Comparative Reliability Analysis for Single and Dual CAN (FD) Systems

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2022 International Conference on Applied Electronics (AE) | 978-1-6654-9482-3/22/$31.00 ©2022 IEEE | DOI: 10.1109/AE54730.2022.9920078

***Abstract*—Modern cyber-physical systems, such as autonomous vehicles, advanced driver assistance systems, automation systems and battery management systems, result in extended communication requirements regarding the reliability and the availability. The Controller Area Network (CAN) is a broadcast-based protocol which is still used as a standard for serial communication between individual microcontrollers due to its reliability and low power consumption. In addition, it provides mechanisms for detecting transmission errors and retransmitting messages in the event of an error. The enhancement CAN Flexible Data-Rate (CAN FD) offers increased data rates and transmission rates in order to meet the data throughput requirements. In this paper, the mechanisms for reliable data transmission in a CAN FD network are analyzed. To improve reliability, a second identical CAN-FD network is added to the system, using the additional CAN interface already available on common microcontrollers. The redundant communication network is examined in terms of failure rates and the mean time to failure. The reliability over the operation time is calculated for the single and the redundant version of the CAN FD network using the failure rate limits of the ASIL levels.**

***Index Terms*—CAN Bus, Dual Bus, Redundancy, Reliability, Functional Safety, Test Setup, Autonomous Systems.**

I. Introduction

Multiple control units, sensors and actuators are required to control complex systems such as autonomous vehicles, automation systems or smart grids. The individual control units are connected via a common communication line and exchange data and instructions in order to coordinate the system control.

Controller area network was first developed for the automotive industry [1] and has become widely used in many other areas such as manufacturing, automation and aerospace due to its advantageous features, including broadcast communication, error detection and error handling mechanism.

The CAN bus provides a versatile and universally applicable field bus, which transmits data reliably and cost-effectively. Safety critical applications and autonomous systems show increased requirements regarding reliability, whereby the safety mechanisms of the CAN protocol are not sufficient.

A consideration of the failure probabilities of the individual components and the cable connections is required to estimate and evaluate the residual risk. To reduce the probability of failure, a redundant communication system consisting of two identical CAN FD networks is proposed. In this way, even in the event of a fault, e.g. triggered by a line break, communication can be maintained using the second network. Fig. 1 shows the schematic structure of a dual CAN network including the CAN controllers and transceivers as well as the microcontrollers and bus lines [2].

To investigate the impact of the redundant design, the reliability values of a single and a dual CAN FD network are calculated below using the failure rate limits specified by the Automotive Safety Integrity Levels (ASIL) according to the ISO standard 26262 [3]. The object of investigation is the reliability of an error-free communication between all network nodes, whereby the individual failure rates of the components and the arrangement of the single components are taken into account.

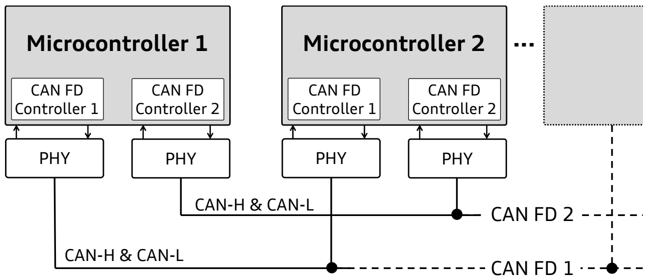

Fig. 1: Schematic structure of a redundant CAN network for CAN 1 and CAN 2 consisting of microcontrollers with integrated CAN controllers and external CAN bus drivers (PHY) [2].

Section II initially provides a selection of related work on redundant CAN networks. The basic functions of the CAN FD bus are described in Section III and the redundant CAN FD network is presented in Section IV. The reliability of a redundant CAN network consisting of two nodes is calculated and analyzed in Section V. The reliability of communication in a vehicle over the average operating time is determined according to the ASIL limits for a single and a dual CAN network. Finally, Section VI provides a conclusion and an outlook on further investigations.

II. Related Work

Already existing dual CAN applications were investigated in a previous work [2]. The dual CAN is used in small aircrafts [4] and in marine propulsion systems [5, 6]. The elevated requirements for reliable communication between the components and the impeded repair possibilities are reasons for this communication design.

The dual CAN is used in a robot arm for space missions. In this case, it is particularly important to ensure error-free operation and maximum availability of the system, since the external conditions in space and the challenging accessibility make it difficult to repair the robot arm. [7]

CAN FD has been evaluated in comparison to the standard CAN and Ethernet in terms of energy consumption, transmission speed and reliability for a decentralized battery management system. The advantages of CAN FD include the improved data transmission rate and the low energy consumption. [8]

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III. Technical Background: Fundamentals of CAN

In order to further investigate the reliability of the redundant CAN bus, the functionality of the CAN FD bus is explained. The terms *reliability* and *failure probability* are defined and the equations for calculating them are given. In addition, the concept of redundancy is explained.
Throughout the remainder of this paper, all considerations refer to the CAN FD bus, unless explicitly stated otherwise.

A. Controller Area Network - Flexible Data-rate (CAN FD)

Due to the characteristic differential signals CAN-H and CAN-L, external interfering signals can already be suppressed and associated erroneous transmissions can be reduced. [9]
Collision Detection (CSMA/CD) of simultaneously transmitted messages is implemented with the Identifier (ID) of each message defining the priority for the arbitration. Due to the additional error detection by the 15-bit CRC (Cyclic Redundant Check) sent after the data field, transmission errors can be detected. The error counters in the CAN controller hardware enable a node to perform self diagnosis and withdraw itself from the bus step by step, if malfunction is detected, and thus prevent the collapse of the entire system. [1]

CAN FD provides an enlarged data field with a length of up to 64 bytes. The transmission rate of the data field can be increased up to 8 Mbit/s (bit rate switching). Lower latencies and a higher number of user data are particularly advantageous for networked control systems [8]. For better error detection, the CAN FD frame contains the error status indicator bit in the control field, which shows the status of the transmitter (1: error-active or 0: error-passive). In addition, the CRC field is extended and the stuff counter is added, indicating the number of stuff bits. [10]

Due to the advantages, the availability of the hardware components and the backward compatibility to the classic CAN, the CAN FD format is used within this work.

B. CAN Communication Error Types

Bus systems offer numerous attack possibilities for errors in the communication. Error sources include the components, the software or even the bus lines themselves. The CAN bus consists of two twisted pair wires (CAN-H and CAN-L). During transmission on the bus line, signal level changes can occur due to external interference signals. Differentially wired AND signals protect against common-mode interference. Mechanical stress (e.g. vibrations) or interference with the bus system can lead to increased errors and thus disconnect one or even several stations from the bus.

According to the ISO 11898 standard [11], *line errors* are defined as follows: a ground fault of the CAN-H or CAN-L line, a connection to the supply voltage of the two lines or also a short circuit between them. Furthermore, the simple interruption of one of the two lines is described. In this paper, the behavior in case of wire breaks is investigated in more detail. Other faults are significantly less common and will not be considered further here [12].

While the low-speed bus (CAN 1.0, 125 kbit/s) still had the possibility to switch off the differential signal in case of failure of one of the CAN-H/CAN-L lines (single-wire operation) in order to still be able to receive the data, this is no longer possible from the development stage of the high-speed bus (CAN 2.0). Therefore, another way needs to be found to keep the bus system in operation. [12]

IV. Reliability Analyses of the Communication Architectures

The *reliability* $P(\Delta t)$ is a measure for the probability of correct operation of a system in a given time interval Δ.

$$\Delta t = t_1 - t_0 \tag{1}$$

It is not directly measurable, but can be determined qualitatively or quantitatively with the help of stochastic processes. The description of the reliability of a system can be used to determine the probability, that no error occurs in a given time interval. It must be defined beforehand, what the actual task of the system is and which states are described as faulty.

The exact opposite of *reliability* is the *failure probability*. It is a measure of the likelihood, that a failure will occur during the specified operation time. To calculate the reliability, a distinction must be made between *multiple-use* systems and *single-use* systems. The reliability of *single-use* systems is characterized by the probability, that the required operation will be completed within the predefined and limited operating time. Systems for *multiple-use* are operated over a longer, non-predefined period. Longevity, availability and durability of the system play a significant role here. In this case, reliability is characterized by the duration of failure-free operation.

Single-use systems are *unrecoverable*, while multiple-use systems are *recoverable*. In addition to the Mean Time To Failure (MTTF), the Mean Down Time (MDT) and the Mean Time Between Failures (MTBF) have to be considered in the reliability analysis of multiple-use systems.

The dual CAN is an *unrecoverable system* as it is not repaired during operation. [13, 14]

The Probability of Failure Free Operation (PFFO) can be calculated with the given distribution function $F(\Delta t)$ [13]:

$$P(\Delta t) = 1 - F(\Delta t) \tag{2}$$

Considering a system consisting of *n* units and assuming that the units have independent constant failure rates (λ), the failure distribution is represented as an exponential distribution (Equ. 3) [15, 16]. The exponential distribution with constant error rates is suitable for representing the failure rate of many electronic components that have survived their infant mortality period [17]. For an exponential distribution, as is the case with reliability, the probability can be calculated as follows:

$$P(\Delta t) = \exp\left(-\lambda \Delta t\right) \tag{3}$$

The parameter λ is the failure rate and describes the reciprocal of the time Δt_{MTTF}, which the system spends in the failure-free state: *Mean Time To Failure* (MTTF).

$$\Delta t_{\mathsf{MTTF}} = \int \exp\left(-\lambda t\right) dt = \frac{1}{\lambda} \tag{4}$$

The calculation of the reliability of a system depends on the Δt_{MTTF} of the individual components and on the arrangement of the individual components. The structure of the components can basically be divided into serial and parallel arrangements.

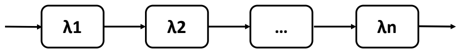

Fig. 2: Serial arrangement of individual components with their corresponding failure rates ($\lambda_{1...n}$).

A. Serial Arrangement of the Components

For determining the reliability of a set of components n with independent error rates and different Δt_{MTTF} in serial order (Fig. 2), their reliability functions are multiplied, which implies the addition of their exponents [13, 17]:

$$P(\Delta t) = \exp\left(-\Delta t \sum_{i=1}^{n} \lambda_i\right) \tag{5}$$

$$\Delta t_{\mathsf{MTTF}} = \int_{0}^{\infty} \exp\left(-t \sum_{i=1}^{n} \lambda_i\right) = \frac{1}{\sum_{i=1}^{n} \lambda_i} \tag{6}$$

B. Parallel Arrangement of the Components

Parallel systems (Fig. 3) successfully perform their tasks when the first unit runs without errors or when the first unit fails and the second one successfully takes over the tasks. The number of parallel strings as well as low failure rates of the individual components positively affect the reliability of the overall system.

If each component has its own failure rate λ_i, the following equations for parallel circuits are obtained [13, 17]:

$$P(\Delta t) = 1 - \prod_{i=1}^{n} (1 - \exp(-\lambda_i \Delta t)) \tag{7}$$

$$\Delta t_{\mathsf{MTTF}} = \frac{1}{\lambda} \sum_{i=1}^{n} \frac{1}{i} \tag{8}$$

The reliability in a combination of serial and parallel structures can be calculated iteratively and is discussed in more detail in Section V-B and Fig. 5.

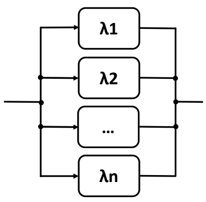

Fig. 3: Parallel arrangement of individual components with their corresponding failure rates ($\lambda_{1...n}$).

C. Types of Redundancy

Depending on the requirements of the safety level, the realization of the redundancy can be adapted. In stages of varying complexity, for example, only the bus line and the CAN transceivers can be duplicated, thus creating a single-redundant network. It is also possible to duplicate or multiply the CAN controllers and the CPU as well as the power supply to the nodes in order to minimize the *probability of failure*. Moreover, a distinction is made between two implementations of redundancy: In the case of *cold redundancy*, only one section of the multiple bus systems is active at the same time. As soon as a fault is detected in the main communication network (send or receive errors as well as missing heartbeat messages [18]), the backup network can be accessed and communication is shifted to the second network. In this case, transmission errors may occur, since the change of communication channels cannot take place immediately and without delay. The advantage of this method is a lower implementation effort as well as the lower energy consumption of the system.

Another redundancy method is *hot redundancy*. Using this, both communication channels are always in operation at the same time. Each message is sent and received on both channels. It can be checked by comparing the two networks to see if they are working properly, and in the event of an error, it can be reported. The reliability of the system is increased under the assumption of independent failure probabilities, i.e. the non-existence of common cause failures. The presence of common cause failures, in contrast, reduces the advantage depending on its probability compared to independent failures.

V. Redundant Communication Network using Dual CAN

The reliability of a single and dual CAN network is considered in this section. In this context, successful operation means failure-free communication between all nodes of the system. In this case, the failure of a single component, such as a CAN controller, already constitutes an error and is considered a failure of the system. The probability of a remaining partial function of the communication network is *not* considered, Accordingly, the reliability of an entire failure-free communication with a single and dual CAN network between two nodes is calculated and analyzed hereafter.

A. Dual CAN Network Consisting of Two Nodes

The communication link between two nodes in the CAN network consists of the two microcontrollers, two internal CAN controllers each, the associated CAN transceivers and the redundant bus line connecting the two nodes (Fig. 1). The design of the redundant components affects the probability of common cause failures. To reduce common cause failures, measures, such as routing the two CAN bus lines locally separate and using different variants for the plug connectors, can be useful. Even these measures cannot completely avoid common cause failures, so the independent failure probabilities used in the following are merely assumptions.

The components of a single (Fig. 4) and a dual (Fig. 5) CAN network are assigned the individual error rates, which are labeled λ_1 to λ_7 and shown in Tab. I. As a transmitted CAN message from one microcontroller to the other one passes all CAN communication components (CAN controller, CAN transceiver and the bus line), the error rate of each component has to be considered and included in the calculation as well. The error rate of the power supply is neglected.

Table I: Failure rates of the components in the CAN network

Failure rates	Component
λ_1, λ_7	Microcontroller
λ_2, λ_6	CAN-Controller
λ_3, λ_5	CAN-Transceiver
λ_4	Bus line & plug connectors

The components in the *single* network are connected in series. In the *redundant* network, a second identical, parallel communication network is added between the microcontrollers and is considered in the reliability calculation. [4]

B. Calculation and Comparison of the Overall Reliability of a Single and Dual CAN Network

The calculation of the reliability of the complete system is performed using the equations presented in Section IV. Based on Fig. 4 serial and parallel arrangements of the individual components are used in the system layout.

a) The *single-CAN* implementation consists of two nodes, each consisting of a microcontroller, a CAN transceiver and controller, which are connected via the bus line. As shown in Fig. 4 failure rates λ_i are assigned to each component (C). Equation (5) is used to calculate the reliability of the single CAN network.

$$P_{\mathsf{C1-7.single}}(\Delta t) = \exp\left(-\Delta t \sum_{i=1}^{7} \lambda_i\right) \tag{9}$$

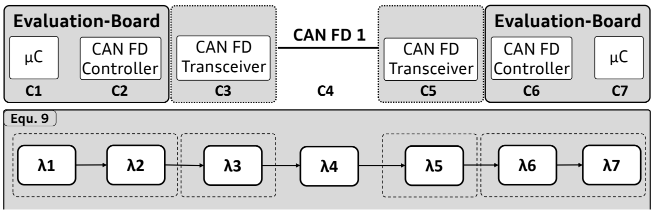

Fig. 4: Single CAN network with two nodes considering the error rates of the individual components, including two microcontollers, CAN FD controllers, CAN FD transceivers and one bus line. The failure rates (λ_{1-6}) belong to the above components (C_{1-6}). To calculate the reliability of this network Equ. 9 is used.

b) The calculation of the reliability of the *dual-CAN* requires several partial calculations performed iteratively (Fig. 5). Initially, the reliability of one of the parallel sections is calculated as a sequence of serial connections of the components. The parallel sections extend from the CAN controller of one node (λ_2) to the second CAN controller (λ_6). Using the equation (5) the serial interconnection can be calculated:

$$P_{\mathsf{C2-6.single}}(\Delta t) = \exp\left(-\Delta t \sum_{i=2}^{6} \lambda_i\right) \tag{10}$$

Since both the parallel (par) sections consist of the same components and thus have the identical failure probability, the equation (7) can be applied to calculate the reliability of the parallel sections.

$$P_{\mathsf{C2-6.par}}(\Delta t) = 1 - \left(1 - \exp\left(-\Delta t \sum_{i=2}^{6} \lambda_i\right)\right)^2 \tag{11}$$

In combination with the serial components (Equ. 5), we obtain $P_{\mathsf{dual}}(t)$ for the reliability of the redundant CAN bus system:

$$P_{\mathsf{dual}}(\Delta t) = \exp\left(-\lambda_1 \Delta t\right) \cdot P_{\mathsf{C2-6.par}}(\Delta t) \cdot \exp\left(-\lambda_7 \Delta t\right) \tag{12}$$

The ISO 26262 standard defines error rates for defined safety levels of the Automotive Safety Integrity Level (ASIL) according to a hazard and risk analysis. The ASIL levels from A to D define the permissible error rates from 10^{-5}/h

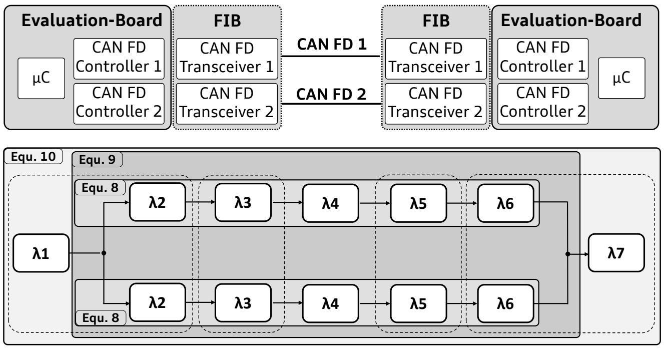

Fig. 5: Dual CAN network with two nodes considering the error rates of the individual components including two separate bus lines, four CAN FD transceivers, four CAN FD controllers and two microcontrollers. The equations 10 , 11 and 12 are required to calculate the reliability.

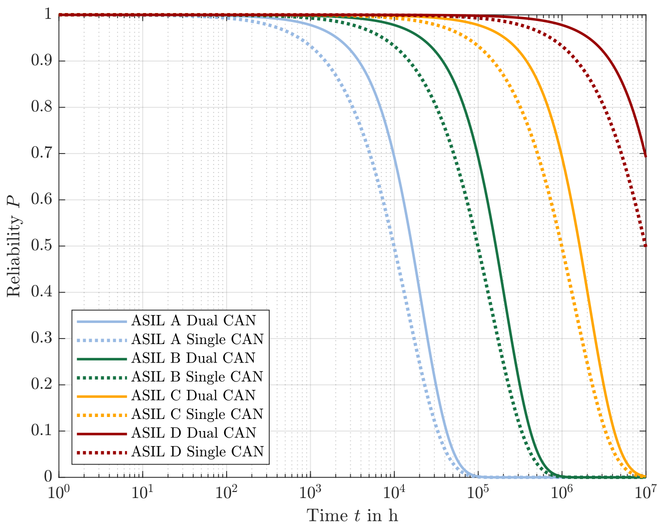

Fig. 6: Comparison of the reliability values for single and dual CAN using the failure rate limits for ASIL levels A to D according to the ISO26262 standard.

to 10^{-8}/h. Figure 6 shows the reliability over the operating time for a single CAN (Equ. 9) and a dual CAN (Equ. 12) network using the failure rate limit values corresponding to the ASIL Levels.

For short operating times of up to 1000 h, there are only minor differences between the single and the dual CAN and between the individual ASIL levels. From an operating time of approx. 3000 h, differences between the ASIL levels and the single and dual CAN become apparent.

For a more detailed comparison between the ASIL levels and between the single and the dual CAN, the reliability values for an operating time of 1000 h and 10000 h are compared in Table II. By calculating the improvement factor

$$f = (1 - P_{\mathsf{dual}}/P_{\mathsf{single}}) \tag{13}$$

a comparative measure is obtained. Especially for ASIL level A, the use of the dual CAN over an operating time of 10000 h shows a significant advantage: The reliability improves by 28% compared to the single CAN network. As the operating time increases, the improved reliability of the dual CAN network becomes more evident, although this effect decreases with an increase in the ASIL level. At ASIL level D, the dual CAN network shows only an improvement of 0.50% compared to the single CAN network at an operating time of 10000 h. An operating time of 10000 h corresponds to an operating time of 1.3 years for continuous operation, as is the case e.g. with a satellite.

At lower ASIL levels (A–B), using a dual CAN network is a way to improve reliability in a cost-efficient way, since components meeting a lower ASIL level are less expensive. The values for λ_i have to be adjusted for a concrete application with respect to the used components (microcontroller, bus length etc.). [20, 21]

Table II: Reliability values according to the limits of the ASIL levels A to D for an operating time of 1000 h and 10000 h for a single and dual CAN network and the improvement factor (Equ. 13)

ASIL Level	Operation Time	Single CAN	Dual CAN	Improvement Factor
A: $\lambda = 10^{-5}$	1000	0.932	0.978	4.65%
A: $\lambda = 10^{-5}$	10000	0.497	0.692	28.24%
B: $\lambda = 10^{-6}$	1000	0.992	0.998	0.50%
B: $\lambda = 10^{-6}$	10000	0.931	0.978	4.64%
C: $\lambda = 10^{-7}$	1000	0.9992	0.9998	0.05%
C: $\lambda = 10^{-7}$	10000	0.9324	0.9779	4.64%
D: $\lambda = 10^{-8}$	1000	0.99993	0.99994	0.005%
D: $\lambda = 10^{-8}$	10000	0.99301	0.99798	0.50%

C. Calculation of the Reliability for a Single and Dual CAN Network with a Variable Number of Participants

Following, the equations for determining the probability of a completely error-free communication between n communication nodes with independent failure rates for serial and parallel arrangement are presented.

1) Single CAN: In the single version of the CAN network, a common bus line connects the communication nodes (Fig. 2). For CAN communication, each nodes has a CAN controller, CAN transceiver and a supply line to the bus line (Equ. 14).

$$\lambda_{\text{CAN}} = \lambda_{\text{controller}} + \lambda_{\text{transceiver}} \tag{14}$$

Combined with the failure rate of the microcontroller, the following term for the exponent results for the serial arrangement of the subcomponents of a node (Equ. 15):

$$\lambda_{\text{node}} = \lambda_{\text{CAN}} + \lambda_{\mu\text{C}} \tag{15}$$

Consequently, equation 16 applies to the probability of fault-free operation:

$$\begin{aligned} P_{\text{single}}(\Delta t) &= \exp\left(-\Delta t \sum_{i=1}^{n} \lambda_i\right) \\ &= \exp\left(-\Delta t \cdot (\lambda_{\text{node}} \cdot n + \lambda_{\text{busline}})\right) \end{aligned} \tag{16}$$

2) Dual CAN: For the redundant design of the CAN network, the nodes are connected to each other via two separate bus lines (Fig. 3). The supply lines, the CAN transceiver and the CAN controller (Equ. 14) are designed redundantly while each node has only one microcontroller. Equation 17 shows the calculation of the probability of error-free operation for n nodes in a dual CAN network. The exponent of 2 here presents the number of parallel executions.

$$P_{\text{dual}}(\Delta t) = e^{-\lambda_{\mu\text{C}} \cdot n} \left[1 - \left(1 - e^{-(n \cdot \lambda_{\text{CAN}})\Delta t}\right)^2\right] \tag{17}$$

D. Example of Application: Single and Dual CAN in Vehicles

For a better classification, the reliability of a single and a dual CAN network in a vehicle is considered below. During the service life of a vehicle, an average mileage of 300,000 km is assumed. At an average speed of 50 km/h, the operating time equals to 6000 operating hours:

$$t = \frac{s}{v} = \frac{300000\,\text{km}}{50\,\text{km/h}} = 6000\,\text{h}$$

Table III: Probability of fault-free operation for single and dual CAN during an operating time of 6000 h considering the failure rate limits corresponding to ASIL A to D

ASIL Level	Single CAN	Dual CAN	Improvement Factor
A: $\lambda = 10^{-5}$	0.657	0.827	20.56%
B: $\lambda = 10^{-6}$	0.959	0.987	2.84%
C: $\lambda = 10^{-7}$	0.995	0.998	0.30%
D: $\lambda = 10^{-8}$	0.9995	0.9998	0.03%

Table III shows the reliability for an operating time of 6000 hours for a single and dual CAN network for the ASIL levels A to D.

Using ASIL level A, the dual CAN network leads to the most significant reliability increase of about 20 percent compared to the single CAN network. As the ASIL level increases, the reliability improvement achieved by the implementation of a second CAN bus decreases. When designing the vehicle communication according to ASIL level A, a dual CAN network is recommended due to the more favorable components compared to the other ASIL levels and the significant reliability gain.

VI. Conclusion and Outlook

The benefit and necessity of a redundant bus system for safety-critical applications was demonstrated and confirmed on a typical system architecture. For this purpose, formulas for calculating the reliability and the MTTF for serial and parallel arrangement of components with different, independent failure rates were provided. The probability of a fully functioning communication in a single and a dual CAN network was calculated and analyzed using the failure rate limits corresponding to ASIL levels A to D. The redundant design of the dual CAN network shows a significant improvement in reliability especially over longer operating periods and at lower ASIL levels. Considering the failure rate limits according to the ASIL A, the dual CAN network showed an improvement of the probability of failure free operation of 28% over an operating period of 10000 h.

The described concepts allow to estimate the effect of a redundant design of the communication network, whereby the failure rates of the components have to be specified by the manufacturer and the arrangement (serial, parallel) thereof must be taken into account.

In a next step, the effect of repaired partial buses and message redirection on the reliability of the communication is tested.

Acknowledgment

The authors thank M. Farmbauer for supporting the project with helpful questions and insightful discussions.
This work was supported by Hanns-Seidel-Foundation grant funded by the German Federal Ministry of Education and Research (BMBF).

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