Chapter 8
Next Generation of Semiconductors for Advanced Power Distribution in Automotive Applications

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8.1 Introduction

Power distribution is a quite complex topic in vehicles. One of the major legal requirements is the regulation for reduction of CO_2 given by the European Union. In Fig. 8.1, the development of the average CO_2 of major car makers fleets from 2007 to 2011 is shown.

The CO_2 target for 2015 was 130 g/km, for 2021 this target is decreased to 95 g/km. Please refer to [1]. Exceeding the targets given by European Union leads to a penalties for the car maker. This penalty is up to 95 €/g. Most of the car makers met the 2015 limits, nevertheless the 2021 limit will be much more difficult to attain. All the low hanging fruits (e.g. start/stop functionality) for reduction of emission are already implemented. To achieve lower values significant effort must be spent.

One gram of CO_2 is equivalent to 40 W electrical power dissipation. A similar consideration can be done with mass. Reduction of one gram CO_2 is equivalent to 20 kg mass reduction. Thus any reduction of power dissipation or mass helps to reduce CO_2.

For electrical system major trends can be seen in the market:

- Mechanical components are replaced by electro-mechanical.
  - Examples for this are water pump, oil pump, fan, turbo boost or power steering. The advantage of electro-mechanical components is the possibility of efficient and demand orientated control.

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A. Baschirotto et al. (eds.), *Wideband Continuous-time ΣΔ ADCs, Automotive Electronics, and Power Management*, DOI 10.1007/978-3-319-41670-0_8

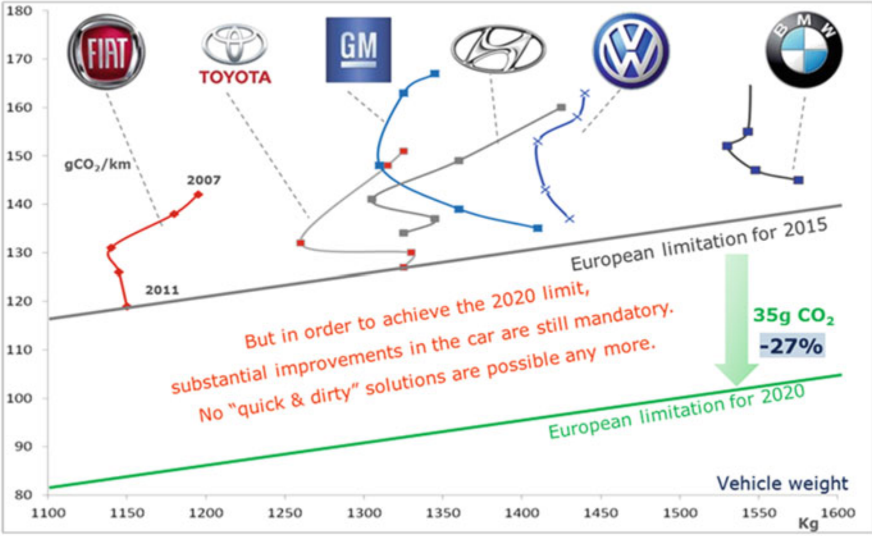


Fig. 8.1 Development of CO_2 emission for major carmakers from 2007 to 2011

- Reduction of electrical idle losses.
  - All operating currents of devices result in power dissipation. Semiconductors have here a clear advantage compared to standard relays.
- High reliability
  - The acceptance of a failure in the car is decreasing from year to year with the clear target: zero defects.
  - Due to increased number of loads and increased load activations high robustness is mandatory.
- Lower system cost

In parallel to the classical 12 V power network several carmakers have introduced the 48 V power net. The driver for this new voltage class is the supply of high power loads, energy recuperation and the use of the starter as motor for torque boosting in hybrid vehicles. Beside 48 V specific challenges the 48 V power network face the same challenges than the 12 V power net.

8.2 Power Network

8.2.1 Classical Centralized Power Network

In Fig. 8.2 a typical 12 V power network is shown. The system contains three fuse boxes.

Usually the pre-fuse box is located directly at the battery terminal thus the line from battery terminal to the pre-fuse box is a non-protected line. A broken pre-fuse is very rare, thus the pre-fuse box need not be accessible by driver or mechanics. The other two fuse boxes are located in the front (e.g. under the hood) and/or in the rear of the vehicle (e.g. trunk). Those two fuse boxes must be accessible by driver and must have the possibility to replace a fuse without going to the garage. Those requirements lead to a centralized power net.

The wiring harness of such a typical power net has approximately a mass of 30 kg, contains 90 fuses and 20 relays. The cable length of all wires is approximately of 2 km.

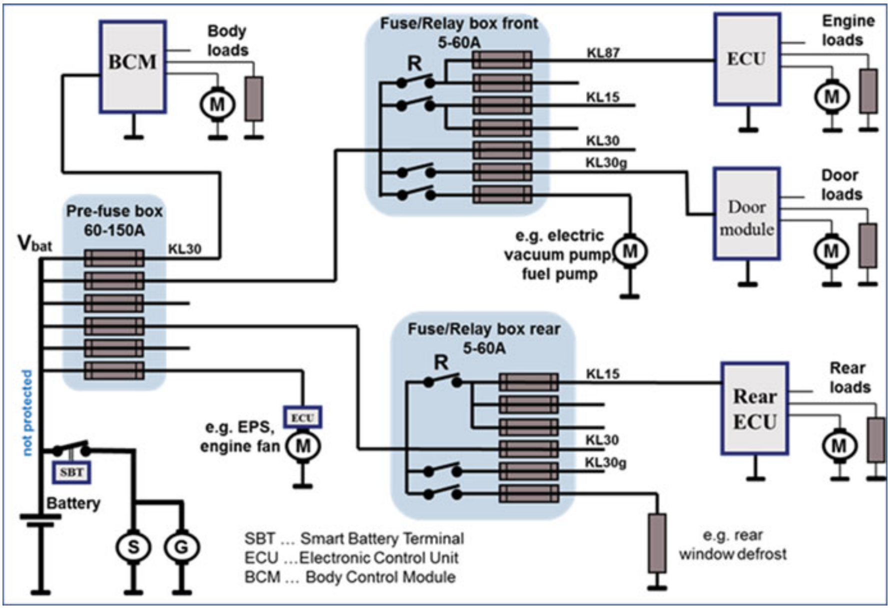


Fig. 8.2 Typical 12 V centralized power network

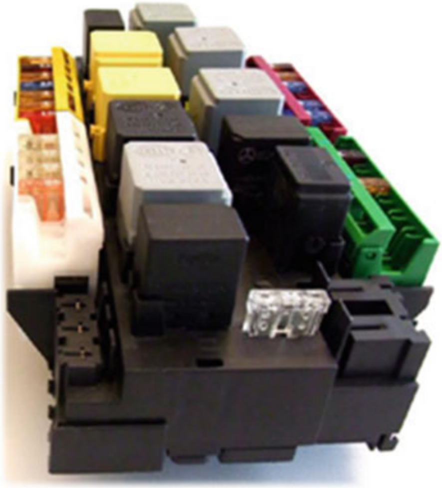


Fig. 8.3 Typical relay and fuse box

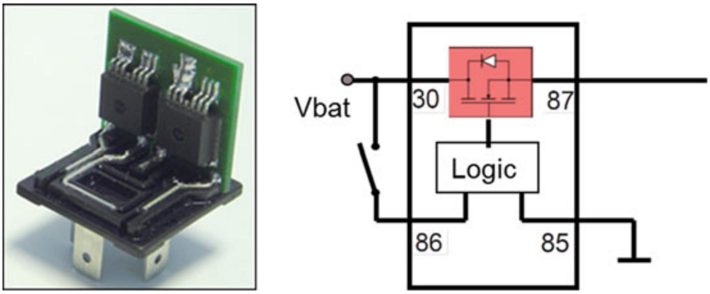


Fig. 8.4 Semiconductor switch inside relay housing

Figure 8.3 shows a typical classical relay and fuse box:

8.2.2 Enhanced Classical Centralized Power Network

Some vehicle functions (e.g. start/stop) require switching cycles larger than 200,000. Today those functions are driven by semiconductor switches since a relay has a limited number of switching cycles and does not fulfill the requirements.

In this system the relay box is a mix of relays, fuses and semiconductors. The change from relays to a semiconductor switch can be done even without having to make a change in the fuse box itself. Figure 8.4 shows the simplest way to replace a relay. This is done by placing semiconductors as a power switch inside the housing of a relay. This type of relay is called **S**olid-**S**tate **R**elay (SSR).

This simple relay replacement enables a high number of switching cycles, high reliability and low idle current consumption. A mechanical relay has power

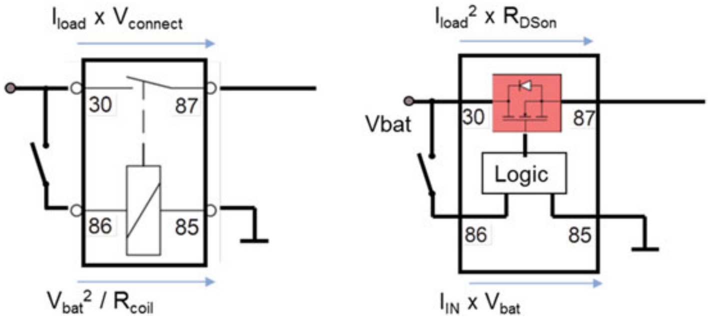


Fig. 8.5 Equivalent circuit diagram of relay and semiconductor switch

dissipation (P_{diss}) of (see Fig. 8.5):

$$P_{diss} = I_{load} * V_{connect} + V_{bat}^2 / R_{coil} \quad (8.1)$$

While I_{load} is the load current, $V_{connect}$ the voltage drop across mechanical switch, V_{bat} the battery voltage and R_{coil} the resistance of the coil driving the relay. For a semiconductor device I_{in} is the operating current of the switch itself and R_{dson} is the on resistance of the power switch.

The semiconductor switch (see Fig. 8.4) has a power consumption of:

$$P_{diss} = I_{load}^2 * R_{dson} + I_{in} x V_{bat} \quad (8.2)$$

A high current relay can have a power dissipation of 5 W typical. A semiconductor switch has below 1 W typical. In the case of replacing five relays in one vehicle this is a power dissipation reduction of five times 4 W = 20 W. 20 W is equivalent to a CO_2 saving of half a gram. Beside the standard relays there also exists a more expensive bi-stable relay where current through the coil is needed only in case of switching transition.

Some applications require reverse blocking. This means no current through the switch in case of reverse battery. Unfortunately the semiconductor power transistor has an intrinsic body diode which is conducting in reverse battery condition. In case of reverse blocking requirement a second power transistor is required to be used in serial connection as shown in Fig. 8.6. The mechanical switch of a relay has inherent reverse battery blocking.

To have the same R_{dson} compared to a single switch the R_{dson} of the two switches in serial have to be reduced by half of the original value. This leads to significant higher semiconductor cost.

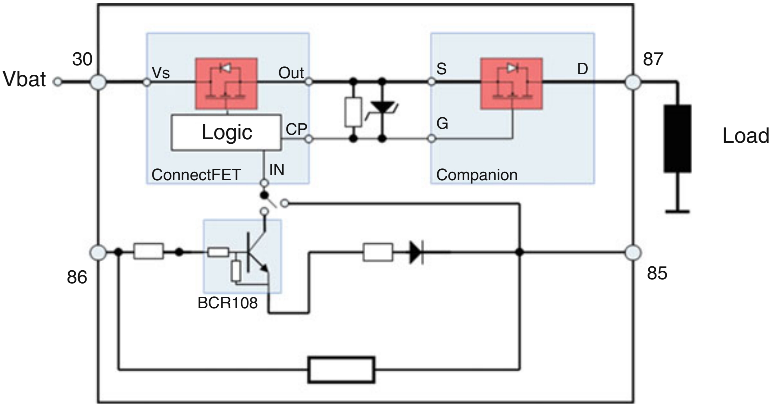


Fig. 8.6 Possible concept for reverse blocking semiconductor switch

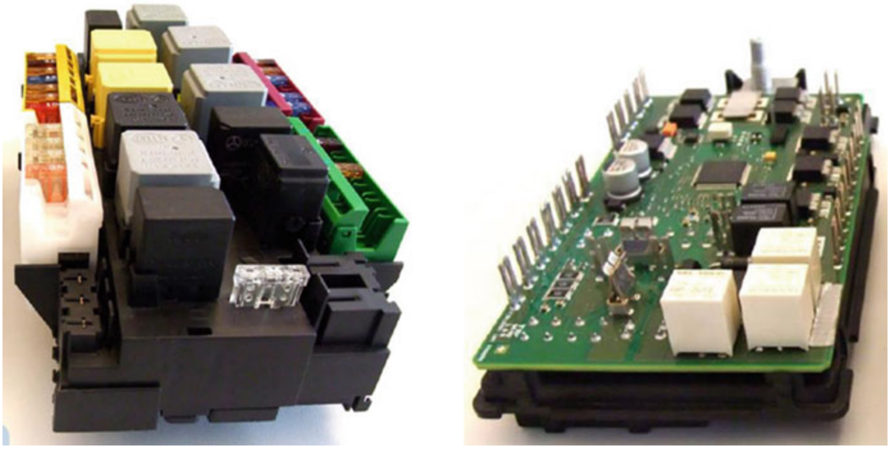
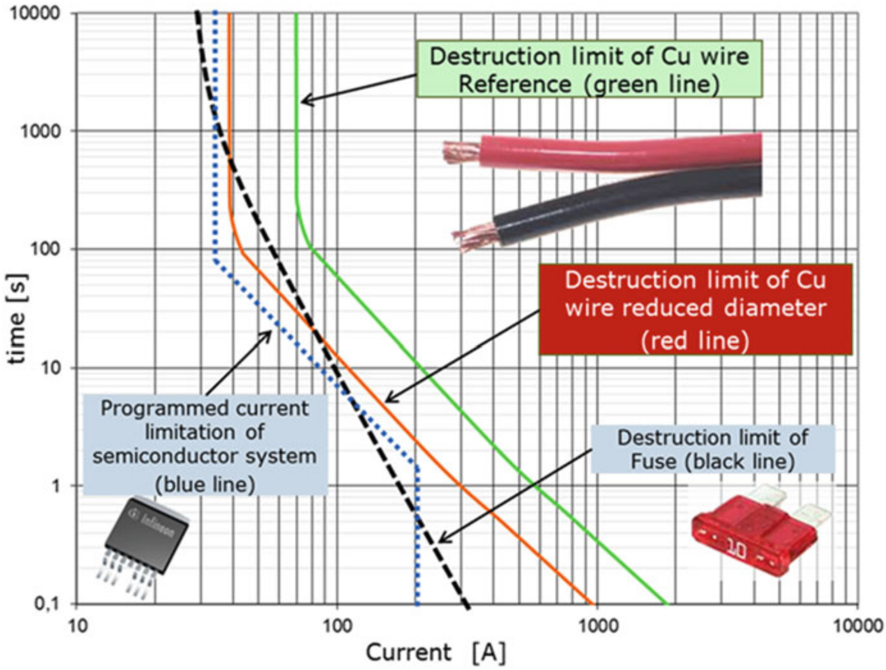


Fig. 8.7 Classical vs. semiconductor based electronic power distributing box with semiconductor relay and fuse function

8.2.3 Semiconductor Based Centralized Power Network

To completely remove accessible fuses from a power distribution box a "semiconductor only system" approach is required. Figure 8.7 shows how a replacement of the fuse box could look like without changing the power network. Please refer to [2].

In addition to not having any accessibility requirements, the advantage of such a system is optimal usage of wires, small volume, enhanced diagnosis, low idle current and high reliability. The weight of this system is reduced by 50 % compared to a classical fuse and relay box. The three relays in this system implement the reverse blocking requirement.



Graph 8.1 Current over time capability of cable, fuse and semiconductor

Let's have a more in-depth look on the optimal usage of wires.

The need of a certain current at the load determines what wire diameter is required and the wire determines what fuse is required. Aging, tolerance and temperature behavior of the fuse must be considered as well. To ensure safe operation the wire with its dedicated diameter must be able to handle more current over time than the fuse. With all the fuse tolerances and a wire more robust than the fuse, the safety margin of the wire compared to the load is usually quite significant.

A semiconductor power switch provides the possibility of a real time current measurement and the wire diameter can be optimized to the load profile. The safety margin of current over time of load versus wire depends on the current measurement accuracy of the semiconductor only.

Graph 8.1 shows the current over time diagram with two different wire diameters.

The black line is the current over time characteristic of the fuse. In this example the reference wire (green line characteristic) is needed to ensure a more robust wire compared to fuse. The use of a reduced wire diameter with the fuse would cause the risk of a damaged cable in case of overload at 40 up to 80 A. In this region the fuse has more current capability than the reduced wire. Using a semiconductor controlled by a microcontroller the overload protection can be programmed slightly below the maximum allowed value of the reduced wire diameter. This is an optimal use of the wire. Please refer to [3]. This saves cost and weight. For reliability reasons the absolute maximum dynamic peak current of semiconductors has to be limited. This has a positive effect to connectors or PCB traces, but also on voltage dips at the power net. On the other hand it has to be considered carefully in case high inrush currents are needed to load capacitors.

8.2.4 Semiconductor Based Decentralized Power Network

To gain even more saving potential there is the possibility to change from a centralized to a completely different decentralized power network (see Fig. 8.8).

This system can be realized as a backbone power network (see Fig. 8.9). In this system there is a main backbonefeed line across the vehicle. The backbone system provides a significant saving of wires.

For locations where power is needed there are small subsystems connected to the feed line with a low number of switches which supply the loads close to point of load. To avoid power losses the switches have to be in the low one digit mΩ area or even below. The subsystem (see Fig. 8.10) has a microcontroller and communication unit (e.g. Lin/CAN) on board.

A further new challenge is the current consumption in the on state. Some of the switches must be in on state even during parking/key off. Here the big challenge is to

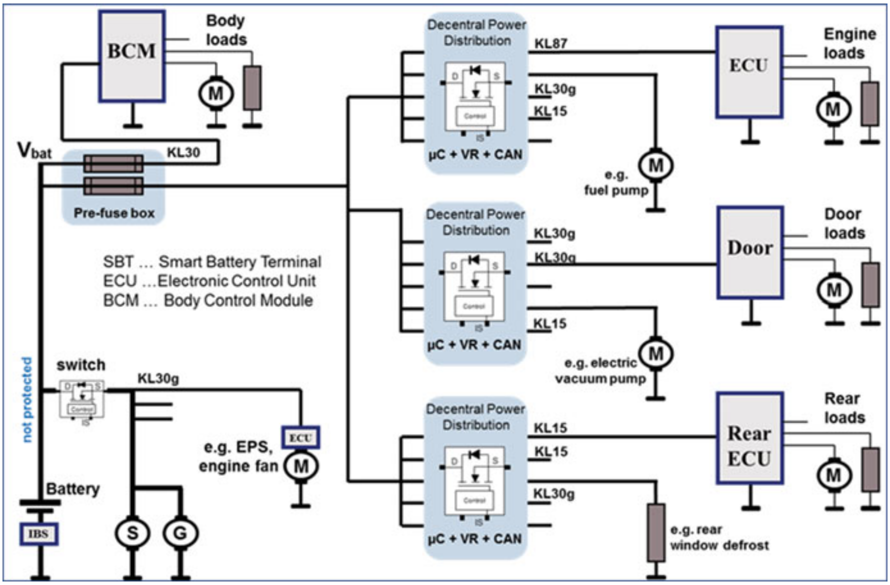


Fig. 8.8 Example of decentralized power network

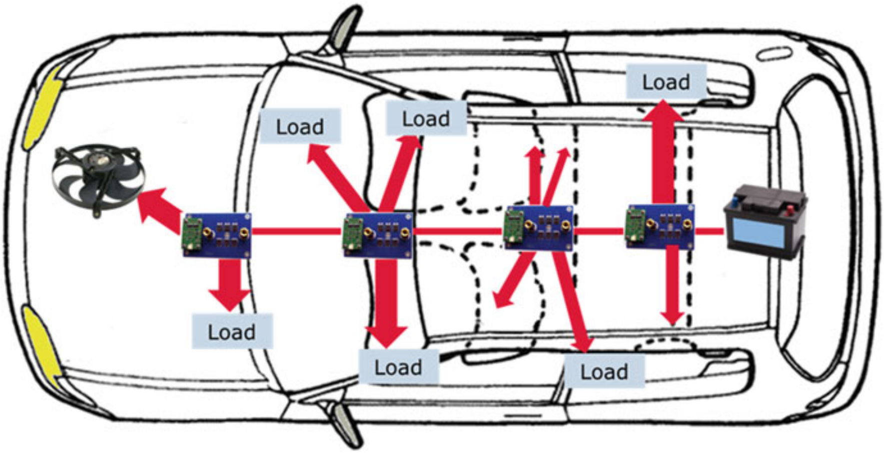


Fig. 8.9 Decentralized backbone system

Fig. 8.10 Example of a subsystem—demonstrator by Infineon

have a very low current consumption. On vehicle level the total current consumption has to be in the mA range. For a single switch this means a current consumption of less than 30 μA. To have an optimal use of the system current sensing and wire protection has to be active during key-off as well. In off state such a current consumption is no challenge. Today's products have already a quiescent current significant lower than 1 μA typical in the off state.

At high currents the energy stored in magnetic fields of the wire inductance can be tremendous. In case of emergency switch off caused by a short circuit or overload, during turn off the semiconductor device must be able to dissipate the energy of the wire inductance. Therefore a high energy capability of the power semiconductor for single or repetitive pulses is a significant advantage. An alternative is the use of external freewheeling or suppressor diode which is additional cost to the system.

Infineon provides here the highly integrated PROFET™ switches which incorporates a broad range of smart features like diagnose and protection. The intelligent power high side switches consist of a DMOS power transistor and CMOS logic circuitry for complete built-in protection and diagnosis. They offer protection against e.g. overload, over temperature, short circuit for all kinds of automotive applications. The family provides switches with an ON resistance down to 1 mΩ which is applicable for load currents up to 40 A DC typical.

In case of higher load currents discrete MOSFETs are suitable as switches. To control MOSFETs an external driver IC is needed. One drawback of the discrete solution is the increased board space on printed circuited board. Further the implementation of diagnosis, protection and robustness is more difficult to achieve. Modern MOSFETs are optimized for low on resistance but have low repetitive energy capability in comparison to PROFET™ switches.

In case of reverse blocking requirement one additional switch at input may be required. This switch is needed only once per module.

8.2.5 Comparison of Different Components and Systems

In Tables 8.1 and 8.2 a summary of all properties at component and system level can be found.

Table 8.3 shows the description of rating:

8.3 Conclusions

For carmakers power distribution is "the" hot topic regarding power net architectures. They are forced to adapt their power network to the new requirements.

Semiconductors will be the enabler for this change. Advantages are optimal usage of wires, removal of accessibility requirements, small volume, enhanced diagnosis, low idle currents and high reliability.

Although semiconductors can be more expensive than relays and fuses at the component level, the change on system level will pay off due to savings in wiring harness, weight and power dissipation.

The main challenges for semiconductors are increased power density, precise diagnosis, high reliability, low idle/quiescent currents and acceptable costs.

Table 8.1 Comparison on component level

Component	Cost	Weight	Power losses in ON state	Peak current capability	Reliability	Diagnostic capability	Self-protected	No of switching cycles	Reverse blocking capability
Fuse	++	+	++	++	−	−−	++	++	−−
Mechanical relay	+	o	−−	++	−	−−	−−	−−	++
Mechanical bi-stable relay	o	o	++	++	−	−−	−−	−−	++
Solid state relay	o	++	+	+	++	++	+	++	−−
Solid state relay reverse blocking	−	++	+	+	++	++	+	++	++

Table 8.2 Comparison on system level

Type of power network	Total system cost	System weight	Flexibility in accessibility	Usage of wire	Wiring harness weight	Power losses in ON state	Reliability	Diagnosis capability	No of switching cycles	Reverse blocking capability
Classical centralized mechanical relays + fuses	+	–	––	––	––	––	––	––	––	++
Enhanced classical centr. mechanical and solid state relays + fuses	+	–	––	––	––	–	–	––	–	o
Semiconductor based centr. mechanical and SS relays	+	+	+	++	+	+	++	++	++	o
Semiconductor based decentralized SS relays only	++	++	++	++	++	+	++	++	++	o

Table 8.3 Description of rating

Symbol	++	+	o	−	−−
Rating	Very good	Good	Neutral	Poor	Very poor

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2. Journal ATZ Elektronik issued 3/2013. Architekturstudie zur Leistungsverteilung im KFZ. Dr. Alfons Graf and Dipl.-Ing. Jürgen Kositza Infineon Technologies, Dipl.-Ing. Tobias Raithel Daimler AG
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