Reliability of Thermal Relays in Automotive Applications

Master of Science Thesis in Electric Power Engineering, written at KTH - Royal Institute of Technology, based on work performed at Scania CV AB

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Master of Science Thesis
SCHOOL OF ELECTRICAL ENGINEERING
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Maria Ballesteros Hernando

Abstract

Despite the vast increase of relays in automotive applications, little is known of how to perform reliability tests on them. Reliability of relays is defined as the probability of a relay to function without failure, when operated correctly, for a given period of time, under stated conditions.

Accordingly, there is a need for improving life-expectancy test methods for relays. The immediate objective of this research project is to develop a guideline of how to check reliability of relays.

Identifying the main parameters that affect reliability, perform an endurance test and material analyses of the tested relays were the main areas of interest in this work. In addition, common failure modes during the relays performance were identified.

The results show that supplied voltage, breaking current and load type are parameters that affect arc duration and, thus, the contact damage. Most common failure modes were contact welding and increase in contact resistance due to arc erosion and oxide formation. Moreover, contact resistance stability has been proved to be a factor capable to determine the quality of contacts and to predict early failures in relays.
Sammanfattning

Trots den omfattande ökningen av reläer i biltillämpningar så är lite känt om hur man utför pålitliga tester på dem. Reläers pålitlighet kan definieras som sannolikheten för ett relä att fungera utan fel när den opereras korrekt under en given tidsperiod och under angivna villkor.

Följaktligen så finns ett behov av att förbättra testmetoder för den förväntade livslängden hos reläer. Det huvudsakliga ändamålet med detta examarbete är att utveckla riktlinjer för hur man undersöker pålitligheten hos reläer.

Arbetet har utförts vid Scania CV AB i Södertälje och de huvudsakliga intresseområdena var att identifiera de viktigaste parametrar som påverkar pålitligheten hos reläer samt att utföra uthållighetsstest och materialanalys på de reläer som provades.

Resultaten visar att matningsspänningen, brytströmmens magnitud samt lasttype är parameterar som påverkar ljusbågens brinntid och, därigenom, kontaktskador. De mest förekommande felmoderna är kontaktsvetsning och ökning av kontaktresistansen på grund av ljusbågserosion och oxidformation. Resultaten visade vidare att kontaktresistansens stabilitet är en faktor som indikerar kontaktkvaliten och kan användas för att prediktera tidiga felfall i reläerna.
I would like to express my sincere appreciation to my examiner, Oskar Wallmark and my supervisors, Mattias Forslund and Dan Magnusson, for their support and helpful input during my thesis project.

I am very grateful for the assistance provided by all the people in my team at Scania, RECT; whenever help or information was needed, it was received. I wish to acknowledge the help provided by Jan Hellgren and Tommy Andersson with all the electronics and Ismo Turpeinen for his assistance with the laser measurements. Furthermore, special thanks to Henrik Koponen, for his encouragement over the course of the project.

Finally, I am most grateful to my loving family who have shown nothing but support and encouragement throughout my entire work.

María Ballesteros Hernando

Stockholm, February 2017
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**Nomenclature**

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<tbody>
<tr>
<td>A</td>
<td>AC.</td>
<td>Alternating Current</td>
</tr>
<tr>
<td></td>
<td>ADS.</td>
<td>Automatic Disconnection Supply</td>
</tr>
<tr>
<td>B</td>
<td>BSE.</td>
<td>Back Scattered Electrons</td>
</tr>
<tr>
<td>C</td>
<td>CRS.</td>
<td>Contact Resistance Stability</td>
</tr>
<tr>
<td>D</td>
<td>DC.</td>
<td>Direct Current</td>
</tr>
<tr>
<td>E</td>
<td>EM.</td>
<td>Electro-Magnetic</td>
</tr>
<tr>
<td></td>
<td>EMF.</td>
<td>Electromotive Force</td>
</tr>
<tr>
<td>G</td>
<td>GC-MS.</td>
<td>Gas Chromatography-Mass Spectrometry</td>
</tr>
<tr>
<td>I</td>
<td>ISO.</td>
<td>International Standard Organization</td>
</tr>
<tr>
<td>L</td>
<td>LOM.</td>
<td>Light Optical Microscopy</td>
</tr>
<tr>
<td>M</td>
<td>MCBF.</td>
<td>Mean Cycles Before Failure</td>
</tr>
<tr>
<td></td>
<td>MTBF.</td>
<td>Mean Time Between Failures</td>
</tr>
<tr>
<td></td>
<td>MTTF.</td>
<td>Mean Time To Failure</td>
</tr>
<tr>
<td>P</td>
<td>PE.</td>
<td>Primary Electrons</td>
</tr>
<tr>
<td></td>
<td>PMDC.</td>
<td>Permanent Magnet Direct Current</td>
</tr>
<tr>
<td></td>
<td>PSV.</td>
<td>Polytec® Scanning Vibrometer</td>
</tr>
<tr>
<td></td>
<td>PWM.</td>
<td>Pulse-Width Modulation</td>
</tr>
<tr>
<td>R</td>
<td>RL load.</td>
<td>Resistive-Inductive load</td>
</tr>
<tr>
<td>S</td>
<td>SE.</td>
<td>Secondary Electrons</td>
</tr>
<tr>
<td></td>
<td>SEM.</td>
<td>Scanning Electron Microscopy</td>
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### Units

<table>
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<th>Unit</th>
<th>Abbreviation</th>
<th>Physical Quantity</th>
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<tbody>
<tr>
<td>Second</td>
<td>S</td>
<td>Time</td>
</tr>
<tr>
<td>Meter</td>
<td>M</td>
<td>Length</td>
</tr>
<tr>
<td>Kilogram</td>
<td>Kg</td>
<td>Mass</td>
</tr>
<tr>
<td>Meters per second</td>
<td>m/s</td>
<td>Speed</td>
</tr>
<tr>
<td>Newton</td>
<td>N</td>
<td>Force</td>
</tr>
<tr>
<td>Newton per unit of area</td>
<td>N/m²</td>
<td>Hardness</td>
</tr>
<tr>
<td>Bar</td>
<td>bar</td>
<td>Pressure</td>
</tr>
<tr>
<td>Celsius / Kelvin</td>
<td>°C / K</td>
<td>Temperature</td>
</tr>
<tr>
<td>Inverse degree Celsius</td>
<td>°C⁻¹</td>
<td>Coefficient of thermal expansion</td>
</tr>
<tr>
<td>Radians per second</td>
<td>rad/s</td>
<td>Rotational speed</td>
</tr>
<tr>
<td>Ampère</td>
<td>A</td>
<td>Current</td>
</tr>
<tr>
<td>Volt</td>
<td>V</td>
<td>Voltage</td>
</tr>
<tr>
<td>Watt</td>
<td>W</td>
<td>Power</td>
</tr>
<tr>
<td>Joule</td>
<td>J</td>
<td>Energy</td>
</tr>
<tr>
<td>Tesla</td>
<td>T</td>
<td>Strength of magnetic field</td>
</tr>
<tr>
<td>Hertz</td>
<td>Hz</td>
<td>Frequency</td>
</tr>
<tr>
<td>Ohm</td>
<td>Ω</td>
<td>Resistance</td>
</tr>
<tr>
<td>Ohm-metre</td>
<td>Ω·m</td>
<td>Resistivity</td>
</tr>
<tr>
<td>Farad</td>
<td>F</td>
<td>Capacitance</td>
</tr>
<tr>
<td>Henry</td>
<td>H</td>
<td>Inductance</td>
</tr>
<tr>
<td>Samples per second</td>
<td>Sa/s</td>
<td>Sample rate</td>
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1 Introduction

Nowadays, the quantity and complexity of electric circuits is constantly increasing, especially in the automotive industry [1]. The electrical contact has always been an essential part of the electric circuit. Therefore, ensuring reliable connections is crucial to manage a successful operation of the system [2].

1.1 Background

What is a relay? As a first approach, a relay is basically an electrically operated switch [3] widely used in engineering. Many of the relays used in automotive applications, specifically the electromechanical relays, are termed as ISO relays and adhere to a standard pattern determined by the International Standards Organization. Some examples of patterns for relays include Super ISO, ISO 280, Mini 280 ISO and Micro 280 ISO. However, there are many other relays that do not follow any ISO standard which is the case for numerous protection relays designed for particular unique applications.

Due to the growth of the electrical system in trucks, the amount of relays has increased rapidly. Therefore, both the complex nature of the connection system and the performance requirements have challenged the industry to design smaller, environmentally friendly but yet robust components [4]. The engineering of any kind of relay requires a deep understanding of the physics of the electric contacts, the properties of the contacts’ materials as well as the chemistry of degradation processes [5]. A contact material must have reliable characteristics such as high electrical and thermal conductivity, high resistance to arc erosion and welding, low vapor pressure and high resistance to the deterioration effects of oxide, sulphide and other compounds that cause insulation between the contact surfaces [6] [7].

Most electrical circuits have overload protections that break the power supply in the event of an electric overload. These protections consist of automatic circuit breakers, i.e., electrical switches designed to protect a circuit from damage caused by overcurrent or short circuits [8]. Its basic function is to interrupt current flow if a certain requirement is not fulfilled and the system is at risk. Another device that enables the interruption of the current in an electric circuit, in case of overload, is the fuse which operates once and then must be replaced [9] [10]. However, unlike fuses, overload protection relays can be reset, either manually or automatically, to restore normal operation. The generic function of circuit breakers and fuses consists of removing power from a faulty system and is often abbreviated as ADS (Automatic Disconnection Supply).

In contact operation, both establishing and breaking the circuit (power ON and OFF, respectively), an electric arc can occur causing erosion of the electric contact surfaces
and can even lead to welded surfaces or defective protection [2] [11]. The selection of the material, the design of the contact area, the opening velocity of the contacts and many other parameters must be chosen carefully to satisfy all the requirements of each electrical switch [12]. When looking at the relays in automotive applications it is acceptable to affirm that failure modes reveal either contact welding or significant contact resistance due to excess of arc erosion or oxide formation [13].

The fact that electrical contacts are generally a weak link in the electrical system causes doubts about the ability of some connection designs to provide effective long term reliable connections, especially when contacts are in motion [14] [15]. In addition, no clear guideline on how to test reliability of relays or any global endurance test method exists. In this context, it is crucial to develop a life-expectancy test for relays under realistic conditions [2] [16].

1.2 Purpose and goals
The purpose of this thesis is to develop a test method for a thermal overload protection relay in order to create a general guideline with recommendations on how the reliability of relays should be verified. The work described in this thesis has been carried out at Scania CV AB in Södertälje, Sweden, during the autumn and winter of 2016-2017.

Identifying the main parameters that affect reliability is one of the areas of interest, with focus on the arcing effect. After these parameters are identified, the next goal is to analyse the impact they have on the performance of relays and how they correlate to each other. The latter sets the basis for a life length test study. After testing, the analysed relays are examined using several material analysis techniques with the purpose of identifying failure modes and comprehend in detail the working principles of the relays. Moreover, contact resistance stability is investigated in order to determine whether it is a suitable parameter to predict early failures in contacts.

The final goal is to design a reliability test able to define if one type of relay is significantly more reliable than another, what failures can be expected and its lifespan.

1.3 Limitations
The first limitation in this thesis is the reduced time. Three relays of different type and working principle are tested to analyse the main parameters affecting the performance of relays. However, only one type, a thermal overload protection relay, is used in the life-expectancy tests and in the further investigations, because of the long duration of the test experiments. In addition, the number of samples used in the life-length tests is limited for the same reason. Therefore, the predictions made in this thesis might not be accurate enough.
All tests were carried out under ambient conditions in the laboratory, i.e. no specific environments are simulated during the experiments. The main reason is that testing different environments would increase the complexity of the experiments as well as the time needed to design them.

Finally, as it will be shown later, the lifespan of relays is highly influenced by the electric load connected to them. It is possible to differentiate five different types of loads. However, only resistive and inductive loads were studied, since they are the most common loads in automotive applications. In addition, the relay used in the experiments is a thermal protection relay that switches inductive loads in its particular application. Therefore this thesis is focused on this specific load type.

1.4 Methodology
With the purpose of achieving the goals of the thesis, a literature survey was made first. Interviews were conducted as well as email conversations with widely experienced engineers in the different areas of investigation. Practical experiments and tests were carried out in the laboratory. Finally, some conclusions were drawn from the test results and a guideline of how to verify reliability in relays was created.
2 Electric Relays

2.1 Overview
In the same way as is not possible to imagine a human body without heart or bloody vessels, it is not possible to imagine the world today without electric circuits. Every device one can think of will include some kind of electric circuitry. This is especially true in automotive applications, where the quantity and complexity of the electric circuits is constantly increasing. As electrical contacts and consequently, relays, are essential parts of the electric circuits, ensuring consistent connections is decisive if we want to build a successful reliable system.

To define the notion of a relay, one should start by stating that a relay is an electrically operated switch. However, to understand the physics of relays one must begin with the fundamental principles of electric contacts.

There are many different types of relays with different working principles. For example, there are relays responsive to light, temperature, location in space, air or liquid pressure, etc. [3]. It is obvious that it is very complex to consider all known types of relays in detail within the scope of this thesis but the aim of this section is to give the reader a good overview of relays, especially when considering automotive applications.

2.2 Electric contact principles and materials
It is unfeasible to create a solid surface totally smooth as all solid surfaces are, on the microscale, rough. Contact between two surfaces will strongly depend on the surface topography and will occur at discrete points created by the mechanical contact asperities, as shown in Figure 1 [2].

![Figure 1 Difference between real and nominal contact area and schematic diagram of the interface of two electric contacts.](image)

As it can be appreciated in Figure 1, in a typical electrical junction the real contact area is considerably smaller than the area of the contact pins, i.e. the nominal contact area. The current is able to flow through the junction using the contact spots, as can be seen in Figure 2. Common electrical interfaces are coated with metal components such as silver. This metal mating can suffer oxidation which acts as an electrical insulating layer. The interface is only capable of transferring electricity when metal-to-metal contact
spots are produced. This means that the oxide films must be ruptured or displaced at the asperities. Therefore, the area of electrical contact is substantially smaller than the true area of mechanical contact [2].

As the material used for electrical conduction is reduced, the current flow lines approach each other at the interface to flow through the contact spots. This together with the fact that contaminant films of, for example, oxides, have a large electrical resistivity, increases the electrical resistance in the contact interface.

The contact resistance strongly depends on the number of contact spots at the interface, which increases to some extent with the normal load applied in the contacts. It is determined by the number and dimensions of the contact spots. In addition, electrically conductive spots are only the parts of the mechanical contacts where the insulating oxide layers are fractured or dispersed, which is more likely to happen if a higher normal force is applied between the contacts. However, too high forces can cause fretting, which increase resistance. Consequently, predicting the number of metal-to-metal contact spots is a complex task [2].
With the purpose of ease the calculation of the contact resistance, the Greenwood approximation [17], [2] is used to estimate the contact resistance:

\[ R_c = \rho \left\{ \frac{1}{2na} + \frac{1}{2\alpha} \right\} \]  (1)

Where \( \rho \) is the resistivity of the conductor, \( a \) is the mean spot radius and \( n \) is the number of spots used to calculate \( a \), i.e. \( a = \sum_{i=1}^{n} a_i \), being \( a_i \) the radius of the \( i \)th spot. Then, the radius of such a cluster of spots, \( \alpha \), is referred as the Holm radius (see Figure 3) [17] [2].

As a first approximation, the Holm radius may be estimated from the real electric contact area, \( A \), as [2]:

\[ \alpha = \left( \frac{A}{\pi} \right)^{1/2} \]  (2)

According to Greenwood, the mechanical contact area or real contact area, \( A_c \), is controlled by the plastic deformation of the asperities and it is proportional to the force applied to the electrical interface, \( F \), and the plastic flow stress or hardness, \( H \), of the softer material as [2]:

\[ F = A_c H \]  (3)

According to Greenwood’s data, experimental investigations suggests that the second term in equation (1) is more dominant when \( a > 0.05 \) units. Hence, for most engineer purposes the Holm radius is sufficient to estimate the electrical contact resistance. It is assumed that the electrical interface does not carry electrically insulating films and is characterized by a sufficient number of spots distributed within the Holm radius, \( \alpha \), so the contact resistance, expressed in equation (1) can be approximated as [2]:

\[ R_c = \frac{\rho}{2\alpha} \]  (4)

As the area of true electric contact is defined in (2) as \( A = \pi \alpha^2 \), it is possible to define the mechanical real contact area, \( A_c \), including the coefficient \( \eta \), to represent the unity factor of clean asperities.

\[ A_c = \eta \pi \alpha^2 \]  (5)

Using the equation in (3), (4) and (5), the contact resistance can be expressed as:

\[ F = A_c H \rightarrow F = \eta \pi \alpha^2 H \quad \text{and} \quad R_c = \frac{\rho}{2\alpha} \rightarrow \alpha = \frac{\rho}{2R_c} \Rightarrow F = \eta \pi \left( \frac{\rho}{2R_c} \right)^2 H \]

\[ R_c = \left\{ \frac{\rho^2 \eta \pi H}{4F} \right\}^{1/2} \]  (6)
The presence of interfacing contaminant films modifies the equation in (6) by adding a new term to the right-hand side. Even though it is not a fully accurate expression for contact resistance, it is generally valid and precise enough over a wide range of mechanical loads.

2.2.1 Materials in electric contacts

This section concerns the main materials used for coating electric contacts. A contact material must have reliable characteristics such as high electrical and thermal conductivity, high resistance to arc-erosion and welding, low vapour pressure and high resistance to the deteriorating effects of oxide, sulphide, and other compounds that cause insulation on contact surfaces [2].

The contact system of a relay is one of the most important parts and it does not only consist of contact straps or pins, as can be seen in Figure 4. A contact system is also formed by two current conducting elements (1,2) usually made of elastic materials like beryllium bronze or phosphor bronze. They supply current to the contacts and also the necessary contact pressure. The actual contacts (3,4) are often made of a two-layer bimetallic pins. They usually consists of a copper base and a coating. This coating is the key element that must be chosen carefully to ensure high reliability of the relay. It is also common to have a return spring (5) that helps the contacts returning to its resting position.

![Figure 4 Main parts in a relay contact system](image)

In this section, various types of materials utilized as coatings for arcing contacts are described in terms of chemistry, general physical properties and material structure. Manufacturing technologies are also important since some materials can be manufactured by several widely different manufacturing processes and, as a result, materials with identical chemical compositions can have very different performance characteristics.

- Silver (Ag): It is one of the most popular elements used in coatings thanks to its ductility, which makes it easy to form the contacts into various different shapes. In addition, it is quite cheap and has a high electrical and thermal conductivity, thus, its transient resistance is rather low. On the other hand, the main drawback is its high tendency to erode, especially when affected by arcing. It is generally alloyed with other
elements to increase its hardness. Sulphitation affects silver, causing silver sulphide in sulphur-containing atmospheres. This increases the contact resistance drastically. Finally, silver contacts are used in applications switching a wide range of currents at low-medium voltages [3].

- **Platinum (Pt):** The main advantage of this element is its high corrosion resistance. It is therefore much less sensitive to oxidise compared with silver. On the other hand, it has an extremely low hardness in pure form so it is always alloyed with other elements like Iridium. Platinum-iridium (PtIr) has excellent resistance to arcing as well as excellent performance in corrosive environments but it comes with a very high price. It is generally used in low power and average power contacts [3].

- **Tungsten (W):** This element has a limited area of application due to its high contact resistance. It consists of a very hard and refractory material with a very high melting and boiling points. It has a very high resistance to welding as well as mechanical wear. On the other hand, it oxidises easily forming thick oxide layers. Therefore, it requires high contact forces to fracture the oxide films [3]. It is mainly used in applications which require high frequency switching like automotive ignition systems and horn contacts [2].

- **Silver-tungsten alloy (AgW):** The main advantage of this alloy is its high resistance to contact welding so it is adequate in applications with powerful arcing contacts. It is also a hard alloy with a high melting point. The main drawbacks are its high resistance, because of the presence of tungsten, and its tendency to oxidise.

- **Silver-nickel alloy (AgNi):** Silver and nickel have virtually no mutual solubility and they are commonly used in contacts in a wide range of applications [2]. Silver-nickel contacts provide good arc-extinguish properties and low oxidation. Main drawback is that it tends to form sulphide surface films but it has a high electrical conductivity, close to pure silver [3]. They are similar to silver-tungsten but the content of nickel is lower compared to the content of tungsten [2]. Silver-nickel is the alloy used in the contacts of the thermal relay analysed in the experimental part of this thesis work.

- **Silver-copper alloy (AgCu):** The main advantage of these contacts compared with pure silver contacts is that their resistance to welding and mechanical wear is higher. On the other hand, they possess higher contact resistance.

- **Silver-palladium (AgPd):** This material, together with platinum alloys, are the most widespread noble metal alloys used in electric contacts. Silver-palladium has been used for many years in telecommunication applications due to its stability. Thanks to its chemical stability and its low resistance to corrosion and sulphitation, it can be used in applications that require low electric noise and more stability in contact resistance [2]. In addition, it is not prone to contact welding but it has a tendency to absorb organic
gases and form polymeric surface films. To prevent surface film formation, it can be coated with gold, but this will make the contact even more expensive.

○ Gold-silver (AuAg): It is also a noble metal composite used in some contacts where high levels of accuracy are required. Gold-silver contacts have the lowest and most stable contact resistance, even with low currents and voltages. However, they have a low resistance to welding. This is the reason why this type of contact is used in measuring systems that work with low currents and voltages so no welding can occur and accuracy is managed.

○ Silver-cadmium oxide (AgCdO): It consists of a ceramic metal composite with high resistance to arcing and mechanical wear, as well as stable properties. It has higher resistance when compared with pure silver but generally lower resistance when compared with silver-tin oxide contacts. In addition, it is prone to welding and tends to form sulphide surface films [2]. There is an important ecological incentive for replacing silver-cadmium oxide with silver-tin oxide due to the high toxicity of cadmium.

○ Silver-tin oxide (AgSnO): Silver-tin oxide materials have become the most popular material for relays and contactors worldwide, replacing the silver-cadmium oxide type contacts since cadmium has been restricted in many countries due to its toxicity. Silver-tin oxide contacts come with a large variety of additives used to adjust the properties of the material. The most popular additives are indium oxide, bismuth oxide, copper oxide, tellurium oxide and tungsten oxide [2]. Silver-tin oxide type contacts have better erosion resistance and welding resistance than silver-cadmium contacts. On the other hand, they generally have higher contact resistance but this problem has been solved by increasing the contact forces. At present, there is enough evidence to demonstrate that the silver-tin contacts can replace silver-cadmium oxide in most applications with a similar performance. [2].

2.3 Types of relays and their applications

In the past, electric circuits usually carried a limited range of current, up to a few hundreds of amperes [2]. Currently, this current range has increased enormously, challenging the science of electrical contacts. Modern relays must be able to break the operating current without causing any damage, from high power circuits passing currents of several mega-amperes to electronic circuits, with currents in the range of microamperes. Thus, a suitable way to classify relays is according to their rated current. However, the following classification is made according to the working principles of the main types of relays.
2.3.1 The Electromagnetic Relay

The simplest, most common and ancient relay is the well-known electromagnetic relay (EM relay), operated by means of a solenoid. The underlying principle applies to a wide range of relays, from low current switching devices used in a wide range of products like automobiles or domestic electronic appliances, to the high voltage relays found in the electric grids and the solenoid that controls, for example, a starter motor in a truck.

Basic elements of this relay can be seen in Figure 5:

![Electromagnetic relay construction](image)

Figure 5 Electromagnetic relay construction

As its name implies, this relay is an electro-magnetic device that converts magnetic flux into a pulling mechanical force which operates the electrical contacts within the relay. The most common form of EM relays consists of an energizing coil called the “primary circuit” wound around a permeable iron core [18]. A magnetic flux is created when the coil winding is energized by applying a voltage across its terminals.

The iron core consists of two parts: the magnetic core, which is the fixed part, and the armature, a moveable spring loaded part that completes the magnetic field circuit by closing the air gap between the fixed yoke and the moveable armature. The armature closes the magnetic circuit as it is attracted to the magnetic core thanks to the created magnetic field. This armature is allowed to move freely within the generated magnetic field closing the electrical contacts that are attached to it.

When the coil is de-energized, i.e., the voltage applied across its terminals is removed, the armature returns to its initial position and the contact opens.

The previous diagram shown in Figure 5 corresponds to a simple EM relay. However, as the breaking current increases, the complexity of the relay increases too, especially the insulation system. Insulation system must provide galvanic isolation of the input circuit (winding) from output one (contacts).
Take, for example, the solenoid switch in the starter motor of a truck [19]. In this case, the use of a power relay like the solenoid switch is essential due to the high current in starter motors. It can be as high as 1500A on cars and as much as 2500A on commercial vehicles [20]. The purpose of this solenoid is to be able to switch a high current by means of a relatively low control current in the primary circuit.

The two main functions performed by the solenoid switch built into a starter motor are [19]:

- It moves the drive pinion outwards so it engages in the engine’s ring gear.
- It closes the switch which completes the motor’s primary electric circuit.

Its design, shown in Figure 6, corresponds to the solenoid switch use in BOSCH® starter motors [19].

The solenoid core (4) protrudes into the solenoid coil from one side, while the movable armature (1) protrudes from the other side. The solenoid housing, core and armature, together form the magnetic circuit. When a voltage is applied across the solenoid winding (2 and 3), a magnetic field is generated that draws the armature into the coil. That armature movement is utilized firstly to move the pinion along its longitudinal axis and secondly to close the contacts (6, 8) of the relay switch.

The solenoid coil generally consists of a pull-in winding (2) and a hold-in winding (3). When the coil first starts to draw in the armature, the air gap between the armature and the core is relatively large and a high magneto-motive force is needed, provided by the pull-in winding.

As the armature retracts, the air gap closes up and the magnetic force increases significantly. When the armature is fully retracted, i.e. when there is only a minimal residual air gap, the force of the hold-in winding on its own is sufficient to hold the
armature in position until the starting sequence is completed. The pull-in winding is thus short-circuited when the main-circuit switch and the ignition switch are closed [19].

When the solenoid is switched off, i.e. the voltage applied across the solenoid coil is decreased to zero, the contacts must open. The return spring (10) assists in this operation by helping the armature to return to its resting position.

The solenoid switch circuit is shown in Figure 7:

2.3.2 Reed Relays

A first step towards understanding reed relays is to comprehend the mechanism of a reed switch [3]. A reed switch is an electrical breaker operated by an applied magnetic field. This switch is actuated by a coil, making a reed relay. However, reed relays are not the same as conventional EM relays, even though they are also actuated by means of a magnetic field. In reed relays, a thin plate made of a magnetic material acts as the contact and the magnetic core at the same time and no armature is needed. Figure 8 shows a picture of several reed switches.
When the coil is energized, a magnetic field is created and the contacts, which are magnetic, are attracted to each other and close. One end of the thin plate is fixed while the other end is covered with some electro-conductive material and is able to move when an external magnetic field is applied.

It is possible to consider the reed relay as an electromagnet that controls one or more reed switches. As the electromagnet acts on the switches without the need of physical contact, no armature is required to move them, as in the case for the conventional EM relays. The decrease in weight and number of moving parts of the relay, provides these relays with the ability of switching much faster than relays with armature. In addition, reed relays are mechanically simpler, increasing the lifespan of these relays.

Ferromagnetic materials are used in the contacts of reed switches. One of the most common is the Permalloy, an iron-nickel alloy usually with 25% of nickel in the alloy [3].

The first reed relay was made for low-power applications (up to 60 W). Later on, some reed relays were developed for power range applications from 100-1000W. High power reed relays, for applications of over 1000W, are more complex, bigger and more expensive.

There are no rubbing elements, full protection of contacts from environmental impact and the possibility to create a favourable environment in the contact area, are some of the aspects that provide these relays with considerable long lifespan, especially when compared with the conventional EM relays. The main limitation is the maximum power they can handle.

In the past, the telephone industry was the main field for reed relays. Nowadays, reed relays have continued their issues outside the telephone industry such as automatic test equipment and electronic instrumentation due to their hermetic seal, fast operate time, extended life and highly consistent contact performance.

Concerning the automotive industry, reed relays are found in some applications such as electric car chargers, automobile sun visors, early brake sensing, exhaust emission sensing and power windows, among others.

2.3.3 Thermal Relays

Thermal relays are commonly used as protective elements that automatically break an electric circuit to prevent overheating. This overheating can be produced in case of overcurrent, therefore, these mechanisms are often used as overload protection.

Thermal relays are essentially mechanical bi-stable devices which, when heated or cooled, provide movement. There are a large number of methods which can be used, but one of the most common is the bimetal strip which, when heated, deforms to either break or
make the circuit. In this thesis, the focus is set on this type of relay which is used in the experimental part and testing in order to develop the test method for relays, although other EM relays are also taken into account in some of the measurements.

The bimetal relay basically consists of two different metals such as nickel, iron, copper, tungsten or aluminium, among others, that together form a bimetallic strip. The different linear expansion coefficients of the metals produce a mechanical bending movement when the strip is subjected to heat. In Figure 9 it is possible to see how the different thermal expansion in the two metals of the strip leads to a larger sideways displacement of the metal with higher expansion coefficient.

![Diagram of a bimetallic strip](image)

In Figure 9, Metal 1 has a larger thermal expansion coefficient compared with Metal 2. The following equations describe the bimetal strip behaviour:

\[
\Delta L_1 = L \cdot \Delta T \cdot \alpha_1 \tag{7}
\]

\[
\Delta L_2 = L \cdot \Delta T \cdot \alpha_2 \tag{8}
\]

Where \( L \) is the initial length of the strip and \( \Delta T \) is the change in temperature, equal for both materials in the strip. The thermal expansion coefficients of each metal are \( \alpha_1 \) and \( \alpha_2 \), where \( \alpha_1 > \alpha_2 \). Therefore, the length increase for the first metal \( \Delta L_1 \) is larger than the length increase for the second metal, which results in bending of the strip.

As it has been explained, the cause of overheating is usually due to an overcurrent. In the event of an overcurrent, the electric circuit will be heated up due to the Joule effect, as losses will increase. A coil of wire is then used to heat the bimetal strip which bends. This interrupts the current in the circuit and it will be reset when the bimetal strip has cooled down. In Figure 10 it is possible to see the bimetallic relay mechanism.
2.3.4 High Voltage Relays

Nowadays, technologies applying high voltages (HV) are constantly increasing. Take, for example, the power lasers, industrial accelerators, high frequency metal and dielectric heating [3]. There is therefore a need for relays operating under voltages from 5 to 300 kV or even higher.

Relays switching high voltages can be divided into [3]:

- Contact HV relays. They may be open or sealed (gas-filled or in vacuum) and also reed ones.
- Solid-state semiconductor HV relays.
- Cathode-ray HV relays.

The use of vacuum or gas as the dielectric environment in HV sealed relays allows enhancement of the switching characteristics of the relay.

However, all these HV relays should be appraised individually to get a clear and adequate understanding of the topic, which is out of the scope of this thesis project. Chapter 6 in the book “Electric Relays. Principles and Applications” written by Vladimir Gurevich gives a good knowledge on this topic [3].

2.3.5 Electronic Relays

The focus of this section will be set on the semiconductor relays. According to electroconductivity of materials, it is possible to distinguish conductors (usually metals) with very low resistance; dielectrics, with high resistance; and semiconductors, which can cover an enormous intermediate range of values of specific electrical resistance.

Most common semiconductors in today’s electronic devices are germanium and silicon. The conducting properties of these crystalized materials are altered in electronics by deliberate, controlled introduction of impurities, the so called “doping” of the crystal structure. This enables the creation of semiconductor junctions between differently-doped regions of the crystal. All the modern electronics, like diodes, thyristors or transistors, are based on the behaviour of charged particles (ions and electrons) as well
as the electron holes at the junctions [3]. Diodes, thyristors and transistors, can all be used as switches. They have the leading role in switching for low power and high-power electronics, like rectifiers, inverters, frequency converters or Pulse Width Modulation, PWM, techniques. Their main advantage is that power losses are very low.

2.3.6 Other relays
There are many other different types of relays with different working principles. For example, there are relays responsive to light, temperature, location in space, air or liquid pressure, etc. [3]. It is obvious that it is quite complex to consider all known types of relays in detail within the scope of this thesis but, those described above provide a general view of the most relevant relays, especially in the context of automotive applications.

Among the rest of the relays it is interesting to mention time relays, differential relays and frequency relays, which are very important for power grids.

More information about specific relays can be found in the book “Electric Relays. Principles and Applications” written by Vladimir Gurevich [3].
Reliability is defined as the probability of an equipment or process to function without failure, when operated correctly for a given period of time, under stated conditions. Reliability in relays, and in all electrical contacts in general, is strongly linked with the real contact area and the changes that can occur at the contact surfaces. These processes depend on a great number of factors that will be presented in this section.

3.1 Factors influencing contacts life. Failure modes

As a first approach, factors affecting reliability can be divided into performance factors governed by the operating conditions and the design-technological factors determined by the manufacturing characteristics of a contact unit [2]. In Figure 11, a set of performance and design-technological factors that affect reliability is presented.

It can be appreciated from the graph that performance factors affecting reliability are those related with environmental conditions. Although they are extremely important and should be considered when selecting a relay for a specific application, they will not be deeply analysed in this thesis.

Some of the major mechanisms leading to failure are related with arc erosion and material transfer in the plasma developed between the contacts mostly at opening but also at closing operations. At this point, the internal performance factors are the ones that play the most significant role but the design-technological factors are also important, since the selection of the proper materials and shape of the contacts is crucial in managing an acceptable life length of the relay.

In this project, these failure mechanisms will be analysed by studying the influence of different representative variables in the performance of the relays. Other mechanisms leading to the failure of a relay are chemical corrosion owing to the environment and mechanical wear due to sliding, rolling or fretting motions. However the focus in this project will be on failures linked with the electric arc as it is the main cause of automotive relay deterioration.
The arc drawn when the contacts open causes contact erosion. At this moment, the current can reach several times the nominal operating current. High current will make the temperature of the switch increase. In addition, the impact when contact closes may cause bouncing which, together with high current, can lead to welding of the contacts as well as severe arc erosion. Therefore, it is important to understand perfectly the dynamics of the contact mechanism at both opening and closing of any switch.

Erosion and welding of the contact surfaces are the more noticeable reasons that can cause an electric contact to fail. However, as it has been said, other causes can also be identified. In Figure 12 the main causes of the deterioration of relays are presented:

Although all causes of relays decline influence the failure of a relay, when looking at the relays used in automotive applications the failure modes reveal either contact welding or significant contact resistance due to excess of arc erosion [13].

During all contact surface interactions a change in the contact resistance occurs [2]. Those changes can be really complex, i.e., depending on the contact mechanical operating system, the ambient atmosphere, the contact material and the arc characteristics, it is possible for the contact resistance to increase, decrease, or remain nearly unchanged [2]. Film formation usually results in an increase in the contact resistance. In addition, higher contact resistance implies higher losses when current flows, therefore the temperature increases resulting in additional film formation. On the other hand, contact erosion can also reduce the contact resistance drastically. It is possible to erode so much of the contact surface during each arcing operation that a new contact surface of virgin metal is exposed each time, and thus low contact resistance is maintained.

In the following sections, the two main processes of electric contact degradation will be briefly described, i.e., the two main failure modes: contact welding and contact erosion.
3.1.1 Contact welding

Contact welding is a phenomenon that occurs in every contact to some extent. It is only when the strength of the weld prevents the proper operation of the contacts that it becomes a serious problem. It can occur if a high enough current passes through closed contacts and causes the contact spot to melt, but also contact welding can happen during contact closure and even as contact opens.

- **Welding of closed contacts:**

  The temperature of the contact spot, $T_c$, is given by the Kohlrausch’s equation, that establishes the voltage-temperature relation in an electric contact [2]:

  \[ T_c^2 = T_0^2 + U_c^2 \cdot 10^7 K \]  

  (9)

  Where $T_0$ is the ambient temperature and $U_c$ is the voltage drop across the contacts.

  Equation (9) is obtained based on the assumptions that the outer surfaces of the conductors are thermally insulated from the external environment so the heat produced within the a-spots can be dissipated only by conduction through the bodies, i.e., adiabatic contact. Under these conditions, the electric and thermal current flow lines follow the same paths, and hence the electric potential and isothermal surfaces coincide within the conductors [21]. Assuming the welding occurs when the contact area reaches the melting point of the contact materials, i.e., $T_c = T_m$, the voltage across the closed contacts, when they weld, will be:

  \[ V_m = U_c(T_c = T_m) = \left(10^{-7}(T_m^2 - T_0^2)\right)^{\frac{1}{2}} \]  

  (10)

- **Welding during contacts closure:**

  It is possible to form an arc as a contact closes, especially if bouncing occurs. Once the arc has formed, it can cause melting at the contacts. When the contacts close, the molten spots on the surfaces will solidify and a weld is formed. Fortunately for most switching devices, the arc at contacts closure is short and the welds that form are usually weak [2].

- **Welding as contacts open:**

  It is possible to observe welding as contacts open even though it is an unusual event. It can result from a poor mechanical design of the switch that allows contact “chattering” as they open [2], i.e., there can be contact sliding or repeated opening and closing operations before the contacts finally part. It can also occur if contacts open too slowly, so the molten particles from rupture of the molten metal bridge solidifies and a weld is formed.
3.1.2 Erosion of the contact surface

Contact erosion is defined as the material loss of the contact surfaces. It is one of the severest consequences of the electric arc. However, erosion is also caused due to mechanical factors like micro-motion of the contacts. Contact arc-erosion occurs because the cathode and the anode under the roots of the stationary arcs can be heated up to the boiling point of the contact material.

The phenomenon of contact erosion is further complicated by mechanical stresses on the contact during the impact at closing operation. Consequently, it is difficult to present general principles that describe the qualitative aspects of arc erosion. Only electrical testing of the final design of the switch will provide the actual erosion that the contact will experience.

Amount of arc and mechanical erosion depends on [2] [7]:

- The current level
- The circuit resistance
- The structure of the contact material
- Contact forces
- Type of load (inductive, capacitive)
- The arcing time
- Open contact gap
- Bounce on making and breaking contact
- Design of arc chamber
- Supply conditions (AC or DC)
- The contact material
- Opening velocity
- The shape and size of the contact
- Motion of the contact
- Number and frequency of make/break cycles

In the following chapters 5 and 6, some tests will be performed on different relays to see the influence of some of these parameters and all possible correlations between them, specifically, current level, arcing time, opening velocity, bouncing and type of load. In addition, contact materials will also be analysed as well as the geometry, shape and size of the tested contacts. Other parameters are not taken into account as they are not as relevant in automotive relay applications. For example, influence of supply conditions will not be considered because, for automotive relays, DC supply is assumed.

However, one of the parameters which has a strong impact on the reliability and lifespan of relays is the type of electric load it is connected to. The next section deals with this topic.

3.2 Effect of the load type in relays lifespan. Inductive kickback effect

Selecting the correct relay for a specific application is critical for the longevity of the relay. Therefore, it is crucial to study the load that relay will be subjected to, as the expected lifetime will vary depending on the type of load [2]. Relay manufacturers specify
how long their relays will last and, for resistive loads, manufacturers’ specifications are typically fairly accurate [22]. However, if the load is capacitive or inductive, the lifespan will be shorter than the manufacturers’ specifications. Loads can be classified into five general types:

- Resistive loads: As these loads are simple resistive elements, the current flow through the contacts will be fairly constant, although some increase may occur due to arcing during making or breaking operations. Ideally, a relay with a purely resistive load can be operated at its nominal voltage and current ratings while reaching its full expected lifespan. However, industry practice is derating relays to 75% of the stated capacity [22].

- Inductive loads: Switching inductive loads is difficult because the current tends to keep on flowing in inductors after the contact opens. This is known as the inductive kickback effect that will be explained in detail later. It creates large voltage spikes that can damage the electric contacts. Industry practice is derating relays to 40% of the relay’s stated capacity when switching inductive loads [22].

- Capacitive loads: Capacitive loads demand high in-rush currents that can be limited by using resistors in series. Without a limiting resistor, contact welding may occur when switching on a capacitive load. A typical derating for relays using capacitive loads is 75% of the relays’ stated capacity [22].

- Motor loads: With these loads both, high in-rush current and inductive kickback effect will occur. In the first instance, when an electric motor starts up, it has very low impedance and requires a large in-rush current in order to build up a magnetic field and start to rotate. Once it is running, it generates a back electromagnetic force and behaves as an inductive load, causing a large inductive spike when the relay opens. The result is: large in-rush current at start up and arcing when stopping. Therefore, typical industry practice is derating relays to 20% of the relays’ nominal capacity [22].

- Incandescent loads: Incandescent loads are considered as resistive loads but the resistance of a hot tungsten filament can be 10 to 15 times greater than the resistance when it is cold [22]. Therefore, high in-rush current into cold filaments can damage the relay contacts and consequently relay values are derated to 10% of the stated capacity [22]. Again, as in the case of capacitive loads, a current limiting resistor in series with the filament can be placed to limit the in-rush current [22].

Table 1 shows the typical derating factors for relays based on the type of load switched [22].
Table 1 Relay derating factors

<table>
<thead>
<tr>
<th>Type of load</th>
<th>Percentage of rated value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistive</td>
<td>75%</td>
</tr>
<tr>
<td>Inductive</td>
<td>40%</td>
</tr>
<tr>
<td>Capacitive</td>
<td>75%</td>
</tr>
<tr>
<td>Motor</td>
<td>20%</td>
</tr>
<tr>
<td>Incandescent</td>
<td>10%</td>
</tr>
</tbody>
</table>

Figure 13 shows the principal transient behaviour of the five types of loads:

![Figure 13 Principal transient behaviour of the five types of loads](image)

In the automotive industry, the most common loads are motor or inductive loads. Both of them cause voltage spikes in the relays at breaking operation, i.e., the inductive kickback effect.

The so called “inductive kickback” phenomenon is the large voltage spike that occurs whenever the current flowing through an inductor is abruptly switched off. It can result in the destruction of some circuit components if it is not handled properly [23].

The voltage across an inductor can be modelled with the following law:

\[ V = -L \frac{dl}{dt} \]  (11)

Where \( \frac{dl}{dt} \) is the partial time derivative of current flowing through the inductor, \( L \) is the inductance value and \( V \) is the voltage across the inductor. Therefore, the current flowing through an inductor cannot change instantaneously, as it will cause theoretically an infinite voltage spike.

Take a RL series circuit with a DC supply voltage. At a first stage, when the load is switched ON, the abrupt increase of the voltage applied across the inductor will cause the current to ramp up with an exponential behaviour, as seen in Figure 14.
The current will rise up to the value determined by Ohm’s law, i.e., the applied voltage divided by the inductor resistance. In addition, the time constant $\tau$ (see Figure 14) that characterises the current rise in an inductor is:

$$\tau = \frac{L}{R}$$ (12)

While the current rises, the inductor establishes a magnetic field which gives the inductor its characteristic behaviour: changes in current are resisted by the magnetic field as it adjusts to the shifting current. If the current flow increases, the energy from the magnetic field must also increase and energy will be drawn from the current flow to increase the magnetic field energy. On the other hand, if current flow decreases, energy from the magnetic field must also decrease and energy will be contributed from the field to the current flow.

It has been explained, when the voltage across an inductor is suddenly switched ON, the current rises exponentially but, what if it is abruptly switched off? Then, the magnetic field established by the inductor will provide its stored energy in an effort to force the current to remain flowing. This energy stored in the magnetic field is given by the following expression:

$$Energy = \frac{1}{2} L I^2$$ (13)

With the aim of maintaining the current flow in the absence of any external applied voltage, the inductor establishes a very large voltage differential across its terminals, using the energy from the magnetic field. For a brief time, the voltage across the inductor will spike to very high levels, as shown in Figure 15.

The voltage spike may exceed the specifications of many of the components in an electric circuit, such as the overload protection relays, since they are not rated for these high voltage values. Most of them will work well for several cycles but under extreme
circumstances, as arcing will occur in every breaking operation of the switch, it will be eventually damaged or even welded.

3.3 Life-length testing

Reliability can be defined as the ability of a system or component to perform its required functions under stated conditions for a specified time [24]. It can be estimated with life-length tests by examining the failure rates of a certain sample of products. When talking about the reliability of relays, the best way to analyze it is by defining or approximating the number of cycles it can operate before failure. This measurement is the so called MCBF, Mean Cycles Before Failure [25]. Other measures such as MTTF, Mean Time To Failure, or MTBF, Mean Time Between Failures, are less representative, as reliability in relays is greatly determined by the number of switching cycles it has been subjected to, and not simply how long it has been in service [25].

However, the MCBF does not provide a complete description and other considerations must be taken into account like the electrical load, the operating current, the number of samples used for the estimation or the switching frequency. All these parameters will determine the confidence of the estimation. A well-designed reliability test is able to define if one type of relay is significantly more reliable than another, the failures which can be expected and the lifespan of the relay.

Even though a large number of relay tests and standards exist, degradation rates of power connectors according to the switched loads cannot be determined precisely, which makes the electrical systems less reliable and maintenance really difficult.

In this concept, the aim of this thesis work will be to develop a realistic life-length test method for automotive relays. Knowing the estimation of the number of switching cycles a relay will last under different electrical load conditions (MCBF) is important when deciding if a specific relay is the best choice. A rigorous reliability testing program is
therefore an essential tool for providing customers with technical support and also for improving the product quality [25]. Thus, it is of considerable interest to [2]:

- Identify the major parameters determining the character and lifespan of power connections in terms of their mechanical and metallurgical metal-to-metal characteristics.
- Quantify the limitations of these parameters and establish reliability criteria under different operation and environmental conditions (current, temperature, voltage, ...)
- Provide palliative measures to ensure satisfactory performance.
- Review existing test methods and new tendencies, like accelerated testing procedures which allow better connector life specifications.

In this section, the theoretical overview about life-length testing that has been followed to obtain the test results in this thesis is presented.

Accelerated methods were applied in every life-length test in order to shorten the time it takes to carry them out. These methods can be: test at a high switching frequency, increase the nominal current or voltage, increase the load and many others. After the life-length tests, the failure modes were investigated by examining the morphology of the contact surfaces, giving a better understanding of the failure mechanisms.

However, it is important to know how accelerating conditions will affect the relays, i.e., if the conditions differ too much from reality, the test results will be useless. Therefore, adhering to the recommendations of some experts, the following method has been applied in this research. First, relays were tested under nominal parameters (type of load, current and voltage). In this way, an estimation of the number of cycles a relay will last was obtained, as well as a study of the expected failure mechanisms. Later on, these parameters were varied in order to accelerate the tests and obtain more samples of failed relays.

As has been explained, one of the main disadvantages of life-length tests is the length of time they need to be completed. Therefore, one can wonder if there are other tests able to predict early failures in relays. The answer to this question is affirmative, the so called parametric tests.

Two parametric tests have shown considerable accuracy in predicting early failures, the magnetostrictive test (TWIST) and the contact resistance test (CRS), developed by RTS®. They are based on the principle that smooth, clean and well aligned contacts will provide superior long-term reliability.
• TWIST test can only be applied to dry-reed relays as it is based on the phenomenon caused by the magnetic flux of the coil current interacting with the flux of the load current [26]. The contact plates can be subjected to twist in relation to each other when the two mentioned fluxes interact, causing contact surface irregularities and eventual contact failure. This test is out of the scope of this thesis project as it can only be applied to dry-reed relays.

• CRS test (Contact Resistance Stability) is focused on contact resistance variability. High-quality contacts will provide strongly controlled and repeatable contact resistance measurements over many cycles [27]. In this test several measurements of the contact resistance are recorded to obtain the so called CRS value, which is the difference between the maximum and the minimum value of the contact resistance. A high CRS value indicates a higher probability of early life failures. As a reference, high-quality contacts will show very repeatable measurements, typically a CRS value of 1 to 2 milliohms for a nominal contact resistance of 50 milliohms [26] [27].

Finally, one of the most common ways to study the lifespan of switching devices is the Weibull statistical analysis. Notably, the two-parameter Weibull distribution is very well suited for predicting the lifespan of any kind of relays. Among its advantages it must be highlighted that there is no need of large size samples to obtain accurate predictions [28].

First step in any Weibull statistical study, is to obtain raw data by taking a representative set of samples and cycling them to failure, counting the number of cycles before they fail. Like any other prediction method, the accuracy increases with the number of samples, specifically, the increase is in proportion to the square of the number of samples.

The two parameter Weibull distribution is mathematically defined by the probability density function as shown in (14) [29], where \( n \) is the number of cycles before a certain relay fails.

\[
f(n) = \frac{\beta}{\eta} \left( \frac{n}{\eta} \right)^{\beta - 1} e^{-\left(\frac{n}{\eta}\right)^{\beta}}
\]

Where:

\( f(n) > 0, \; n > 0; \)
\( \beta > 0, \; \eta > 0; \)

The first parameter, \( \eta \), is the scale parameter or characteristic life that gives the life expectancy at the point when 63.2% of the population has failed. The second parameter, \( \beta \), is the shape parameter and is related with the failure rate. Beta values greater than
1 indicate wear-out failures, i.e., increasing failure rate with time, while beta values equal to 1 indicates constant failure rate [26]. Both parameters can be estimated with the expressions in (15) [29]:

$$\eta = \frac{MCBF}{\Gamma(1 + \frac{1}{\beta})}; \quad \beta = \left(\frac{\sigma_n}{MCBF}\right)^{-1.086}$$

(15)

Where MCBF is the mean cycles before failure and $\sigma_n$ is the standard deviation of the historic data of cycles before failure. $\Gamma$ is the Gamma function.

Once $\eta$ and $\beta$ have been determined, the equation in (14) is completed. However, the probability density function is not the most common expression to plot the Weibull distribution.

Instead, the cumulative distribution function, $F(t)$ is plotted. It is also called the unreliability function and is defined as:

$$\frac{d}{dt}F(n) = f(n)$$

(16)

Therefore, the cumulative distribution is calculated by solving a simple integral:

$$F(n) = \int_0^n f(n)dn = \int_0^n \left(\frac{\beta}{\eta}\right)^{\beta-1} e^{-\left(\frac{n}{\eta}\right)^{\beta}} dn = -e^{-\left(\frac{n}{\eta}\right)^{\beta}}\bigg|_0^n = 1 - e^{-\left(\frac{n}{\eta}\right)^{\beta}}$$

$$F(n) = 1 - e^{-\left(\frac{n}{\eta}\right)^{\beta}}$$

(17)

With these calculations, it is possible to predict several results like the MCBF, the life expectancy, which corresponds to $\eta$, the probability of failure after a certain number of cycles, estimation of expected infant mortality, wear out characteristics and other pertinent reliability data.

In Figure 16, an example of a Weibull chart from RTS®, Relay Testing Services, available in [26] is shown. It corresponds to a reliability study where samples of a reed relay were life tested with resistive loads of 1 Volt/10 mA, 10 Volt/1 mA, 10 Volts/100 mA, 10 Volt/1 Amp and 30 Volts/100 mA (Supplied voltage/Demanded current):
Finally, a chart summarizing the main facts and ideas in relays endurance testing and the future trends is shown in Table 2.

Table 2 Endurance tests. Today’s and tomorrow’s methods

<table>
<thead>
<tr>
<th>PRESENT ENDURANCE TESTS</th>
<th>FUTURE ENDURANCE TESTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Relays are tested to failure and the number of cycles before failure is recorded in order to predict their lifespan</td>
<td>• Relays will continue being tested to failure, counting the number of cycles.</td>
</tr>
<tr>
<td>• Difficulties in failure mode detection</td>
<td>• Automatize measurements will be introduced, i.e., in situ measurements of contact resistance, voltage spikes and arc duration, among others</td>
</tr>
<tr>
<td>• Accelerated methods are being investigated</td>
<td>• Endurance test will include failure mode detection</td>
</tr>
<tr>
<td></td>
<td>• Accelerated methods will decrease the time needed to perform the test, managing better connector life specifications</td>
</tr>
</tbody>
</table>
4 Electric arcing theory

Arc discharge consequences such as material migration by erosion, welding and high contact resistance are the main problems for switches and relays in automobiles [13].

In this section, a theoretical study of electric arcing will be performed in order to understand material migration by erosion. The starting point will be the principle of mass lost per operation of the contact, which can be given by:

\[
\text{mass loss} = f(\text{total power input into the contacts})
\]

The total mass flow in a contact during an electric arc is shown in Figure 17. It is a mixture of the following components:

1- Metal vapour evaporated from the arc roots
2- Metal droplets ejected from the arc roots
3- Metal re-deposited back onto the contact surfaces

Modelling mass loss happens to be a complicated task because the erosion products are quite difficult to predict. Furthermore, designing an accurate model of the total power that goes into the contacts is also a complex problem.

For a single switching operation, when the contact is opening, there is a transition in the direction of material transfer as a function of the arc erosion going from anodic to cathodic transfer. Therefore, it is possible to differentiate two phases in an electric arc: the metallic phase, with anodic material transfer and the gaseous phase, where the material transfer is reversed to cathodic transfer. Gaseous phase will only occur if the arc is strong enough, i.e., if the applied power is enough to reach the gaseous phase.
4.1 Metallic Phase in an Electric Arc

At the early opening stage the gap between the contacts is small, i.e. less than approximately 5 to 10 microns. In this initial stage, the anode is eroding and some mass is transferred to the cathode. It is known as the metallic phase of an electric arc [2].

As the next section will explain, if the arc has enough energy the gaseous phase will take place as the gap between the contacts becomes larger. In this phase the transfer of materials during the arc erosion process reverses. For low voltage DC applications like automotive switching, depending on the type of electrical load the accumulated material transfer can be significant [2].

Returning to the metallic phase, i.e. at the beginning of the break operation, because of the electrode surface roughness, the current carrying spots of contact are reduced to a few points. This results in ohmic heating which melts the contacts material. At a later point, the molten material is pulled to a bridge, the so called molten bridge, as shown in Figure 18 [30].

Further separation of the contacts results in the rupture of the molten bridge that causes the gap between the contacts to be filled with metal vapour. This gap is so small that the electrical field can reach over hundreds of V/cm [19] and the cathode acts as an electron emission source. The electrons emitted from the cathode, while being accelerated by the electrical field, move towards the anode. Due to inelastic collisions between metallic vapour and these electrons, the ionization of metal vapour and the generation of many more electrons can be observed at this stage. They are the so called electron avalanches [19]. As a result of the metallic phase, the arc is ignited. In this phase, the metal vapour assists the arc, i.e., the arc takes place in the metal vapour. It is possible to differentiate three different particles: the electrons (-), the metallic ions (+) and the metallic atoms, as can be appreciated in Figure 19.
Electrons impact at the anode and metallic ions affected by the electrical field impact at the cathode which results in the deposition of the metallic ions on the cathode. In conclusion, during the metallic phase, the material transfers from anode to cathode.

![Figure 19 Material transfer in the metallic phase](image)

4.2 Gaseous Phase in an Electric Arc
As the gap between the contacts continues to increase, higher ionization potential atmospheric ions play a larger part in arc conduction mechanism. With time, the deposition of metal ions on the cathode together with the deletion of metal ions through interdiffusion between metal vapour and the surrounding gas cause a reduction of metal vapour between electrodes and the atmosphere gas becomes the main medium between contacts [2]. This gas will be ionized if the applied power is enough so the gaseous ions will become dominant and the arc gaseous phase starts.

In this phase the gaseous ions bombard the cathode. As a result, the sputtered particles have enough energy to transfer to the anode and redeposit there. In conclusion, during the gaseous phase, the material is transferred from the cathode to the anode, as can be understood from Figure 20.

![Figure 20 Material transfer in the gaseous phase](image)
Further separation of the contacts results in arc extinction, since it causes the circuit parameters to drive the arc below its minimum sustaining current. The extinction of the arc is a quite detailed process with different behaviour if the current is ac or dc, being the last one the hardest to extinguish.

In conclusion, to analyse mass loss, the net material transfer to be assessed corresponds to the balance of the metal and gaseous phases where both, gain and loss happen either at the cathode or at the anode.

Suggested future work would be to develop a general macroscopic electrical contact arc erosion model that will describe the mass loss during the whole opening process. However this study is beyond the scope of this thesis. Later on this model should be validated with the corresponding experimental measurements.
5 Methodology

After a thorough review of literature and analysing all the factors that can cause contact damage, it is safe to affirm that arc discharge consequences such as erosion and contact welding are the main problems for relays in automotive applications. The next step is therefore to identify the parameters that affect the electric arc and consequently the material transfer, the erosion, and the risk for contact welding and damage.

First of all, arc duration, current and type of load are some of the main parameters that affect the reliability of relays. Some experiments are carried out in this thesis to see the influence of all of them and analyse all possible correlations between them.

Secondly, contact opening and closing speeds are other parameters worth studying. These two speeds influence arc duration and their analysis could determine whether or not contact bouncing occurs, which is an important cause of damage in all switching applications.

After all the analysis and experiments related to the parameters that can affect a relay lifespan, and thus its reliability, a life-length test needs to be designed. Different relays under specific conditions will be tested to failure with the aim of determining their life expectancy.

Later on, a study of the contacts after the life-length test must be done to analyse failure mechanisms and the damage in the contact surfaces within the scope of carrying out materials analysis of the tested relays.

Finally, the Contact Resistance Stability (CRS) test is performed in order to investigate whether it is an effective tool capable to predict early failures in relays.

5.1 Measuring the relevant parameters

As been explained, there is a large number of parameters influencing the electric arcing phenomenon in a switch. However, the breaking current levels and the load type have proved to be two of the most significant factors regarding arc duration and thus, damage of the contact surfaces due to arc erosion and welding.

Other relevant parameters are the opening and closing speeds of the contacts and, in general, the displacement of the movable contact with respect to the stationary contact. The study of the opening and closing speeds might be useful to detect bouncing.

The following test setup is performed in order to see the influence of all the mentioned parameters in contact damage and to analyse all possible correlations between them. The obtained results will be helpful to understand the life-length test results.
5.1.1 Apparatus

Experimental apparatus used to measure the different parameters of interest are presented in this section. The instrumentation and circuitry used to analyse the influence of breaking current, arc duration and connected load is presented in Figure 21. It consists of a voltage source (1) that can supply 0-60V and up to 18A, enough for this test purpose. This source supplies power to one of the three different loads (4) representing three different levels of inductance. The resistance (3) is common to all the loads but can be varied so the current can be controlled. The tested relay (5) is between the loads and the power source and works by connecting and disconnecting the load.

The circuit setup for testing an electromagnetic relay is presented in Figure 21. The coil is energized by pressing a manual switch (2) and makes or breaks the relay’s contacts. Other relays can be tested in this setup like, for example, a thermal relays. In that case, the setup varies and no manual switch is needed as the relay will open automatically when the current exceeds a certain value.

With this setup it is possible to measure the current in the circuit using a shunt resistor (6). The voltage drop across the contacts was recorded with the oscilloscope (7). Finally, a photodiode was used to measure the arc duration (8). This gives an output voltage signal correlated to the light intensity of the arc. Therefore, it gives a very low voltage as its output when there is no arc and a high voltage as its output when the arc is taking place. The higher this output voltage in the photodiode, the higher the intensity of the arc and thus, more damage to the contacts is expected.

![Figure 21 Circuit setup for measuring arc duration, arc voltage and current with different inductance levels](image-url)
The oscilloscope model used for the measurements was MSOX3024A Mixed Signal Oscilloscope with 200 MHz bandwidth and 4 analog channels, which ensures arc voltage and current sampling and display of their waves in the oscilloscope screen. Its maximum sample rate is 4 GSa/s (4\( \times 10^9 \) samples per second). Figure 22 shows the mentioned oscilloscope.

![Oscilloscope used for the measurements](image)

The photodiode was protected with a circuit with capacitors that can be seen in Figure 23. An OPT101 was the selected sensor for the measurements of the light intensity of the arc, as well as the arc duration. It is a monolithic photodiode with on-chip transimpedance amplifier [31].

![Photodiode with protective condensers](image)

A 100Ω resistor was used to remove noise coming from the power supply line \( V_{cc} \). A 100 \( \mu \)F capacitor ensured that the amplifier saw a low impedance power supply across a wide range of frequencies.
The aim of the next test was to measure the contact opening and closing speeds as well as the displacement, in order to detect bouncing if the contacts and study the impact that the opening and closing speeds have in the arc. The laser used was the PSV-500-3D Scanning Vibrometer. It is a state of the art tool able to quickly and accurately determine operating deflection shapes for structural vibration validation. This model covers a frequency range up to 20 kHz.

The whole equipment (Figure 24) includes a scanning head with the laser beam, a tripod, a special lens for the scanning camera that enables scanning small surfaces (limitation of 2 mm² surfaces), the system cabinet and the Polytec® Scanning Vibrometers (PSV) software package.

5.1.2 Experimental Conditions

The circuit was supplied according to the voltage found in the automotive application that the components are designed for, i.e. 27.6-27.7 V, which is the voltage supplied by a truck battery. The power source was replaced by a 28V battery (supplied voltage 27.6-27.7V) but similar results in the test were observed.

Six different experimental conditions were performed for the arc voltage and arc duration measurements for each tested relay in order to study the relation between all the variables involved:

- Resistive load, 4.96A
- Resistive load, 9.3A
- Resistive load, 14.15A
- Inductive load, 4.96A
- Inductive load, 9.3A
- Inductive load, 14.15A
There were three possible values for the inductance in the load which helped in analysing the influence of the inductance levels in electric contacts damage, arc duration or arc voltage. The relays were tested at room temperature and the material in the tested contact was silver based.

In the case of the displacement test, the laser measured the speed of the breaking and making operations with no load connected to the contacts. The scanning head was placed on a tripod with a special lens that enabled the scanning of small surfaces. All devices are plugged into the system cabinet and a computer, where the laser software is installed, as can be seen in Figure 24.

Test and measurements have been carried out with an electromechanical relay whose characteristics are presented below:

- **Electromechanical relay with diode:**

It is an electromechanical relay whose coil is protected with a fly-back diode, connected in parallel with the coil. It is limited by a continuous current of 70A and its nominal voltage is 24V.

A schematic of the relay’s connections is presented in Figure 25 where pins 30 and 87 represent the relay’s contacts and pins 85 and 86 represent the coil. When the coil is energized (there is a positive voltage across the coil, pins 85-86), the contact closes and when the voltage across the coil is zero the contacts will open. The working principle of the electromechanical relay is explained in detail in chapter 2.

It is important to notice that there is another diode in series with the coil and therefore the relay must be adequately connected so that this diode is polarized properly. The diode in parallel with the relay coil protects it from voltage spikes that are caused by the coil whenever the voltage across it drops.

![Figure 25 Connections of the electromechanical relay with diode](image)

![Figure 26 Outside view of the EM relay with diode with and without the plastic case](image)

The relay is protected by a plastic case as can be seen in Figure 26.
Other relays were used to perform the measurements and to check if the results and conclusions drawn from the first relay were valid for others. These relays were:

- **Electromechanical relay with resistor:**

  It is very similar to the relay with diodes but instead of having a diode in parallel with the coil, this relay has a resistor. It is also limited by a continuous current of 70A and its nominal voltage is 24V. The schematic circuit can be seen in Figure 27. In this case the coil suffers more since there is no diode preventing voltage spikes.

![Figure 27 Connections of the electromechanical relay with resistor](image)

![Figure 28 Outside view of the EM relay with resistor](image)

- **Thermal overload protection relay:**

  This relay consists of a bimetallic strip that breaks the circuit when the current exceeds a certain level. Current passing through the relay generates losses and, due to the Joule effect, the temperature of the spring increases. When it exceeds a certain temperature, it will bend breaking the circuit. When the temperature decreases, the bimetal strip will return to its initial position and makes the contact. The working principle of the bimetallic relay is explained in detail in the second chapter.

  In Figure 29 it is possible to see all the different parts in this relay and in Figure 30 the relay itself [32].

![Figure 29 Illustrated parts breakdown of the thermal relay](image)
The remaining experimental part was focused on this relay. It is used as an overload protection for the electric motor that drives the power window in the truck.

![Figure 30 Outside view of the thermal relay](image)

In this specific application, the polarity of the relay is changed when the window goes up or down. A schematic diagram of the H-bridge used to operate the motor in these directions is shown in Figure 31 [33].

As stated in the electric arcing theory in chapter 4, the polarity of the relay affects the material transfer and thus, the erosion. Therefore, it would be interesting to consider both polarities in the life-length test. In this way, the worst case scenario is determined. However, the “switching polarity case” was not tested, i.e., to perform the endurance test switching the polarity of the relay in each cycle.

![Figure 31 H bridge [33]](image)

It can be questioned why the H-bridge is not controlled with 4 transistor and 4 diodes, avoiding the problems that the thermal relay is experiencing and thereby preventing damage to the electric motor that drives the power window by controlling the current through the motor and coasting the motor in case of overcurrent. The main reason for this is that the solution of the overload thermal protection with the two relays in the H-bridge is considerably less expensive, simpler, does not require any control units and is adequate enough for this application. However, in the new trucks generation, the auto-up function is included, and in this case the power window is driven with 4 transistors and 4 diodes controlled by means of a control unit. No thermal protection is required (Appendix A).
5.2 Life length test

The next step after determining which parameters can affect a relay’s lifespan was to perform a life-expectancy test. The thermal relays were tested to failure with the aim of determining their lifespan. The goal was to design a method to test the reliability of the thermal relay but could also be effective for other types of relays.

5.2.1 Apparatus

The life length test setup is shown in Figure 32. Basically four relays were tested at the same time, each one connected to an individual inductive load.

A Sorensen SG Series power supply was used in this test, capable of providing 0-100V and enough current to the four branches of the circuit, 0-50A. It is a general-purpose power supply designed specifically for laboratory testing with good ripple and regulation characteristics. It can work in constant voltage or constant current mode, but for the life-length tests, constant voltage was assumed. Again, the voltage was set up to 28V, as it is the voltage found in the truck.

![Life length test setup with four thermal relays](Figure 32)

Furthermore, a resistor bank with four resistors was utilized. All resistors in the four loads had the same value, so the breaking current was the same in the four thermal relays. Each resistor was connected in series to one inductor and then to the relay.

The idea was to count how many cycles each relay could make until it died. To do so, a counter connected across each relay was used. To prevent damage to the counter due to
the voltage spikes that occurred across the thermal relays, four EM relays were used. All of these EM relays were connected to the voltage source \( V_{cc} = 28V \).

A picture of the setup used for the life-length tests can be seen in Figure 33:

![Picture of the setup for the life length test](image)

5.2.2 Experimental Conditions

The circuit was supplied with the voltage according to the automotive application they are designed for, i.e., 27.6-27.6 V, which is the voltage supplied by a truck battery.

The values of loads connected to each branch were:

- **Load A**: \( R_A = 2.7 \Omega; L_A = 1.4 \, mH; \) "Grey Relay"
- **Load B**: \( R_B = 2.7 \Omega; L_B = 3.4 \, mH; \) "Golden Relay"
- **Load C**: \( R_C = 2.7 \Omega; L_C = 3.8 \, mH; \) "Red Relay"
- **Load D**: \( R_D = 2.7 \Omega; L_D = 7.3 \, mH; \) "Blue Relay"

Therefore, the current in each branch should be approximately 10A, but it was a bit lower due to extra resistance and losses in the connections.

The different inductance levels helped later with analysing the influence of the inductive loads in relays’ lifespan, failure mechanisms and contacts damage.

The relays were tested in room temperature and the materials in the tested contacts were silver-based. The colour names for the relays correspond to the colours used in Figure 32 and in the graphs later presented in the “Results” section.

Test and measurements were carried out with the bimetallic thermal relay described in section 5.1.2.
Conditions presented in this section correspond to the baseline case. Later, as it will be explained in the next section, the supplied voltage, and therefore the current, were increased in order to accelerate the endurance test.

Finally, the Weibull plot for the baseline case, i.e. 28V, was calculated for only one of the inductance levels in the experiment. The chosen level was the third, 3.8mH. The reason for this was that the application concerning this relay is protecting the motor in the power window of the truck. An analysis of this motor gave a resistance of 2.7Ω and an inductance of 3.6-3.8mH. The closest model for this motor was, therefore, the inductive load C:

\[ \text{Load C: } R_C = 2.7 \, \Omega; L_C = 3.8 \, mH; \text{ "Red Relay"} \]

The explanation why the motor can be replaced by an RL load is that whenever the protective relay is operated in the power window, the motor connected to it is in standstill.

The equivalent electrical circuit of a Permanent Magnet Direct Current (PMDC) motor is illustrated in Figure 34, where \( V_a \) represents the voltage supplied to the motor across the coil armature. The electrical equivalent of the armature coil can be described by an inductance, \( L_a \), in series with a resistance, \( R_a \), in series with an induced voltage, \( V_c \), which opposes the voltage source. The induced voltage is generated by the rotation of the electrical coil through the fixed flux lines of the permanent magnets [34]. This voltage is referred as the so called back electromotive force (emf).

The back emf can be written as [34]:

\[ V_c = k_v \cdot \omega_a \]  

(18)
Where $k_v$ is the velocity constant determined by the flux density of the permanent magnets, the reluctance of the iron core in the armature and the number of turns of the armature winding. $\omega_a$ is the rotational speed of the armature.

As explained, in this test the rotor of the electrical machine was blocked, so the rotational speed $\omega_a$ was equal to zero. Therefore, the back electromotive force $V_c$ was also zero and could be removed. The equivalent model of the motor was then simplified by just the coil resistance and inductance, as shown in Figure 35.

![Figure 35 Equivalent electrical circuit of a PMDC motor with the rotor blocked](image)

5.3 Material analysis

Finally, material analysis was carried out using the tested relays to analyse contact materials and failure modes. First, contacts in several brand-new thermal relays were examined using Light Optical Microscopy (LOM) and Gas Chromatography-Mass Spectrometry (GC-MS) techniques. The aim of this was to have a clear idea of how the relay looks like before being used. After this, several samples of the relays from the life-length tests were examined. In this case, first the relays were subjected to a 2D X-ray inspection. This way the relays were inspected without damaging or breaking them. After the X-ray, LOM inspection was carried out. This allowed us to choose which contacts to look at using Scanning Electron Microscopy (SEM) techniques.

All these analysis were be very valuable in understanding the failure mechanisms of the relays and the behaviour of the contact surface materials in this specific silver based contact.

The three main techniques used, LOM and SEM and GC-MS, and the experimental conditions and methodology followed in this analysis are presented in this section.
5.3.1 Light Optical Microscopy, LOM

Light Optical Microscopy, LOM, was the technique performed prior to the Scanning Electron Microscopy technique, SEM. LOM techniques have some advantages when compared with SEM techniques. For example, performing LOM analysis is less time-consuming and the instruments are much less expensive than SEM instruments. Further, certain features like the natural colour can be better observed with LOM [35]. LOM examination is therefore faster and can cover a large area. Thus, with the LOM analysis it could be determined whether additional SEM analysis was required for a specific sample.

LOM analysis was first used in an initial study of several new contacts to understand how they looked like when they were not used as a baseline for the analysis.

Later on, after performing the endurance tests in several samples under different operating conditions, the failed relays were examined using the LOM technique. LOM analysis in the samples was performed at room temperature.

5.3.2 Scanning Electron Microscopy, SEM

Scanning Electron Microscopy, SEM, is a technique that uses a focused beam of electrons to create an image of a sample. It works by processing the signals that the interactions of the electrons with the atoms in the sample produce. These signals contain information about the sample surface’s topography and composition [36].

The types of signals used in this analysis produced by the SEM included Secondary Electrons, SE, and Back-Scattered Electrons (BSE). Both signals result from interactions of the electron beam with atoms at various depths within the sample and are explained in detail below.

The SEM technology needs the electrons in the beam to be accelerated in an electric field by a potential difference that can vary according to the nature of the samples. This voltage accelerates the electrons that bombard the sample after passing through several lens so the primary electron beam that reaches the sample is as small as possible. When the primary electron beam (PE) interacts with the sample, the electrons lose energy by repeated random scattering and absorption. The energy exchange between the electron beam and the sample results in the reflection of high-energy electrons by elastic scattering, emission of secondary electrons by inelastic scattering and the emission of electromagnetic radiation, each of which can be detected by specialized detectors [36].

The different interactions between the electron beam and the sample are shown in Figure 36.
The most common detection mode is the Secondary Electron Imaging, SEI. It reveals details less than 1 nm in size of the sample topography. Back-Scattered Electrons (BSE) are beam electrons that are reflected from the sample. In the analysis, BSE is used along with the spectra made from the characteristic X-rays. The images obtained from the BSE provide information about the distribution of different elements in the sample, as the intensity of the BSE signal is strongly related with the atomic number (Z) of the specimen.

![Mechanisms of emission of secondary electrons (SE), backscattered electrons (BSE) and characteristic X-rays from atoms of the sample](image)

The Scanning Electron Microscope used in this project was the Carl Zeiss Sigma Variable Pressure Analytical SEM, an equipment capable of producing exceptional images at high and low accelerating voltages. The device is shown in Figure 37:

![Scanning Electron Microscope](image)

The samples were observed in a vacuum chamber whose internal pressure was $8 \times 10^{-5}$ mbar, approximately. They were assembled rigidly on a specimen holder using a
conducted adhesive. It was important that specimens for conventional imaging were electrically grounded to prevent the accumulation of the electrostatic charge.

As we were dealing with metallic samples, high voltage levels were expected to accelerate the electrons in the beam, since metallic specimens do not suffer damage in general, as can happen with the biological samples. This allowed to take advantage of a lower wave length and, therefore, a better resolution in the obtained image. In the experiments, this voltage was set to 20-25kV and it was called the Extra High Tension level, EHT.

5.3.3 Gas Chromatography-Mass Spectrometry, GC-MS

GC-MS techniques combine the features of gas chromatography and mass spectrometry to identify different substances in a sample. In this project, this technique was used to identify organic materials in the new relays.

To get a better understanding of the organic components that exist in the brand-new relays, a sample of four relays was cleaned and another sample was not. The first sample was cleaned using pure toluene. Each relay was placed in a small container with $2.4 \pm 0.1 \text{ml}$ of toluene. The relays were submerged in toluene for two weeks before starting the GC-MS examination [37].

GC-MS examinations require a mobile and a stationary phase. The mobile phase, i.e. the carrier gas, is comprised of an inert gas like helium, argon or nitrogen. The stationary phase consists of a capillary column [37].

The different strengths of interaction of the sample with the stationary phase determine separation of the compounds, according to the like-dissolves-like rule. One of the factors that influences more in the separation and detection of the components in the sample is the polarity of the components versus the polarity of stationary phase on the column used. In this project, a non-polar column is used.

5.4 CRS test

As it was explained in chapter 3, high-quality contacts will prove strongly controlled and repeatable contact resistance measurements over many cycles [26]. The company RTS® (Relay Testing Services) has developed the Contact Resistance Stability test, CRS test, which is focused on contact resistance variability. It is called RDEL test in the company articles [26] [27] [28], but no definition for this acronym has been found so the name has been changed. In this test, several measurements of the contact resistance were recorded to obtain the so called CRS value, which is the difference between the maximum and the minimum value of the contact resistance.
 CRS test was carried out as follows: The contact resistance was measured initially. Then the contacts were cycled 5 times prior to a measure. This was repeated 10 times while the contact resistance value was recorded. Therefore the relays were cycled 50 times and a total of 10 values of the resistance was obtained.

The contact resistance was measured by supplying the circuit with a low voltage (3, 4 and 5V) and measuring the current, $I$, and the voltage drop, $V_{\text{drop}}$, across the relay by means of a multimeter. Afterwards, the contact resistance, $R_c$, was obtained by applying Ohm’s law: $R_c = V_{\text{drop}} \cdot I$.

After testing a sample of 20 relays, two groups were formed according to the CRS value:

- **GROUP P**: Group of relays with low acceptable CRS value, i.e., small contact resistance variability.
- **GROUP F**: Group of relays with high CRS value, i.e., excessive contact resistance variability.

A high CRS value might indicate a higher probability of early life failures. As a reference, high-quality contacts will show very repeatable measurements, typically CRS will be around 1 to 2 milliohms for a nominal contact resistance of 50 milliohms.

In the test performed on the thermal relays, the limit between the CRS value that determined if a relay belonged to group P or group F was set to 3 milliohms, considering the relay had a nominal contact resistance of 70 milliohms. With this limit, the number of relays in group P was 16 and only 4 relays were in the failure F group.

Apparatus and test setup in the CRS test were the same as those used for the life test described in section 5.2.

With the two populations of relays, group P and group F, an accelerated life test was carried out following the experimental conditions explained in 5.2 but with 40V in the supply source. The goal was to check whether the CRS test was actually able to predict early failures and that relays in group F, i.e., the ones that did not passed the CRS test, clearly showed less lifespan compared to the relays in group P.
6 Results and Discussion

6.1 Arc duration and arc voltage tests

In these tests, the mutual effect of arc duration, arc voltage, current levels and connected load among each other was examined. One of the most representative arc voltage characteristics on break operation for a resistive circuit is shown in Figure 38.

![Figure 38: Arc voltage characteristics for the EM relay with diode with resistive load for different current levels](image)

In resistive loads, the arc voltage was always close to the supplied voltage with no voltage spikes, i.e., arc extinction voltage was close to the supplied voltage and only metallic phase of arc occurred.

However, when load became inductive, inductive kickback effect occurred. Theoretical explanation of this effect can be found in section 3.2 of the report. It is possible to see the spikes caused by the inductive load during the breaking operation in Figure 39. These voltage spikes extended the arc duration and allowed gaseous phase development in the arc.

![Figure 39: Arc voltage characteristics for the EM relay with diode with inductive load for different current levels](image)
High current emphasized this phenomena as can also be seen in Figure 38 and 39. It was found that arc duration was considerably longer with inductive loads when compared with the resistive case. When dealing with inductive loads the arc was dominated by the gaseous phase that depends basically on the breaking current. However, other facts might influence the arc duration in resistors, such as the contact materials or the relay working principle. In inductive circuits, the long gaseous phase masked the effect of materials or other factors that could be appreciated in resistive circuits.

In Figure 40 shows different voltage arc variations for different current levels, switching three different inductive loads in each level. The inductance influence was one of the key points of this study, as we were dealing with relays in automotive applications where inductive components are often found.

![Figure 40 Voltage variation for different breaking currents and different inductance levels](image)

The arc voltage was found to be enhanced with the increasing inductance and therefore the gaseous phase was developed leading to longer arc duration. In the graphs it can also be noticed that the higher the inductance level, the higher the peak voltage of the spike.

In Figure 41 the parallel curves show the influence of inductance in arc duration for different current levels.

![Figure 41 The influence of inductance in arc duration for different current levels](image)
6.2 Speed and bouncing test

It is understandable that the opening speed of the electric contacts in a relay will influence the arc and its duration. The lower the opening speed, the higher the arc duration but the less the intensity of the arc. Therefore, at low opening speeds the arcs are long and the contacts have to withstand this harmful phenomenon for a longer time. However, according to literature, [13], at speeds lower than few cm/s, arc voltage remains close to the metallic phase value and the current follows an exponential smooth decrease. Thus, even in the case of inductive loads being switched, as the current does not experience a sudden decrease, there is not a strong inductive effect. When the speed is increased, the arc voltage shape is modified by a high voltage spike during the gaseous phase, especially when kickback effect occurs, i.e. fast current interruption in inductance loads.

The aim of this test was to measure the opening speed and the closing speed profiles of the contacts. With this measure, it would be possible to obtain the displacement profile and check whether or not the movable contact is bouncing. The main device used for this test was a laser, capable of measuring vibrations. The question was whether it was possible to use it to obtain the speed profile of the contacts when they opened or closed.

However, limitations were obvious. The electric contact areas in relays for automotive applications were not big enough. Surfaces close to 2 mm² that open and close at relatively high speeds were some of the main limitations that caused this test to be unrealizable. As the result of the tests were not satisfactory, only one example will be shown in Figure 42 and 43.

![Figure 42 Laser measurements at closing operation](image)
The previous graphs correspond to the opening and closing operations of an electromechanical relay. The gap between the contacts was approximately 3 mm so the final displacement at the end of each operation must be around 3 mm, and it is clearly much higher in the graphs. Therefore, it was possible to conclude that this laser device is not adequate for this kind of measurement.

An alternative to the laser is a high speed camera. With this type of camera it is possible to record the arc and obtain a much more accurate picture of the electric arc between the contacts. However, this experiment is out of the scope of this thesis and is left for future work in the topic.

It is important to underline the difficulties that both the laser and the high speed camera involve. In both cases, it must be possible to access the contacts, either with the beam or with the lens of the camera. This can cause problems when the contacts are sealed, as accessing them could modify their behaviour or even destroy the relay.

![Graphs showing laser measurements at opening operation](image)

*Figure 43 Laser measurements at opening operation*

![Graph showing output voltage signal of the photodiode](image)

*Figure 44 Output voltage signal of the photodiode*
Finally, other device used to measure arc duration and arc intensity was the photodiode. With the result obtained with this device, it was possible to compare different arcs from switching different loads and to analyse which one is more intense. In Figure 44 it is possible to see the output signal of the photodiode in yellow and the arc voltage in blue. Therefore, the conclusion was that this device is suitable for measuring arc duration. However, there is an important obstacle to take care of: it must be possible to access the contacts and place the diode precisely next to them to obtain accurate results.

Due to the possible inaccuracy of the measurements taken with the photodiode, no data of the arc intensity were recorded. However, several captures of the output signal given by the photo-sensor were taken. It was observed that clearly inductive loads generated more intense arcs when they were switched compared with resistive loads. In Figure 45 and 46 it is possible to see this phenomenon.

A suggested future work is to link the output voltage signal of the photodiode to the actual value of light intensity of the arc and record the numerical data. All the measurements must be taken with the diode in exactly the same position.
6.3 Life length test

In this test the relays were tested until they stopped working. Contact resistance and arc duration were measured several times during the test. The purpose of these two measurements was to have a better understanding of the failure mechanism of the tested relay. As explained in the previous chapter, only the thermal protection relay was tested here.

The baseline case for this test was the nominal voltage in the truck battery, i.e., 28V. Then, different scenarios were simulated by increasing the supplied voltage. This way the test was accelerated and a quick failure was obtained so the time needed to perform the test was decreased.

The relays were tested to failure in all scenarios. In the first graph, the cycles to failure are shown according to the different supply voltages, for the four tested loads.

It can be appreciated in Figure 47 that the number of cycles for voltages levels up to 31-32 V was relatively high. However, when the voltage was increased over this level, the number of cycles dropped dramatically. The reason for this was that the thermal relay is designed to work at 28V across the contacts gap. If this voltage was increased, the lifespan of the relay declined significantly.

As it was expected, the number of cycles decreased when the inductance increased. This was caused by the inductive kickback effect that generated high voltage spikes across the contacts damaging them.

Following on from this, the results obtained in the baseline case test (28V) for the contact resistance and the arc duration are shown in Figure 48 and 49.
The contact resistance was not very variable in the early life of the relay. However, when the relay was close to failure, the contact resistance increased severely and the current stopped flowing through the branch of the circuit where the relay was connected.

A considerable difference in the number of cycles can be seen in Figure 48 when the increase in the contact resistance of the golden curve occurred compared with the red one. However, a similar lifespan was expected for these two tested relays as they were switching similar loads. Nevertheless, there was another factor influencing this situation. As explained in chapter 3 and will be studied in detail with the CRS test, high-quality contacts will provide strongly controlled and repeatable contact resistance measurements over many cycles [26]. Looking at the variation of the contact resistance in the golden curve, it was considerably stronger than the variation of the contact resistance of the relay in the red curve during the early life of the relay.

Arc durations profiles are shown in Figure 49, also for different loads. Initially the arc lasted around 500-600 µs. It increased up to 700-900 µs and stabilized in this range until its failure was close to happening. When the contacts were damaged, the performance of the relay started to fall away and the arc duration increased from 1ms to 5-6ms. In the last cycles of the contact, just before welding occurred, extremely long arcs took place. Longer than 100ms arcs were noticed in this thermal relay, like the one shown in Figure 50 (arc voltage variation versus time shown).

Figure 48 Contact resistance variation with number of cycles for different loads

Figure 50 also shows how the relay performance in the last instants of its life was noticeably aggravated. In the case shown, bouncing occurred when the contact closed, creating a huge arc before the contacts closed completely. Later, when the contacts
opened again, another intense and long arc occurred. These long arcs, that took place during the last cycles of the relay’s life, damaged the contacts severely and caused, in most of the cases, the welding of the contact surfaces. They also caused considerable ohmic heating and erosion which increased oxidation and other degradation processes. This explains the contact resistance increase at the end of the relay’s life.

Figure 49 Arc duration variation with number of cycles for different loads

Figure 50 Mediocre performance of one thermal relay seconds before welding
Finally, the Weibull plot for the baseline case, i.e. 28V, was calculated for one of the inductance levels in the experiment, specifically the 3.8mH inductance. The reason for this is explained in the fifth chapter, “Methodology”.

As mentioned, the accuracy of a prediction increases with the number of samples. Specifically it increases in proportion to the square of the number of samples. The main drawback of this result was that the number of relays tested was reduced to 5, so little accuracy was achieved and it is not possible to confirm that the lifespan of this relay when switching a 3.8mH inductive load is equal to the value obtained in the Weibull plot.

The Weibull plot is shown in Figure 51:

![Weibull plot](image)

*Figure 51 Weibull plot*

It can be seen that the obtained life expectancy in this case is 120.370 cycles before failure. This value corresponds to the scale parameter, \( \eta \), of the Weibull distribution or characteristic life that gives the life expectancy at the point where 63.2% of the population has failed (unreliability = 63.2%). The graph is plotted with Matlab® using the equations in section 3.3. The code used can be seen in the Appendix B.

The obtained value for the shape parameter is: \( \beta = 33.96 \). It is related with the failure rate and, as it is greater than 1, it indicates wear-out failures, i.e., increasing failure rate
with time. Finally, all the relays tested in the different scenarios were kept for the next step of the study, material analysis.

6.4 Material analysis

The microstructure of the contacts in the thermal relay was characterized by a light optical microscope (LOM) and some morphologies were characterized by scanning electron microscopy (SEM). In addition, X-Ray scanning was performed on the failed contacts to get an idea of how the contacts looked like before opening them for the LOM and SEM examination.

In the first part of this section, the new contacts are studied. This is be the reference case to understand the tested contacts more fully. To perform this analysis, LOM images of the new contacts were taken and shown in Figure 52, 53, 54 and 55.

![Figure 52 Moving contact in a new relay](image1)

![Figure 53 Fixed contact in a new relay](image2)

![Figure 54 Side view of the contact pair](image3)

![Figure 55 Cross section of the contact pair](image4)

It can be seen that the contacts are silver plated as it was stated in the manufacturer specifications. However, not all the contact pin is silver, but just a thin layer that covers the contact surfaces. This can be seen in the cross section picture, where the main material conforming the contact pair is copper.
Two contacts were tested with GC-MS techniques, one of them previously cleaned with pure toluene. The results found did not show a remarkable difference in the composition of the samples.

Figure 56 shows a representative chromatogram of one of the samples.

The most abundant organic components are:

- A – Unable to determine. Most likely it is the same composite as B
- B - 9-Octadecenamide. With 97% of confidence, represents the 64% of the organic material in the sample.
- C – Methanone. With 99% of confidence, represents the 13% of the organic material in the sample.

Other organic components found were mainly benzoic acids and other types of amides. It must be pointed out that the thermal relay had a small sticker in one of its sides and the organic components detected in this analysis might come from the sticker.

In the appendix the whole data obtained from the GC-MS analysis is given.
The next step was to analyse the contact surface morphology and composition of the tested relays used in the endurance test. The interaction between the arc and the contact pair is a complex phenomenon involving several mechanisms of material erosion and deposition. In addition, surface morphology and composition changes can cause variations in the contact resistance which, as was shown in the life-length test results, it increased with repeated arcing.

An analysis of the contact surfaces topology was done with an X-ray scanning of the contact pair followed by a LOM examination. All the relays used in the life length test were examined with this technologies and most relevant and pertinent results will be presented in this report.

One of the most common failure modes is contact welding, especially at high voltage supply conditions. An example of this failure mode is shown in the following figures. It corresponds to the relay tested at 32V switching an inductive load of 3.4mH.

Figure 57 X-ray image of the contact pair (32V)

Figure 58 Side view of the contact pair (32V)

Figure 59 Fixed contact of the welded relay (32V)

Figure 60 Moving contact of the welded relay (32V)
It can be noticed that in this case the material transfer went from the fixed contact to the moving one. The polarity in the life length test for this relay was set so that the fixed contact was the anode and the moving contact was the cathode. Therefore, the material transfer went from anode to cathode and the dominant phase in the electric arc was the metallic phase.

The weld of the contacts when the supplied voltage was increased became bigger and the contacts damage increased drastically. In the following pictures, Figure 61 to 64, it is possible to see the contacts of the relay that was tested at 40V with the same inductive load as the one shown before and same polarity. The welding spot is approximately 3 times bigger than the welding of the contact tested at 32V.

Another very common failure mode, especially when the supply voltage was low, was contact resistance increase and inability of the relay to make the circuit. In this case, the contacts were considerably damaged and the contact surface had decreased significantly, compared to the initial one, due to high levels of erosion.

In the following images, Figure 65 to 76, it is possible to see several pictures of this failure mechanism for relays tested at 28V connected to different loads with different inductance levels.
It was possible to notice that, as all the cases shown before (from Figure 57 to Figure 76) were connected with the same polarity during the endurance test, the contact that was more damaged was the movable, which corresponds with the cathode.

If the polarity was changed, it was possible to observe that the material transfer was reversed, and went from the moving contact to the fixed one. This comparison can be seen in Figure 77:
Therefore, it is possible to conclude that, in most of the cases, the material transfer went from anode to cathode and so the dominant phase in the electric arc was the metallic phase. However, as previously discussed in chapter 4, with high inductive loads, the material transfer can be reversed due to a dominant gaseous phase in the arc. This had been seen in the case of highest inductive load with the polarity set as: movable contact was the anode (+) and fixed contact was the cathode (-). Figure 78 and Figure 79 show the LOM results.

![Figure 78 Fixed contact – cathode. Tested at 28V 7.1mH](image1)

![Figure 79 Movable contact – anode. Tested at 28V 7.1mH](image2)

The last pictures show a hole in the fixed contact and some material accumulation and sputtered drops in the surface of the movable contact. This means that the material transfer was going from the fixed contact (cathode -) to the movable (anode +). This was attributed to the high inductance used in this test that made the gaseous phase of the arc dominant. As was explained in the electric arcing theory in chapter 4, the material transfer in the gaseous phase goes from cathode to anode.

The last step of the material analysis was the SEM examination of the contacts. The most characteristic observations will be presented for the analysis of the contacts tested at 28V and different levels of inductance. Two different types of images were obtained:

- The BSE images provided information about the distribution of the elements in the samples, as the intensity in the BSE signal is strongly related with the atomic number (Z) of the specimen. Dark parts in BSE images represent light elements, like copper and oxides, while white parts correspond to heavy elements, like silver.

- Secondary Electron Imaging, SEI, revealed details of the sample topography. The SE signal has more difficulty in escaping from holes or porous in the surface and it is detected with less intensity in the detector. Therefore, holes or pores appear as dark parts in the SE images.
The first contact shown was tested with 28V switching an inductive load of 1.4mH. SE images of the whole contacts, both fixed and movable, are shown in Figure 80 and 81:

It was possible to observe a porous structure in the contact area while the rest of the contact surface was non-porous but had some sputtered particles, especially in the fixed contact. Porous structures and sputtered particles can be seen in the following diagram in Figure 82.

The pores became bigger the closer they were to the welding spot. This was caused by the material transfer process during the arc and the erosion that the contacts suffered.

The failure in this contact was obviously the welding of the contact surfaces. The fractured welding was clearly seen in both, the moving and the fixed contact.

BSE images were taken for the same contact. The results are shown in Figure 83 and 84.
As the contact suffered welding, the information given with this analysis was affected by the thermal runaway caused during the welding in the contact materials. However, it was possible to see some silver in the light parts of the images and some copper oxide in the dark part of the image. This observation was confirmed by the spectral analysis as can be noticed in Figure 85. There was considerably more copper detected in the hole created by the welding in the contact area (spectrum 2). However, surrounding the contact area the silver coating is still intact (spectrum 1).

In other contacts, similar results were found. Porous structures in the area of contact were common, where copper and silver particles form some kind of blending, as can be seen in Figure 86. Again, dark particles represent copper oxide (spectrum 1) and light particles represent silver (spectrum 2).
Figure 86 Spectra analysis of copper and silver particles

The increase in copper on the contact surfaces can explain why the contact resistance increased, as copper is more likely to oxidise than silver. Copper oxide film formation caused the contact failure. Another observation in Figure 86 is the different shape of the copper and silver particles. Copper particles had more shape than silver the ones, the later having a more rounded shape.
Following on from this, other examples of damaged eroded contacts were studied. They did not present welding but the contacts were damaged and experienced a severe high contact resistance increase (Figure 87 to 94).

The contacts were eroded, the silver coating was removed and the copper material came out, increasing the contact resistance and forming oxide layers. Dark parts in the BSE images show, once again, copper surfaces where erosion was strong and silver coating disappeared.

One interesting sample was the relay tested with the higher inductive load. As observed in the LOM analysis, peculiar bubbles were formed in the movable contact. Let us turn our attention to the SEM analysis of this sample.

A strong contrast was not observed in the BSE images, Figure 93 and 94, which means that the silver coating was still in the contact. Neither was an oxide film formation observed. The contact failed due to an increase in the contact resistance. This increase was caused because the contact surfaces were severely eroded and the bubbles on them created a reduced contact area. The dark particles represent iron based elements that come from the cutting when opening the relay for its analysis.
The different results concerning the polarity used in the life-length test are explained with the SEM images. As previously discussed, the polarity chosen for the relay tests determined the material transfer between the contacts, being the most common case to observe the material traveling from anode to cathode, with a dominant metallic phase in the electric arc.

<table>
<thead>
<tr>
<th>LOM Fixed Contact</th>
<th>SEM Fixed Contact</th>
<th>LOM Movable Contact</th>
<th>SEM Movable Contact</th>
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<tbody>
<tr>
<td>Polarity I – Fixed contact = Anode + ; Movable contact = Cathode -</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><img src="image1" alt="LOM Fixed Contact" /></td>
<td><img src="image2" alt="SEM Fixed Contact" /></td>
<td><img src="image3" alt="LOM Movable Contact" /></td>
<td><img src="image4" alt="SEM Movable Contact" /></td>
</tr>
<tr>
<td>Polarity II – Fixed contact = Cathode - ; Movable contact = Anode +</td>
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<td><img src="image7" alt="LOM Movable Contact" /></td>
<td><img src="image8" alt="SEM Movable Contact" /></td>
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</tbody>
</table>

From Table 3 it can be inferred that the material transfer travelled towards the cathode. This was the case in most situations, with just one exception at the highest inductance level. In that sample, the material transfer was reversed due to the electric arc gaseous phase.

In the first polarity case, the microstructures observed in the contact areas presented a blending aspect as was shown in Figure 86 or Figure 95. As before, light particles represent silver and dark particles are copper based.

![Figure 95 Microstructure of the contact area. Polarity I](image9)
Also porous structures were observed in the contacts, Figure 96, with higher percentage of copper found in the pores.

However, the microstructures observed when the polarity was reversed were slightly different. Porous structures were again common but this time the porous were filled with silver, as it can be seen in Figure 97. The microstructure looked like a copper matrix with silver particles in the pores. A possible explanation might be that the silver coating was traveling during the arc to the porous contact filling the pores. Another important characteristic that was observed is that the percentage of oxygen in the welding (spectrum 3) was higher. This can be explained as oxidation is a function of temperature and the welding material experienced high temperatures and thus, high oxidation.
Finally, a cross section of a welded contact is presented. The porous structures could be appreciated even inside the weld, in the movable contact (cathode). In addition, the silver in the cathode was displaced and there was a high percentage of copper on it. However, as expected, the anode was almost intact, showing no damage.

The following pictures show the SEM and LOM images:

Figure 98 SEM pictures. Welding cross section. Tested at 40V, 3.8mH

Figure 99 LOM picture. Welding cross section. Tested at 40V, 3.8mH
6.5 CRS test results

The CRS test was performed as was explained in the methodology section in chapter 5 to a population of 20 relays. The failure rate obtained was **4/20 or 20%**, i.e., 4 relays did not pass the CRS test and belonged to the F group. The rest of the sample, i.e., 16 relays, belonged to group P. As a reminder, the CRS value is the difference between the maximum and minimum value of contact resistance recorded for each relay and groups P and F are:

- **GROUP P**: Group of relays with low acceptable CRS value, i.e., small contact resistance variability. In this test, **CRS ≤ 3**.
- **GROUP F**: Group of relays with high CRS value, i.e., excessive contact resistance variability. In this test, **CRS > 3**.

With the two populations of relays, group P and group F, an accelerated life test was carried out switching the relays at 40V. The following results were obtained for the number of cycles before failure.

![Figure 100 Contact Resistance Stability test results](image)

Relays with a very low contact resistance variability showed a really high lifespan with 52 mean cycles before failure, MCBF (blue column). From the sample of 20 relays, only 3 relays belonged to this population, i.e. 15%.

As the average contact resistance of the relays was around 70 milliohms, a CRS value up to 3 milliohms was considered acceptable. The group of relays with CRS value in between the range 2-3mΩ was the largest with 13 relays, i.e. the 65%. The MCBF for this group was 37.
The previous two groups represented the P population with an average of:

\[ MCBF_P = 52 \cdot \frac{3}{16} + 37 \cdot \frac{13}{16} = 39.81 \text{ cycles} \]

Finally, the relays that belonged to the F group represented the 20% of the total population. After the life-length test, they showed a value for \( MCBF_F = 15 \text{ cycles} \), considerably lower than the result obtained for the relays in group P.

In conclusion, the CRS test is able to predict early failures as relays in group F, i.e., those that did not passed the CRS test, clearly showed less lifespan compared with the relays in group P.

*Table 4 Contact Resistance Stability test results*

<table>
<thead>
<tr>
<th></th>
<th>GROUP P</th>
<th>GROUP F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Cycles Before Failure (MCBF)</td>
<td>40</td>
<td>15</td>
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</table>
7 Guideline for Checking Reliability of Relays

The final goal of this thesis is to develop a guideline on how to check the reliability of relays. Therefore, here are some recommendations according to the findings of this research project:

- First, measure the contact resistance variability in the early life of the relays in the sample. To do that, follow the methodology in the CRS test.
- Check that the failure rate in the CRS test is acceptably low.
- Cycle the relays that passed the CRS test till failure and predict their life expectancy using a Weibull plot. Use nominal voltage and same or equivalent load in this test.
- Record some measurements of the contact resistance during the life-length test to later help with identifying failure modes.
- Check if the life expectancy of the relays is acceptable for the applications the relays are designed for.
- If the life-expectancy test is very time-consuming, perform some accelerated test methods for the specific tested relay.
- Analyse some of the samples with SEM and LOM techniques to know the expected failure modes of the tested relay.
As it has been stated in this report, guaranteeing reliable electric contacts in automotive applications is essential for the successful operation of a system. Currently, there is little experience on how to perform reliability tests and therefore, the goal of this research project is to develop a guideline with recommendations to assess and check reliability in relays.

Some of the major mechanisms leading to a relay failure are related with arc erosion and material transfer in the plasma developed between the contacts when breaking and making the circuit operations. In addition, the selection of the proper materials and shape of the contacts is crucial to achieve an acceptable life length of a relay.

It has been proved that breaking current and load type, among others, are some of the most significant parameters affecting arc duration and thus, damage of the contact surfaces due to arc erosion and welding. Therefore, they have been chosen to be studied in the first experiments of the present research. The main conclusions were:

- Inductive loads present longer arcs when compared with resistive loads.
- The higher the inductance level, the stronger, more intense and longer the electric arc.
- Inductive loads create voltage spikes across the relay’s terminals when the current is interrupted.
- Resistive loads do not present voltage spikes so the arc extinction voltage is close to the supplied voltage.
- The higher the breaking current, the worse for the relay, as it experiences longer arcs.

Another relevant parameter is the opening and closing speed of the contacts and, in general, the displacement of the movable contact in relation to the stationary contact. The study of the displacement of the movable contact is able to detect bouncing. However, the laser equipment used to perform the speed measurements showed to be not suitable for this test. The proposed suggestion is to use a High Speed Camera with a high rate of frames per second, fast enough to capture the electric arc.

After the parametric analysis, the life-expectancy test was carried out. Contact between two surfaces occurs at discrete points. The contact resistance of a relay strongly depends on the number and size of these contact spots. Therefore, it was chosen as an interesting parameter to keep track of during the life-expectancy tests. Moreover, arc duration was also measured. The conclusions drawn from the life-length test of the thermal relay are:
In most cases, the contact resistance increases during the first cycles of the relay’s life. Later on, it decreases again to its nominal value.

When the contacts are close to failure, the contact resistance increases noticeably.

Arc duration is more or less constant during the first half of the relay’s life.

When the relay is close to failure, it experiences long arcs. These arcs increase in duration until the relay fails.

Long arcs involve high arc erosion of the contacts and a large amount of ohmic heat which increase oxidation. This explains the contact resistance increase.

The ohmic heat generated during the long electric arcs can lead to contact welding.

Reliability in relays highly depends on the materials used in the contacts. They must provide the contacts with high electrical and thermal conductivity, high resistance to arc erosion and welding, low vapor pressure and high resistance to the deterioration effects of oxides, sulphides and other compounds that cause insulation. Therefore, analyzing the materials in the tested relays was considered an interested task for this research. The main findings are:

- The studied contacts are made of copper and are silver plated.
- Two groups of contacts were tested, one of them previously cleaned with GC-MS techniques. The results found do not show a significant difference in the composition of the newly cleaned and uncleaned contacts.
- Most common failure modes are contact welding and contact resistance increase due to excess of arc erosion.
- It has been proved that the electric arc involves material transfer between anode and cathode. To analyse mass loss it has to be assessed the net material transfer that corresponds to the balance of metal and gaseous phases where both gain and loss happen either in the cathode or in the anode.
- In most cases, material transfer goes from anode to cathode, so the dominant phase in the electric arc is the metallic phase. In addition, the contact that is generally more damaged is the cathode.
- Only in one case with the highest inductance level has it been possible to see cathodic material transfer, thus, being the gaseous phase of the arc the dominant stage. This is because when switching inductive loads, the arc is stronger and this could lead to the dominant gaseous phase.
- At high voltages, the failure mode is always contact welding.
- Porous structures are observed in the contact area with a mixture of copper and silver particles. These porous structures are also observed inside the material in the welds.
- Silver particles are very rare in welded surfaces.
• There is a high content of copper in the contact surfaces that can explain why the contact resistance increases, as copper is more likely to oxidise than silver and oxide coatings cause insulation.
• The content of oxygen in the welded parts is higher. This can be explained as oxidation increases with temperature and welded material has experienced high temperatures.

Moreover, contact resistance stability has been proved to be a factor capable to determine the quality of a contact and to predict early failures in relays.
Several research lines can be proposed in order to have a deeper knowledge on the reliability of the relays:

- To analyse other parameters that affect relays’ performance, like the contact forces or the open contacts’ gap. It should be taken into account that contacts in automotive applications are in motion and suffer vibrations that can cause fretting and fretting-corrosion. How this motion can affect reliability should be studied.

- Try to measure the opening and closing speeds with a High Speed Camera able to capture the arc. Check how bouncing affects the reliability of relays.

- A suggested future line of work is to link the output voltage signal of the photodiode to the actual value of light intensity of the arc and record the numerical data. All the measurements must be taken with the diode in the exact same position. This way it would be possible to obtain data of the arc intensity of different arcs, in different relays and compare the results.

- Automatize the measurements taken during the life-expectancy test and increase the number of relays in the samples used to predict the lifespan. This way the accuracy of the predictions will be higher.

- In the case of the thermal relay, it would be interesting to consider both polarities in the life-length test and simulate the case of “switching polarity”, i.e., change the polarity of the relay in every opening and closing cycle.

- Simulate different environments during the life-expectancy test according to the relay’s application.

- Investigate about other possibilities in accelerated testing procedures for relays to achieve better connector life predictions.

- Final suggested future work is to develop a general macroscopic electrical contact arc erosion model that will describe the mass loss in the whole breaking process. Later on this model should be validated with the correspondent experimental measurements.


A- Possible solutions for the H-bridge that controls the motor in the power window:

The way the motor is controlled in the power window is based in just a special switch:

To prevent the switch from high currents, two relays could be added between the switch and the motor. In this solution, the switch controls the relays’ coils. It is still cheap but the volume needed increases substantially.
The switch is not subjected to high currents

Simple → No Electric Control Unit, ECU, needed

The bridge could be controlled with four transistors and four diodes. This solution is found in the New Generation of SCANIA trucks due to the incorporation of new functions like the “auto-up”, i.e., the window goes up without the need of holding the “go-up switch”.

In this case, there is a need of current control by means of a control unit that switches ON and OFF the transistors according to the signals given by the window switches and the current flowing through the motor.
## Results from GC-MS analysis

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Methanone, bis[4-(diethylamino)phenyl]- 182540 000090-93-7 99
Glabridin                182412 059870-68-7 59
2,6-Di-tert-butyl-4-(2,4-dimethylphenyl) 182649 203786-39-4 59

C- Code for Weibull distribution plot:

```matlab
% WEIBULL DISTRIBUTION
load('cycles_before_failure.mat')
t=1:1:140000; %Cycles vector, from 1 cycle before
tm=mean(CyclesData); %Mean CFB
sig=std(CyclesData); %Standard deviation

BETA= (sig/tm)^-1.086; %shape parameter-beta
ETA=tm/(gamma(1+1/BETA)); %scale parameter

weibull=(BETA/ETA)*(t/ETA).^(BETA-1).*exp(-(t/ETA).^BETA);

unreliability=1-exp(-(t/ETA).^BETA);

loglog(t,unreliability*100)
axis([60000 150000 1 99.9])
```