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VEHICULAR DIGITAL COMMUNICATION

Master of Science Thesis

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ABSTRACT

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The vehicles such as cars, trucks and buses were once fairly simple from the electric perspective. The internal combustion engine needed originally very little other electricity than spark to operate. The ever-tightening regulations, especially from emission perspective, have leaded the development to complicated electric systems, most of which currently still operate onboard individual vehicles.

Currently the modern vehicles carry dozens of electronic control units onboard them. These communicate with each other over data bus system, CAN being the most widespread of them, by exchanging digital data packets. Pressing down the accelerator pedal on a modern car triggers an electric data exchange in the system where one of the possible outcomes is the fuel being fed into the engine. This depends on how the software based steering is set up; which are the included conditions that must be fulfilled. Furthermore there is no direct, mechanical link between the pedal and the fuel fed into the engine. These kinds of electric inputs currently come from the driver in the vehicle, but could come also wirelessly from outside.

The onboard digital data communication as above exists already. Something that is emerging as we speak at the end of 2017 is the inter-vehicular communication. This brings in the discussion the wireless technologies such as future 5G mobile networks and Dedicated Short Range Communication (DSRC). In the future the data will no longer be relayed only onboard an individual vehicle, but also between vehicles and infrastructure. The umbrella term for this communication is Vehicle-to-everything (V2X). These technologies enable number of applications such as autonomous driving, platooning and automatic emergency braking, only to name a few.

In this study, we review the state of the art in the field of connected vehicles. We also create and test a software function for climate control system of a bus thus providing a practical example of how we can control a real life phenomenon such as air temperature with SW steering.

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Autot, bussit ja kuorma-autot olivat alunperin verrattain yksinkertaisia kulkuneuvoja sähköjärjestelmiensä puolesta. Polttonestekäyttöiset moottorit tarvitsivat käydäkseen lähinnä vain sytytysjärjestelmän. Alati kiristyvät säädökset varsinkin päästöjen osalta ovat johtaneet kehityksen monimutkaisiin ajoneuvokohtaisiin ohjausjärjestelmiin.

Nykyaikasen ajoneuvon sähköjärjestelmässä on voi olla jopa kymmeniä ohjausyksiköitä, jotka kommunikoivat digitaalisesti keskenään tietoväylän välityksellä, joista laajimmalle levinnyt teknologia on CAN. Kaasupolkimen painaminen laukaisee sähköisen tiedonkulun, jonka yksi mahdollinen lopputulos on polttonesteen syöttö moottoriin. Tämä riippuu siitä, miten ohjelmistopohjainen ohjausjärjestelmä on toteutettu; minkä ehtojen tulee täyttyä, jotta näin kävisi. Lisäksi nykyisessä ajoneuvossa ei ole kiinteä yhteyttä polkimen ja polttonesteen syötön välillä. Tällainen impulssi tulee nykyisissä järjestelmissä kuljettajalta polkimenpainaisuna, mutta teknisesti sen olisi mahdollista tulla myös ajoneuvoen ulkopuolelta langattomana signaalina.

Kuvaillun kaltainen digitaalinen tiedonsiirto on arkipäivää nykyisissä ajoneuvoissa. Tätä kirjoitettaessa, loppuvuodesta 2017, keskusteluun nousevat yhä enemmän myös ajoneuvojen ja infrastruktuurin välinen kommunikointi. Tällöin kyseessä olevat sellaiset tulevaisuuden teknologiat kuin tulevat 5G mobiiliverkot ja Dedicated Short Range Communication (DSRC). Tulevaisuudessa tieto ei liiku pelkästään yksittäisen ajoneuvon sisällä, vaan myös ajoneuvon ja sen ympäristön välillä. Kattokäsite näille teknologioille on Vehicle-to-everything (V2X). Nämä mahdollistavat kuljettajattomat autot, älykkään jonoajamisen sekä automaattiset hätäjarrutukset.

Tässä työssä käydään läpi aihepiiriin liittyvät viimeisimmät teknologiat. Työssä luodaan ja testataan lisäksi ohjelmistofunktion linja-auton ilmastointijärjestelmään. Tämä toimii esimerkkinä siitä, miten ohjelmistopohjaisella ohjausjärjestelmällä pystytään vaikuttamaan reaalimaailman ilmiöön, joka esimerkissä on matkustamon lämpötila.

PREFACE

This piece of work has provided me an opportunity to combine two worlds; my day job and the world of academia. During the days, it has been product development of climate systems of buses and at academia information technology. As odd a couple it might sound at first, the two are very much connected in many ways, and will be even more so within the not-so-distant future. I expect this study to keep itself relevant for at least some more years to come.

The technical content and the form it is presented here would never been the same without particularly two people; Eero Kalevo at Microteam Oy and my supervising professor Sami Hyrynsalmi at the university. Eero opened up his extensive knowledge to my disposal and Sami made sure it got presented according to the best practices that the academia demands. Without much background in scientific writing, I started rather to enjoy it as we went along and the whole of it started to take shape.

The greatest supporters of this endeavor have been my friends and family. Never failing to have faith in me and always being there to nourish me when so needed. Should I separately name someone, it would be my parents-in-law Helena and Jarkko Nurmi. Your support in every possible way has been priceless. Without you this study would virtually not exist here to read now, perhaps never.

I wish to conclude this study and the studies as whole by presenting my sincere thanks for all the people enabling this to be the trip it in the end turned out to be, every single encounter has mattered, you made it unique and for that I am forever grateful.

In Paimio 18 December 2017

Sami Kaurila

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ABBREVIATIONS

5G	Fifth generation wireless network technology
ABS	Anti-locking Brake System
BS	Base Station
CAN bus	Controller Area Network, one of the vehicle bus systems
CVIS	Cooperative Vehicle Infrastructure System
DESRIST	Design Science Research in Information Systems and Technology
DO	Digital Output
DSR	Design Science Research
DSRC	Dedicated Short Range Communication
ECU	Electric Control Unit, Engine Control Unit
eMBB	Enchanced Mobile Broadband
EMI	Electromagnetic Interference
EU	European Union
GPS	Global Positioning System
GSM	Global System for Mobile Communications
HAP	Harmonization Action Plan
HWG	Standards Harmonization Working Group
ITS	Intelligent Transportation Systems
ITU	International Telecommunications Union
LTE	Long Term Evolution
MIT	Massachusetts Institute of Technology
MS	Mobile Station
NRZ	Non-return-to-zero signal pattern
NTC	Negative Temperature Coefficient
OBD	Onboard Diagnostics
OBU	On-board Unit
PWM	Pulse-width modulation
RSE	Roadside Equipment
RSU	Roadside Unit
USDOT	United States Department of Transportation
UTP	Unshielded Twisted Pair Cable
V2X	Vehicle to everything
V2I	Vehicle to infrastructure
V2V	Vehicle to vehicle
V2N	Vehicle to network
V2P	Vehicle to pedestrian

ΔT	Delta Temperature, temperature difference
Mbps	Megabits per second
ms	millisecond

1. INTRODUCTION

The vehicles on the roads are becoming more and more digitalized. Long gone are the days when cars, buses and trucks were purely analogically operated. For decades the combustion engines did run on mechanical carburetors and on hardwired electric systems that were fairly simple. This same functional simplicity was also the case with the other sub-systems such as gearboxes and brakes.

The first steps into vehicular digitalization were electric control units (ECU) for the different on-board systems. An ECU is a mini computer that gets inputs and provides outputs. Between the input and output there is an algorithm that processes the information. A good and one of the earliest examples of a typical application are the ABS brakes. An ABS ECU receives input of the rotational velocity of a wheel. The output restricts the brake force when the wheels are about to stop spinning.

In the first electrically steered systems there were separate ECUs for each sub-system such as fuel injection, driveline and ABS brakes. Currently a modern combustion engine can have dozens of ECUs controlling different parts of the engine operation alone. The development from a very limited number of separate, individually controlled systems has led to complicated electric architectures of interconnected systems onboard a single vehicle.

For the past decade, the automotive industry has experienced perhaps the biggest disruption since its initial birth in early 20th century. The electric vehicles are about to turn from expensive niche products to the industry standard of the future. This concerns cars and heavy traffic alike. There are governmental regulations with announced target dates from when all the new cars must be emission free in the given country. Many cities and countries in Europe are planning to ban petrol and diesel cars by 2040 [1,2], some of the first ones being Norway and Netherlands the aim on the year 2025 [3].

Most of the major car manufacturers have electric car development projects ongoing and dozens of electric models are expected to be available within next few years [4]. Cities are declaring zero emission zones in the city centers [2] and bus manufacturers are developing, or already delivering, hybrid or even all-electric buses.

At the same time when the drivelines get electrified, the driverless technologies start to emerge. These systems rely on sensor inputs and a real time, onboard processing of the data. The cars must know where they are positioned both, in relations to other vehicles and also in geographical location. All the processing of data is software based. The amount of binary data created and processed by traffic will most likely increase. There are industry sources who have estimated that children born these days (2016) will never drive cars themselves [5]. Accurate or not, that anyhow indicates the rapidity of the development experienced in this field as well.

Another recent and closely related development is wireless internet which has become commonplace during the past years. At first mobile internet and cars might seem to be an odd couple. However, these two are very tightly connected. Essentially autonomous driving and connected cars will not exist without reliable and effective mobile data transfer [6,7]. In the very same way as most of the major car manufacturers are having electric vehicle development projects ongoing, they are involved in the development of next generation 5G networks [8].

The development from individual digital systems onboard of individual vehicles is going towards inter-vehicular, wireless network where vehicles send outputs and receive inputs and thus adjust their interaction with each other, and also with infrastructure and pedestrians.

The objective of this study is twofold. Firstly, we review the state of the art: what are the architectural building blocks of the digital communication systems of the modern cars. Secondly, we create a new software function for one of these systems to provide a practical example of a digital communication onboard a vehicle.

The remaining of the thesis is structured as follows. Chapter 2 discuss the used research framework, namely *Design Science*. Chapter 3 goes through the related work done in this field and Chapter 4 presents the artifact that is developed for the research of this thesis. It is followed by the evaluation of the artifact in Chapter 5. Finally, the last chapter summarizes the study.

2. DESIGN SCIENCE

In this chapter, we review the design science research approach. The background of the methodology is presented together with the essential research concepts.

2.1. Background of Design Science

The methodology of this study is Design Science. The concept of Design Science was first introduced by R. Buckminster Fuller in 1957. Fuller defined Design Science to be a systematic way of designing [9]. The term was again used by Sydney A. Gregory in 1966 when he defined the difference between scientific method and Design Science. In Gregory's view, design is not a science, but instead Design Science refers to scientific study of design. These terms were further used and popularized by Herbert Simon in 1968 in his Karl Taylor Compton lectures a Massachusetts Institute of Technology (MIT) [10].

Based on his research and these lectures, Simon went on to release a book, *The Sciences of the Artificial* in 1969. The book has since been followed by second and third editions in 1981 and in 1996. Nevertheless, the design science research (DSR) relies still on the fundaments presented on the original publications. Some of the most prominent modern day figures in this area are Professor Alan R. Hevner from the University of South Florida and Professor Samir Chatterjee from the Claremont Graduate University in California. Hevner notes that a lot of his research is based on the work of Herbert Simon [11]. Hevner and Chatterjee have frequently worked together. They have also founded Design Science Research in Information Systems and Technology (DESRIST) conference in 2006, which has since become a discussion forum and a presentation platform for all leading design information system researchers [12].

2.2. The Concept

In the essence of the design science are artifacts. They are made-up objects to serve a human purpose [10]. In our case these artifacts are software and hardware solutions in the field of vehicular electric architecture. Simon defined artifact as below:

"Whereas natural sciences and social sciences try to understand reality, design science attempts to create things that serve human purposes. It is technology-oriented. Its products are assessed against criteria of value or utility – does it work? Is it improvement? Building an artefact demonstrates feasibility. We build constructs, models, methods and instantiations. [10]"

Simon spelled the word *'artefact'*, while Hevner uses *'artifact'*, as will we.

An artifact is an object or a system that has number of inputs and outputs. In design science research it is important to understand what an artifact does and what are the principles of the function. This abstractive depth is enough for also this study.

Let us make a simple example of an electronic control unit (ECU). Very much like any other design science artifact, an ECU contains inputs and outputs. The values of the inputs are computed in the ECU and the values of the outputs are results of this. It is useful for us to understand the principle of the function; which the inputs are and perhaps how the output values are calculated. For one to understand this, we do not need to go into the molecular level of electronics. For functional purposes this would be a too deep abstractive level and thereby not purposeful. This above is an example of a physical design object, but the same analogy concerns also processes and the other abstractive artifacts.

2.3 Design Science Cycle

The development of artifacts is iterative in nature and carried out in cycles. Figure 1 presents the process as proposed by Hevner and Chatterjee [12]. In the core of this process is to build artifacts and processes. They are designed and evaluated firstly as objects of design. We must have an artifact to work on. For an artifact to interact with the surrounding reality there are two cycles: *a relevance cycle* and *a rigor cycle*.

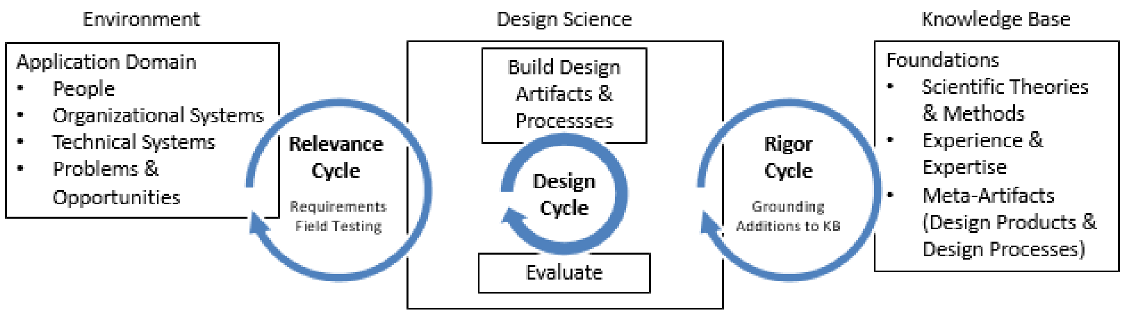

Figure 1. *Design Science Cycles.*

2.3.1. Relevance Cycle

The purpose of the relevance cycle is to assess the artifacts against the requirements; how well does the artifact meet the need(s) it is supposed to fulfill [12]. These needs are the very reason it exists in the first place. As shown in Figure 1, this circle tests the artifact in its target environment. The counterparts in the operation are such as people and different technical and organizational systems. As artifacts are artificial in nature, they can be modified to meet, not only the existing needs, but also the possible future opportunities. In this cycle the artifact is put to test in real environment and the possible problems will get identified. Multiple artifacts can be tested with same assessment criteria. The field test can apply standardized test methods. The users may fill in a standard questionnaire. These are some of the ways to make the testing repeatable and comparable. The ultimate question is how well the artifact fulfills the need it is supposed to serve.

2.3.2. Rigor Cycle

Rigor cycle grounds the findings with the existing knowledge. Rigor cycle is there to utilize, and to complement the knowledge base. The knowledge base contains the scientific studies and knowledge that is already gained. This is the connection between design science and the natural sciences [12]. A product of design science can work without us fully understanding why. The reasons behind are to be found via the rigor cycle and from the scientific study. Mankind had built seaworthy, floating vessels over 800 000 years before Archimedes came with his principle and the concept of buoyant force, i.e. the scientific explanation behind the phenomenon [13,14]. The popularity of social media is perhaps another well-descriptive example of this. There the ideas and products are taken directly to the market pass the academic study [11].

2.3.3. Criticism on Design Science

There are views in the community that perceive Design Science more as a form of consulting, rather than a real, serious science [15]. Some of the criticism can be accepted. There is certainly an element of trial and error involved in the whole of it. Simon originally defined Design Science as scientific study of design, not as science as such. To further understand this, it is useful to clearly distinguish the relevance and rigor cycles from each other.

The rigorous, “hard” scientific information is there in the rigor cycle. These results and scientific theories are well-grounded, peer-reviewed and generally accepted. These should only be questioned in case of some new, opposite evidence that proposes them wrong.

The relevance cycle is more on the progressive side. It is there to test the new artifacts and ideas. In this cycle, some of the artifacts prove themselves wrong instantly, some of them live a bit longer, and some will eventually be accepted as new additions to the knowledge base. In the latter cases, the mentioned trial and error eventually creates new science.

3. STATE OF THE ART

In this chapter, we review the different systems, standards and technologies that relate to the modern vehicular architecture.

3.1 Intelligent Transportation System

Intelligent transportation systems, often referred as ITS, are advanced applications, that aim to provide innovative services relating to different modes of transport [16]. Transport here means the physical transportation of people and goods. ITS consists of a broad range of wireless and wire line communications -based information and electronic technologies [17]. Especially the recent developments in areas of mobile computing, wireless communication and remote sensing are major contributors in development of ITS. The vehicles already are sophisticated computing systems with their various on-board sensors and computers. The new elements are the wireless communication, computing and sensing properties. Interconnected vehicles not only collect info of themselves and the surroundings, but also exchange information with the other vehicles [18].

3.3.1. Standardization of ITS

There are both European [16] and American standards for the ITS. On top of this, there are harmonization activities, which aim to establish common architectures, standards, policies and other critical processes that benefit as being as similar as practical across the regions [17]. The standards define an interrelated architecture of systems, that work together to deliver transportation services. The standardized architecture defines how the system functionally operates and how the interconnections of the information exchanges between the systems takes place and accomplishes these transportation services. An ITS architecture is functionally oriented and not technically-driven. It describes what needs to be done, rather than how it is done. This allows it to be effective over time [19].

In January 2009, the responsible parties at United States Department of Transportation (USDOT) and at the European Commission signed an implementing arrangement to develop coordinated research programs, specifically focusing on cooperative vehicle systems [17]. In November 2009, an agreement called *EU-US Joint Declaration of Intent on Research Cooperation in Cooperative Systems* was signed. The agreement defines the more exact form of cooperation by introducing clear goals [17]:

- Support, wherever possible, global open standards to ensure interoperability of cooperative systems worldwide and to preclude the development and adoption of redundant standards;
- Identify research areas that would benefit from a harmonized approach and that could be addressed by coordinated or joint research; and
- Avoid duplication of research efforts.

The work toward these goals is carried out in several working groups, co-led and staffed by representatives of both USDOT and the EU. One of the most active working groups in this area is called Standards Harmonization Working Group (HWG). HWG provides the basis of the EU-US work in ITS harmonization as defined in Harmonization Action Plan (HAP). There are five tracks of the HAP which are presented below with the current status as of December 2017:

- High-level assessment ("landscape") – ***completed in 2011***
- Agreement on governmental harmonization principles – ***final draft***
- Gap/overlap analysis for standard's needs – ***planning underway***
- Facilitation of harmonization of specific standards – ***ongoing***
- Planning future cooperation – ***ongoing***

As we can see, only the first activity of high-level assessment is completed as of May of 2017. This describes well the phase of development also on more general level. In this technical area there are more planned activities, than there are completed ones. ITS is still in its infancy with the pilot projects acting as catalyst for the development and growth [18].

3.4. Fifth Generation 5G Mobile networks

The generations of wireless telephony are noted with order number and generation, i.e. by now we have had 0G, 1G, 2G, 3G and 4G networks. The first two generations were radio networks in all their simplicity and since 2G the network has been digital. This has enabled users to submit and receive digital data over the network. The 2G is most often referred to as GSM (Global System for Mobile Communications) and was first introduced in the beginning of the 1990's. Each new generation since the 2G has provided users with improved capacity and speed by number of different techniques.

The latest generation currently in use is 4G, commercially often referred to as LTE (Long Term Evolution). The required peak transfer rates for 4G networks are 1 Gbps for fixed services and 100 Mbps for moving services up to 500 km/h and latency below 5 ms [20]. These being the targeted peak values, the experienced average rates are lower. For the safety critical V2X applications even more is needed, and the coming 5G networks are expected to provide this [8]. Latency plays a key role in the safety critical applications. Per definition latency is the time that data travels from source to destination, hence implying the delay of a given network [21]. Target level for 5G is below 1 milliseconds (ms), whereas for 4G it is the mentioned 5 ms. The target transfer rate for 5G is 100 Mbps downlink in densely populated urban area. The test code for this is called Dense Urban -eMBB (Enhanced Mobile Broadband). The targeted peak value for 5G is 20 Gbps. Furthermore, to secure the reliability of the network, the demanded mobile interruption time is 0 milliseconds, interruption time being the shortest time duration during which no user plane packets can be exchanged [22]. This practically means that the client must have an interruption free connection always.

These demands and standards for the networks are developed by International Telecommunications Union (ITU). ITU is a United Nations agency dedicated for information and communications technologies. ITU currently has 193 member countries and almost 800 private sector entities and academic institutions [23].

The 5G standards are currently still in work and therefore the figures above are not confirmed yet. The main document for 5G performance requirements is called IMT-2020. The name refers to year 2020 when the specifications are planned to start to come out. ITU's timeline for the ongoing work is presented below in Figure 3 [24].

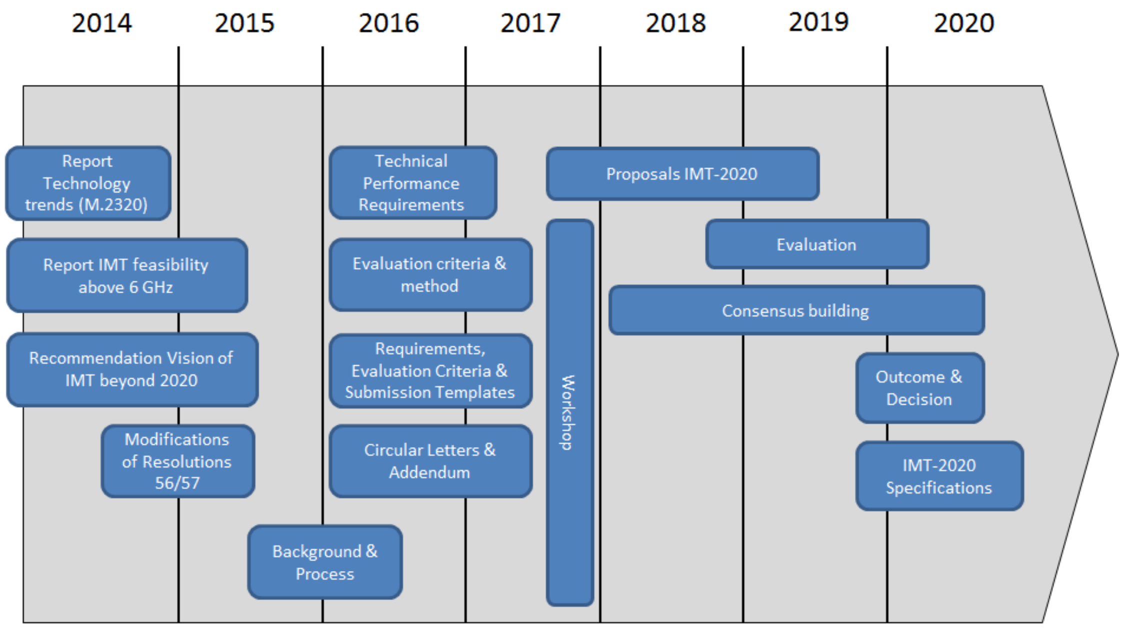

Figure 2. *ITU timeline for 5G implementation.*

By the time this study is being written, in the second half of 2017, the work on the requirements is about to be finished. There is a scheduled meeting in November 2017 with the aim to have a final approval on the drafter requirements [25], i.e. among other things the mentioned transfer rate figures and latency.

3.4. V2X, Vehicle-to-everything

The earlier introduced ITS is the umbrella term for the complete ecosystem of intelligent transport systems. The complete system consists of subsystems. The hierarchy of these subsystems is presented below in Figure 2. V2X, vehicle to everything, is used both in academia and in industry to describe all the systems and means to exchange information between a connected vehicle and its surroundings. In the next chapters, we go through V2X with the three included sub-concepts and the related technologies.

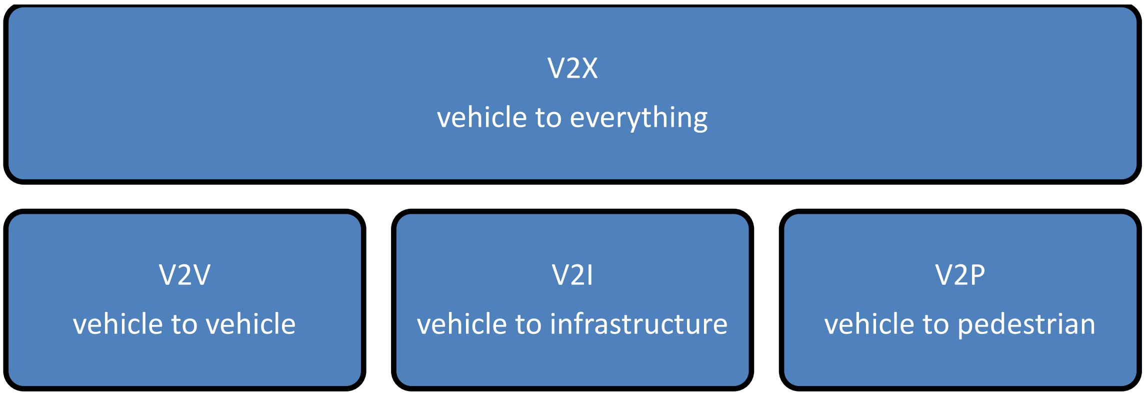

Figure 3. *Terminology, vehicle to everything communication.*

3.3.1. V2V and V2I

The reason to have communication between the vehicles and infrastructure is to enhance the transportation safety and effectivity [26]. Some examples of these applications are collision prevention or platooning. Simply put V2V helps the vehicles to position themselves in their current status in relation to each other and their surroundings, including the geographical location.

Near zero communication latency and packet loss is of utmost importance in V2V [26]. The demand for low latency derives itself from the mobile nature of the vehicles. The higher the speed and bigger the network latency, the greater the travelled distance during the delay. Some of the V2V communications that are less safety critical can be relayed in a network that has higher latency; these would be for instance driver information systems [26].

The used technology in V2V and V2I is called Dedicated Short Range Communications (DSRC), which is based on IEEE 1609 and IEEE 802.11p standards [27, 28]. There are two classes of devices in a DSRC system: Onboard units (OBU) and Roadside units (RSU). RSUs are sometimes also referred to as Roadside Equipment (RSE). In a cellular environment, these would be correspondingly named mobile station (MS) and base station (BS). There are also two types of communications enabled by the OBUs and RSUs: V2V and V2I [28]. Figure 4 below illustrates the interaction between the agents in the system.

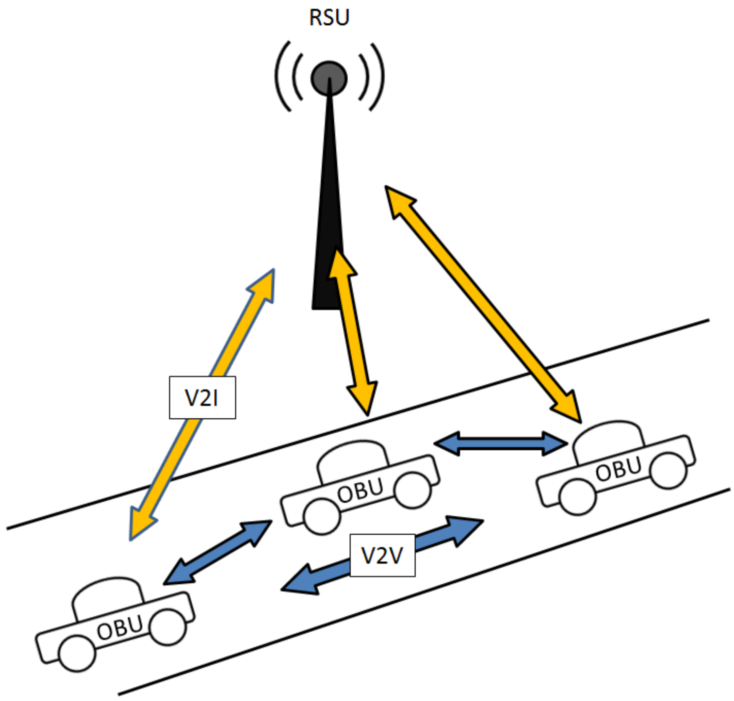

Figure 4. *V2V and V2I communications.*

DSRC system has some significant benefits when compared with the cellular network. Firstly, it allows direct communication between the OBUs. In a cellular network, the connections between mobile stations would go via base stations. This direct connection enables the low latency of the DSRC. The other benefit is that the OBUs are likely to be embedded and connected in the vehicular onboard systems such as controlled area network (CAN) and FlexRay, while MS is usually detached from the CAN [28].

One example of a rapid V2V application is safety enhancing queue driving. When the first car brakes the system enables all the connected vehicles to brake simultaneously. In the non-connected conventional traffic, the safety in these situations relies on brake lights and the following driver's reaction times. In the same vein, the vehicles can accelerate collectively and follow the first vehicle in the queue, a feature that is referred to as *platooning*. This results not only to improved safety, but also transport efficiency due to reduction of typical rubber-band-like consequent accelerating and breaking. Especially the heavy traffic benefits from reduced total aerodynamic load as the first vehicle in the queue paves the road for the rest.

These kind of V2V applications do not fully rely on infrastructure and will therefore work even in more rural areas [18]. On the other hand, the system as whole needs to be very robust, as failure may cause loss of life and property [28]. This means that the

OBU communication must be robust enough also without constant connection to the infrastructure.

There are two ways to approach the V2I communications on the conceptual level. Sometimes V2I is limited to concern only the local DSRC communications between the vehicles and local RSUs. It means another category is needed to cover the communication between the vehicle and the rest of the wireless network. This category is called Vehicle to Network (V2N). In this study, we include the V2N communication in V2I. By this, we follow the direction set by the United States Department of Transportation [29]. From the technical point-of-view, it makes no difference; the things are only categorized in another way. It is still useful to acknowledge what V2N is as it is sometimes used in this field.

The RSUs are local as explained above. They communicate with the vehicles over DSRC connection. The typical application can be for instance toll collection or approaching traffic light intersection. The RSUs can be connected to internet and work as the link that provides internet access and information also for the vehicle.

The vehicles can also gain direct network access passing the RSUs and instead applying a mobile network connection. This connection is no longer dependant on the distance between vehicles and RSUs, rather than on the cellular network coverage.

3.3.2. V2P

V2P covers not only pedestrians, but also other nonvehicle occupants such as bicyclists. It needs to consider various means of nonvehicle transportation and situations such as people walking, children being pushed in strollers, people using wheelchairs or other mobility devices, passengers embarking and disembarking buses and trains, and people riding bikes [30].

The V2P systems can be implemented in vehicles, in the infrastructure or with the pedestrians themselves to provide warnings [30]. The vehicle mounted systems consist of different kinds of sensing technologies such as radars and cameras to map the immediate surroundings. These are connected to the V2X via CAN bus or similar bus system.

The infrastructure mounted units can be for instance fixed sensing technologies at the intersections. These would sense when there are pedestrians crossing the road, and can warn the drivers, or even automatically brake the vehicle and prevent any collision. The path of information goes from infrastructure sensor to the vehicle via DSRC and the on-board communication is treated again via CAN bus. This system is safety related and needs to be very robust and secure. One may imagine a relatively small system failure, in which the radar senses an approaching pedestrian correctly, but the on-board system triggers acceleration controller instead of braking.

The solutions where pedestrians provide the warnings themselves consists of different types of applications they may carry with them. Any technical device that can provide exact enough location information into DSRC can be such a solution.

There are three types of technology categories developed in the V2P research [30]:

- Unilateral Pedestrian Detection and Driver notification. Technologies that provide collision alert only to the driver.
- Unilateral Vehicle Detection and Pedestrian notification. Technologies that provide collision alerts only to the pedestrian.
- Bilateral Detection and Notification Systems. Technologies that provide collision alerts to both drivers and pedestrians in parallel.

Each of these systems can be enhanced by communicating with infrastructure. A pedestrian device that communicates with infrastructure has the possibility to more accurately interpret and predict the pedestrian movement preventively, than a pedestrian device that only communicates with the vehicle within a short range [30].

3.3.3. Cooperative Vehicles Infrastructure -project

A proof-of-concept proposal for V2X was provided by Cooperative Vehicles Infrastructure – project (CVIS). CVIS was co-funded by the European Union and is a functional concept for a V2X system [26]. In the future development and commercialization of the technology the design details may change, but the on-board system architecture of the CVIS includes many essential building blocks of the system and gives a good base level view of how it is set up. Figure 5 visualizes the layout of the system [26].

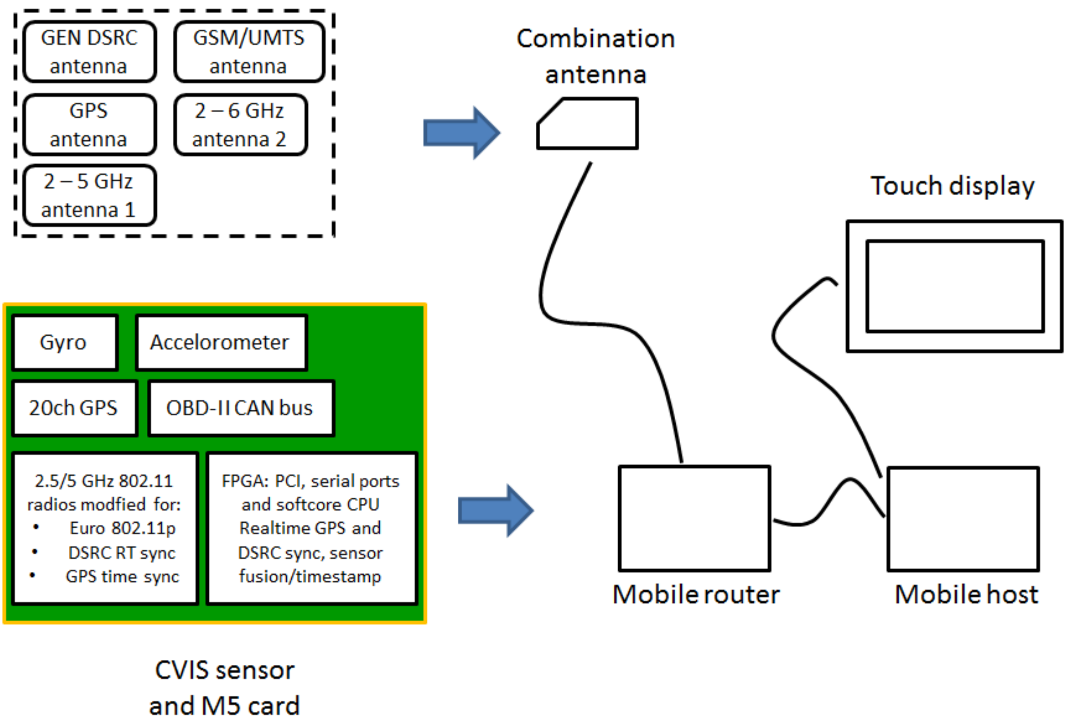

Figure 5. *CVIS on-board architecture.*

The on-board components are located on an individual vehicle and enable V2V and V2I communications. The touch display works as the input and output interface for the people traveling in the vehicle. The mobile router and mobile host are two computers. Mobile host is doing the computing for the vehicle communication applications as well as for the user interface [26].

Mobile router integrates a special-purpose card that includes sensors and resolves time-critical tasks on the hardware level. Such tasks may include for instance real-time acquisition of location [26] or the DSRC computing for V2V safety related applications.

The antenna contains the needed receivers and transmitters for dialogue with DSRC, cellular and GPS systems. Gyroscope and the accelerometer are used to sense the changes in the vehicles linear and angular acceleration.

The CAN bus interface is present as there are various sensors and controllers present on-board of a vehicle and CAN is the gateway to include them in the V2X system. Typically, these sensors may include velocity, direction, temperature, airbag status, rear and front cameras and parking assistance radars [26].

3.4. CAN bus

CAN bus is one of the vehicle bus protocols and standards. A vehicle bus is an electronic architectural solution that interconnects the electronic components on-board a vehicle. Instead of having dedicated wires running between all the different electronic control units, the information is multiplexed into digital packets. The packets for different vehicular functions are transferred over the same physical wiring. This reduces the amount of needed copper wiring, which means improved hardware simplicity and less cost and weight [31]. Furthermore, the system becomes digitally steered, which means improved accuracy in operation, which is performed by computers.

3.3.1. Background

CAN was originally developed in the beginning from 1983 by Robert Bosch GmbH in Germany and approved in 1986 by SAE Congress in Detroit [32]. SAE stands for Society for Automotive Engineers, a professional association and standards developing organization for engineering professionals [33]. The physical and data link layers are specified in ISO 11898 standard [31,34]. It has since been applied in number of vehicular applications globally. The patents for CAN protocol are owned by Robert Bosch GmbH, and license fees apply for the external suppliers who wish to manufacture compatible components [35].

As mentioned, CAN is only one of the vehicular bus standards. It is the most widespread automotive bus standard globally [31,32,36] and was applied also in the CVIS project [26]. There are also other similar bus systems available such as FlexRay which was mentioned earlier.

From legal point of view, all new vehicles were required to be equipped with an OBD-II (On-board Diagnostic II) -interface since beginning of 1996 in U.S. [37]. Europe followed in 2001 for petrol vehicles and in 2004 for diesel vehicles with EOBD (European OBD) which is the European name for OBD-II [38]. The main driver to make OBD a mandatory feature was the possibility to control the ever-tightening emission restrictions. OBD can be accessed with a diagnostic tool to view correct function of the electronic system and the components. OBD-II can even autonomously monitor and adjust the vehicle emission performance to keep the vehicle “clean” over the lifetime [39].

OBD II is standardized to run on five different signal protocols, out of which CAN is one. This makes vehicle bus as electronic architecture even an indirect legal requirement.

3.3.2. Transfer rate

The main characteristic of CAN bus system is that it does not require a separate master computer. Instead, the system consists of interconnected nodes. The nodes are connected by a twisted pair cable that can be either shielded on un-shielded. The maximum data transfer rate in the system depends on the length of the bus, i.e. the longest distance of two nodes. Maximum rate of 1 Mbps is reached with system length up to 40 meters. Table 1 below shows the decrease in the rate with system lengths [40].

Table 1. *CAN bus signalling rates and distance between the nodes.*

Bus length (m)	Signaling Rate (Mbps)
40	1
100	0,5
200	0,25
500	0,1
1000	0,05

3.3.3. Twisted pair cable

The nodes are connected to each other with a twisted pair cable with standardized number of twists per meter. In this study, we concentrate on the J1939 standard unshielded twisted pair (UTP) cable which has twist rate of 40 twists per meter and the cable colours are yellow and green. As the system is digital and messages are binary, they consist of ones and zeros. Figure 6 illustrates the voltage levels which correspond the two bits [41].

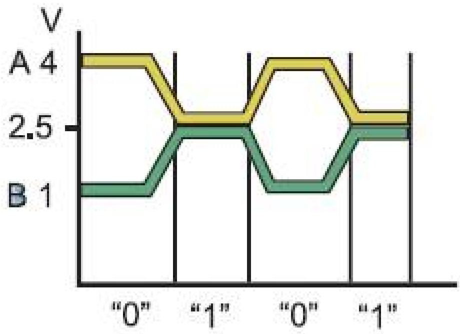

Figure 6. *Voltage level and bits.*

The simultaneous voltage levels in the two wires is interpreted to the two bits; 0 and 1 accordingly

- Yellow 4 V; Green 1 V bit 0
- Yellow 2,5; Green 2,5 V bit 1

This type of signalling is called non-return-to-zero signal pattern (NRZ) [42], which essentially means that there is no neutral position neither for bit 0 nor bit 1. Instead, both bits are presented with an active voltage level which differs from 0 V.

The twisted pair cable has one very special characteristic, as this construction cancels out electromagnetic interference (EMI) from external sources and prevents crosstalk with other, neighbouring cables. It also reduces the cable's own electromagnetic emittance thus making it more neutral on the other cables nearby. It was originally invented by Alexander Graham Bell in 1881 as a solution for the electromagnetic interference in the telegraph and open-wire phone lines [43].

3.3.4. End termination

The ends of the CAN bus are terminated with 120 ohm resistors as shown in Figure 7 below [31,44].

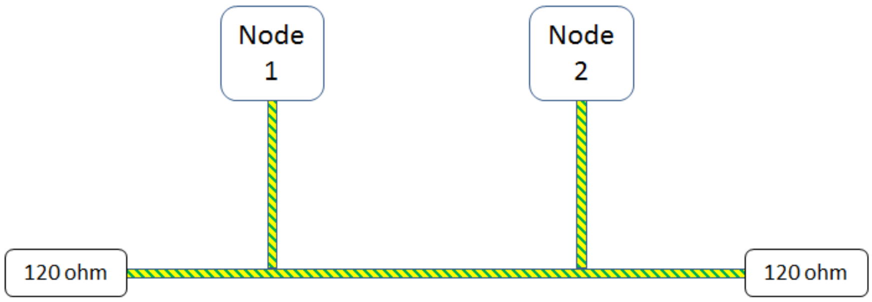

Figure 7. *End termination of the CAN bus.*

The end termination works as a damper and prevents the signals from reflecting from the ends of the cable, as this might otherwise occur. The reflected message could be received by the nodes and thus creating unwanted communication and errors within the bus. Figure also visualizes the bus philosophy topology-wise; the nodes are connected as branches to the bus frame line that runs between the terminating resistors.

3.3.5. Transceiver

A key element in the system is transceiver that both transmits and receives information to and from the bus [36]. CAN is a broadcast system, which means that the transmitting node places the data on the network for all nodes to access. Each of the nodes can send and receive messages, but not simultaneously. The network designer defines the nodes that need the transmitted data by using filters, i.e. messages from some nodes can pass and all the others are ignored. If the filters are not applied by the designer, some of the processing time will be used in sorting the messages [40]. Figure 8 visualizes the data flow model with filters.

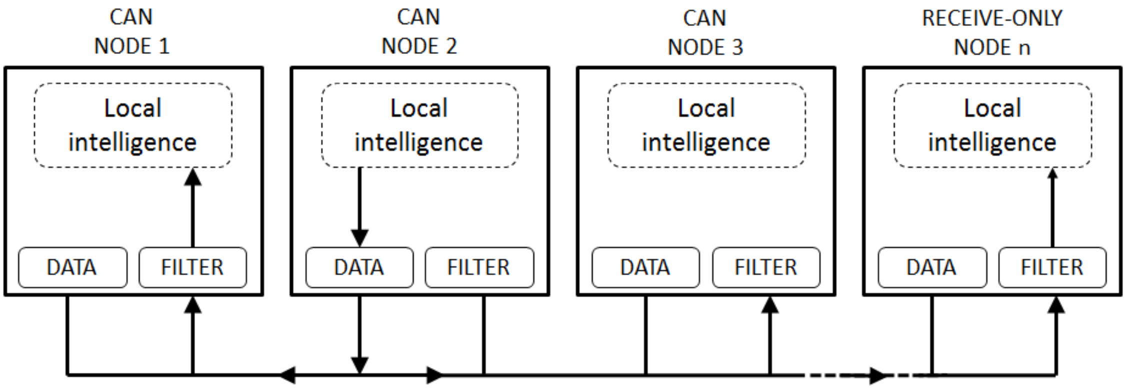

Figure 8. *CAN bus data flow model.*

Node 2 transmits data and the filter on node 3 is set not to receive it. By using the ABS brakes as an example, the transmitted data from node 2 could be rotational velocity of a wheel. This data is important for the nodes that control the brake pressure (nodes 1 and n), but not needed for the passenger room climate system (node 3). This logical filtering in the design enhances the overall effectiveness of the system [40].

3.3.6. CAN data frames

There are two types of data frames used, a standard format and an extended format. Both must be able to be run and be tolerated on a same system. The difference between these two is the length of the identifier; 11 bits on the base format, and the extended format contains 29 bits [42]. Both frame types have their own benefits. The standard frame with 11 bits provides shorter bus processing time which is useful on time critical and safety concerned functions. The extended frame with 29 bits enables a wider message identification space.

The identifier is unique for each transmission and the system designer can use them to create prioritization for messages [40]. In the automotive domain systems such as brakes, or the already discussed V2V applications, would have greater priority than for instance wind shield wipers.

Table 2 illustrates the structure of the 11-bit identifier standard frame. The structure is the same for both frames, only the field details differ between the two [45].

Table 2. *Standard CAN data frame.*

Field name	**Length (bits)**	**Description**
SOF, start of frame	1	Denotes the start of transmission
Identifier	11	Identifies the message and represents the priority.
RTR, remote transmission request	1	Dominant. Destination node can request data from source by sending remote request.
IDE, identifier externsion.	1	Represents in which format the message is. Dominant (0) for 11-bit, recessive (1) for 29-bit.
Reserved bit (r0)	1	Reserved bit
DLC, data length code	4	Number of bytes of data (0-8)
CRC, cyclic redundancy check + delimiter	16	Error detection checksum
ACK + delimiter	2	Transmitter sends recessive and receiver asserts dominant on successful reception
EOF, end of frame	7	Marks the end of the frame
IFS, Interframe Space	7	The time required by the controller to move a correctly received frame to its proper position in a message buffer area.

The extended frame structure incorporates few changes and additions [45]. The complete structure is below in Table 3 and the description of the additional frames in Table 4.

Table 3. *CAN bus extended frame data fields.*

SOF	Identifier	SRR	IDE	Identifier 2	RTR	r1	r0	DLC	Data (0-8 bytes)	CRC	ACK	EOF	IFS

Table 4. *Additional frames in the extended frame.*

Field name	Length (bits)	Description
Identifier 2	18	Additional 18 bits
Substitute Remote Request (SRR)	1	Replaces RTR in the standard message frame.
Reserved bit (r1)	1	Reserved bit.

As shown, the differences between the standard frame and extended frame do not concern the data fields. Both frames are capable to transmit data up to 8 bytes, i.e. in total 64 single bits in a single frame. The allocation of the bits is addressed in more detail in Chapter 4.

4. CREATING A VEHICULAR SW FUNCTION

In this chapter, we create a new software function by using the building blocks introduced in the previous chapters, some application specific systems and components, as well as design science. The task is to create a climate steering function for a bus. For the sake of clarity, the heavy vehicle to transport passengers is from now on referred as *bus*, and the vehicular information network as *CAN bus* or *data bus*. The task is performed by a work group consisting of five people working on the actual system with the components and software. Another five persons are supporting in the testing.

While the exact task here limits to a climate system, the concepts of inputs and outputs and applying a data bus for the communication is of more general nature. These functional principles can be generalized to most data bus based systems. Thus, the created system is just an example and the same principles can generalized to other kinds of services.

4.1. Prerequisites

Creating a new function begins from a real life need which needs to be fulfilled. The human passenger of a bus needs a pleasant environment to travel in. By experience, i.e. based on the information in the *knowledge base*, we know that this means a space free of draught, which can maintain desired temperature. The operating temperatures around the planet vary from some minus 40 Celsius degrees up to plus 50 degrees. Naturally, these extremes are too harsh environments for a human being to stay in for any longer period. In fact, a comfortable temperature range is quite narrow. There are individual differences of what is experienced as pleasant. Some may consider 19 C to be little on the cold side while for others it is clearly too low. The same differing opinions concern also the upper limit; which temperatures are experienced to be too high. The humidity of the air alters the experience even further. These interdependencies create a set of demands in which not all of them can be simultaneously fulfilled.

Considering that a bus is a mean for mass transport carrying dozens of passengers, an approximation is needed. In this case, we set our desired target for all individual passengers:

- Target temperature 22 degrees Celsius in the cabin
- Ambient temperature 40 degrees Celsius
- Maximum time 120 minutes to come down from 40 °C to 22 °C
- Temperature difference (ΔT) within the passenger room maximum 2 °C

The hardware to fulfill this task is introduced in Section 4.3.

4.2. Rigor Cycle and Knowledge base

As stated in the prerequisites, the system should work towards temperature of +22 °C in ambient temperature of +40 °C. This is done by using the cold available from the AC system. From the knowledge base, we are able to retrieve the needed components and their capacities:

- Compressor 560 cubic centimeters (cc)
- AC unit cooling capacity 35 kW
- CAN bus with the needed actuators and temperature sensors as explained in Section 4.4.

These specific components with the mentioned capacities are selected based on the following criteria:

1. Theoretically the capacity is able to remove the desired amount of heat from the air
2. Earlier testing has confirmed that the system with these characteristics delivers according to prerequisites

The software component with certain set of functional parameters is our *artifact*. By the means of Design Science, the specific compilation of components presented in the next comes from the rigor cycle and knowledge base. They have been selected to be parts of the vehicular system by knowledge gained by their technical properties and earlier testing. The hardware is not put together from scratch.

The final version of the software component to control the system is created by testing. The functional logic can be created deductively up to certain extent, but the exact parameter values can be successfully set only by testing in real life conditions. For one, computational fluid dynamics (CFD) simulation can be used as support when designing the geometry of the air duct. It is however very difficult to include in the simulation all the variables that may occur in real life situations. This follows well the essence of Design Science. The mentioned deductive design represents the rigor cycle in this study. The real life testing of a physical model is the relevance cycle. The connection between this specific study and the theory of Design Science is presented in Table 5.

***Table 5**. The connection between the study and Design Science concepts.*

Design Science	The study
Artifact	The software component to regulate AC system
Rigor cycle	Previous test results Previous simulation results. Constantly reality checked with test results. Theory of thermodynamics
Relevance cycle	Testing in real life hot conditions

4.3. Hardware

The main components of the climate control system are shown in Figure 9.

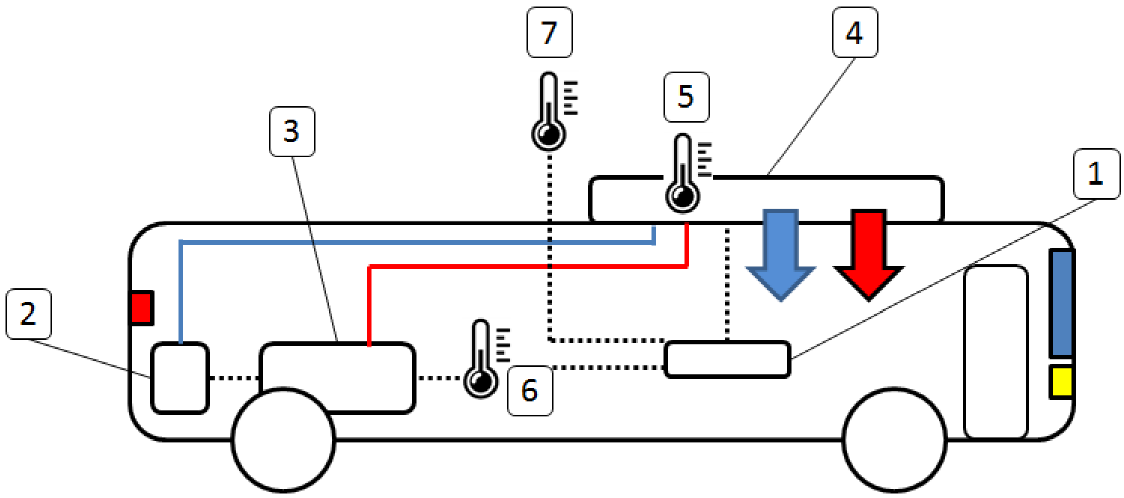

***Figure 9.** Climate control hardware.*

The numbered components in the figure are the following:

1. *Steering system*. CAN bus and the interconnected components.
2. *AC compressor*. The compressor is used in the summer conditions to create cold by utilizing the refrigeration cycle.
3. *The engine*. The excess heat from the engine coolant is used to heat up the passenger room in cold conditions.
4. *Roof unit* is located in front part of the roof behind the b-pillar. The unit has radial fans inside and fulfils three purposes:

- *Ventilate*. Only fans on, no cold or heat supplied.
- *Heat* (red arrow). The engine heat is fed into the unit.
- *Cool* (blue arrow). The AC compressor provides refrigeration.

5. *Temperature sensors* inside the roof unit. The sensors measure the temperature of the air that is fed into unit and out from into the passenger room.
6. *Temperature sensor* inside the passenger room. This sensor measures the temperature inside the passenger room.
7. *Temperature sensor* ambient temperature. This sensor measures the ambient temperature outside the vehicle.

The components presented above visualize the complete heating and AC system. In this study we concentrate only on the AC system and the roof unit.

4.4. Roof unit function

Figure 10 presents the hardware setup for the passenger room ventilation, heating and cooling in more detail. The essential functions are provided with the roof unit together with the CAN based steering system.

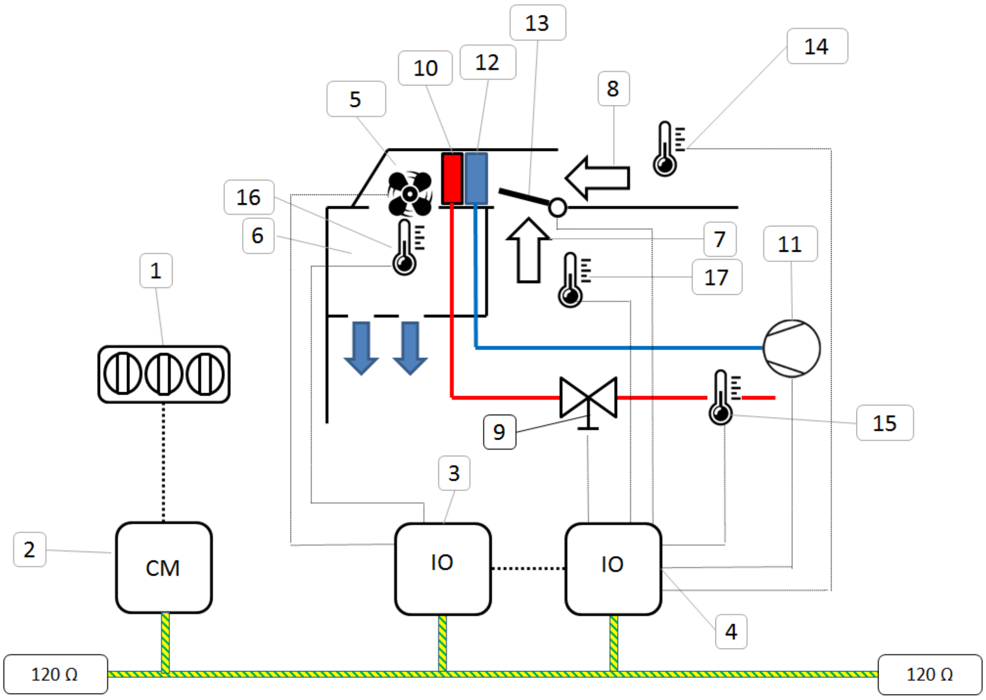

Figure 10. *Roof unit control.*

The numbered components in the figure are the following:

1. *The driver control panel* is the driver's interface to the system. It allows the driver to set the targeted temperature for the passenger room. The

output is a resistance value (Ω) which is converted into digital form in the control module.

2. *Control Module* (CM). A node in the CAN bus. Receives and transmits messages in the CAN bus.
3. *Input-Output module*. As above.
4. *Input-Output module*. As above.
5. *Electric fan* creating the air flow from the roof unit into the passenger room. The fan is powered with an electric direct current (DC) motor. The fan speed is steered to regulate the air speed and volume in the cabin.

   The fan speed is handled as a value between 0 and 1000, the 0 being no activation and 1000 full, or 100%. The fan speeds are steered with a pulse-width modulated (PWM) signal.

   The PWM signal is created by switching on and off the power feed to the fan motor. The higher the switching frequency is on, the more total power over time the motor receives and thus higher the fan speed and the consequent air flow into the passenger room. The advantage of PWM is the high efficiency. When the switch is off, there is virtually no current. When the switch is on, there is not voltage drop across the switch. The power is the product of voltage and current. The loss is thereby close to zero in both scenarios. The frequency of switching on and off is high, and this digital nature of switching on and off suits the CAN bus well.

6. *Air duct* distributes the air for the complete length of the passenger room.
7. *Re-circulated air* from the passenger room is used to save energy, i.e. in AC mode it is more feasible to recirculate already cooled air through the roof unit that to take if hot fresh air. In heating mode, fresh air is prioritised instead as it contains more humidity than air conditioned air, which is characteristically dry. The air intake is steered with the fresh air flap (13).
8. *Fresh air* taken in from outside

   Fresh air used mainly in the heating mode. Used also periodically in AC mode to take in oxygen to prevent the passengers from suffocating.

9. *Electric on/off -valve* regulates the amount of heat in the heat exchanger in the roof unit. The valve opens the hot coolant feed from the engine into the roof unit heat exchanger.

10. *Heat exchanger* transfers the heat from the coolant into the air. The heat exchanger is deployed in the heating mode when heat is needed in the passenger room.
11. *AC compressor* pressurizes the refrigerant and thus employs refrigeration cycle.
12. *Evaporator coil* evaporates the pressurized refrigerant and provides cold. The function is the opposite of heat exchanger; evaporator cools down the air that is fed into the passenger room.
13. *Air flap* regulating the air intake to the roof unit. The position of the flap defines whether fresh air or re-circulated air is fed into the unit. Software controls the position automatically:
    - Always open in heating and ventilation modes to avoid humidity condensation
    - Closed in AC mode, opened every five minutes for 30 seconds to feed in oxygen

The flap is operated with an electric servo motor.

14. *Ambient temperature sensor*
15. *Coolant temperature sensor*
16. *Temperature sensor* for the air that is blown into the passenger room
17. *Temperature sensor* passenger room

The type of all the sensors is negative thermal coefficient (NTC). Effectively this means that the higher the temperature, the lower the resistance value as shown in Figure 11 [44].

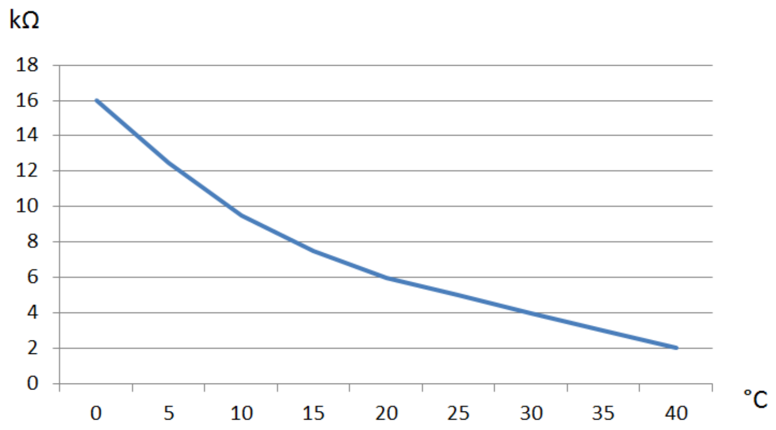

Figure 11. *NTC thermal sensor.*

Here only the temperature range from 0 to 40 degrees Celsius is shown for sake of readability. The resistor values are considerably higher in the sub-zero temperatures as the shape of the curve even here hints. In either case, these are the analogue resistance values that the sensor is sending to the IO modules.

4.5. Control module and IO modules

Control module is similar as the other IO modules with one big exception; control module has and RS-232 -connector to connect a PC to the system. This connection is used to have advanced user interaction with the system. By advanced, we mean interaction that takes place during development work and service, as opposed to the everyday interaction that the driver carries out via the driver control panel. During development work, it is used to supervise the function of the SW, and to manipulate parameter values when so needed and a PC connected in RS-232 provides this interface.

The location of the IO modules on the vehicle is selected based on the location of the components they are steering to obtain shortest possible cable length [41]. The data bus may not exceed certain maximum lengths as mentioned earlier. Exceeding these lead into reduction in bitrate. The less there is cable on-board, the more effective the application is also form weight and cost perspective.

With the mentioned exception of the external connecter, the control module and IO modules share the same basic architecture that consists of:

- CPU
    - All the modules not only route, but also process data
- Memory
    - The different parts of the software are stored on different IO modules, not solely only on the control module. The design philosophy is to have it stored to a module that also processes it. The memory circuit is a non-volatile flash memory, i.e. the information remains stored even without power supply.
- Analogue-digital converter
    - Converts the analogue signals to digital form
- Inputs
    - Digital inputs, DO
    - Analogue inputs
    - Resistor inputs
- Outputs
    - Digital outputs
    - PWM outputs

4.6. Digital signaling

The digital signals are created with a bit allocation tool that allows designer of the system to create them literally bit by bit. Figure 12 is a view from the tool. It represents one of the data frames with the included signals.

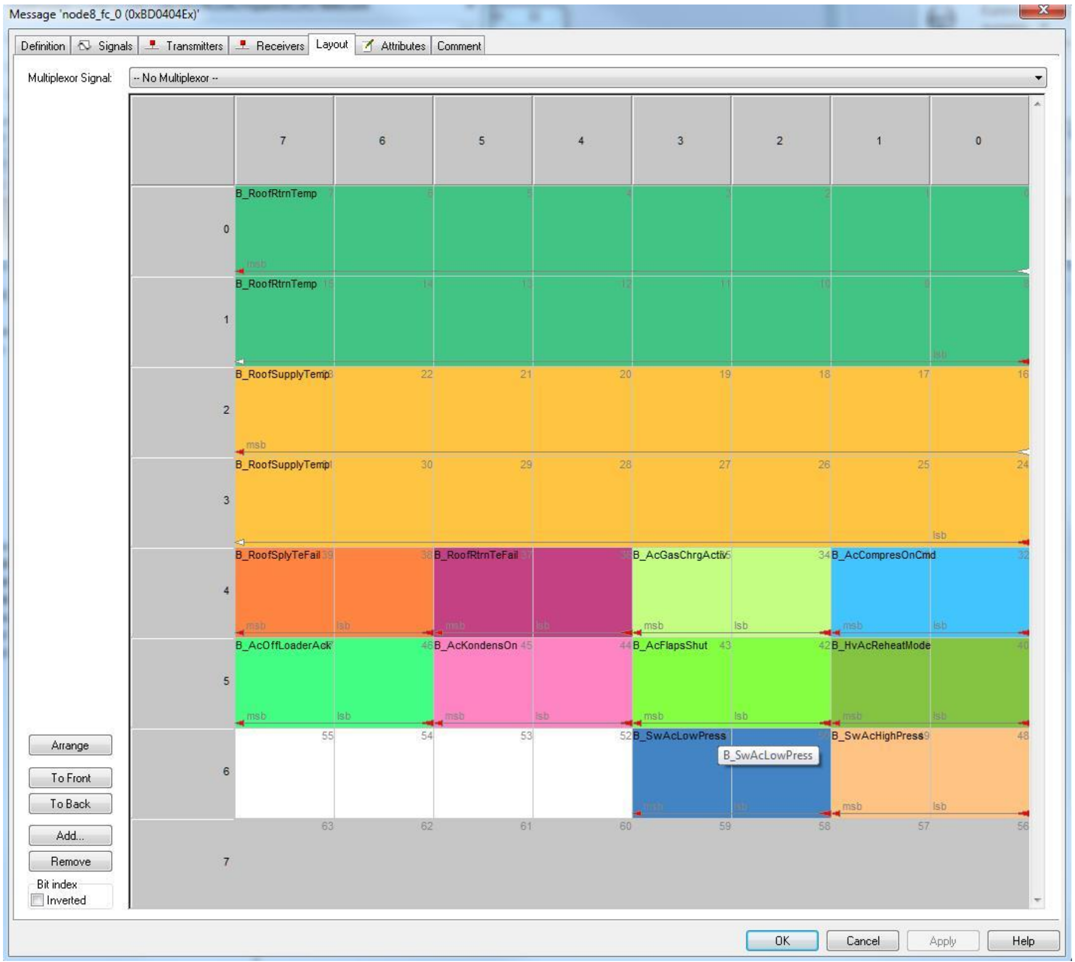

Figure 12. Bit allocation tool.

In the tool, each cell represents an individual bit. Each row contains 8 bits consequently making up every row to be one byte. Each of the CAN frames is able to carry maximum 8 bytes as explained earlier in Section 3.3.

This specific frame contains 2 pieces of 16 bit signals and 10 pieces of 2 bit signals. The type of information defines how many bits are needed. Here the 16 bit signals are for temperature information:

- Temperature information of sensor (16) roof supply temperature. Bytes 2 and 3 in Figure 12, signal name B_RoofSupplyTemp.
- Temperature information (17) the temperature inside the cabin, i.e. the air that is sucked back into the AC unit. Bytes 0 and 1 in Figure 12, signal name B_RoofRtrnTemp.

The 2 bit signals are there to send information of current state; whether the concerned function is active or not.

Table 6 contains the number of states that can be communicated with different amount of bits.

Table 6. *Bits and states.*

Bits (n)	Number of states 2^n
1	2
2	4
3	8
8	256
16	65 536

The bit amounts 2 and 16 are emphasized since they are used in the studied system.

4.6.1. The 16 bit signals

The reason why 16 bits are needed for the temperature is the desired resolution for the data. The temperatures in these sensors range from -50 °C up to 100 °C. The temperature range is hereby 150 degrees in total. The used 16 bits enable 65 536 states to be used, which means resolution of

$$\frac{150\ degrees}{65\ 536\ states} \approx 0{,}003 \text{ Degrees / state.}$$

This is well above the needed resolution, the desired system need for regulation is 0,1 degrees. For comparison 8 bits with 256 states would enable only around 0,59 degrees / state for the given temperature range.

4.6.2. The 2 bit signals

It would be possible to create a two state signal containing on/off –data only with one bit:

- Bit 0, off
- Bit 1, on.

Instead, we use 2 bits. This enables four different states to be used as in Table 7.

Table 7. *State table 2 bits.*

Bits	State	Description
01	True	On
00	False	Off
11	Void	No value written in the variable
10	Error	Value not within accepted limits

This creates the core of diagnostics, which was even one of the driving factors in development and implementation of data bus systems as discussed earlier. Instead of only relaying on and off signals, there is also an inbuilt way to follow the status of an individual component.

4.7. SW in AC mode

The hardware needed in AC mode is described below in Figure 13, which is a modified version of Figure 10. In this version, only the components active in AC mode are left in to make it more readable. For readability also the original position numbering is kept the same, hence it is not consequently rolling.

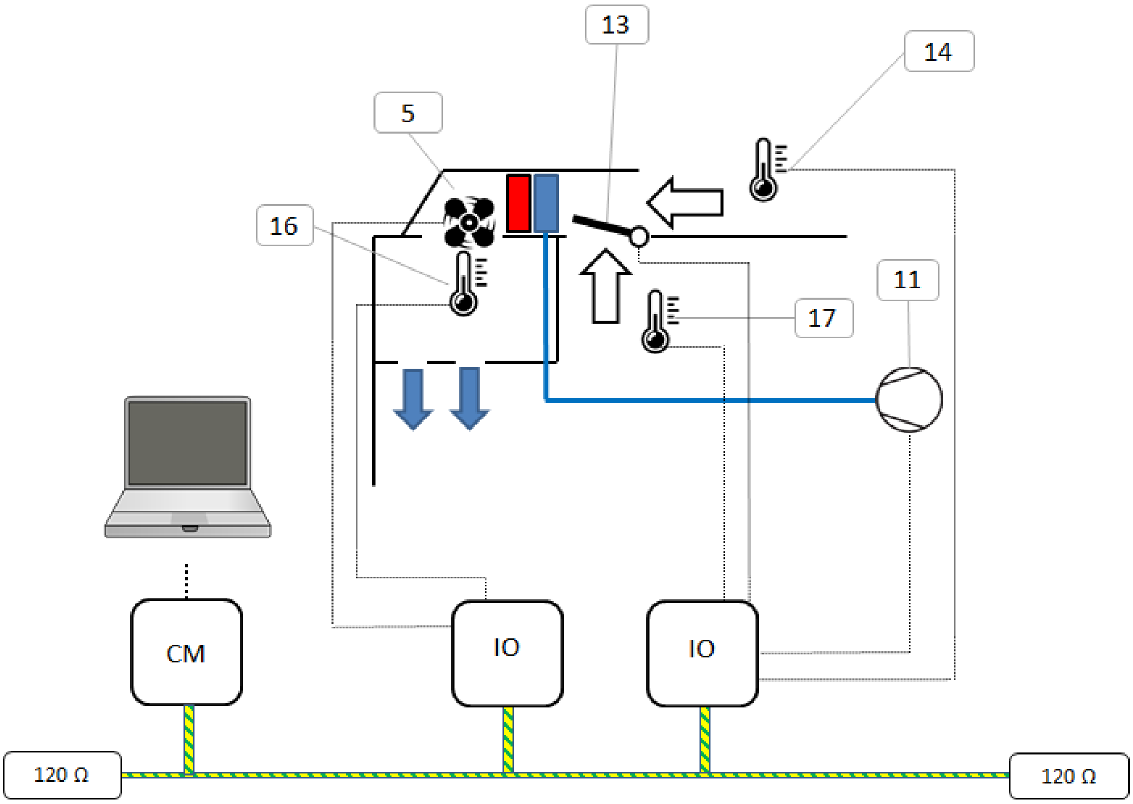

Figure 13. *System in AC mode.*

In normal operation the system is manipulated by the driver via the control panel in the dashboard. For testing and development purposes a laptop computer is connected to the control module as shown.

To operate the system in AC mode, we need the following inputs and outputs to and from the CAN bus:

(5) Output fan speed control

(11) Output compressor activation

(13) Output fresh air flap movement

(14) Input ambient temperature

(16) Input air temperature out from the AC unit

(17) Input air temperature air in the passenger room

The concerned outputs and inputs are visualized with their respective data flows in Figure 13.

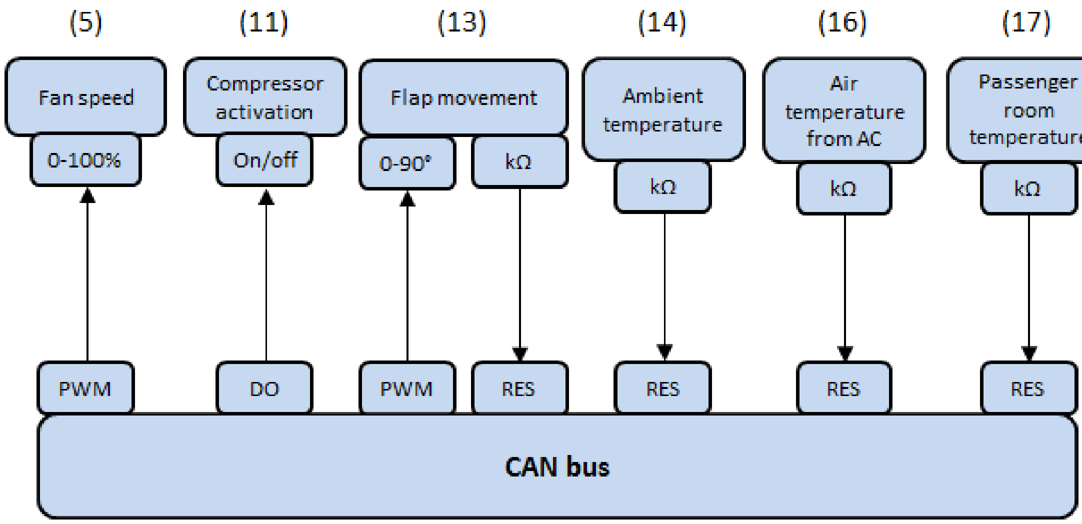

Figure 14. *Data flow outputs and inputs.*

- Fan speed (5) is controlled with a PWM signal from the IO module. We are able to manipulate the fan speed between 0% (no activation) and 100% (maximum rotational velocity).
- Compressor activation (11) is controlled with a DO output. Compressor is either active or not.
- Flap movement (13) is controlled with a step motor, thus the PWM signal can position the flap to any position between 0 and 90 degrees. There is also a resistor value as output from the step motor, this signal supplies constant information of the flap position which allows the system to calibrate the flap steering as desired. By relying only on the PWM frequency, the geometrical structure could for instance wear over time and the position of the flap no longer correspond that of the original intent.
- The temperature sensors (14, 16, 17) all send resistor value as input to the can bus.

The data exchange described above enables the system to impact the temperature in the passenger room in a controlled manner.

4.8. Base SW and parameters

The version of the SW with the respective parameters is collected via rigor cycle from the knowledge base. The basic functional logic is created both deductively and by earlier testing. The forthcoming testing may well prove need for updates and changes in terms of both; functional logic and parameter values. These are constantly updated based on the findings in relevance cycle when so needed.

By parameter updates we refer only to *output values*. The only reason to adjust *input values* is when there would be a systematic offset on a sensor value. This would depend on the component properties. It would be corrected by including a standard offset in the SW. Otherwise the inputs are there to provide as correct as possible information of real life phenomena, and as such should not need to be manipulated.

3.3.1. Fan speed parameters

The fan speed is controlled on the PWM signal and can have any value between 0 to 100%. Again, from the knowledge base we already know that the applicable upper limit is limited to what is experienced comfortable by the passengers.

The lower limit depends on physics. By blowing out smaller air volume through the evaporator coil the cooling performance reduces and eventually the evaporator coil will freeze from the humidity in the air and thus preventing the system from functioning at all. Another prerequisite is sufficient ventilation. In AC mode, not too much emphasis is placed on this as we know that the evaporator coil condensates the humidity. Air conditioned air is typically dry due to this. In heating mode, a completely different set of rules apply, and the lowest feasible fan speed is defined by the rate of ventilation.

Based on this background, the base level fan speed in AC mode is set to be between 40 and 100% as function of the ΔT between the set temperature and passenger room temperature as shown in Figure 15. The SW follows this curve when pulling down the temperature.

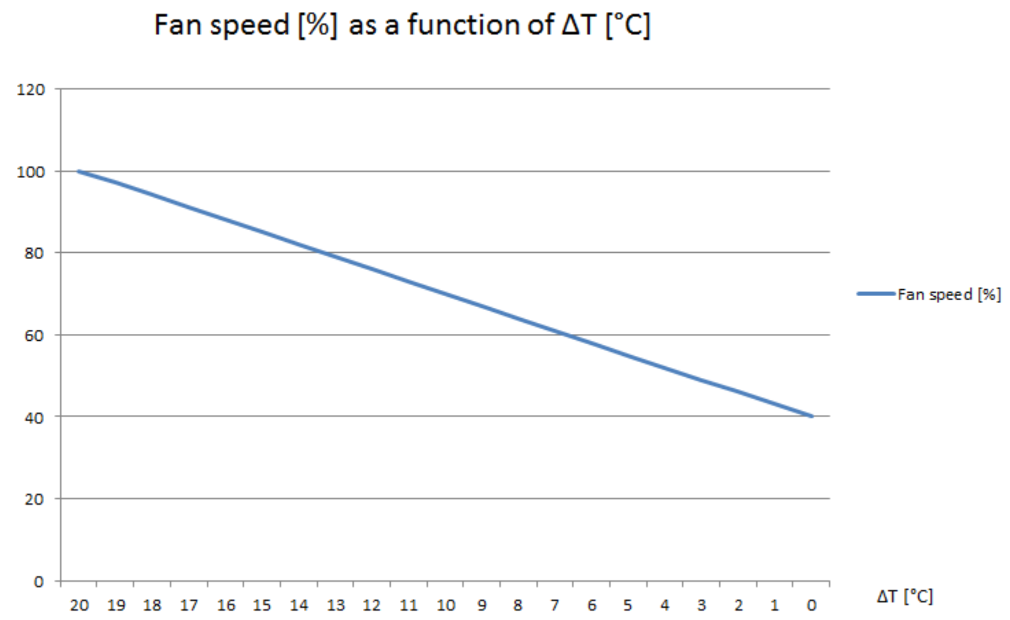

Figure 15. *Fan speed [%] as a function of ΔT.*

This is a concrete parameter that our artifact possesses. The SW ramps down the fan speed as the temperature difference between what we want and what we have diminishes.

It is good to acknowledge that the ΔT can also be greater than 20 °C, in which cases the fan speed is maintained at 100%. Also, the ΔT can be less than 0. This represents a scenario where we have colder in the passenger room than what we have as target temperature and the system goes into heating mode. From SW perspective this is a completely different regulation scenario and another fan speed curve will apply. The heating mode is not within the scope of this study.

4.8.1. Compressor activation parameters

The compressor is activated by the SW when the temperature in the cabin is higher than the set temperature. The activation is made with and digital output signal and as such is on or off.

The compressor activation takes in as input also the information of the ambient temperature. One may imagine a situation, where:

- Set temperature 22 °C
- Passenger room temperature 25 °C
- Ambient temperature 20 °C.

This may occur on a sunny day, when the ambient temperature is relatively close to the set temperature, and the passenger room temperature is more than desired. Here it would make no sense to activate the compressor to supply cold, when we can use instead colder ambient air for this purpose. Ambient air is fed in by the fresh air flap as described in the next chapter.

To know the temperature difference between air out from the AC (16) unit and air into the AC (17) has a diagnostic significance. This will point out a failure mode where AC compressor is activated correctly, but the evaporator coil does not supply cold as expected during correct operation.

4.8.2. Air flap movement parameters

The flap is moved between the end positions. When the system is started, the flap is moved to both end positions and those are written in as the session specific positions. This eliminates the impact of mechanical wear that may happen over time and would affect the flap air tightness in the closed position.

The input signal for the flap position is the resistance input from the potentiometer in the step motor. From technical perspective it is possible to move the flap into any other position between the mentioned 0° and 90°, but this possibility is not used in this specific application. Flap in a middle position would enable the system to constantly mix fresh and re-circulated air.

In AC mode, the flap is most of the time closed and opened only every 5 minutes for 30 seconds to feed in oxygen.

4.8.3. Summary of the parameters

The discussed parameters in our test conditions, i.e. AC mode, are collected below.

- Fan speed follows a curve on ΔT between set temperature and current temperature
- Compressor activation depends on ΔT as above, but in more limited sense; compressor is always activated when:
  Set temperature < current temperature
- Air flap operation sequence is closed 5 minutes, open 30 seconds.

This set of parameters is enough to regulate the temperature in normal operating conditions.

5. TESTING AND RELEVANCE CYCLE

In this chapter, we present the relevance and rigor cycles that are needed in order to verify the desired function of the system.

5.1. The test setup

The solution is tested by performing a *temperature pull down*. In a pull down, the vehicle is placed in hot ambient conditions, which in this study is the already mentioned 40 °C. The vehicle is placed in +40 °C for 2 hours in order to *soak* the structure, i.e. to heat up the structural elements. Without proper soaking the structure might not be completely up to the ambient temperature, which would enable too quick pull down thus distorting the results.

The pull-down curves presented in the next chapters are compiled from two separate real-life tests of an unnamed tourist bus. The pull-down curves of any successful, similar test will be very similar in shape to ones presented below. The software parameters together with mechanical design and the capacities of the fans, air ducts and related components make the exact test result application specific.

5.2. Result logging

The testing is recorded with a data logger with measuring interval of 30 seconds. Three thermocouple sensors are used to measure the temperature at standardized places within the cabin. The positions are shown in Figure 16.

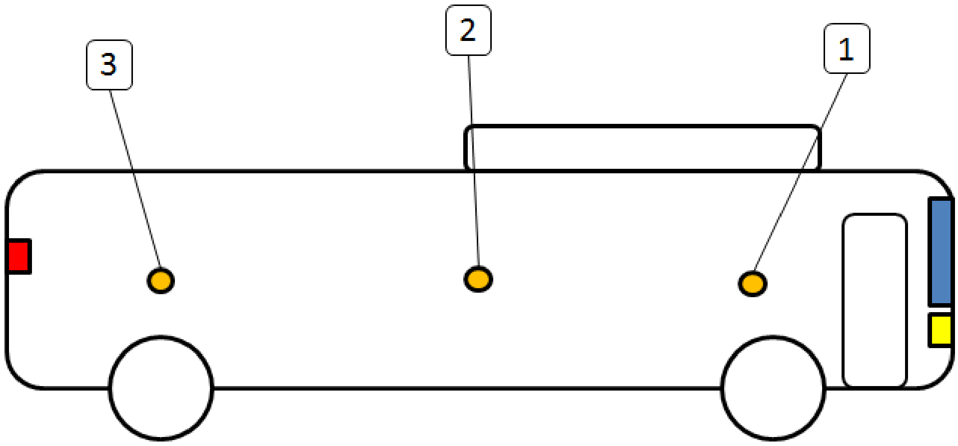

Figure 16. *Sensor location logging.*

All three sensors are placed 1,1 m from the floor level at the middle of the aisle. The locations of the sensors shown in the figure are following:

- Sensor 1 first seat row
- Sensor 2 middle of the vehicle
- Sensor 3 last seat row

The philosophy with this sensor layout is that we do not only measure at which rate the temperature comes down from 40 °C, but also how evenly it happens throughout the passenger room. The logging interval is 1 second and the test result will be three separate *pull down curves*. As per prerequisites, all three should lie within 2 °C and come down from 40 °C to 22 °C in maximum 2 hours. This is the concrete requirement and test result that our artifact must meet in order to be approved as good enough.

5.3. First relevance cycle

The first test cycle, i.e. the first relevance cycle, is started with the conditions as described above. The chamber and the bus are warmed up to 40 °C and the system *set temperature* is set to 22 °C. In other words, the system works towards 22 °C reading on the sensor number 17. The vehicle is uploaded with the base software as described in Chapter 4.

Results of the first test are below in Figure 17.

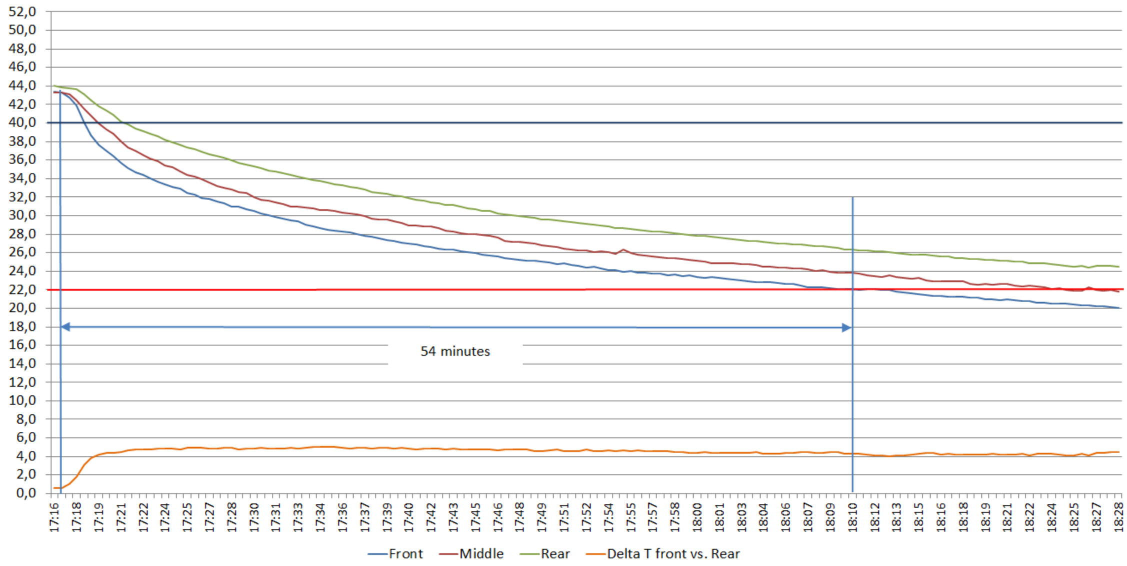

Figure 17. *Pull-down first test.*

The most crucial information in the results is how well the given prerequisites are met. The original prerequisites and their corresponding test result comments are collected below in Table 8.

Table 8. *Prerequisites vs. results.*

Prerequisite	**Comment**
Target temperature on passenger head level 22 °C within 120 minutes	Met in front after 54 minutes, in middle 68 minutes, not met in the rear during the whole test.
Ambient temperature 40 °C	Ok. Temperature in the cabin 43 – 44 °C at test start due to solar radiation.
Temperature difference (ΔT) within the passenger room maximum 2 °C	Not ok. Actual ΔT between 4 and 6 °C.

The curves visualize the main problem with the functionality; the temperature balance in the passenger room is not within the required limits. The lowest curve named *Delta T rear vs. front* is drawn out of the pull-down results to visualize the biggest difference during the duration of the complete test. The ΔT is above 4 °C while the target is 2 °C. The test is stopped before the rear sensor is down to 22 °C.

On the positive side, the target temperature is reached in the front much quicker than within the required 120 minutes. This hints that we do not need to increase the total cold capacity, but instead to find a better way to make the cold air also reach the rear part of the passenger room. Instead of only pouring in more cold in the back, we could make the front part to respond a little slower.

The simplest way to move to the desired direction is to adjust the fan speed. The higher the air flow in the air duct, the more turbulent it will grow thus hurting the air velocities in the furthermost parts of the duct. In our case this means the rear of the vehicle. At the same time the cold air volume pushed out directly below the AC unit will be less.

5.3. Second rigor cycle

Based on the results collected in the first relevance cycle, we go back to knowledge base and review results of a similar test. The vehicle is the same.

The results are presented below in Figure 18.

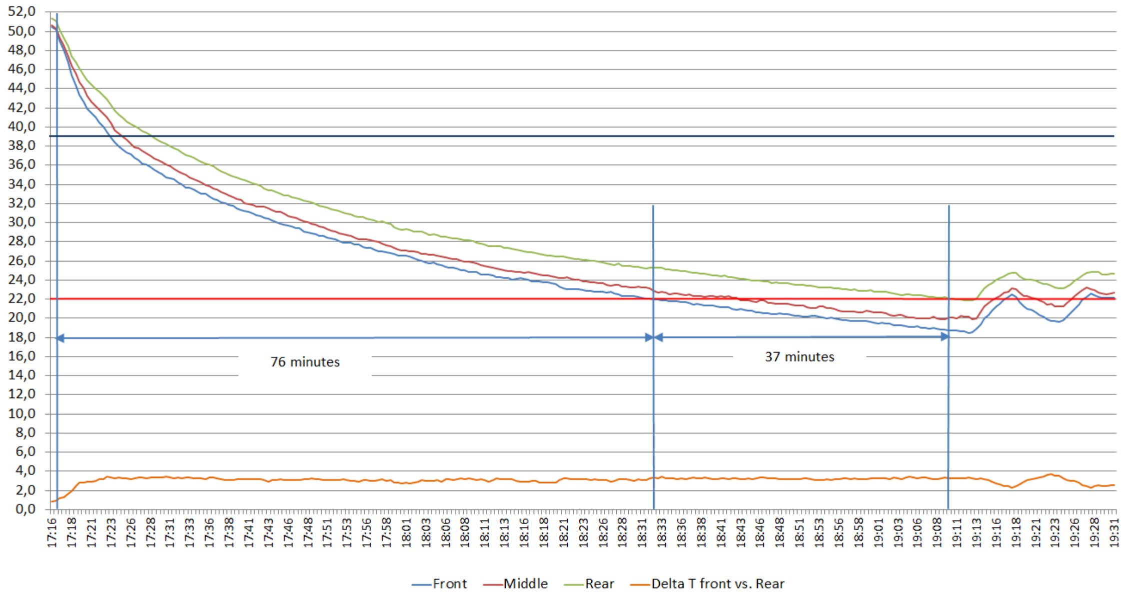

Figure 18. *Pull-down second test.*

The difference in this test is that the ambient was 1 °C lower, leveling at 39 °C. The interior start temperature was few degrees higher due to solar load. This simulates a scenario where less cold is available for the passenger room compartment.

As visible on the curve, by reducing the amount of relative cold two things will happen:

- The temperatures in the passenger room are more even, below 4 °C
- The pull-down time will be longer, 113 minutes in this test

Even in this test, the temperature balance is not within the required 2 °C.

5.4. Second relevance cycle

For the second relevance cycle of testing we propose to introduce two updates which are discussed below. By these changes we expect to gain even enough temperature readings within the given 120 minute requirement. The actual real life testing of the second relevance cycle is not within the scope of this work.

5.4.1. Updated fan speed curve

An updated fan speed curve (green) is presented in Figure 19. Also the original curve (blue) is visible for comparison.

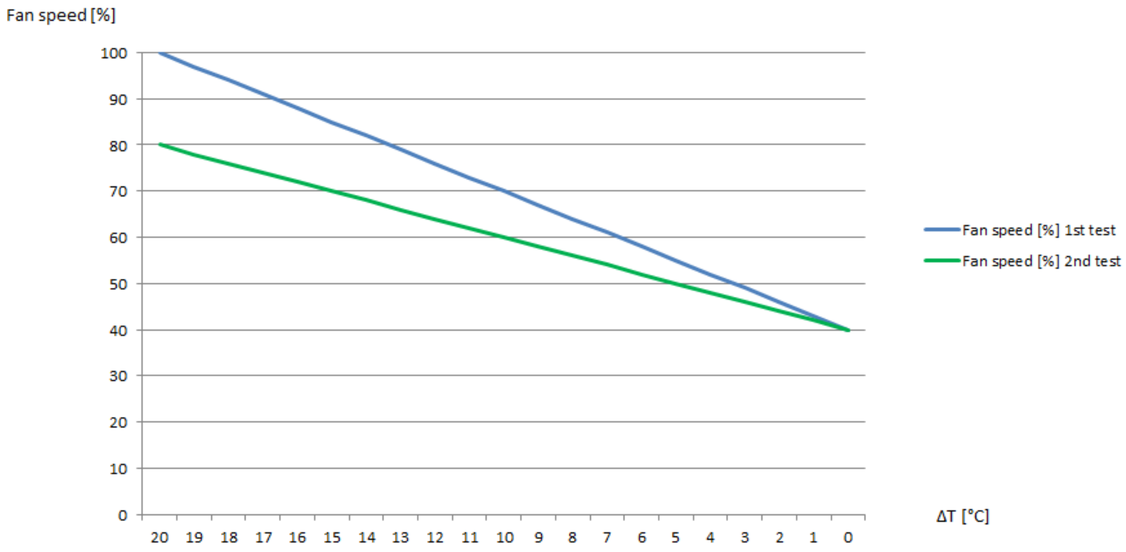

Figure 19. *Fan speed vs. temperature difference.*

The original curve has maximum fan speed of 100% while here we limit the maximum to 80%. The minimum is still 40% due to the limitations mentioned earlier, i.e. ice formation.

5.4.2. Mechanical update in the air duct

As seen from the previous results, the smaller amount of cold does not fully take the temperature balance below 2 °C. A geometrical improvement is proposed to further enhance the system performance towards the requirement. What is suspected to happen is visualized in Figure 18.

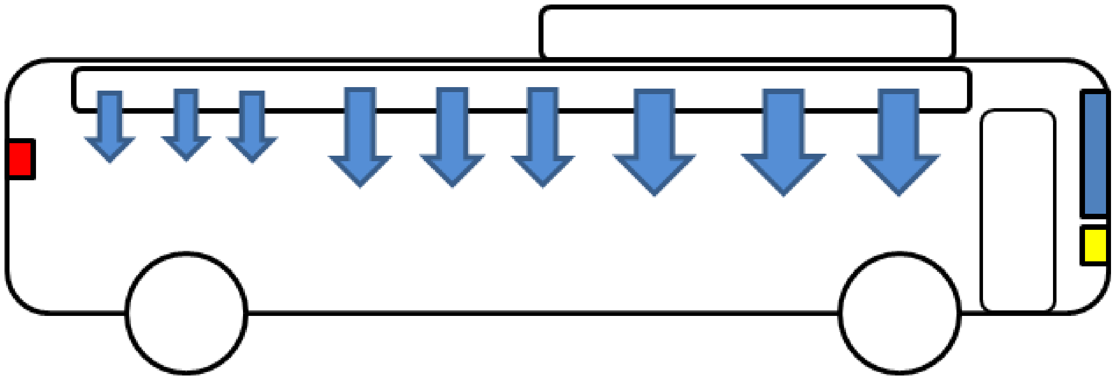

Figure 20. *Unbalance in air volume.*

The cold from the roof unit is distributed into the passenger compartment by the air duct. The AC unit is located in the front part of the vehicle, which is the other end of the air duct. The sizes of the blue arrows illustrate the relative portions of the cold air volume. Most of the air comes out directly below the unit and drops down proportionally along the duct. To improve this in the mechanical solution is not within the scope of SW design. It is however proposed to be done before the next test as SW updates alone most likely cannot provide the required performance.

6. SUMMARY

We have reviewed the state of the art in the field of vehicular digital data communications. There are parallel, on-going activities in standardization and industrial development. The vehicles will start to interact with each other and their surroundings. The on-board digital communication will stretch itself to off-board; intra-vehicular will be complemented with inter-vehicular.

We have also created a software function for one of the specific technical areas within the domain. The method of Design Science was put to practice and the benefits became illustrated. In an environment with numerous variables it is effective to create a base-line solution from the knowledge base and to iteratively run relevance cycles to find out the critical characteristics of the system at hand. It is also noteworthy how the limitations of the design in the physical world can be improved up to certain extent with software, but not necessarily all the way.

While the example case here is a CAN bus based climate control system of a heavy vehicle, the basic concepts of relaying information and digital signals can be generalized to cover a wider spectrum of applications. In the case of this study the inputs were mainly temperatures and the outputs different types of signals for actuators that aim to reach certain temperatures. However the inputs could be information of any real life phenomena such as the distance of the other vehicles or the geographical position for a system such as the mentioned emergency braking system.

The principles presented here can be applied to any application, that utilize binary computing and frame based data transfer. The oncoming technologies under the V2X umbrella will utilize the same principles. Some of the communication will be wireless, but it is nevertheless digital and binary.

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