generation of transceivers known as **SIC transceivers** (ISO 11898-2:2024). SIC transceivers actively improve the signal quality on the bus through:

- **Edge Symmetry Enhancement:** Active equalization of rising and falling edges reduces asymmetry that causes bit timing errors at high data rates
- **Ringing Suppression:** Active damping of bus ringing after recessive-to-dominant transitions enables shorter bit times
- **Backward Compatibility:** SIC transceivers are fully backward compatible with CAN 2.0 and CAN FD nodes. A bus segment can mix SIC and non-SIC transceivers, though the full 10 Mbps data rate requires all nodes to use SIC

CAN / CAN FD / CAN XL Compatibility

The three CAN generations are designed for incremental deployment. Key compatibility rules:

- **CAN FD nodes** can coexist with classical CAN nodes only if CAN FD tolerant transceivers are used, or if separate bus segments are connected via gateways
- **CAN XL nodes** are backward compatible with CAN FD, and can send/receive CAN FD frames natively. CAN XL controllers include a full CAN FD implementation
- **Mixed CAN XL + CAN FD networks** operate in "compatibility mode" where CAN XL nodes fall back to CAN FD data rates for shared frames, but can use 10 Mbps for CAN XL-only frames
- **SIC transceivers** improve signal quality for all frame types (classical CAN, CAN FD, and CAN XL) on the bus, even when connected to non-SIC nodes

Higher Layer Protocol Support

CAN XL's SDU Type field enables standardized identification of which higher-layer protocol the frame carries. Currently defined SDU types include:

Table 10-4 CAN XL SDU Type Values (CiA 611)

SDT Value	Protocol	Description
0x01	Classical Content	Content compatible with CAN / CAN FD interpretation
0x03	CANopen	CANopen XL frames (CiA 1301+)
0x05	J1939	J1939 parameter groups in CAN XL frames
0x07	IEEE 802.3 (Ethernet)	Ethernet frames tunneled in CAN XL
0x09	IPv4 / IPv6	IP packets directly encapsulated in CAN XL

Table 10-5 CAN Protocol Comparison Summary

Feature	CAN 2.0	CAN FD	CAN XL
Max Data Bytes	8	64	2048
Max Bit Rate	1 Mbps	8 Mbps (data)	10+ Mbps
Identifier Length	11/29 bit	11/29 bit	11/29 bit
Standard	ISO 11898	ISO 11898-1:2015	CiA 610-1
Backward Compatible	N/A	Yes (CAN 2.0)	Yes (CAN FD)
Transceiver	ISO 11898-2	ISO 11898-2:2016	ISO 11898-2:2024

10.3 Migration Considerations

When migrating from Classical CAN to CAN FD or CAN XL, several factors must be considered:

Hardware Requirements

- **CAN Controller:** Must support CAN FD/CAN XL
- **Transceiver:** Must support higher bit rates
- **Clock:** Higher accuracy required (typically 40 MHz or 80 MHz)

Network Design

- **Bus Length:** Shorter maximum lengths at higher bit rates
- **Topology:** More critical at higher speeds
- **Termination:** May require active termination for CAN XL

> **Mixed Network Considerations**
>
> In a mixed network with Classical CAN and CAN FD nodes, CAN FD frames will be detected as errors by Classical CAN nodes. Use CAN FD tolerant transceivers (like TJA1043) that can ignore CAN FD frames, or implement gateway nodes to separate network segments.

Software Migration

```
// Classical CAN Frame
struct CanFrame {
    uint32_t id;        // 11 or 29 bit
    uint8_t dlc;        // 0-8
    uint8_t data[8];
};

// CAN FD Frame
struct CanFdFrame {
    uint32_t id;        // 11 or 29 bit
    uint8_t dlc;        // 0-15 (maps to 0-64 bytes)
    uint8_t data[64];
    bool brs;           // Bit Rate Switch
    bool esi;           // Error State Indicator
};
```

Chapter 11: EMC Testing and Harness Design

Electromagnetic Compatibility (EMC) is critical for CAN bus systems in automotive environments. Vehicles contain numerous sources of electromagnetic interference, and CAN networks must operate reliably in these harsh conditions.

11.1 ISO 11452 Testing

ISO 11452 specifies test methods for evaluating the immunity of electronic components in vehicles to electromagnetic disturbances. These tests ensure CAN systems can withstand radiated electromagnetic fields.

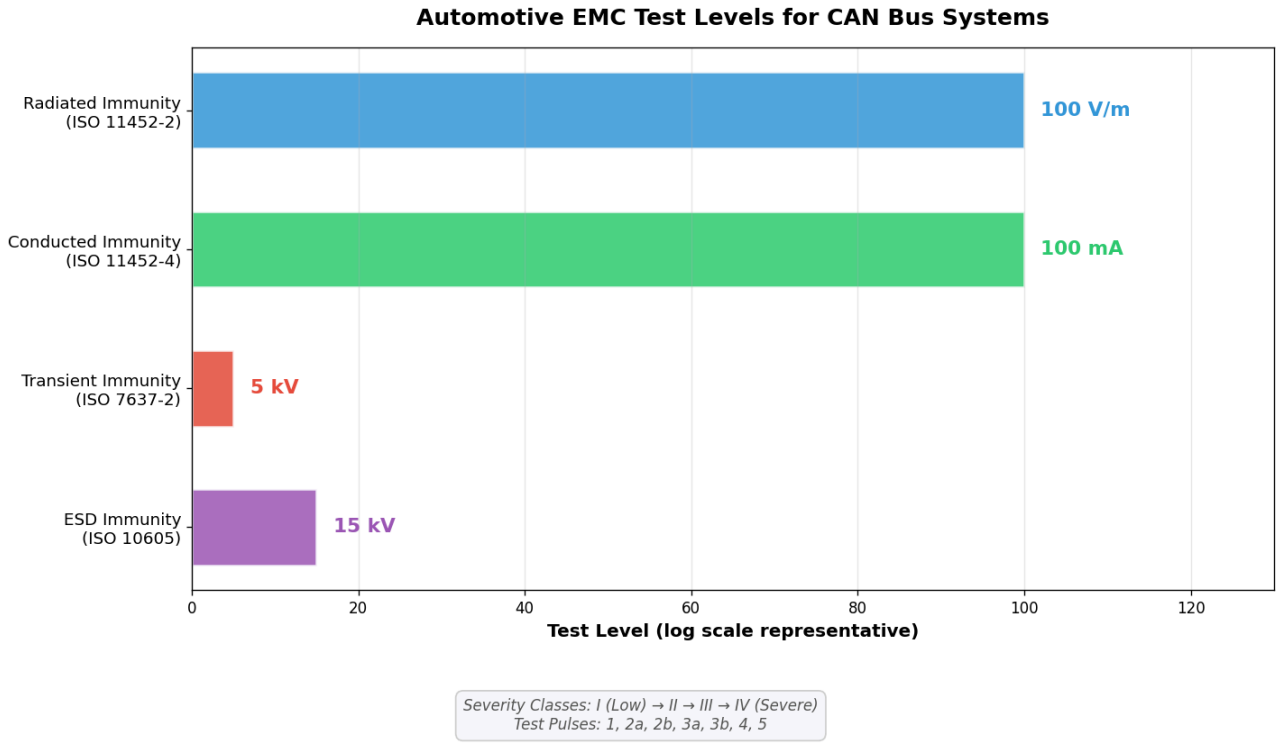


Figure 11-1 *Automotive EMC Test Levels for CAN Bus Systems*

ISO 11452-2 (Radiated Immunity)

This test subjects the device under test (DUT) to electromagnetic fields in an anechoic chamber:

Table 11-1 ISO 11452-2 Test Levels

Level	Field Strength	Application
I	25 V/m	General passenger vehicles
II	50 V/m	Commercial vehicles
III	75 V/m	Severe environments
IV	100 V/m	Extreme environments, military

ISO 11452-4 (Bulk Current Injection)

BCI testing injects RF currents directly into the wiring harness:

Table 11-2 ISO 11452-4 Test Levels

Level	Current	Frequency Range
I	25 mA	1-400 MHz
II	50 mA	1-400 MHz
III	75 mA	1-400 MHz
IV	100 mA	1-400 MHz

11.2 ISO 7637 Transients

ISO 7637-2 specifies test pulses that simulate transient disturbances occurring in vehicle electrical systems. These transients can cause communication errors or permanent damage if not properly protected.

ISO 7637-2 Test Pulses

Table 11-3 ISO 7637-2 Test Pulses

Pulse	Description	Amplitude	Source
1	Negative transient from inductive load disconnection	-100V to -600V	Disconnection of inductive loads
2a	Positive transient from inductive load switching	+50V to +100V	Parallel inductive loads
2b	DC motor transient during de-energization	+10V to +50V	DC motor stopping
3a	Negative fast transients (burst)	-100V to -200V	Switching processes
3b	Positive fast transients (burst)	+75V to +150V	Switching processes
4	Voltage drop during engine start	-6V to -12V	Starter motor engagement
5	Load dump (alternator disconnection)	+65V to +200V	Alternator load dump

> **Load Dump Protection**
>
> Pulse 5 (Load Dump) is the most severe transient, occurring when the battery is disconnected while the alternator is charging. Modern vehicles use centralized load dump suppression (CLDS), but CAN transceivers must still withstand these transients. Use transceivers with built-in load dump protection (e.g., TJA1057 with 58V rating).

11.3 Harness Design Guidelines

Proper harness design is essential for EMC performance and signal integrity. Following best practices during design and installation can prevent many CAN communication issues. This section covers stub connections, common mistakes, and design anti-patterns to avoid.

Stub Connection Design

Stubs are the connections from the main bus to individual ECUs. The stub length and connection method directly impact signal quality. At higher data rates, stub length becomes increasingly critical.

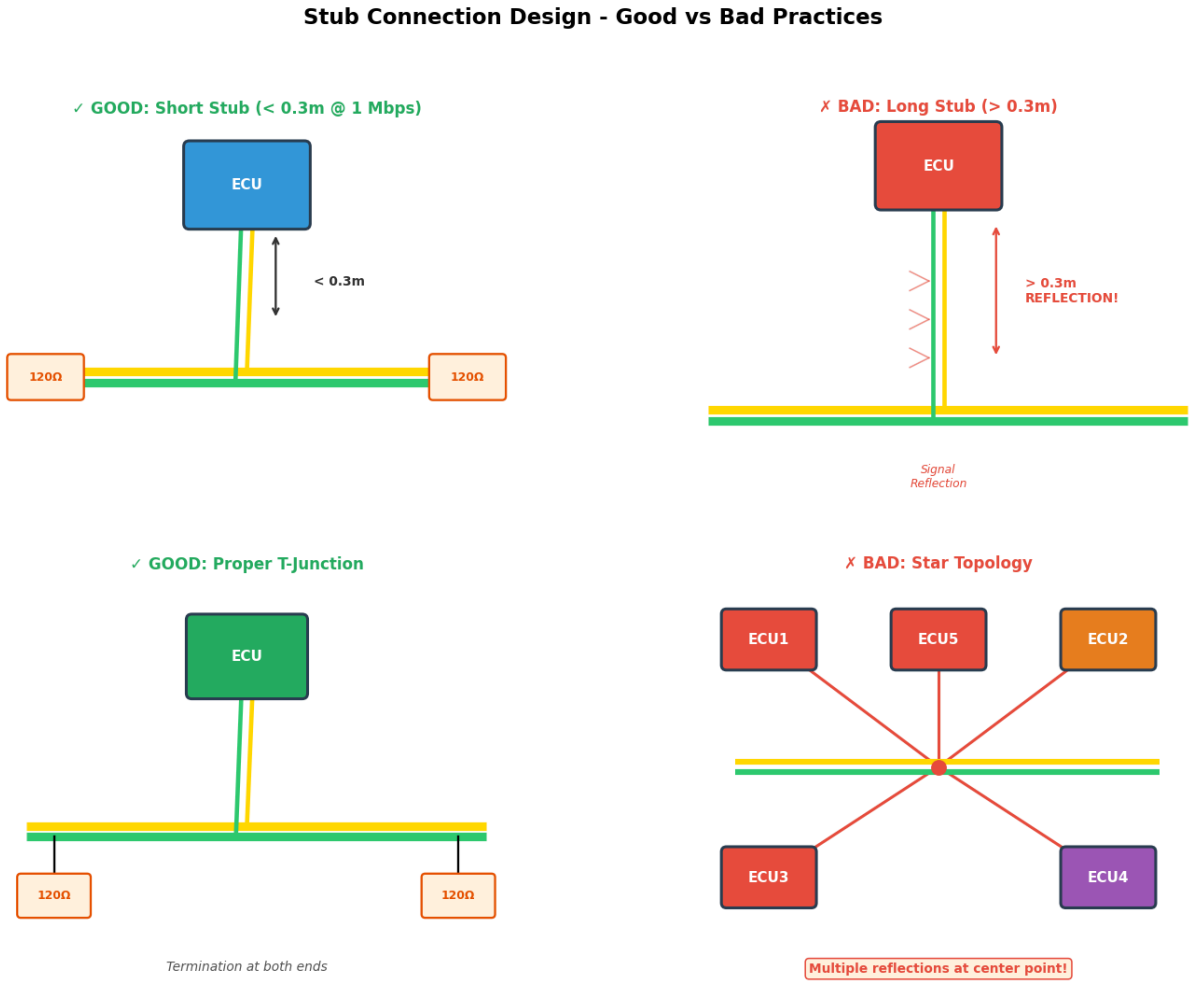


Figure 11-2 *Stub Connection Design - Good vs Bad Practices*

Stub Length Guidelines

The maximum allowable stub length depends on the data rate. As data rate increases, stub length must decrease to prevent signal reflections.

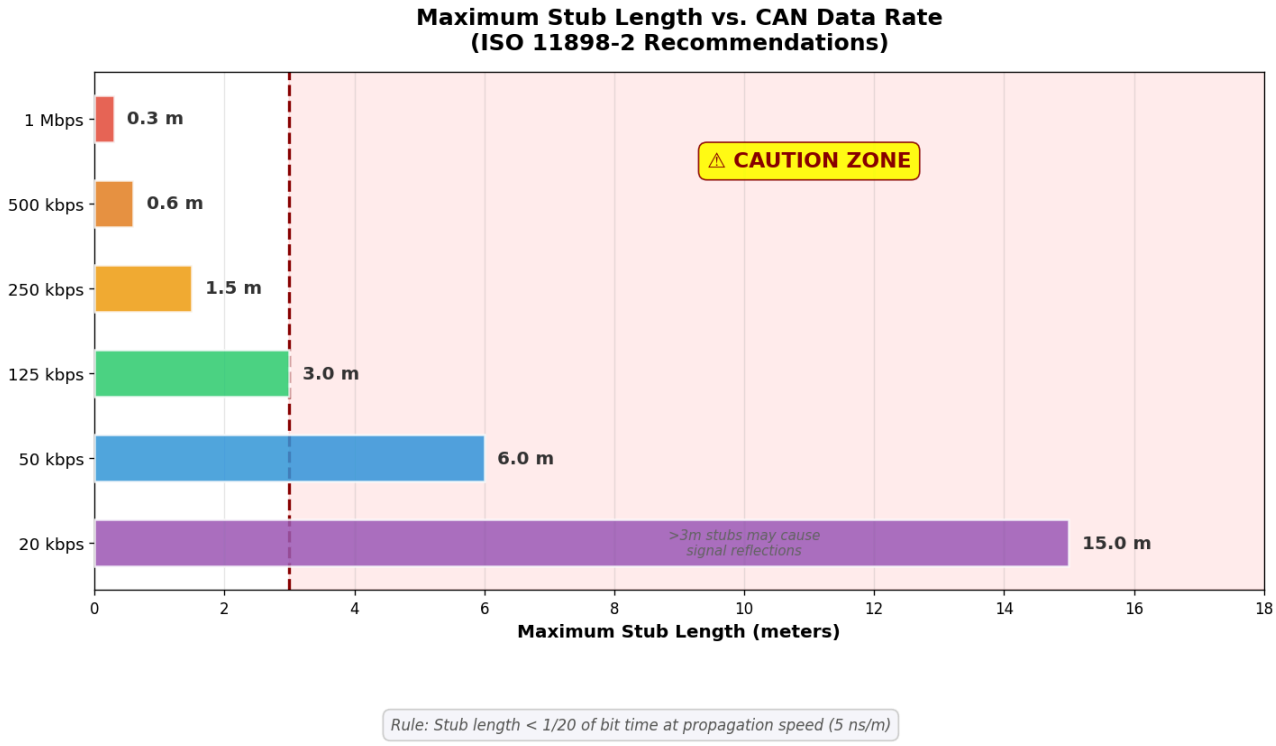


Figure 11-3 *Maximum Stub Length vs. CAN Data Rate*

Stub Length Rule of Thumb

$$L_{stub(max)} = t_{bit} \times v_{prop} / 20$$

Where t_{bit} is the bit time and v_{prop} is the signal propagation velocity in the cable (typically 5 ns/m for twisted pair)

Table 11-4 Stub Length vs. Data Rate

Data Rate	Bit Time	Max Stub Length	Status
1 Mbps	1 µs	0.3 m	Critical
500 kbps	2 µs	0.6 m	Critical
250 kbps	4 µs	1.5 m	Moderate
125 kbps	8 µs	3.0 m	Relaxed
50 kbps	20 µs	6.0 m	Flexible

Stub Length Critical Warning

At 1 Mbps, a stub longer than 0.3 meters creates significant signal reflections that can cause bit errors. For CAN FD at 5 Mbps data phase, stub length should be limited to 0.1 meters or less. Always measure and verify stub lengths during installation.

Common Design Mistakes (Anti-Patterns)

The following diagrams illustrate common mistakes in CAN harness design that lead to communication problems:

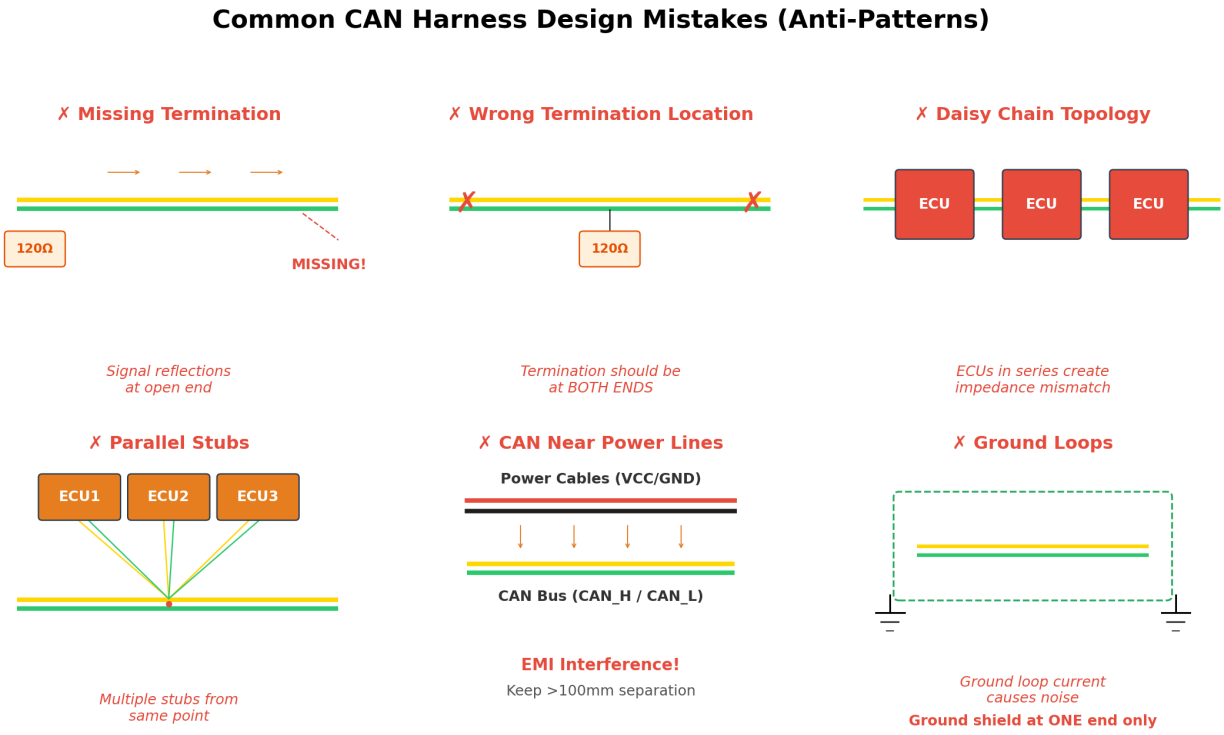


Figure 11-4 *Common CAN Harness Design Mistakes (Anti-Patterns)*

Anti-Pattern 1: Missing Termination

Missing or incorrect termination is the most common cause of CAN bus problems. Without proper termination at both ends of the bus, signals reflect back and create standing waves.

Termination Verification

Always verify termination resistance with a multimeter (power off). Measure between CAN_H and CAN_L at any point on the bus. The reading should be approximately 60Ω (two 120Ω resistors in parallel). Readings significantly different from 60Ω indicate a termination problem.

Anti-Pattern 2: Star Topology

Star topology, where multiple stubs connect to a central point, creates multiple reflection points. Each branch of the star acts as an impedance discontinuity, causing signal degradation.

> **Star Topology Exception**
>
> Low-speed CAN (ISO 11898-3, fault-tolerant) supports star topology with specific transceivers. However, high-speed CAN (ISO 11898-2) must use linear bus topology only.

Anti-Pattern 3: Daisy Chain Through ECUs

Connecting ECUs in series (daisy chain) creates impedance mismatches at each node. The ECU's internal circuitry presents a non-120Ω load to the bus, disrupting signal integrity.

Anti-Pattern 4: Ground Loops

Grounding the cable shield at both ends creates a ground loop. Current flowing through the shield induces noise in the signal conductors through capacitive and inductive coupling.

Cable Routing Best Practices

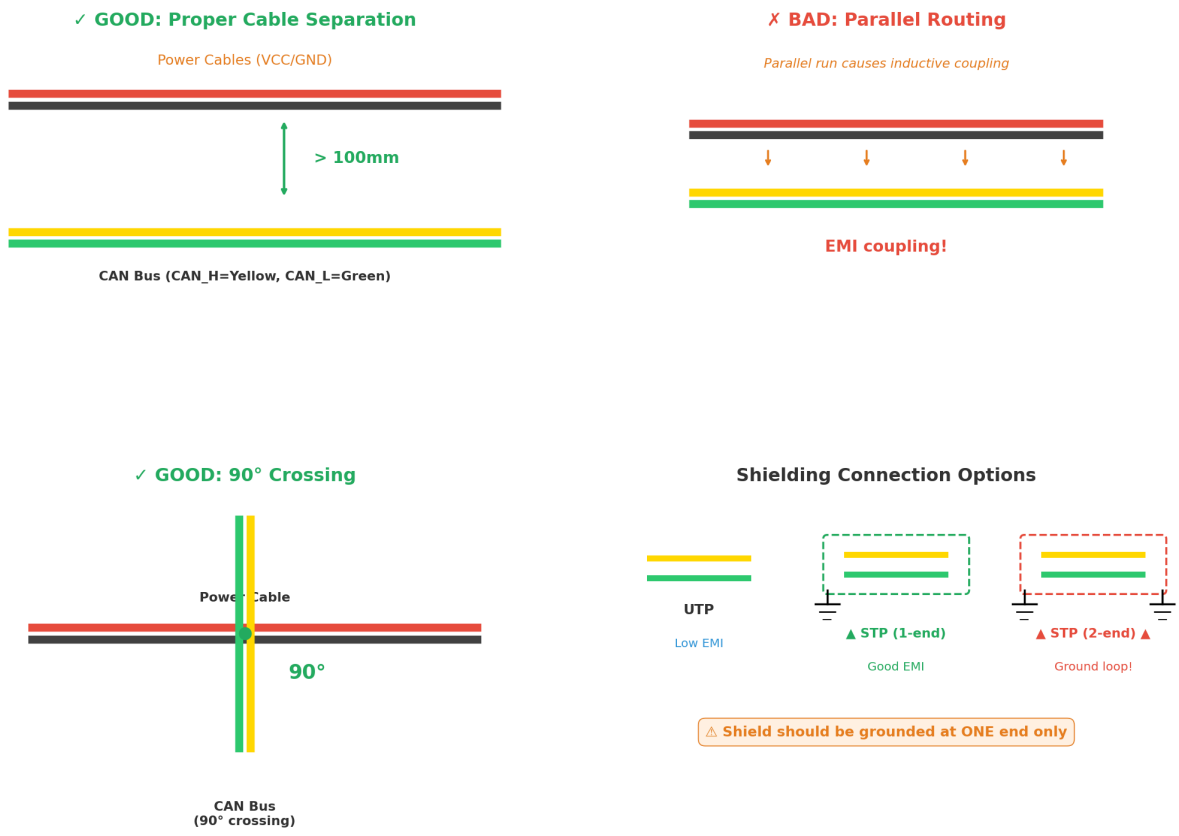


Figure 11-5 *Cable Routing and Shielding Best Practices*

Separation from Power Lines

Table 11-5 Minimum Separation Distances

Power Cable Type	Minimum Separation	Notes
Low current (< 5A)	50 mm	General wiring
Medium current (5-20A)	100 mm	Accessory circuits
High current (> 20A)	200 mm	Starter, alternator
Ignition coils	300 mm	High voltage pulses
RF antennas	500 mm	Radio frequency

Crossing Power Cables

When CAN cables must cross power cables, always cross at 90° angles. This minimizes the coupling area and reduces inductive interference. Never run CAN cables parallel to power cables for extended distances.

Shielding Options

Table 11-6 CAN Cable Shielding Options

Type	Application	Effectiveness	Cost
Unshielded (UTP)	Controlled environments, low EMI	Basic	Low
Single shielded (STP)	General automotive	Good	Medium
Double shielded	High EMI environments	Excellent	High
Armored	Heavy machinery, extreme conditions	Maximum	Very High

Shield Grounding

The shield should be grounded at one end only, typically at the diagnostic connector side. Grounding at both ends creates ground loops that can induce noise. The ungrounded end should be insulated to prevent accidental contact.

Connector Selection

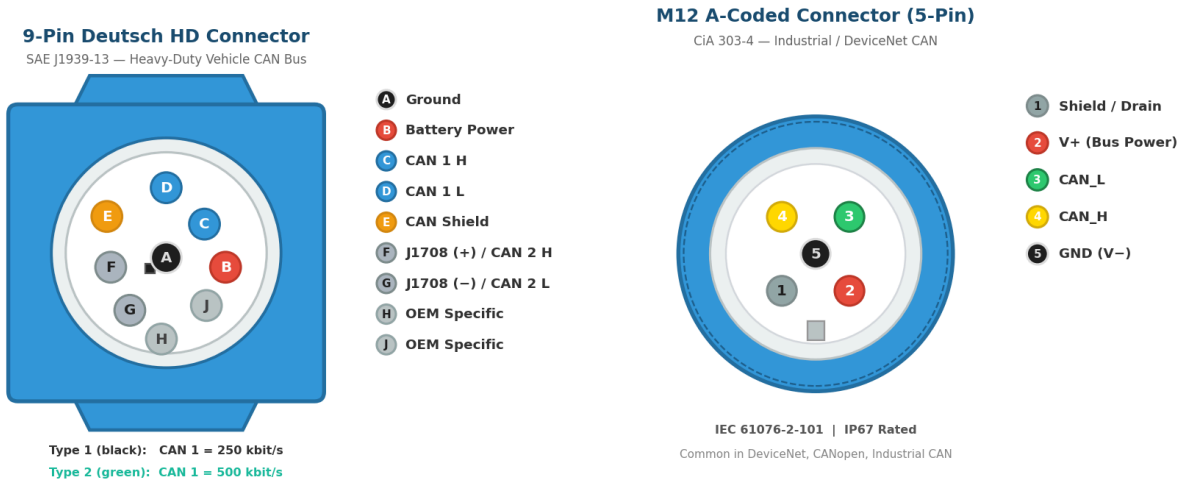


Figure 11-6 *9-Pin Deutsch HD (SAE J1939-13) and M12 A-Coded (CiA 303-4) Connector Pinouts*

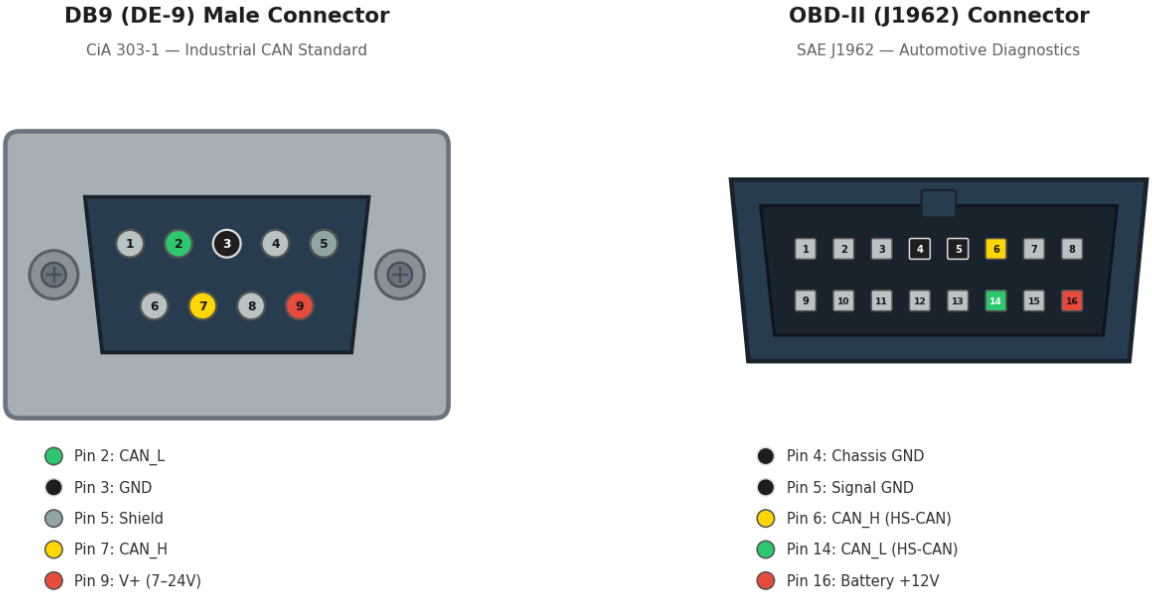


Figure 11-7 *DB9 and OBD-II Physical Connector Views with Pin Identification*

Connector Requirements

- **Shield continuity:** Use connectors that maintain 360° shield continuity
- **Strain relief:** Prevent cable damage from vibration and movement
- **IP rating:** Choose appropriate ingress protection for the environment
- **Gold plating:** Use gold-plated contacts for corrosion resistance
- **Locking mechanism:** Prevent accidental disconnection

Common Connector Types

Table 11-7 Common CAN Connector Types

Connector	Application	Pins	Standard
DB9 (DE-9)	Industrial, diagnostic tools	9	CiA 303-1
OBD-II (J1962)	Automotive diagnostics	16	SAE J1962
M12	Industrial automation	5	IEC 61076-2-101
Deutsch DT	Heavy-duty vehicles	2-12	SAE J1939-13
RJ45	Ethernet-CAN gateways	8	IEC 60603-7

Signal Integrity Considerations

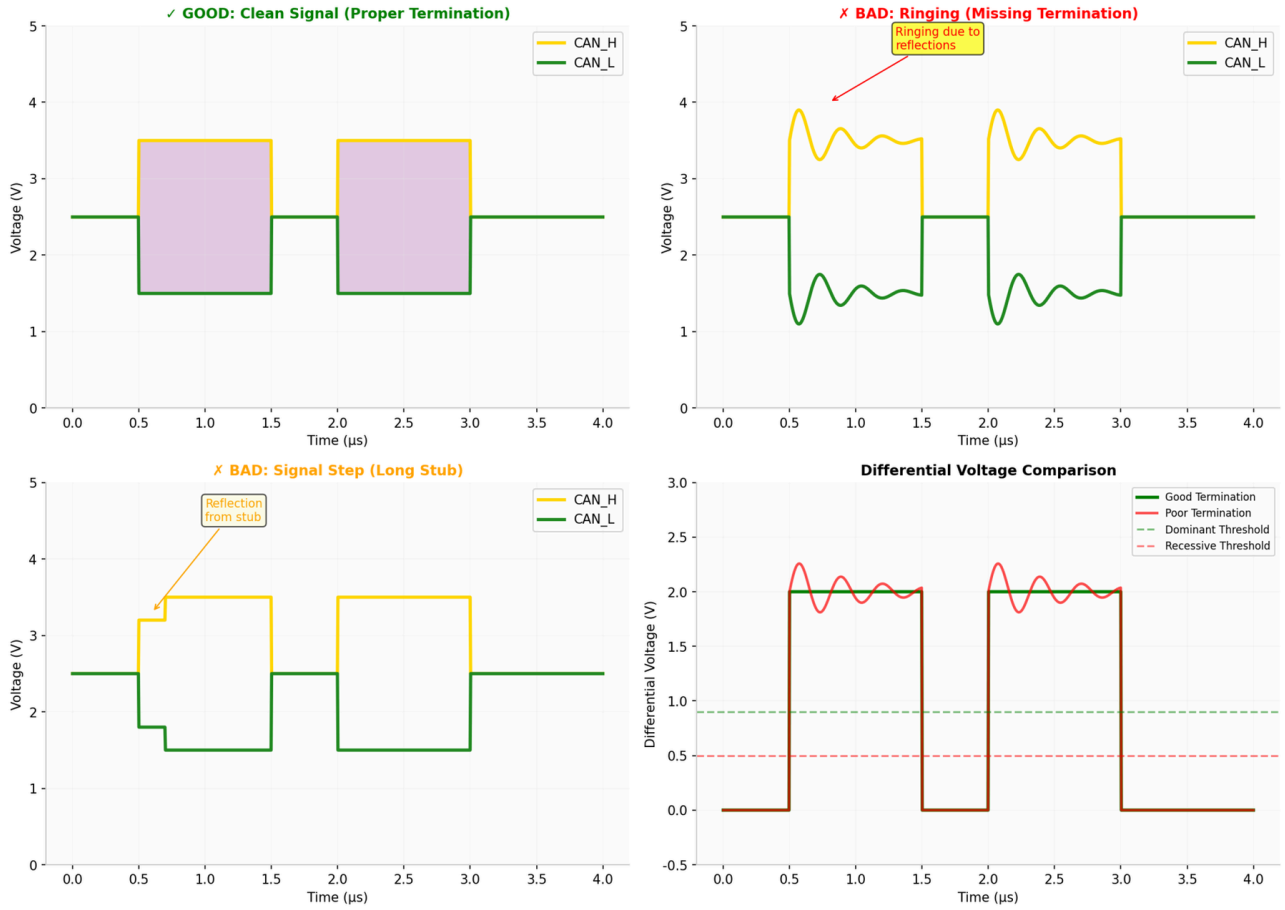


Figure 11-8 *Signal Integrity - Termination Effects on Waveform Quality*

Common Mode Chokes

Common mode chokes can improve EMC performance by filtering common-mode noise while allowing differential signals to pass:

```
Common Mode Choke Specifications:
- Impedance: 100-1000 Ω at 100 MHz
- Current rating: 100-500 mA (match transceiver requirements)
- DC resistance: < 1 Ω (minimize voltage drop)
- Saturation current: > 2× operating current

Recommended Placement:
- Install near connector entries
- Place on both CAN_H and CAN_L lines
- Use bifilar wound chokes for best common-mode rejection
```

Installation Checklist

Pre-Power-Up Verification

Before applying power to a new CAN installation:

1. Verify termination resistance: 60Ω ± 10Ω between CAN_H and CAN_L
2. Check for shorts: No continuity between CAN_H/CAN_L and power/ground
3. Verify stub lengths: All stubs within specification for data rate
4. Inspect routing: Minimum 100mm from power cables
5. Check shield grounding: Grounded at one end only
6. Verify connector integrity: All pins properly seated

Design Verification

Always verify EMC performance through testing. Pre-compliance testing during development can identify issues early, reducing costly redesigns. Final validation should be performed at an accredited EMC test facility. Document all harness routing and maintain as-built drawings for future troubleshooting.

Chapter 12: Practical Implementation

Implementing a reliable CAN network requires careful consideration of system architecture, bus loading, and gateway design. This chapter provides practical guidance for real-world CAN system development.

12.1 System Architecture

Modern vehicles use multiple CAN buses organized by function and data rate requirements. A typical automotive network architecture includes:

Table 12-1 Typical Automotive CAN Bus Architecture

Bus	Data Rate	Connected Systems	Characteristics
Powertrain CAN	500 kbps - 1 Mbps	Engine, Transmission, ABS	High priority, real-time
Body CAN	125 kbps - 250 kbps	Doors, Windows, Lights, HVAC	Comfort features
Infotainment CAN	125 kbps - 500 kbps	Radio, Navigation, Display	High data volume
Diagnostic CAN	500 kbps	OBD-II, Service Tools	Standardized access
Chassis CAN	250 kbps - 500 kbps	Suspension, Steering, Braking	Safety critical

Typical Multi-Bus Architecture:

- Powertrain CAN (500 kbps) → Central Gateway
- Body CAN (125 kbps) → Central Gateway
- Infotainment CAN (250 kbps) → Central Gateway
- Chassis CAN (500 kbps) → Central Gateway
- Central Gateway → OBD-II Diagnostic Port

Gateway Design Considerations

The gateway node connects different CAN buses and manages message routing:

- **Message filtering:** Only forward relevant messages between buses
- **Protocol translation:** Convert between CAN 2.0 and CAN FD if needed
- **Security:** Implement firewall functions to isolate critical buses
- **Diagnostics:** Provide unified diagnostic access to all buses

12.2 Bus Loading Analysis

Bus loading is a critical parameter for CAN network design. Excessive loading can cause message delays and priority inversion issues.

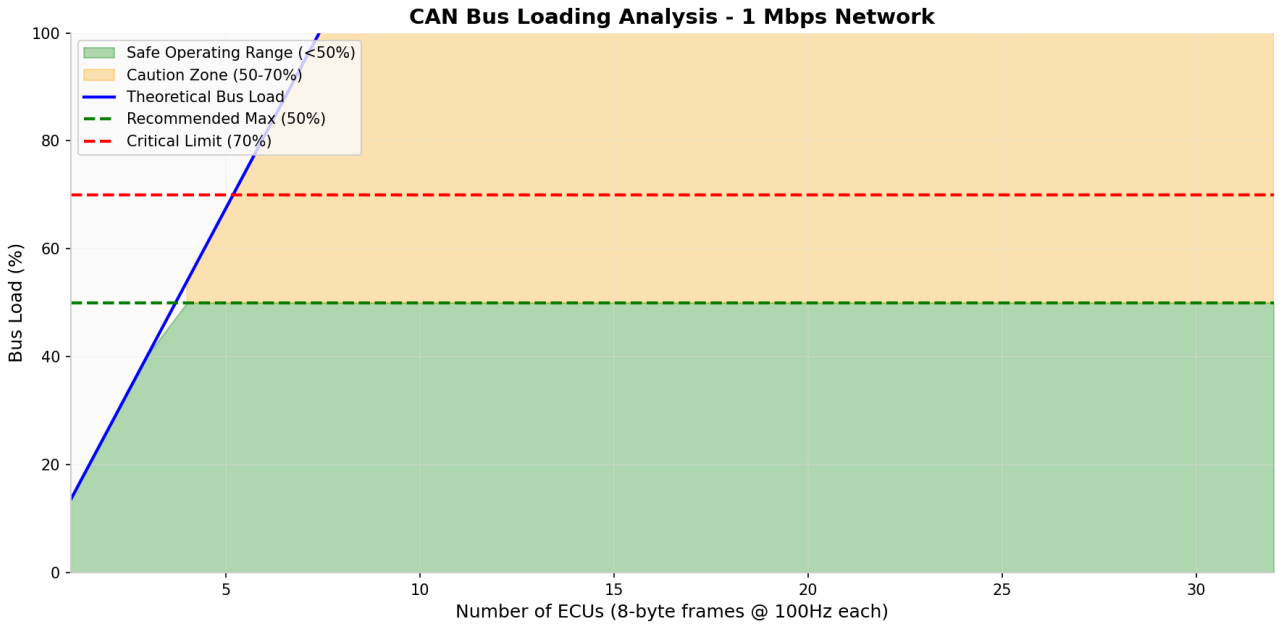


Figure 12-1 *CAN Bus Loading Analysis - 1 Mbps Network*

Bus Load Calculation

$$Bus\ Load = \frac{\sum_{i=1}^{n} (Frame\ Size_i \times Rate_i)}{Baud\ Rate} \times 100\%$$

Example calculation for a 500 kbps bus:

```
Messages:
- Engine RPM: 130 bits × 100 Hz = 13,000 bits/s
- Vehicle Speed: 130 bits × 50 Hz = 6,500 bits/s
- Coolant Temp: 130 bits × 10 Hz = 1,300 bits/s
- (20 more messages at various rates)

Total: 180,000 bits/s
Bus Load: 180,000 / 500,000 = 36%
```

Table 12-2 Bus Loading Guidelines

Bus Load	Status	Recommendation
< 30%	Excellent	Ample headroom for future expansion
30-50%	Good	Normal operating range
50-70%	Caution	Monitor for latency issues
70-85%	Warning	Priority inversion risk, redesign recommended
> 85%	Critical	Network will experience significant delays

> **Worst Case Latency**
>
> At 50% bus load, a high-priority message may be delayed by one lower-priority frame. At 70% load, the delay can be several frames. Always perform worst-case response time analysis for safety-critical messages.

12.3 Gateway Design

The gateway is a critical component in multi-bus architectures. It must handle message routing, protocol conversion, and security functions.

Gateway Message Routing

```
// Example Gateway Routing Table
struct RoutingEntry {
    uint32_t can_id;        // Source CAN ID
    uint8_t  source_bus;    // Source bus number
    uint8_t  target_bus;    // Target bus number
    uint32_t new_id;        // Translated CAN ID (optional)
    uint8_t  priority;      // Routing priority
};

RoutingEntry routing_table[] = {
    // Route Engine RPM from Powertrain to Infotainment
    {0x0CFFF048, POWERTRAIN_BUS, INFO_BUS, 0x0CFFF048, 5},

    // Route Door Status from Body to Infotainment
    {0x18FEF103, BODY_BUS, INFO_BUS, 0x18FEF103, 3},

    // Route Diagnostic requests to all buses
    {0x18EA00F9, DIAG_BUS, ALL_BUSES, 0x18EA00F9, 1},
};
```

Gateway Performance Requirements

Table 12-3 Gateway Performance Specifications

Parameter	Typical	High Performance
Message Latency	< 5 ms	< 1 ms
Throughput	2000 msg/s	10000 msg/s
Routing Table Size	256 entries	1024 entries
Buffer Size	64 messages	256 messages
Protocol Conversion	CAN 2.0 ↔ CAN FD	CAN ↔ LIN ↔ FlexRay

Cybersecurity Considerations

Modern gateways must implement cybersecurity measures including message authentication, intrusion detection, and secure firmware updates. The gateway serves as the primary security boundary between vehicle buses and external interfaces.

Chapter 13: Troubleshooting

CAN bus troubleshooting requires a systematic approach and appropriate diagnostic tools. This chapter covers common faults, diagnostic procedures, and best practices for maintaining reliable CAN communication.

13.1 Common Faults

CAN bus issues can be categorized into physical layer faults and protocol layer faults.

Physical Layer Faults

Table 13-1 Common Physical Layer Faults

Fault	Symptoms	Cause	Solution
Open Circuit	No communication, bus stuck recessive	Broken wire, loose connection	Repair wiring, check connectors
Short CAN_H to VBAT	Bus stuck dominant	Wiring damage	Isolate and repair short
Short CAN_L to GND	Bus stuck dominant	Wiring damage	Isolate and repair short
CAN_H/CAN_L Short	No differential signal	Wiring damage	Isolate and repair short
Missing Termination	Signal reflections, errors	Failed resistor, missing ECU	Check 60Ω between CAN_H/CAN_L
Incorrect Termination	Signal reflections	Wrong resistor value	Install correct 120Ω resistors
Ground Offset	Intermittent errors	Poor ground connection	Improve grounding

Protocol Layer Faults

Table 13-2 Common Protocol Layer Faults

Fault	Symptoms	Cause	Solution
Bit Timing Mismatch	Intermittent errors, Bus Off	Incorrect sample point	Verify bit timing configuration
Duplicate Node IDs	Address conflicts (J1939)	Configuration error	Assign unique addresses
High Bus Load	Message delays, lost frames	Too many messages	Optimize message rates
EMI Interference	Random errors	Poor cable routing	Improve shielding, routing
Faulty Transceiver	Single node causing errors	Hardware failure	Replace transceiver/ECU

13.2 Diagnostic Tools

Effective CAN troubleshooting requires appropriate diagnostic tools:

Essential Tools

Table 13-3 CAN Diagnostic Tools

Tool	Purpose	Typical Use
Digital Multimeter	Voltage, resistance measurements	Check termination, shorts
Oscilloscope	Signal waveform analysis	Verify signal quality, timing
CAN Analyzer	Protocol analysis	Message monitoring, error detection
Scan Tool	Vehicle diagnostics	Read DTCs, live data
Network Tester	Physical layer testing	Cable testing, signal integrity

Voltage Measurements

```
Normal Bus Voltage Measurements:

CAN_H to Ground:
- Recessive: 2.5V ± 0.5V
- Dominant: 3.5V ± 0.5V

CAN_L to Ground:
- Recessive: 2.5V ± 0.5V
- Dominant: 1.5V ± 0.5V

CAN_H to CAN_L:
- Recessive: 0V ± 0.5V
- Dominant: 2.0V ± 0.5V

Termination Resistance (power off):
- CAN_H to CAN_L: 60Ω ± 5Ω (two 120Ω in parallel)
```

Oscilloscope Analysis

Key waveform characteristics to verify:

- **Differential voltage:** Should be ~2V dominant, ~0V recessive
- **Rise/fall times:** Typically 20-50 ns for high-speed CAN
- **Signal symmetry:** CAN_H and CAN_L should be mirror images
- **Noise:** Minimal noise on both lines

Waveform → Fault Cheat Sheet

The following figure provides a visual reference for identifying CAN bus faults from oscilloscope waveforms. The top row shows healthy signal characteristics, while the bottom section maps common waveform anomalies to their root causes:

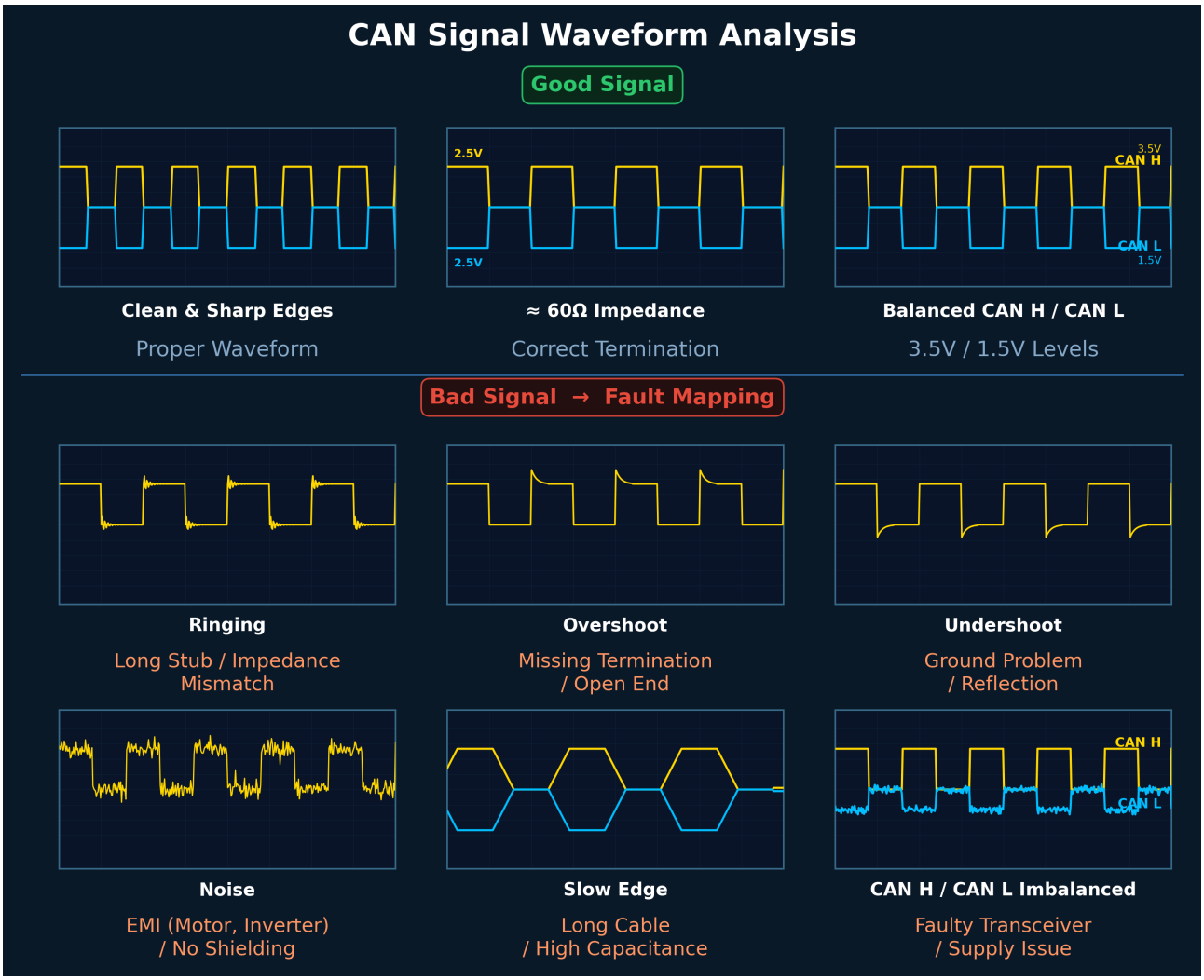


Figure 13-1 *CAN Signal Waveform Analysis — Good Signal vs Fault Mapping*

Table 13-4 Waveform Anomaly Diagnosis

Anomaly	Root Cause	Verification Steps	Solution
Ringing	Long stub, impedance mismatch, missing termination	Check stub length < 20 cm; verify 120Ω + 120Ω present	Shorten stubs, correct impedance, add missing termination
Overshoot	No termination, open end reflection	Measure CAN_H–CAN_L ≈ 60Ω	Install proper 120Ω termination resistors at both bus ends
Undershoot	Ground problem, signal reflection	Check GND continuity; verify ECU ground reference is common	Repair ground connections, ensure single-point grounding
Noise	EMI (motor, inverter), no shielding	Check cable shielding; measure proximity to power lines	Add shielded cable, reroute away from EMI sources, add common mode choke
Slow Edge	Long cable, excessive capacitance, too many nodes	Measure cable length; count nodes on bus	Reduce cable length, reduce node count, use higher quality cable
CAN H/L Imbalanced	Faulty transceiver, supply voltage issue	Compare CAN_H and CAN_L symmetry; check transceiver supply	Replace faulty transceiver/ECU, verify power supply

13.3 Field Debug Procedure

A systematic 10-step field troubleshooting procedure that resolves approximately 90% of CAN bus problems:

Step-by-Step Debug Procedure

Table 13-5 CAN Bus Field Debug Procedure

Step	Action	Details	Expected Result
1	**Multimeter — Resistance**	Ignition OFF. Measure CAN_H ↔ CAN_L resistance.	~60Ω = OK | ~120Ω = single termination | ~40Ω = extra termination | ∞ = broken wire
2	**Physical Inspection**	Verify: terminations at bus ends, stub lengths, twisted pair used, no splices	All connections secure, topology correct
3	**Oscilloscope — Connect**	Probe CAN_H and CAN_L (preferably differential measurement)	Clean square wave visible
4	**Waveform Analysis**	Compare waveform against cheat sheet (Figure 13-1)	Identify any anomalies: ringing, overshoot, noise, etc.
5	**Speed Reduction Test**	Reduce bus speed (e.g. 500 kbps → 250 kbps)	If errors disappear → confirmed physical layer problem
6	**Node Isolation**	Disconnect ECUs one by one	Identify which node is causing the problem
7	**Stub Test**	Disconnect long branch lines	Signal improves → stub is the problem
8	**Termination Test**	Remove one termination → observe; replace with precision resistor	Identify faulty or missing termination
9	**EMI Test**	Start motor, activate DC-DC converter, observe signal changes	Identify EMI-sensitive conditions
10	**Transceiver Validation**	Test with single ECU; compare against known-good ECU	Identify faulty transceiver

> **Golden Rule**
>
> If reducing the bus speed makes the problem disappear, it is 100% a physical layer issue. Do not look for software bugs.

Real Vehicle Problem Scenarios

Table 13-6 Common Vehicle CAN Problem Scenarios

Scenario	Symptoms	Root Cause	Solution
CAN fails when engine starts	OK at ignition ON, CAN error/bus-off when engine running. Oscilloscope shows increased noise and distorted edges.	Alternator/inverter EMI, poor grounding	Use twisted pair + shield, fix GND reference, reroute cable away from power lines, add common mode choke
ECUs intermittently disappear	Random timeouts, DM1 messages come and go. Oscilloscope shows ringing + edge distortion.	Long stubs, star/T-branch topology	Shorten stubs to < 20 cm, convert star topology to linear bus
Errors only at high speed	250 kbps OK, 500 kbps errors	Impedance mismatch, poor cable quality	Use proper 120Ω cable, verify termination, replace cable
No communication at all	CAN completely dead. Multimeter shows ∞Ω.	Broken wire, disconnected connector	Continuity test, check all connectors
Weak signal levels	CAN_H/CAN_L differential voltage too low	Triple termination (≈40Ω), excessive bus loading	Remove extra termination — keep only two 120Ω ends
Single ECU corrupts bus	Bus crashes when specific ECU is connected	Faulty transceiver, dominant-stuck output	Remove faulty ECU, replace transceiver

> **Field Statistics**
>
> Approximately 80% of CAN bus problems originate from the physical layer (wiring, termination, connectors) and only 20% from software or configuration issues. Always check the physical layer first.

CAN FD Debug Differences

CAN FD requires stricter physical layer tolerances due to higher data phase bit rates (2–5 Mbps). The same wiring faults that are tolerable at classical CAN speeds become critical at CAN FD data rates:

Table 13-7 Classical CAN vs CAN FD — Physical Layer Sensitivity

Parameter	Classical CAN	CAN FD	Impact
Max Stub Length	< 30 cm	< 10 cm	Reflections at data phase speed cause bit errors
Ringing Tolerance	Moderate — can tolerate small reflections	Very low — even small reflections cause CRC errors	Stricter impedance matching required
Cable Quality	Standard cable acceptable	True 120Ω twisted pair mandatory	Impedance mismatch amplified at high frequency
Termination Precision	±10% tolerance	±5% or less recommended	Small deviations create visible reflections
Edge Timing	Soft edges acceptable	Sharp, clean edges required	Slope control and rise/fall time critical

CAN FD Specific Failure Modes

- **Data Phase Crash:** Arbitration phase works fine but data phase fails — caused by high-frequency physical layer faults
- **CRC Error Spikes:** Random CRC errors during data phase — caused by small reflections invisible at arbitration speed
- **Bit Stuffing Errors:** Edge distortion at data rate causes bit timing violations

CAN FD Debug Strategy

CAN FD debugging approaches RF-level signal integrity analysis. Follow this sequence: (1) Test at low data rate first, (2) Test with only 2 nodes, (3) Cut all stubs, (4) Inspect edges with oscilloscope, (5) Replace cable if needed. For CAN FD systems, successful communication requires classical CAN rules applied more strictly — especially stub length, impedance matching, and signal integrity.

13.4 Best Practices

Following best practices during design, installation, and maintenance can prevent many CAN bus issues:

Design Best Practices

- Keep bus load below 50% for normal operation
- Use twisted pair cable with proper impedance
- Implement proper termination at both bus ends
- Minimize stub lengths (< 0.3m at 1 Mbps)
- Route CAN cables away from high-current power lines
- Use shielded cables in high-EMI environments
- Implement proper grounding (single point for shield)

Installation Best Practices

- Verify termination resistance before powering up
- Check for shorts between CAN_H, CAN_L, power, and ground
- Use proper connectors with strain relief
- Label all CAN cables clearly
- Document the network topology and node addresses

Maintenance Best Practices

- Monitor bus load and error counters regularly
- Log diagnostic trouble codes for trend analysis
- Perform periodic physical layer testing
- Update firmware to address known issues
- Maintain spare parts for critical components

> **Troubleshooting Checklist**
>
> When troubleshooting CAN issues, follow this systematic approach: (1) Verify physical connections and termination, (2) Check voltage levels with multimeter, (3) Analyze waveforms with oscilloscope, (4) Monitor messages with CAN analyzer, (5) Check error counters in ECUs, (6) Isolate nodes to identify faulty device.

Chapter 14: J1939 with CAN FD

SAE J1939-22 defines the adaptation of the J1939 protocol for CAN FD networks, enabling higher-layer protocol support while leveraging the increased bandwidth and payload of CAN FD. This chapter covers the Multi-PG mechanism, CAN FD Transport Protocol, and enhanced network management capabilities that J1939-22 introduces for modern heavy-duty vehicle networks.

14.1 Multi-PG and Contained PGs

Classical J1939 maps one Parameter Group (PG) per CAN frame. With CAN FD's 64-byte payload, J1939-22 introduces the **Multi-PG** concept, allowing multiple Parameter Groups to be packed into a single CAN FD frame. Each embedded PG is called a **Contained PG (C-PG)**.

Multi-PG Frame Structure

A Multi-PG frame uses a dedicated PGN and packs one or more C-PGs sequentially into the data field. Each C-PG carries its own header that identifies the original PGN, enabling the receiver to demultiplex the contents.

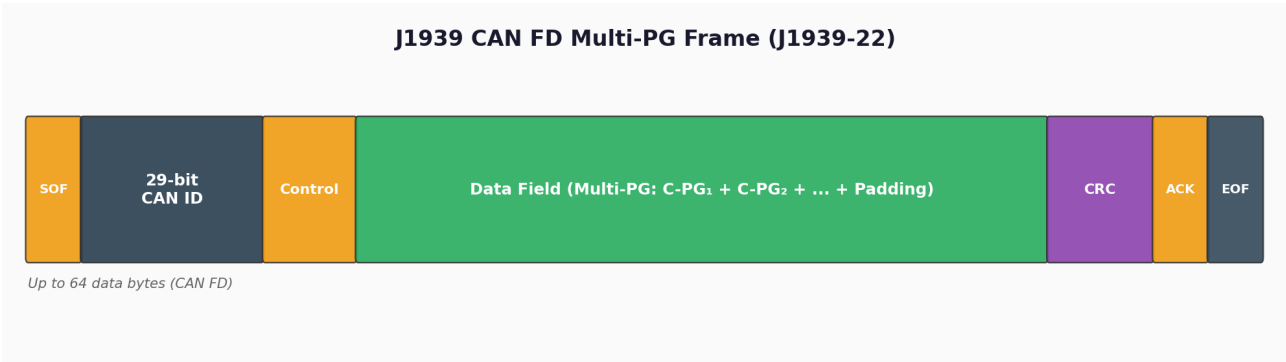


Figure 14-1 *J1939 CAN FD Multi-PG Frame Overview (J1939-22)*

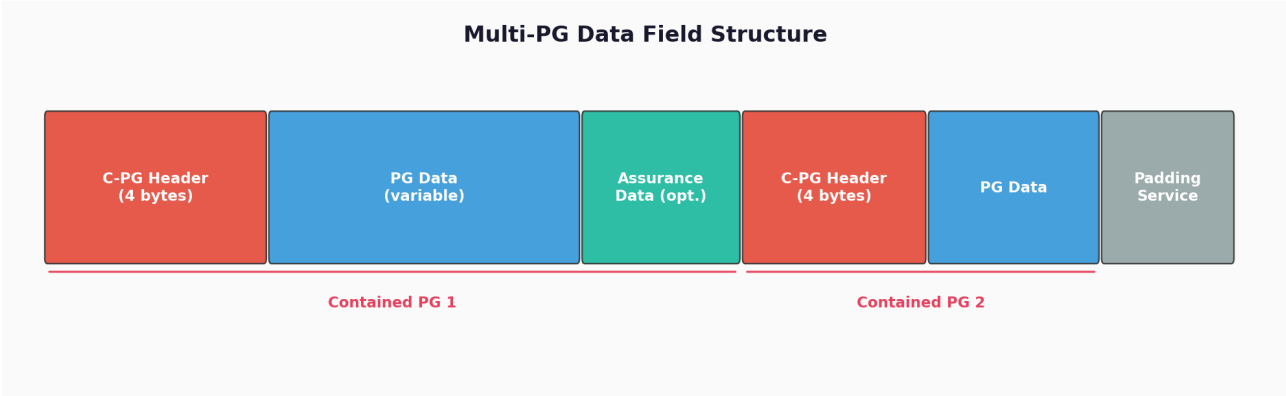


Figure 14-2 *Multi-PG Data Field Structure with Contained PGs*

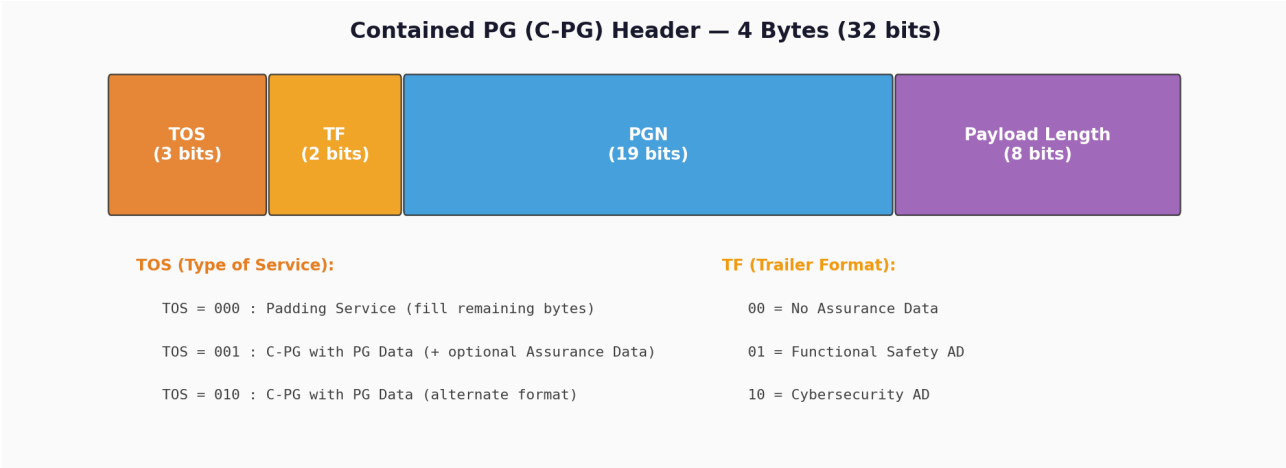


Figure 14-3 *Contained PG (C-PG) Header — TOS and TF Fields*

Contained PG Header Fields

Table 14-1 Contained PG (C-PG) Header Structure

Field	Size	Description
Type of Service (TOS)	4 bits	Priority and QoS parameters for the contained PG
Transmission Format (TF)	4 bits	Indicates C-PG addressing mode (PDU1 or PDU2)
PGN	18 bits	Parameter Group Number of the contained PG
Data Length	Variable	Length of the C-PG payload following the header

Multi-PG Bandwidth Efficiency

Multi-PG significantly reduces bus overhead in CAN FD networks. By packing multiple small PGs (e.g., 2-byte sensor values) into a single 64-byte frame, the ratio of protocol overhead to useful data drops dramatically. For example, four 8-byte PGs sent individually require four CAN FD frames with arbitration, CRC, and interframe spacing overhead each. As a single Multi-PG frame, the same data needs only one set of overhead fields — a bandwidth saving of approximately 60%.

CAN FD Identifier Mapping

J1939-22 supports both 11-bit and 29-bit CAN identifiers. For the traditional 29-bit extended format, the mapping remains consistent with classical J1939, preserving backward compatibility for the arbitration phase:

Table 14-2 J1939 CAN FD 29-bit Identifier Fields

Bit Position	Field	Description
28–26	Priority	Message priority (0 = highest, 7 = lowest)
25	Reserved	Reserved for future use (set to 0)
24	Data Page	Extends PGN address space
23–16	PDU Format (PF)	Determines PDU1 (PF < 240) or PDU2 (PF ≥ 240)
15–8	PDU Specific (PS)	Destination Address (PDU1) or Group Extension (PDU2)
7–0	Source Address	Sending node's address (0–253)

14.2 CAN FD Transport Protocol

J1939-22 defines a new FD Transport Protocol (FD.TP) optimized for CAN FD's larger frames. While classical J1939 TP (BAM/CMDT) is limited to 7 bytes per TP.DT frame, FD.TP leverages CAN FD payloads to transfer large data sets more efficiently.

FD Transport Protocol Messages

Table 14-3 J1939 FD Transport Protocol Message Types

Message	PGN	Description
FD.TP.CM	0x1CEC	Connection Management — initiates and controls transfer sessions
FD.TP.DT	0x1CEB	Data Transfer — carries payload segments up to 63 bytes each
FD.TP.EOMS	—	End of Message Session — confirms successful reception
FD.TP.Abort	—	Connection Abort — terminates session on error

FD.TP vs Classical TP Performance

The performance advantage of FD.TP over classical TP is substantial due to the larger data segment size per frame:

Table 14-4 Transport Protocol Comparison: Classical TP vs FD.TP

Parameter	Classical TP (J1939-21)	FD.TP (J1939-22)
Bytes per DT frame	7	Up to 63
Maximum transfer size	1785 bytes	> 100 kB (extended)
Frames for 1785 bytes	~255 + CM	~29 + CM
Session management	CTS/EOM handshake	Enhanced flow control with EOMS
Concurrent sessions	Limited	Multiple simultaneous sessions supported

> **Mixed Network Operation**
>
> In gateways connecting classical J1939 (CAN 2.0B) segments with J1939-22 (CAN FD) segments, care must be taken to fragment Multi-PG frames back into individual PGs for the classical side. FD.TP sessions must be converted to classical BAM/CMDT sessions, adjusting timing parameters accordingly. This fragmentation introduces latency that must be accounted for in real-time control applications.

14.3 Network Management and Functional Safety

J1939 Network Management (J1939-81) provides address claiming and conflict resolution mechanisms essential for plug-and-play operation of ECUs on the bus. J1939-22 extends these capabilities for CAN FD networks while maintaining backward compatibility.

Address Claiming Protocol

Each J1939 node must claim a unique source address (0–253) on the network before transmitting. The Address Claimed message (PGN 0xEE00) carries the node's 64-bit NAME field, which serves as a globally unique identifier and determines priority during address conflicts.

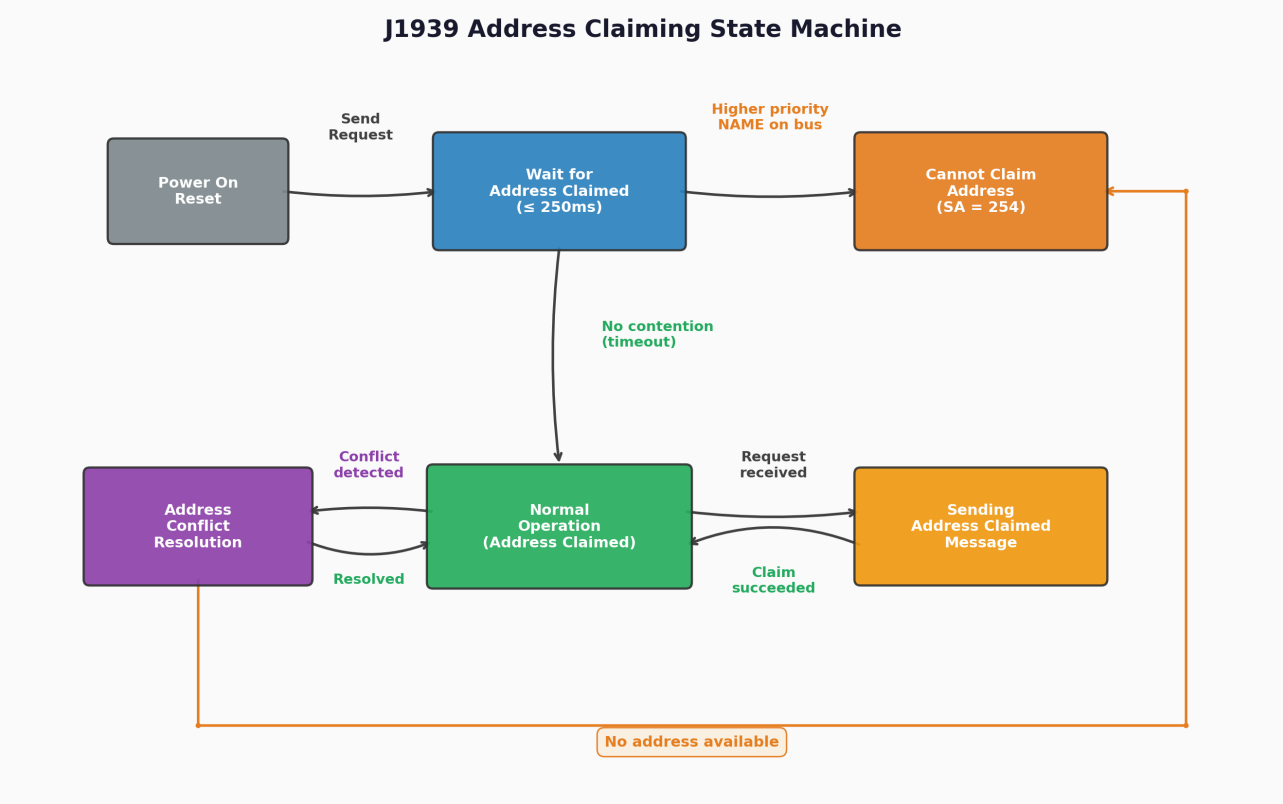


Figure 14-4 *J1939 Address Claiming State Machine*

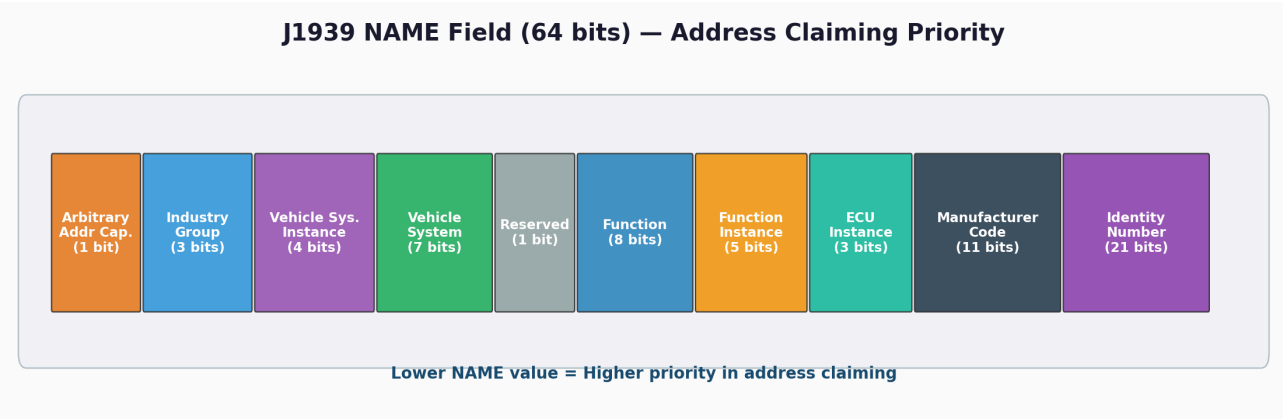


Figure 14-5 *J1939 NAME Field (64 bits) — Address Claiming Priority*

J1939 NAME Field Structure

Table 14-5 J1939 NAME Field — 64-bit Unique Identifier

Bits	Field	Description
63	Arbitrary Address	1 = node can negotiate address, 0 = fixed address
62–59	Industry Group	Application area (0 = Global, 1 = On-Highway, 2 = Agriculture, etc.)
58–55	Vehicle System Instance	Differentiates multiple identical systems
54–48	Vehicle System	Identifies the vehicle system (engine, transmission, etc.)
47–40	Function	Specific function of the ECU within the system
39–35	Function Instance	Instance of the function
34–32	ECU Instance	Instance of the ECU for this function
31–21	Manufacturer Code	SAE-assigned manufacturer identifier
20–0	Identity Number	Manufacturer-assigned unique serial number

Conflict Resolution

When two nodes claim the same address, the NAME field values determine the winner. The node with the **lower numeric NAME value** wins the address. The losing node must either select an alternative address (if Arbitrary Address bit = 1) or go to the Cannot Claim Address state (sending PGN 0xEE00 with source address 254).

> **J1939-17: CAN FD Physical Layer**
>
> SAE J1939-17 specifies the physical layer for J1939 CAN FD networks. It defines dual bit rates: 500 kbit/s during the arbitration phase and 2 Mbit/s during the data phase. This conservative approach compared to CAN FD's theoretical maximum of 8 Mbps ensures reliable operation with existing J1939 wiring harnesses and connector systems in harsh commercial vehicle environments. The standard also addresses transceiver requirements, bus timing tolerances, and oscillator specifications for J1939 CAN FD nodes.

Functional Safety Considerations

Modern J1939 CAN FD implementations must address functional safety (ISO 26262) requirements. Key mechanisms include:

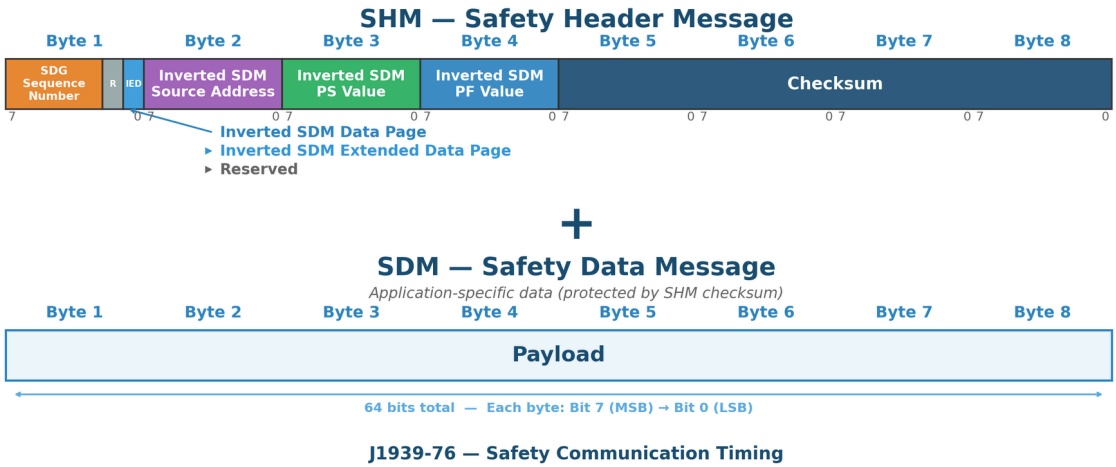
- **Error State Indicator (ESI):** CAN FD's ESI bit allows immediate detection of error-passive transmitters, improving fault containment
- **CRC Improvements:** CAN FD's 17/21-bit CRC with stuff-bit counting provides stronger error detection than classical CAN's 15-bit CRC
- **End-to-End Protection:** Application-level E2E protection (e.g., AUTOSAR E2E Profile 6) should supplement CAN FD's built-in error detection for safety-critical PGs
- **Alive Counter:** Monitoring message sequence numbers helps detect frozen or stale data from faulty ECUs
- **Timeout Monitoring:** Heartbeat-based supervision detects silent node failures within defined reaction time

14.4 J1939-76 Functional Safety Communication

SAE J1939-76 defines a safety communication layer on top of J1939 that ensures data integrity for safety-critical applications up to ASIL D (ISO 26262). The standard introduces a paired message mechanism using a **Safety Header Message (SHM)** and a **Safety Data Message (SDM)**.

SHM/SDM Message Structure

For each safety-critical PGN, the producer transmits two consecutive messages: the SHM (containing integrity verification data) followed by the SDM (containing the actual safety payload). The consumer validates the SHM before accepting the SDM data.



J1939-76 — Safety Communication Timing

SDG Timing Basis	SCT Maximum	SRVT Maximum
≤ 200 ms	150% of time basis	50% of time basis
> 200 ms	Time basis + 100 ms	100 ms

Figure 14-6 *J1939-76 Safety Header Message (SHM) and Safety Data Message (SDM) Structure*

SHM Field Descriptions

Table 14-6 Safety Header Message (SHM) Fields

Byte	Field	Description
1 (bits 7-1)	SDG Sequence Number	Incrementing counter (0–127) per Safety Data Group, detects message loss or repetition
1 (bit 0)	Reserved	Reserved for future use
1 (IED bits)	Inverted Extended Data Page / Data Page	Inverted values of the SDM's DP and EDP fields for cross-verification
2	Inverted SDM Source Address	Bitwise inverse of the SDM's Source Address field
3	Inverted SDM PS Value	Bitwise inverse of the SDM's PDU Specific field
4	Inverted SDM PF Value	Bitwise inverse of the SDM's PDU Format field
5-8	Checksum	32-bit CRC calculated over the SHM header and corresponding SDM data

Safety Communication Timing

J1939-76 defines two critical timing parameters that the consumer monitors for each Safety Data Group (SDG):

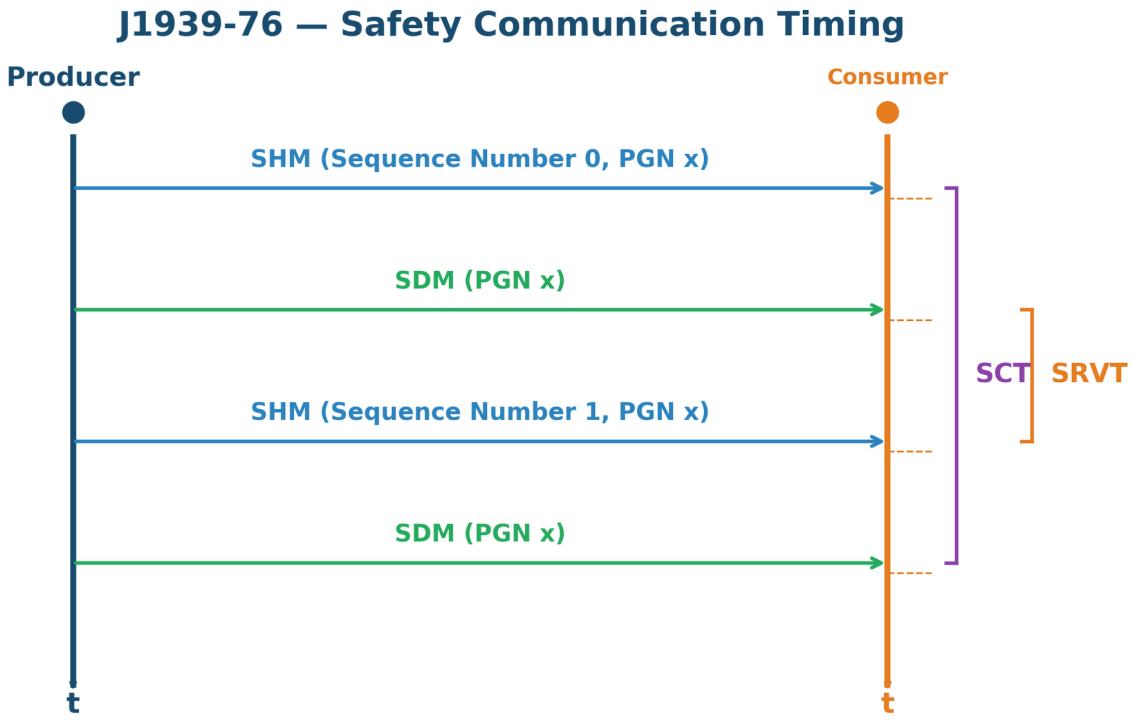


Figure 14-7 *J1939-76 Safety Communication Timing — Producer/Consumer with SCT and SRVT*

Table 14-7 J1939-76 Safety Timing Parameters

Parameter	Full Name	Description
SCT	Safety Communication Time	Maximum allowed time between two consecutive valid SHM/SDM pairs for the same PGN. If exceeded, the consumer enters a safe state.
SRVT	Safety-Related Valid Timeout	Maximum allowed time between the SHM and its corresponding SDM within a single safety data group. If exceeded, the data pair is discarded.

> **J1939-76 Validation Process**
>
> The consumer must perform the following checks before accepting safety data: (1) verify the SDG Sequence Number has incremented correctly, (2) confirm the inverted identifier fields in the SHM match the SDM's actual identifier fields, (3) validate the 32-bit checksum against the received data, and (4) verify both SCT and SRVT timing constraints are met. If any check fails, the safety data is rejected and the application-defined fault reaction is triggered.

Chapter 15: CANopen Protocol

CANopen is a CAN-based application layer protocol standardized by CAN in Automation (CiA). Defined primarily in CiA 301, it provides a standardized communication framework widely used in industrial automation, medical devices, maritime systems, and embedded control. CANopen implements a device model, communication profiles, and configuration mechanisms that enable interoperable multi-vendor networks.

Standard History and Specification Documents

CANopen was originally developed by Bosch and published as a European standard (EN 50325-4). The CAN in Automation (CiA) international users' and manufacturers' group maintains and evolves the specification. Key specification documents include:

Table 15-1 CANopen Specification Documents

Document	Title	Scope
CiA 301 (DS 301)	CANopen Application Layer	Core specification: Object Dictionary, NMT, SDO, PDO, communication model
CiA 302 (DS 302)	Additional Application Layer Functions	NMT master features, flying master, boot-up, configuration management
CiA 303-3 (DR 303-3)	Indicator Specification	LED behavior for CAN and device status indication (green/red patterns)
CiA 305	Layer Setting Services (LSS)	Node-ID and baud rate assignment via CAN without pre-configuration
CiA 306	Electronic Data Sheet (EDS)	Machine-readable device description format for configuration tools
CiA 4xx	Device Profiles	Domain-specific profiles (401: I/O, 402: Drives, 404: Measuring, etc.)
CiA 1301	CANopen FD	Extension for CAN FD networks: 64-byte PDO/SDO, enhanced MPDO

Network Structure

A CANopen network follows a **master/slave** architecture coordinated by the Network Management (NMT) protocol. One node acts as the **NMT Master** (typically the PLC or central controller), managing the lifecycle and state transitions of all other nodes on the bus. Key characteristics include:

- **Node-ID Assignment:** Each device on the network is assigned a unique Node-ID (1–127). Node-ID 0 is reserved for NMT broadcast commands. The Node-ID determines all default COB-IDs for that device's communication objects.
- **NMT State Machine:** Every node follows a defined state machine: *Initialization → Pre-Operational → Operational → Stopped*. The NMT Master controls transitions via NMT commands (Start, Stop, Pre-Operational, Reset Node, Reset Communication).
- **Heartbeat / Node Guarding:** Network health is monitored through either Heartbeat (preferred, producer-driven) or Node Guarding (legacy, master-polled). Heartbeat messages are transmitted at configurable intervals by each node, allowing the NMT Master and consumers to detect node failures.
- **Boot-Up Message:** When a node completes initialization, it broadcasts a boot-up message (COB-ID = 0x700 + Node-ID) to announce its presence on the network.

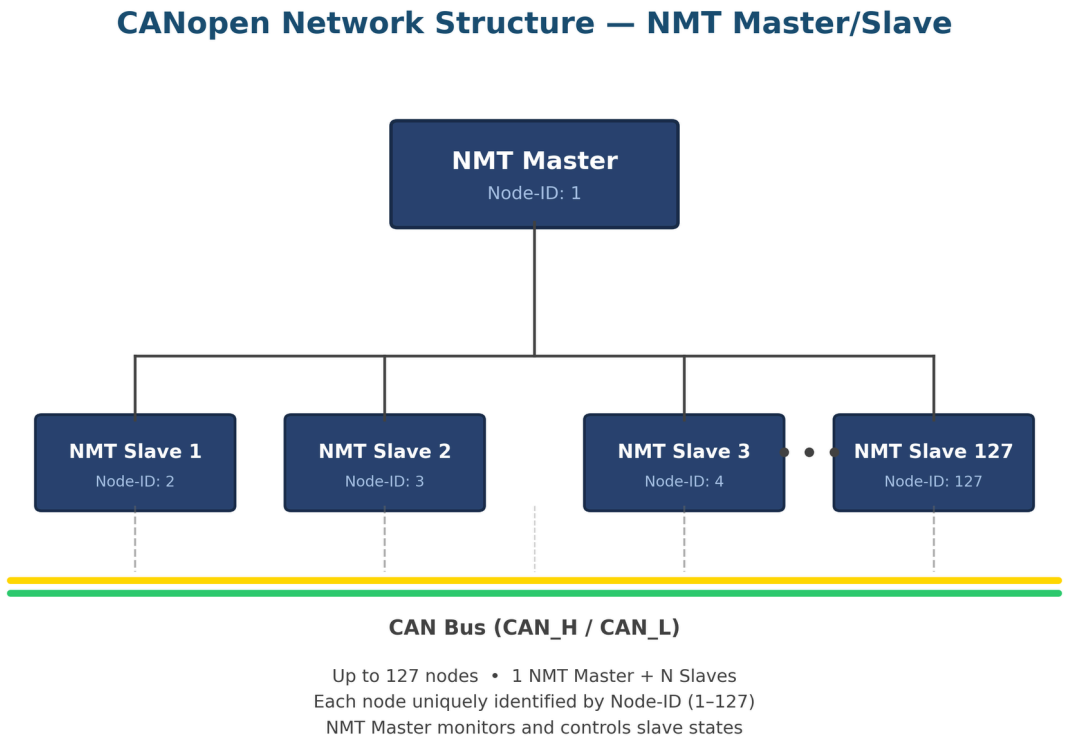


Figure 15-1 *CANopen Network Structure — NMT Master with Slave Nodes*

Device Model

Every CANopen device implements a standardized internal structure defined by CiA 301. The device model consists of three interconnected components: the Communication unit (protocol stack), the Object Dictionary (central data repository), and the Application (device-specific functions).

- **Communication Unit:** Handles all CAN bus interactions including PDO (Process Data Object) exchange for real-time data, SDO (Service Data Object) transfers for configuration and parameterization, NMT state management, SYNC synchronization, EMCY emergency messages, and TIME timestamp distribution.
- **Object Dictionary (OD):** The central data structure of every CANopen device — an ordered table of 16-bit index entries (0x0000–0xFFFF), each with optional 8-bit sub-indices. The OD contains all communication parameters, device profile entries, and manufacturer-specific data. Indices 0x1000–0x1FFF hold communication profile entries; 0x6000–0x9FFF hold device profile entries.
- **Application:** The device-specific functionality (e.g., motor control, sensor reading, I/O management) that reads from and writes to the Object Dictionary. The application layer is decoupled from the communication layer through the OD, enabling standardized access to device data regardless of vendor implementation.

This three-layer architecture ensures that any CANopen-compliant configuration tool can access, configure, and diagnose any device on the network through the standardized Object Dictionary interface, enabling true multi-vendor interoperability.

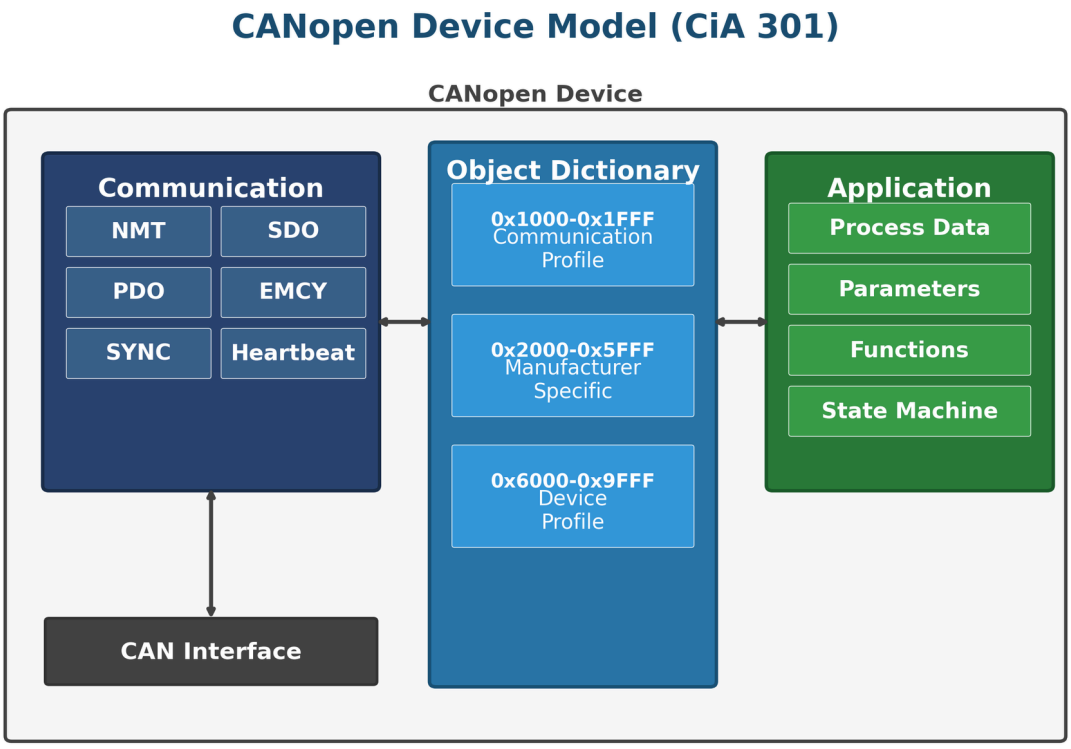


Figure 15-2 *CANopen Device Model (CiA 301) — Communication, Object Dictionary, and Application*

15.1 Architecture and Communication Objects

A CANopen network consists of an **NMT Master** that coordinates network state, and one or more **NMT Slave** nodes. Each node is identified by a unique Node-ID (1–127) and communicates through predefined communication objects, each assigned a COB-ID (CAN Object Identifier) based on a standardized allocation scheme.

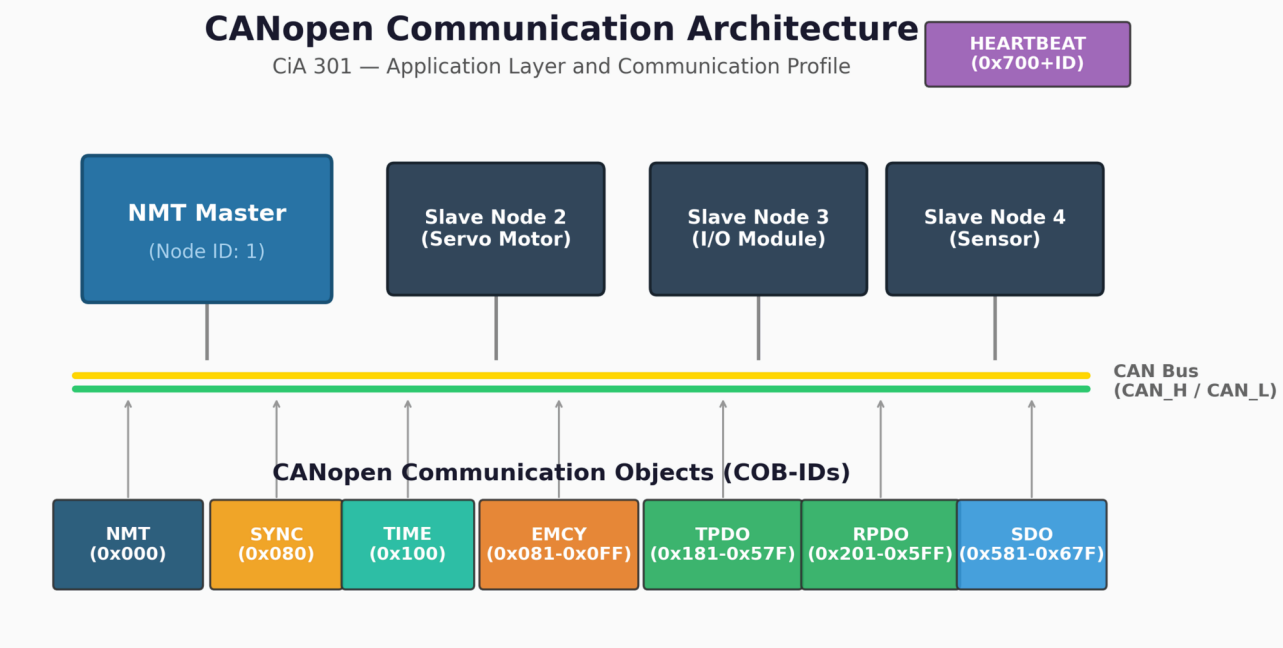


Figure 15-3 *CANopen Communication Architecture — Nodes, Bus, and Communication Objects*

Communication Object Types

The pre-defined COB-ID allocation for all communication objects is shown in Figure 15-4.

Pre-defined COB-ID Allocation (CiA 301)

Function	COB-ID Range	Protocol
NMT	0x000	Master → Slave
SYNC	0x080	Producer → Consumer
TIME	0x100	Producer → Consumer
EMCY	0x081 – 0x0FF	Producer → Consumer
TPDO1-4	0x181 – 0x4FF	Producer → Consumer
RPDO1-4	0x201 – 0x57F	Producer → Consumer
SDO (Tx)	0x581 – 0x5FF	Client / Server
SDO (Rx)	0x601 – 0x67F	Client / Server
Heartbeat	0x701 – 0x77F	Producer → Consumer

Figure 15-4 *Pre-defined COB-ID Allocation (CiA 301)*

NMT State Machine

Each CANopen node operates in one of the following NMT states, controlled by the NMT Master via two-byte NMT commands (COB-ID 0x000):

Table 15-2 CANopen NMT States and Allowed Communication Objects

State	NMT Command	Allowed Objects
Initialization	—	Boot-up message only
Pre-operational	0x80	SDO, EMCY, NMT, Heartbeat, SYNC, TIME
Operational	0x01	All objects (PDO + SDO + NMT + EMCY + Heartbeat + SYNC + TIME)
Stopped	0x02	NMT and Heartbeat only

> **Boot-up Sequence**
>
> After power-on, a CANopen node enters Initialization, executes internal setup, then automatically transitions to Pre-operational state. It announces its presence by sending a boot-up message (Heartbeat frame with state 0x00) on COB-ID 0x700 + Node-ID. The NMT Master can then configure the node via SDO before issuing the "Start Remote Node" command (0x01) to enter the Operational state where PDO communication begins.

15.2 SDO and PDO Services

CANopen provides two fundamentally different data exchange mechanisms: **SDO** (Service Data Object) for configuration and parameter access, and **PDO** (Process Data Object) for efficient real-time data exchange.

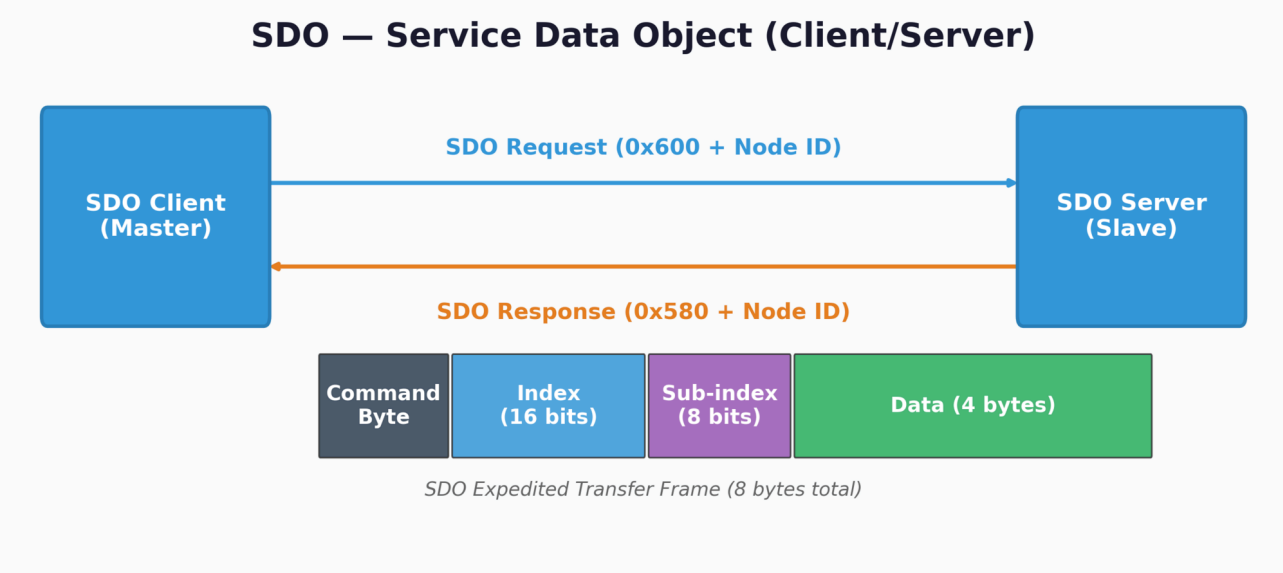


Figure 15-5 *SDO — Service Data Object (Client/Server) Communication*

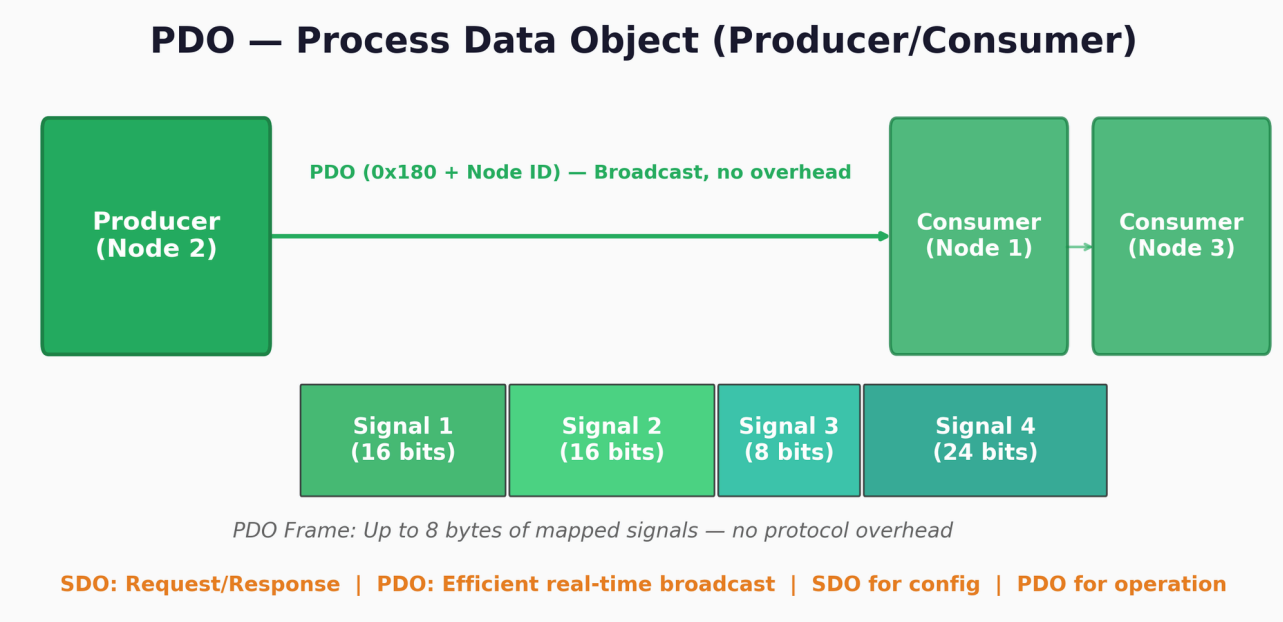


Figure 15-6 *PDO — Process Data Object (Producer/Consumer) Communication*

Service Data Object (SDO)

SDO uses a client/server model for reading and writing Object Dictionary entries. The SDO client (typically the configuration tool or NMT Master) sends a request, and the SDO server (the target node) responds. SDO supports three transfer modes:

Table 15-3 SDO Transfer Modes

Mode	Data Size	Frames Required	Use Case
Expedited	1–4 bytes	1 request + 1 response	Single parameters (node ID, heartbeat time, etc.)
Segmented	5+ bytes	Initiate + N segments + confirm	Medium-length data (string parameters, arrays)
Block	Large	Initiate + N blocks + confirm	Firmware download, large data sets

SDO Frame Structure

An SDO expedited transfer frame is always 8 bytes and contains the following fields:

Table 15-4 SDO Expedited Transfer Frame Layout (8 bytes)

Byte	Field	Description
0	Command Byte	Transfer type, direction, and data size indicator
1–2	Index	16-bit Object Dictionary index (little-endian)
3	Sub-index	8-bit sub-index within the OD entry
4–7	Data	Up to 4 bytes of parameter data (expedited mode)

Process Data Object (PDO)

PDOs provide the most efficient real-time data exchange on a CANopen network. Unlike SDO, PDO frames carry **no protocol overhead** — the entire 8-byte CAN payload is available for process data. PDOs use a producer/consumer model where one node transmits a PDO and any number of nodes can receive it.

PDO behavior is highly configurable through the Object Dictionary:

- **Event-driven:** PDO is transmitted when a mapped signal changes
- **Timer-driven:** PDO is transmitted at a configured interval (event timer)
- **SYNC-driven:** PDO is transmitted upon reception of the SYNC object
- **Remote request:** PDO is transmitted in response to an RTR frame

PDO Mapping

PDO mapping defines which Object Dictionary entries are packed into a PDO frame. Static mapping is configured before the node enters Operational state, while dynamic mapping (CiA 301) allows reconfiguration at runtime via SDO. Each mapped object is defined by its Index, Sub-index, and bit length. The total mapped length must not exceed 64 bits (8 bytes). For example, TPDO1 might map three sensor values: Temperature (16-bit at 0x6000:01), Pressure (16-bit at 0x6000:02), and Status (8-bit at 0x6001:00), occupying 40 of the available 64 bits.

15.3 Object Dictionary, EDS and DCF

The Object Dictionary (OD) is the central data structure of every CANopen device. It defines all device parameters, communication settings, and application data as a standardized set of indexed entries. The OD structure follows the rules specified in CiA 301 and is divided into well-defined address ranges.

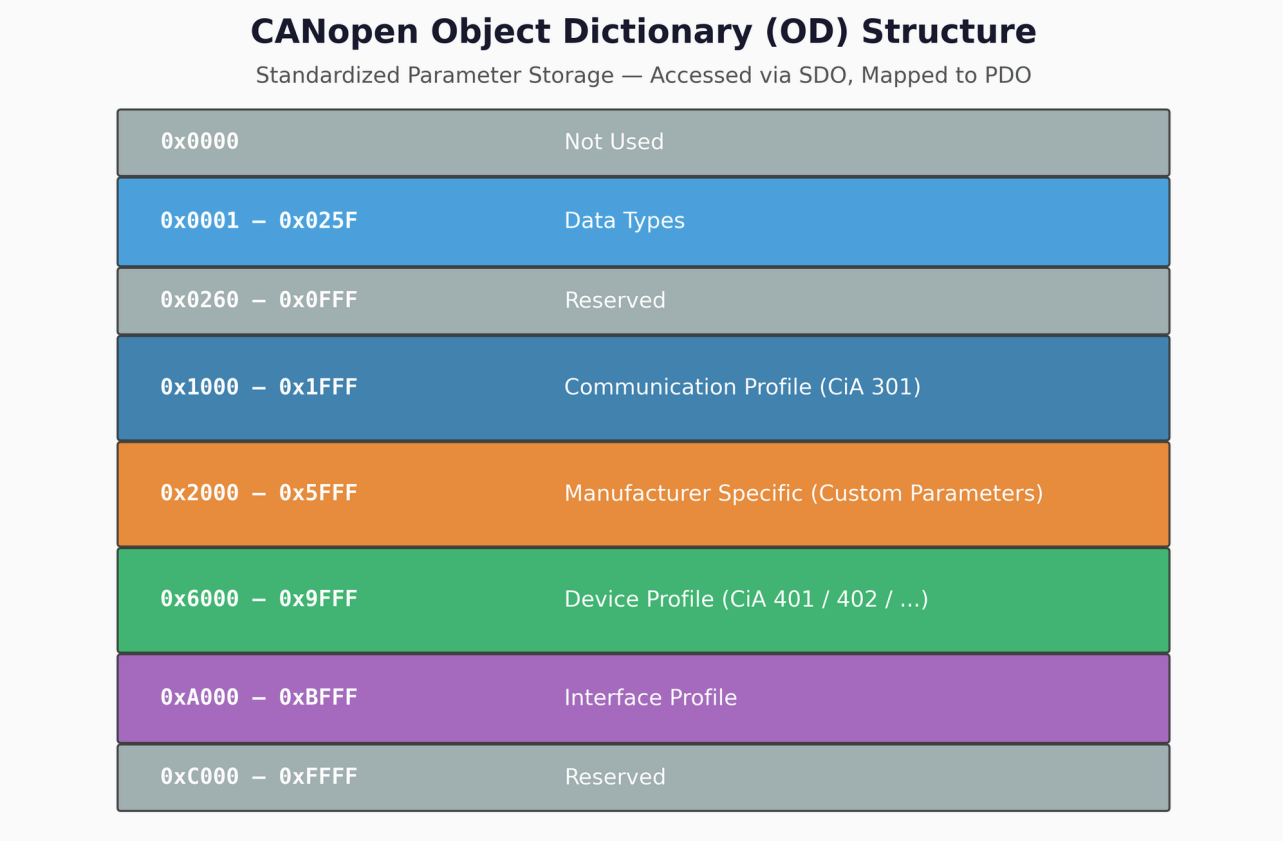


Figure 15-7 *CANopen Object Dictionary (OD) Index Structure*

Key Communication Profile Entries (0x1000 – 0x1FFF)

Index	Name	Type	Access	Category
0x1000	Device Type	UNSIGNED32	ro	M
0x1001	Error Register	UNSIGNED8	ro	M
0x1008	Device Name	STRING	ro	O
0x1017	Heartbeat Producer Time	UNSIGNED16	rw	O
0x1018	Identity Object	RECORD	ro	M
0x1200	SDO Server Parameter	RECORD	ro	M
0x1400	RPDO1 Comm. Parameter	RECORD	rw	O
0x1600	RPDO1 Mapping	RECORD	rw	O
0x1800	TPDO1 Comm. Parameter	RECORD	rw	O
0x1A00	TPDO1 Mapping	RECORD	rw	O

M = Mandatory O = Optional

Figure 15-8 *Key Communication Profile Entries (0x1000 – 0x1FFF)*

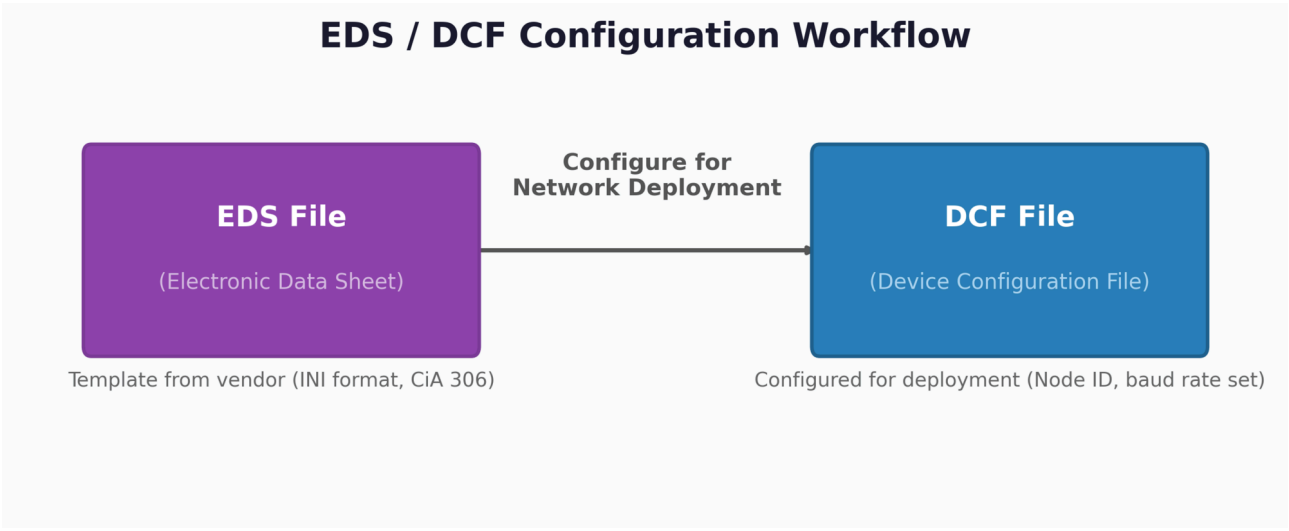


Figure 15-9 *EDS / DCF Configuration Workflow*

Object Dictionary Address Ranges

Table 15-5 Object Dictionary Index Allocation

Index Range	Section	Description
0x0000	Not used	Reserved
0x0001–0x025F	Data Types	Standard and complex data type definitions
0x0260–0x0FFF	Reserved	Reserved for future CiA specifications
0x1000–0x1FFF	Communication Profile	CiA 301 parameters: Device Type, Error Register, Heartbeat, SDO/PDO config
0x2000–0x5FFF	Manufacturer Specific	Custom parameters defined by the device manufacturer
0x6000–0x9FFF	Device Profile	Standardized application objects (CiA 401 I/O, CiA 402 Drives, etc.)
0xA000–0xBFFF	Interface Profile	Network and interface-related parameters
0xC000–0xFFFF	Reserved	Reserved for future use

Key Communication Profile Entries

Table 15-6 Essential OD Entries (Communication Profile Area)

Index	Name	Type	Access	Category
0x1000	Device Type	UNSIGNED32	ro	Mandatory
0x1001	Error Register	UNSIGNED8	ro	Mandatory
0x1008	Device Name	STRING	ro	Optional
0x1017	Heartbeat Producer Time	UNSIGNED16	rw	Optional
0x1018	Identity Object	RECORD	ro	Mandatory
0x1200	SDO Server Parameter	RECORD	ro	Mandatory
0x1400	RPDO1 Communication Parameter	RECORD	rw	Optional
0x1600	RPDO1 Mapping Parameter	RECORD	rw	Optional
0x1800	TPDO1 Communication Parameter	RECORD	rw	Optional
0x1A00	TPDO1 Mapping Parameter	RECORD	rw	Optional

EDS and DCF Files

The **Electronic Data Sheet (EDS)** is a standardized file (CiA 306) that describes a device's complete Object Dictionary in a machine-readable INI-like text format. The EDS is provided by the device manufacturer and contains:

- All Object Dictionary entries with index, sub-index, data type, and access rights
- Default values and value ranges for each parameter
- PDO mapping capabilities and communication parameters
- Device identification information (vendor ID, product code, revision)

The **Device Configuration File (DCF)** is derived from the EDS by a configuration tool. While the EDS describes what a device *can* do, the DCF defines what it *will* do in a specific network configuration. The DCF adds:

- Assigned Node-ID and baud rate
- Specific PDO mapping configuration for the target application
- Customized parameter values for the deployment
- Heartbeat timing and other network-specific settings

> **EDS/DCF Configuration Workflow**
>
> The typical CANopen commissioning workflow begins with importing the device manufacturer's EDS file into a network configuration tool (e.g., Vector CANopen Architect, Ixxat canAnalyser, or CODESYS). The tool displays the device's capabilities and allows the engineer to configure PDO mappings, heartbeat timing, Node-ID assignment, and application parameters. The tool then generates a DCF file for each node, which can be downloaded to the devices via SDO during the Pre-operational phase or stored in non-volatile memory for automatic configuration at startup.

Device Profiles

CiA defines standardized device profiles that specify the OD entries in the Device Profile area (0x6000–0x9FFF) for specific device categories:

Table 15-7 Key CANopen Device Profiles

Profile	Description	Typical Applications
CiA 401	Generic I/O Modules	Digital/analog inputs and outputs
CiA 402	Drives and Motion Control	Servo motors, stepper motors, frequency inverters
CiA 404	Measuring Devices	Sensors, encoders, transducers
CiA 406	Encoder Interface	Absolute and incremental encoders
CiA 410	Inclinometer	Tilt sensors, angle measurement
CiA 418	Battery Modules	Battery management systems

> **CANopen vs CANopen FD**
>
> CiA 1301 defines CANopen FD, extending the classical CANopen framework to CAN FD networks. Key differences include: SDO and PDO payloads can use the full 64-byte CAN FD capacity, MPDO (Multiplexed PDO) support is enhanced, and new frame formats accommodate the larger data fields. However, CANopen FD nodes cannot directly interoperate with classical CANopen nodes on the same bus segment without a protocol gateway. For new designs, carefully evaluate whether the increased bandwidth justifies the additional complexity and reduced ecosystem maturity compared to classical CANopen at 1 Mbps.

Chapter 16: CAN DBC File Format

A CAN DBC file (CAN database) is a structured text file that contains the rules for decoding raw CAN bus data into human-readable physical values. DBC files describe messages, signals, their encoding parameters, and metadata — serving as the essential "dictionary" for interpreting any CAN network.

16.1 DBC Syntax and Structure

A DBC file is organized into sections, each beginning with a keyword. The two most critical sections define **messages** (BO_) and **signals** (SG_):

Message Definition (BO_)

```
BO_ <CAN_ID> <MessageName>: <DLC> <Transmitter>
 SG_ <SignalName> : <StartBit>|<Length>@<ByteOrder><Sign> (<Scale>,<Offset>) [<Min>|
<Max>] "<Unit>" <Receiver>
```

Table 16-1 DBC Message Syntax (BO_)

Field	Description	Rules
CAN_ID	CAN identifier in decimal	For 29-bit IDs, bit 31 is set as extended flag (ID + 0x80000000)
MessageName	Unique message name	1–32 chars, [A-z], digits, underscores
DLC	Data length code	Integer 0–1785 (8 for Classical CAN, up to 64 for CAN FD)
Transmitter	Sending node name	Vector__XXX if unknown

Signal Definition (SG_)

Table 16-2 DBC Signal Syntax (SG_)

Field	Description	Example
StartBit	Bit position in payload (0-indexed)	24
Length	Signal length in bits	16
ByteOrder	@1 = Little-endian (Intel), @0 = Big-endian (Motorola)	@1
Sign	+ = unsigned, − = signed	+
Scale	Multiplication factor	0.125
Offset	Added after scaling	0
[Min|Max]	Physical value range	[0|8031.875]
Unit	Engineering unit string	"rpm"

Complete DBC Example — J1939 Engine Speed and Vehicle Speed

```
VERSION ""

NS_ :
    CM_
    BA_DEF_
    BA_
    BA_DEF_DEF_

BS_:

BU_:

BO_ 2364540158 EEC1: 8 Vector__XXX
 SG_ EngineSpeed : 24|16@1+ (0.125,0) [0|8031.875] "rpm" Vector__XXX

BO_ 2566844926 CCVS1: 8 Vector__XXX
 SG_ WheelBasedVehicleSpeed : 8|16@1+ (0.00390625,0) [0|250.996] "km/h" Vector__XXX

CM_ BO_ 2364540158 "Electronic Engine Controller 1";
CM_ SG_ 2364540158 EngineSpeed "Actual engine speed calculated over a
minimum crankshaft angle of 720 degrees divided by the number of cylinders.";
CM_ BO_ 2566844926 "Cruise Control/Vehicle Speed 1";

BA_DEF_ SG_ "SPN" INT 0 524287;
BA_DEF_ BO_ "VFrameFormat" ENUM "StandardCAN","ExtendedCAN","reserved","J1939PG";
BA_DEF_ "BusType" STRING ;
BA_DEF_ "ProtocolType" STRING ;
BA_DEF_DEF_ "SPN" 0;
BA_DEF_DEF_ "VFrameFormat" "J1939PG";
BA_DEF_DEF_ "BusType" "";
BA_DEF_DEF_ "ProtocolType" "";
BA_ "ProtocolType" "J1939";
BA_ "BusType" "CAN";
BA_ "VFrameFormat" BO_ 2364540158 3;
BA_ "SPN" SG_ 2364540158 EngineSpeed 190;
```

J1939 DBC ID Convention

J1939 uses 29-bit extended CAN IDs. In DBC files, the extended ID flag is stored by adding `0x80000000` to the CAN ID. For example, CAN ID `0x0CF00400` becomes DBC ID `2364540158` (= 0x0CF00400 + 0x80000000 = 0x8CF00400 = 2364539904 + 254). The `VFrameFormat` attribute `"J1939PG"` identifies this message as a J1939 Parameter Group.

16.2 Signal Decoding

The decoding process converts raw CAN data bytes to physical engineering values using the linear formula:

DBC Signal Physical Value

$$\text{Physical Value} = (\text{Raw Value} \times \text{Scale}) + \text{Offset}$$

Step-by-Step Example: Decode EngineSpeed from Raw CAN Frame

Given the raw CAN frame:

```
CAN ID: 0CF00400    Data: FF FF FF 68 13 FF FF FF
```

Step 1 — Identify the message: CAN ID `0x0CF00400` matches DBC message EEC1 (ID 2364540158 with extended flag).

Step 2 — Extract raw signal bytes: Signal EngineSpeed starts at bit 24 (byte 3, bit 0) with length 16 bits. The raw bytes at positions 3–4 are `0x68` and `0x13`.

Step 3 — Apply byte order: Little-endian (@1) → LSB first: raw value = `0x1368` = **4968** decimal.

Step 4 — Apply scale and offset:

EngineSpeed Calculation

$$\text{EngineSpeed} = 4968 \times 0.125 + 0 = 621.0 \text{ rpm}$$

Byte Order: Intel vs Motorola

The byte order significantly affects how multi-byte signals are extracted from the CAN data field:

Table 16-3 Intel (Little-Endian) vs Motorola (Big-Endian) Byte Order

Property	Intel (@1) — Little-Endian	Motorola (@0) — Big-Endian
LSB Position	At start bit	At start bit
MSB Position	Higher byte addresses	Lower byte addresses
Byte Fill Direction	LSB → MSB: left to right	MSB → LSB: right to left
Common In	J1939, most European OEMs	Many Asian OEMs, some legacy systems

Byte Order Mismatch

Using the wrong byte order is the single most common source of incorrect CAN signal decoding. If decoded values appear wrong by orders of magnitude or produce unexpected negative numbers, verify the byte order setting first. J1939 signals are always little-endian (Intel), but OEM-specific CAN messages may use either convention.

16.3 Advanced DBC Features

Comments (CM_)

DBC files support comments for messages, signals, and general descriptions:

```
CM_ BO_ 2364540158 "Electronic Engine Controller 1";
CM_ SG_ 2364540158 EngineSpeed "Actual engine speed.";
CM_ "This DBC file covers the J1939 powertrain network.";
```

Attributes (BA_DEF_ / BA_)

Attributes extend DBC metadata with custom properties. Common attributes include:

Table 16-4 Common DBC Attributes

Attribute	Scope	Description
BusType	Global	Bus type string ("CAN", "CAN FD")
ProtocolType	Global	Protocol identifier ("J1939", "OBD2")
VFrameFormat	Message	Frame format (StandardCAN, ExtendedCAN, J1939PG)
SPN	Signal	SAE J1939 Suspect Parameter Number
GenMsgCycleTime	Message	Nominal transmission cycle time in ms
SystemSignalLongSymbol	Signal	Extended signal name (beyond 32-char limit)

Signal Multiplexing

Multiplexing allows the same CAN ID to carry different signals depending on the value of a multiplexor signal. This is used in OBD-II (where the PID acts as multiplexor), UDS, and CCP/XCP protocols:

```
BO_ 2024 OBD2_Response: 8 ECU
 SG_ ServiceMode m : 0|8@1+ (1,0) [0|255] "" Tester
 SG_ PID m : 8|8@1+ (1,0) [0|255] "" Tester
 SG_ EngineRPM m12 : 16|16@1+ (0.25,0) [0|16383.75] "rpm" Tester
 SG_ VehicleSpeed m13 : 16|8@1+ (1,0) [0|255] "km/h" Tester
 SG_ CoolantTemp m5 : 16|8@1+ (1,-40) [-40|215] "°C" Tester
```

> **Multiplexor Syntax**
>
> In the SG_ definition, `m` after the signal name designates the **multiplexor** signal. `m12` means this signal is valid when the multiplexor value equals 12 (PID 0x0C = Engine RPM). `m13` is valid when PID = 0x0D (Vehicle Speed). This mechanism enables a single CAN ID to carry hundreds of different parameters — the DBC tool selects the correct decoding rule based on the multiplexor value.

DBC File Tools and Ecosystem

Table 16-5 DBC File Software Ecosystem

Tool	Type	DBC Capability
Vector CANdb++	Commercial Editor	Full DBC creation, editing, validation
PEAK Symbol Editor	Free Editor	DBC creation and symbol management
SavvyCAN	Open Source	DBC decode, reverse engineering
cantools (Python)	Open Source Library	Parse, encode, decode DBC programmatically
asammdf (Python)	Open Source Library	MF4 log files + DBC decoding + plotting
CANalyzer / CANoe	Commercial	Real-time DBC decode, simulation, testing

> **Standard DBC Files for Common Protocols**
>
> Standardized DBC files are available for J1939 (from SAE — covers all standard PGNs/SPNs), OBD-II (standard PIDs), and ISOBUS. These allow immediate decoding of standard parameters across any vehicle or machine using that protocol. Manufacturer-specific signals (proprietary PGNs, custom PIDs) require OEM-specific DBC files which are typically confidential.

Chapter 17: CAN Bus Data Logging & Analysis

Data logging is an essential practice in CAN bus engineering — it allows engineers to capture, store, and analyze real-time bus traffic for development, diagnostics, compliance, and fleet management. This chapter covers the complete data logging pipeline, from hardware interfaces and file formats to software tools and Python-based analysis techniques.

17.1 Introduction to CAN Data Logging

CAN data logging captures raw or decoded bus messages for offline analysis. The logged data can include timestamps, CAN IDs, DLC (Data Length Code), and the data payload — enabling engineers to reconstruct the exact sequence of events that occurred on the bus.

Why Log CAN Data?

- **Development & Testing:** ECU calibration, protocol validation, regression testing, and integration verification
- **Diagnostics & Troubleshooting:** Capturing intermittent faults, DTC logging, fault replay, and root cause analysis
- **Fleet Monitoring:** Remote diagnostics, predictive maintenance, fuel efficiency tracking, and OTA update verification
- **Compliance & Certification:** Emissions data recording (J1939/OBD-II), type approval documentation, and audit trails
- **Incident Analysis:** Post-crash data extraction, event reconstruction, and liability documentation

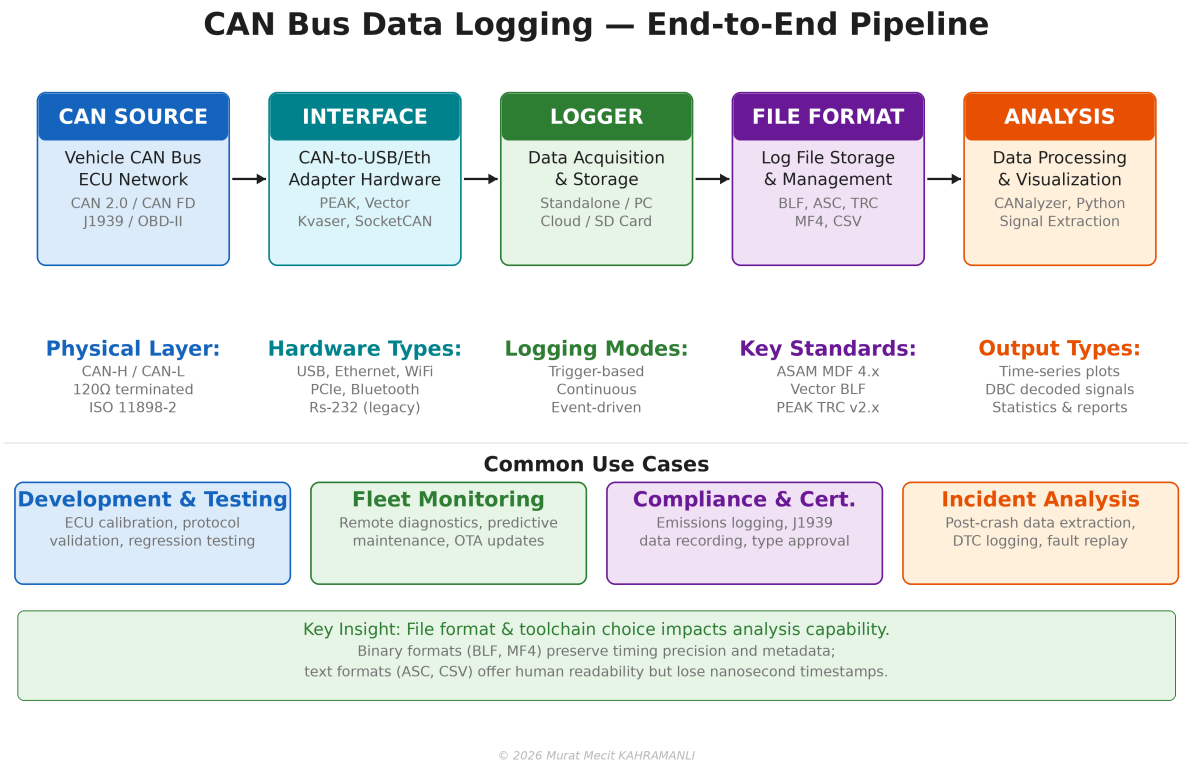


Figure 17-1 *CAN Bus Data Logging — End-to-End Pipeline: From vehicle CAN source through interface hardware, data acquisition, file storage, to analysis and visualization.*

Logging Architecture

A typical CAN data logging setup consists of five stages:

1. **CAN Source:** The vehicle or device CAN bus (CAN 2.0A/B, CAN FD, J1939, OBD-II)
2. **Interface Hardware:** CAN-to-USB, CAN-to-Ethernet, or CAN-to-WiFi adapter
3. **Data Acquisition:** Logger software or standalone hardware recording to storage
4. **File Format:** BLF, ASC, TRC, MF4/MDF, or CSV files
5. **Analysis & Visualization:** Signal extraction, plotting, statistics, and reporting

17.2 CAN Log File Formats

The choice of log file format significantly impacts storage efficiency, analysis capability, and tool compatibility. The five most common formats in the CAN ecosystem are BLF, ASC, TRC, MF4, and CSV.

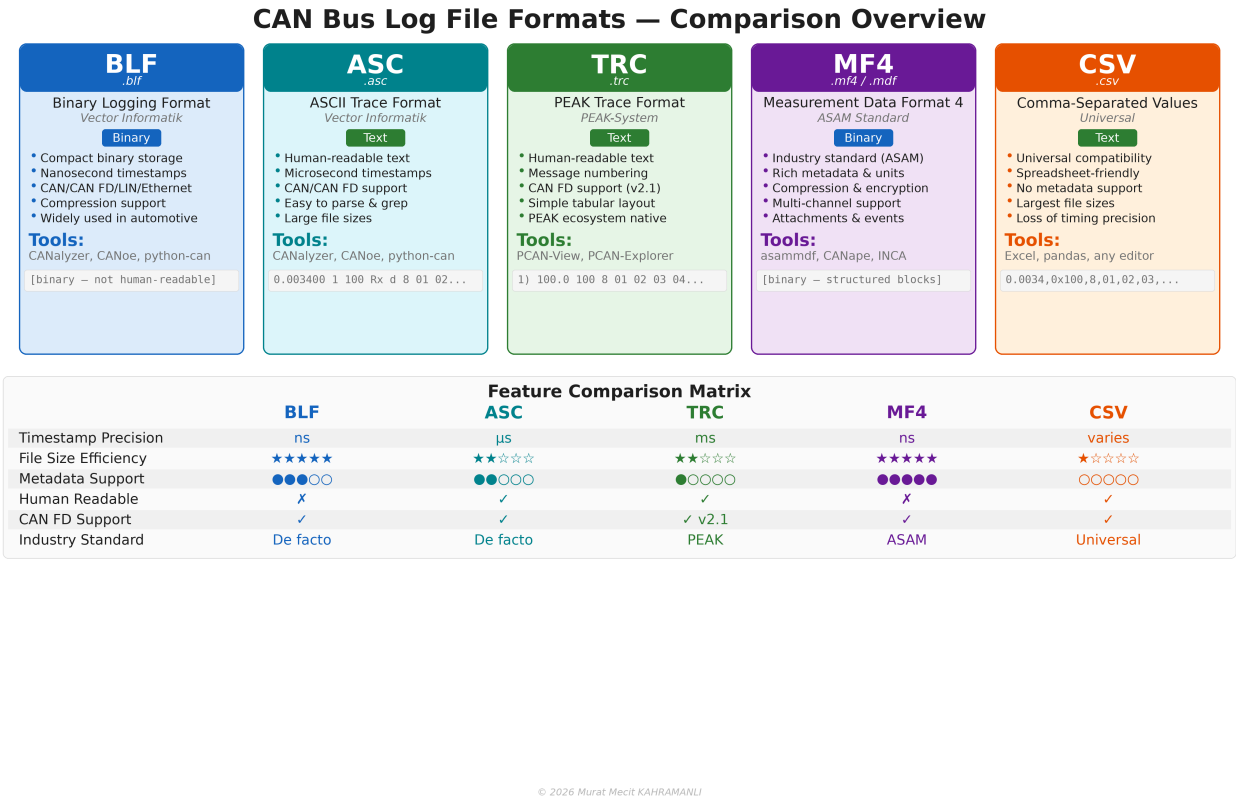


Figure 17-2 *CAN Bus Log File Formats — Comparison Overview: BLF, ASC, TRC, MF4, and CSV with feature matrix.*

BLF — Binary Logging Format (Vector)

BLF is Vector Informatik's proprietary binary format, widely used in the automotive industry. It offers compact storage with nanosecond timestamp precision and supports CAN, CAN FD, LIN, and Automotive Ethernet. BLF files can be read by CANalyzer, CANoe, and the open-source `python-can` library.

```
# Reading a BLF file with python-can
import can

log = can.BLFReader('vehicle_trace.blf')
for msg in log:
    print(f"  {msg.timestamp:.6f}  ID: 0x{msg.arbitration_id:03X}  "
          f"DLC: {msg.dlc}  Data: {msg.data.hex()}")
```

ASC — ASCII Trace Format (Vector)

ASC is a human-readable text format also from Vector. Each line contains a timestamp, channel, CAN ID, direction, DLC, and data bytes. While easy to read and parse, ASC files are significantly larger than BLF and have microsecond (not nanosecond) precision.

```
date Wed Jan 15 10:23:45.123 am 2025
base hex  timestamps absolute
 0.003400 1  100       Rx   d 8 01 02 03 04 05 06 07 08
 0.008200 1  200       Rx   d 8 A1 B2 C3 D4 E5 F6 07 18
 0.013100 1  7DF       Tx   d 8 02 01 00 00 00 00 00 00
```

TRC — PEAK Trace Format

TRC is PEAK-System's native trace format. Version 1.x supports CAN 2.0 only, while version 2.1 adds CAN FD support. TRC files use a simple tabular text layout with message numbering.

```
;$FILEVERSION=2.1
;   Start time: 15.01.2025 10:23:45.123
;
;   Message Number)  Time  ID   DLC  Data Bytes
     1)      0.0     100    8   01 02 03 04 05 06 07 08
     2)    100.0     200    8   A1 B2 C3 D4 E5 F6 07 18
     3)    200.0     7DF    8   02 01 00 00 00 00 00 00
```

MF4/MDF — Measurement Data Format (ASAM)

MDF (Measurement Data Format) is the ASAM standard for measurement data storage. MDF4 (file extension `.mf4` or `.mdf`) is the current version, offering rich metadata, compression, multi-channel support, and embedded attachments. It is the recommended format for professional automotive data acquisition.

CSV — Comma-Separated Values

CSV is a universal text format supported by virtually every tool. While easy to use with spreadsheets and scripts, CSV files are the largest format option, offer no metadata support, and lose timing precision due to text-based number representation.

```
timestamp,id,dlc,data
0.003400,0x100,8,01 02 03 04 05 06 07 08
0.008200,0x200,8,A1 B2 C3 D4 E5 F6 07 18
0.013100,0x7DF,8,02 01 00 00 00 00 00 00
```

Table 17-1 CAN Log File Format Comparison

Feature	BLF	ASC	TRC	MF4	CSV
Type	Binary	Text	Text	Binary	Text
Timestamp Precision	ns	µs	ms	ns	varies
File Size Efficiency	Excellent	Poor	Poor	Excellent	Worst
Metadata Support	Medium	Low	Low	Excellent	None
Human Readable	No	Yes	Yes	No	Yes
CAN FD Support	Yes	Yes	v2.1+	Yes	Yes
Compression	Yes	No	No	Yes (zlib)	No
Primary Tool	CANalyzer	CANalyzer	PCAN-View	CANape/asammdf	Any

17.3 ASAM MDF Standard

The ASAM Measurement Data Format (MDF) is the industry-standard binary file format for storing measured data in automotive development. The current version, MDF4 (ASAM MDF v4.x), supersedes the legacy MDF3 format and is supported by all major measurement tools.

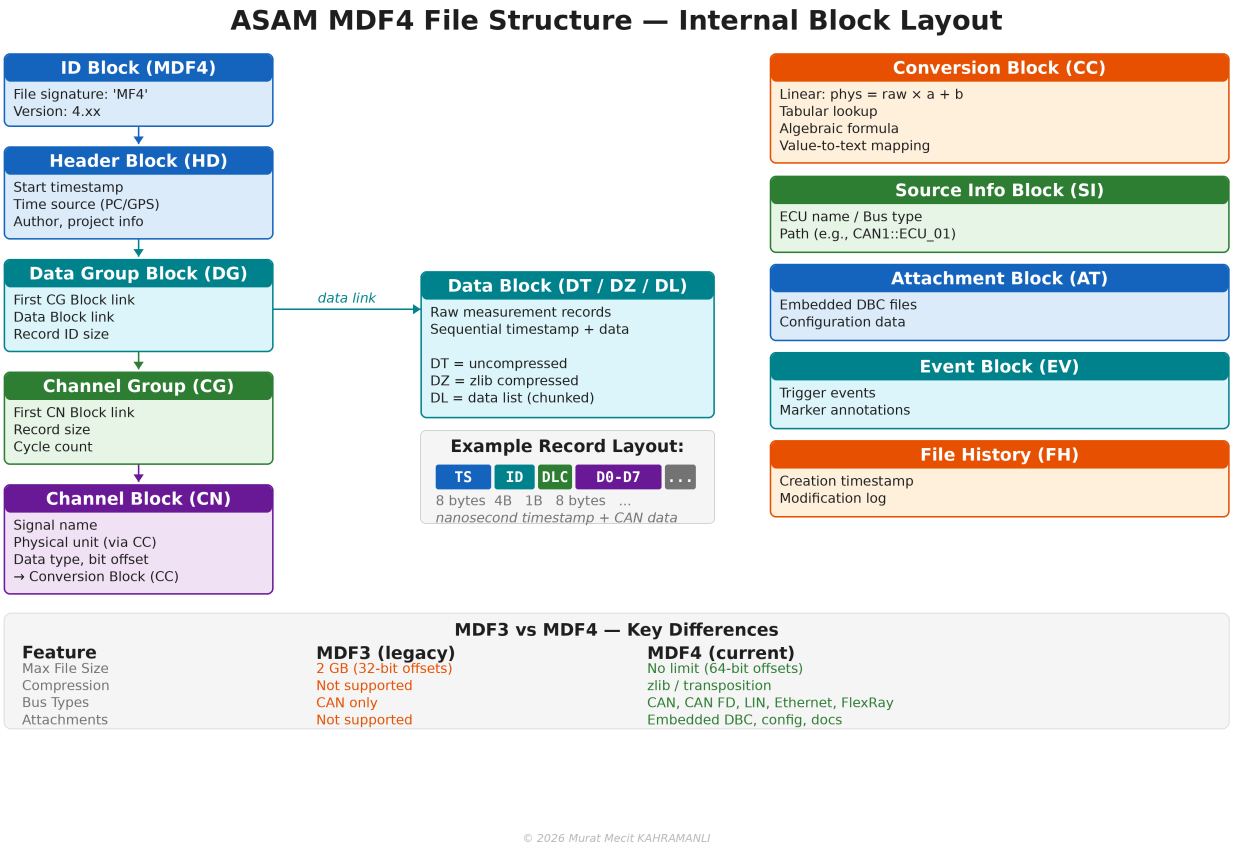


Figure 17-3 *ASAM MDF4 File Structure — Internal Block Layout: Hierarchical organization from ID Block through Header, Data Groups, Channel Groups, Channels, and Data Blocks.*

MDF4 Block Hierarchy

An MDF4 file is organized as a linked list of typed blocks:

- **ID Block:** File signature ('MF4') and version identifier
- **Header Block (HD):** Start timestamp, time source (PC clock, GPS, PTP), author, and project metadata
- **Data Group Block (DG):** Links to Channel Group and Data blocks; defines record structure
- **Channel Group Block (CG):** Groups related channels (signals) with shared timestamps
- **Channel Block (CN):** Individual signal definitions with name, unit, data type, and bit offset
- **Conversion Block (CC):** Physical value conversion rules (linear, tabular, algebraic, value-to-text)
- **Data Block (DT/DZ/DL):** Raw measurement records — DT (uncompressed), DZ (zlib compressed), DL (chunked data list)

MDF4 Advantages Over MDF3

Table 17-2 MDF3 vs MDF4 Key Differences

Feature	MDF3 (Legacy)	MDF4 (Current)
Max File Size	2 GB (32-bit offsets)	No limit (64-bit offsets)
Compression	Not supported	zlib / transposition
Bus Types	CAN only	CAN, CAN FD, LIN, Ethernet, FlexRay
Attachments	Not supported	Embedded DBC, config, documentation
Events	Basic markers	Rich event blocks with metadata
Encryption	Not supported	AES-128/256 encryption
XML Metadata	Not supported	Structured XML metadata blocks

17.4 CAN Logging Hardware

CAN logging hardware ranges from simple USB adapters for PC-based logging to sophisticated standalone data loggers that operate autonomously in vehicles. The choice depends on the use case, budget, and required features.

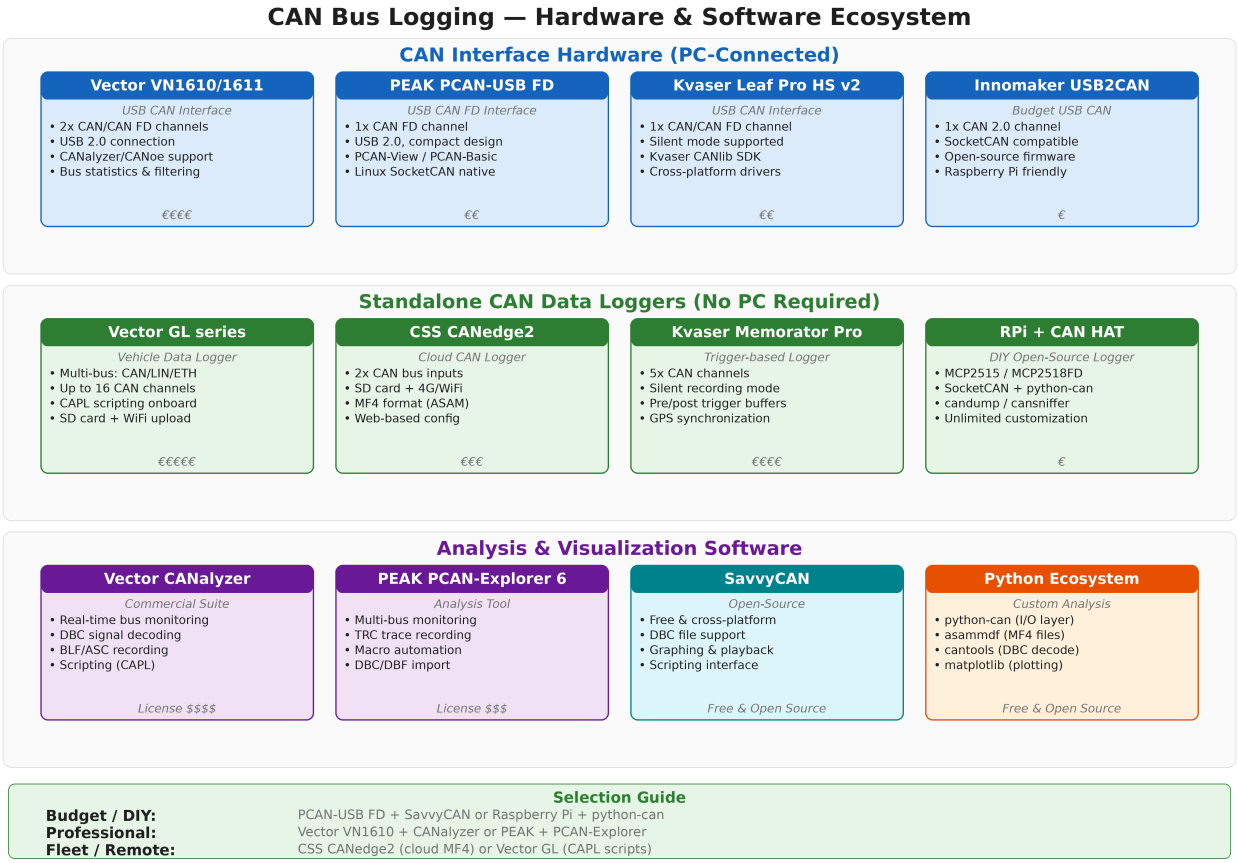


Figure 17-4 *CAN Bus Logging — Hardware & Software Ecosystem: CAN interfaces, standalone loggers, and analysis software from major vendors.*

PC-Connected CAN Interfaces

These devices connect to a PC via USB, Ethernet, or PCIe and require companion software for logging:

Table 17-3 CAN Interface Hardware Comparison

Device	Connection	CAN FD	Channels	Software	Price Range
Vector VN1610/1611	USB 2.0	Yes	2	CANalyzer/CANoe	€€€€
PEAK PCAN-USB FD	USB 2.0	Yes	1	PCAN-View/PCAN-Basic	€€
Kvaser Leaf Pro HS v2	USB 2.0	Yes	1	Kvaser CANlib SDK	€€
Innomaker USB2CAN	USB 2.0	No	1	SocketCAN (Linux)	€
Intrepid ValueCAN 4-2	USB 2.0	Yes	2	Vehicle Spy	€€€

Standalone CAN Data Loggers

Standalone loggers operate without a PC, recording directly to SD cards, internal memory, or uploading to cloud services:

- **Vector GL series:** Professional vehicle data loggers with up to 16 CAN channels, CAPL scripting, and WiFi/4G upload. Used extensively in OEM development and fleet testing.
- **CSS Electronics CANedge2:** Compact cloud-connected CAN logger with 2 CAN channels, SD card + 4G/WiFi, logging in ASAM MF4 format. Features web-based configuration.
- **Kvaser Memorator Pro 5×HS:** 5-channel CAN logger with trigger-based recording, pre/post trigger buffers, GPS synchronization, and silent bus operation.
- **Raspberry Pi + CAN HAT:** DIY open-source logger using MCP2515 or MCP2518FD CAN controllers. Runs SocketCAN + python-can for unlimited customization at minimal cost.

Linux SocketCAN Setup

For budget-friendly and highly customizable logging, Linux SocketCAN provides a native kernel-level CAN interface:

```
# Set up CAN interface
$ sudo ip link set can0 type can bitrate 500000
$ sudo ip link set can0 up

# Basic logging with candump
$ candump -l can0                    # Log to candump-*.log
$ candump -L can0 > trace.asc       # Log in ASC format

# Advanced: python-can with SocketCAN
import can
bus = can.interface.Bus(channel='can0', interface='socketcan')
logger = can.BLFWriter('capture.blf')
notifier = can.Notifier(bus, [logger])
# ... recording in background ...
```

17.5 Analysis Software & Python Ecosystem

CAN data analysis spans from commercial GUI tools to open-source Python libraries. The Python ecosystem has become particularly powerful for automated, scriptable, and reproducible analysis workflows.

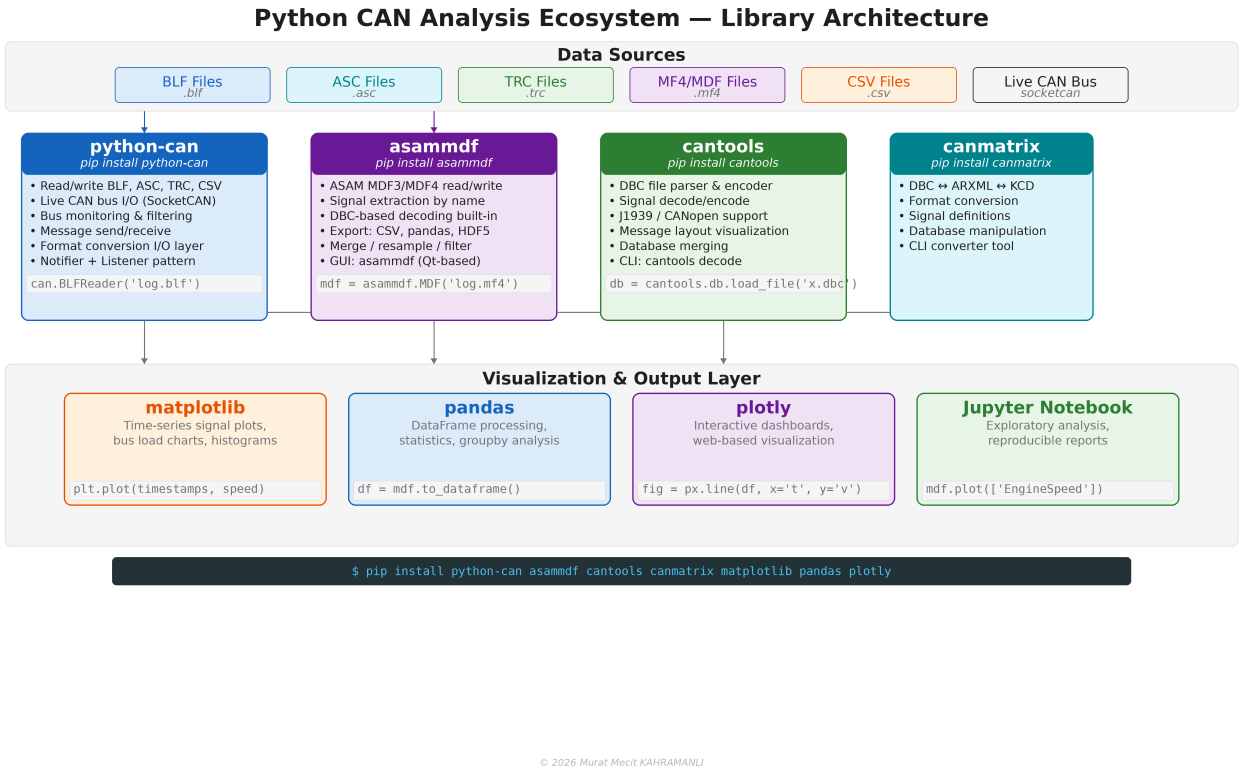


Figure 17-5 *Python CAN Analysis Ecosystem — Library Architecture: Data sources, core libraries (python-can, asammdf, cantools, canmatrix), and visualization output layer.*

Commercial Analysis Tools

Table 17-4 CAN Analysis Software Comparison

Tool	Vendor	Key Features	License
CANalyzer	Vector	Bus monitoring, DBC decode, BLF/ASC recording, CAPL scripting	Commercial
CANoe	Vector	Full simulation + analysis, network design, automated testing	Commercial
PCAN-Explorer 6	PEAK-System	Multi-bus monitoring, TRC recording, macros, DBC import	Commercial
Vehicle Spy	Intrepid CS	Multi-protocol analysis, scripting, simulation	Commercial
SavvyCAN	Open-source	Free, cross-platform, DBC support, graphing, scripting	Free (GPL)

Python Libraries for CAN Analysis

python-can — The foundational CAN library for Python. Provides a unified interface for reading/writing BLF, ASC, TRC, and CSV files, as well as live CAN bus I/O through SocketCAN, PCAN, Kvaser, and Vector interfaces.

```
import can

# Read a BLF file and print all messages
log = can.BLFReader('vehicle_trace.blf')
for msg in log:
    print(f"  {msg.timestamp:.6f}  0x{msg.arbitration_id:03X}  "
          f"[{msg.dlc}]  {msg.data.hex(' ')}")

# Convert BLF to ASC
with can.BLFReader('input.blf') as reader:
    with can.ASCWriter('output.asc') as writer:
        for msg in reader:
            writer.on_message_received(msg)
```

asammdf — The primary library for ASAM MDF3/MDF4 files. Supports signal extraction by name, DBC-based decoding, export to CSV/pandas/HDF5, and comes with a Qt-based GUI.

```
from asammdf import MDF

# Open an MF4 file
mdf = MDF('measurement.mf4')

# Extract specific signals
speed = mdf.get('VehicleSpeed')
rpm = mdf.get('EngineRPM')

# Export to pandas DataFrame
df = mdf.to_dataframe()

# Apply DBC decoding
mdf_decoded = mdf.extract_bus_logging(
    database_files={'CAN': ['vehicle.dbc']}
)
```

cantools — A DBC file parser and signal decoder/encoder. Supports J1939 and CANopen protocol extensions. Provides both a Python API and a command-line interface.

```
import cantools

# Load DBC database
db = cantools.db.load_file('vehicle.dbc')

# Decode a CAN message
msg_def = db.get_message_by_frame_id(0x100)
decoded = msg_def.decode(b'\x01\x02\x03\x04\x05\x06\x07\x08')
print(decoded)
# {'EngineSpeed': 1234.5, 'VehicleSpeed': 67.8, ...}

# Encode a CAN message
data = msg_def.encode({'EngineSpeed': 1500.0, 'VehicleSpeed': 80.0})
print(data.hex())
```

canmatrix — A CAN database conversion library. Converts between DBC, ARXML (AUTOSAR), KCD (Kayak), SYM, and other database formats.

```
import canmatrix

# Convert DBC to ARXML
canmatrix.formats.convert('vehicle.dbc', 'vehicle.arxml')

# Load and inspect a database
db = canmatrix.formats.loadp('vehicle.dbc')
for msg in db:
    print(f"  0x{msg.arbitration_id.id:03X}  {msg.name}  "
          f"DLC={msg.size}  Signals={len(msg.signals)}")
```

17.6 Practical Analysis with Python

This section demonstrates complete analysis workflows using the Python ecosystem.

Workflow 1: BLF Log → DBC Decode → Plot

```
import can
import cantools
import matplotlib.pyplot as plt

# Load DBC and BLF
db = cantools.db.load_file('vehicle.dbc')
log = can.BLFReader('drive_test.blf')

# Collect decoded signals
timestamps = []
speeds = []
rpms = []

for msg in log:
    try:
        msg_def = db.get_message_by_frame_id(msg.arbitration_id)
        decoded = msg_def.decode(msg.data)
        if 'VehicleSpeed' in decoded:
            timestamps.append(msg.timestamp)
            speeds.append(decoded['VehicleSpeed'])
        if 'EngineRPM' in decoded:
            rpms.append(decoded['EngineRPM'])
    except (KeyError, cantools.db.DecodeError):
        pass  # Unknown message or decode error

# Plot results
fig, (ax1, ax2) = plt.subplots(2, 1, figsize=(14, 8), sharex=True)
ax1.plot(timestamps[:len(speeds)], speeds, color='#1565C0', linewidth=1)
ax1.set_ylabel('Vehicle Speed (km/h)')
ax1.set_title('CAN Bus Log Analysis — DBC Decoded Signals')
ax1.grid(True, alpha=0.3)

ax2.plot(timestamps[:len(rpms)], rpms, color='#2E7D32', linewidth=1)
ax2.set_ylabel('Engine RPM')
ax2.set_xlabel('Time (seconds)')
ax2.grid(True, alpha=0.3)

plt.tight_layout()
plt.savefig('analysis_output.png', dpi=150)
plt.show()
```

Workflow 2: MF4 Signal Extraction with asammdf

```
from asammdf import MDF
import matplotlib.pyplot as plt

# Open MF4 and extract signals
mdf = MDF('fleet_recording.mf4')

# List all available signals
for i, group in enumerate(mdf.groups):
    for ch in group.channels:
        print(f"  Group {i}: {ch.name} [{ch.unit}]")

# Extract and plot specific signals
speed = mdf.get('VehicleSpeed')
fuel_rate = mdf.get('FuelRate')
coolant = mdf.get('CoolantTemperature')

fig, axes = plt.subplots(3, 1, figsize=(14, 10), sharex=True)

axes[0].plot(speed.timestamps, speed.samples, color='#1565C0')
axes[0].set_ylabel('Speed (km/h)')

axes[1].plot(fuel_rate.timestamps, fuel_rate.samples, color='#E65100')
axes[1].set_ylabel('Fuel Rate (L/h)')

axes[2].plot(coolant.timestamps, coolant.samples, color='#2E7D32')
axes[2].set_ylabel('Coolant Temp (°C)')
axes[2].set_xlabel('Time (s)')

for ax in axes:
    ax.grid(True, alpha=0.3)

plt.suptitle('MF4 Signal Analysis — Fleet Recording', fontsize=14)
plt.tight_layout()
plt.savefig('mf4_analysis.png', dpi=150)
```

Workflow 3: J1939 Log Analysis

```
import can
import cantools

# Load J1939 DBC
j1939_db = cantools.db.load_file('J1939.dbc')

# Read log file
log = can.BLFReader('truck_highway.blf')

# J1939 PGN extraction
engine_data = []
for msg in log:
    # Extract PGN from 29-bit CAN ID
    pgn = (msg.arbitration_id >> 8) & 0x3FFFF

    if pgn == 0xF004:  # Electronic Engine Controller 1 (EEC1)
        decoded = j1939_db.get_message_by_frame_id(
            msg.arbitration_id).decode(msg.data)
        engine_data.append({
            'time': msg.timestamp,
            'rpm': decoded.get('EngineSpeed', 0),
            'torque': decoded.get('ActualEngineTorque', 0),
            'load': decoded.get('DriversDemandEnginePercentTorque', 0),
        })

print(f"Collected {len(engine_data)} EEC1 messages")
print(f"RPM range: {min(d['rpm'] for d in engine_data):.0f} - "
      f"{max(d['rpm'] for d in engine_data):.0f}")
```

17.7 Format Conversion Workflows

Converting between CAN log formats is a common task when switching tools or preparing data for different analysis pipelines. Python libraries make this straightforward.

Common Conversion Paths

Table 17-5 CAN Log Format Conversion Matrix

From → To	Tool / Library	Command / Code
BLF → ASC	python-can	`can.BLFReader` → `can.ASCWriter`
BLF → CSV	python-can	`can.BLFReader` → `can.CSVWriter`
BLF → MF4	asammdf	`MDF.from_bus_logging` from BLF source
ASC → BLF	python-can	`can.ASCReader` → `can.BLFWriter`
TRC → BLF	python-can	`can.TRCReader` → `can.BLFWriter`
MF4 → CSV	asammdf	`mdf.to_dataframe().to_csv()`
MF4 → pandas	asammdf	`mdf.to_dataframe()`
DBC → ARXML	canmatrix	`canmatrix.formats.convert()`

Universal Converter Script

```
#!/usr/bin/env python3
"""Universal CAN log format converter using python-can."""
import can
import sys

READERS = {
    '.blf': can.BLFReader,
    '.asc': can.ASCReader,
    '.trc': can.TRCReader,
    '.csv': can.CSVReader,
}

WRITERS = {
    '.blf': can.BLFWriter,
    '.asc': can.ASCWriter,
    '.csv': can.CSVWriter,
}

def convert(input_file, output_file):
    in_ext = '.' + input_file.rsplit('.', 1)[-1].lower()
    out_ext = '.' + output_file.rsplit('.', 1)[-1].lower()

    reader_cls = READERS.get(in_ext)
    writer_cls = WRITERS.get(out_ext)

    if not reader_cls or not writer_cls:
        print(f"Unsupported format: {in_ext} or {out_ext}")
        return

    count = 0
    with reader_cls(input_file) as reader:
        with writer_cls(output_file) as writer:
            for msg in reader:
                writer.on_message_received(msg)
                count += 1

    print(f"Converted {count} messages: {input_file} → {output_file}")

if __name__ == '__main__':
    convert(sys.argv[1], sys.argv[2])
```

MF4 Export with DBC Decoding

```
from asammdf import MDF

# Open MF4 file and decode with DBC
mdf = MDF('raw_recording.mf4')
mdf_decoded = mdf.extract_bus_logging(
    database_files={'CAN': ['vehicle.dbc']}
)

# Export decoded signals to CSV
df = mdf_decoded.to_dataframe()
df.to_csv('decoded_signals.csv', index=True)

# Export specific signals only
speed = mdf_decoded.get('VehicleSpeed')
rpm = mdf_decoded.get('EngineRPM')
import pandas as pd
pd.DataFrame({
    'time': speed.timestamps,
    'speed_kmh': speed.samples,
}).to_csv('speed_only.csv', index=False)

print(f"Exported {len(df)} records to CSV")
```

> 💡 **Best Practice**
>
> For long-term archival, use ASAM MF4 format — it preserves nanosecond timestamps, metadata, and can embed DBC files. For quick sharing and debugging, ASC or CSV provide immediate human readability. The `python-can` + `asammdf` + `cantools` combination covers virtually all CAN data logging and analysis needs.

Appendix A: Reference Tables

A.1 CAN Identifier Ranges

Table A-1 Standard CAN 2.0A Identifier Ranges

Range (Hex)	Range (Dec)	Usage
0x000-0x0FF	0-255	Highest priority system messages
0x100-0x3FF	256-1023	High priority messages
0x400-0x6FF	1024-1791	Medium priority messages
0x700-0x7EF	1792-2031	Low priority messages
0x7F0-0x7FF	2032-2047	Lowest priority, diagnostic

A.2 J1939 Address Assignments

Table A-2 Common J1939 Source Addresses

Address (Hex)	Address (Dec)	Function
0x00	0	Engine Controller #1
0x01	1	Engine Controller #2
0x03	3	Transmission Controller
0x0B	11	Brake System Controller
0x14	20	Instrument Cluster
0x21	33	Body Controller
0x33	51	Cab Controller
0x80	128	Primary Diagnostics Tool
0xF9	249	OBD-II Tool
0xFE	254	Null Address (cannot claim)
0xFF	255	Global Address (broadcast)

A.3 UDS Data Identifiers (DID)

Table A-3 Common UDS Data Identifiers

DID (Hex)	Description
F180	Boot Software Identification
F181	Application Software Identification
F182	Application Data Identification
F183	Boot Software Fingerprint
F184	Application Software Fingerprint
F185	Application Data Fingerprint
F186	Active Diagnostic Session
F187	Vehicle Manufacturer Spare Part Number
F188	Vehicle Manufacturer ECU Software Number
F189	Vehicle Manufacturer ECU Hardware Number
F18A	System Supplier Identifier
F190	VIN (Vehicle Identification Number)
F197	System Name or Engine Type
F193	System Supplier ECU Hardware Version Number
F194	System Supplier ECU Software Version Number
F199	Programming Date
F19D	ECU Serial Number

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