Chapter 1

Industrial motivation

With increasing demand on new electronic technologies in passenger cars, the electronic equipment embedded in the vehicle has boomed over the last two decades. Today, innovative power electronics systems are investigated and under current development for the upcoming fuel cells and hybrid vehicles. Responsible for diverse functional and controlling driving applications, the electronic equipment is consequently a vital element of a passenger car.

Before opening a passenger car, the temperature of the seat can be regulated by the control unit of the auxiliary heating system. By driving, the park assistant control unit and the back drive camera help parking out by signalizing the distance with other obstacles. The steering control unit makes the handling easier. The engine control unit regulates its operation; the speed limit control unit regulates the speed of the vehicle according to the vehicle ahead. The headlights and wipers switch on depending on if it is dark or raining outside. The list goes on: most of the functions of a vehicle are regulated by electronic control units. What a potential client is expecting of a Mercedes-Benz passenger car is a high level of security, comfort and styling. Therefore, reliability and performance of the electronic equipment must be ensured wherever it is positioned in the vehicle. To increase the robustness of electronic devices, a new method has been reported in [1] based on a more integrative development process between engineering and testing. At Daimler AG, the reliability of the electronic equipment is evaluated during two development phases: a first one involving numerical simulations and a second testing phase. The role of the simulation in the development process is presented in the following.

1.1. Digital development process

During the development process of a passenger car, the integration of the electronic equipment in the vehicle results from the intervention of different departments. The functional group checks that the integration of an electronic component meets the requirements towards packaging, performance, architecture in the whole vehicle, buildability and production. In the department Energy Management of Daimler AG, the energy sources and power systems of the whole vehicle are analyzed regarding consumption and emission reduction for several operating conditions. Moreover, the temperature of critical components of the vehicle is examined within a thermal management process. On that score, the thermal management process contributes to the integration of the electronic equipment in the vehicle towards performance and packaging.

During the last 30 years, the development of a passenger car relied mainly on experiments with physical prototypes, while simulations were only required to support measurements. In order to increase the speed and grade of maturity of the development process of a vehicle, digital methods involving numerical simulations are employed today already in the early stages of the development process [2]. The development process is structured in different phases, which follow a determined process control quality plan, as shown in figure 1.1.

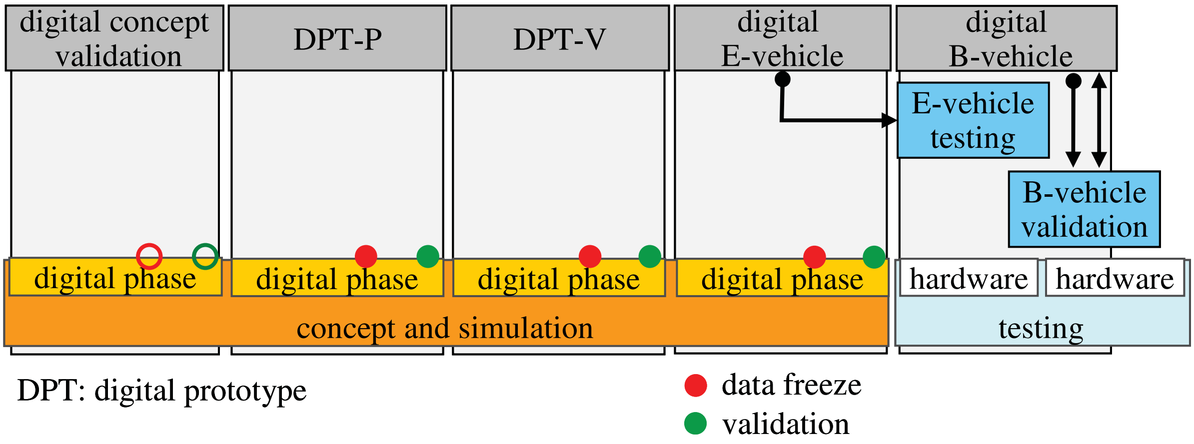

Figure 1.1. Digital prototype phases in the development process.

The development process of a passenger car is composed of a first development phase with digital prototypes (DPT) and a second one with real hardware prototypes. Each function of the vehicle – e.g. crash, pedestrian protection, NVH, stiffness and fatigue strength, ride and handling, underbody dynamic, aerodynamics, energy and thermal management, EMC, refrigerant and cooling cycles – is evaluated successively at each phase of the digital development process yielding to optimization cycles. Therefore, possible development conflicts can be detected in the early stages of the development process. Moreover, a common digital prototype is used by each numerical discipline, increasing the development efficiency. With successive evaluations of the vehicle functions, the digital prototype can reach a high degree of maturity before the first hardware prototype is developed. The DPT process begins with a first concept phase, during which new concepts are analyzed numerically based on the previous vehicle class. Together with the project manager, the simulation can help to define the advantages and drawbacks of a new concept. In the second stage DPT-P, the concepts decided at the previous phase are evaluated in the new digital target prototype. First recommendations for optimization are made during this stage. In the third phase DPT-V, the digital prototype is evaluated considering the serial production maturity and provides a first description of the specifications. Each function of the digital prototype is numerically inspected a last time before the development of the first hardware prototype. If necessary, final corrections of the interior and exterior can be done before the fabrication of the assembly tools. With the following digital E-vehicle phase, the testing departments are now carrying the responsibility in the development process and the simulation intervene for layouts of a vehicle or specific problems. Within this stage, the hardware vehicles are extensively tested and finishing can be provided if necessary. Finally, each property of the definitive hardware prototype is examined a last time; then, the prototype is released for serial production.

1.2. Electronic equipment in a passenger car, heat transfer mechanisms

For multiple reasons such as the architecture of electronics, cabin styling and assembly facilities for serial production, the electronic equipment is often located in small enclosures of the vehicle (figure 1.2). There, the electronic device tends to warm up over the time until its temperature operating range, which can lead to a drop in its performance, reliability or life expectancy. Depending on the position of the electronic device in the vehicle, its temperature can be affected by convection, conduction and radiation.

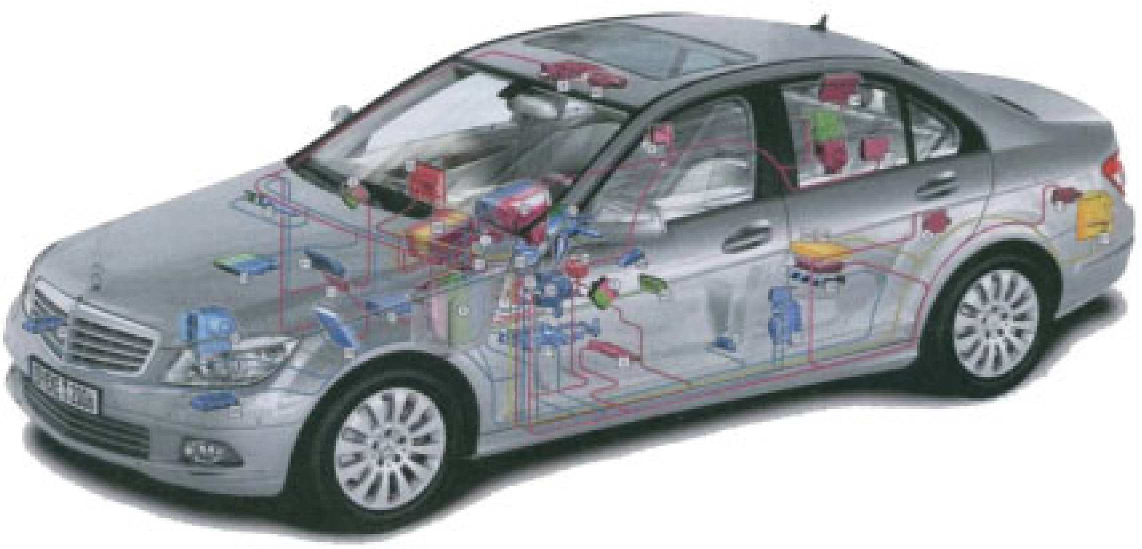

Figure 1.2. Packaging of the electronic equipment in the current Mercedes-Benz C-Class.

1.2.1. Heat sources

Two main heat sources in a passenger car are to consider affecting the electronics temperature:

- The underhood by driving, which may affect the temperature of the whole body shell by conduction;
- Local heat sources generated by the operation of electronic devices.

1.2.2. Heat transport by convection

To cool some electronic devices like the sound amplifier or the TV-tuner, an internal axial fan switches on at a fixed ambient temperature. In such cases, heat transport may rely on a forced convective flow induced by a pressure gradient. Some enclosures like under the trunk are completely sealed, so that without electronics fan running the heat transport results from the slight differences of air density conjugated with buoyancy forces, i.e. pure natural convection. Because of the complex inner geometry of the vehicle, some enclosures are connected to each other or to the cabin by small openings or leakages. For particular operating conditions, these leakages may let stream a certain air flow rate inside and outside the vehicle. For example, in the aggregate compartment containing the battery next to the engine compartment, leakages can be found at the contact between the engine hood and both fenders and under the battery for the evacuation of rain water. By driving the vehicle, a complex pressure distribution appears under the engine hood creating a significant flow rate through the leakage. Moreover, leakages are found in the rear-end compartments to the trunk and to the outside through the underbody of the rear bumper. Experiments by idle of the vehicle were carried out in a climatic chamber to determine the effect of the setting of the sliding roofs and air conditioning on the flow rate in the rear-end compartments. With roof and windows closed and air conditioning activated with maximum mass flow rate, overpressure in the cabin creates a slight air flow in the rear end compartment outgoing in the underbody with a volume flow rate of 3×10^{-4} m³/s. With a leakage in the cabin, i.e. roof slightly opened, the rear end compartment is streamed with a volume flow rate of 1.2×10^{-4} m³/s if the air conditioning delivers a maximum flow rate sufficient to provide an overpressure in the cabin.

In such complex systems, both convective sources, the buoyancy-driven flow and the pressure gradient of the mean flow, have to be considered. The resulting heat transport may result from a mixed convective flow. For each kind of convection (natural, forced or mixed), the convective heat flux from solid to fluid can be defined as follows, whereby h is highly dependent on the flow conditions:

$$\dot{q}_{convection} = h(T_s - T_{ref}) \tag{1.1}$$

1.2.3. Heat transport by conduction

Most of the electronic equipment is mounted on steel or aluminum plates, which are tightly screwed on the body shell (figure 1.3). Both are highly conducting materials, which can easily transport the heat from distant sources.

Figure 1.3. Packaging of the electronics in the right rear-end of the Mercedes-Benz E-Class.

Moreover, the electronic components of systems like the sound amplifier and the TV-tuner are mounted on multi-layers printed wiring boards (PWBs) of isolator substrates FR4 and copper tracks, which permit conduction. In an electronic component, heat is generated at the junction, where conduction lies in the sub-micron regime. For other macroscopic regime conduction, the Fourier law can be used to describe the conductive heat transfer:

$$\vec{\dot{q}}_{conduction} = -k\,\overrightarrow{grad}(T_s) \tag{1.2}$$

1.2.4. Heat transport by radiation

Between different surfaces of a passenger car, the transmitted radiation can be indirect. Therefore, the heat transfer is based on surface exchange between the electronic components and the case of the electronic device, also between the case and the body shell or other compartment surfaces. For each surface, the incident, absorbed, emitted and reflected heat fluxes must be taken into account in the balance. With F_{ji} the view factor from the surface j to i, the fraction of the heat flux emitted by all surfaces j incident on surface i is given by:

$$\dot{q}_{ji} = \sum_{j} \dot{q}_j F_{ji} = \sum_{j} (\varepsilon_j \sigma T_j^4 + \rho_j \dot{q}_{ij}) F_{ji} \tag{1.3}$$

The net radiant heat flux at the surface i (absorbed heat rate) can be written as the difference between the incoming (incident) and leaving (reflecting and emitting) heat fluxes:

$$\dot{q}_{radiation} = \dot{q}_{ji} - \rho_i \dot{q}_{ji} - \varepsilon_i \sigma T_i^4 \tag{1.4}$$

Using equation 1.5 for grey and opaque surfaces with ε and ρ respectively the surface emissivity and reflectivity, the net radiant heat flux is finally provided by:

$$\varepsilon_i + \rho_i = 1 \tag{1.5}$$

$$\dot{q}_{radiation} = \varepsilon_i \dot{q}_{ji} - \varepsilon_i \sigma T_i^4 \tag{1.6}$$

Accordingly, heat transport by radiation may be considered in case of high temperature on surfaces of relatively high areas. Typical examples of radiation surfaces in a passenger car are the exhaust gas system and the engine compartment. Moreover, solar radiation on the car body may affect significantly the temperature of the electronic equipment for particular cases, as the aggregate and rear-end compartments.

1.3. Use cases for the electronics temperature

Use cases are defined to evaluate the electronics performance during both digital and hardware phases of the development process. Based on the specifications, it is checked that the electronic equipment runs within its optimal temperature range during a certain operating time. Depending on the location of the electronic device in the vehicle, its temperature may be more or less affected by one or another heat transfer mode (convection, conduction and radiation) and different operating conditions may have an effect on its temperature. Use cases are consequently defined by the following operating conditions:

- Driving mode and setting of air conditioner, windows and sliding roof;
- Operating mode of the electronic equipment and electrical load situation;
- Climatic conditions (weather, environment temperature).

Most of the electronic equipment embedded in a passenger car is damageable at high operating temperature range. But, in case of a common lead-acid battery, its efficiency at lower operating temperature range must also be verified. Consequently, two use cases with critical climatic conditions are chosen to test the devices in their high or low critical range. The running mode of the electronic equipment is defined by standards in case of most electronic components. Moreover, use cases must be representative of a "mean" driver and correspond to realistic driving conditions.

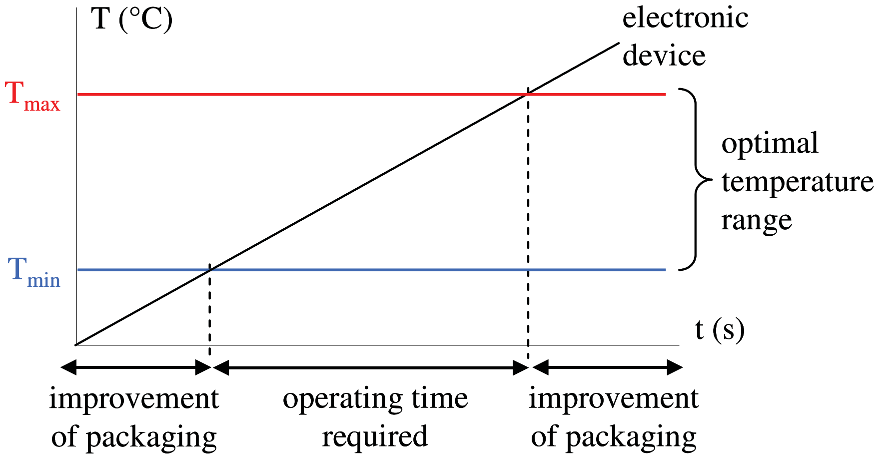

Figure 1.4. Use cases of winter and summer used for the thermal management of electronics; the dependence of the device's temperature with time is arbitrarily constant.

One use case, typically a case of winter, states an extreme low environment temperature to test the warm-up of the battery at low temperature range. Moreover, due to the extreme warm-up of the running air conditioner at low environment temperatures, the electronic equipment in the cockpit is also tested with the use case of winter. With this use case, the time necessary for the electronic equipment to reach its lower operating temperature range can be determined, as shown in figure 1.4. Correspondingly, the arrangement of the device can be revised to reduce this time period and improve the efficiency of the electronic device at low temperatures. The second use case, a case of summer, is used to check most of the electronic devices at high temperature range. Of particular interest in the development process is the time period of operation until overheating (figure 1.4). If this time period is shorter than the required operating time stipulated by the specifications, additional packaging or another construction of the device in the vehicle must be decided to increase the operating time.

Usual use cases define a period of pre-conditioning of several hours followed by a period of uphill driving with load trailers and finally by idle with engine running. The driving and idle period are highly affecting the solid temperatures of the vehicle with time. Due to their high heat load capacity, the engine compartment and the body shell of the passenger car need a very long time before their temperatures reach a constant value. Therefore, the solid temperatures of the vehicle are transient during the operating time settled by the use case. Moreover, the convective heat transfer is also varying with time, due to the transient solid temperatures and the possible activation of fans. It is consequently important to consider the evolution of the temperature of the electronics under transient operating conditions. More details can be found in [3].