Selecting a connector system for harsh environments

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EPEC

This White paper introduces selecting a connector system for harsh environments

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1. Preface

The world is full of different connectors. Connectors are available in many different shapes, sizes, materials and colors. It might seem that selecting a connector system to suit perfectly in the intended application is a trivial task. But there is a lot more to it.

Most connectors are located in such environments that do not pose too strict requirements for the connector system in terms of size, shape, current throughput, ingress protection levels, vibration performance and so on. But when you start to list the requirements of a mobile working machine environment, the options to choose from narrow down drastically. Connector systems should support the design of a high-quality system built on top of a machine and therefore there is a lot more to a high-quality connector than just high ingress protection level. From system architecture and harness design point of view, the right amount of contacts is important so that the harness stays simple and easy to assemble and service. The ability to withstand vibration and high acceleration mechanical shocks is vital. Also, extreme temperatures are often to be found in mobile Electronic Control Unit (hereafter ECU) operating environments.

Connectors are obviously not the only components in the control system that must withstand harsh environments, so the connector design must support high quality ECU and wire harness design. Manufacturability of wire harness or ECU is crucial when electronic systems get more complex and the price must be kept in control.

This white paper has been written to help a mobile working machine builder, electronic control system integrator, system architect or an ECU design engineer in their job by providing important points that should be taken into consideration when selecting a connector system for demanding applications.

Typical operation environment for an ECU.

2. CAN bus design considerations

Electronic control units in mobile machinery communicate with each other with almost no exceptions via a field bus. CAN bus has established its place as the industry standard for 20+ years now. As the amount of data increases, classical CAN 2.0 is also evolving from maximum speed of 1Mbit/s to CAN FD (Flexible Data rate) which can reach up to 5Mbit/s. Also, next evolution versions of CAN are in sight, CAN XL will someday reach up to 10Mbit/s data rates.

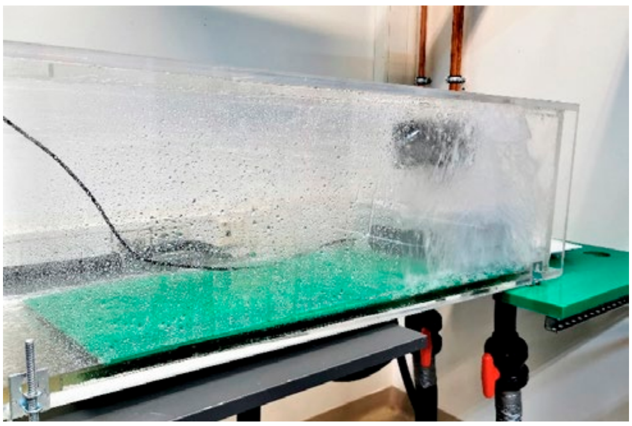
What kind of requirements does CAN set to the connector system? CAN is a robust and fault-tolerant field bus, and especially at speeds below 500kbit/s it is not too picky on the cable nor the connector. But when bit-rate increases from 500kbit/s up to 1Mbit/s or even higher, the significance of a proper signal path provided by the cable and the connector system becomes more relevant. Even more so, when the environment is critical in terms of EMC (Electromagnetic Compatibility) and the CAN emissions must be kept low and tolerance against external electromagnetic fields high. For most demanding applications, a tight twisted pair with 360-degree shielding is the way to go. The connector system must support this with short untwisted length of the signal pair and secure cable shield connection.

CAN bus uses a differential, single twisted pair signal that has a characteristic impedance of 120 Ω. The bus must be terminated with 120-ohm resistors from each end of the bus. Also, a ground return path shall be provided between nodes, and if cabling incorporates shielding, this should be able to connect to the connector also. To connect CAN sensors to the system, a supply voltage to the sensor is needed too. So, to take all scenarios into account, we need 5 connector pins for a single CAN bus. For sensors, a 5-pin A-coded M12-connector is the choice of most manufacturers, since it serves almost all features a properly cabled CAN would need. The only downsides are bulky (and costly) cables and cable branching. For a more common ECU connector, rectangular plastic connector, a perfect design would incorporate following features: CAN bus cables separated from I/O cabling, inbuilt selectable bus termination resistor and the possibility to branch the bus to the next ECU/sensor. Designated ground and shield pins for each CAN bus are very useful also. Sometimes the service technician will want to connect to the CAN bus for diagnostics, a perfect connector design would make this both easy and simple.

3. Protection against environment

Anyone who has been dealing with harsh environment systems is usually familiar with most common IP (Ingress Protection) classes. But what distinguishes these different protection classes from each other? Here we focus only on dust tight IP6x classifications since these are the most common ones to appear in waterproof connectors. Both IP65 & IP66 are 3-minute water spray tests from 2,5m to 3m distance, with different nozzles and water flow. In IP65, the nozzle diameter is 6,3mm and water flow 12,5 liters per minute. These figures add up to approximately 0,3 bar pressure. For comparison, IP66 water flow is significantly higher, 100 liters per minute from a 12,5mm nozzle. That is almost two times the diameter of IP65 nozzle, and the pressure in IP66 is around 1bar, more than 3 times the pressure of IP65. Both tests are normally made with roughly room temperature water, the deviation between EUT (Equipment Under Test) temperature and water should be kept smaller than 5 degrees (Kelvin).

IP67 is probably one of the most recognized tests, a static immersion test in 1-meter deep water for half an hour. IP68 is also a static immersion test, but in this test the depth and the immersion time is specified by the manufacturer. So, if you see IP68 classification, it should always be accompanied with specification for immersion depth and time. Currently the highest classification IP69 / IP69k represents basic equipment that is protected against high-power steam washers. In practice, there is quite minimal difference in the testing procedure between IP69 and IP69k. IP69 comes from the IEC 60529 and IP69k from the ISO 20653 standard. Both are generally used, but ISO 20653 is more often used in the automotive industry. When you look at a sealed connector, there is one big difference between IP69/IP69k rated connectors compared with the lower classifications: in IP69/IP69k the sealing material (silicone in most cases) is usually protected by harder material (plastic/metal) since the water spray is so intensive that the seal would easily fail if a direct water spray hits it. To give you a rough idea of the IP69 tests compared to lower classification spray tests, here are the important figures: 15 liters per minute, 100 bar pressure with water temperature of 80 degrees.
Also, one important note is that IP classes are only cumulative up to IP66. This means that if a device fulfills IP67 it does not automatically gain IP66 classification if not tested separately.
A device designer or system designer should also take into consideration that most of the weatherproof connectors fulfill their ingress protection classification only mated with a corresponding connector. Some connectors can have different ratings for mated / unmated connectors, but if the manufacturer does not specify this accordingly, the assumption should be that the rating is for a mated pair only. So, if some connectors are left unconnected in a system, cap / sealed empty connector must be used to provide for the proper protection of the whole system.



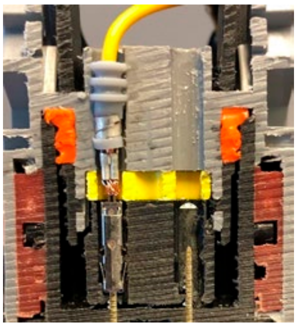
IP65 test performed inside acrylic tube.

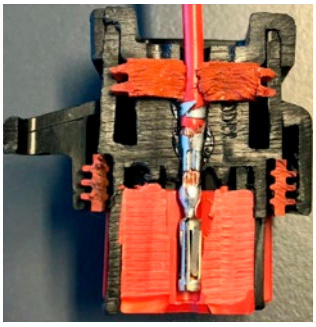
4. Wire sealing systems

How a wire or a cable seals when it enters the connector is probably the most important sealing interface in a watertight connector. A good practice to mount a control unit is to consider water running along the cables into the connector. Often the placement of the control unit is not optimal, so the connector must be able to withstand water running along the cables.

Multi-pin I/O connectors traditionally have 2 different approaches for wire sealing: connector integrated family seal and SWS (single wire sealing) system. Let us take a closer look at these two connector structures. The name "family seal" evidently comes from the fact that this single seal takes care of sealing all the wires going into the connector. Family seal design incorporates few millimeters thick sealing part inside the connector. This part is often made of silicone or a similar, very flexible material. There are through holes in this part for each conductor, and sometimes a very thin membrane in each hole (TE Connectivity's AMPSEAL connector). The function of this membrane is to plug unused holes (connector contacts). Once a wire with a crimp in the end is inserted into the connector, this membrane will be punctured. Holes in this sealing part are dimensioned smaller in diameter than the conductors to be able to form a seal around the conductor. This type of sealing system is easy to use, since wire seals and blind plugs are all incorporated in the connector. No need for external wire seals and blind plugs. The ease of course comes with some compromises: if different sizes of wires are routed to the connector, a seal hole can be too big for smaller wire gauges and water can flow into the connector through it. Also, if wires are pulled in a 90 degree angle from the connector it is possible that the hole in this sealing part is stretched to the side and is not able to perform a full 360-degree seal any longer. Another consideration to keep in mind is that if the wire crimp is not made according to specifications, it could rip the edges of the sealing hole especially if the wire is inserted and retracted multiple times through it. Also, if a wire is removed and a contact is left empty an additional blind plug must be inserted since the membrane is punctured at this point and cannot act as a blind plug anymore.

Single wire sealing system (SWS) is a different approach to this conductor sealing challenge. In a SWS connector (TE Connectivity's LEAVYSEAL connector) there are no seals in the connector for the wires. Silicone SWS seals are inserted into the wires before the crimp and once crimped, the back part of the crimp holds the SWS seal in place. In the connector, each contact has own cylinder -shaped cavity. As each wire is now sealed with a barrel-like silicone seal crimped into the wire, 360-degree sealing surface to the connector body and wire insulation is several millimeters long. This kind of seal can be inserted and retracted from the connector body with no degradation or risk to the sealing performance. Contacts left unconnected must be sealed with blind plugs. Different sized SWS seals are available for different wire sizes, so it is possible to have numerous different size wires going into the same connector without compromising the sealing performance. The downsides of this wire sealing system are: one further assembly step is required in the crimping procedure, and the need of multiple sealing parts and plugs. Fortunately for the machine builder, wire harnesses are mostly manufactured by dedicated harness manufacturers who have automatic application machines for the SWS seals.





Single Wire Sealing (SWS) example featuring TE Connectivity's LEAVYSEAL connector
Family seal system example featuring TE Connectivity 's AMPSEAL connector

5. Contact system performance

Contact system performance is easily overlooked when a suitable connector in terms of pin count, operation and form-factor has been found. However, contact system is the part of a connector system that has the biggest research and development work put in. Let us take a brief insight into the different properties of any contact system and how these properties relate to each other.

Current carrying capability is dependent on many different parameters, contact size being the most obvious of them. When two flat metal surfaces are placed against each other the current is conducted through the microscopic peaks in the flat metal. In electrical connector contacts, these peaks are exaggerated to mountains and current flow path is directed to these "contact points". The amount and size of these contact points significantly determine the current carrying capability of a contact pair. The size of the contact point is determined by contact normal force, e.g. how much spring force there is to clamp a female contact against the male contact. The greater the force, the larger the contact point and therefore also the higher the current carrying capability.

Connector contacts are usually plated with tin, while higher performance/harsh environment connector contact outer plating is done with silver or gold due to their higher resistance against corrosion. All of the mentioned metals are quite soft. When a contact with high normal force is mated, it always results in deformation of the plating metal. This helps with contact point formation, but it has downsides as well. High normal force and contact metal deformation means very limited amount of mating cycles and high contact retention force. High contact retention force sets challenges for connector cavity blocks and headers. Generally speaking, gold plated contacts can withstand the highest amount of mating cycles. Gold and silver plating are quite equal in terms of current carrying capability, in some applications silver might even be slightly better. All contacts have resistance and resistance creates heat as a function of current. When environment temperature increases, the maximum current of contact pair decreases so that the overall temperature of the connector is kept in the safe zone. This is called connector de-rating.

5. Connector mounting (ECU design considerations)

A connector defines the ECU (Electronic Control Unit) design from many different angles: mechanical enclosure is of course defined greatly by the connector(s). PCB (Printed Circuit Board) layout architecture and electro-mechanical design of an ECU is full of compromises, and the application defines which of them can be made and which cannot be made.

Here are a few points that should be taken into consideration when designing a connector interface to a product.

Mechanical *stress to PCB. Is the connector subjected to high forces caused by thick cables, big and heavy mating connector, high number of mating cycles etc.? What is taking up this force?*

Sealing *system between connector and enclosure. What are the sealing requirements for this interface, and what requirements does the connector set for the enclosure? Of course, this interface can also be deleted completely from the equation by using enclosure integrated connector body together with a PCB header, or an over molded solution where connector pins are molded inside a plastic enclosure with an integrated connector body. These solutions often require close co-creation with the connector manufacturer and might not be the most economical solution for low and medium volume products. For high-volume products, these solutions can enhance the manufacturability and lower the cost of the connector system at ECU side.*

Connector *space requirements from PCB / enclosure. Some connectors use relatively large space on a PCB Can you sacrifice PCB space for connector support? Do you have a need to place components near connector pins?*

Manufacturability *is always a very important part of any design. Two main points in manufacturing related to connectors are mounting and electrical connection to PCB. Often sealed device connectors require both, but in some cases just a solder joint or press-fit -connection is all that a connector requires for it to stay sufficiently attached. Additional mounting methods include, but are not limited to, screws, rivets, snap-in clips, gluing.*

Device connectors can be roughly divided into PCB mounted and panel mounted with wires. A panel mounted wire connector is mounted to enclosure, and short wires from the connector are then connected to PCB. These wires are often connected to PCB with a wire-to-PCB connector, but also soldering can be used. The benefit of this type of connector is full mechanical isolation between the connector and PCB. This is useful in applications where the connector is subjected to high mechanical forces. This kind of solution is serviceable especially if a wire-to-board connector is being used in the PCB end. Also, PCB does not dictate the placement of the connector, so this creates a lot of flexibility for the mechanical design. Downsides of panel mount wire connectors are, without limitation, labor intensive manual assembly in production, poor signal integrity for fast signals as well as multiple connection points (connector - wire and wire - PCB).

In some high vibration / shock environments it is vital to provide very effective support for the cable to protect the connector from excess forces caused by the cable. Incorporating a cable clamp to the unit design would prolong the connector lifetime. Cable clamping would also make sure that no water ingress happens in connector caused by excess pull in the cable, a family sealed connector problem that was described earlier in this paper.

Diesel engine ECU with inbuilt cable clamps. (Image courtesy of TE Connectivity)

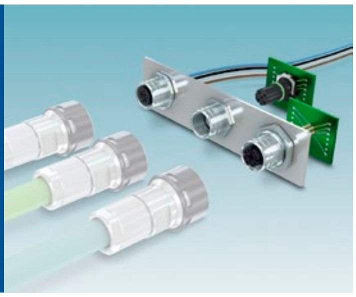
6. Receptacle

Snap-in latch type connector TE Connectivity`s AMPSEAL connector. (Image courtesy of TE Connectivity)

A receptacle or wire side connector is equally important in achieving the desired performance for a connector system. In most cases a connector can meet the certified ingress protection level only mated with a receptacle that is, of course, assembled with suitable wire seals for the cables used. A receptacle is also the human interface of a connector system and usability preferences of connector operators must be taken into consideration.

Most ingress protected connectors have a heavy-duty locking mechanism, whereas some device internal connectors rely on friction locking or plastic tabs. Since water and dust will greatly affect the friction of a connector, these kinds of locking mechanisms are not reliable enough in connectors meant for harsh environments. Most common locking mechanisms in these connectors can be divided into circular and rectangular connectors: for circular connectors, the most common are threads, twisting and push-pull locking. Push-pull locking has become more popular over the last years, and connectors that have traditionally been thread or twist-locked have now push-pull locked siblings.

Push-pull connectors with different device interfaces; from left to right panel mount with wires, 2-piece SMD and thru-hole one-piece connector. (Image courtesy of Phoenix Contact)



Rectangular connectors are often locked with a simple snap-in latch, which is a simple and cost-effective solution but sometimes a pain to open without special tools.

Also, for high contact number connectors a single snap-in latch is not sufficient to keep the connector straight and locked. Over the last years, lever-locked receptacles have become more common. The benefits of a lever locked receptacle include the following: visual indication if the connector is fully mated & locked or not. Controlled mating of the connector; leverage to the insertion for the lever, this is especially helpful with high-current connectors where required insertion force is quite high. Also, lever lockable connector usually provides a possibility to use safety wire locking to prevent unwanted, unintended, or unsupervised unmating of the connector. A lever-locked connector is also simple to unmate, and it is highly unlikely that the locking interface becomes destroyed during unmating with lever-locked connectors.

A rectangular lever-locked connector of TE Connectivity`s LEAVYSEAL connector.

As the amount of connections in a single connector increases, the wire harness weight also increases and creates stress for the receptacle and contacts. Especially in environments with constant vibration or high G shocks, wire harness support clamps are essential. Even if the receptacle can withstand high G and rough vibration environments, a freely hanging wire harness can destroy the plating of wire contacts.
Connector manufacturers usually also perform vibration and shock tests for a connector system with cables supported from recommended distance. Clamping the cables to the mounting base is an efficient way to protect the connector from excess forces generated by heavy cable harness.

Electrical contacts inside the receptacle body must be secured in place. Often these locking mechanisms are plastic tabs or clips, and the releasing procedure can either require a specific contact release tool or not. If the contact is almost impossible to remove without a designated tool, it is more likely that a removal tool is being used and less damage happens to the connector housing during this servicing procedure.

7. Connector flammability

Some mounting locations require the materials to be self-extinguishing or flame retardant. These kinds of requirements could be found for example in trucks that have extended sleep-in cabins. For human safety, materials inside the cabin must be self-extinguishing to protect sleeping humans.

The most commonly used flammability classification among mobile machinery connectors is the UL-94 burning test. Most common classifications for plastic connectors are HB (horizontal burning) and V-0 (vertical zero). These tests describe how a material performs when subjected to a burner flame. Basically, HB burns and does not go off by itself and V-0 burns slowly and fades by itself.

PBT (Polybutylene terephthalate) plastic mixed with glass fiber is the material most commonly used in sealed mobile machinery connectors. This material's flammability rating is normally UL94 HB but can be modified with additives to self-extinguishing UL94 V-0 classification. This may sound simple, but there is more to it. Additives make this PBT+GF plastic less elastic and more sensitive to low temperatures & vibration. For this reason, it has proven to be quite difficult to convert existing HB headers to V-0 without sacrificing vibration performance and operating temperature range. Therefore, a V-0 requirement for a connector should always be thoroughly grounded.

What if the header (device side) and receptacle (wire harness side) are made of different materials? Let us take an example of a situation where the header is HB material and the receptacle is higher class, self-extinguishing V-0. When mated, the receptacle covers the header almost completely. Some manufacturers would specify this kind of combination as HB and some as V-0. The UL-94 test is performed with a blow torch separately for both, but this is hardly considered as a real-life scenario. What would then be the real-life scenarios where flammability ratings could be evaluated?
In normal operation, a fault in the electric circuit and a faulty or missing fuse could cause excess heat in the contact pair inside the connector system. This could lead to a fire inside the connector, but the contact pair would probably be almost completely encapsulated by self-extinguishing V-0 receptacle. How about a fire from an external source? The V-0 material is designed to be self-extinguishing and therefore keep the fire from spreading and lessen the total mass of the burning material on a machine. In our example case, the receptacle covers the header, so it protects the lover flammability rating header from catching fire.

8. Conclusion

Many aspects must be taken into consideration when selecting a connector system for any application, and it becomes especially challenging when connectors are subjected to tough environmental conditions and are mounted in machines that have a long lifetime. Such requirements are standard for mobile working machines. These conditions are challenging for connectors, and eventually it is for the user to utilize the connector in a way it is intended so that it can perform as specified.

Besides electronics, connectors are the most important component in any ECU and can even have a significant effect on the performance of the device. A good connector system enables trouble-free operation for many years to come, and a poor one can cause unexplained trouble from the beginning and even restrict the performance specifications of an ECU.