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Further Development of Autonomous Drive-by-Wire Hardware

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Thesis

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The rise of modern society has seen a growth in autonomous vehicle technology. As an answer to harsh weather issues that hinder most driver-less vehicles, Sensible 4 creates autonomous solutions for all weather conditions. A Sensible 4 project concerning retrofitting an electric vehicle is the main topic of this paper with a focus towards further drive-by-wire development. The main goal of this project is to establish a foundation for the manufacturing of the mentioned electric vehicle.

Signals essential for autonomous control were measured using an oscilloscope and analyzed for vehicle integration. Additionally, tests and comparisons between two Controlled Area Network (CAN) gateway devices were made for optimum monitoring, cable sizing was calculated utilizing conductor properties, protective devices were selected considering cable choices, and a system schematic diagram was created using computer-aided design software.

The result of the project is a stable foundation for the production of a driver-less electric vehicle which is retrofitted by Sensible 4. All features discussed in this paper will be utilized in the vehicle during its operation.

After retrofitting is concluded, the vehicle will be used in a fleet operation to provide driver-less and shared mobility in all weather conditions to busy urban areas.

Keywords	Autonomous Driving, Drive-by-Wire, CAN, Wiring, Schematic

Contents

List of Abbreviations

AD	Autonomous Driving
ADCU	Autonomous Driving Control Unit
CAN	Controlled Area Network
CSA	Cross Section Area
DbW	Drive by Wire
ECU	Electronic Control Unit
EMC	Electromagnetic Compatibility
OEM	Original Equipment Manufacturer
PC	Personal Computer
PWM	Pulse Width Modulation
VCU	Vehicle Control Unit

1 Introduction

Rapid advancements in modern technology have given rise to the development of vehicles capable of navigating through the environment without human control. Autonomous driving has become a pivotal subject towards the progress of vehicle technology. [1, 427.] However, many obstacles lay before the ultimate goal of creating a truly self-sufficient vehicle, and among them is the issue of harsh weather conditions which can severely limit the functionalities of sensors as indicated in a report by the U.S. Department of Transportation [2, 4].

Sensible 4 is a company founded as an answer to these weather concerns, and being primarily a software company, it produces autonomous solutions for any type of vehicle. In some projects, development of autonomous vehicles at Sensible 4 includes hardware design and implementation, which is the case in the project encompassing this thesis work. The particular subject of this thesis paper is the further development of hardware used in autonomous control of a vehicle with an electrical power-train. The development is done on the basis of the hardware previously developed by Sensible 4 for a conventional power-train vehicle.

A solid foundation towards autonomous hardware implementation into the electric vehicle is the central goal of this thesis work and the progression of development begins with understanding the requirements necessary to adapt to the electric power-train type and the constantly evolving Sensible 4 Autonomous Driving (AD) system. For successful integration, utilization of original vehicle signals is evaluated and further developed, which includes examination of the vehicle CAN system and its monitoring. In order to ensure uncorrupted operation, conductor dimensions used in the conventional power-train vehicle needed to be re-assessed and validated along with protective device selection and Electromagnetic Compatibility (EMC) considerations. Finally, sufficient documentation was required in the form of a schematic diagram for internal use in manufacturing and maintenance.

2 Technical and Theoretical Background

A closer technical inspection of the Sensible 4 AD system must be presented in order to proceed with the work done for this thesis project. This includes an overview of the AD structure, vehicle electronics, and theoretical background for conductor sizing and electromagnetic compatibility.

2.1 System Overview

An autonomous vehicle must be capable of perceiving its surroundings and navigating through the environment safely, without actions from a driver. A sufficient level of AD is achieved by utilizing a plethora of sensors, control units and actuators.

As mentioned previously, this project involves an electric power-train vehicle. The vehicle is retrofitted by Sensible 4 with an internally developed autonomous system, which is arranged in a hierarchical structure as indicated in Figure 1. Two distinct elements may be identified: the high level control system providing significant computational power, and the low level control structure managing autonomous actuators and vehicle signals.

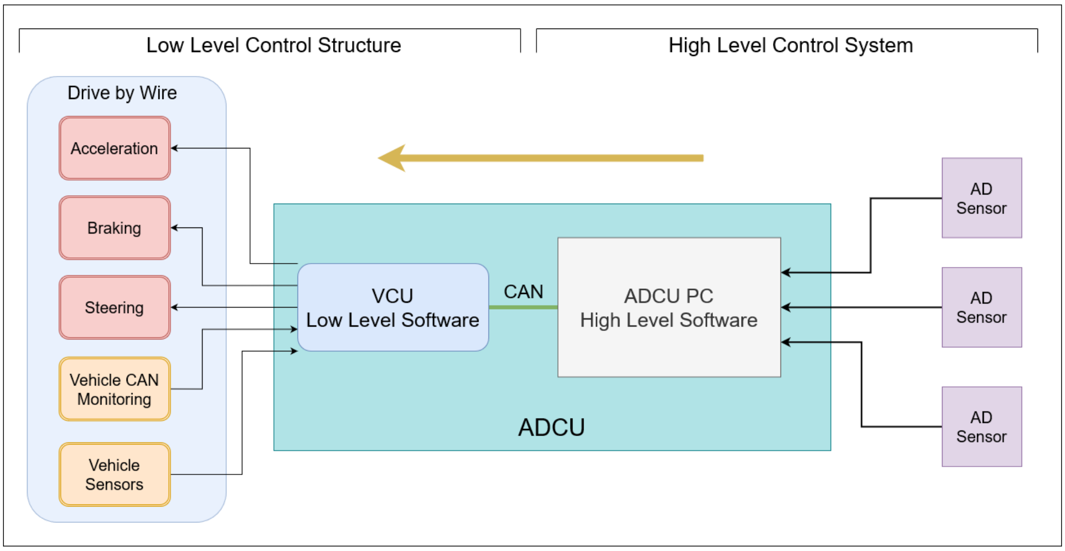


Figure 1: Overview of the system architecture

A number of AD sensors are placed along the vehicle profile in order to obtain as much visibility as required for sufficient autonomous operation. Data from these sensors is interpreted by the internally developed high level software and executed through a high performance Personal Computer (PC). During operation, the high level software performs localisation, obstacle detection and visualisation of the received data. Based on those, necessary vehicle maneuvering is determined by the AD control system and relayed to the low level Vehicle Control Unit (VCU) through a CAN bus.

Following the instructions from the high level software, the VCU performs the intended vehicle manipulation by means of Drive by Wire (DbW) which is explained in more detail in the following sub-section. In addition to the communication with high level software, the VCU contains multiple safety features, which are, similarly to all VCU features, implemented through the so-called low level software.

At the center of the Sensible 4 autonomous system stands an internally designed Autonomous Driving Control Unit (ADCU) hosting the aforementioned PC, VCU, secondary power distribution and certain local control units.

2.1.1 Drive by Wire

In the automotive industry, *drive-by-wire* refers to electrical systems that assist or replace traditional mechanical links in vehicles [3, 4]. Control systems such as steering, braking, fuel injection and other vehicle features are being controlled using electrical structures which are lesser in weight and offer superior diagnostic abilities.

A Sensible 4 DbW designed for this vehicle is installed in the car as the basis of low level autonomous control. It includes control of steering and braking with retrofitted actuators, acceleration manipulation, diagnostics, certain safety functions, and monitoring of vehicle CAN communication. As it was stated in the introduction to this paper, the electric vehicle DbW is further developed on the foundation of the DbW designed for the conventional power-train vehicle.

Certain vehicle original signals provide benefits that can be used in the autonomous operation system. Namely, the acceleration pedal position signal may be utilized and reproduced by the autonomous low level software to accelerate the vehicle. Similarly, the brake pedal position signal provides information on the brake pedal status which might require low level software action in certain cases. These particular signals are measured, compared to previous DbW designs and further developed during this project. Methods and results are shown in Section 3.1.

2.2 Dual Battery Operation

Seeing as an electric vehicle is the focus and subject of this project, attention needs to be paid to the change of traction system compared to the conventional power-train vehicle version.

In this electric vehicle, a high voltage traction battery is used as the main source of energy and naturally, provides power for the vehicle to locomote. In addition to the traction battery, a low voltage automotive battery is present for powering all 12V equipment and ancillaries, and instead of a typical alternator found in traditional power-train vehicles, a high-voltage DC-DC converter steps down the traction battery voltage in order to charge the 12V battery.

The Sensible 4 autonomous system includes an additional 12V automotive battery, which is added in parallel to the vehicle's own 12V battery. A separation relay controlled by the VCU is placed between the two low voltage batteries in order to isolate the Sensible 4 system and therefore, minimize the impact on the original vehicle system. The batteries are connected only when the monitored voltage is acceptable and the Original Equipment Manufacturer (OEM) system is powered. Otherwise, the batteries are disconnected so that the vehicle's original battery is never drained due to the additional Sensible 4 battery. Figure 2 provides a simplified diagram to demonstrate the main power architecture where the separation relay is reduced to a switch element.

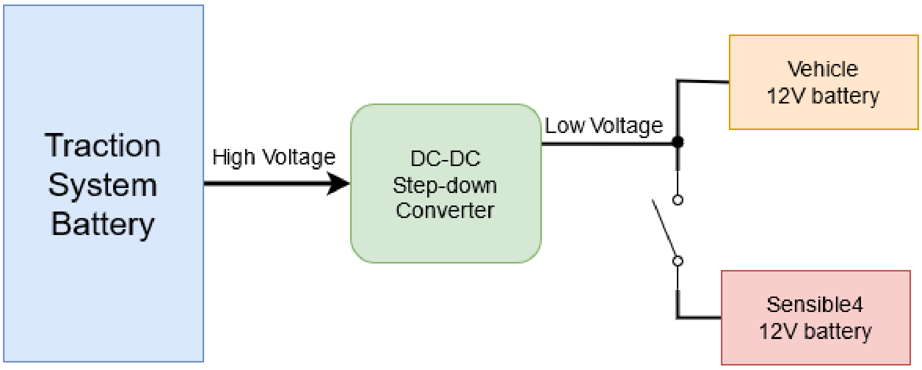


Figure 2: Vehicle power architecture with added Sensible 4 components in parallel

An issue that might arise with an additional battery is that the high voltage DC-DC power output limit is not sufficient to support two batteries and all the AD components. A severe stress test was performed by Sensible 4 colleagues on a traditional power-train vehicle to determine vehicle power consumption after the autonomous system was installed. Based on these experimental results and the converter manufacturer specification, it was concluded that the converter is sufficiently capable of handling the power requirement.

2.3 CAN Bus Isolation Necessity

CAN bus is a serial, high speed communication protocol with a differential pair of wires as the physical medium. It was originally developed for use in the automotive industry and therefore, a large number of CAN buses can be found in modern vehicles as communication among many control units and peripherals. [4, 464-467.]

Utilizing the information shared in the vehicle CAN network lessens the effort of creating abundant monitoring systems since some vehicle original sensors might already provide advantageous data. The desired approach for observing the vehicle CAN network is for the VCU to read all useful vehicle CAN information and act accordingly. Unfortunately, the VCU model used in this project possesses only four CAN channels, two of which are used in the Sensible 4 DbW system. Therefore, only two channels are left for monitoring vehicle CAN.

Due to the fact that the CAN protocol uses a pair of differential signals, and a twisted pair of wires is standardised for those signals, it is robust and resistant to interference.

However, it has been observed internally at Sensible 4, that monitoring connections to the vehicle CAN system are not as straightforward as they might seem. Long cable additions and possible device incompatibility issues result in errors from vehicle diagnostics which might disrupt operation even though the vehicle is essentially functional. For this reason, it is desired to galvanically isolate the Sensible 4 components from the vehicle CAN bus wiring as close to the wire splits as possible. This is especially prudent in case of failure in the Sensible 4 system so that the vehicle original CAN bus may be restored nearly to the original state of function, which minimises the impact on vehicle's own systems.

In addition, since the vehicle CAN network provides useful information for the AD system, it is prudent to monitor as many vehicle CAN buses as possible. Furthermore, only certain messages from a single CAN channel are useful in autonomous operation. As stated before, the VCU has a limited amount of monitoring channels, therefore, it is crucial to find a device that acts as a CAN gateway/router and has galvanically isolated CAN transceivers that have the ability to couple CAN channels with different specifications. The process of testing and selecting a sufficient device will be described in Section 3.2.

2.4 Electromagnetic Compatibility

An autonomous vehicle contains a large amount of supervision and control signals, many of whom are system critical. It is important therefore, to protect those signals from external interference and ensure steady operation without interruption. In this project, only EMC regarding cabling shall be considered. Essentially, there are three types of electromagnetic coupling that might be considered when cables are discussed: capacitive coupling, inductive coupling, and electromagnetic coupling which is the combination of the former two in far field situations [5, 44].

Capacitive coupling results from the interaction of electric fields between circuits near each other. Figure 3 presents a theoretical representation of capacitive coupling between two conductors. According to *Henry W. Ott* [5, 44], the induced noise voltage from one cable to another may be reduced to Equation (1) in most practical cases, where ω is the angular frequency of the source, R is the resistance of the circuit connected to conductor 2, C_{12} is the stray capacitance between the conductors, and V_1 signifies the source of interference.

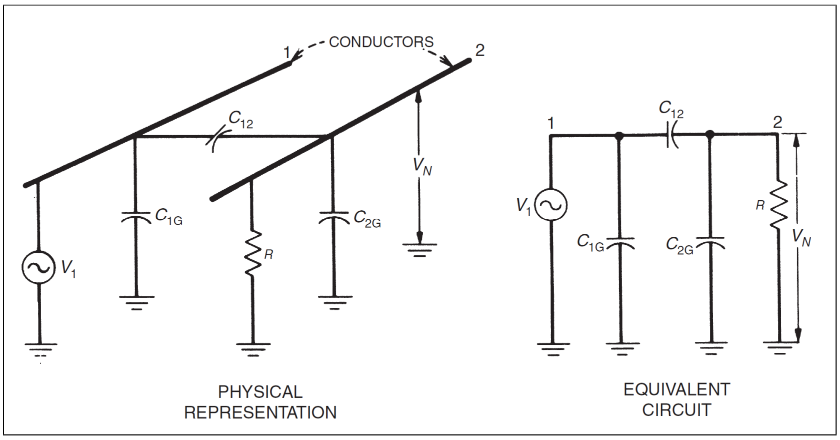


Figure 3: Capacitive coupling between two conductors. Reprinted from [5, 45]

$$V_N = j\omega RC_{12}V_1 \qquad [V] \tag{1}$$

Inductive coupling however, appears as a result of a magnetic field produced by a current flowing through a conductor. Similarly to the capacitive coupling case, Figure 4 shows an inductive coupling representation.

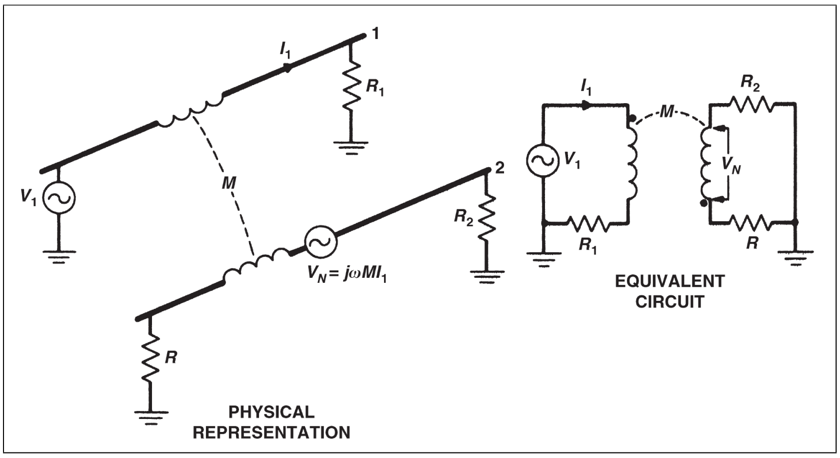


Figure 4: Inductive coupling between two conductors. Reprinetd from [5, 53]

Induced noise voltage to a conductor can be determined with Equation (2) in which M is the mutual inductance between two circuits, and I_1 is the current passing through the source conductor.

$$V_N = j\omega M I_1 \qquad [V] \tag{2}$$

Precise calculations of induced noise voltages are complicated, especially in cases where there is no constant alternating sources, but rather un-even changes in current flow and voltage levels. However, the information laid out in this sub-section will serve as moderate guidance towards EMC.

2.5 Wire Dimensioning and Protection

In order to ensure that the planned electrical system is working as intended, the cabling needs to have sufficient current carrying capabilities. In addition to that, it is crucial to plan for a proper safety system to protect the devices and cables, but most importantly, to avoid any accidents that could cause harm to humans.

Initially, a suitable cross-section area is determined for nominal current situations which is followed by ascertaining sufficient short circuit protection. Finally, the length of the cable is evaluated in the case of a fault current and adjustments are made in case a discrepancy is found.

2.5.1 Cross-Sectional Area

Choosing the right type of cable depends on multiple factors, namely length, required cross-sectional area, voltage, current and insulation to name a few. Furthermore, it is closely related to the choice of the fuse protecting the particular device. An important cable characteristic to consider is its resistance dependent on the conducting material resistivity (ρ), length (L) and cross-sectional area (A). The resistance is calculated using Equation (3). It needs to be noted that the majority of device power delivery cables in this project do not utilize the so-called chassis-ground return, therefore, the length is multiplied by two to take the full path into account. In cases where the device is virtually connected to the chassis-ground directly such as the main power cables, the mentioned multiplier is omitted.

$$R = \rho \cdot \frac{2L}{A} \qquad [\Omega] \tag{3}$$

Certain locations in the vehicle experience temperature rises which is a potential risk due to the fact that the resistance of the conductor rises as well. It is therefore prudent to take the temperature difference immediately into account so as not to require separate resistivity calculations for different cases. The resistivity then takes the form implanted into Equation (4), [6, 140]. ρ_0 represents the resistivity of the conductor at 20°C, α is the temperature coefficient of the conductor, T is the maximum temperature the cable insulation can handle, and T_0 = 20°C.

$$R = \rho_0 \cdot [1 + \alpha(T - T_0)] \cdot \frac{2L}{A} \qquad [\Omega] \tag{4}$$

During vehicle operation, the chosen cable for a certain device will have a voltage drop across it. The idea is to minimize this drop as much as possible while paying attention to cable cost and reasonable size. Due to power supply ranges of utilized devices, it is accepted that a 5% voltage drop across a conductor is reasonable for the purpose of power delivery [7, G19]. The voltage drop can be calculated simply by utilizing Ohm’s Law as indicated by Equation (5), which will prove useful in determining the minimum cross-sectional area. Naturally, I is the nominal current through the conductor, and R signifies the resistance of the cable.

$$V_{drop} = I \cdot R \qquad [V] \tag{5}$$

After understanding these two aspects, the task is to determine the cross-sectional area of the wire according to the nominal current consumption of the device (I), acceptable voltage drop (V_{drop}), length (L) and particular choice of cable. Re-arranging and combining Equation (4) with Equation (5), Equation (6) is obtained for calculating minimum Cross Section Area (CSA) needed for typical operation.

$$A = \rho_0 \cdot [1 + \alpha(T - T_0)] \cdot \frac{I \cdot 2L}{V_{drop}} \qquad [mm^2] \tag{6}$$

After a suitable conductor CSA is discovered with Equation (6), its protection may be defined as described in the following section.

2.5.2 Short Circuit Protection

In the event of device malfunction, there is a possibility of a short-circuit which could potentially be dangerous due to high currents. Following the calculation for an adequate cross-section, the short circuit capability of the cable needs to be inspected and an appropriate fuse needs to be selected. It is of vital importance to select a fuse that will disconnect the faulty path before the conductor melts and causes further damage to the designed system. For this choice, the thermal constraints of the conductor need to be determined. In other words, it is important to calculate the time it takes for the conductor to melt under the short circuit current. In this case, the 12V battery specifications determine the minimum short-circuit current that could occur.

The time (t_c) the conductor can withstand the short-circuit current may be calculated using Equation (7), where k is a factor dependent on the insulating material, A is the cross-sectional area of the conductor, and I_{sc} is the minimum short-circuit current that could occur. It is necessary to take into account that Equation (7) is only valid when t_c is less than 5 seconds. [7, G30.]

$$t_c = \frac{k^2 \cdot A^2}{I_{sc}^2} \qquad [s] \tag{7}$$

Now that the time constraint of the conductor is known, a proper fuse may be selected. In addition to the voltage rating, the most important characteristics to consider are the fuse nominal current rating and the I^2t parameter stating the thermal energy at which the fuse element melts. First of all, the desired current at which the fuse trips (Ia), needs to be less than the short circuit current that the source can provide so that the fuse trips before the short-circuit current appears.

Using the time-current characteristic diagram in the data-sheet of the particular fuse under evaluation, it can be determined how long it takes for a fuse to trip at a certain current. Taking the time-current characteristic and the stated maximum continuous current of the device into account, a proper fuse can be selected.

2.5.3 Maximum Length

Finally, the previous calculations need to be considered in determining the maximum length for the used cable. If the maximum length is exceeded, there is a possibility that the chosen cross-section area and/or fuse would not behave as expected.

To determine the maximum length, it is accepted that the voltage at the fuse will be 80% of the nominal voltage during short-circuit [7, G31]. In this calculation, the current is considered to be the tripping current of the fuse (I_a), since that is the maximum current that would occur before the fuse disconnects the device. The current may be seen in Equation (8), where U is the supply voltage of the system and R is the calculated resistance of the conductor.

$$I_a \leq \frac{0.8 \cdot U}{R} \tag{8}$$

Re-arranging the conductor resistance Equation (4), and substituting the information from Equation (8), Equation (9) can be obtained, which is used to review the maximum length that can be used for the selected cross-section area and protection device.

$$L \leq \frac{0.8 \cdot U \cdot A}{2 \cdot I_a \cdot \rho_0 \cdot [1 + \alpha(T - T_0)]} \tag{9}$$

3 Methods

Practical work executed for this project shall be described in this chapter. To begin with, essential DbW signals are measured and evaluated. Then, a solution for a CAN isolation and gateway device is found and tested which is followed by the dimensioning of cables and fuse selection. Finally, the development of the electrical schematic of the system is explained.

3.1 Vehicle Original Signals

There are two significant vehicle signals that need to be considered in this project in order to further develop the Sensible 4 DbW system. Namely, the acceleration pedal position and brake pedal position signals. To begin with, these signals are measured in the electric vehicle and compared with their counterparts in the traditional power-train vehicle. Further development to the autonomous DbW is then made according to those measurements.

3.1.1 Brake Intention Signal

It was found that in the electric version of the vehicle, there is a sensor measuring the brake pedal position and it is used to detect the drivers intention to actuate the pedal. Due to the fact that this sensor is not present in the conventional power-train vehicle, it needs to be investigated so that its purpose could be discovered. Furthermore, it needs to be determined whether this signal should be integrated into the system under development.

The measurement was done using the PicoScope 4425A oscilloscope manufactured by Pico Technology. Four channels were utilized to connect to each of the pins of the sensor connector while it was in its original place in the vehicle. A screenshot of the measurement in Picoscope 6 Automotive software can be seen in Figure 5.

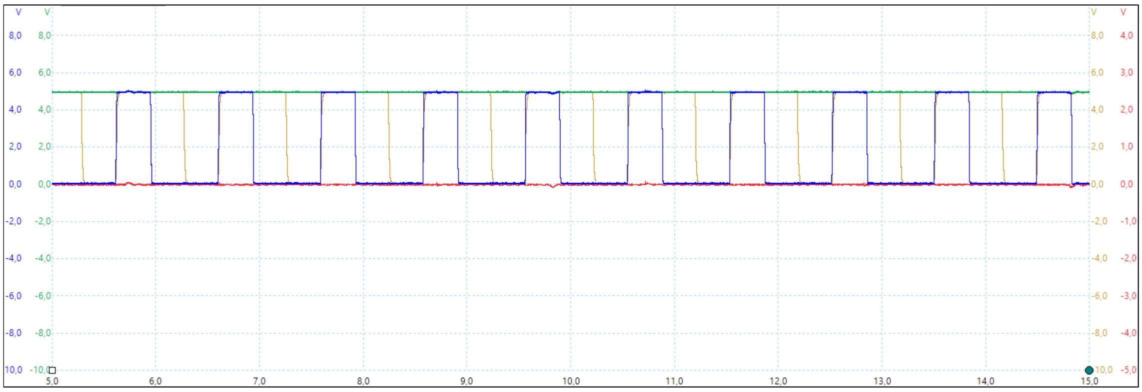


Figure 5: Measurement of the brake intention sensor copied from PicoScope 6 Automotive

By observing the oscilloscope display, it is evident that the green and red channels represent the 5V supply and supply ground respectively. Additionally, there are two square wave signals observed through the blue and yellow channels. A precise parameter measurement was created in the PicoScope 6 software to obtain more information about these square waves, specifically their frequency and duty cycle. The result can be seen in Figure 6 with no activity in pedal movement.

Channel	Name	Value	Min	Max	Average	σ	Capture Count	Span
D	Duty Cycle	66,1 %	66,1 %	66,1 %	66,1 %	0,000 %	1	Whole trace
D	Frequency	1,014 kHz	1,014 kHz	1,014 kHz	1,014 kHz	0 Hz	1	Whole trace
A	Duty Cycle	33,9 %	33,9 %	33,9 %	33,9 %	0,000 %	1	Whole trace
A	Frequency	1,014 kHz	1,014 kHz	1,014 kHz	1,014 kHz	0 Hz	1	Whole trace

Figure 6: PicoScope measurement results for duty cycle and frequency of channel A (blue) and channel D (yellow)

According to the PicoScope 6 measurement, the frequency for each of the square wave signal was 1kHz. Additionally, the duty cycles of these signals were 34% for the blue channel, and 66% for the yellow channel while the pedal was released completely. Pressing the pedal resulted in the duty cycles shifting until both of them were at 50% when the pedal was fully pressed. Considering these measurements, it was concluded that the square waves are Pulse Width Modulation (PWM) signals with inverted duty cycles between them, indicating pedal travel to the vehicle drive-train control unit.

Since the change in duty cycle appeared to only be approximately 15%, it was challenging to determine whether this change is linear across the full sensor travel. Therefore, the sensor was disconnected and taken out of the vehicle so that its full range may be tested. The PicoScope oscilloscope was again used to observe the PWM signals with enabled measurement tracing which created a clear graph of the duty cycle variation. The sensor was then manually rotated to its full extent. As can be seen in Figure 7, the duty cycle variation is linear across the full sensor travel. In addition to linearity, the graph demonstrates the complete functionality of the sensor with the horizontal axis representing the sensor angle in degrees, and the vertical axis representing the duty cycle percentage.

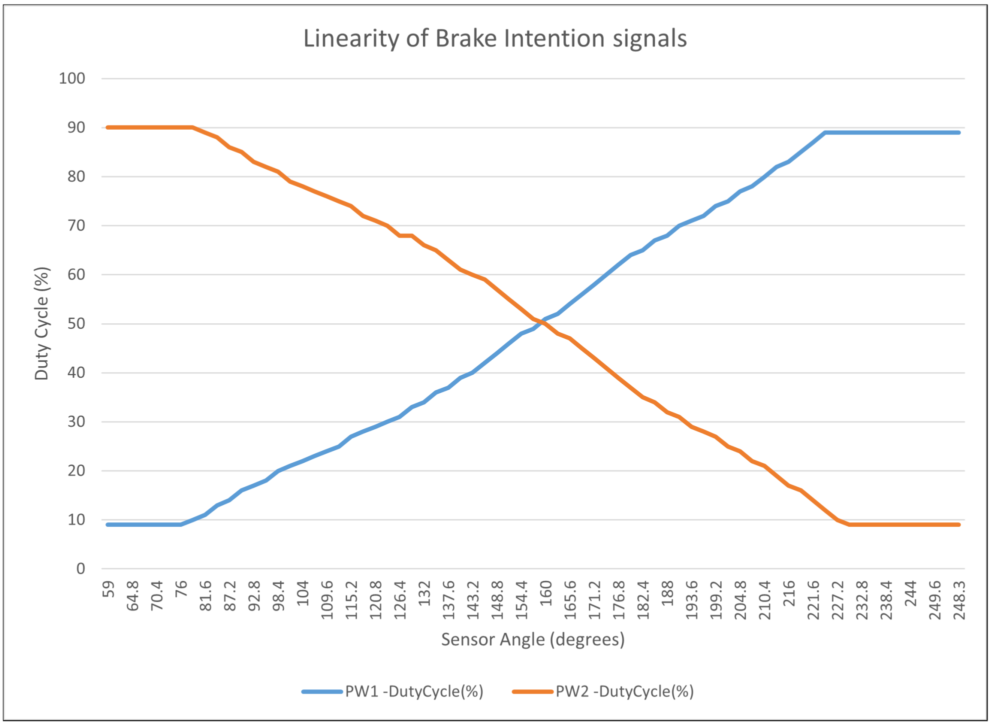


Figure 7: Measurement of brake intention duty cycle linearity. Horizontal axis: sensor angle in degrees. Vertical axis: PWM duty cycle

In the vehicle's own system, in addition to the brake intention sensor, a simple switch is located at the brake pedal which serves the purpose of informing a control unit that pedal travel has begun. The AD braking is designed so that during autonomous operation, the brake pedal is actuated by a linear actuator to constantly linger at the point where brake pressure starts to activate the brakes. This is intended to shorten the delay in autonomous braking. Unfortunately, the vehicle's brake switch then indicates that the brake pedal is being pressed and therefore acceleration can't be requested for safety reasons. In the Sensible 4 DbW of the traditional power-train vehicle, the switch is simply physically moved so that it is activated later in the pedal travel thus solving the issue. This solution is adopted into the DbW for the electric vehicle. Because of that, there exists a narrow window of pedal travel where the brake pedal switch and the brake intention sensor output divergent information about the status of the brake pedal.

Avoiding miss-matched signals that could potentially introduce errors in vehicle original diagnostics is important for reliable autonomous vehicle operation. Therefore, after the study of the brake intention sensor, it was concluded that it needs to be simulated by the VCU, which is capable of outputting PWM signals appropriate for this purpose. In order to easily switch between the OEM signal source and the simulated AD source, two relays were designed to be placed between the VCU and the OEM wiring. This can be seen in Figure 8.

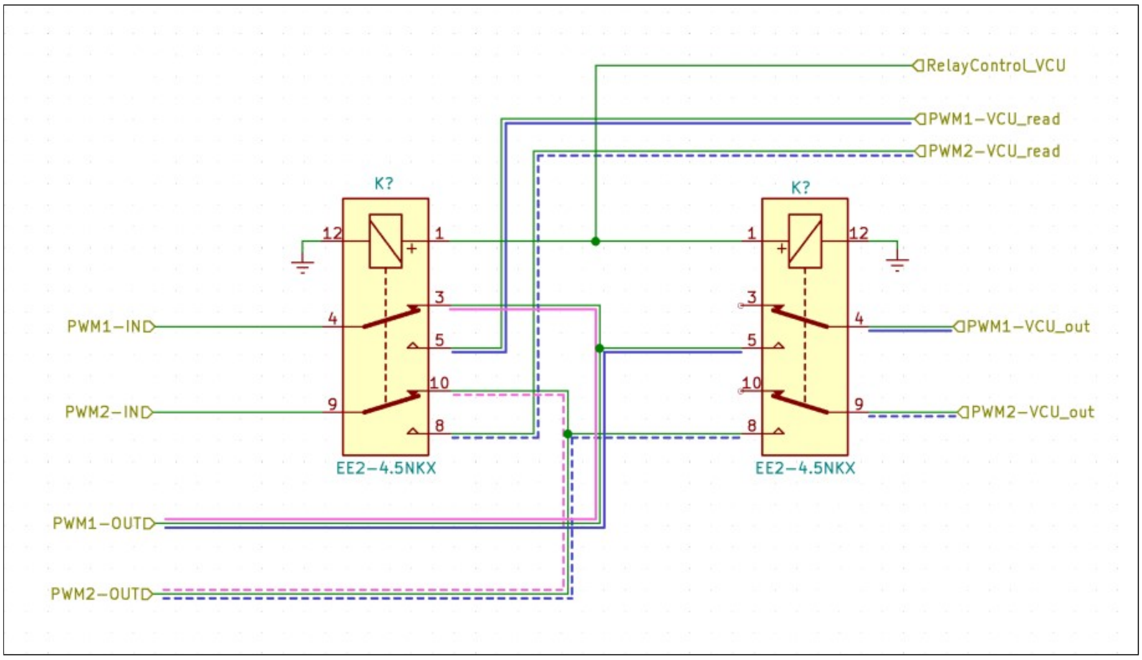


Figure 8: Representation of brake intention signal relays

During manual driving, the PWM signals are simply routed back and the original signal path is preserved as indicated by the pink lines. In contrast, during autonomous operation, the VCU reads the two PWM signals and reproduces a similar output with adjustments regarding the aforementioned brake pedal travel difference. This is represented by the blue lines in Figure 8.

3.1.2 Accelerator Pedal Signals

In the previous project it was found that the accelerator pedal position is determined by utilizing two Hall-effect sensors that are read by the vehicle's own Electronic Control Unit (ECU) as two analog signals with different linear slopes. Oscilloscope measurements with the Picoscope 4425A proved that these signals are identical to their counterparts in the conventional power-train version of the vehicle. Furthermore, it was discovered that these signals provide up to 99.5% of acceleration request. To achieve the desired acceleration and speed, these signals are reproduced by the VCU during autonomous operation similarly to the brake intention signals. Given that this strategy has worked well in the conventional power-train vehicle project, no intention was made to modify it.

In addition to the pedal position signals, it has been learned previously that a pedal point of resistance switch (part of the vehicle original system) is activated at the end of pedal travel. By experimental tests, it was realized that this switch, when triggered, overrides the vehicle speed limit set by the cruise control or it may be used for a more aggressive acceleration. In certain marginal situations, there is a discrepancy between the VCU simulated acceleration pedal position and the point of resistance switch. An example of this is if the vehicle is operating in autonomous mode and the VCU is sending a certain simulated pedal travel signal. In case there is a valid reason for the vehicle operator to rapidly press the pedal fully, the vehicle diagnostics will generate an error due to the disparity of the switch being activated while the simulated signal is not indicating full pedal travel.

In order to determine a solution for this obstacle, the signal of the point of resistance switch was measured with PicoScope 4425A oscilloscope, results of which are shown in Figure 9. In the measurement, the blue channel demonstrates the voltage level of the signal pin, and the red channel shows the resistance to the chassis-ground. When the pedal is not pressed to the point of resistance, the output voltage level from the sensor is at 4V and the resistance to ground is virtually infinite. Once the limit switch is triggered, the output voltage drops to approximately 800mV, and the resistance measurement displays 2.5kΩ. Furthermore, it was discovered that the point of resistance switch signal provides the range from 99.5% to 100% of throttle request.

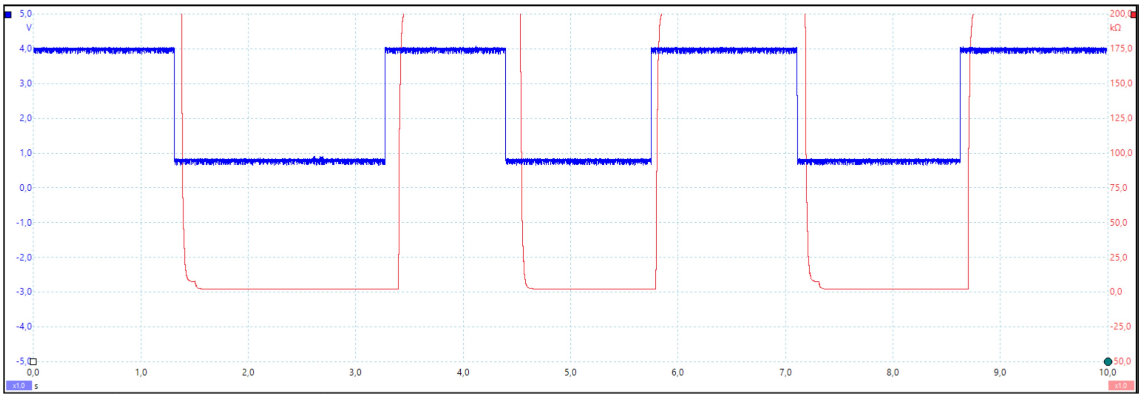


Figure 9: Picoscope measurement of the point of resistance switch

Since there is no extensive information from the manufacturer about this particular sensor, the pedal was disassembled in order to obtain more information and to investigate possibilities for mitigation of discrepant signals. It was discovered that the switch is not accessible and therefore no physical modifications could be done to the actual component. Due to the fact that this signal is not safety critical, a simple solution is to mechanically limit the whole pedal so that it reaches the point of resistance, but no further so as not to activate the switch. This solution would not require cumbersome reverse engineering and the acceleration request of 99.5% would be sufficient for the intended purpose of the vehicle.

3.2 CAN Gateway Solution

The premise and requirement for a CAN gateway was already stated in the technical background section as a necessity for a galvanically isolated CAN interface that has the ability to route desired messages from multiple vehicle CAN channels to the VCU.

Two devices were found to be sufficient for the purpose and were chosen to be studied closely. Namely, the *Ixxat CANbridge NT 420*, and *PCAN-Router Pro FD*. Study and comparison was planned to be accomplished by setting up a test for these two interfaces and comparing their abilities before selecting one of them for use in the vehicle.

The test was devised according to the current CAN monitoring in traditional power-train vehicles. Two vehicle CAN channels were connected to the device under test, and one channel was connected through a PCAN-USB device to a PC acting as the VCU so as to confirm that only the required messages are routed through to the monitoring channel. Both gateways were programmed to forward only desired messages, prior to the test. The diagram describing the test set-up can be seen in Figure 10.

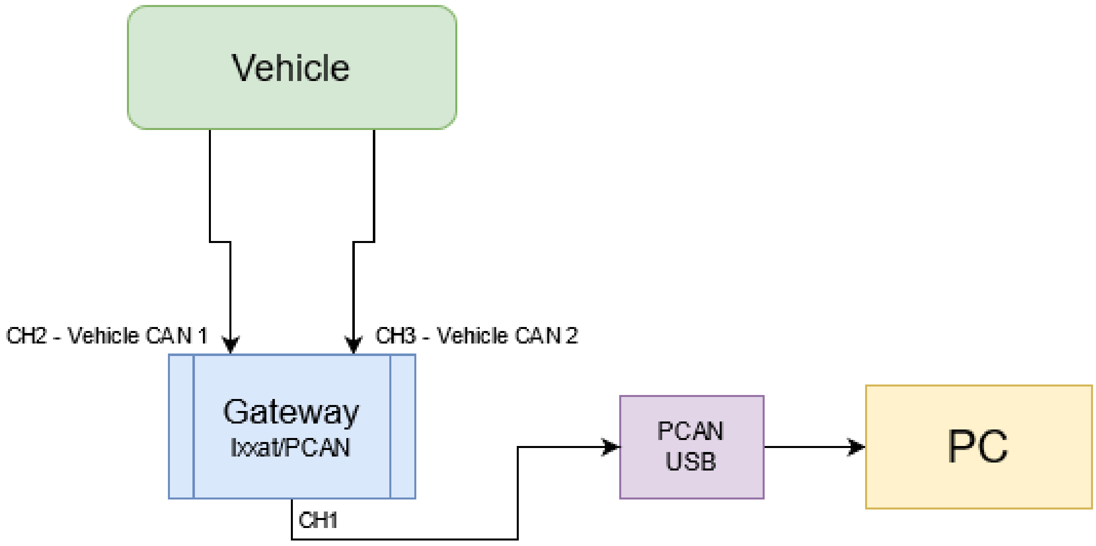


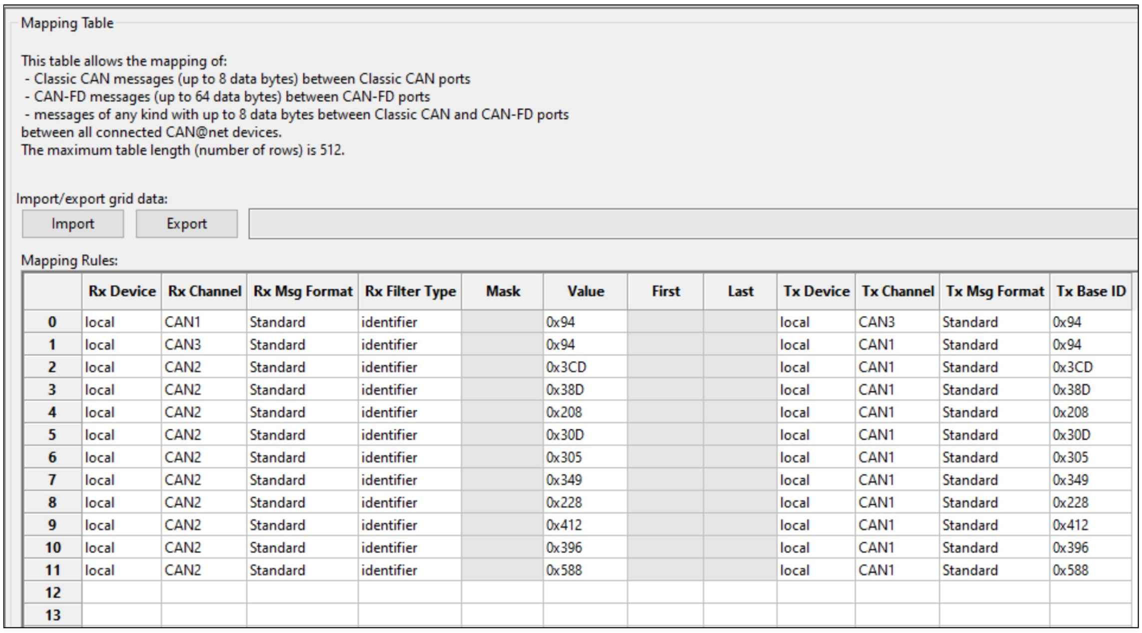
Figure 10: Diagram of the gateway test

Each of the devices will be described in more detail in the following sub-sections.

3.2.1 Ixxat CANbridge NT 420

”The CANbridge NT is a universal, intelligent CAN topology component, that allows the coupling of several CAN networks with different baud rates or frame formats” [8, 6]. The CANbridge NT 420 has four available CAN channels and by default, galvanically isolated CAN transceivers.

The manufacturer of the device offers an intuitive graphical software interface for device set-up and CAN message mapping. First, and foremost, the baud rate for each channel is set according to the baud rate of the vehicle channel connected to it. Following that, a mapping table shown in Figure 11 is created for forwarding only desired messages to designated channels.


Mapping Table

This table allows the mapping of:
- Classic CAN messages (up to 8 data bytes) between Classic CAN ports
- CAN-FD messages (up to 64 data bytes) between CAN-FD ports
- messages of any kind with up to 8 data bytes between Classic CAN and CAN-FD ports
between all connected CAN@net devices.
The maximum table length (number of rows) is 512.

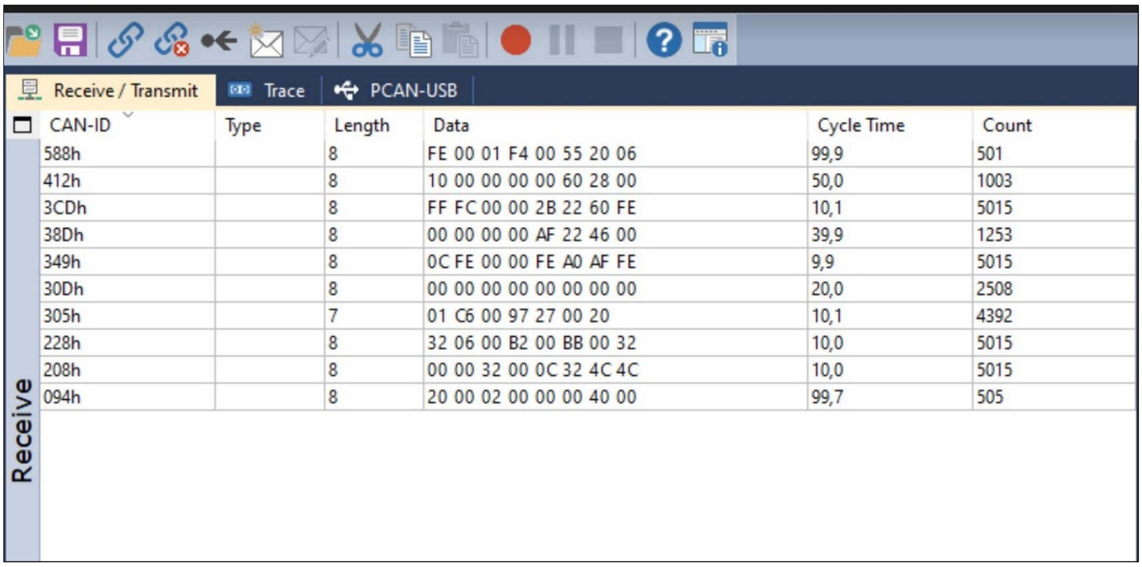
Import/export grid data:
Import Export

Mapping Rules:

	Rx Device	Rx Channel	Rx Msg Format	Rx Filter Type	Mask	Value	First	Last	Tx Device	Tx Channel	Tx Msg Format	Tx Base ID
0	local	CAN1	Standard	identifier		0x94			local	CAN3	Standard	0x94
1	local	CAN3	Standard	identifier		0x94			local	CAN1	Standard	0x94
2	local	CAN2	Standard	identifier		0x3CD			local	CAN1	Standard	0x3CD
3	local	CAN2	Standard	identifier		0x38D			local	CAN1	Standard	0x38D
4	local	CAN2	Standard	identifier		0x208			local	CAN1	Standard	0x208
5	local	CAN2	Standard	identifier		0x30D			local	CAN1	Standard	0x30D
6	local	CAN2	Standard	identifier		0x305			local	CAN1	Standard	0x305
7	local	CAN2	Standard	identifier		0x349			local	CAN1	Standard	0x349
8	local	CAN2	Standard	identifier		0x228			local	CAN1	Standard	0x228
9	local	CAN2	Standard	identifier		0x412			local	CAN1	Standard	0x412
10	local	CAN2	Standard	identifier		0x396			local	CAN1	Standard	0x396
11	local	CAN2	Standard	identifier		0x588			local	CAN1	Standard	0x588
12												
13												

Figure 11: Ixxat CAN configurator software

During the test, the device performed exactly as desired with no issues regarding the coupling of channels with different baud rates and specifications. Furthermore, all the desired messages were visible in the *PCAN-View* software used to read CAN messages on a PC as shown in Figure 12.


Receive / Transmit Trace PCAN-USB

Receive

CAN-ID	Type	Length	Data	Cycle Time	Count
588h		8	FE 00 01 F4 00 55 20 06	99,9	501
412h		8	10 00 00 00 00 60 28 00	50,0	1003
3CDh		8	FF FC 00 00 2B 22 60 FE	10,1	5015
38Dh		8	00 00 00 00 AF 22 46 00	39,9	1253
349h		8	0C FE 00 00 FE A0 AF FE	9,9	5015
30Dh		8	00 00 00 00 00 00 00 00	20,0	2508
305h		7	01 C6 00 97 27 00 20	10,1	4392
228h		8	32 06 00 B2 00 BB 00 32	10,0	5015
208h		8	00 00 32 00 0C 32 4C 4C	10,0	5015
094h		8	20 00 02 00 00 00 40 00	99,7	505

Figure 12: View of the PCAN-View software used to read CAN messages

The advantages of the *CANbridge NT 420* are its compact size, simplicity of graphical configuration, and lower cost. In contrast, a downside is the amount of available CAN channels that would require two cascaded gateways to be used. An additional downside is the mechanical wire contact type of the device, which is a wire screw-in terminal. This type of connection potentially places stress on the wires unless additional support is designed.

3.2.2 PCAN-Router Pro FD

The *PCAN-Router Pro FD* is a six channel CAN gateway with flexible CAN transceiver options, CAN FD capabilities, and 4 digital inputs/outputs [9, 5]. Galvanic isolation is not a built in feature, and therefore, a specialized *TJA1044-ISO* transceiver was requested from the manufacturer.

Firmware for the device is created using the manufacturer development package with GNU compiler for C and C++ programming languages. This requires knowledge of C++, and therefore configuration is not as straightforward as the *Ixxat CANbridge NT 420*.

The development package supplied by *PEAK System* contains a C compiler, build tools, code examples of basic functionalities, and a flashing tool for transferring the compiled binary executable files to the device. *Visual Studio Code* was used to develop a custom firmware built on example code from the manufacturer.

Initially, the baud rates for each CAN channel are set with Listing 1.

```
static const CANTiming_t  Timing_CANx[6] = {
_40M_500K_80____4M_80_ISO,^^I  // CAN1
_40M_500K_80____4M_80_ISO,^^I  // CAN2
_40M_125K_80____1M_80_ISO,^^I  // CAN3
_40M_500K_80____4M_80_ISO,^^I  // CAN4
_40M_500K_80____4M_80_ISO,^^I  // CAN5
_40M_500K_80____4M_80_ISO^^I  // CAN6    };
```

Listing 1: C++ code for setting CAN channel baud rate

Following that, the messages that should pass through the filter are added as noted in Listing 2 with *RangeLow* and *RangeHigh* representing low and high limits of the message ID range desirable for the filter.

```
CAN_FilterAdd ( CAN_BUS2, CAN_MSGTYPE_STANDARD, 0xRangeLow, 0xRangeHigh)
```

Listing 2: C++ code line for including a message ID to the filter

Finally, the message routing is executed by a simple *switch-case* function nested in an *if* statement. The initial part of that code is presented in Listing 3 to demonstrate the working principle. If there are no existing errors in the *message receive* function for any of the channels, a *switch-case* statement runs through each channel and forwards their filtered messages to the monitoring channel from which the VCU reads.

```
if ( CAN_UserRead ( CAN_BUSX, &RxMsg) == CAN_ERR_OK)
{
    switch ( RxMsg.hBus)
    {
        case CAN_BUS2:   // message received from CAN_Ch2

        CAN_Write ( CAN_BUS1, &RxMsg);  // forward message to CAN_Ch1
        break;
```

Listing 3: C++ code for routing messages from channel 2 to channel 1

The *PCAN-Router Pro FD* proved successful in the test with no discovered issues. The results were identical to the *Ixxat CANbridge NT 420* results presented in Figure 12.

A disadvantage of the *PCAN* gateway is its considerable size, and what might be considered as complicated firmware development. However, the firmware development in C++ allows for higher customizability and more features are available because of the digital inputs and outputs of the device. In addition, this device grants 6 channels which is deemed sufficient for desired operation and in regards to mechanical connections, *D-SUB9* connectors needed for the interface will alleviate undesired stress on the cables.

3.2.3 Solution Overview

The gateway test proved that both gateways are capable of producing the same satisfactory results, thus the selection falls in terms of practicality and accessibility. Since the *PCAN-Router Pro FD* offers a larger amount of CAN channels and higher flexibility with firmware, it was selected for use in the vehicle.

Four vehicle CAN channels are fed into the gateway and their messages are routed to channel 1 from which the VCU reads the filtered information. A diagram describing this may be seen in Figure 13.

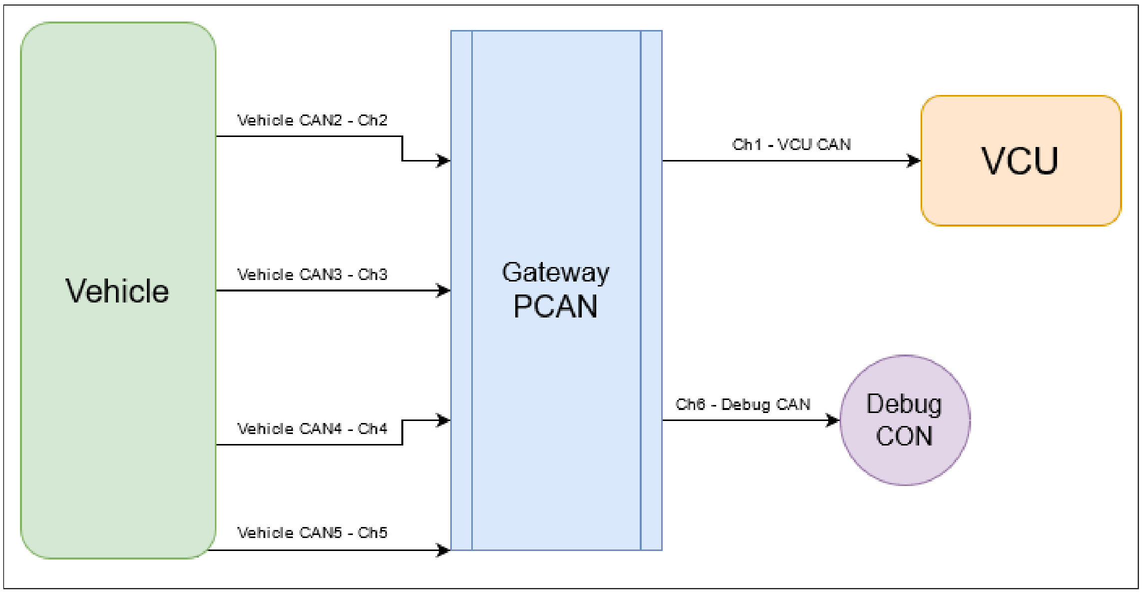


Figure 13: Overview diagram of the final solution

The final gateway channel is planned to be used for debugging and research purposes. Digital input capabilities of the device will be used to select which channel is routed to the debugging port in order to alleviate cluttering that would occur if all channel messages were routed to a single port. This feature is beyond the scope of this thesis and shall be developed in the future.

3.3 Selection of Cables and Protective Devices

A previous chapter section 3.2 described the theory behind choosing conductors and protective devices. Those methods and equations were used to evaluate an internally developed Sensible 4 interactive calculator used for swift calculations of cable sizes and fuse ratings. An example of the calculator usage may be seen in Figure 14. By providing information about nominal voltage, nominal current, desired cable length, cable characteristics, power source specifications, and intended fuse details, a minimum CSA is calculated and presented in the lowest cell block. Considering this result, a suitable CSA is selected according to practical considerations. The selected CSA is then fed back into the calculator for validation of selection.

It should be noted that only copper conductors are to be used in this project and therefore, resistivity of copper at reference temperature is chosen and adjusted to square millimeters as $\rho_0 = 1.7 \times 10^{-8}$ Ωm. Similarly, the temperature coefficient of resistivity is taken as $\alpha = 0.0039$ per °C. [10, 775-786.]

DC cable dimensioning calculator			
System parameters			
Variable	**Define value:**	**Units**	**Details**
U	12.0	V	Nominal voltage
I_nominal	1.0	A	Nominal current
I_sc	300.0	A	Short-circuit current capability (e.g. car battery)
I_a	10.0	A	Fusion current (breaking capacity) of fuse at t_c
I2t_fuse	2.8	A2s	Check tab "fuse ratings" or manufacturer's specs
L	5.0	m	Length of conductor
V_drop	5.0	%	Max allowed voltage drop percentage
Ch_return?	☐	bool	Chassis return (one-way loss) for current
Insulator	PVC	list	Insulation material of copper conductor
T	60.0	C	Max operating temp of conductor insulator
Chosen A	0.50	mm2	Chosen gauge. Must be bigger than Minimum below
Results			
Parameter	**Value**	**Units**	**Details**
V_drop	0.600	V	Voltage drop at nominal V
ρ	0.020	Ωm	Resistivity at the given temperature T
Resistance	0.300	Ω	Total resistance of conductor
t_c	0.037	s	Time of conductor thermal constraint (valid for <5s)
L_max	24.174	m	Maximum length allowed at I_a (valid for t_c<5s)
I2t at I_a	3.674	A2s	Melting I2t=square pulse I2t
A	0.331	mm2	Minimum CSA (gauge)

Figure 14: Internally developed conductor dimensioning calculator

Due to their reliability, all selected fuses are manufactured by *Littlefuse*. In order to ensure desired stability though, the manufacturer's recommendations need to be taken into account. In the *Littlefuse Fuseology Selection Guide* [11, 2] it is recommended that fuses be operated at no more than 75% of the nominal current rating established in test conditions at 25°C. Therefore, taking a 5A rated fuse as an example, the nominal current of the device protected by that fuse should not exceed 3.75 amperes so as not to trigger a false disconnection in real-world conditions.

Another subject to consider in fuse selection regards operation where a hierarchical power distribution is employed. Such is the case in the subject of this thesis. The 12V battery is followed by the main power distribution block containing larger fuses that protect individual subsystems, which in turn contain secondary fuses to protect individual devices. The main intention of device fuses is to protect the device, and the point of the main fuses is to protect the subsystem in case of a wiring fault in between the primary and secondary power distribution block.

Fuse selectivity is a design method to ensure that low-level fuses act quicker than the fuses protecting their subsystem. If selectivity is achieved, only the malfunctioning area will be affected by the fuse interruption. A descriptive diagram demonstrating this idea is presented in Figure 15. In the case that the main fuse interrupts quicker than a device fuse, all systems under that particular main fuse shall be rendered inoperative.

In order to adhere to fuse selectivity, the fuse interruption time needs to be known for the desired interruption current explained in the theory chapter. The time-current curve presented in the particular fuse datasheet gives insight to the time it takes for the fuse to melt at a certain current and those diagrams were used to ensure desired operation in this project.

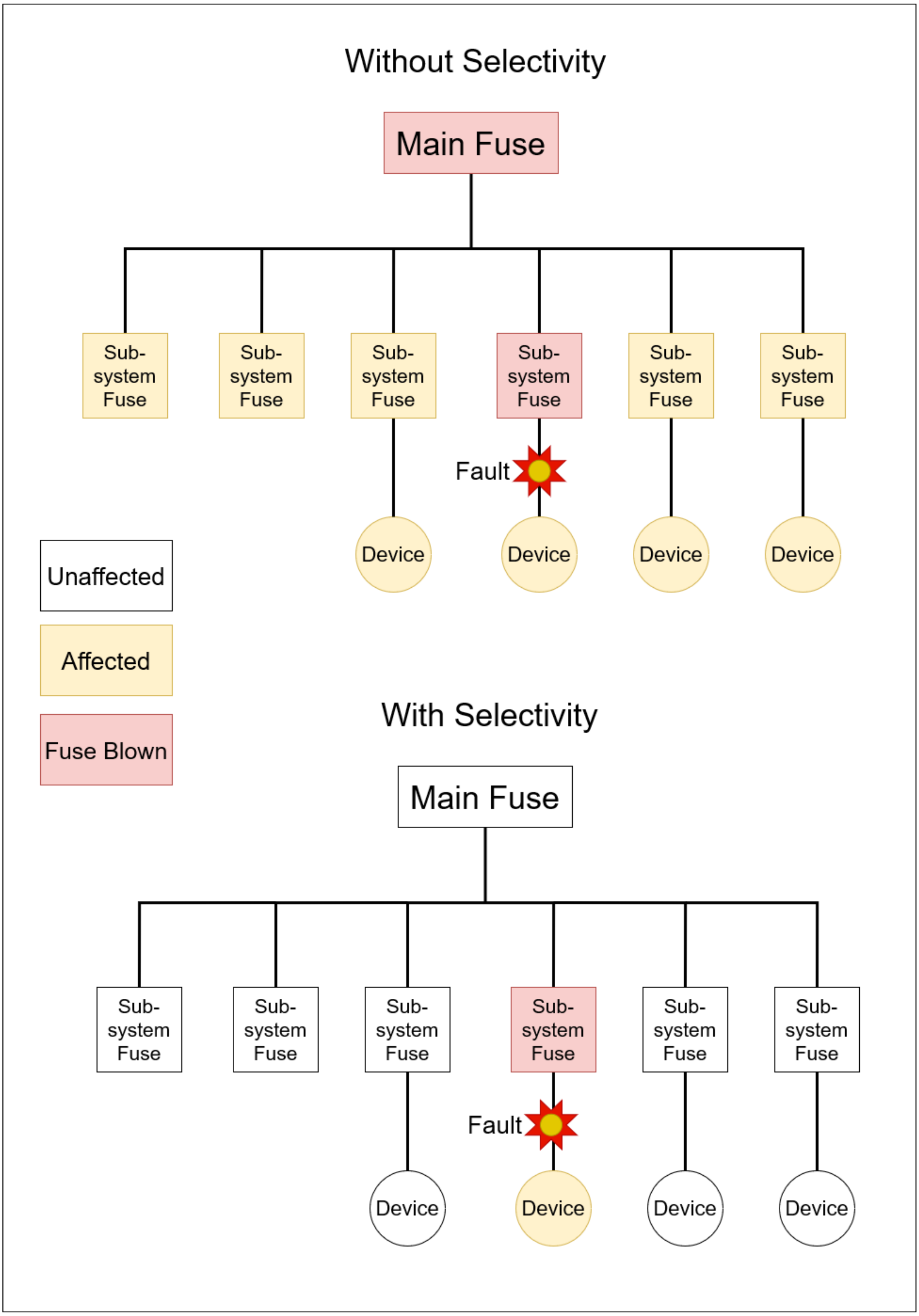


Figure 15: Graphical representation on the importance of fuse selectivity

3.4 EMC Solutions

In practical situations, it is often complicated to obtain reliable theoretical values for induced noise voltages explained in the theory chapter. However, utilizing the theoretical knowledge as guidance for practical solutions results in alleviation of interference issues.

Henry W. Ott [5, 46] states that in case of capacitive coupling, if the conductors are moved farther apart, the capacitance C_{12} decreases, thus decreasing the induced voltage on conductor 2. This of course, refers to Equation (1) and Figure 3 on page 7. The separation of conductors works in the case of inductive coupling as well since mutual inductance weakens over distance. The first step taken towards this was the separation of connector functionalities of the ADCU. Power cables for low profile devices were routed through one connector, while signal wires and control cables were routed through another. Additionally, power delivery cables for the braking actuator motor were relocated to a separate connector due to the inductive load of the motor and high possibility of interference.

Similarly, in the wiring harness it is intended to separate high current power cables from sensitive signals as much as space and practical concerns allow. This mainly includes the braking and steering motor cables and primary power distribution cables. The manufacturing of the wiring harness is outside of the scope of this thesis and chronologically occurs after the thesis work.

Another approach towards lesser electromagnetic interference is cable shielding. For proper shielding, the length of the center conductor that extends beyond the shield needs to be minimized, and a good ground connection must be provided for the shield [5, 50]. Signals such as the brake intention, brake pressure, acceleration pedal position, and CAN wiring, are all planned to be connected using a shielded cable terminated to ground inside the ADCU box.

Collectively, there are no precise EMC methods utilized in this project, but rather, practical steps have been taken to ensure that systems are operating without pestilent issues.

3.5 Documentation Creation

With the purpose of creating useful and intuitive documentation for internal use at Sensible 4, a comprehensive schematic diagram of the vehicle electric systems was created by utilizing the open-source software named Ki-CAD.

In addition to internal use, there exists a scenario where customers might require these plans as well. In recent pandemic developments, travelling to foreign locations for troubleshooting is likely not an option. Therefore, customer operators might be required to perform repair work with remote help from Sensible 4. This was kept in mind while the schematic diagrams were developed to represent the electrical systems as closely as possible and with sufficient information.

As an improvement from past schematics diagrams, multi-core cables were grouped into buses which is a feature of Ki-CAD intended to visually improve schematics from cluttering. That way, by highlighting a single wire, its full path inside the cable, across the vehicle is shown in the top view. Moreover, additional sub-sheets were added to incorporate new features and clarify the overall structure. The top-view of the vehicle schematic can be seen in Figure 16.

In addition to the schematic, an extensive sheet of cable codes and properties was created to aid the manufacturing of the wiring and identifying cables in case of repair work. This document includes chosen cable types, the determined cross-sectional area, length, marking type and additional specific information about routing.

The schematic diagram and the cable codes and properties sheet, collectively support the retrofitting process of the vehicle and aid troubleshooting operations that might be necessary during product testing and operation.

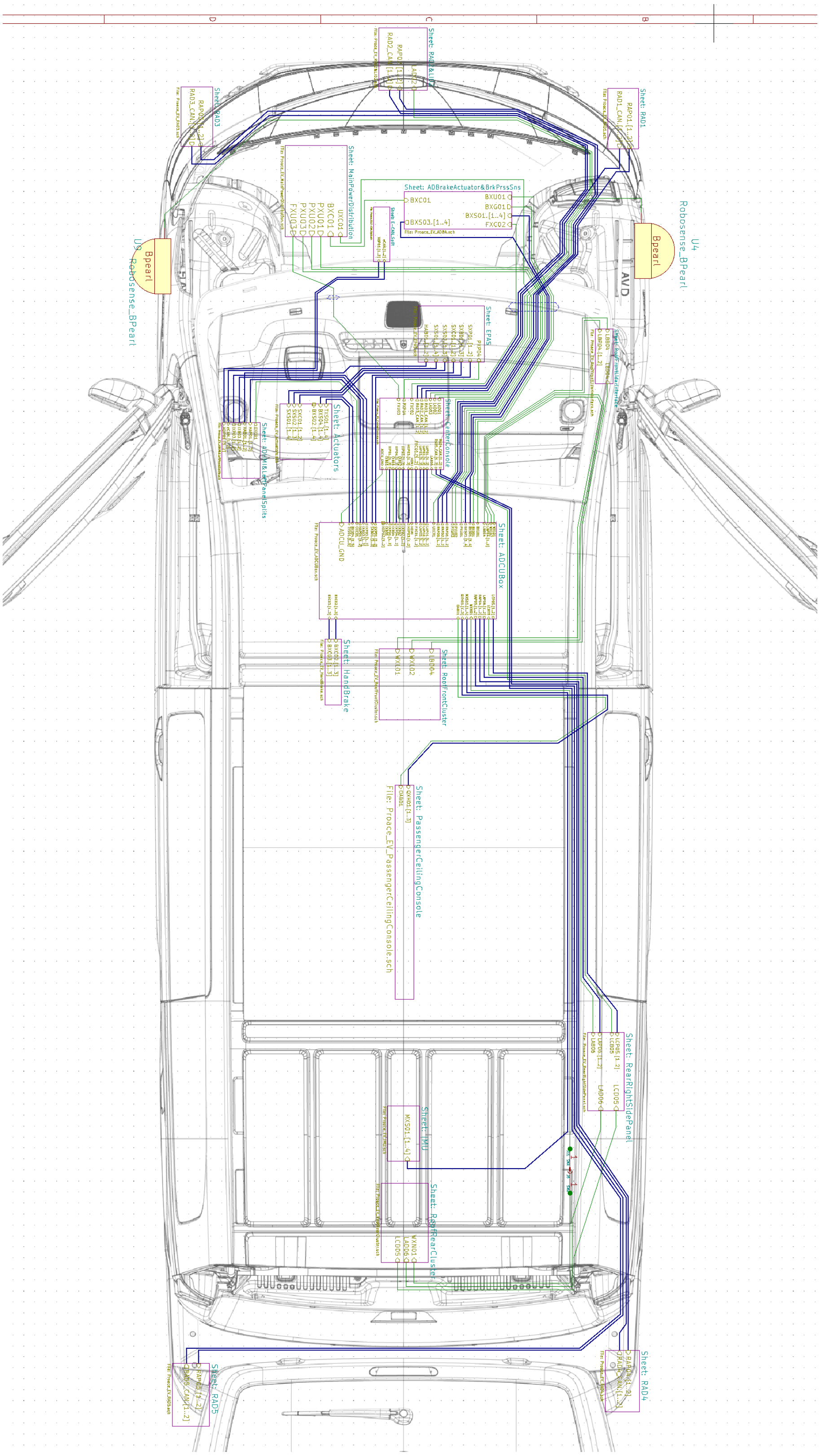


Figure 16: Top view of the schematic diagram

4 Results

The introduction to this paper presented the goal of creating a solid foundation towards autonomous hardware implementation into the electric vehicle. This goal contains several topics concerning the further development of autonomous DbW. Results of each subject contributed to reaching the set goal.

As it was described in section 3.1.1, a solution for the brake intention signal simulation was reached and after a sufficient amount of testing hours are performed in the vehicle, the working principle of the brake intention signal solution will be validated. Similarly, the acceleration pedal point of resistance signal was successfully mechanically suppressed and the acceleration pedal position signal solution was once again validated for the electric vehicle project.

The CAN gateway tests proved that both devices initially chosen for the purpose were sufficiently capable of performing the required function. According to the desired number of vehicle CAN channels to be monitored and cost efficiency, the *PCAN-Router Pro FD* was chosen as the device to be used in the vehicle. This choice will also provide benefits for future development for a debugging channel due to its digital input/output capabilities.

Due to the re-dimensioning of wire sizes, many cables were able to go down a size, which creates a thinner harness and therefore, more options are created for cable routing. Additionally, the fuse ratings were validated and modified where necessary, leaving solid calculations behind the decisions made for wiring and protection. This will undoubtedly have value in future Sensible 4 projects. Manufacturing and routing of the wiring harness has been started at the final stage of this thesis paper and will continue onward until the vehicle is ready for testing and finally operation.

As an aid for wiring harness manufacturing, the electrical schematic diagram in Ki-CAD was created. It also serves as guidance in possible repair work that could arise during the operation of the vehicle. Even though Ki-CAD presents sufficient wiring diagrams, it was mainly created for use in printed circuit board design, and therefore lacks features that would automate many steps in creating a wiring harness. An example of which was the need to create an additional sheet explaining cable codes and properties to accompany the Ki-CAD schematic. An improvement in this issue would be to migrate to software intended specifically for designing wiring harnesses.

The results of each of these sub-topics have collectively contributed to the further development of autonomous DbW for an electric power-train vehicle. Based on the design foundations established in this thesis work, the autonomous DbW will be retrofitted into the electric vehicle and operation will commence.

5 Conclusion

The goal of this thesis project was to further develop the drive-by-wire for the autonomous control system of an electric drive-train vehicle compared to the DbW of a traditional power-train vehicle which was the focus of a past Sensible 4 project. A wide range of topics were covered to encompass all major issues that needed to be considered.

Original vehicle signals were analyzed and integrated into the Sensible 4 system which now also includes a new CAN gateway used for monitoring vehicle OEM CAN channels. The wiring of the AD structure was improved by careful dimensioning and consideration of protective devices as well as EMC issues. Finally, suitable schematic documentation was created for the harness manufacturing and future troubleshooting.

The topics discussed in this paper established firm ground for the continuation and completion of the Sensible 4 electric vehicle project discussed throughout this document. Features explained will be used in the final product and eventually the retrofitted vehicles will provide driver-less and shared mobility to busy urban areas.

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