Abstract
This article gives an overview about safe-guarding CAN FD for applications in trucks. The present situation of CAN networks in Daimler trucks is described. Furthermore capabilities and implications for the future usage of CAN FD in truck architectures are shown from the physical layer point of view.

Daimler Trucks was among the very first adopters of the CAN networking technology. In the beginning of the 1990s CAN was introduced into the SK (schwere klasse: heavy class) truck. In the first application (Euro 2 engines) there were only two CAN ECUs (electronic control units) running at 125 kbit/s with a special truck low-speed physical layer (ISO 11992). Since then, with every step in the evolution of the electronic architecture the number of CAN networks, CAN ECUs and the total amount of transmitted data increased as shown in Figure 1.

Networks for future truck architectures
For the next step in truck architectures, networks running only with classic CAN will not be able to keep up with the growing demand for the bandwidth. More powerful networking technologies that could be used in future truck architectures are CAN FD (a further development of the CAN protocol), Flexray (already successfully introduced into passenger cars), and Ethernet (Broadcom automotive 100-Mbit/s Ethernet that is just about to have its debut in passenger cars). Figure 2 gives a comparison of properties of classic CAN with CAN FD and Flexray dedicated for trucks (for passenger cars it may differ). Since the automotive version of Ethernet is a switched networking technology that does not support shared media, it is not included into this comparison. The overview distinguishes between CAN with ≤500 kbit/s (the past at Daimler Trucks) and CAN with ≥500 kbit/s (the present situation at Daimler Trucks).

The main aspects are:
- **Bandwidth:** Classic CAN will not provide enough bandwidth in future. CAN FD will increase the available bandwidth. Flexray would have the most potential with respect to bandwidth.
- **Cost:** It can be expected, that CAN FD will cost approximately as much as classic CAN. Flexray would be more cost intensive due to additional capabilities.

![Figure 1: Evolution of CAN networks at Daimler Trucks](image-url)
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- Economical solutions for series applications
- Optimized for industrial applications
- Solutions for stationary and mobile use
- Software support for bus-analysis, measurement and control

EPEC 5050 Control Unit
Based on 32 bit processor
Memory:
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- RAM 4 MByte / 8 MByte
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- PLCopen Application Max Size
  - 1 MByte / 3 MByte
- Temperature Range: -40°C ... +70°C

EPEC 3724 Control Unit
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Memory:
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- RAM 1 MByte
- Non-Volatile: 8 KByte
- PLCopen Application Max Size
  - 768 KByte
- Temperature Range: up to +85°C

EPEC 3606 Control Unit
Based on 16/32 bit processor
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- RAM 1 MByte
- Non-Volatile: 8 KByte
- PLCopen Application Max Size
  - 768 KByte
- Temperature Range: up to +85°C

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<table>
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<th>Architecture based on:</th>
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<th>CAN 2.0B ≥ 500kbit/s</th>
<th>CAN 2.0B + CANFD</th>
<th>CAN 2.0B + FlexRay</th>
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<td>Diagnosis/ Flashing</td>
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</table>

Figure 2: Comparison of CAN, CAN FD and Flexray for trucks

expenses for software and physical layer.

- Transmission line length: For trucks and especially omnibuses the possibility to use long transmission line lengths is an important criterion. CAN using up to 500 kbit/s allows for adequate transmission line lengths, whereas CAN with more than 500 kbit/s is significantly limited with respect to transmission line length. CAN FD and also Flexray will allow for longer transmission line lengths comparable with the classic CAN networks running at up to 500 kbit/s.

- Flexibility: In the electronic architecture from the truck it has two dimensions. Firstly, truck architectures have a long life span (might be twice the life span of a passenger car architecture), in which they have to be extendable for new features or regulations. CAN FD would maintain flexibility in this case because it is as easy to handle as classic CAN and provides enough bandwidth. Flexray requires a complete pre-definition of the communication schedule, which could be a difficult and ineffective job with regard to future extensions. Secondly, there is a broad diversity of different vehicles (light trucks, heavy trucks, omnibuses, special-purpose vehicles etc.) and markets (Europe, North America, South America, Asia etc.). The intention is to reuse the core of the electronic architecture for all vehicles and markets and to adapt it to the respective needs. This can be handled flexibly using CAN or CAN FD, however finding one common Flexray communication schedule would be a challenging job. Working with vehicle-dependent communication schedules would be even more complicated.

- Hardware availability: It is very good for CAN and is also good for Flexray. There are promising announcements for coming CAN FD products. To use these in the next architecture step these products have to be ready for production in 2016.

- Diagnosis and flashing: Flashing can be quite slow using classic CAN. It could be accelerated significantly using CAN FD especially due to the extended payload frames. However this requires that the link into the vehicle also supports CAN FD. Using Flexray, the flashing speed depends mainly on the design of the communication schedule.

Signal integrity of truck CAN physical layer

The question has to be answered whether CAN FD will be suitable for the physical characteristics of truck and bus architectures. To give a first estimation of the obtainable bandwidth, two example topologies taken from real vehicles are examined. The example is taken from one of the five main CAN networks of the vehicle. It is connecting ECUs on the truck as shown in Figure 3. There is one common electronic architecture for all vehicles using the same type of ECUs performing the same functions. However, depending on the vehicle type, the physical structure of the topology can be very diverse. The example truck topology (9-m vehicle) uses a classic CAN network with stubs in this case. In an articulated bus (20-m vehicle) it is a passive double star topology.

Typical characteristics of truck and omnibus topologies are long transmission line lengths (up to 50 m between two ECUs) and large number of ECUs within one vehicle and within one physical CAN network. CAN allows to handle the variety of topologies, but the physical layer in large topologies is challenging. Figure 4 shows the structure of the example topologies in detail on the left side. On the right side a CAN signal integrity graph is shown, which can be used to evaluate the physical characteristics of a CAN topology. The articulated bus topology might also have some optional ECUs (not shown in Figure 3). All calculations are based on the topology shown in Figure 4.

Figure 3: Example truck and omnibus architecture
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To evaluate a CAN topology dozens of signals have to be checked and, if done manually, the worst-case signal might be missed. Therefore Daimler R&D developed the signal integrity graph (Figure 4 right side). One topology is described in one graph that shows all relevant topology characteristics including the worst-cases. In order to get the signal integrity graph all physical signal relationships between all nodes in the network have to be measured or simulated. All analog bus and digital Rx (receive) signals are synchronized on the falling edge of the Tx (transmit) signal and plotted in an intersected manner. The result shows two areas: The red area comprises all analog bus waveforms that can be found in the network; overshoots, ringing or the shape of the transitions from dominant to recessive can be examined. The blue-shaded area includes all Rx signal slopes relative to the Tx slope. Thus, the position and extent of the blue-shaded area directly corresponds to the minimum and maximum propagation delay between the nodes. The truck topology shows comparatively clean bus signals, ringing decays quickly and there is only a little delay. However the articulated bus topology shows more ringing, reflections and it has considerably more delay due to the more complex structure of the topology.

Round trip delay

A relevant value for the CAN protocol controller is the maximum round trip delay in the network between the ECUs, which can be extracted directly from the signal integrity graph. The maximum round trip values of both example topologies are plotted in a bar graph shown in Figure 5. They represent the typical case (light blue bar). For worst-case estimations, the temperature-dependent tolerances of the transceiver and EMI (electromagnetic interference) jitter have to be considered (grey bars) and the CC delay (dark blue bar) has to be added. Oscillator tolerances in the ECUs have a similar effect that can be expressed as an additional delay; the respective values are added as grey bars at the sample point positions. In the example (Figure 5) a direct clocking of the controller by a crystal is assumed. In case a PLL (phase-locked looped) clock is used, the clock tolerance might be larger. The maximum bit-rate in the network is limited by the maximum round trip delay. It has to be smaller than the time position of the sample point within one bit-time. If the round trip delay is too large, the arbitration and acknowledge mechanism does not work anymore resulting in error frames on the network. These limits are shown in Figure 4 for different bit-rates and sample points.

The resulting safety margins in Figure 5 show, that the truck topology would work with 800 kbit/s, though only with a small safety margin. The articulated bus topology will only work safely with 500 kbit/s. This calculation shows that in trucks and omnibuses the maximum acceptable bit-rate (500 kbit/s and 667 kbit/s) is already reached. Further increase with the classic CAN network will...

![Figure 4: Truck and omnibus topology with signal integrity graph](image)

![Figure 5: Round trip delay and bit-timing](image)
not be possible. The limiting factor is the round trip propagation delay between the nodes.

The potential of the CAN FD physical layer

However, today’s CAN physical layer (high-speed) has the potential for higher speeds. The bit-rate is only limited by the arbitration and acknowledge mechanism, not by signal integrity on the network. CAN FD can overcome the bit-timing bottleneck of classic CAN enabling more data throughput without changing topologies and physical layer hardware. Figure 6 shows what happens to the CAN signals when the bit-rate is accelerated, e.g. in the fast data phase of a CAN FD frame. The calculation uses the truck example topology (Figure 3 and Figure 4). The signal integrity graphs show an increase of the bit-rate from 500 kbit/s to 1 Mbit/s and finally to 2 Mbit/s (Figure 6a to Figure 6c). It can be seen that the shape of the slopes does not change and the relative delay time stays the same. Only the steady state part of the bit is contracted. The lower graph in Figure 6d shows a detail of a CAN bit stream with 2 Mbit/s in the example topology. It can be seen that the analog waveforms as well as the digital Rx signals are well transmitted over the physical layer. At approximately 2 Mbit/s, the extent of the bit in relation to the extent of the signal slopes shows, that a further increase would not be reasonable.

The first simulation results show, that even in truck and omnibus topologies approximately up to 2 Mbit/s for the data phase of the CAN FD protocol would be possible using the current transceivers and current topology structures. For the arbitration phase today’s common bit-rates of 500 kbit/s to 667 kbit/s have to be maintained to ensure correct arbitration and acknowledge. Of course, these theoretically calculated results still have to be confirmed by mea-

Figure 6: Signal integrity graphs

Figure 7: Average bit-rate with CAN FD protocol
measurements with real hardware.

**Increased data throughput with CAN FD**

The calculations above give a first estimation of possible arbitration phase and data phase speeds in the CAN FD message. These values permit to estimate the average data throughput that can be achieved with CANFD under these physical layer conditions. The upper three graphs in Figure 7 are plotted for arbitration speeds of 500 kbit/s to 800 kbit/s. The horizontal axis represents the bit-rate in the fast data phase of a CAN FD frame, while on the vertical axis the resulting average bit-rate is plotted, assuming that only 8 byte payload frames are used. In this case no changes to the application software would be necessary when using CAN FD, besides an adoption of the CAN driver software. Figure 7a shows that the average bit-rate could be nearly doubled for an arbitration speed of 500 kbit/s and 2 Mbit/s for the data phase using only 8-byte data frames and the 29-bit CAN-IDs (identifiers), which is common in trucks. There could be more gain in average bandwidth for networks using the 11-bit CAN-IDs e.g. in passenger cars. The estimation does not include stuff bits.

Apart from the faster bit-rate in the data segment, CAN FD also enables transmission of frames with a payload of up to 64 bytes. The two lower graphs in Figure 7 show the effect of the extended payload length, assuming that all transmitted frames make completely use of the respective payload. It is evident, that the gain in average bit-rate is maximized when frames with long payload are used. For example, in a truck network with an arbitration speed of 500 kbit/s and a data-phase speed of 2 Mbit/s with 8 bytes of payload would make a little less than a 1-Mbit/s average bit-rate. However, when using the whole 64 bytes of the payload, the yield is a little higher than a 1.5-Mbit/s average (Figure 7d). This means an increase of approximately 50 % of the average bit-rate. Also this estimation neglects stuff bits. Using more than 8 bytes of payload will have a direct impact on the applications and the ECU’s operating system as these are currently developed to deal with 8 bytes of payload only. Especially applications using the J1939-based protocols and vehicle flashing applications could benefit from the extended payload length.

Figure 8 shows an example, which is taken from a real truck communication cycle. Only the messages that are transmitted cyclically every 10 ms are shown. Some ECUs need to transmit more than 8 bytes of payload resulting in a burst of frames that take approximately 3.5 ms to be transmitted. Figure 8 shows the reduction in transmission time achievable using CAN FD with an 8-byte payload and fast transmission of the data, with extended payload but without fast transmission of the data and with both mechanisms combined. In all configurations CAN FD reduces the necessary transmission time and allows more data to be transmitted on the network.

**Next steps**

In order to safeguard the CAN FD technology for the integration into vehicles, real hardware for testing is necessary. Until now microcontrollers with integrated CAN FD controller are not available. A CAN FD IP is already available from Bosch as a VHDL code. Therefore Bosch, Daimler and NXP jointly developed a sample gateway device based on an FPGA implementation. It can be used to build up entire CAN FD networks and perform hardware tests of topologies, signal integrity and EMC as well as software tests such as gateway algorithms. According to the company, the ECU in Figure 9 represents the world’s first CAN FD-based gateway device. The power supply unit, connectors, size and housing are designed to use it in a laboratory or vehicle environment.

### Table - CAN FD Message Types

<table>
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<tr>
<th>CAN (29-bit CAN-ID) 667 kbit/s</th>
<th>CAN FD std. arb. 667 kbit/s data 2 Mbit/s 8-byte frames only</th>
<th>CAN FD extd. arb. 667 kbit/s data 667 kbit/s 64-byte frames</th>
<th>CAN FD extd. arb. 667 kbit/s data 2 Mbit/s 64-byte frames</th>
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<tbody>
<tr>
<td>18 x 8-byte msg. 3,537 ms</td>
<td>18 x 8-byte msg. 2,088 ms</td>
<td>2 x 8-byte msg. 0,405 ms</td>
<td>2 x 8-byte msg. 0,232 ms</td>
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<tr>
<td>1 x 32-byte msg. 0,497 ms</td>
<td>1 x 32-byte msg. 0,214 ms</td>
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<td>1 x 48-byte msg. 0,689 ms</td>
<td>1 x 48-byte msg. 0,278 ms</td>
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<tr>
<td>1 x 64-byte msg. 0,881 ms</td>
<td>1 x 64-byte msg. 0,342 ms</td>
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<tr>
<td>Σ 3,537 ms</td>
<td>Σ 2,088 ms</td>
<td>Σ 2,472 ms</td>
<td>Σ 1,066 ms</td>
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</tbody>
</table>

**Figure 8:** Example of different CAN FD configurations
The sample gateway device will be used to confirm the first simulation results given in this article. Furthermore it will be used to perform various investigations to answer open questions and finally derive design rules for the CAN FD networks. It is not intended to go into series production and will only be used for R&D purposes. Some of the topics to be investigated are:

- Clock/jitter tolerance
- EMC emissions
- Robustness against EMC
- Robustness of transceiver delay compensation
- Signal integrity, asymmetric delay
- Qualification of transceivers
- Interoperability of different bit-time and clock settings
- Interoperability of different controllers
- Software tests
- Gateway strategies

A final validation of the CAN FD technology and its possibilities will be made when it has passed these tests.

Conclusion

CAN FD is a promising bus technology that allows designing cost-optimized and flexible architectures for trucks and omnibuses in the future. First estimations show that in typical truck and omnibus networks bit-rates in the data field of approximately 2 Mbit/s would be possible without changing the physical layer and the network topology. In combination with the extended payload the average data throughput could be increased by a factor of three depending on the application. The main advantage of CAN FD for trucks is the increase of average data throughput for the applications, which will maintain flexibility for future extensions and diversity of vehicles. This enables extension of the life time cycle of existing electronic architectures.

At Daimler, CAN FD currently has the status of a predevelopment project. To use CAN FD in the next vehicle generation in approximately 2016 and 2017, a dependable roadmap of micro-controllers with included CAN FD IP must be available by mid of 2013. Especially, the availability of a micro-controller suitable for gateway applications with at least four CANFD controllers is a precondition for the series introduction.