CAN FD for commercial vehicles: Chances and challenges

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Commercial vehicles include road, off-highway as well as off-road vehicles. Many of them are equipped with multiple CAN networks. Some of them are already at their lim-its regarding the busload. The CAN FD data link layer is an option to overcome these limits. However, the physical layer needs to be designed more carefully. Additionally, low-volume applications require the reuse of already existing higher-layer protocols and application software. The paper discusses the chances and challenges to intro-duce CAN FD in commercial vehicle control systems.

The market of commercial vehicles is highly fragmented. Each class of commercial vehicles has its own requirements. There is a wide range of volume demands meaning that the question: who is the system designer, is answered differently.

Low-volumes are usual in some construction machines. In worst-case just a few are sold annually. On the other hand, some standard trucks are produced in medium volumes (some 50000 and even more). In general, the higher the volume the more the OEM takes responsibility of the system design. The system design for vehicles produced in low-volumes are sometimes out-sourced entirely.

OEMs (original equipment manufacturers) with higher volumes design the networks by themselves. This includes the physical network design as well as the higher-layer protocols.

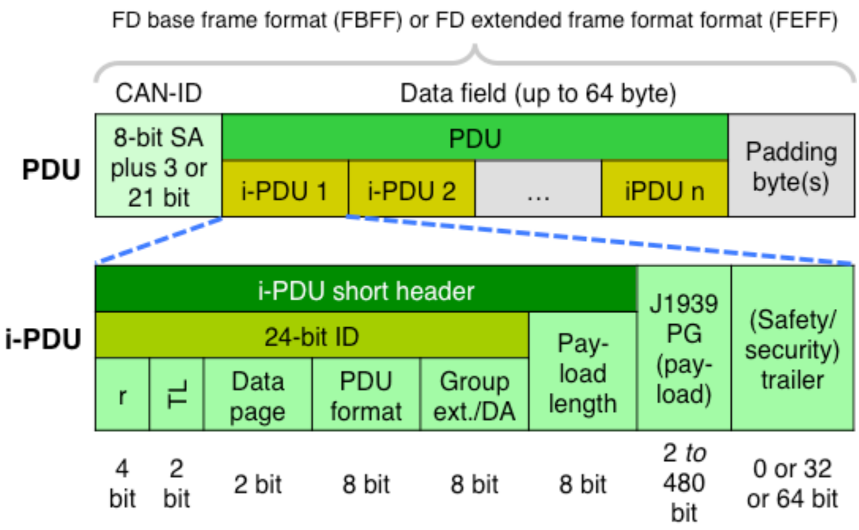
Classical CAN networks were easy to design compared with the higher performing CAN FD networks. In particular, the physical layer design was not too challenging. CAN FD networks require a much more precise development. Each physical layer element may cause a mal function, when not optimized. At higher bit-rates, the available margin to stabilize the bit value becomes very small.

Star topologies should be avoided and in line topologies the not terminated stubs should be as short as possible.

In order to suppress ringing on the bus-lines, several options are possible. One of them is to terminate each node with a high resistance. Another option is the usage of ringing suppression circuits as proposed in CiA 601-4. Unfortunately, most of the makers of commercial vehicles have not yet sufficient experience in the design of CAN FD networks. Therefore, CiA collects first results from the passenger car industry and provides them in the CiA 601 series of recommendations.

Re-using existing CAN-based protocol stacks

Already in the early days of the Classical CAN technology, the truck and bus OEMs developed the SAE J1939 higher-layer protocol family. Especially the J1939-71 specification introduced the concept of SPNs (suspect parameter numbers) and PGNs (parameter group numbers). And the J1939-21 specification comprised several transport protocols to overcome the 8-byte limitation of the Classical CAN data frames. With CAN FD and its 64-byte data frames these limits are partly not more relevant. Theoretically, all existing PGNs can be mapped into CAN FD data frames. It is even possible to map multiple PGNs into one CAN FD data frame. The legacy 8-byte Parameter Groups (PG) are mapped into iPDUs. In order to be compliant with AUTOSAR, the iPDUs use a 32-bit Short Header (see Figure 1).



KEY DA (destination address); ID (identifier) PDU (protocol data unit); PG (parameter group); SA (source address) TL (trailer length)

Figure 1: Proposed mapping of Parameter Groups into CAN FD data frames

The header comprises the PDU format information and the Group Extension/ Destination Address as known from the SAE J1939-21. The Source Address is part of the CAN-ID. This means, each ECU uses the same CAN-ID for all messages to be transmitted. The receiving nodes need to evaluate each iPDU to interpret the value.
In order to be more flexible regarding the PG length is not limited to 8 byte. The length may vary between 2 bit and 480 bit. Of course, the length must be given in the iPDU Short Header. Due to future safety and security requirements, the proposal introduces an optional 32-bit or 64-bit trailer. Information about the trailer length is also given in the Short Header. There are four reserved bits for future protocol extensions. One bit should be used as an escape bit to migrate to alternative protocol definitions.

Using current PGN definitions, you can map up to six PGs into one CAN FD data frame, when not using the safety/security trailer. Of course, due to the data field size steps, it is necessary to add padding bytes. The content of them have not been specified yet. They should contain bit pattern, which don't cause stuff-bits. Additional stuff-bits would decrease the protocol efficiency.

If you like to down- or upload larger data packages, it is recommended to use the transport protocol as defined in ISO 15765-2. This protocol is widely used in passenger cars and in European trucks and buses for downloading software as well as for diagnostic purposes.

The Source Address is part of the CAN-ID. It is not yet decided how to use the remaining three respectively 21 ID bits. They may remain manufacturer-specific.

CANopen FD in the pipeline

CANopen networks are used in some commercial vehicles for the more machine-oriented applications. In particular, body builders rely on the flexible communication services of CANopen. For refuse collecting vehicles, the CiA 422 CANopen application profile is well established. Also many truck-mounted cranes use CANopen as an embedded network. Some of these body applications are connected to the in-vehicle networks by means of a gateway. Iveco provides for its trucks a standardized CiA 413 compatible gateway, which links CANopen and J1939.

Also in these body applications increasingly more bandwidth is required. In addition, there are payloads with more than 8 byte are necessary, when safety and security is introduced.

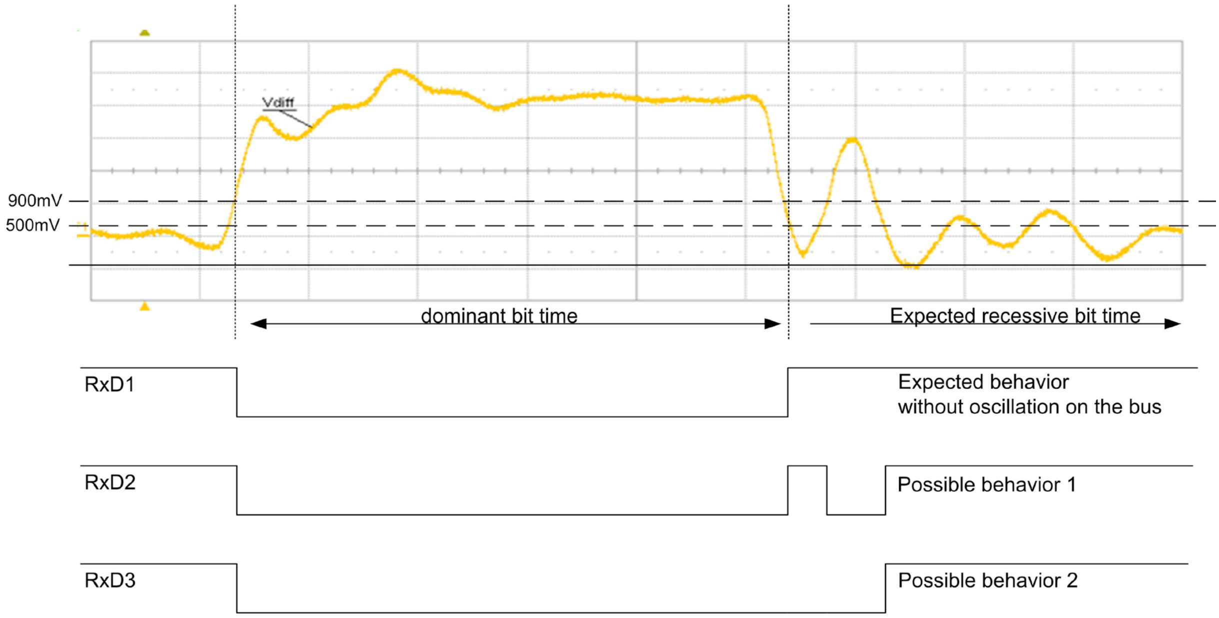


Figure 2: Critical ringing at the transition from dominant to recessive

CiA members are currently specifying the CANopen FD application layer. Some of the CANopen communication services (e.g. NMT, Heartbeat, EMCY, SYNC, and TIME) will remain unchanged. However, they will be transmitted using CAN FD data frames with the option to transmit them faster.

Of course, PDOs will make use of the longer data fields. However, it is intended to limit the number of mapped process data to 64 as in CANopen. Bit-wise mapping would increase the configuration effort.

The most change is regarding the access to the object dictionary. The SDO services are completely redesigned. The newly introduced USDO (Universal SDO) services feature a byte-wise organized protocol overhead. Bit shifting is not more necessary. This simplifies protocol stack im-plementations. On the other hand, the pro-tocol overhead is larger. The USDO allows addressing nodes in sub-layered networks. This is important for complex body applications with multiple CANopen FD networks.

General physical layer recommendations

The new edition of the ISO 11898-2 does not standardize the node and system design in detail. It just specifies the transceiver.

Also the ISO 11898-1 standard does not provide detailed information about the node and system design. It is just mentioned that all nodes should implement oscillators with the same frequency or multiple of them. Allowed are 20 MHz, 40 MHz, and 80 MHz. It is also specified that all nodes should use the same bit-timing settings for the arbitration phase respectively the data-phase.

For commercial vehicles, the CiA 602 series specifies to use so-called high-speed transceivers compliant with new edition of ISO 11898-2. The CiA 601-1 specification, released in summer 2015, collects the first experiences made by some OEMs. It includes recommendations for node and system design. The physical interface to the network running the CAN FD data link layer protocol shall comprise a CAN transceiver compliant to ISO 11898-2. The symmetry of dynamic parameters such as propagation delay, twisted wire/untwisted wire, parasitic capacitive load is very important. The reflection and the ringing in the network are also very important and should be as small as possible. Proper functionality is guaranteed if occurring cable-reflected waves do not suppress the dominant differential voltage levels (Vdiff) below 900 mV and do not increase the recessive differential voltage level above 500 mV at each individual CAN node (see Figure 2).

Table 1: Recessive bit-time at the receiving node's RxD pin

Bit-rate (data phase)	$t_{Rec(RxD)}$ (min)	$t_{Rec(RxD)}$ (max)	t_{bit} (nominal)	Load on CAN
1 Mbit/s	n.a.	n.a.	1000 ns	60 Ω‖100 pF
2 Mbit/s	370 ns	570 ns	500 ns	60 Ω‖100 pF
5 Mbit/s	110 ns	225 ns	200 ns	60 Ω‖100 pF

To cover the higher bit-rates in the data phase, the dynamic parameters of the transceiver are specified in more detail as in Classical CAN. The important dynamic parameters are:

- Transceiver loop delay symmetry of the transmitting node,
- Transceiver Tx delay symmetry of the transmitting node,
- Transceiver Rx delay symmetry of the receiving node.

In ISO 11898-2 and in the data sheets of transceiver products, the transceiver loop delay is specified. According to ISO standard up to 255 ns are proposed. The trigger level for the falling edge (recessive to dominant) is specified to 30% of the logical voltages swing and for the rising edge (dominant to recessive) to 70%. The loop delays for the dominant-to-recessive and the recessive-to-dominant transition can be different. The Tx and Rx delay symmetry parameters given in ISO 11898-2 are used to calculate the jitter on the Rx pin. Table 1 shows the resulting min and max values for the recessive bit length seen by a receiving node. The following effects are not considered in CiA 601-1: the behavior of the network itself such as ringing or additional propagation delay of the dominant-to-recessive transition, and clock tolerances.

One other recommendation is to implement transceivers qualified for higher bit-rates as you like to use. It makes design less challenging, when you have a higher margin (see Figure 3). Additionally, it is recommended to enable the transmitting node delay compensation (TDC), if running the network with a bit-rate higher than 1 Mbit/s. As mentioned above, the recessive bits can be much shorter than the dominant bits. Consequently, the sampling of a recessive bit in a transmitting node is potentially more critical than the sampling of a dominant bit. Figure 3 shows the most important effects that lead to a delay.

The CiA 602-1 physical layer

For commercial vehicles, the CiA 602-1 specification gives some rules and recommendations. Line topology with short stubs (just a few cm) preferable with CAN-in and CAN-out connectors as shown in Figure 4 should be used. The topology shall meet the requirements as specified in SAE J1939-14, if not specified differently in this document. The maximum network length is 40 m terminated at both ends with 120-Ω resistors. The maximum number of nodes is 10. For closely neighboring devices a star topology may be used to interconnect up to eight ECUs.

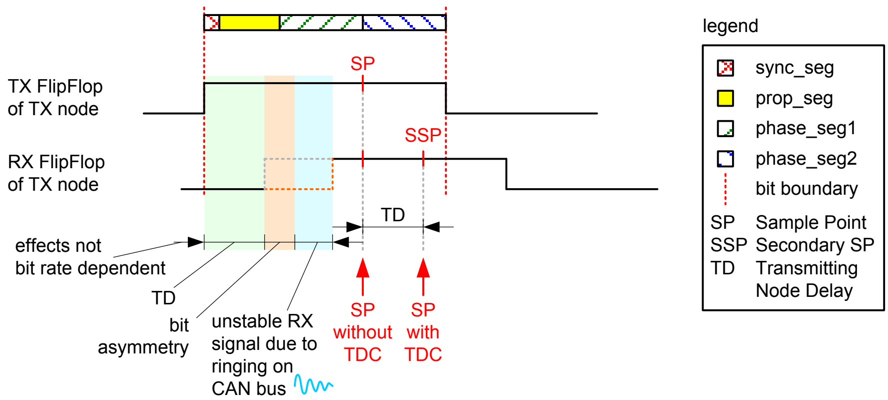


Figure 3: Sampling of a recessive bit at the transmitting node with and without TDC

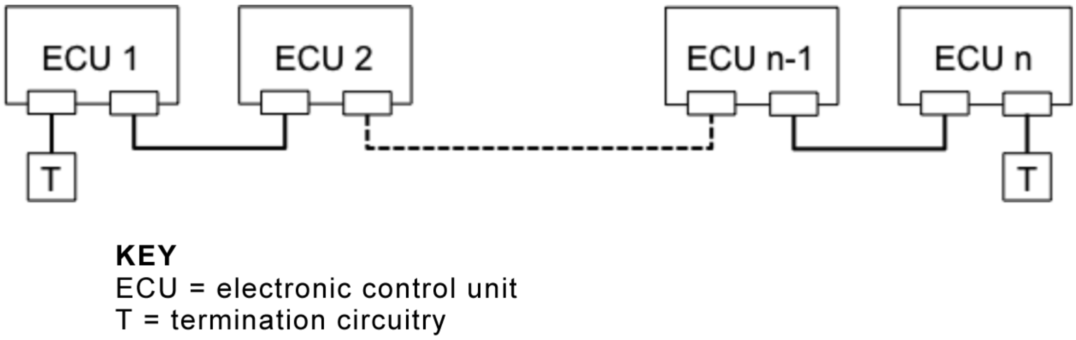


Figure 4: Recommended line topology

All physical layer elements (e.g. transceiver, termination resistor, capacitor, cable, and connectors) shall be qualified for temperature ranges from -40 °C to +85 °C (for cabin networks) or -40 °C to +125 °C (for engine networks). The cable shall meet the requirements as specified in SAE J1939-11 and SAE J1939-14 on the specified temperature range. Also the cable impedance shall match the impedance of the busline termination on the specified temperature range.

The termination circuitry shall be located at both ends of the backbone (trunk) cable or in two of the connected nodes preferable with the longest distance.

The termination circuitry should be split in two 60-Ω resistors with a tolerance of ±1 % and a 250-mW rating. The power rating of both resistors should be 250 mW. At the center tap between the two resistors a 4,7-nF capacitor with 100-V rating should be connected to ground. In case of four 30-Ω resistors, the tolerance should be ±1 % and the power rating 250 mW. This approach improves the ECU's robustness to common-mode irradiation. When using the not recommended 120-Ω resistors at both ends the tolerance should be ±2 %.

The 60-Ω termination resistor for star topology shall feature a 2-% tolerance. In case of the preferred splittermination the two 30-Ω resistors should provide a 500-mW rating and a ±1-% tolerance. The 4,7-nF capacitor to ground should be rated for 100 V. For EMI reasons, the transceiver and the termination and protection circuitry should be arranged within 50 mm of the ECU's connector on the PCB. The traces for the CAN_H and CAN_L lines between the ECU's connector needs to be lay out in a symmetrical way to avoid additional signal asymmetry.

The used connector should feature an impedance matching the impedance of the cable and of the other physical layer elements. The untwisted length of the wire in the area of the connector shall be as short as possible and shall not exceed 50 mm. CAN_H and CAN_L shall use directly ad-jacent pins within one ECU connector in order to limit the impedance step at the connector.

Each node shall provide a connection to the network (CAN) ground. This ground shall be connected to the ECU ground via the C1 capacitor as shown in Figure 4.

Table 2: Arbitration phase bit-timing settings

Bit-rate kbit/s	**Clock** MHz	**BRP**	**Sync segment** t_q	**Prop segment** t_q	**Phase segment 1** t_q	**Phase segment 2** t_q	**SJW** t_q
500	40	1	1	47	16	16	16
	80	2	1	47	16	16	16
667	40	1	1	41	9	9	9
	80	2	1	41	9	9	9

The CAN ground needs to be connected to as many pins as necessary to support two ground wires from the harness depending on the used connector family.

This additional connection is used as an EMC countermeasure to protect the CAN network against electromagnetic irradiation in case star quad cables are used. Two lines of the star quad cable serve as a shielding, the capacitor prevents DC currents on the shield.

Only crystal oscillators should be used for clock generation. The tolerance should be less than 0,15 % across temperature range and lifecycle aging. This tolerance includes the tolerance of the crystal used, deviations and variations caused by the clock generation circuitry inside the ECU, e.g. the PLL circuit. The jitter (i.e. the MTIE = maximum time interval error) should not be greater than ±5 ns over any consecutive 13 bit-times of the arbitration phase.

All nodes in a network segment should be clocked with a frequency of 40 MHz or 80 MHz. All nodes in a network segment should use identical time quanta lengths (e.g. 25 ns or 50 ns). Table 2 and Table 3 recommend the bit-timing for arbitration and data phase.

It is recommended to keep the PCB traces between CAN controller and CAN transceiver short. There should be no active additional devices components between CAN controller and CAN transceiver such as level shifters, logic circuitry, galvanic isolators etc. or passive components such as additional resistors, capacitors etc.

In case that a galvanic separation between controller and transceiver is required a transceiver with integrated galvanic separation should be used.

Generally, the capacitive load of external CAN_H and CAN_L pins measured to ECU ground should not exceed 47 pF including ESD protection circuitry and other physical layer components.

The ESD protection should impede signal symmetry between CAN_H and CAN_L as little as possible. Consequently, a single integrated circuitry solution is preferred to a dual circuitry solution.

In order to improve EMC robustness of a ECU, a common mode choke may be placed into the CAN_H and CAN_L lines. It is recommended to place the choke di-rectly in front of the transceiver. The choke should have bifilar winding. Its stray in-ductance should be less than 0,25 μH. The common mode impedance is recom-mended to be in the range between 50 μH and 100 μH.

Summary and outlook

The CAN FD network design rules and recommendations for commercial vehicles are still under development. They may change on the made experiences, when the first prototypes are running on roads. Also the higher-layer protocols as specified in CiA 602-2 and CiA 301 version 5.0 are not yet finalized. OEMs are invited to participate and contribute to these approaches.

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[4] CiA 602-2, CAN FD for commercial vehicles – Part 2: Application layer