CAN XL In-Vehicle Network Validation

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CAN XL addresses the increasing bandwidth requirements of modern automotive systems. Due to the easy adaptation and reusability of the already existing CAN protocol, which is probably the most widespread network protocol in vehicles, the flexible data rate and the much higher payload offer a good solution to the constantly growing flow of information. However, the protocol itself presents some challenges to the designer. The dynamic behaviour of a system cannot be predicted by manual calculations. This forces designers to use simulation or measurement to analyse the network for robust design and to investigate critical effects that change as CAN evolves. While the propagation delay was the limiting factor for high-speed CAN networks, this changed completely with CAN FD and SIC. In the case of CAN XL, the impact of the new transceiver and protocol modifications such as the stuffing rule or the switch between SIC and FAST mode must be checked. All of this ends up in having a validation of the physical layer to improve the signal quality and ensure correct communication with accurate results even under worst case conditions.

Development of the CAN technology

In the 1980s the Controller Area Network (CAN), also known as Classical CAN was developed for the industrial applications and adapted for use in automotive industry.

CAN enables the transmission of bit rates up to 1 Mbit/s via unshielded twisted pair cables. The size of the payload is limited to 8 bytes and an 11-bit identifier for the Classical Base Frame Format (CBFF). To achieve bit rates up to 1 Mbit/s the Classical Extended Frame Format (CEFF) was developed, which allows a 29-bit identifier. The identifier is used for prioritization to differentiate the data type and addressing.

Due to its versatility, high robustness, high data rate and flexible network design, CAN has established itself as a main standard in the automotive sector and is therefore used in many different domains in vehicles.
The maximum possible cable length and the network structures that can be implemented depend on the transmission speed.

Appropriate evaluation and validation of the transmission properties and signal behavior of the networks are required for the use in vehicles. The propagation delay of the signal is particularly important for the investigation of CAN networks. For example, a propagation delay that is too long can lead to incorrect sampling of a bit, which on one hand makes correct arbitration impossible and on the other hand leads to incorrect data transmission (error frames). Such a network would be unsuitable for use in the vehicle and would have to be adapted to the requirements.

Controller Area Network with Flexible Data rate (CAN FD) is the further development of Classical CAN. With CAN FD, the transmission of higher bit rates up to 8 Mbit/s is possible. This is associated with a significantly larger payload of up to 64 bytes. The 29-bit identifier is used as standard for CAN FD. Due to the higher transmission speeds compared to Classical CAN, the cable lengths for CAN FD may have to be reduced depending on the transceiver and the transmission line used.

The higher transmission rates lead to further restrictions in the sampling time range relevant for the CAN FD data phase. The clock tolerance and signal asymmetry in the network play a particularly important role here. If these parameters deviate too much, the shifted bit length can lead to incorrect sampling of the bit, resulting in an incorrect data transmission (error frames). For example, there is a shift in the signal asymmetry between the recessive to dominant and dominant to recessive slope changes within the transmitter, i.e. also the receiver. It is recommended that the clock tolerance should not be set too high as otherwise there may be a discrepancy between all transmitting and receiving network nodes.

Furthermore, effects like ringing, can occur in Classical CAN and in CAN FD network. These effects, which are also caused by the increasing complexity of various network structures, lead to errors in signal transmission.

In order to minimize these particular effects, especially the ringing, methods have been developed which are referred to as Signal Improvement Capability (SIC). The use of these methods significantly improves the signal behavior and robustness of CAN FD networks. With the use of SIC transceivers, these special network effects can be significantly reduced. Between CAN-High and CAN-Low, the SIC transceiver impedance of the recessive state is changed from its high ohmic value to the transmission line characteristic impedance.

CAN XL the new technology

CAN XL is the latest generation of CAN, which provides a configurable data bit rate up to 20 Mbit/s and a large payload size up to 2048 byte. CAN XL offers not only scalability but also flexibility, with the assistance of proper Physical Media Attachment (PMA) implementations and the adaptation of bit rate, complex In-Vehicle Networks (IVN) such as star and linear buses with long stubs can be achieved.

CAN XL maintains the reliability of Classical CAN and CAN FD. The bus access CSMA/CR method (Carrier Sense Multiple Access/Collision Resolution) is still used. This way, the transmission of more important messages is ensured. In case of a CAN XL frame with large payload size, the new fragmentation feature offers to reduce the latency in the IVN.

However, unlike CAN FD protocol with 29-bit identifier, CAN XL supports only 11-bit identifiers. This contains the priority ID of the frame. Information regarding addressing and type of data are now in the data field and not part of the identifier anymore, leading to a faster and more effective data rate. Another improved function in CAN XL is the CRC (Cyclic Redundancy Check). CRC in Classical CAN is 15 bits, and in CAN FD 17 or 21 bits. The data phase in CAN XL, however, has two CRC fields: the 13-bit Preface CRC (PCRC) and the 32-bit Frame CRC (FCRC). This leads to a reliable transmission with a Hamming distance of 6.
Not only existing features have been improved in CAN XL, new functions are now also introduced including:

- Separation of priority (in arbitration field) and addressing functionality (now in control field). This enables running several higher layer protocols/applications on the same bus.
- Supporting virtual CAN network ID (VCID), which results in simplified frame filtering as well as enhanced security.

With these remarkable enhancements and new features, CAN XL could be used for service-oriented communication (such as Ethernet tunneling) as well as signal-based communication (faster CAN FD). Making CAN XL not only ideal for further development based on the existing E/E architectures, but also suitable for the requirements of future Zonal IVN architecture.

All the above-mentioned features improve the technology and handling of CAN XL, however, it does not affect the IVN validation. The first change that affects the work of a designer is bit stuffing. Two types of stuff bits are used in CAN XL: dynamic (in arbitration phase) and fixed (in data phase).

In arbitration phase, after every five consecutive bits, a complementary dynamic stuff bit is added. In data phase, a fixed stuff bit is inserted after each 10th bit, starting from and including the DL1 bit up to the end of the FCRC field as illustrated in Figure 1. The maximum number of consecutive bits is therefore 11, and existing worst-case patterns must be adapted.

Arbitration behavior in CAN XL is similar to the arbitration in Classical CAN and CAN FD, hence, the used validation criteria for arbitration phase still applies for CAN XL including:

- Clock tolerance considering the bit timing settings within the arbitration phase.
- Arbitration scenarios and correct sampling of the acknowledge bits with the focus on the propagation delays between different nodes for a dominant to recessive edge and vice versa.

One of the biggest changes in terms of validating a network is the new mode of operation. CAN XL has two operating modes:

Mode switching OFF / Error Signaling ON

Since mode switching is software configurable, a CAN SIC XL PMA implementation behaves like a regular CAN FD SIC implementation (with possibly larger payload size) when mode switch is OFF. In this case, error signaling must be enabled. CAN XL is in this scenario compatible with Classical CAN and CAN FD. This operating mode is suitable for bit rates up to 8 Mbit/s in data phase.

CAN XL modes play an essential role for judging the asymmetry of signal edges. When the transceiver is in SIC mode, the data phase validation process involves same criteria as CAN FD including:

- Clock tolerance considering the bit timing settings within data phase to ensure correct communication.
- Scenarios with focus on signal timing requirements are used. Signal symmetry of the recessive and dominant bits is especially important to ensure safe sampling of each bit and becomes more important as the bit rate increases.
- Analogue ringing measurement of the differential signal at each node.

More detailed information on simulation validation criteria of CAN FD networks can be found in [1].

Due to the changed stuff rate in CAN XL data phase, the used worst-case patterns need to be adjusted accordingly. For validating IVN, a worst-case pattern, which is a combination of consecutive bits, is used as stimulus pattern for each transmitting node on the CAN bus. Depending on the test case, this pattern could differ. For example:

- By evaluating the analogue ringing (so called settle time criteria), the longest bit sequence without re-synchronization is used as worst-case pattern. In this scenario the pattern consists of, 11 dominant bits followed by several recessive bits.
- For signal symmetry test cases, the used pattern resembles a worst-case condition for charging and discharging the capacitances in the network. This worst-case pattern consists of 11 dominant bits followed by one recessive bit. Since the signal timing requirements for this single bit are defined in the latest ISO 11898.

Mode switching ON / Error Signaling OFF

For bit rates up to 20 Mbit/s, CAN SIC XL implementations are needed. These devices require NRZ (Non-Return-to-Zero) coding for arbitration as well as PWM (Pulse Width Modulation) coding for data phase.

Here, SIC mode is used in arbitration phase and FAST mode with push-pull (level 0/level 1) driver is used in data phase. The CAN XL protocol controller signals the mode switch during ADS (Arbitration Data Sequence) and DAS (Data Arbitration Sequence) fields. To make the receiving nodes capable of reading level 0/level 1 signals, the receiver needs to switch to FAST RX mode and adjust thresholds accordingly. To switch the receiver mode, the receiving nodes transmit level 1 signals at their TxD pin to signal the mode change throughout the data phase. The PMA switches between modes during ADH (arbitration to data high bit) and DAH (data to arbitration high bit) in CAN XL frame.

ADS field consists of four bits, ADH, DH1, DH2 and DL1 as shown in Figure 1 below. The ADH bit, which is the last bit with nominal bit time, is evaluated with settle time to ensure correct sampling of the subsequent DH1 bit, which is the first bit in the CAN XL data field. Since the ADH bit is ignored by the protocol controller, this switch scenario is less critical for the overall network validation. However, it needs to be checked in large networks which include many reflections.

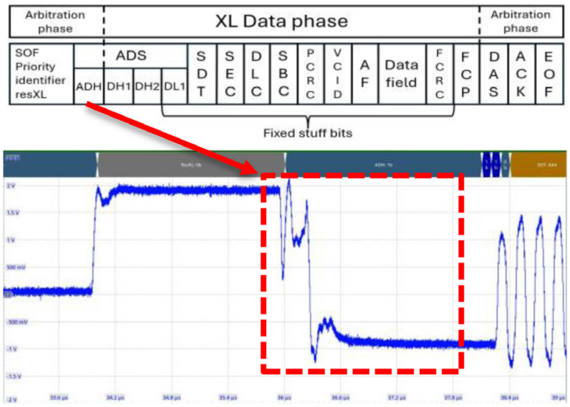


Figure 1: Arbitration to data phase mode switch

It is to be noted in this mode, error signalling is disabled. Hence, validation criteria regarding the reception of own messages are not required.

In FAST mode, the output signal is a symmetric alternating differential signal of level 0 and level 1. Both these levels are controlled by the transmitter. Moreover, receiver thresholds in FAST mode are +/-100 mV according to [2], both levels are symmetric to the receiver thresholds. Therefore, the signal asymmetries in both transmitter and receiver are now significantly smaller compared to all previous implementations.

With the higher achieved data bit rates up to 20 Mbit/s in FAST mode, eye diagram analysis is essential for validating and evaluating the data phase of CAN XL networks. The settle time considers only the shortening of the bit. Eye diagram takes into account the shortening and lengthening of the bit as well as the transitions and bus levels of all bits in FAST mode.

Functional description of eye diagram and sample point

Eye diagrams are often used to display the various signal transitions of the transmitted bit stream as a function of the signal clock in an amplitude/time domain diagram. For CAN XL the individual signal transitions of the FAST mode are superimposed to form an eye. With this form of visualization, various influencing factors such as jitter, noise, skew, ringing and other network effects can be displayed and easily evaluated to check the signal integrity. In addition, rise/fall time and symbol duration can be used.

A basic criterion for evaluating the influencing factors is a polygon, also known as an eye mask. The shape of the polygon is mainly determined by considering selected parameters based on the latest ISO 11898. The following parameters are used to define the area of the eye mask:

- bit rate,
- temperature (low/room/high),
- upper/lower voltage level (threshold),
- rise/fall time (20 % - 80 %),
- bit width variation (Tx/Rx),
- communication controller,
- clock tolerance (oscillator/PLL - Phase Lock Loop).

For the assessment, this eye mask is now placed in the eye opening. The final positioning of the eye mask in the eye opening is then determined using the sample point.

The position of the eye mask in the eye, as well as selected influencing factors with corresponding assignment to the signal curve, can be seen in the following diagram.

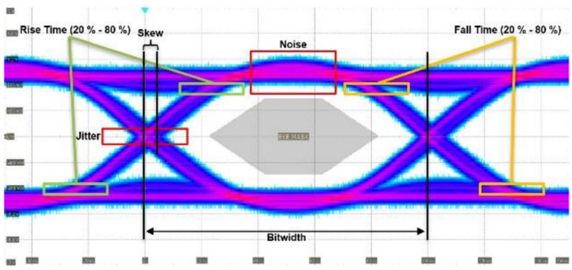


Figure 2: Eye diagram – embedded eye mask with labeling of the influencing factors

The following effects, among others, are important for the choice of the position of the sample point:

- clock tolerance,
- controller impact,
- PMA impact,
- network effects.

These effects cause the length of the bit to shorten or to lengthen, as shown in the following Figure 3. Therefore, the sample point for the FAST mode should be positioned in a range between approximately 50 % and 80 % of the bit length. When the position of the sample point is shifted, the position of the eye mask must also be adjusted accordingly.

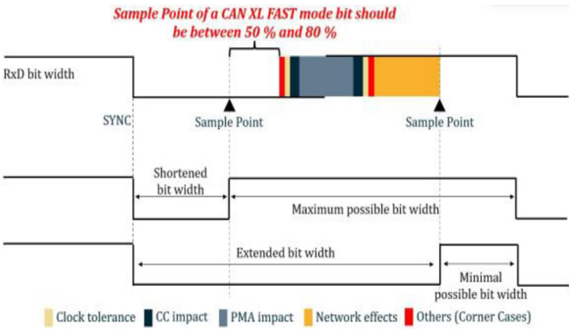


Figure 3: Impact of the effects on the positioning of the sample point

If signal sequences lie within this eye mask, the signal integrity is compromised and bit errors may occur in the transmitted bit stream. In this case, the eye mask is violated and must be evaluated as FAIL. If the eye mask is not violated, this would be evaluated as PASS.

The procedure described here is to be evaluated as in the section below under worst case conditions using software validation via an example network. It shows how validation is carried out using the eye diagram with the eye mask described above and whether any additional conditions and parameters need to be considered.

Description of an example network and general conditions for validation

The network consists of nine participants, with an overall cable length of 24.85 m. The two most distant nodes are 14 m apart and are each terminated with a 100 Ω resistor. The CAN XL communication takes place over special evaluation boards.

The following electrical components have been used for the network:

- CAN XL Communication Controller (CAN XL IP),
- CAN SIC XL Transceiver,
- Common Mode Choke (CMC),
- CAN XL Unshielded Twisted Pair cable (UTP).

The selected transceiver and the controller fulfill the requirements of the latest ISO 11898. The CMC and the UTP used also meet the requirements for the CAN XL network communication.

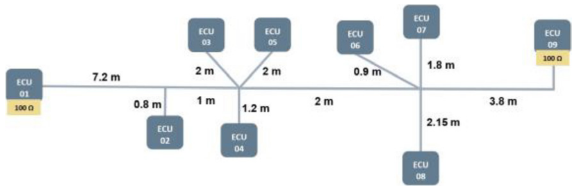


Figure 4: Example network – For simulation and measurement

The following special framework conditions were selected for the validation:

- For the transmission in FAST mode in the example network, a worst-case pattern was selected which consists of all possible combinations of the signal transitions of the bit stream.
- In order to generate the strongest possible ringing, the network structure was chosen so that the different lengths of the network participants form as many multiples of each other as possible.
- Use of the bit rates 10 Mbit/s and 12.3 Mbit/s. The higher the bit rate selected, the fewer variations are to position the eye mask in the eye opening in combination with the sample point.

The validation of the simulation results is carried out with a defined test setup and the special framework conditions listed above.

Assessment of the evaluation criteria

Normally, every possible network-transmitter and receiver combination is tested as part of a network validation. This was carried out for the example network described before. However, not all combinations are mentioned here in favor of two selected participants. The nodes not listed here have passed for both 12.3 Mbit/s and 10 Mbit/s according to the defined evaluation criteria. The validation of the physical layer using software simulation, taking into account the framework conditions mentioned, led to the following results.

For a bit rate of 10 Mbit/s the network has passed the simulation. For a bit rate of 12.3 Mbit/s the network did not pass the simulation. It should also be noted that the validation was carried out at room temperature.

As an additional safeguard for the results, the configuration software available for the evaluation boards was used to check the error conditions within the protocol IP. The software can be used to determine whether the transmitted signal can be received and decoded.

It can be concluded that the eye diagrams obtained by simulation and the eye diagram recorded by measurement are almost identical. This applies to both bit rates.

Validation for 12.3 Mbit/s

In Figure 5 and Figure 6 of the simulation and the measurement results, it can be observed that the eye mask is violated based on the selected sample point. A shift of the sample point by 1 MTQ (Minimum Time Quantum) to the right and therefore also the eye mask, would only lead to a reduction in the violation. The eye mask would be furthermore violated, but now on both sides! Over the software of the evaluation boards is confirmed, that the transmission between the two selected participants is faulty, as shown in Figure 7. The network has therefore failed the validation.

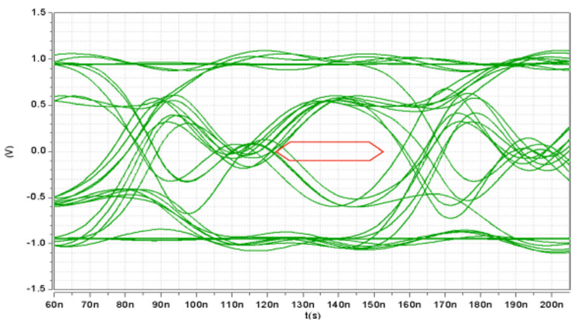


Figure 5: Simulation – Eye diagram 12.3 Mbit/s FAST mode

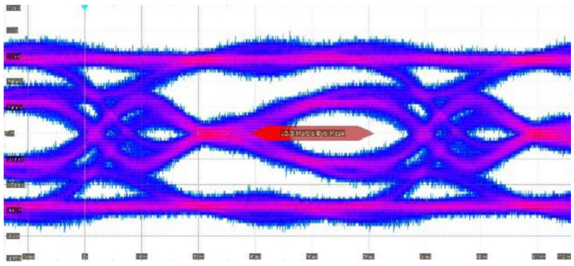
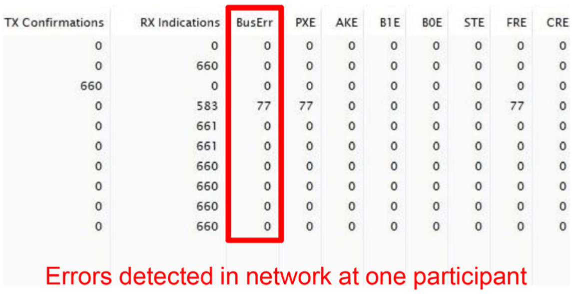


Figure 6: Measurement – Eye diagram 12.3 Mbit/s FAST mode



TX Confirmations	RX Indications	BusErr	PXE	AKE	B1E	B0E	STE	FRE	CRE
0	0	0	0	0	0	0	0	0	0
0	660	0	0	0	0	0	0	0	0
660	0	0	0	0	0	0	0	0	0
0	583	77	77	0	0	0	0	77	0
0	661	0	0	0	0	0	0	0	0
0	661	0	0	0	0	0	0	0	0
0	660	0	0	0	0	0	0	0	0
0	660	0	0	0	0	0	0	0	0
0	660	0	0	0	0	0	0	0	0
0	660	0	0	0	0	0	0	0	0

Errors detected in network at one participant

Figure 7: Evaluation board – Software results for 12.3 Mbit/s

Validation for 10 Mbit/s

With the bit rate of 10 Mbit/s, the eye mask is unharmed for both the simulation (Figure 8) and measurement (Figure 9) depending on the selected sample point. Moving the sample point by 1 MTQ to the left or right in the specified range does not result in violation of the eye mask. The software of the evaluation boards confirms that the transmission between the selected participants is error-free (Figure 10).

In comparison to the bit rate of 12.3 Mbit/s, the bit length for 10 Mbit/s is greater by 18.75 ns. This leads to less pronounced ringing, which means the eye opening is larger in height and width. The skew has also decreased significantly compared to 12.3 Mbit/s.

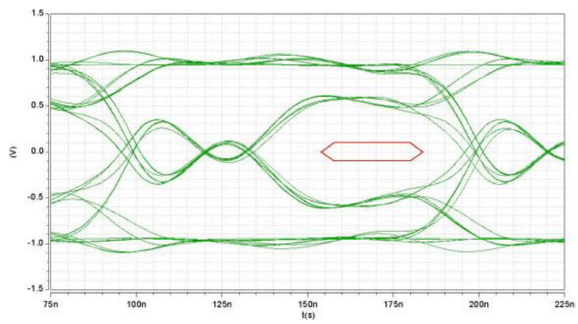


Figure 8: Simulation – Eye diagram 10 Mbit/s FAST mode

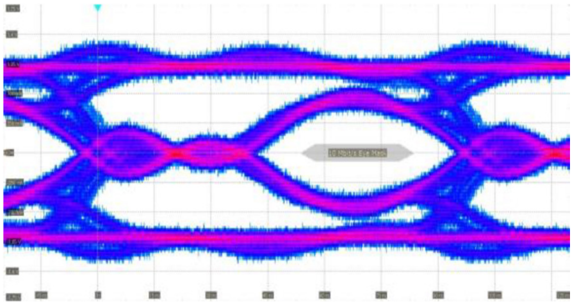


Figure 9: Measurement – Eye diagram 10 Mbit/s FAST mode

TX Confirmations	RX Indications	BusErr	PXE	AKE	B1E	B0E	STE	FRE	CRE
0	0	0	0	0	0	0	0	0	0
0	536	0	0	0	0	0	0	0	0
535	0	0	0	0	0	0	0	0	0
0	535	0	0	0	0	0	0	0	0
0	535	0	0	0	0	0	0	0	0
0	535	0	0	0	0	0	0	0	0
0	534	0	0	0	0	0	0	0	0
0	534	0	0	0	0	0	0	0	0
0	535	0	0	0	0	0	0	0	0
0	535	0	0	0	0	0	0	0	0

No errors detected in the network

Figure 10: Evaluation board – Software results for 10 Mbit/s

Although the reduction of the bit rate to 10 Mbit/s shows an improvement in the signal behavior of the network.The evaluation must not only consider the room temperature The following Figure 11 shows the signal behavior for high, room and low temperature as a result of the simulation in single eye diagram. It is clearly visible that the eye mask is not violated, hence, the network passed the validation for all three temperatures. However, effects like the production spread could lead to FAIL condition even at 10 Mbit/s.

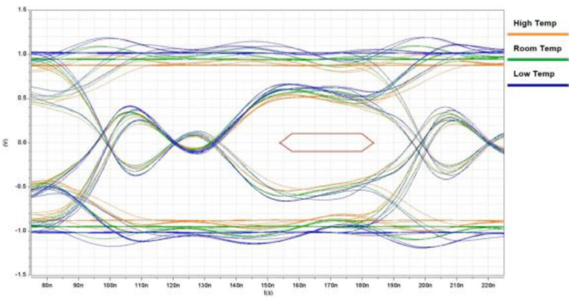


Figure 11: Eye diagram simulation with temperature variations – 10 Mbit/s FAST mode

Summary

As a new technology in the CAN family, CAN XL not only brings innovations such as higher bit rates, larger payload, new stuffing rules and mode switch functions. The innovations are also accompanied by new requirements for networks that need to be evaluated and validated. These includes the transition from SIC to FAST mode and the FAST mode itself.

In both simulation and measurement, the same sample point settings are used as a basis. Since the compared eye diagrams are almost identical, both evaluation results are the same. The simulation results were verified with the measurement results. The models and automatisms used are therefore already at a very good level.

It has been proven with the example network that simulation is a strong tool for the validation of CAN XL networks. Based on this, it is sufficient to use the validation and evaluation method presented here for the assessment of CAN XL networks in FAST mode via software simulation in the future. This makes it possible to validate and evaluate different network designs quickly, effectively and precisely within the framework of specified criteria and different conditions like temperature-dependent scenarios, Vcc variations and production tolerances.

Future perspective and outlook

CAN XL with its higher bandwidth and higher transmission speeds requires a differentiated consideration of further factors which can compromise the signal integrity. These factors have not been considered so far in the validation of early CAN networks. These factors are only of minor importance for CAN, CAN FD and CAN FD SIC and are therefore often not taken into account in network validation. However, for CAN XL they should be further examined and defined.

In particular, the use of special electronic and electrical components such as CMC, ESD diodes, connectors or the untwisted area of UTP cables could now have a greater influence on signal integrity. The near end and far end crosstalk, which have no relevance for CAN and CAN FD, may occur more frequently due to the increased bandwidth in CAN XL.

Therefore, it can be assumed that an optimal design of special electrical components for the CAN XL networks will be necessary in the future in order to minimize the different influencing factors.

References

[1] Isensee, Patrick; Ishikawa, Manabu: CAN FD Network Validation Simulation, validation criteria and an automated evaluation, 2017

[2] NA 052-00-31-03 AK (ISO/FDIS 11898-2): 29.11.2023, Road vehicles – Controller area network (CAN) – Part2: High-speed physical medium attachment (PMA) sublayer

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