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Racing vehicle wiring harness design

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Abstract

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The purpose of this thesis was to design the wiring harness for Elmer Racing's er8 GT Time Attack racing vehicle. Work began with defining the specifications for the wiring harness and choosing the components which could fulfil these requirements. Particular focus was placed on component and material choices throughout the wiring harness while considering weight, modularity, and cost.

The environment in which a racing vehicle wiring harness must perform is harsh. These environmental requirements have to be considered in every phase of the design. In addition, the components have to be easily repairable or replaceable.

The electrical documentation was manufactured using Zuken E^3 software in conjunction with Microsoft Excel for calculations and documentation also Autodesk Inventor Professional 2022 software was used for 3D modelling and wiring harness routing.

The end result of this thesis was electrical documentation for the wiring harness manufacturing and bill of materials for connectors, sensors and devices which will be ordered closer to the manufacturing of the wiring harness.

Keywords: wiring harness design, wiring harness, race car electrics, racing vehicle wiring harness

Tiivistelmä

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Insinöörityön tavoitteena oli suunnitella Elmer Racingin tulevaan kilpa-ajoneuvoon johtosarja. Lisäksi oli tarpeen suunnitella ja valita johtosarjan valmistukseen käytettävät liittimet, johtimet sekä tarvittavat johtosarjan suojamateriaalit. Johtosarjan tarkoitus on yhdistää kaikki ajoneuvon sähköjärjestelmään kuuluvat komponentit ja se on yksi ajoneuvon merkittävimmistä osakokoonpanoista.

Kilpa-ajoneuvoihin kohdistuvat ympäristötekijät ovat poikkeuksellisen haastavia. Komponenttien on kestettävä tärinää, vettä, erilaisia kemikaaleja ja suuria lämpötilan vaihteluita. Lisäksi komponenttien tulee olla helposti korjattavia tai vaihdettavia sekä kevyitä.

Työ aloitettiin kartoittamalla ajoneuvon sähköjärjestelmään tulevat komponentit ja järjestelmiltä vaadittavat toiminnallisuudet. Kun sähköjärjestelmän komponentit oli valittu, alettiin vertailemaan erilaisia mahdollisia modulaarisia johtosarjarakenteita sekä liittimiä. Sähköjärjestelmien piirikaavioiden suunnitteluun ja muun tarvittavan valmistusdokumentaation valmistamiseen käytettiin Zuken E^3 -ohjelmistoa.

Johtosarjan sijoittelun, haaroituspisteiden ja haarojen pituuden suunnittelemiseen käytettiin Elmer Racingiltä saatua ER8 kilpa-auton 3D-mallia sekä Autodesk Inventor 2022 Professional 3D-suunnitteluohjelmistoa.

Työn tuloksena saatiin valmistettua työntilaajalle tarvittava dokumentaatio johtosarjan valmistukseen ja komponenttien tilaamiseen, kun kilpa-auto edistyy siihen vaiheeseen, että johtosarjan valmistus on ajankohtaista.

Avainsanat:	Johtosarja, johtosarjan suunnittelu, ajoneuvon sähköjärjestelmät, kilpa-auton johtosarja

Contents

List of Abbreviations

CNC:	Computer Numerical Control
CFD:	Computational Fluid Dynamics
CAD:	Computer aided design
WTAC:	World Time Attack Challenge
CAN:	Controller Area Network
ISO:	International Organization for Standardization
EMC:	Electromagnetic compatibility
OEM:	Original equipment manufacturer
ETFE:	Ethylene tetrafluoroethylene
FEP:	Fluorinated ethylene propylene
PTFE:	Polytetrafluoroethylene
ECU:	Engine control unit
CMA:	Circular Mil Area

1 Introduction

Elmer Racing is an auxiliary business name for Elmer Technology Development Ltd. Elmer racing specializes in designing and manufacturing components for various motorsport applications and protype components for non-motorsport applications. The company has experience and in-house capabilities to manufacture components using a 5-axis CNC mill and an 8-axis CNC turn-mill machine. Elmer racing also provides various design services from CFD-analyses to racing vehicle performance optimization and simulation.

The company is best known for their THOR racing engine. The engine is designed and manufactured by Elmer Racing here in Finland. It has been used to win the World Time Attack Challenge three times in a row [1].

Elmer racing has also been designing and developing their own racing vehicle named er8 GT to participate in the previously mentioned WTAC. For this racing vehicle a wiring harness was needed. Together with the customer it was decided that we wanted to design a wiring harness with maximum modularity and serviceability, since this wiring harness will be used for a longer time than one season.

In this thesis we wanted to find alternatives to the wiring harness techniques used in top-level motorsport. Also, we wanted to find the best components for Elmer Racing’s use case considering weight, modularity and serviceability.

2 CAN bus

For the scope of this thesis a brief overview of the CAN bus and its features are provided. The main focus is the requirements relevant for designing a wiring harness.

CAN bus is a bus standard designed for automotive use but is also widely adopted outside of the automotive industry. CAN bus allows the devices also called nodes or control units, connected to the bus to communicate without a host computer. If a bus topology is used it allows all of the nodes connected to the bus to receive all of the information transmitted to the bus. [2, pp. 92–93.]

A bus for communication between devices reduces the amount of wiring needed resulting in a lighter and more cost-effective wiring harness. Before bus systems became widely adopted into passenger vehicles the electronic modules communicated to each other with point-to-point direct analog signal lines. This meant that every device had to be directly wired to the device it wanted to communicate with. This leads to a more complex architecture and expensive wiring harness due to the amount of wiring required. [2, pp. 82–83.]

CAN bus systems can be overwhelming because the range of different implementations are vast. Even though there are several ISO standards defining different layers of CAN bus communication none of these standards cover the higher-layer applications or CAN bus implementation completely for example, the connectors, wiring or wire colours which should be used. This results in varying implementations of CAN bus systems and might lead to problems with conformity between devices. [3, Ch. 1.6.1.]

2.1 CAN bus properties

The CAN bus, as well as other bus communication implementations provide a multitude of advantages in terms of the communication between devices. This chapter provides some of the key features of the protocol structure of the CAN bus.

Hierarchical ranking of messages allows the most important messages to have priority on broadcasting to the bus. Every CAN bus message contains an identifier at the start of the message frame. This identifier determines the message priority. A message with a higher priority will be broadcast to the bus first if two nodes are trying to broadcast at the same time. The length of every message is limited; therefore, the maximum broadcast time for a message is also limited for a given bit rate, which guarantees latency for messages with the highest priority. [3, Ch. 2.1.]

Flexible configuration when using CAN bus in a bus topology allows for removing and adding nodes without modifying used hardware or software on any node. [3, Ch. 2.1.]

Multimaster operation allows all the nodes to broadcast to the bus without a separate master if the bus is free. If two or more nodes start broadcasting at the same time the bus conflict is resolved by message priority [3, Ch. 2.1]. If a node connected to the bus stops functioning the rest of the nodes can still communicate on the bus as every node is their own master. This ensures redundancy, since communication on the bus is not dependent of a single master. [2, p. 96.]

CAN bus protocol includes numerous signaling and error detection methods which ensure the quality and security of transmissions on the bus. In addition, when the bus returns to the idle state after an error it will automatically attempt retransmission of corrupted messages. CAN bus also automatically disconnects faulty nodes from the bus. [3, Ch. 2.1.]

2.2 CAN bus according to ISO 11898 standard

As previously stated, a CAN bus can be implemented in different topologies and mediums, but the most common type of CAN bus is the one defined by the CAN standard, part ISO 11898-2 also known as “high-speed CAN”. Another part of the same ISO standard, ISO 11898-3, defines another type of CAN bus for lower transfer speeds and a more fault tolerant design also known as “low-speed CAN”. [3, Ch. 4.2.] Both of these implementations use a two-wire line design, with CAN high and CAN low lines. [2, p. 94.]

Even though the used bit rate for a given network can be chosen the CAN protocol clearly states that the bit rate must be fixed for a network. Usually the electrical system in a vehicle contains multiple CAN networks at different speeds in these applications a “gateway” must be used to transfer information between networks. [3, Ch. 3.6.1.]

2.2.1 ISO 11898-2 high-speed CAN

The high-speed CAN as defined in ISO standard 11898-2 uses bit rates ranging from 125 kbits/s to 1 Mbit/s.

The main characteristics defined in the ISO standard 11898-2 are

- a bit rate of 125 kbit/s to 1 Mbit/s,
- a network length of up to 40 meters at the maximum bit rate,
- a recommended stub length of 0,3 m at the maximum bit rate,
- a network with nodes from 2 up to 30,
- the transfer medium used is a twisted differential pair with ground return,
- a line impedance of 120 Ω,
- a wire resistance of 70 mΩ/m,
- a nominal signal propagation time of 5 ns/m on the bus,
- recessive state voltage of 2,5 V on CAN_H & CAN_L lines,
- dominant state voltage of 3,5 V on CAN_H,
- dominant stage voltage of 1,5 V on CAN_L. [2, pp. 94–95]; [3, Ch. 4.2.1.]

2.2.2 ISO 11898-3 low-speed fault tolerant CAN

The low-speed CAN is defined with a network speed between 10 to 125 kbit/s. The benefit of using a slower bit rate is increased communication distance and added redundancy. A low-speed CAN bus can remain functional even while there are faults in the network. For example, if one of the two lines in a differential pair CAN bus is short-circuited to the ground, the system can switch transmission to the remaining wire, resulting in an asymmetrical single-wire medium with respect to the ground. [3, Ch. 4.3.1.]

The main characteristics defined in the ISO standard 11898-3 are

- a bit rate of up to 125 kbit/s,
- a network length of up to x meters, determined by the capacitive load of the bus, usually five hundred meters at 125 kbit/s.
- a network with nodes from 2 up to 20,
- the transfer medium used is a twisted differential pair with ground return,
- low EMC radiation,
- an overall terminating resistance close to 100 Ω,
- recessive state voltage of 0 V on CAN_H line,
- recessive state voltage of close to 5 V on CAN_L line,
- dominant state voltage of close to the power supply voltage 5 V or 3,3 V on CAN_H,
- dominant stage voltage of close to 0 V on CAN_L. [2, pp. 94–95]; [3, Ch. 4.2.1.]

2.3 Physical layer requirements

The physical layer is the hardware required for a CAN network to operate. The hardware is responsible for converting the ones and zeros into electrical pulses to be sent to other nodes on the bus. These nodes then convert the electrical pulses back into ones and zeros. The physical layer is always implemented in hardware. [4, p. 2.]

This chapter focuses on implementing a high-speed CAN bus as defined in the ISO standard 11898-2, since a similar implementation is used in the er8 GT project racing vehicle. This type of a CAN bus is the easiest to implement since most of the third-party devices are made to conform with the high-speed CAN bus standard. In addition, the maximum length, number of nodes and the bit rate of 1 Mbit/s is sufficient for the devices used in the er8 GT CAN bus.

In terms of latency and redundancy this type of a CAN bus is the best option for the er8 GT. All of the critical signals related to the ignition, fuel injection, transmission control, emergency stops, and active suspension are directly wired to the electronic control unit of the car so in the event of a faulty CAN bus the car can retain most of its functionality.

2.3.1 Basic communication requirements

In a CAN bus a minimum of two nodes must be used to initialize communication. The transmitted message must be acknowledged in the ACK bit by a receiver. The controller transmitting will send out an error flag if the message is not properly acknowledged. [4, p. 3.]

2.3.2 Topology

The bus topology shown in Figure 1 is the easiest to implement and is most frequently used with CAN. As mentioned earlier, this type of topology allows easy removal and adding of nodes to the bus. The CAN bus can be constructed using other topologies as well, for example as a ring or star topology. For the scope of this thesis focus is placed on the bus topology implementation even though the same principles are mostly applicable to other topologies.

For the er8 GT project a bus topology was chosen because all of the third-party devices are designed to be used as a standard high-speed CAN bus node. In addition, this type of implementation allows for easy modifications and additions in the future.

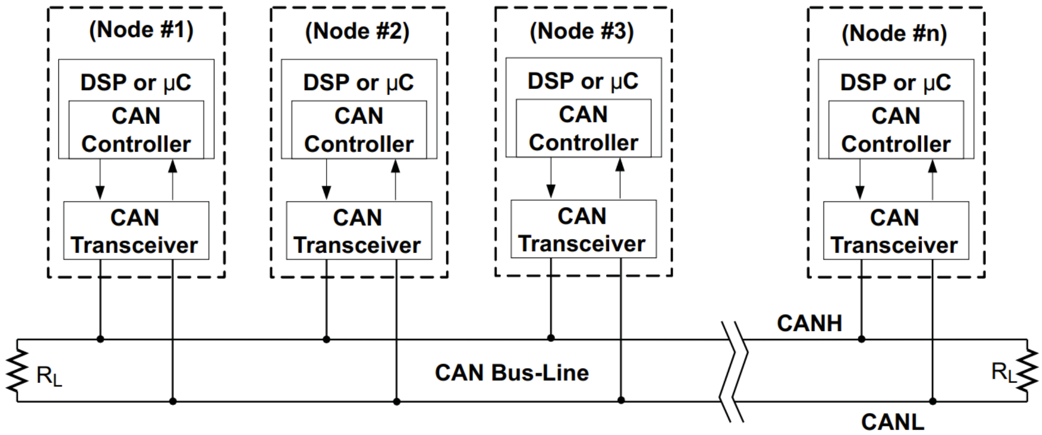


Figure 1 Typical high-speed CAN bus implementation [4, p. 5].

2.3.3 Bus length & bit rate

The maximum CAN bus length is dependent on the selected bit rate, the higher the bit rate the shorter the maximum length of the bus. Table 1 lists the suggested bus lengths depending on the bus bit rate.

Table 1 Suggested Cable Length vs bit rate [4, p. 5].

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

The major factors limiting the bus length as signaling rate increases are time varying. Cable bandwidth limitations degrade the signal transition time and cause inter-symbol interference thus limiting the achievable signaling rate as the bus length increases. [4, p. 5.]

For a CAN bus, the signaling rate also depends on the total system delay. A message must travel down and back between the two most distant nodes on the network using a twisted-pair cable. This means that the delays caused by the distance between furthest nodes, delays within the CAN bus nodes and the signal propagation delay of the twisted-pair cable have to be considered. [4, p. 5.]

Furthermore, the resistance of the cable and input resistance of the CAN transceivers affect the amplitude loss of the signal. In addition to the previously mentioned parameters there are a many other variables which may degrade the transmitted signal.

2.3.4 CAN bus cable

Unshielded twisted-pair cable with a characteristic impedance of 120 Ω is commonly used; however, in electrically harsher environments it is recommended to use a shielded twisted-pair cable.

If a shielded cable is used, the shielding must be grounded at a single point at the CAN bus source. The reasoning for this will be later explained in chapter 3.5.2 regarding cable shielding. If the CAN bus lines are individually shielded the same terminating technique should be used. [4, p. 6.]

2.3.5 Line terminations

Since the high-speed CAN bus standard uses twisted-pair cable with the characteristic impedance of 120 Ω, terminating resistors of matching impedance are used at the end of the lines. The terminating resistors minimize signal reflection caused by impedance mismatching. [4, pp. 6–7.]

Two different terminating methods are recommended for high-speed CAN bus. Figure 2 gives an example on the standard method of using 120 Ω terminating resistors at the ends of the bus. [4, pp. 6–7.]

When choosing the terminating resistors, their ability to withstand short-circuits to power supply voltage should be taken in account [4, pp. 6–7].

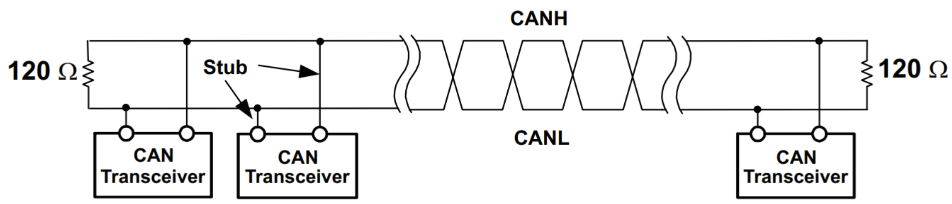


Figure 2 High-speed CAN bus with standard termination [4, p. 7].

The other common terminating method is the split termination, shown in Figure 3. It uses two 60 Ω terminating resistors and a coupling capacitor. The added benefit of this type of termination is the ability to filter out high frequency noise on the bus. A typical value for the coupling capacitor used in a high-speed CAN bus is 4,7 nF. This configuration generates a 3 dB point at 1,1 Mbps, but the chosen capacitor value is dependent on the signaling rate of the bus. [4, p. 8]

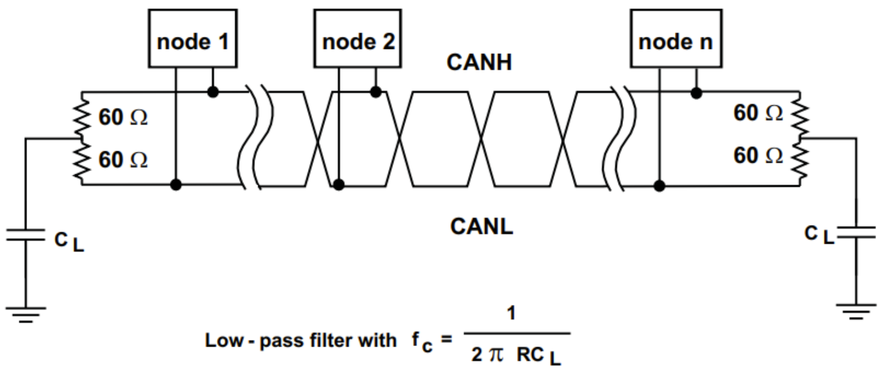


Figure 3 High-speed CAN bus with split termination [4, p. 8].

2.3.6 Stub length

The connections also called “stubs” from nodes to the bus should be kept as short as possible since they are unterminated at the ends, they are prone to signal reflection in the wires.

It is also possible to lengthen the stubs for example by lengthening the driver transition time with a resistor. [4, p. 10.] Still a general rule is to keep the stub length under one meter and under 0,3 m when using the High-Speed CAN bus as specified in the ISO 11898 Standard.

This problem is also related to the transmission speed of the bus, with lower transfer speeds the bus and stub lengths can be longer without significant effect on the performance, but with higher speed implementations the length of the stubs can create problems if not addressed properly. [3, Ch. 3.4.2.]

2.3.7 Node Spacing

The electrical characteristics and responses of a CAN bus are primarily defined by the inductance and capacitance distributed along the physical media. The media is defined as cables or conducting paths, connectors, terminators, and the CAN nodes. As devices and connectors are added to the network at unequal spaces the capacitance increases and the impedance of the bus lowers, this causes impedance mismatching between loaded and unloaded sections of the bus.

A relationship between the minimum node spacing on a bus as a function of the distributed media capacitance and load capacitance can be defined as shown in Figure 4.

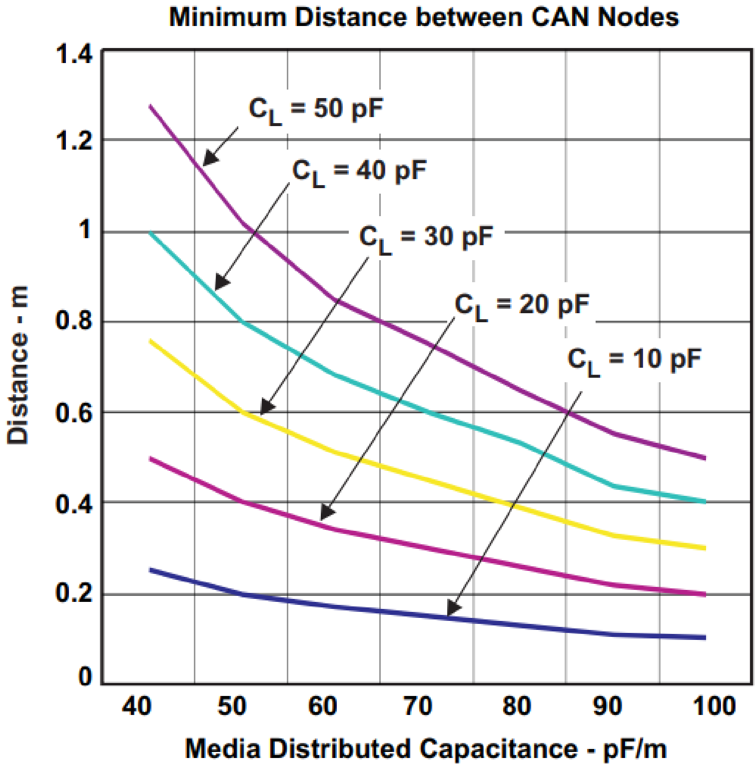


Figure 4 Minimum CAN node spacing on a bus with device capacitance and media capacitance [4, p. 13].

Load capacitance is shown as C_L on Figure 4, it includes all physical connections if the distance from the bus to the transceiver is electrically short, in other words as long as the stub length is short. Typical transceiver capacitances range from 10 pF to 16 pF, circuit board traces add around 0,5 pF/cm to 0,8 pF/cm. [4, p. 13]

Media distributed capacitance ranges from 40 pF/m – 70 pF/m. For example a low-capacitance unshielded-twisted-pair cable has a capacitance of 40 pF/m [4, p. 13].

3 Signal integrity & Electromagnetic compatibility

Signal integrity is described as the analysis, design and validation needed to carry signals intact over distance. The design and practices used to achieve adequate signal integrity range from printed circuit board design to, in this case, wiring harness design and architecture. [5, p. 1], [6, p. 1].

Electromagnetic interference (EMI) is a form of environmental pollution. EMI has effects ranging from crackles in a radio transmission to more severe malfunctions in safety-critical systems. Electromagnetic compatibility (EMC) on the other hand, means that a device should be able to function satisfactorily in its electromagnetic environment and not cause electromagnetic interference to other devices in the same environment. [7, p. 3]; [8, p. 1.] There are multiple standards and directives regarding electromagnetic compatibility in different applications which will not be covered in this thesis.

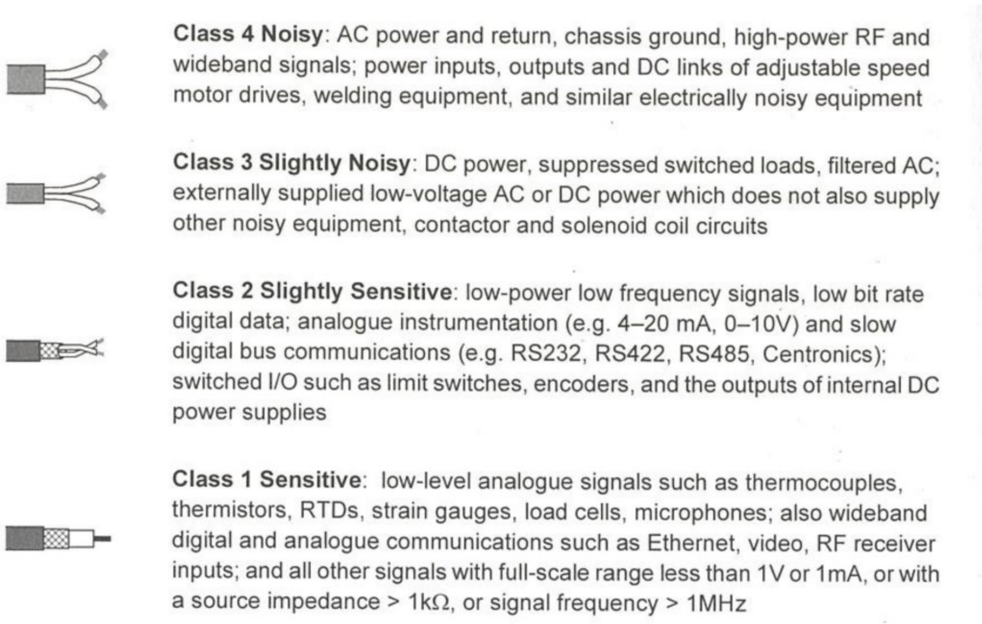
Since the topic of signal integrity and electromagnetic compatibility is broad, this chapter will only focus on the design choices which can be made during the wiring harness and electrical system design phase to ensure sufficient signal integrity and avoid problems with interference.

3.1 Noise and Interference

Noise means any other electrical signal in a circuit other than the desired signal. If the noise signal causes problems in a circuit, it is considered to be interference. Noise cannot be completely removed, but it can be reduced until it no longer causes interference. [7, p. 4.]

3.2 Sources of interference

The automotive environment contains various sources of interference within the car as well as interference sources coming from outside of the car. Interference in the form of signal pulses is generated during switching on and off components such as electric motors, solenoids, and actuators. In addition, high-frequency interference signals can be produced by periodic switching operations, commonly found in ignition systems, DC motors and central processing unit clock signals. [2, pp. 486–491.] Figure 5 shows classification of cables depending on the signal they carry, this classification does not come from automotive standards but is used in other industries [8, p. 418].



Class 4 Noisy: AC power and return, chassis ground, high-power RF and wideband signals; power inputs, outputs and DC links of adjustable speed motor drives, welding equipment, and similar electrically noisy equipment

Class 3 Slightly Noisy: DC power, suppressed switched loads, filtered AC; externally supplied low-voltage AC or DC power which does not also supply other noisy equipment, contactor and solenoid coil circuits

Class 2 Slightly Sensitive: low-power low frequency signals, low bit rate digital data; analogue instrumentation (e.g. 4–20 mA, 0–10V) and slow digital bus communications (e.g. RS232, RS422, RS485, Centronics); switched I/O such as limit switches, encoders, and the outputs of internal DC power supplies

Class 1 Sensitive: low-level analogue signals such as thermocouples, thermistors, RTDs, strain gauges, load cells, microphones; also wideband digital and analogue communications such as Ethernet, video, RF receiver inputs; and all other signals with full-scale range less than 1V or 1mA, or with a source impedance > 1kΩ, or signal frequency > 1MHz

Figure 5 Cable classifications [8, p. 418].

3.3 Noise coupling mechanisms

In order for noise to be a problem there has to be a noise source, a receptor which is susceptible to the noise and a coupling path for the interference [8, p. 222].

3.3.1 Conductively coupled noise

One of the ways to couple noise into a circuit is through a conductor. For example, a wire going through a noisy environment may pick up noise and conduct it to another circuit where it causes interference. If the designer cannot make changes to the wire routing the noise must be decoupled or filtered out before the wire enters the circuit in which it causes interference. [7, p. 32.]

3.3.2 Common impedance coupling

Common impedance coupling occurs when two different circuits share a common impedance, usually a common ground or a power supply. As currents flow from the two different circuits through a common impedance, the voltage drop across the impedance observed by each circuit is affected by the current of the other circuit. Figure 6 shows two circuits which share a common return path. Z_K represents the common impedance which in this case is the wire.

This can be eliminated by removing the common impedance [8, p. 224]. In the case of a common ground wire this could be done by connecting the grounds of these two circuits using a separate wire for each, from the grounding point in the chassis, this of course adds the amount of wiring, complexity, cost, and weight of the wiring harness.

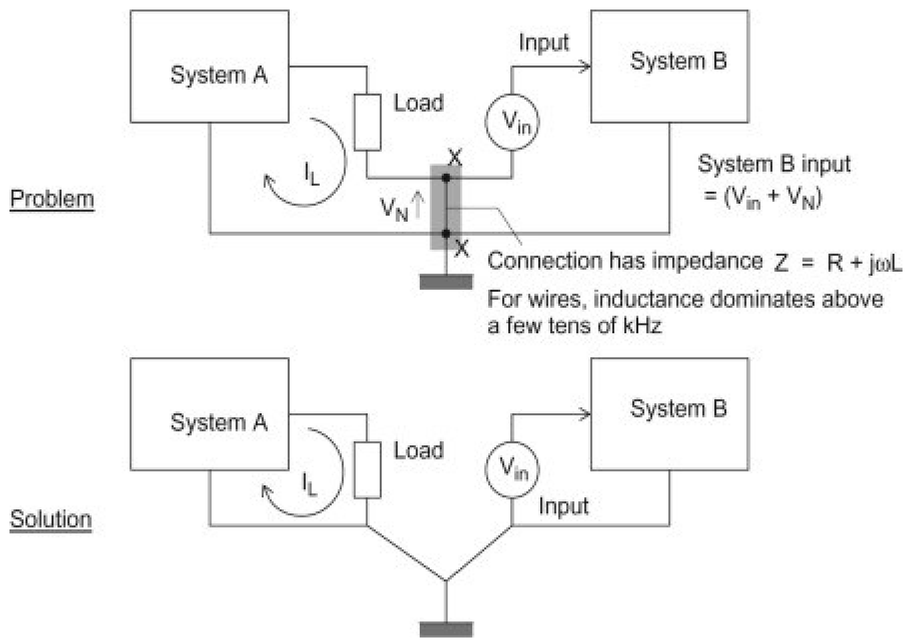


Figure 6 Two circuits sharing a common ground and a solution with separate grounds [8, p. 224].

3.3.3 Electric and magnetic field coupling

Radiated electric and magnetic fields are another form of noise coupling. Alternating current in a conductor creates a magnetic field around the conductor. If another conductor is nearby, the magnetic field will induce a voltage in it. In the case of electric induction, a changing voltage on a conductor creates an electrical field around it which can also induce a voltage to a nearby conductor. In neither of these cases a direct connection between the circuits is needed for the circuits to interfere with each other. [8, pp. 224–225.]

In the case of magnetic field, the coupling can be represented as mutual inductance. The equivalent circuit would be a voltage generator in series with the circuit receiving the noise. This type of coupling is also referred to as inductive coupling. Figure 7 displays an example circuit and an equivalent circuit. [7, p. 38]; [8, p. 224.]

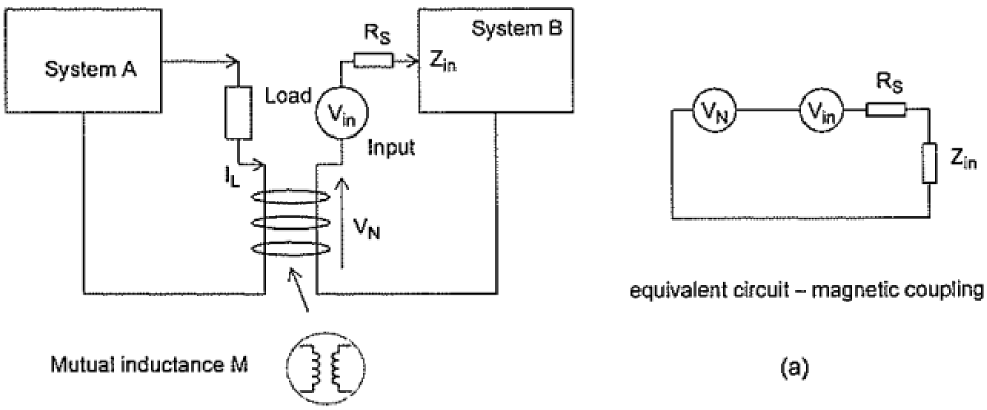


Figure 7 Magnetic induction [8, p. 225].

When the interference is caused by electric induction, the coupling between circuits can be represented with a capacitor. Therefore, this type of coupling is referred to as capacitive coupling. This results in the noise being injected as if from a current source to the victim circuit. Figure 8 shows an example circuit of electric induction and an equivalent circuit representing the victim. [7, p. 37]; [8, p. 225.]

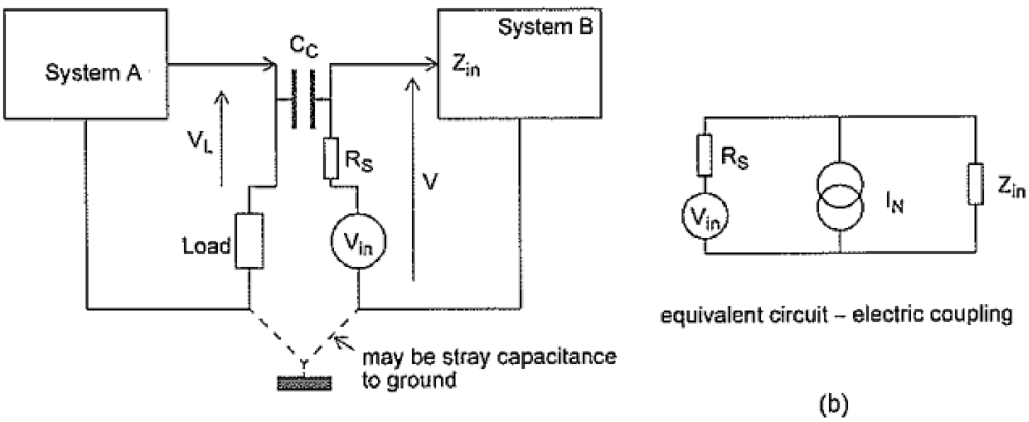


Figure 8 Electric induction [8, p. 225].

3.4 Galvanic action

A noise voltage may also appear if dissimilar metals are used in the signal path. This is because two dissimilar metals and moisture or water vapor produce a galvanic couple. The noise voltage is dependent on the two metals and their positions in the galvanic series. The farther apart the two metals are in the galvanic series the larger the voltage. When using same metals, no potential difference is developed. [7, p. 33.] Table of the galvanic series is provided in appendix 1.

In addition to the noise voltage produced the use of dissimilar metals can cause corrosion. This corrosion can be slowed down considerably by using metals closer to each other in the galvanic series. One of the most common combinations of metals used is copper and aluminium, in this case corrosion can be slowed by tin-coating the copper, since tin is closer to aluminium in the galvanic series. [7, p. 34.]

Galvanic corrosion might not be a problem in some indoor applications, but in a vehicle's wiring harness which can be exposed to different kinds of electrolytes, usually water, the use of dissimilar metals in connections should be avoided.

3.5 Cabling & Connectors

Because of their length cables act as efficient antennas which can pick up or radiate noise. This chapter focuses on the ways to minimize noise in an electrical system.

3.5.1 Crosstalk

Crosstalk refers to any phenomenon by which signals transmitted on a circuit affect another circuit in undesired ways. This is usually caused by capacitive or inductive coupling from a source circuit to a victim circuit. In wiring harnesses this poses a problem since multiple conductors of different circuits run parallel and in proximity inside the wiring harness. For clarification, noise caused by capacitive coupling from a circuit to another will be referred to as capacitive crosstalk and noise caused by inductive coupling will be referred to as inductive crosstalk. [8, p. 342.] Figure 9 displays different crosstalk coupling paths between circuits within a cable.

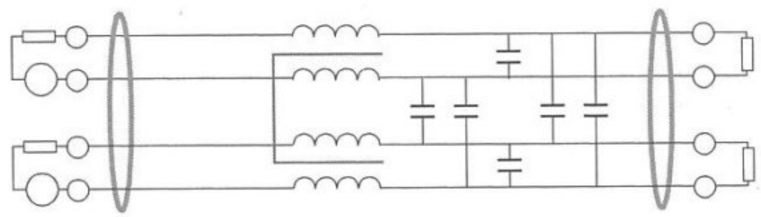


Figure 9 Crosstalk coupling paths between circuits within a cable [8, p. 342].

Capacitive crosstalk

The noise voltage caused by capacitive coupling is dependent on the frequency of the noise source, the resistance of the victim circuit to ground, the mutual capacitance between conductors, and the magnitude of voltage in the source circuit. Usually, the voltage or frequency of the source cannot be modified, this means that reducing capacitive coupling must be done by lowering the victim circuits resistance to ground or by decreasing the mutual capacitance. [7, p. 46]

In terms of wiring harness design the capacitance and thus noise can be decreased by changing the orientation of the wires, by shielding or by physically increasing the distance between the conductors.

Orientation of the conductors affects the mutual capacitance because it changes the overlapping area. In practice this means that wires carrying higher currents such as 12 V supply wires in a car, should not be set parallel to signal wires carrying analog signals. If these power conductors must cross paths with signal wires it is advisable to orient the conductor perpendicular to each other. Increasing the distance between wires in a car can be accomplished by for example running the 12 V supply wires physically through another route in the car and routing the more delicate signal lines through another route. In practice this can be difficult when trying to accomplish a tightly packaged wiring harness and minimize the amount of wiring used. In these situations, using a shielded wire is advisable, also using a twisted-pair wiring reduces capacitive interference pick up. [8, p. 353.]

Inductive crosstalk

Noise caused by inductive coupling between two circuits can be lowered by decreasing the flux density affecting the victim wire. This can be done by physically separating the conductors or by twisting them together, however twisting the wires together only lowers the inductive noise if the current returns through the other twisted wire and not through ground. As the current flows through a twisted-pair, the magnetic fields created by both of the wires cancel each other out. The noise can also be lowered by altering the angle between the source and victim circuits. Screening on the conductors can also be used. [7, pp. 52–56.]

Regarding wiring harness design signal, power and their return lines should be coupled closely and preferably by twisting when possible. Circuits which are prone to inductive coupling noise should be physically placed further apart from circuits emitting noise. If signal wires prone to inductive coupling must cross wires emitting inductive noise, the wires should cross perpendicular and not be placed parallel. As with minimizing capacitively coupled noise these methods can be hard to physically implement in a tightly packaged wiring harness.

3.5.2 Shielded cables

The noise received and transmitted by a wire can be greatly reduced by using shielded cables also referred to as screened cables. Optimum shielding of the cables depends on multiple factors, there are different methods for dealing with low frequency and higher frequency noise. In addition, there are various different types of shielded cables, all of which have their own use cases. [8, p. 344.]

Shielded cable at low frequencies

When screening at low frequencies (20 Hz to 300 Hz), a shield grounded at one end only provides good shielding from capacitively coupled noise, but none from magnetic fields, scenario a in Figure 10. To shield from magnetic fields, the shield must be grounded at both ends, since this allows induced current to flow in the shield, scenario b in Figure 10. This induced current will negate the induction effect in the wire inside the shield, but this effect will only become apparent above the cable cut-off frequency. The cut-off frequency is a function of the shield’s inductance and resistance. For braided shields this frequency is around 1-2 kHz and for aluminium foil screens 7-10 kHz. At frequencies above five times, the cut-off frequency the voltage induced in the shielded wire remains constant with frequency, which means that the noise voltage remains constant even while the frequency rises. [7, pp. 62–64]; [8, p. 344.]

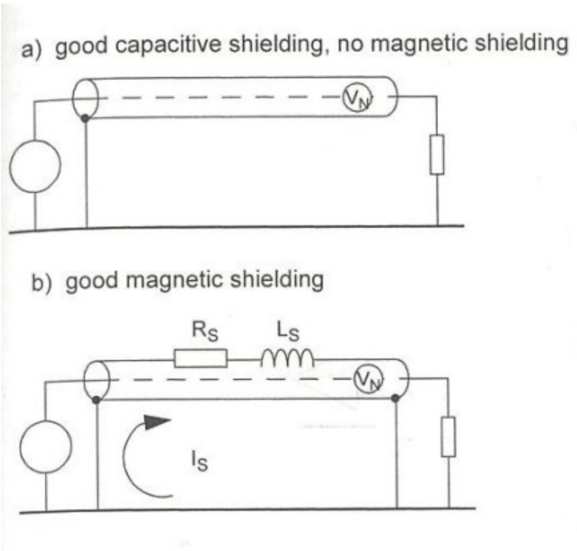


Figure 10 Magnetic shielding effectiveness versus screen grounding [8, p. 345].

When shielding conductors from emitting magnetic fields the same method applies. Because both shielding conductors from noise as well as shielding conductors from emitting noise, rely on the same principle of a current flowing through the shield and that the frequency is substantially higher than the cut-off frequency, this makes magnetic shielding against low frequencies difficult. When the frequency is below five times the cut-off frequency shielding against magnetic fields doesn't yield better results than using an unshielded cable. [7, pp. 50–51]; [8, p. 344.]

If shielding is only needed for low frequency capacitively induced interference shielding the cable from only one end is sufficient and widely used [8, p. 344].

Shield grounding

When grounding the shield at both ends two problems emerge. Firstly, when there is current flowing through the shield it becomes a circuit conductor; therefore, any voltage dropped across the shield impedance will appear as a noise voltage in series with the signal. To minimize magnetic pickup from low frequency noise sources, one end of the circuit should be isolated from the ground, circuit loop area should be minimized, and the screen should not be a part of the circuit. This is best achieved when using a shielded twisted-pair cable, the shield should be grounded at one end only so that the shield protects against noise caused by capacitive coupling and the twisted pair minimizes magnetic coupling. It should be kept in mind that at higher frequencies the stray capacitance at the ungrounded end of the shield reduces shielding efficiency because undesired ground and shield currents can start to flow. [8, p. 345.]

The other problem, regarding the shield grounding emerges if there are significant voltage differences between the shield grounds when it is grounded at both ends. When there is potential difference between the ground points a current will flow through the shield and it is only limited by the shield and ground point impedances, both of which can be very low. In some cases, the current can rise high enough to damage the cable. This usually becomes a problem in cables between buildings or at large sites, so in theory this should not be a problem in a vehicle setting, but potential differences between grounding points can also form in vehicles where the environmental factors come into play. [8, p. 345.]

The possible potential differences between shield end grounds is the main reason why many engineers avoid grounding cable shields at both ends, but as explained earlier this of course is dependent on the use case, which also means that grounding the shield at both ends should be decided depending on the case. [8, p. 345.]

Shielded cable at radio frequencies

At higher frequencies up to and beyond 1 GHz when the cable length approaches a quarter wavelength of the frequency, screen currents caused by external fields start to have an effect. Also, at these high frequencies practically all conductors are longer than a quarter of the wavelength of the frequency. However, at these high frequencies skin effect comes in to play, this prevents the coupling of these noise voltages from the shield to signal wires inside the shield. Thus, at these frequencies grounding the shield at both ends and letting the screen current flow does not introduce a noise voltage in the signal wire inside the shield. Only when using a shield which does not provide complete optical coverage such as a braided shield this effect is compromised.

Different types of cable screens

The shielding performance of a cable depends on the construction of the shield. Many types of different shielded cables are available, the most common ones are shown in Figure 11. The shielding performance of a shield is expressed through shield transfer impedance. Some specialty cables for more demanding environments are also available at a higher cost. Also of course it is not always necessary to buy shielded cable, depending on the use case, unshielded wires can be wrapped in different shielding materials. [8, pp. 347–348.] In terms of wiring harness design there are a variety of different wiring harness protection materials in which multiple wires can be placed inside and the protection material contains a shielding. Different types of wiring harness protection materials will be discussed in chapter 6.4.

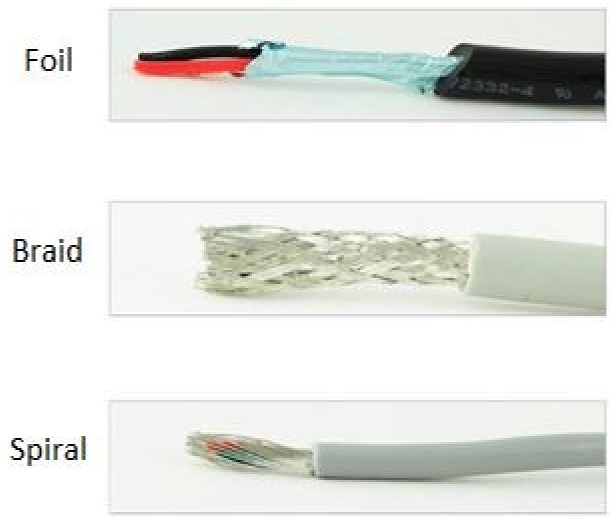


Figure 11 Three main shield types used in cables. [9].

Spiral shields consist of wires helically wound around onto the cable

- These shields are flexible,
- cost-effective,
- larger pitch angle of the wounding results in weakened shielding,
- poorer shielding capabilities than a braided shield,
- should not be used at frequencies above 100 kHz [7, pp. 81–83]; [8, p. 348].

Braided shields consist of wire woven into a braid which acts as a shield on the cable.

- These shields are also very flexible and have high strength,
- provide a coverage between 60 % to 98%,
- higher coverage braids have better shielding but are stiffer,
- less effective than solid conductors,
- provide good shielding from electric fields under UHF,
- reduced magnetic shielding due to distortion in the shield current,
- reduced optical coverage due to holes in the braid leads to even lower shielding capabilities above 10 MHz [7, pp. 79–81]; [8, p. 348].

Laminated tape or foil shields usually consist of a thin aluminium layer placed around the cable, or a copper foil or tape can be used, which provides better shielding, but is also more expensive.

- Provides full coverage,
- higher resistance of the shield means higher cut-off frequency,
- hard to terminate properly,
- good protection against electric fields,
- low cost,
- not as durable as braided shields,
- flexible,
- small in diameter. [7, p. 98]; [8, p. 348.]

In addition, there are many variations of cables which use more than one of these different types of shields, for example some cables use a combination of foil and braided shields to combine the advantages of good coverage provided by the foil and better termination of the braid, these types of cables have good shielding properties up to 100 MHz [7, p. 81]; [8, p. 348].

3.5.3 Terminating the cable shield

A shielded cable is only as good as its weakest link; most of the shielded cable problems are due to improper termination of the shield. For a proper shield termination, the termination should be done at the proper end or ends of the shield, the termination connection should have a low impedance and the termination should have a 360 degree contact with the shield. [7, pp. 84–85]; [8, p. 350.]

Some military connectors as well as standard coaxial cable connections allow for an easy 360-degree shield connection, but especially with automotive connections a pigtail is usually needed to terminate the shield. Different types of shield terminations are shown in Figure 12. [7, pp. 84–85]; [8, p. 350.]

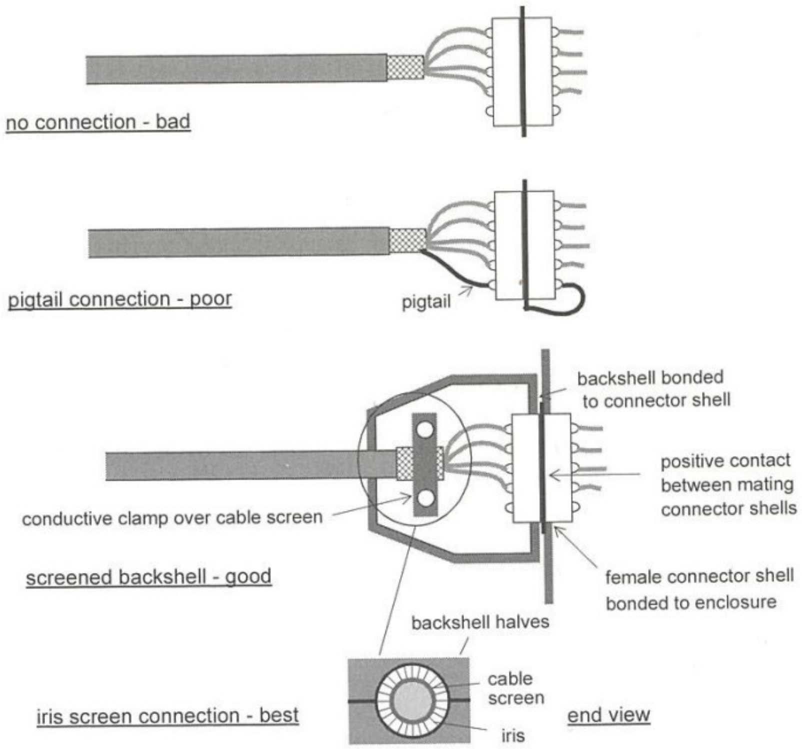


Figure 12 Different shield terminations [8, p. 345].

Pigtail terminations should be avoided if possible. Pigtails do not provide a uniform termination to the shield. This causes the shield currents to concentrate on one side of the shield thus decreasing the shielding. If, however pigtail terminations need to be made, the length of the pigtail should be kept as short as possible. At low frequencies, under 10 kHz, pigtail terminations for cable shields can be acceptable. [7, pp. 84–87]; [8, pp. 350–351.]

3.5.4 Unshielded wires

Shielding the wires is not always necessary and using unshielded wires when applicable lowers costs and eliminates the problem of shield termination and grounding. In addition, different noise filtering mechanisms can be implemented in the devices to remove noise and thus removing the need for shielding. [8, p. 352.]

3.5.5 Twisted pair

Twisted pair is in many cases the most cost-effective way to reduce both magnetic and capacitive noise pick-up. Twisting the wires ensures a uniform distribution of capacitance to structures outside the cable. Twisting is particularly effective at reducing low frequency magnetic noise pick-up because it reduces the effective magnetic loop to almost zero. To prevent crosstalk between lines, different number of twists per unit length are used and the direction of twisting can be reversed between adjacent pairs.

3.6 Grounding

Properly designed ground systems are one the primary ways to minimize noise and ensure a safe system. [7, p. 106]

Grounds can be categorized as signal grounds and safety grounds. For the scope of this thesis, this chapter will focus on signal grounds as they are more prone to interference. Proper safety grounding is also important since it minimizes any potential differences between conductive structures and ensures the operation of safety devices like fuses in the event of a fault. [7, p. 107.]

3.6.1 Signal grounds

Signal grounds are used as a reference potential for a system or a circuit. When designing signal grounds, they should not interrupt the ground return path and they should return the current through the lowest impedance path. In addition, common impedance coupling should be taken in consideration when designing the signal grounds. [7, p. 120.]

At low frequencies the resistance of the ground path is dominant, and the current will flow through the path with lowest resistance to the source. At higher frequencies the inductance of the ground path becomes dominant, and the current will flow through the path with lowest inductance. When there is current flowing in ground returns a voltage drop is also created, this voltage drop is often referred to as ground noise voltage. This noise voltage will affect all devices which are connected to the same ground. Since ground noise voltage also obeys Ohm’s law the noise can be minimized by lowering the ground impedance and decreasing ground current. [7, pp. 120–123.]

Ground systems always require compromises. The designer should try to maximize the advantages and minimize the disadvantages. [7, p. 123.] Figure 13 shows three different grounding topologies.

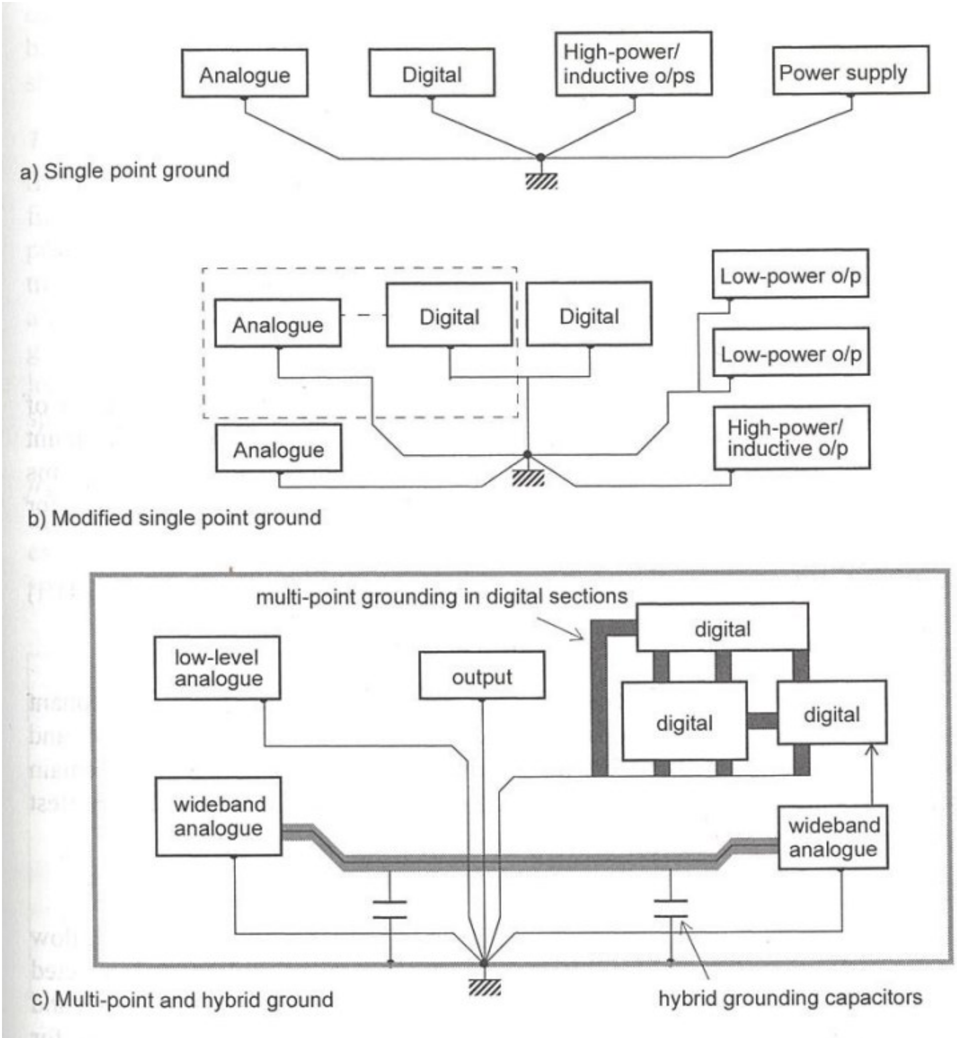


Figure 13 Different grounding systems [8, p. 265].

Single-point grounds

This type of grounds are best suited for low frequencies from dc up to 20 kHz. Single point grounding allows for directing the currents where the designer wants, which decreases the ground current. Decreasing the ground current lowers the ground noise voltage. Also, single-point grounding is an effective way to prevent ground loops. [7, p. 124.]

A parallel or star connection should be preferred instead of a series connection because a series connection adds more noise. When using a series connection, the most critical circuit should be nearest to the main grounding point. Also, in a series configuration the connected circuits should operate in similar voltage ranges since high return currents will affect low-level circuits through common ground impedance. [7, p. 125.] However, from a physical implementation standpoint the series type of connection is much easier to implement than a star or parallel ground system. Usually, the most practical solution is combining both, this way acceptable ground noise voltage levels can be achieved while avoiding unnecessarily complex wiring. This can be achieved by grouping the wires selectively, based on their voltage levels and noise levels. Meaning low-level circuits can share the same ground wire, whereas high-level circuits can share another common ground wire. [7, p. 125.]

Also, in order to minimize impedance and to minimize noise pick-up and radiation the ground wires should be kept as short as possible. [7, p. 126.]

At high frequencies single-point grounds are almost impossible to achieve because parasitic capacitance closes the loop to the nearest ground. [7, p. 129.]

Multipoint grounds

Multipoint grounds are usually used in high frequency applications. Multipoint ground systems minimize ground noise voltage by minimizing ground impedance, which at high frequencies means lowering ground inductance. This means that circuits are connected to the nearest low-impedance ground. [7, p. 128.]

Normally a single point system is sufficient below 100 kHz above that a multipoint ground system is best. [7, p. 129.]

Ground loops

Ground loops can form when a circuit has more than one possible ground return path. Ground loops can cause noise and interference in circuits. In some cases, it is necessary to limit the noise or eliminate the ground noise path, but ground loops are not always bad. In the case of a shield grounded at both ends, a shield current is desired to flow to suppress magnetic coupling. Also, attempting the removal of every ground loop can cause more problems than the ground loops initially. Measures against ground loops should only be taken if the noise in the signal becomes significant. [7, pp. 142–144.] Figure 14 shows a ground loop between two circuits.

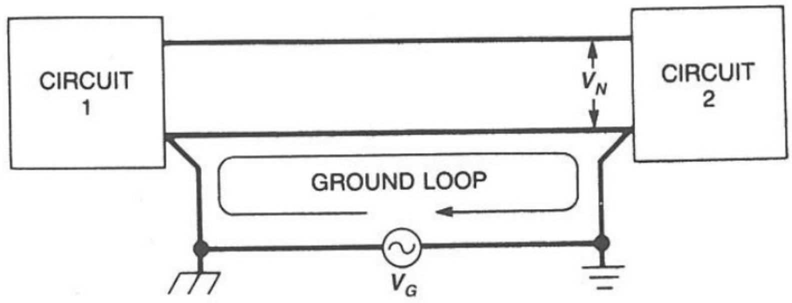


Figure 14 Ground loop between circuits [7, p. 143].

If ground loops are a problem, there are three ways to minimize their effect. Firstly, ground loops should be avoided by using single-point grounds. This is effective at low frequencies, but it can exaggerate the problem at high frequencies due to parasitic capacitance. The second way is to tolerate them by minimizing ground impedance or by increasing the signal voltage level. Ground loops can also be eliminated by using transformers, common-mode chokes, or optical couplers. [7, p. 144.]

4 The er8 GT project car

The desire to manufacture a race car to demonstrate the engineering capabilities of Elmer Racing has been in the works for a long time. At first the car was designed to be raced in the roadsport-class, but as time went on and after the success of their in-house designed and built THOR engine in the WTAC. Plans were changed to make the car to compete in Time Attack as well.

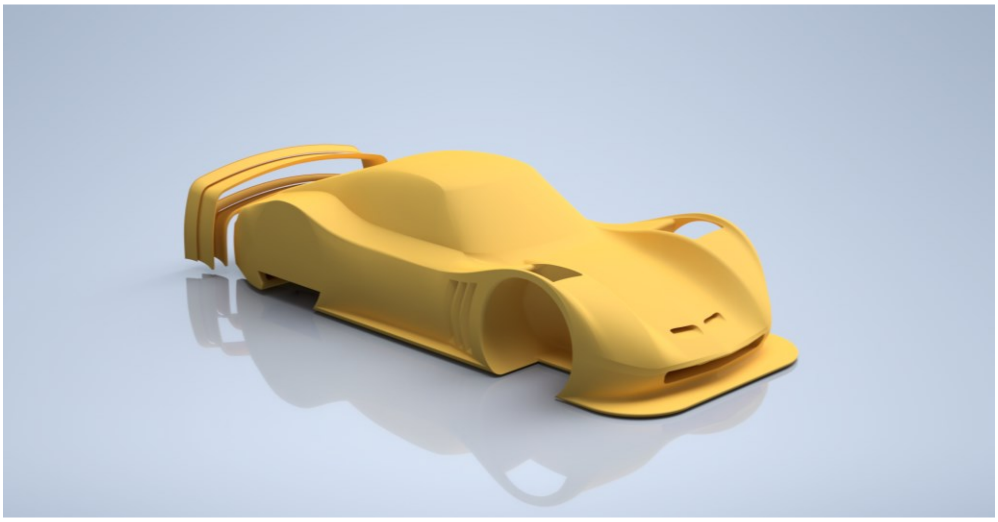
The base car is a 1973 Opel GT, this car was chosen because of its narrow body and aerodynamic design from the factory. Picture 1 shows the car as it was purchased.

Picture 1 The Opel GT as purchased.

At the time of writing this thesis, the car's body has been heavily modified and is mounted on a jig table. The engine mounting points have been made in the front of the car, the rear differential and transmission are mounted in the rear of the car. Picture 2 shows the er8 GT in its current state. The current state of the car allows for easy modifications. For example, fabrication of grounding points, making holes for bulkhead connectors through panels and attachment of wire harness mounting clips. The negative side with the current state of the car is that there are no exact locations for all components, this means that designing an exact wiring harness is impossible until every component has been placed into their exact positions either in a CAD assembly or in real life.

Picture 2 The er8 GT Project car in its current state.

A lot of the design has been put into the suspension geometry of the car and the aerodynamic kit, which will improve aerodynamic performance of the car. Picture 3 shows a current 3D-render of the aerodynamic package.



Picture 3 Er8 GT body.

The main features of the er8 GT project car are as follows:

- In-house built and designed, 4-cylinder, 4.0 litre turbocharged petrol THOR engine, set up to provide around 1000 horsepower.
- Inhouse built and designed aerodynamic package.
- Inhouse built and designed suspension with active dampening and height control.
- Inhouse built and designed engine management system.

5 System design

The system design was initiated by mapping out all the functions that the system must accomplish. It was also necessary to take environmental factors into consideration and factor in the cost of the components, weight and the possible expansion needs in the future.

5.1 Desired functions

At the start of the project, along with the customer we made a list of all the functions we needed the electrical system to perform. After we had listed all of the variables that we wanted to measure, and a list of all the electronic devices we wanted, the list was divided into following categories depending on their function:

- engine sensors and devices,
- engine accessory sensors and devices,
- suspension & chassis sensors and devices,
- transmission sensors and devices,
- fuel supply sensors and devices,
- front & rear lights,
- interior devices,
- brake system sensors.

All of the sensors and devices can be seen in the electrical documentation in appendix 2.

5.2 Weight & cost

Since the electrical system is going to be installed in a racing vehicle, considering weight in every sub-system of the car is crucial. Everything should be as light as possible. The centre of gravity and weight distribution along the car has significant effect on the dynamic performance of the car.

Saving weight in the wiring harness is most easily done by removing wires or making them shorter. In practice this usually means that the routing along the car should be planned in a way that wire lengths can be minimized. To remove wires a communication bus can be used between devices instead of physically routing each signal individually to multiple devices. The use of a digital communication bus also has benefits in signal integrity when compared to low level analog signals.

In addition to wiring, the devices and sensors should be as light as possible, however at some point this comes down to cost. For example, a generic Bosch water temperature sensor can cost 15 € and weigh 30 g, and a water temperature sensor made by Texense for motorsport use can cost 115 € and weight 15 g. In this case you would be paying 105 € extra for a weight saving of 15 g, depending on the budget a 15 g weight saving for 105 € is reasonable. With wiring, connectors, sensors, and devices the question of “Is the more expensive option worth it?” quickly arises. Almost everything is available lighter in weight if price is not an issue.

Since the er8 GT project car is funded solely by Elmer Racing a balance between cost, weight, durability, and sufficient functionality was set as the primary goal.

5.3 Modularity

From the start of the system design, it was known by both parties that changes to the vehicle and its components are likely to happen before it is finished. So, modularity and adding functionalities to the wiring harness later had to be considered. One of the ways to achieve modularity was through CAN bus expansions. We wanted to design the CAN bus in a way that devices could be easily removed and added by moving the place of the terminating resistor of the bus. For example, for a dynamometer session more than one lambda sensor is used, but for a race multiple lambda sensors are unnecessary weight.

5.4 Environmental requirements

The environment in which a race car wiring harness needs to perform is harsh. Water, high humidity, chemical spills, vibrations, high temperatures and high temperature changes are usually the main causes for malfunctions. Unfortunately, there is not much data on these topics available to the public. Top level motorsport teams have most likely measured their own data sets and set requirements for the components they use, but for others typically choices are made by what has worked in the past.

The easiest way to handle these environmental effects is to avoid them if possible. For example, a device should not be placed into the engine compartment where high temperatures are present if it is not necessary. If these environmental effects cannot be avoided the system should be designed in a way that the environmental effects to the system are minimized.

6 Component selection

Correct component selection based on the project needs, budget and functionality was one of the main points of this thesis. Therefore, after we had compiled the list of the desired. We set out to find the physical components to fill out these requirements. For the scope of this thesis the component selection mainly focuses on wiring harness components.

6.1 Sensors & Devices

When using third-party sensors and devices there is usually not an option to choose the connector of that component. It would be ideal for a designer to be able to use the same series of connectors throughout the wiring harness since the same crimping tools and connector accessories could be used in every connector. The use of the same connector series would lower the amount of different tooling and accessories needed and make maintenance easier. In addition, connector housing wire seals have specifications for the minimum and maximum wire thickness. This can be a problem if the type of connector cannot be chosen by the designer. To retain the environmental seal designed by the connector manufacturer the wire outer diameter must comply with these specifications. Often the wiring used in motorsport applications is thinner than the wire used in production cars.

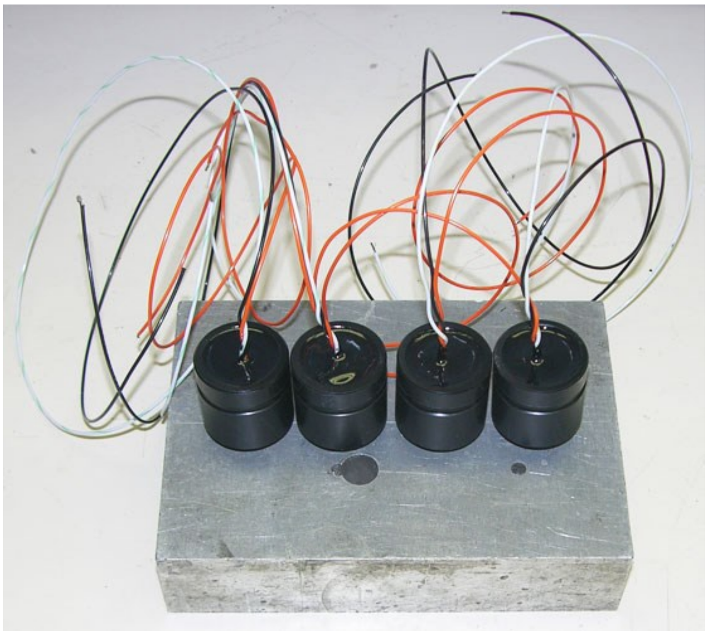
The use of OEM sensors and devices also meant that time had to be used in finding the right connector for that sensor or device. For example, the electronic throttle device used in the er8 GT project is the same one used in General Motors LS3 -engine, which means that we had to find the product numbers for the original Aptiv, formerly Delphi, connector it uses.

6.1.1 Potting

Some wiring harnesses overcome this problem by using a technique called “potting”, it is most frequently used with devices which do not have a connector. An example of this is a panel mounted switch or rotary encoder. This technique can also be used to connect a device to the wiring harness with a different connector than the OEM connector. A temperature sensor potted, shielded with heat shrink tubing and with a connector installed is shown in Picture 4.

Picture 4 Potted and sealed temperature sensor assembly [10].

When potting a sensor, a pigtail is soldered directly to the pins on the device, then a mould surrounding the solder joint is filled with an epoxy resin. This mould can be the original connector housing but depending on the situation for example, a piece of heat shrink tube can be used. The epoxy resin provides a sealing from water, moisture, and foreign objects. It also provides resistance from mechanical vibrations to the solder joint which may cause solder fatigue. Picture 5 shows potted rotary switches from behind.



Picture 5 Potted rotary switches [11].

The final product with heat shrink tubing covering the wires and a connector installed to the end of the pigtail is shown in Picture 6.

Picture 6 Potted rotary encoder with a connector [11].

One of the downsides with potted components is that they usually cannot be purchased as off the shelf products, instead spares must be manufactured in-house in advance.

6.2 Wires and cables

When it comes to wiring and cables, many options are available and the correct wire or cable should be chosen for that particular environment. Usually, the most important factor when choosing a wire or cable is the temperature range it is going to be installed in. Of course, there are many more variables to consider, for example, fire resistance and halogen free insulation materials provide increased safety in the event of a fire.

The wires used in automotive environments always contain multiple strands. Single stranded wires are not designed for applications in which mechanical vibrations are present. In addition, the added benefit of smaller turn radius and flexibility is necessary in the tight automotive environment.

6.2.1 Primary automotive wire types

Automotive manufacturers and standard developing organisations have developed multiple automotive wire standards. These different wire types can be roughly categorized by temperature range, insulation wall thickness and insulation type.

Cross-linked polyethylene automotive wire is often used in more demanding applications in a vehicle for example inside engine compartments. They can withstand higher heat, abrasion, and aging. Cross-linked automotive primary wires come in three different types. These wires have a temperature range of -40 °C to 125 ºC. [11, Para. 2.]

PVC automotive wire is usually used as a general-purpose wire. It is not as durable as cross-linked wires, and the temperature range is -40 °C to 85 ºC with some wire types having a maximum temperature of 105 ºC. These wires are more cost-effective and have good resistance to oil, grease, and acids. [11, Para. 3.]

In the wiring harness designed for er8 GT, some of the wiring outside of the cabin and engine compartment use wires with PVC insulation, for example the starter motor positive lead and battery negative lead to chassis ground. We did not want to use PVC insulated wire inside the cabin, since it can produce toxic gasses when burning.

Appendix 3 contains an overview of these primary wire types in the form of a table.

6.2.2 Aerospace and military wire and cable

Wire and cables designed for aerospace or military applications have to endure even harsher environmental stresses. These types of wires and cables are typically also used at the top levels of motorsport due to their lightweight and extreme performance. Better performance of course comes with greater cost.

ETFE, FEP and PTFE polymers are common insulation and sheathing materials used in these wires and cables. More insulation materials and insulation sheathing materials are also available for demanding applications, but for the scope of this thesis they are not covered.

ETFE commonly referred to as Tefzel™ has an operating temperature of -65 ºC up to +155 ºC depending on the specific wire. Figure 15 shows a radar chart of ETFE properties. The main properties of this wire insulation are:

- good properties at low and high temperatures,
- good resistance to physical abuse,
- high flex life,
- excellent chemical resistance,
- flame retardant and low smoke generation [13].

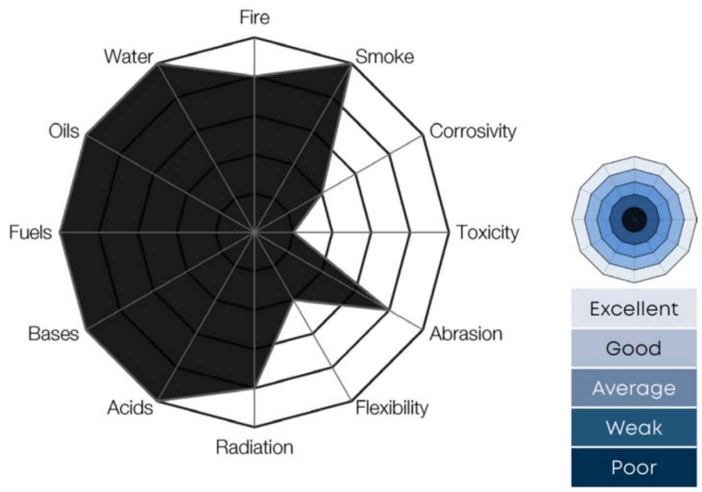


Figure 15 A radar chart presenting ETFE insulation properties [13].

FEP and PTFE also referred to as Teflon™ have very similar properties. The main difference between the two is temperature range, FEP has an operating temperature of -65 ºC up to +205 ºC and PTFE has an operating temperature of -75 ºC up to +260 ºC. [13]; [14.] Figure 16 shows a radar diagram of FEP properties. FEP and PTFE insulation materials are:

- extremely flexible,
- have good resistance to chemicals,
- highly flame retardant and low smoke generating [14]; [15].

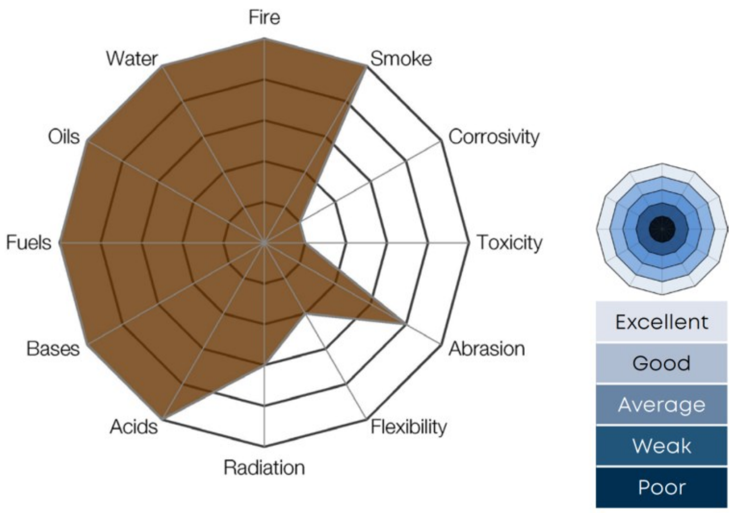


Figure 16 A radar chart presenting FEP insulation properties [14].

For the wiring inside the engine compartment in the er8 GT wiring harness it was decided to use Raychem Spec 55 wire, which has a cross-linked ETFE polymer insulation. This high-performance wire is made for aerospace applications but has become a de facto standard in high level motorsport wiring due to its extreme environmental properties and lightweight. In addition to availability as a primary wire, it can be purchased as a shielded cable with for low level analog sensors and devices with sensitive signals.

These Spec 55 wires have a temperature rating of -65°C to +150°C with tin-plated conductors and a temperature rating of -65°C to +200°C with silver- or nickel-plated conductors [16, p. 2].

The Spec 55 wire (PN: 55A0111) was also available from a local supplier which sells it by the meter, this was a good choice since the customer did not want to by full spools of the wire in every colour needed.

The shielded cables used in the er8 GT Project were also Raychem's Spec 55 shielded cables. It was natural to use the same family of cable for the sensors needing shielded cable due to the cable's high environmental performance. These sensor cables also go through the engine compartment so high temperature rating is necessary. This cable was also available from the same local supplier.

6.3 Connectors

Choosing the connector series used in the wiring harness was definitely the most time-consuming part in the process of component choosing. Automotive connectors are available from many manufacturers for many different use scenarios. We wanted to simplify the tooling and spare parts needed for the wiring harness by using the same connector series in every connection we could. We wanted to find a durable, cost-effective, and easy-to-use connector series. With third-party sensors and devices, we used the OEM connectors.

For choosing the connector series an excel sheet was formed to compare the price, weight, and other properties of similar wire-to-wire connectors. A separate excel sheet for comparing bulkhead connectors for firewall and rear passthrough was made. After the comparison for wire-to-wire connections Deutsch DT family of connectors was chosen and Deutsch Autosport -series connectors was chosen as bulkhead connectors.

A temperature rating higher than +125 °C was needed for connectors located close to heat sources in the engine compartment. Still, even if the wiring harness connectors have a temperature rating of over +125 °C, most of the OEM sensors and devices we used have a temperature rating of only +125 °C, so in terms of temperature the weakest links are going to be the OEM sensors and devices.

6.3.1 Deutsch DT family of connectors

The Deutsch DT family of connectors are widely used in many harsh automotive applications, these general-purpose connectors are environmentally sealed, and connectors are available as wire-to-wire and wire-to-board. [17, p. 111.] Figure 17 shows different Deutsch DT series connectors and accessories.

Figure 17 Picture of various Deutsch DT connectors and accessories [18].

The Deutsch DT family of connectors are also widely used in motorsport and other aftermarket applications. We chose to mainly use these connectors since they are cost effective, easily available, and they use the same crimping tool as the Deutsch Autosport connectors. They are available in many key configurations as well as with a wide range of cavities, displayed in Figure 18. The use of varying keyways throughout the wiring harness is made to ensure that only connectors meant to connect to each other can be connected.

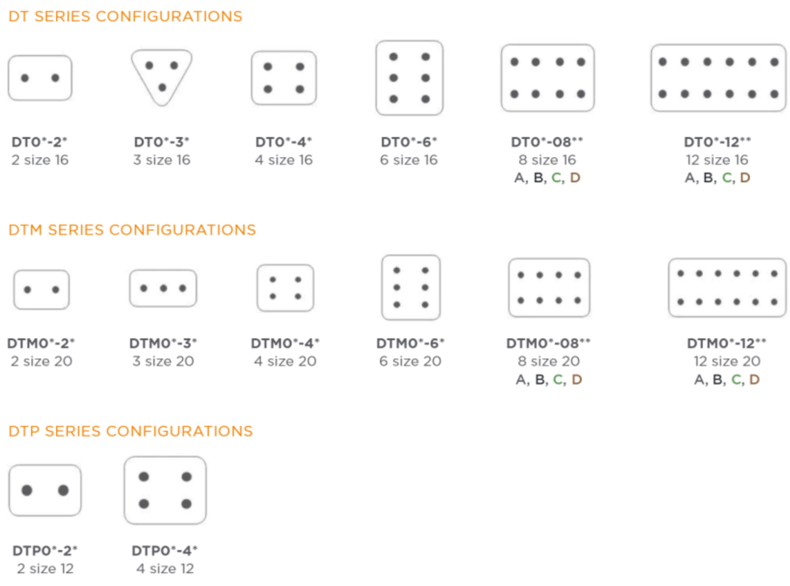


Figure 18 Deutsch DT, DTM and DTP series configurations [17, p. 114].

The Deutsch DT family of connectors consists of Deutsch DT, DTM and DTP series. These connectors differ mostly in their current handling capacity and number of cavities. [17, p. 111.]

Deutsch DT series connector specifications:

- Operating temperatures of -55°C to +125°C and -55°C to +150°C for DTMH series.
- Rated for 100 engagement disengagement cycles without electrical or mechanical defects.
- Connectors show no damage when exposed to most fluids in industrial applications.
- IP68 rating. Dust and waterproof can withstand immersion under 90 cm water. [17, p. 111.]

When choosing the connectors, it is also necessary to consider the wire overall diameter to ensure correct sealing of the connectors, Figure 19 shows the Deutsch DT series connectors wire sealing ranges.

Contact Size	Standard Seal	Extra Thin Seal E-Seal
20 14-22 AWG (2.5-0.35mm²)	.053-.120 (1.35-3.05)	-
16 14-20 AWG (2.0-0.5mm²)	.088-.145 (2.23-3.68)	.053-.120 (1.35-3.05)
12 10-14 AWG (6.0-2.0mm²)	.134-.170 (3.40-4.32)	.097-.158 (2.46-4.01)

Figure 19 Deutsch DT series connector sealing ranges [17, p. 116].

Modifications and accessories

In addition to regular DT family connectors a wide variety of modifications are available to meet application specific needs. These modifications include smaller wire seals, black connector body, higher temperature range, modified connector bodies suitable for shrink boots and different flange modifications. [17, pp. 118–120.] In the er8 GT wiring harness all Deutsch DT family connectors used were ordered with the modification “E004”, this modification is a black connector body. In addition, DTMH connectors and DTM connectors with the modification “EE04” were used in locations where the connectors will be subjected to high heat, since the DTMH connectors and “EE04” modification increases the maximum usable temperature from +125°C to +150°C.

TE Connectivity also provides a variety of accessories for the DT family including backshells, boots and mounting clips but these were included in the er8 GT wiring harness design. Backshells and boots provide a cleaner finish, additional protection, and weather sealing to the connectors, but after consideration we did not want to use them due to the added weight, cost, and complexity. Also, the DT series connectors already have an IP 68 rating so additional weather sealing is not a requirement. Raychem also manufactures heat shrinkable boots for the DT family connectors, but these boots are not included in the design for the aforementioned reasons. In addition, heat shrinked boots make servicing of the wire harness more difficult. [17, pp. 121–130.]

6.3.2 Deutsch Autosport connector series

The Deutsch Autosport connectors were developed from the MIL-C-38999 Series 1.5 Eurofighter connectors specifically for motorsport applications. Since the original Autosport series connectors, the Autosport family of connectors has grown and now contains multiple different connector families for different use cases. [19, p. 3.] Figure 20 shows a picture of different AS series connector housings.

Figure 20 Picture of Deutsch Autosport AS series connectors [19, p. 12].

Deutsch Autosport Connector family specifications:

- Compact and lightweight design.
- Rated for 500 engagement disengagement cycles without electrical or mechanical defects.
- Connectors show no damage when exposed to most fluids in autosport applications.
- IP67 rating. Dust and waterproof can withstand immersion under 1 m water for at least 30 minutes.
- Operating temperatures of -55°C to +175°C. [19, p. 3,12.]

In the er8 GT Project wiring harness these connectors were used for bulkhead connectors from the cabin through the firewall into the engine compartment and through the cabin into the rear of the vehicle. These connectors were chosen due to their compact connecting pin arrangement, lightweight and high durability. In addition, these connectors allow for easy disconnection of wire harness segments which makes maintenance easier. Also, these connectors are widely used in motorsport applications, and they were available from a local supplier. The availability of the bulkhead connectors was also considered, for example the aforementioned Eurofighter circular connectors are quite hard to purchase in small quantities.

Souriau, Amphenol and many others also manufacture similar circular connectors, but Deutsch Autosport connectors were chosen because of the shared tooling with the Deutsch DT family of connectors.

In addition to the regular gold-plated contacts specialty contacts, alumel and chromel contacts are available for use with thermocouples [19, p. 20].

6.4 Wiring harness sheathing

In order to neatly package and protect the wiring harness from abrasion, heat, moisture, impacts and other environmental effects, the wiring harness is often sheathed. The main wiring harness sheathing materials used are plastic tubing, different types of tape, braided sheathing, and heat shrinkable tube. In addition, many other sheathing materials are available like re-sealable sleevings and shielded sleevings for electrically noisy environments. Figure 22 shows a typical wiring harness which is sheathed with plastic tubing.

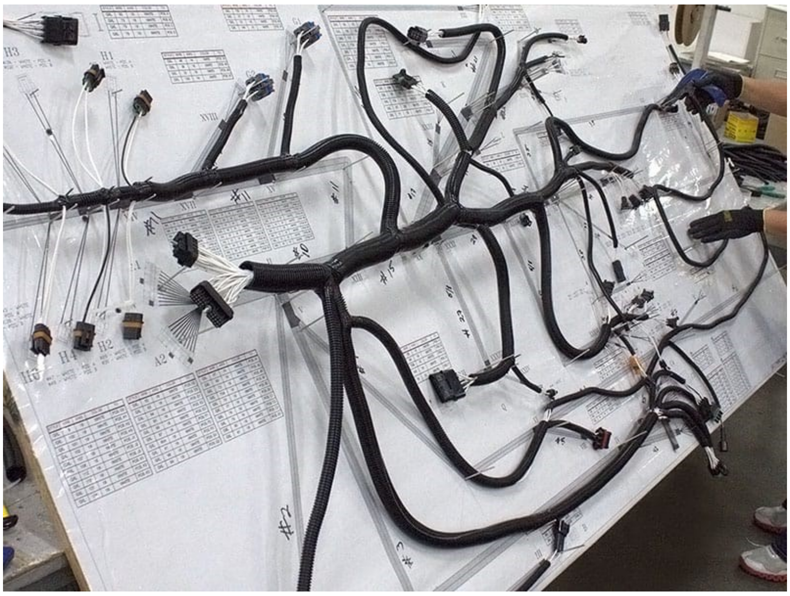


Figure 21 A picture of a mass produced wiring harness with plastic tubing as sheathing [20].

For the er8 GT project we wanted to find a reliable re-sealable wiring harness sleeving. Re-sealable wiring harness sheathing is not often used in motorsport applications. At top levels of motorsport, completely environmentally sealed wiring harnesses with Raychem DR family of products are often used, shown in Figure 22. This means that the connectors have heat shrinkable boots filled with an epoxy resin and the wiring loom is completely sealed with heat shrinkable tubing. This type of implementation increases abrasion and heat resistance as well as protects the wiring loom from any fluids. In addition, it gives a neater finish to the wiring harness. The downsides of a completely sealed wiring harness is that it cannot be easily modified after the sheathing has been heat shrinked, also maintenance is more challenging due to the sealed construction.

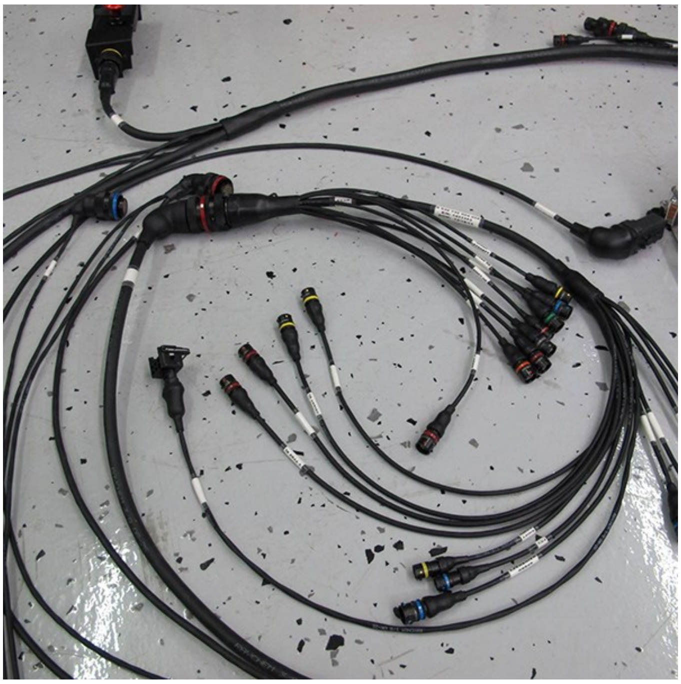


Figure 22 A picture of a sealed wiring harness [21].

We wanted to design a wiring harness which could be later modified and easily repaired, so it was decided to use a sheath which could be opened and closed. Zippertubing’s re-sealable sheathings were chosen, they provide various different types of re-sealable sheathing materials for different environments. For the time being we plan to use Zippertubing’s Zip-Wrap® KWF-24, shown in Figure 23, for high temperature locations and Zippertubing’s Zip-Wrap® PFR, shown in Figure 24, sheathing for lower temperature areas. These sheathing materials can still change depending on availability from our supplier.

Figure 23 Zippertubing Zip-Wrap® KWF-24 [22].

The Zippertubing Zip-Wrap® KWF-24 is a woven Kevlar fabric sheathing with a brass zipper designed for high-heat environments, it has a temperature range of -46 °C to + 177 °C. This sheathing material provides 360-degree sheathing around the wiring harness. It is lightweight, flexible, and extremely abrasion resistant. This sheathing is available with diameters ranging from 1,3 cm to 15,25 cm. In addition, the zipper provides easy access for making modifications and maintenance. Due to its great temperature and abrasion resistance we plan on using this sheathing inside the engine compartment. [22.]

Figure 24 Zippertubing Zip-Wrap® (PFR) [23].

The Zippertubing Zip-Wrap® PFR is planned to be used in the er8 GT project in areas which are not subjected to high heat like inside the cabin. This sheathing has a temperature range of -55 °C to 107 °C. This sheathing also is flame retardant per UL94 V-O standard and free of PVC materials. [23.]

In addition to the aforementioned re-sealable sheathings in some places, shrink tubing and generic woven sheathing braids will also be used. It was agreed on with the customer that specific sheathing materials will be chosen closer to the manufacturing of the wiring harness.

6.5 Miscellaneous components

During the wiring harness assembly and installation miscellaneous components like electrical tape, Kapton tape, zip ties and Kevlar wire can be used to ease the assembly and package the wiring harness neatly. Also, the wiring harness must be attached to the vehicle chassis tightly to prevent vibration and abrasion under harsh conditions.

For the er8 GT project we have not yet decided on the wiring harness securing clips due to uncertainty with the wiring harness sheathing materials and wire harness segment thicknesses. The specific type of wiring harness mounting clips will be specified when the project advances and the wiring harness is manufactured.

7 Electrical design

Zuken E^3.series software was used for electrical design, in conjunction with Microsoft Excel and Autodesk Inventor Professional 2022. Excel was used for calculations and Inventor was used for visualizing the wiring harness to help with the electrical design.

7.1 Fuses and circuit protection

In order to protect the devices and wires in the case of a malfunction circuit protection devices are used. These devices are usually fuses or resettable fuses.

In the case of er8 GT project car a minimal number of fuses were used, the current limitations and circuit breaking is mainly handled by the in-house designed ECU and the LiteBlox lithium-ion starter battery which includes a BMS and multiple safety features, for example an integrated FIA approved kill switch input. A picture of the LiteBlox battery is shown in Figure 25.

Figure 25 LITE⚡BLOX PS20MS 16V lithium-ion battery [24].

7.2 Wire cross-sectional area & wire colours

All of the wires used in the wiring harness have to be sized correctly depending on the current flowing through the wire, the wire length and ambient temperature. Properly color-coded wiring makes identifying wires easier, thus helping with assembly and diagnostics.

7.2.1 Wire cross-sectional area

The automotive electrical system operates at low voltages ranging from 5 VDC for sensor power to around 15 VDC at battery when the alternator is charging. Due to these low voltages, the resistance of the current carrying wire introduces a significant voltage drop in the circuit. Therefore, the wire sizes are calculated to meet the permissible voltage drop. [2, pp. 394–395.] In automotive literature there are many values for the permissible voltage drop along a wire ranging from 2–5 % of the supply voltage. In the er8 wire cross section calculations a 5% voltage drop for calculating the wire sizes was used.

In addition, to the maximum voltage drop along a wire the mechanical strength should be considered. In many applications wires smaller than 0,5 mm^2 are not used due to their limited mechanical strength. With careful precautions such as good harness sheathing, strain reliefs, and sufficient attachment points to the vehicle smaller wires can be used. [2, p. 395]

In the er8 GT project, accurate calculation of the wire cross sections for every wire was impossible since at the time of designing the component placement was not finished. This meant that the wire lengths were estimated in 3D-CAD software. Figure 26 shows the approximated maximum length for a wire from firewall bulkhead connector to the furthest point in the engine, this distance was 1741 mm from the CAD software, but it was increased to 1900 mm for wire cross section calculations.

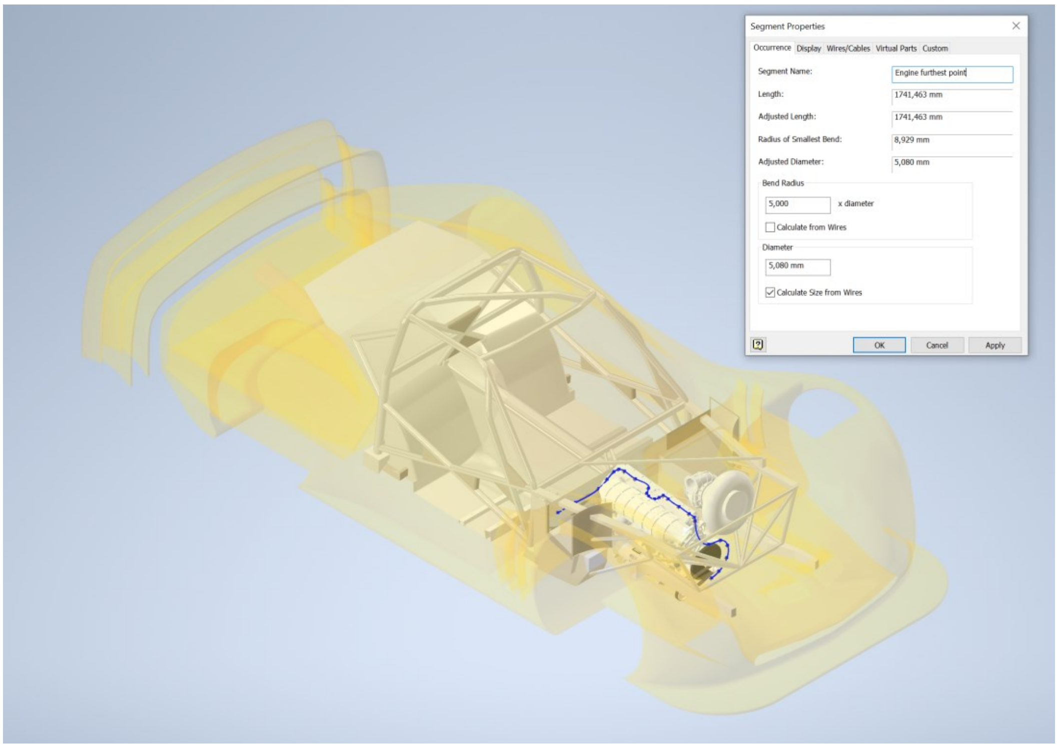


Figure 26 Approximated distance from firewall bulkhead connector to furthest part in the engine.

Another difficult part in calculating the wire cross sections is estimating the continuous current flowing through the wire. Many sensors and devices, especially OEM do not provide sufficient information regarding the devices power use. If accurate current data for devices and sensors is not available, they need to be measured in a test bench. Estimating the continuous current can be difficult for devices which are not operated at full power all of the time, for example devices controlled with a PWM signal or fuel injectors.

The cross-sectional area of wires is also often limited by the connectors in use. For example, the ECU connectors have a maximum wire size of 1,25 mm^2 and the Deutsch Autosport bulkhead connectors used in er8 GT have a maximum wire size of 0,35 mm^2, in these cases the supply voltage for devices with larger current consumption has to be done with splices and by using multiple pins on a connector. For the most part 0,35 mm^2 wiring was sufficient throughout the wiring harness.

A wire cross-sectional area calculator was created in Microsoft Excel to quickly compare wire sizes for given applications shown in Figure 27. The calculator calculates voltage drop along the wire and a CMA value for the wire or wires used. The size of a splice is often given as a CMA value so this makes choosing a suitable splice easier. Since some of the wires carrying higher current need to pass-through a Deutsch Autosport bulkhead connector with 0,35 mm^2 wire this calculator made it a lot easier to calculate how many 0,35 mm^2 should be used to carry these current through the connector with an acceptable voltage drop.

Device	Voltage	Max current per device	Duty Cycle	Amount of devices	Total current rounded to a integer	Wire length	Wires (Qty)	Wire size (mm^2)	Voltage drop	CMA
Analogue sensor feeds	5,00 V	0,01 A	100 %	11	1 A	2,0 m	1	0,35	2 %	691
Digital sensor feeds	5,00 V	0,01 A	100 %	9	1 A	2,0 m	1	0,35	2 %	691
Ignition coil feeds	12,00 V	5,00 A	50 %	4	10 A	2,0 m	4	0,35	2 %	2763
PWM water pump	12,00 V	7,50 A	80 %	1	6 A	2,7 m	1	1,00	3 %	1974
Electronic throttle	12,00 V	5,00 A	100 %	1	5 A	2,0 m	1	0,35	4 %	691
Fuel injector (12 Ω)	12,00 V	1,00 A	100 %	2	2 A	2,0 m	3	0,35	1 %	2072
Fuel pump	12,00 V	5,00 A	100 %	1	5 A	3,7 m	2	0,35	4 %	1381
Starter motor	16,00 V	600,00 A	50 %	1	300 A	1,0 m	1	16,00	2 %	31576
Engine 12V feed	12,00 V	17,00 A	125 %	1	22 A	2,0 m	6	0,35	3 %	4144

Figure 27 Results from the Microsoft Excel wire size calculator.

7.2.2 Wire colours

The Raychem Spec 55 wiring which makes up for most of the wiring in the er8 GT project wiring harness is available in ten colours from our supplier. This means that same colour wires have to be used for multiple signals. In automotive wiring there are no definitive rules for wire colours, and they usually differ depending on the vehicle manufacturer. For the some of the signal’s colours were assigned, these colours are the same in every section of the harness. Table 1 shows these wire colours and their corresponding signals.

Table 2 Wire colours and their corresponding signals.

Colour	**Signal**
Red	12 V
Black	Chassis ground
Blue	5 V
Yellow	Analog ground
Purple	Digital ground
Green	CAN-H
White	CAN-L

7.3 Grounding

The er8 GT car has three main grounding points where all of the components are grounded. These grounding points are located in the rear of the vehicle, inside the cabin and inside the engine compartment.

Attention was especially given to the sensor grounding in order to minimize common ground noise and ground loops. Sensors with similar signals were grouped into the same ground return shown in Figure 28. More detailed grounding schematics can be found in appendix 2 included in the electrical documentation.

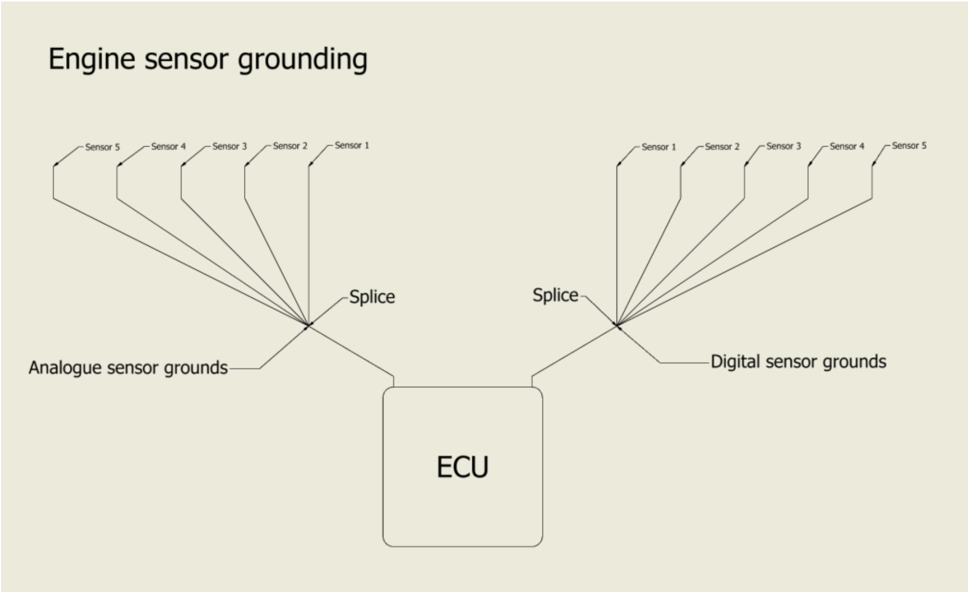


Figure 28 Engine sensor grounding diagram.

The shielded cable shields were only grounded at the ECU end of the cable. This provides protection from electric fields, but none from magnetic fields. The shield was not grounded at both ends to prevent unnecessary ground loops from forming. Also, to minimize the effect of magnetic coupling twisted-pairs were used when possible.

7.4 CAN bus

The CAN bus was designed as a “separate” sub-system to the wiring harness independent from the main loom. The CAN bus design uses a Deutsch 6-pin DTM connector for devices and a Deutsch Autosport 6-pin bulkhead connector for pass-throughs. The use of a 6-pin connector allows us to have reserved pins for 12 VDC, chassis ground, CAN-H, CAN-L lines and two spares for maximum flexibility in adding new CAN bus devices without modifications to the main loom. In addition, spare connectors are also placed around the CAN bus to ensure expandability and modularity in the future.

A schematic of the complete CAN bus can be found in appendix 2 along with the electrical documentation.

7.5 Wiring diagrams

Drawing of the wiring diagrams was started with creating the wiring harness connectors as connector components inside Zuken E^3. These components were given the correct attributes such as pin count, product numbers, minimum and maximum wire diameters. In addition, for all components multiple views were created based on 3D models provided by the connector manufacturer. For all connectors a 3D model was not available, these connectors were modelled separately. Figure 29 shows a design view of a connector.

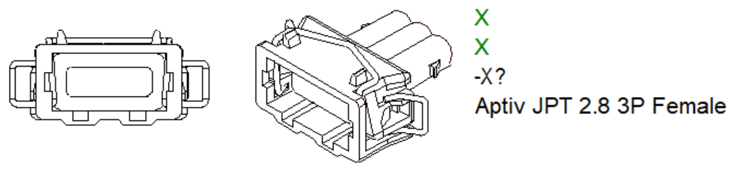


Figure 29 Design view of a connector created in Zuken E^3 software.

With the connectors as components inside Zuken E^3, sensors and devices were modelled as simple blocks with connectors attached to them, shown in Figure 30.

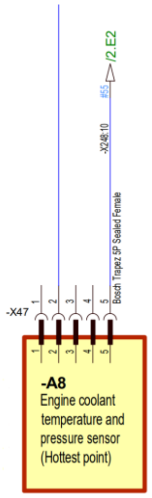


Figure 30 Temperature and pressure sensor as modelled in Zuken E^3.

For the wiring diagrams a top-to-bottom style of drawing was chosen since this way the diagrams were easy to read. The wiring diagram sheets were divided by their placement on the vehicle, for example all of the engine harness components are visible on the same sheet, this was done to make diagnostics easier.

The connections from connector-to-connector were assigned with correct wires and signals. The cross-sections of wires was only made visible on wires which are different than 0,35 mm^2 this was done to avoid cluttering the wiring diagrams. Complete wiring diagrams are in appendix 2.

8 Packaging design

Packaging design was not easy with the er8 GT project's current state. The approximate location of all of the devices was discussed with the customer, but as of now no electrical components have been installed in the vehicle, nor any mounting brackets have been made for those components. Also, the 3D modelled assembly of er8 GT project currently only includes a 3D scan of the body, aerodynamic package, roll cage and powertrain. The wire harness routes were also discussed with the customer and approximate wiring harness routes were agreed on. Figure 31 shows the front section of the loosely modelled wiring harness.

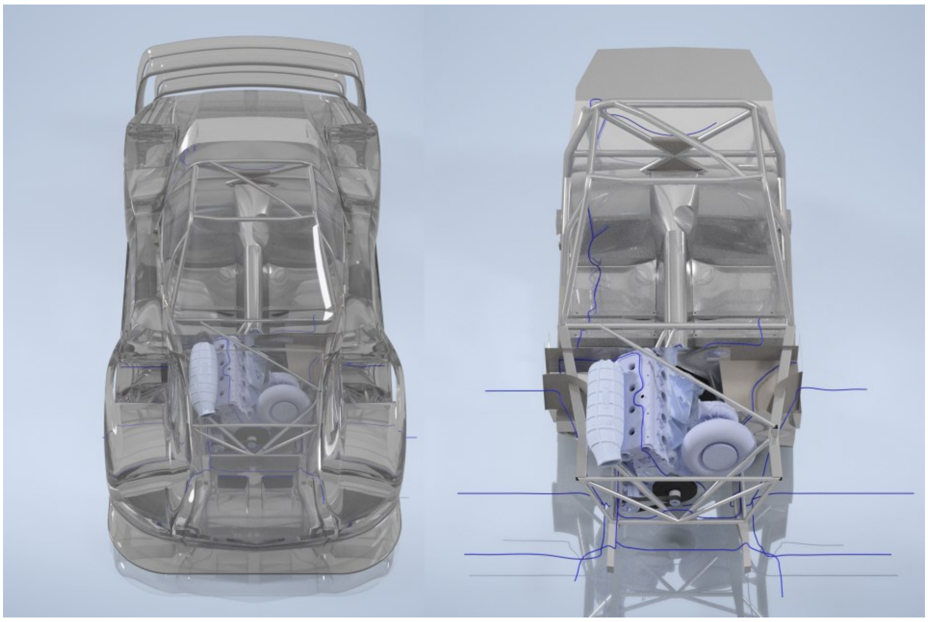


Figure 31 Loosely modelled front harness, shown in blue, on top of the er8 GT assembly file.

Since the component locations and wiring harness routing paths were only approximate a wire harness was loosely modelled inside Autodesk Inventor Professional software on top of the existing er8 GT project assembly file. This loosely modelled wiring harness served multiple purposes:

- It was used to determine wiring harness routing.
- It was used to get approximate wire lengths.
- It was used to get a better understanding of the wiring harness branch of points and to better visualize the harness architecture.

In addition, the approximate wire lengths were used to calculate voltage drops for wires and to calculate the approximate amount of wire needed for the harness.

9 Harness design

The harness design was done using Zuken E^3 software and Autodesk Inventor Professional. The harness manufacturing documentation was made based on the wiring diagrams, the wire lengths and branch of points from the loosely modelled wiring harness. Because of the approximated branch lengths, no meaningful manufacturing tolerances for the wire lengths could be made. An overview of the harness design can be found in appendix 2 included in the electrical documentation.

One of the most important phases in harness design is designing the harness attachment to the vehicle. Since this is one of the main ways of preventing vibration in the wiring harness. In addition, proper strain reliefs are necessary, and the wiring harness should be fixed to something rigid as close to the connector as possible to prevent unnecessary strain and vibrations in the connector. [2, p. 395] For the same reasons connectors should be also fixed to something rigid whenever possible.

Unfortunately, in the er8 GT project accurate wiring harness connecting points to the chassis were not designed in this thesis due to the possible changes in wiring harness routing and component placement as the project advances.

To support the modularity, expandability, and possible future changes to the wiring harness, we agreed with the customer to design the wiring harness layup in a traditional parallel style shown in Figure 32.

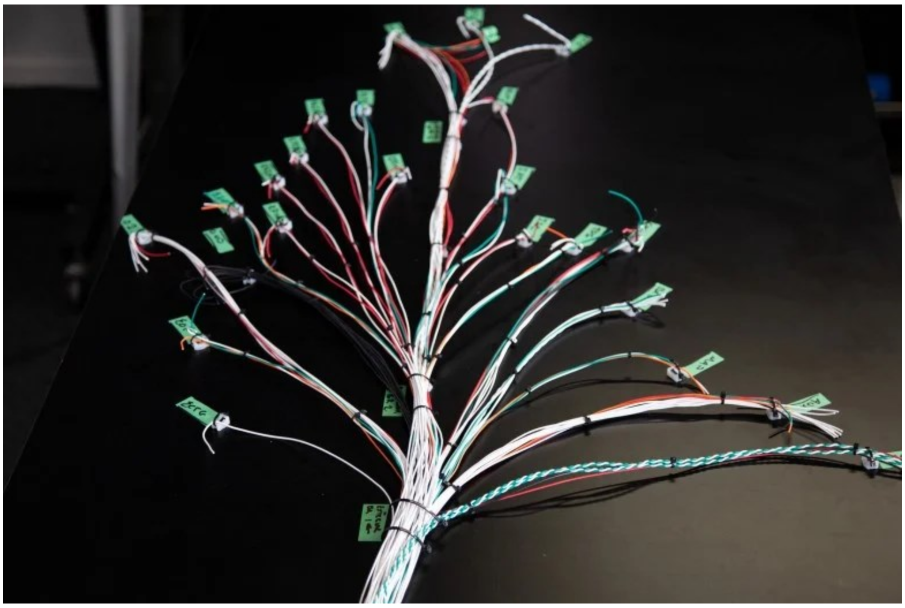


Figure 32 Traditional wiring harness layup [25].

In top level motorsports concentric twisting is usually used in wiring harness layup shown in Figure 33. This method provides better flexibility, even strain on all wires in the bundle and a uniform finish. Although it does come with downsides, the amount of wiring needed is 15-20% more than with a parallel layup because of the twist angle, filler wire is needed to get even layers, also concentric twisting takes a lot more time than a traditional layup [25].

Figure 33 A picture of a concentrically twisted wiring harness segment [25].

10 Conclusions

The goal of this thesis was to design a complete wiring harness for the customers racing vehicle. This included full documentation for purchasing the necessary components, as well as documents regarding the manufacturing and troubleshooting of the wiring harness. The goal of the thesis originally included wiring harness manufacturing, but it was removed during the making of this thesis, since the project car's development has slowed down after customer projects have started to take more time from the er8 GT project. This meant that an accurate wiring harness was not possible to be manufactured at this time. In conjunction, with the customer it was agreed on to produce sufficient documentation so that the wiring harness can be later.

The design of a complete electrical system is a complex task and should be done in conjunction with the development of other subsystems. In this thesis a complete overview of wiring harness design is provided and these design philosophies are also applicable to other wiring harness designs.

In addition to wiring harness design an overview of CAN bus and EMC, regarding wiring harness design is provided, since these are complicated topics and there is a lot of nonfactual discussion related to these topics.

In this thesis a lot of time was used in justifying the component and material choices. Instead of going the usual top-level motorsport wiring route, we wanted to find the best options for our use case. When the cost of the wiring harness is not an issue, it is understandable to use these top-level wiring harness manufacturing methods to eliminate every possible source of malfunction, but in the er8 GT the wiring harness which will be used for longer than one season and modifications are likely to happen, this meant that a completely sealed wiring harness was not an option for this project.

This thesis was a magnificent learning experience, since I have not used Zuken E^3 software before this thesis. In future projects, I would pay more attention to planning the electrical documentation before starting to draw wiring diagrams. In order to get a more cleaner end product. I would assign every signal in Zuken E^3 at an earlier stage of the design and use a bit more time on planning the component naming beforehand, since these are quite time-consuming to correct later.

At the end, the goals of the thesis were met, and the customer was pleased with the end product.

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Galvanic series

Table of the Galvanic series [7, p. 34].

TABLE 1-13. Galvanic Series.

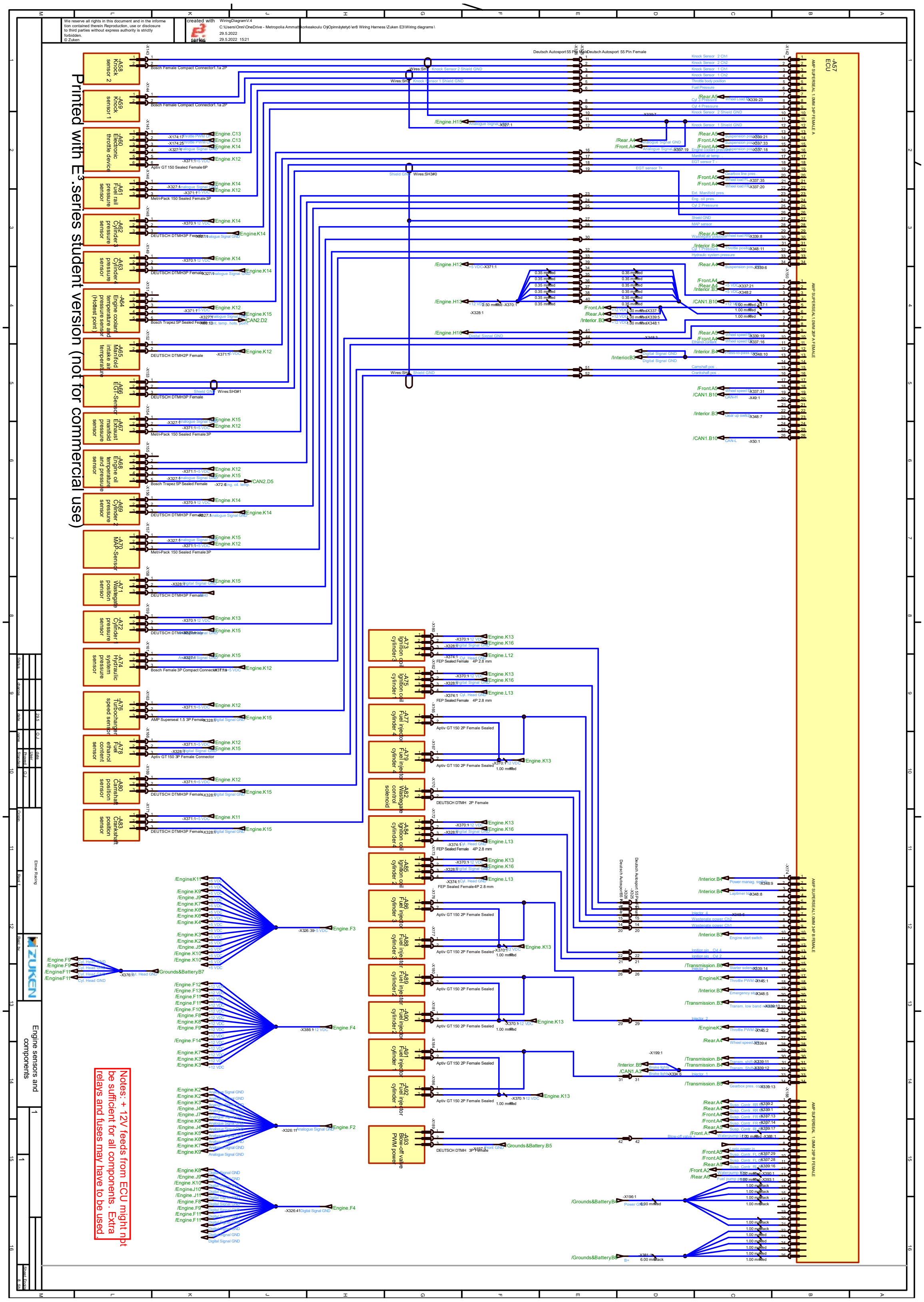
ANODIC END
(Most susceptible to corrosion)

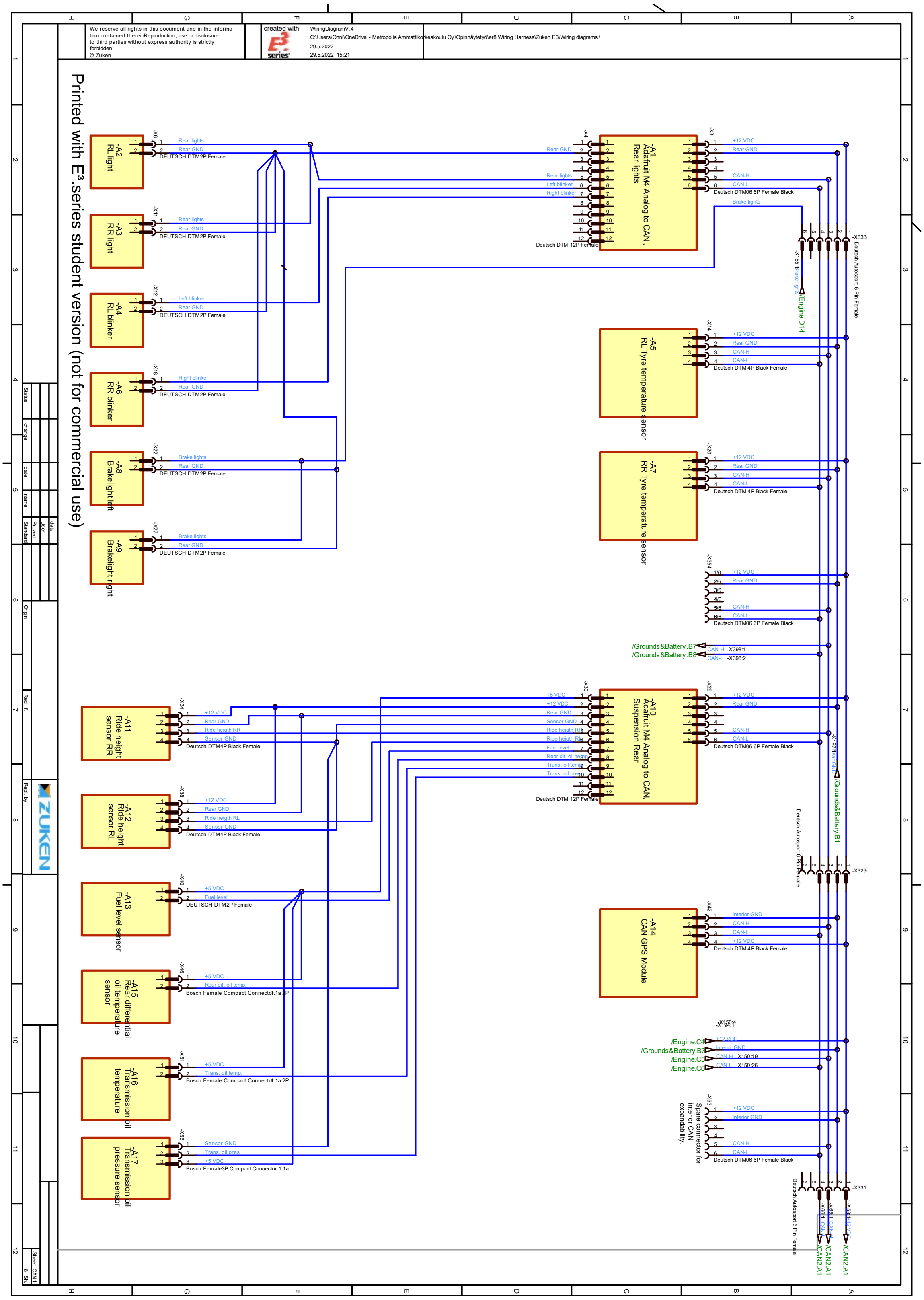
Group I	1. Magnesium		13. Nickel (active)
			14. Brass
	2. Zinc		15. Copper
	3. Galvanized steel		16. Bronze
Group II	4. Aluminum 2S	Group IV	17. Copper-nickel alloy
	5. Cadmium		18. Monel
	6. Aluminum 17ST		19. Silver solder
			20. Nickel (passive)[a]
	7. Steel		21. Stainless steel (passive)[a]
	8. Iron		
Group III	9. Stainless steel (active)		22. Silver
	10. Lead-tin solder	Group V	23. Graphite
	11. Lead		24. Gold
	12. Tin		25 Platinum

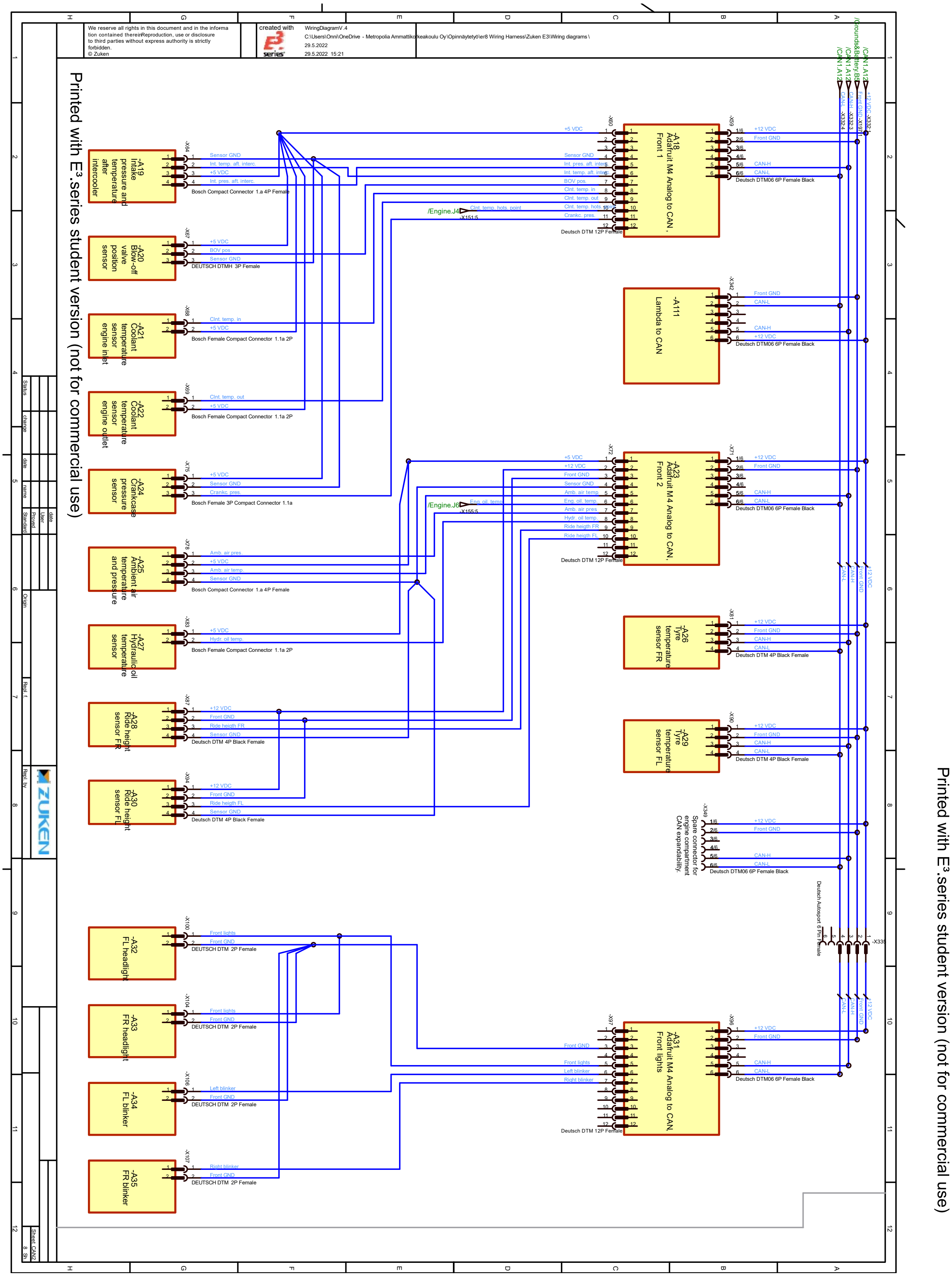
CATHODIC END
(Least susceptibility to corrosion)

[a]Passivation by immersion in a strongly acidic solution.

Electrical documentation




Printed with E3.series student version (not for commercial use)
-A1 Adafruit M4 Analog to CAN, Rear lights
-A2 RL light
-A3 RR light
-A4 RL blinker
-A6 RR blinker
-A8 Brakelight left
-A9 Brakelight right
-A5 RL Tyre temperature sensor
-A7 RR Tyre temperature sensor
-A10 Adafruit M4 Analog to CAN, Suspension Rear
-A11 Ride height sensor RR
-A12 Ride height sensor RL
-A13 Fuel level sensor
-A14 CAN GPS Module
-A15 Rear differential oil temperature sensor
-A16 Transmission oil temperature
-A17 Transmission oil pressure sensor
Spare connector for interior CAN expandability.


Printed with E³.series student version (not for commercial use)
-A18 Adafruit M4 Analog to CAN, Front 1
-A111 Lambda to CAN
-A23 Adafruit M4 Analog to CAN, Front 2
-A31 Adafruit M4 Analog to CAN Front lights
-A19 Intake pressure and temperature after intercooler
-A20 Blow-off valve position sensor
-A21 Coolant temperature sensor engine inlet
-A22 Coolant temperature sensor engine outlet
-A24 Crankcase pressure sensor
-A25 Ambient air temperature and pressure
-A27 Hydraulic oil temperature sensor
-A28 Ride height sensor FR
-A30 Ride height sensor FL
-A26 Tyre temperature sensor FR
-A29 Tyre temperature sensor FL
-A32 FL headlight
-A33 FR headlight
-A34 FL blinker
-A35 FR blinker
Spare connector for engine compartment CAN expandability
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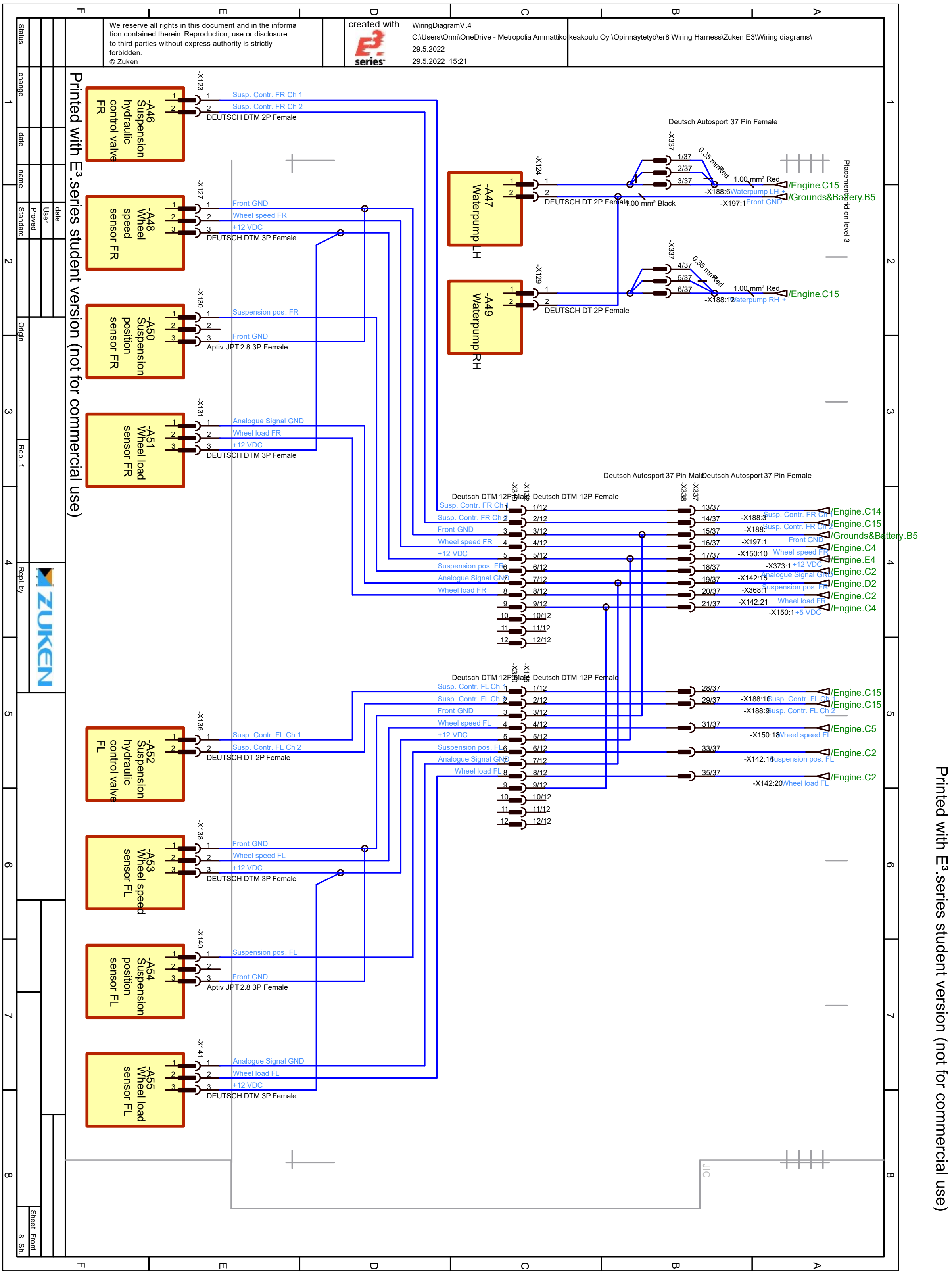
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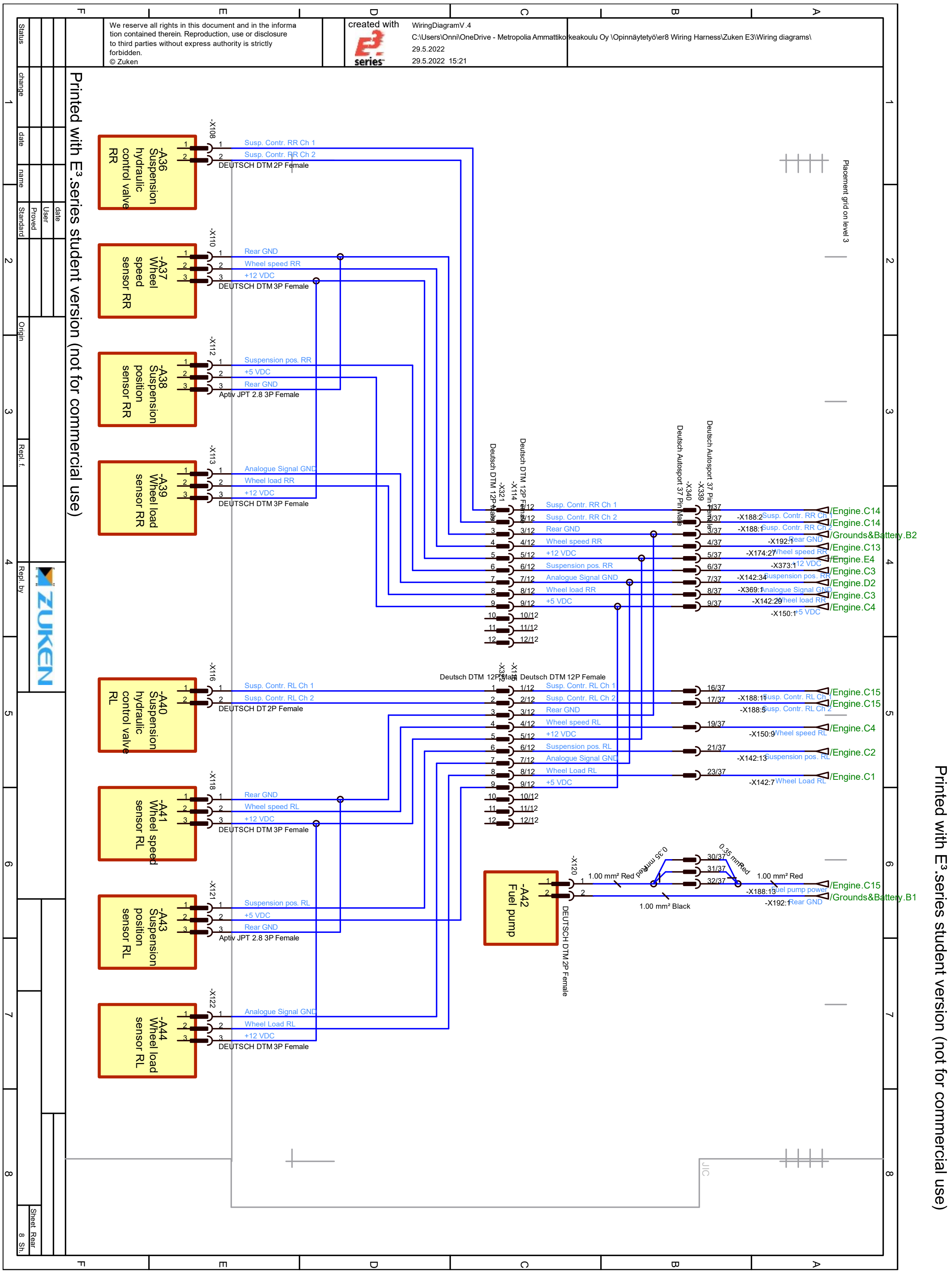
WiringDiagramV.4
29.5.2022
29.5.2022 15:21
Deutsch Autosport 37 Pin Female
Deutsch Autosport 37 Pin Male
Deutsch DTM 12P Male
Deutsch DTM 12P Female
DEUTSCH DTM 2P Female
DEUTSCH DTM 3P Female
DEUTSCH DT 2P Female
Aptiv JPT2.8 3P Female
Susp. Contr. FR Ch 1
Susp. Contr. FR Ch 2
Front GND
Wheel speed FR
+12 VDC
Suspension pos. FR
Analogue Signal GND
Wheel load FR
Susp. Contr. FL Ch 1
Susp. Contr. FL Ch 2
Wheel speed FL
Suspension pos. FL
Wheel load FL
/Engine.C14
/Engine.C15
/Grounds&Battery.B5
/Engine.C4
/Engine.E4
/Engine.C2
/Engine.D2
/Engine.C5
1.00 mm² Red
1.00 mm² Black
0.35 mm² Red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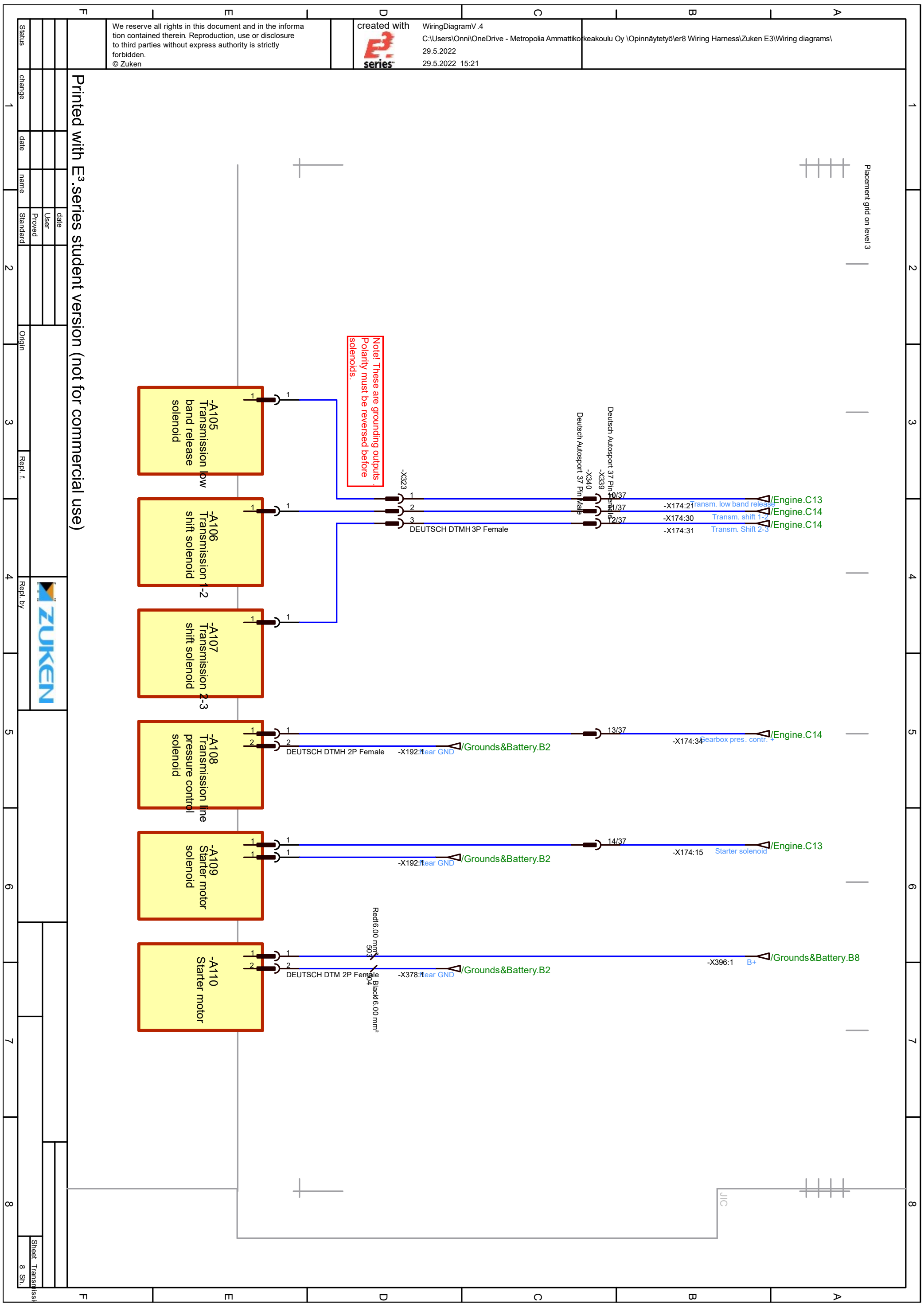
-A36 Suspension hydraulic control valve RR
-A37 Wheel speed sensor RR
-A38 Suspension position sensor RR
-A39 Wheel load sensor RR
-A40 Suspension hydraulic control valve RL
-A41 Wheel speed sensor RL
-A43 Suspension position sensor RL
-A44 Wheel load sensor RL
-A42 Fuel pump
DEUTSCH DTM 2P Female
DEUTSCH DTM 3P Female
Aptiv JPT 2.8 3P Female
DEUTSCH DT 2P Female
Deutsch DTM 12P Male
Deutsch DTM 12P Female
Deutsch Autosport 37 Pin Male
Deutsch Autosport 37 Pin Female
Susp. Contr. RR Ch 1
Susp. Contr. RR Ch 2
Rear GND
Wheel speed RR
+12 VDC
Suspension pos. RR
+5 VDC
Analogue Signal GND
Wheel load RR
Susp. Contr. RL Ch 1
Susp. Contr. RL Ch 2
Wheel speed RL
Suspension pos. RL
Wheel Load RL
Fuel pump power
1.00 mm² Red
1.00 mm² Black
0.35 mm² Red
/Engine.C14
/Grounds&Battery.B2
/Engine.C13
/Engine.E4
/Engine.C3
/Engine.D2
/Engine.C4
/Engine.C15
/Engine.C2
/Engine.C1
/Grounds&Battery.B1
Placement grid on level 3


-A105 Transmission low band release solenoid
-A106 Transmission 1-2 shift solenoid
-A107 Transmission 2-3 shift solenoid
-A108 Transmission line pressure control solenoid
-A109 Starter motor solenoid
-A110 Starter motor
Note! These are grounding outputs. Polarity must be reversed before solenoids.
-X323
DEUTSCH DTMH 3P Female
DEUTSCH DTMH 2P Female
DEUTSCH DTM 2P Female
Deutsch Autosport 37 Pin Male
Deutsch Autosport 37 Pin Female
/Engine.C13
/Engine.C14
/Grounds&Battery.B2
/Grounds&Battery.B8
Placement grid on level 3
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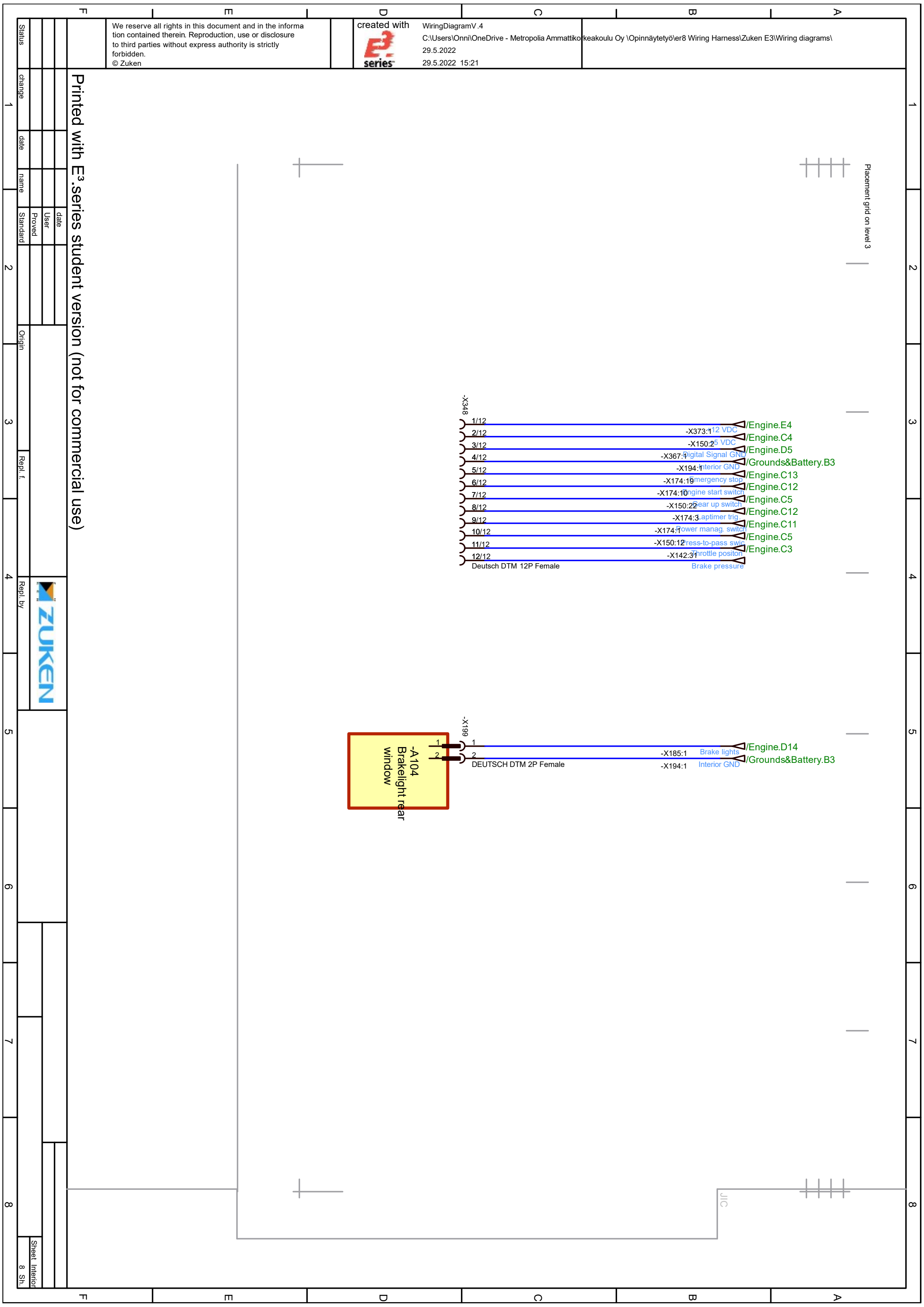
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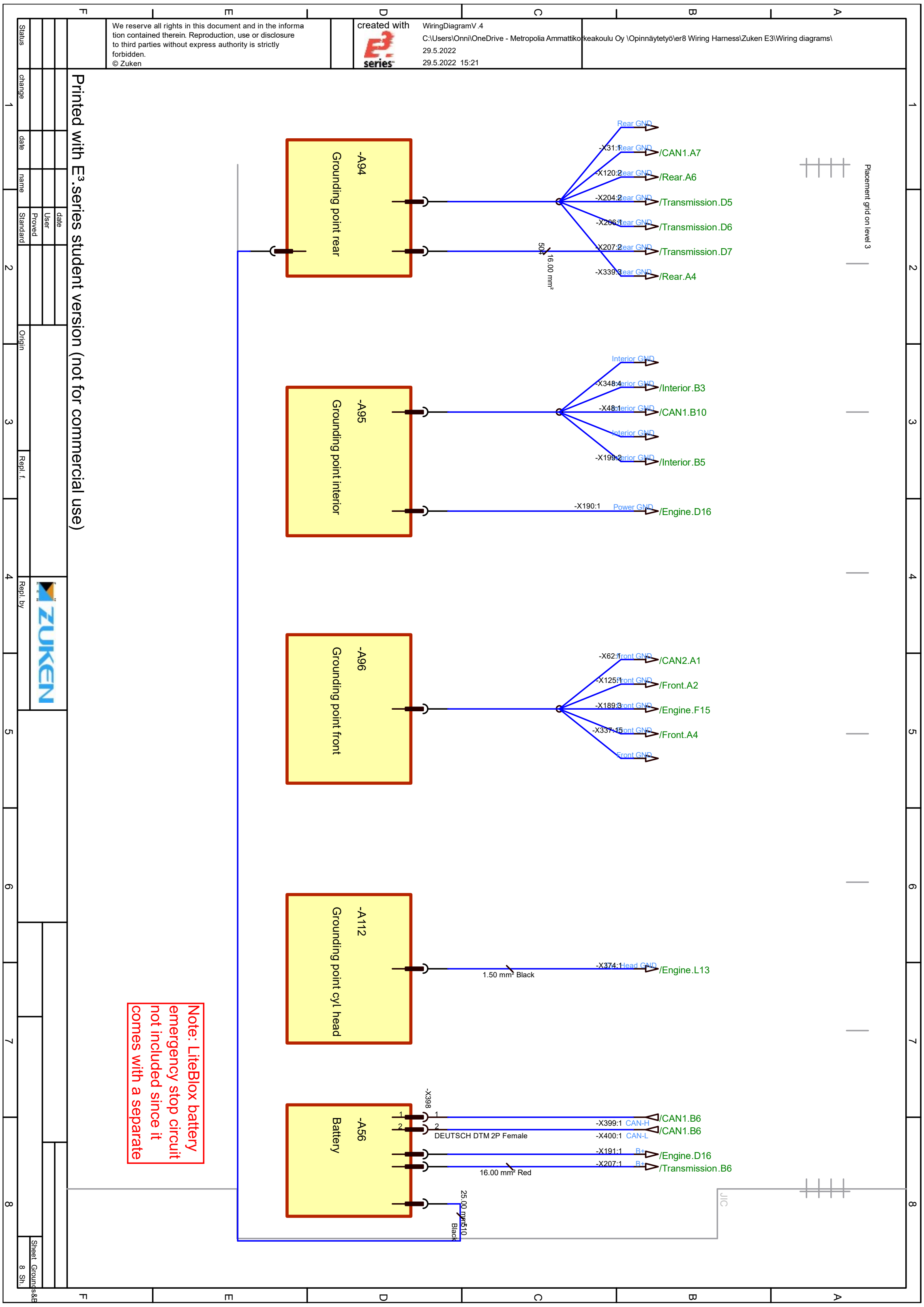
WiringDiagramV.4
29.5.2022
29.5.2022 15:21
-X348
Deutsch DTM 12P Female
/Engine.E4
/Engine.C4
/Engine.D5
/Grounds&Battery.B3
/Engine.C13
/Engine.C12
/Engine.C5
/Engine.C12
/Engine.C11
/Engine.C5
/Engine.C3
-X199
DEUTSCH DTM 2P Female
-X185:1
-X194:1
Brake lights
Interior GND
/Engine.D14
/Grounds&Battery.B3
-A104
Brakelight rear window
Placement grid on level 3
ZUKEN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WiringDiagramV.4
C:\Users\Onni\OneDrive - Metropolia Ammattikorkeakoulu Oy \Opinnäytetyö\er8 Wiring Harness\Zuken E3\Wiring diagrams\
29.5.2022
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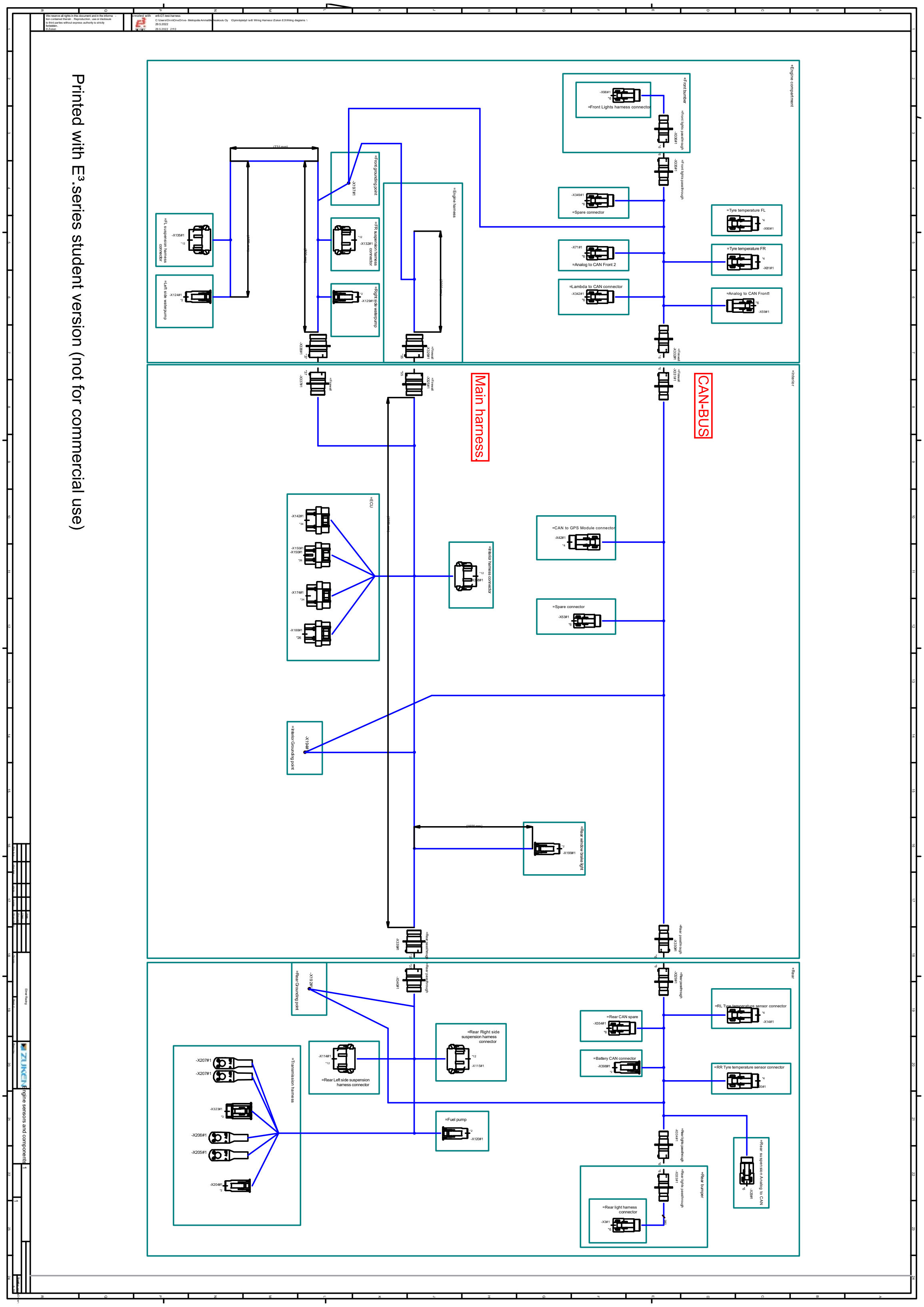
ZUKEN
-A94
Grounding point rear
-A95
Grounding point interior
-A96
Grounding point front
-A112
Grounding point cyl head
-A56
Battery
Rear GND
/CAN1.A7
/Rear.A6
/Transmission.D5
/Transmission.D6
/Transmission.D7
/Rear.A4
16.00 mm²
Interior GND
/Interior.B3
/CAN1.B10
/Interior.B5
-X190:1
Power GND
/Engine.D16
Front GND
/CAN2.A1
/Front.A2
/Engine.F15
/Front.A4
-X374:1
Head GND
/Engine.L13
1.50 mm² Black
-X398
DEUTSCH DTM 2P Female
-X399:1 CAN-H
-X400:1 CAN-L
/CAN1.B6
/CAN1.B6
-X191:1 B+
-X207:1 B+
/Engine.D16
/Transmission.B6
16.00 mm² Red
25.00 mm² Black
Note: LiteBlox battery emergency stop circuit not included since it comes with a separate
Placement grid on level 3
Status
change
date
name
Standard
Proved
User
date
Origin
Repl. f.
Repl. by
Sheet
Grounds&B
8 Sh


Main harness
CAN-BUS
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Primary Automotive Wire Overview

Table of primary automotive wire types [12].

Primary Automotive Wire Overview

Name	Type	Temperature	Use	Specifications
GXL	Cross-Link	-40°C to 125°C	Thin wall. Most common. Engine compartments - higher heat.	Chrysler Specification MS-8900 Ford Specification ESB-M1L85-B (bare copper) ESB-M1L85-A (tinned copper), S.A.E J1128
SXL	Cross-Link	-40°C to 125°C	Standard Wall. Engine compartments where higher resistance is needed.	Chrysler Specification MS-5919 (bare copper) Ford Specification ESB-M1L85-A (bare copper) Ford Specification ESB-M1L8-A (tinned copper)
TXL	Cross-Link	-40°C to 125°C	Extra Thin Wall. Smallest and Lightweight.	MS-8288 (bare copper) Ford Specification ESB-M1L123-A (bare copper) Ford Specification ESB-M1L123-A2 (tinned copper)
GPT	PVC	-40°C to 85°C	General Circuit Wiring	S.A.E J 1128
TWP	PVC	-40°C to 105°C	Thin Wall. Lightweight and Small.	S.A.E J 1128
HDT	PVC	-40°C to 85°C	General Circuit Wire Thickest Wall.	SAE J-1128, Ford M1L-50A, Chrysler MS-3494