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CONSUMABLE COMPONENT LIFETIMES IN PASSENGER IN-
FORMATION SYSTEMS

Master of Science Thesis

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# ABSTRACT

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The majority of failures and maintenance operations of passenger information systems are caused by the so called consumable components – electrical components or modules which have significantly lower expected lifetimes compared to surrounding electronics in a device. This thesis identifies the consumable components and investigates their useful lifetimes within Teleste Corporation's on-board systems portfolio. A better understanding of the required maintenance operations within a passenger information systems' lifetime can be achieved through these approximations. Maintenance and maintainability are becoming more important within the public transport market. Analysis and improvement of maintenance processes are critical in providing efficient support throughout passenger information systems' long lifetime.

# TIIVISTELMÄ

**JANNE PISILÄ**: Kuluvien komponenttien eliniät matkustajainformaatio-järjestelmissä
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Kuluvat komponentit aiheuttavat valtaosan vikatilanteista ja korjaustoimenpiteistä matkustajainformaatiojärjestelmissä. Näiden komponenttien tai moduulien hyödyllinen elinikä on huomattavasti lyhyempi laiteen muuhun elektroniikkaan verrattuna. Tämä tutkielma selvittää kyseiset komponentit ja niiden keskimääräiset eliniät Teleste Information Solutions:in matkustajainformaatiojärjestelmien laittoistoissa. Näin saavutetaan parempi ymmärrys tarvittavista huoltotoimenpiteistä järjestelmän eliniän aikana. Ennakoivien huoltotoimenpiteiden mahdollisuutta tutkitaan. Huollettavuus ja ylläpidettävyys ovat yhä tärkeämpiä kriteerejä julkisen liikenteen markkinoilla. Huoltotoiminnan prosessien tutkinta ja parantaminen ovat kriittisiä matkustajainformaatiojärjestelmien tukitoiminnassa niiden pitkän eliniän aikana.

# PREFACE

The world of public rail transport is an interesting one and full of challenges. Work on passenger information systems bridges several fields of technology and the people managing, developing, and maintaining these systems must have equally varied set of skills. I have learned much during my time at Teleste and I want to express my thanks to all the people who have helped me and provided material for this thesis. Special thanks to management for giving me the opportunity to work on this subject.

The road through university has been long and arduous one. There have been many turns and choices along the way but now I have reached my destination. I want to thank my partner without whom I would not have succeeded. She believed in me during times when I didn't believe in myself. Her help and support have been invaluable in many situations. I also want to thank my parents who saw potential in me and encouraged me to take this path in life. Finally I want to give thanks to my examiner Jukka Vanhala who has given his time and support for this thesis.

This chapter in life is all but done and it is time for a new one…

In Tampere, Finland on 23 October 2018

Janne Pisilä

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# LIST OF SYMBOLS AND ABBREVIATIONS

| | |
|---|---|
| AFR | Annualized failure rate |
| CBM | Condition-based maintenance |
| CCTV | Closed-circuit television |
| CF | CompactFlash |
| ECC | Error correcting code |
| EMI | Electromagnetic interference |
| ERP | Enterprise resource planning |
| GPS | Global positioning system |
| HDD | Hard disk drive |
| LAN | Local area network |
| LCC | Life-cycle cost |
| LED | Light-emitting diode |
| LRU | Line replaceable unit |
| MLC | Multi-level cell |
| eMMC | Embedded MultiMediaCard |
| MTBF | Mean time between failures |
| P/E cycle | Program-erase cycle |
| PIS | Passenger information system |
| PWM | Pulse-width modulation |
| RAID | Redundant array of independent disks |
| Rolling Stock | Vehicles which move on rails (trains, trams and metros). |
| SLC | Single-level cell |
| SSD | Solid-state drive |
| S.M.A.R.T. | Self-Monitoring, Analysis and Reporting Technology |
| SoC | System on a chip |
| SRU | Shop replaceable unit |
| TLC | Triple-level cell |
| QLC | Quad-level cell |

# 1. INTRODUCTION

A Passenger Information System (PIS) is an automated system comprised of number of devices integrated within a public transport vehicle. Its primary purpose is to provide information to passengers on their journey. This is done visually via displays that show route progress and other information and by audio with the use of announcements.

Reliability and high degree of availability are essential in Passenger Information Systems (PIS). A system must often operate long periods of time uninterrupted with minimal oversight. The entire system must be designed to have high degree of automation, robustness, and reliability. Availability figures and required maintenance and repair operations are an important consideration for both the system supplier and the customer who has ordered the system. Failures increase the system running cost, require corrective actions, and leave passengers with negative impressions.

While devices within a PIS are designed with reliability and availability in mind, failures do still occur. Failures can be intrinsic or caused by age. Intrinsic failures do not directly correlate with the age or utilization of a device. As an example on intrinsic failures, an electrical component is lower intrinsic quality than specified and fails at a random point during a device's lifetime. The failure rate of such component remains constant over its useful life period.

Contrary to intrinsic failures, wear in certain components causes devices to fail more often with age. This work focuses on the latter type. In fact, random failures are fairly rare and amount only to a small portion of all repair actions – most failures are caused by aging and wear of consumable components. These components, such as hard drives, naturally get worn out over time, and the system requires periodic maintenance so that they can be replaced with new ones.

This thesis identifies and presents consumable components used in PIS device portfolio including CCTV and aims to estimate their useful lifetimes. Mechanisms and contributing reasons leading to degradation are investigated in detail. Different maintenance concepts are presented which are used or could be used in PIS maintenance. Analysis is done on potential benefits and disadvantages that each concept would bring forth.

This work is based on passenger information systems designed and manufactured by Teleste Corporation and its subsidiaries. These information systems are aimed specifically for the railway industry to be used in rail transport vehicles, also known as rolling stock (consisting of trains, trams and metros). Sometimes the term passenger information

system is used to describe both on-board and stationary systems. However, the scope of this work includes only the former types, and considers them to be synonymous with PIS.

Additionally, this thesis focuses only on hardware related issues. Failures caused by software issues, such as programming errors or corruption are thus outside the scope of this work. If a software issue is caused by an underlying hardware fault, as could be the case with mass memory, then it is considered a hardware failure.

# 2. PASSENGER INFORMATION SYSTEM

A Passenger Information System is an interconnected system of devices installed within a rail transport vehicle with the primary purpose of providing information to passengers about the state of their journey. At the forefront of PIS are its displays; outside displays tell passengers where the vehicle is going and inside ones inform them of current or upcoming station. The system can also include functionality that is not immediately visible to passengers, such as video surveillance. PIS is modular by design and can be configured to suit the customer's needs. The system can be either delivered and installed while a vehicle is being built or it can be retrofitted into an older vehicle which is being overhauled.

This chapter provides introductory context on what a passenger information system is, how it works, and how its operation ties to failure cases. Finally, the main devices of interest are introduced which will be the main subject for the rest of this work.

## 2.1 Functionality

The structure of a PIS can roughly be divided into subsystems. This chapter covers a typical feature-rich configuration for completeness sake, as seen in Figure 1. Systems are often tailored as per customer requirements and may have more or less features than presented here.
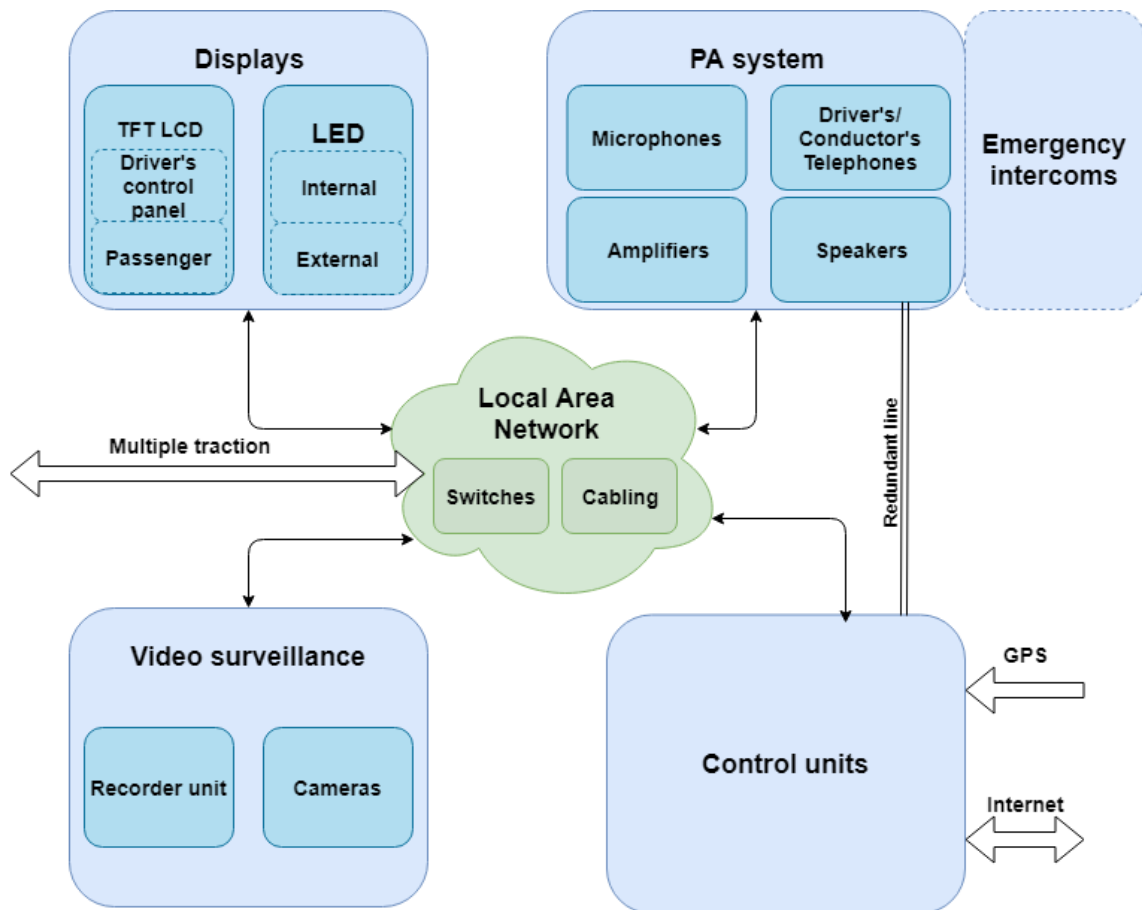
***Figure 1.*** *Structure of a typical passenger information system.*

The above example system includes the following groups:

- **Control units**

  Control units is the comprehensive term for all rack-mounted plug-in units. The system always includes a main control unit which can be accompanied by other, more specialized units. The main unit controls all other sub-systems to at least some extent. It holds route information in its database and updates displays with relevant information as needed via the local area network. Current position and speed of a vehicle is received from Global Positioning System (GPS) or additionally from odometer value. Internet connection enables connectivity with outside systems.

- **Video surveillance**

  Video Surveillance subsystem is comprised of number of IP cameras and a recorder unit or units. Cameras can be situated inside and outside the vehicle: inside for surveillance and safety and outside to provide better situational awareness to the driver. They can also provide evidence in case of an accident. Cameras record video footage that is routed through the network into a recorder which then stores the data in its mass storage. Recording can either be constant or it can be triggered

by an external signal. A system can include just one recorder or several. The choice depends on the amount of cameras, desired storage capacity, and possible need for redundancy.

- **Displays**
Displays form the primary interface between the system and passengers. They are usually the first and most important source of information to a passenger. Displays come in many shapes and sizes and can be situated inside a vehicle and on its exterior walls. LED-displays are designed to provide good visibility and contrast and are capable of displaying text and simple shapes. A common place to see an LED-display is at the front of a vehicle, where it shows the vehicle's destination [16].

    LCD-displays are capable of outputting more complex information. They can show all the stops along the journey, and can also be used for entertainment and advertisement purposes [17].

    The driver has his own display or set of displays for controlling and monitoring the system. Control panels have a touch screen for easy navigation that the driver can use to select and initiate a route, perform announcements and view system diagnostics to name a few functions. Vehicles typically have control panels at both ends, with an option to select an active cabin depending on which direction the vehicle is being driven.

- **Public Announcement (PA) system**
Announcements can either be automatic originating from the control unit and based on current route and location, triggered pre-defined, or free announcements performed by the driver or conductors. In all cases the signals are fed to an amplifier which then produces an announcement through loudspeakers.

    The description of PA system presented here is a simplified one. Audio systems can contain variety of functions based on system specifications, such as automatic ambient noise cancellation or use of digital input and output signals. A door being closed can be signaled to PIS which will then automatically play a warning sound through loudspeakers, as an example.

- **Emergency intercoms**
A PIS can also include emergency intercoms available to passengers. Activating an emergency call alerts the crew, who can then accept the call to open up a two-way communication with the person in need. Implementation of emergency communication differs between systems. Typically a driver can see the emergency call

on his control panel accompanied with an active camera view. He or any other of the vehicle's crew can answer the call.

- **Network**
  All the devices in a system are interconnected through the local area network. Data traffic routing is done by switches which form the backbone of the network. Other transfer protocols can be used for redundancy, such as serial communication, in case the main network experiences a failure. Multiple traction means connecting two or more trains together. The separate LANs will be able to communicate with each other – as an example a call from one train to another would be possible.

## 2.2 Operation

An on-board passenger information system is a mostly automated system and requires minimal input from the train crew. It is typically controlled via a driver's control panel located in a vehicle's cabin. The driver begins a journey by selecting the desired route and the rest are performed automatically. The system resolves its position and velocity from GPS or odometer value. The system's control unit will compare its location with the selected route and when it detects that the vehicle is arriving at a station it will automatically display configured information on displays and perform announcements. Either GPS or an external feed is used to get the vehicle's speed, which is used to estimate the travel time to next station. The system can inform the driver automatically when the vehicle is behind schedule and by how much. If there are tunnels on route or known fringe areas with weak signal strength, odometer data can be used as a supplement to keep track of distance travelled.

Train crew can address the passengers with vocal announcements using a driver's or conductor's microphone or telephone. The driver can also manually play prerecorded announcements using the control panel. In emergency situations passengers can use the emergency intercoms to open a two-way communication with the train crew.

A passenger information system remains in a stand-by mode as long as the vehicle is powered. Some redundancy methods can be employed to keep the system operational over long periods of time and in case of unexpected faults. The network can be arranged in a ring so that a break at any point doesn't disrupt communication. Voice communication utilizes a redundant communication line as per the UIC-568 standard [14]. In case of a network failure the vehicle crew is still able address the passengers because announcements are routed via the UIC-line.

PIS can be interfaced with other train systems as needed. Most commonly the control unit maintains a connection to a central server that logs the status of all vehicles in a fleet. Other way around, external signals can be fed to PIS. For example, doors being closed

can be signaled to PIS which can then play a warning sound through loudspeakers. Outside systems can also be interfaced, such as passenger counting, which could be monitored and controlled using the driver's control panel.

## 2.3   Contributing reasons for failures

The environment onboard rolling stock is challenging for electronics. Movement causes a constant vibration along the vehicle's chassis and gaps and bumps on rails transfer shock to equipment. Vibration is a concern for mechanical design as it can loosen screws and connectors over time. Shock is a more relevant issue for this thesis and is investigated in chapter 4 in the context of hard drives.

While vehicles are often air conditioned, they are still far from a precisely climate controlled environments and there are variations in ambient temperatures. This is especially prevalent on the outside walls of a vehicle where temperatures can vary wildly. Ambient temperature has a direct correlation with the internal temperature of electronic components and higher temperatures have a negative impact on the components overall lifetime [30]. Additionally, a large repeating temperature variation can induce fatigue in components [26]. Control units and network switches are compartmentalized and hidden away from passenger's reach within the vehicles structure. There can be other devices not related to PIS accompanying as well depending on the vehicle construction, and these areas may or may not be ventilated.

There are other challenges as well. High voltage cabling might be routed adjacent to network and low voltage lines which can induce interference. Ground potential in rail networks often has interference leading to grounding issues [29]. Electromagnetic Interference (EMI) is another major issue. Rail vehicles have a lot of high voltage and high power equipment that produce electromagnetic radiation. Displays in particular are prone to interference, because they have a lot of low-tolerance data lanes.

In the end, the issues presented here are challenges for product design, and do not directly cause increased aging or wear. Interferences in voltage supply can be filtered in power supplies, and inductive interference can be mitigated by device chassis shielding and grounding.

## 2.4   Devices of interest

Chapter 2 so far has been an introduction to a passenger information system, its subsystems, and devices. This thesis focuses on consumable electronic components that must be replaced often. Not all devices have such components and thus require no further attention. The following subsections list the devices that are of interest because they require maintenance due to their consumable components. This thesis is based on passenger in-

formation systems designed by the Teleste Corporation, and the following sections provide brief descriptions of each device family and the individual characteristics of each device within.

### 2.4.1 Main control unit

In its current role there are three distinct generations of control unit. The first two generations cover the majority of systems currently in use. Mechanically control units are rack-mounted plug-in units. They use a solid-state drive (SSD) for operating system and general storage in various capacities. Two brands of SSDs have been used and the current brand in use has been updated several times with newer models. The latest generation sees a shift to system on a chip (SoC) implementation that uses an integrated eMMC flash.

### 2.4.2 Recorder

Recorder units are made in two different models which include essentially the same hardware; as a plug-in unit and as a unit with its own enclosure. There are three generations of design with the first two being used in majority of current systems similarly to control units. Recorders use either one or two solid-state drives, one or two hard disk drives, and can include additional compact flash for operating system and video recorder software. SSD models have been updated several times over the recorders' development and are used in various capacities. For hard drives several brands have been used, also in different capacities. Hard disk drives offer larger storage capacities at lower cost per gigabyte. However, they are not quite as reliable as solid-state drives and require shock dampening mounting. Differences between HDDs and SSDs are covered in more detail in chapter 4.

### 2.4.3 LED-displays

The LED-display catalog includes over 30 unique display models. Displays vary in terms of size and LED pitch, from large front displays situated at the front of a vehicle, to smaller internal displays. LED displays include a power supply and relatively simple control logic board which processes incoming messages from the control unit. In terms of long-term reliability the only susceptible parts in LED-displays are the LED-modules themselves. Because displays are available in several different resolutions and with different LED pitches (distance between individual LEDs), several different LED-modules exist as a result. Luckily the same type of LED is used in most displays allowing analysis of only that particular type of LED to be sufficient.

### 2.4.4 TFT-LCD-displays

TFT-LCD-displays also come in various shapes and sizes. Contrary to LEDs, different sizes and aspect ratios necessitate the use of many different types of LCD-panels. In terms

of this thesis the situation is helped somewhat because some  displays share the same type of panel, and certain models are manufactured in large numbers relative to others. Additionally older models which are now obsolete can be excluded from the study. Spare parts for these models are no longer available and therefore repairing them is not possible. Performing analysis on obsolete units offers little benefit as they are not available anymore and their number in the field is diminishing.

The main interest of TFT displays is the backlight and how its brightness depreciates over time. Mechanically the backlight and LCD-panel come in one package. Nearly all newer models use LED backlighting while cold-cathode fluorescent lamps (CCFL) together with inverter boards were used in a number of older models. Because CCFL backlighting has essentially become obsolete by now it is not included in this thesis.

Driving an LCD display is computationally a fairly intensive task and in practice requires an operating system. For this purpose TFTs use a small capacity flash memory for OS and other necessary software. Depending on the display model the flash memory is either detachable, and thus replaceable, or integrated on SoC solution.

# 3.  MAINTENANCE CONCEPTS AND PLANNING

The useful lifetime of a passenger information system is fairly long, around 15 years or even longer, after which the system becomes obsolete and is no longer worthwhile or even possible to maintain. Maintenance actions incur a significant cost during the system's lifetime; none of the components investigated in this work can feasibly operate fault-free for a system's entire duration, and that is not including other intrinsic failures that are to be expected. In the past many customers were satisfied that operational support and repair services were available. However, more recently rolling stock manufacturers and railway operators have become more demanding.

Many customers are calculating the Total Cost of Ownership (TCO) which includes the direct and indirect costs of a product. In the context of passenger information systems the cost structure is comprised of initial purchase and installation costs, operational and maintenance costs, and possible extension or retrofit costs [4]. TCO has a direct link to maintenance and upkeep as potential customers demand reliability statistics and cost estimates caused by maintenance. Therefore developing and analyzing maintenance has benefits already in the sales phase.

Another fairly recent development in sales is a demand for a Life-Cycle Cost (LCC) guarantee by a potential customer. LCC guarantee is essentially a promise by the supplier that a system's cost including upkeep will not exceed a set sum. Providing such a guarantee would require careful consideration on how often maintenance is required, how much it costs and how the cost is incurred, and how maintenance actions are carried out in practice.

Devices in a passenger information system can be categorized as being either Line Replaceable Units (LRU) or Shop Replaceable Units (SRU). LRUs are modular units which can be quickly replaced with a new one and the replacement can be done by a person with minimal training. SRUs on the other hand require qualified technicians and the work must be performed at an appropriate workshop. Technically most devices in a PIS are considered as LRU; they can be removed and replaced as single units, though some may take longer than others depending on the difficulty of installation.

The same categorization can be extended to internal components as well. Most components are regarded as SRUs; their replacement requires expertise and opening the device enclosure exposes the internal electronics to electrostatic discharge. However, some components could be considered as LRUs. An example in the context of consumable components would be hard drives in some devices. Such components would allow more specialized maintenance to be performed on-site by a customer. Normally customers have a

small number of devices as spare parts. When a failure occurs the defective part is replaced with one from the spare stock, and then sent for repairs. LRU components would reduce the reliance on spare devices and allow for more efficient upkeep as only the failed component could be replaced. This would avoid the need to send an entire device for repairs.

Several different concepts exist on how to perform maintenance. The following subchapters describe concepts that are used or could potentially be employed in maintaining passenger information systems. The benefits, disadvantages, and practical challenges of each are presented and considered.

## 3.1 Corrective maintenance

Corrective maintenance is the most basic and most common type of maintenance performed. Essentially corrective maintenance means rectifying a fault so that normal operating condition can be resumed [32]. A fault could be anything from software bugs to human error, but in the context of this work device level hardware failures are of interest. Figure 2 illustrates the process of corrective maintenance as performed by customer's technicians.
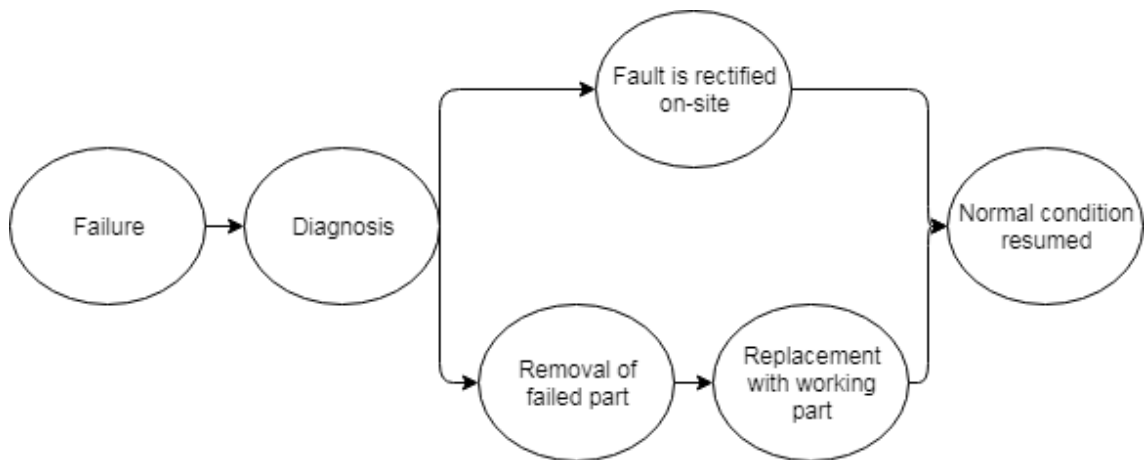


*Figure 2. Corrective maintenance performed by customer.*

Customer's maintenance personnel are trained in installation procedures and basic fault finding. Sometimes the diagnoses can be vague, incorrect, or missing entirely. In some cases a fault can be corrected without having to replace a failed part or a device, either by the customer themselves, or with remote or on-site support. Actual corrective repair, shown in Figure 3, is performed by qualified technicians. Any repair attempts or other tampering by customer or other parties is not permitted, unless otherwise explicitly allowed.

*Figure 3.* *Corrective repair performed on a failed device.*

Corrective maintenance is the most common type of maintenance performed by Teleste's PIS service department and its partners. It is a simple process to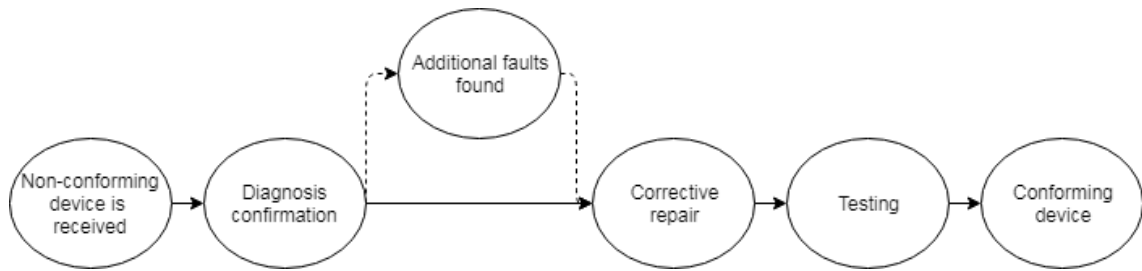 execute: failed devices are sent for repairs which are then sent back once they have been repaired. In many cases corrective maintenance is the only feasible method to use. Such cases are correcting intrinsic failures or repairing devices which have very low failure rates and are essentially maintenance free.

Despite its dominance and simplicity, corrective maintenance does have several downsides. It does little to improve overall reliability of a device as it waits for failures to happen. It has a fairly long lead time between a failure and return of working device. Additionally freight costs make up a large portion of total costs. Often single devices are sent for repairs and then back again.

## 3.2    Preventive maintenance

While corrective maintenance is purely a reactive approach, preventive maintenance is a proactive approach to maintenance, aiming to reduce the amount of failures by replacing components before they fail [33]. Preventive maintenance requires at least rudimentary knowledge on the reliability and expected lifetimes of components to be successful. Too frequent replacement rate would increase maintenance costs significantly and not take full advantage of component reliability, while too long periods would not notably reduce the need for corrective maintenance. It is important to note that preventive maintenance does not eliminate the need for corrective maintenance. Intrinsic failures, and other failures that do not correlate with age and wear will still require corrective actions.

In some other industries preventive maintenance is seen as a periodic maintenance and upkeep aiming to keep equipment in working condition and to increase their useful lifetimes. Passenger information systems are maintenance free in a sense that they do not require adjustment or mending. Preventive maintenance could be used to replace components before they reach their wear-out periods or fail to perform their intended function.

A major problem with purely corrective maintenance model is that it waits for failures to happen, which will inevitably happen while a vehicle is on route carrying passengers. This is of course undesirable. Preventive maintenance would not completely eliminate this from happening but it would significantly reduce the likelihood. Periodic overhauling

of consumable components would keep them in their prime working condition eliminating any failures caused by wear-out.

Preventive maintenance does have some drawbacks and practical challenges. Because components would overall be replaced more often compared to purely corrective maintenance failures caused infant mortality would be increased (refer to Figure 8). To combat this comprehensive burn-in of new components and testing would need to be employed. Preventive maintenance might be a difficult concept to sell to customers. More frequent replacement rate of components would increase material and labor costs, while the benefits of increased availability and customer satisfaction would not clearly translate to savings.

Carrying out preventive maintenance would be logistically challenging. Overhauling an entire fleet of vehicles at once would not be feasible, so the action would need to be carried out one or a few vehicle at a time depending on available resources [18]. New vehicles are typically delivered to end customer as they are coming out of the production lines which means that their commissioning dates can be used as a reference point in determining when to perform maintenance. Spare part stock could be used as a buffer when performing the overhaul; fresh devices are installed from the spare stock while old ones will be refurbished and then returned to spare stock. Displays present a dilemma however. A single coach typically has several displays and an entire train might have dozens. Maintaining spare stock large enough to overhaul an entire train ties a large amount of capital which might not be feasible. Overhauling would also severely deplete the stock leaving other units vulnerable in failure cases.

Preventive maintenance also presents a contractual difficulty with new fleets. As an example, the Sm5 trains in Helsinki commuter rail network are manufactured by Stadler, while Pääkaupunkiseudun junakalusto Oy is the end customer and VR the operator of the vehicles [6]. Stadler maintains the vehicles during their warranty periods, after which the responsibility is transferred to VR, unless some other party is contracted for maintenance. Stadler is likely not interested partaking in long-term maintenance actions since their period of responsibility over the trains is relatively brief. By the time a train's warranty runs out the PIS system would likely need maintenance, immediately presenting VR with a large expense.

Preventive maintenance also fits poorly with the concept of LCC guarantee. A guarantee would be calculated based on existing reliability statistics. Periodic overhauling would not fit into this model as it would alter the reliability of a device if employed. Many of the preventive maintenance benefits do not directly translate to monetary savings even if an accurate LCC with could be given.

## 3.3   Predictive maintenance

Preventive maintenance has a disadvantage in that the maintenance is determined by some pre-calculated criteria, and also might be adjusted to coincide with other maintenance actions. This method is fundamentally inflexible as it is unable to determine the actual condition of a component or equipment which might still have useful life left. Predictive maintenance employs periodic checks or tests to determine the condition of a component or piece of equipment [13]. If the condition is determined to be sufficiently deteriorated a corrective repair action can be scheduled. Predictive maintenance offers superior accuracy compared to its preventive counterpart because of the aforementioned continuous monitoring. This should in theory translate to cost savings as close to maximum amount of life can be extracted from components, reducing any "wastefulness" present in preventive maintenance. On the other hand it requires some extra labor to perform these checks.

In order to work predictive maintenance requires some kind of tools, routines, or techniques for condition measurement. In the context of passenger information systems this would be fairly simple: most storage drives employ Self-Monitoring, Analysis and Reporting Technology (S.M.A.R.T) which collects diagnostic data on the drive. S.M.A.R.T. data monitoring could be used to determine mass storage health, and brightness measurement could be used to determine LED and LCD display brightness. In practice however, both methods present some difficulties. S.M.A.R.T. data is not entirely accurate and it is difficult to determine a point of failure based on the multitude of parameters available [11][25]. It is also rather useless in predicting catastrophic failures. More on S.M.A.R.T. data is presented in chapter 4.1. Measuring display brightness is a rather over scaled method. Additionally measuring brightness is a rather complicated task as it is affected by several variables, such as ambient luminance, distance to source, and angle of measurement. In practice predictive maintenance could be carried out by periodically checking S.M.A.R.T. data in hard drive for critical parameters described in chapter 4.1, and visually inspecting the brightness of displays, possibly doing a subjective comparison to a new display if possible. If infant mortality could be sufficiently reduced it would not be necessary to immediately begin the checks after new equipment has been installed. Displays in particular have effective lifetimes of several years, thus inspecting their brightness would be quite redundant for the first few years. On the other hand performing such efficient checking would become logistically quite challenging. A rolling stock fleet likely has vehicles of different age and after few years the passenger information systems onboard will have a mix of old and refurbished devices due to experienced failures.

A refinement of predictive maintenance, Condition-Based Maintenance (CBM) automates the periodic checks. In CBM, sensors and software components are employed to monitor device condition. These will then provide automatic fault reporting when device or component condition has degraded past a predefined point. CBM provides superior

accuracy compared to preventive or predictive maintenance, as it provides the information exactly when the need arises. This allows for the maximum amount of life to be extracted from components while minimizing failures caused by degradation. [12]

As a downside CBM causes an increase in costs. Implementing the required sensing capability into devices requires product development and software work. The extra logic needed increases material costs. Additionally, any sensors and software must be highly reliable as they need to outlast the components they are monitoring. This presents some practical challenges. As an example, S.M.A.R.T. data monitoring could work as a fairly straightforward method in analyzing hard drive health. However, it would be dependent on host operating system and be susceptible for software corruption. Analysis on whether or not CBM would be beneficial in PIS applications is a complicated issue. The increased product cost would need to be weighed against the benefits of increased reliability and improved maintenance, while being mindful of potential challenges on the way, such as the CBM itself requiring maintenance. All of this would need to be included already when strategies for new products are being developed.

# 4. CONSUMABLE COMPONENTS OVERWIEV

The following subsections present the consumable components that are found in a passenger information systems. These components are the main interest for long term maintenance planning. This chapter provides a description for each component type, defines conditions when a component can be deemed as failed, and explains the causes behind aging process.

## 4.1 Mass memory

*Description:*

Mass memory refers to a permanent data storage medium. Mass memory is typically used to house an operating system and any other data required or produced by a device. Both types of technologies, solid-state drives and spinning disk hard drives, are used in PIS applications. However, hard drives are used exclusively by video recorders.

Solid-state drives (SSD) are used in both 2.5" and CompactFlash (CF) form factors in varying capacities. SSDs are manufactured with two different internal structures: as Single-Level Cell (SLC) and Multi-Level Cell (MLC) NAND flash. SLC flash is capable of storing only a single bit per memory element, whereas MLC is capable of storing two or more bits. Because SLC flash has lower data density it is more expensive to produce and is used only in low-capacity memory modules. Conversely MLC flash is cheaper and is found in higher-capacity drives [25].

Solid-state drives have several advantages over hard drives but also some disadvantages. SSDs have no moving parts; individual bits are represented by NAND cell state. SLC NAND has two voltage levels, corresponding to '0' and '1', while MLC NAND has several voltage levels allowing for single cell to represent two or more bits. NAND flash that can store three bits per cell is sometimes called Triple-Level Cell (TLC), and 4 bits per cell is called Quad-Level Cell (QLC). However, the term MLC often encompasses these types and end-user might not know if MLC flash actually uses TLC or QLC technology. [15][25]

A large number of cells grouped in a grid forms a block. A block has a certain amount of pages, the smallest unit which can be read. A single page cannot be erased, instead an entire block has to be erased at once. This is known as a Program-Erase (PE) cycle. The size of pages and number of pages in a block varies between drive models. Typical page sizes are between 2KB and 16KB, and usual amount of pages in a block are either 128, 256 or 512. Given these values block size varies between 256KB and 8MB. [15]

SSDs also provide much faster read, write and response speeds compared to hard drives. However, in PIS applications faster speeds don't really offer any tangible advantages. Write speed of HDDs provides sufficient bandwidth in video recording even when one recorder is managing numerous cameras. A faster system startup time is neither a useful advantage as trains are usually powered well in advance before taking in passengers.

Hard disk drives use magnetic spinning disks to store information. A rapidly moving mechanical arm is used to read and write information. HDDs store information in sectors which are essentially specific arc lengths along the disk a certain distance from the center. Historically sector size has been 512 bytes but modern drives hold 4096 bytes per sector. Hard disks offer high capacity storage at a low cost but are mechanically more fragile than their solid-state counterparts [1].

SSDs and HDDs have a significant difference in terms of how they manage stored data which has consequences in handling structural failure. A hard drive reads and writes sectors at a time. A sector failure results in a loss of that specific sector as it is remapped. An SSD on the other hand is only able to write a block at a time. If a single cell fails it potentially causes the entire block it is inhabiting to be lost. As mentioned earlier, blocks are much larger in size and may have more serious consequences when failed as a larger amount of data is potentially lost.

*Failure condition:*

In its simplest form a failure is a condition where the device in question is no longer able to fulfill its intended function. For mass memory this essentially means that the storage device is unable to provide data in the exact format that it was once stored in. In practice a mass storage has failed to correctly provide its function if one of the following conditions are present:

1. Stored data is lost
2. Retrieved data is incorrect
3. Catastrophic failure

A common reason for the first condition is a sector or block failure. If a drive experiences what is known as a *final read error*, meaning the read action results in an error even after several retries, it will typically result in sector or block reallocation leading to loss of data [1][25]. A final read error can be caused by the controller being unable to resolve the desired block or sector because it has been damaged. Alternatively a final read error can happen if all the preceding read attempts result in an uncorrectable error, meaning Error Correcting Codes (ECC) are unable correct the data. This ties to the second failure condition, read data being incorrect.

The original mistake leading to data corruption can happen at several stages within the process of writing data – reading data. As mentioned, an error can happen while reading

stored data. It is also possible that data was written incorrectly in the first place and ECC was unable to catch the mistake. When the same data is later read, it'll be correct from the drive's perspective and passed to the operating system which may lead to OS or application level errors. Similarly it is possible for a bit error to go unnoticed during a read operation. These errors that go unnoticed by the drive controller are known as silent errors. [7][15]

Finally catastrophic failure refers to situations where a drive completely ceases to function. Both SSDs and hard drives can experience controller failures or malfunctions which essentially kill the entire drive [15][19]. Hard drives are susceptible to physical damage because of the number of moving parts. Excessive damage from shock, read arm servo failures, and wear on the spinning platter bearings are just some examples of sudden catastrophic failures [7].

Sector errors, silent errors, and complete drive failures are a concern in single drive applications as there is little that can be done to recover from the mentioned conditions. RAID redundancy and higher level redundancy solutions, such as a journaling file system [8], can help mitigate data loss and generally improve system robustness. Still, RAID is not a completely fail-proof solution. The array must know which drive contains the correct data and which should be corrected. Any errors that occur during data reconstruction are particularly dangerous as there is no backup available during that time [7][23].

Sector and block failures are fairly good indicators of mass storage reliability as they are a notable cause for data loss [1][15][23]. They essentially tie together errors from mechanical damage and uncorrectable errors as both result in a final read or write error which in turn leads to sector reallocation. Additionally there is a large number of research done on sector errors, mechanisms responsible for their formation, and resulting effects. However, this does leave silent errors as an unknown variable. Silent errors are difficult to detect because they pass through drive controllers unnoticed making it impossible to determine their occurrence looking at drives alone. There is not much research available on the subject. Mielke's et al. study [15], as cited in Bairavasundaram [1], found silent error rates in HDDs to be between $10^{-16}$ and $10^{-17}$ errors per bit. Rates for SSDs were found to be between $10^{-18}$ and $10^{-22}$, however, the values are not directly comparable [15]. It is impossible to say if silent error rates correlate with drive age but since the values presented here are fairly low focusing solely on sector errors is deemed sufficient.

Both SSDs and HDDs hold a certain number of blocks or sectors in reserve. Typical values are between 2 and 5 percent of total drive capacity [1][25]. Whenever a drive encounters a final write error, it will mark the sector or block as failed, retrieves a spare, and writes data to that instead. This will result in an increase in the drives S.M.A.R.T. attribute *Reallocated Sectors Count* [28]. Reaction to a final read error varies between drives. Some will immediately discard the sector or block and reallocate it to a new one. Others mark the sector as 'unstable' which increases *Current Pending Sector* Count S.M.A.R.T.

attribute [27]. If the sector or block is later successfully read it will be taken back into use and pending sector count is decreased. When a drive has exhausted all of its reserve sectors or blocks it can no longer reliably store data as there is no way to remap unusable sectors or blocks. However, it is very unlikely that a drive would provide error-free reads long enough to exhaust all reserve sectors or blocks.

It is difficult to determine an exact point in time or a condition where a drive could be considered failed. Sector reallocations caused by final write errors are not serious faults on their own but in large numbers they do indicate significant wear on a drive. Final read errors are more serious but do not necessarily indicate failure. The very first reallocation caused by a final read error may cause a serious higher level fault or the drive may endure several. Investigating drives from devices that have come for repairs does not provide a clear answer either. Sector reallocation count attribute does not make a distinction between remapping actions done because of read or write errors [28]. Additionally, as the name implies, current pending sector count only keeps track of sectors that are due for reallocation. Once remapped the value is decreased [27]. Other attributes could give clues, such as uncorrectable error count or CRC error count. However, S.M.A.R.T. is not strictly standardized and drive manufactures implement their own attributes, and leave other attributes unrecorded.

Because an exact point of failure is difficult to determine it is best to look at failure trends and determine a fluid failure threshold based on available data. The effective amount of time a system is operational, as well as environmental aspects, such as ambient temperature, are important aspects to consider.

When a failure finally does happen and a device is sent for repairs, any sector or block reallocations are considered as indicators for severely reduced reliability and aging past useful life. This is an established practice for the company's service department but it has not been reinforced by past research, only by employees' personal knowledge of mass storage reliability. The presence of bad blocks are indeed fairly good indicators of aging and reduced reliability. However, a bad sector is not necessarily as serious of a fault. The significance of these conditions will be explained in more detail in the next section.

*Aging:*

There are several metrics for measuring useful lifetime for SSDs: maximum amount of P/E cycles, mean time between failures (MTBF), and write durability in bytes. Out of these, P/E cycles is probably the most prominent metric.

P/E cycle limit indicates NAND cell durability. Each erase and rewrite action causes minor degradation on transistor level, until erasing is no longer possible or read errors occur because '0' and '1' can no longer be reliably distinguished from one another. Manufacturing defects have a large role here. Cells that have imperfections in their structure will most likely experience a premature failure. The physics behind NAND degradation are

complicated and several papers have been written almost solely on the subject [15][22][25]. Such analysis' are outside the scope of this thesis which focuses more on failure trends.

Typical P/E cycle limits for SLC flash range from 10,000 to 100,000 cycles, whereas MLC is rated in thousands of cycles. This alone would indicate based on P/E cycles that SSDs based on SLC-technology would be vastly more reliable compared to MLC ones. However, research does not really support this notion and instead SLC and MLC are found equally reliable [15][25].

Another often provided reliability figure by manufacturers is write durability in bytes. This value is derived from P/E cycle limit and represents the amount of written data a drive is able to endure. P/E cycle limits and write durability can be tested by accelerated life tests in reasonable timeframes due to SSDs high write speeds. A theoretical stress test where a drive is written to at maximum bandwidth could wear it out rather quickly; a 100TB write durability at 500MB/s would be reached in around 55.5 hours. Accelerated life tests have some merit but they are not directly representative of real-world aging. SLC drives often fail well before their limits while MLC drives might last much longer than what their P/E cycle limits would suggest. [15][22][25]

Finally, an often provided reliability figure is MTBF, calculated using a reliability prediction method, such as Telcordia SR-332, and are typically between 1,000,000 and 2,000,000 hours. MTBF values are calculated based on reliability predictions of all the electrical components within a drive. MTBF alone is neither a representative figure of real-world reliability [24][25].

As was mentioned in failure conditions, drives are replaced if they report a bad sector or block while being repaired. If a solid-state drive develops a bad block there is a high probability that the number of bad blocks starts increasing exponentially – Schroeder et al. study (source figure 8) illustrates how only a handful of bad blocks will likely lead to a future failure [25]. Hard drives do not seem exhibit a similar kind of chain reaction when it comes to sector failures. There is quite a lot of variation between hard drive models. Some exhibit increased sector failure rate with age, whereas other experience sector faults fairly regularly over their lifetimes [1][19].

Sector failures in hard drives are caused by manufacturing defects, physical damage, and wear over time. Imperfections on the drive platter left by manufacturing process can cause some sectors to be unreadable. Vibration and shock can cause a drive's read arm to hit the spinning disk causing enough damage for a sector or sectors to become unusable. Dust particles inside the drive enclosure can cause scratches and may disturb read and write actions enough to cause sector reallocation. Even if the dust clears at some point the sector has already been marked as unusable and remains in failed state. Wear and fatigue in read

arm servo and related mechanisms can cause the arm to "high-fly" or access wrong tracks, resulting in read and write bit pattern errors. [1]

Reliability figures for hard drives are usually given as MTBF values or load/unload cycle limits. These limits represent the amount of times a drive is able to accelerate its disk to operating speed and then stopping again. Typical load/unload cycle limits are in the region of hundreds of thousands. Both metrics describe system level reliability and are poor indicators for real-world reliability – they do not strongly correlate with sector failures. [24].

These estimations alone would suggest that both SSDs and hard disk drives would work for decades under constant utilization, SSD lifetime is related to the amount of data written, and that SLC flash would be vastly more durable than MLC flash. In reality however, age is the most significant metric for both SSDs and hard drives, i.e. how long has a drive been utilized. [15][25].

Temperature is a significant factor for both solid-state and hard disk drives. For SSDs, higher temperatures alter the electrical characteristics of NAND cells and causes accelerated wear [15][22]. In case of hard drives differences at moderate temperatures do not seem to have an effect (30-40°C). However lower and higher temperature ranges do seem to have a negative contribution in terms of reliability, as shown in Figure 4. Higher temperatures are especially pronounced in older drives while the same is not present in one or two year old drives.
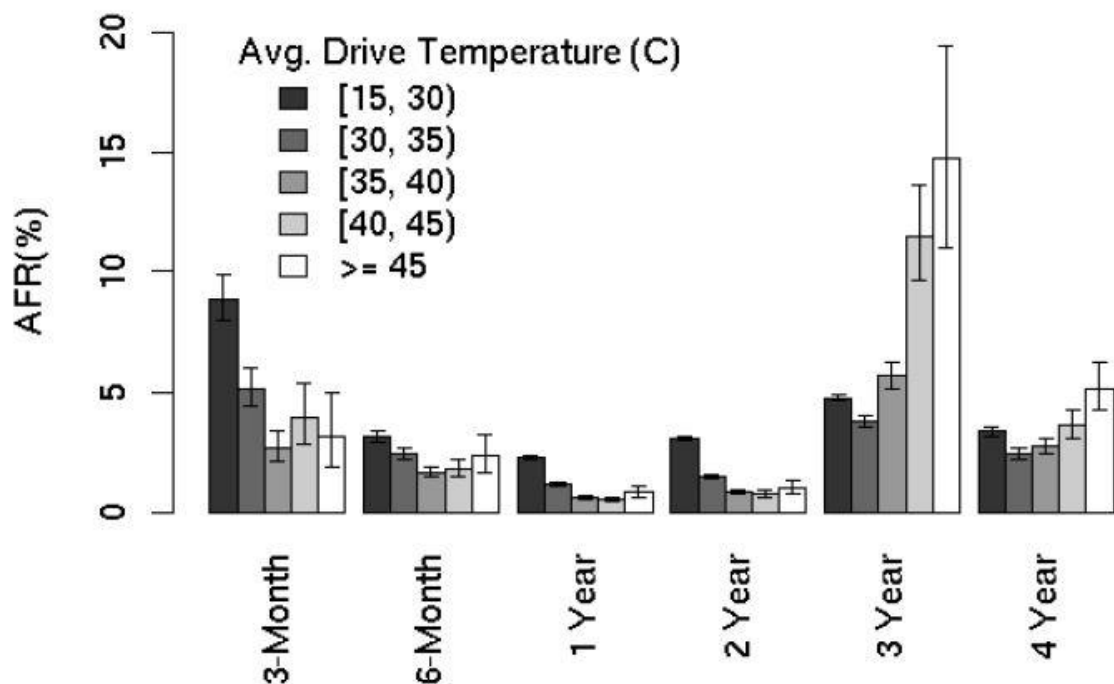


*Figure 4. Drive temperature's effect on HDD failure rate [19].*

It seems intuitive that high utilization would accelerate drive aging and lead to increased failure rates early in life. In actuality such assumption is only partially true. High utilization causes increased failure rates only very early and very late in life [19]. This phenomenon is most likely caused because the stress placed on the drives weeds out the weakest individuals that have just passed their burn-in test, effectively making the rest of the population more robust [19]. See Figure 5 for illustration on this phenomenon; high utilization causes clearly pronounced failure rates on new and old drives. For SSDs drives that had relatively high amount of P/E cycles still failed well before their rated limits. [25]
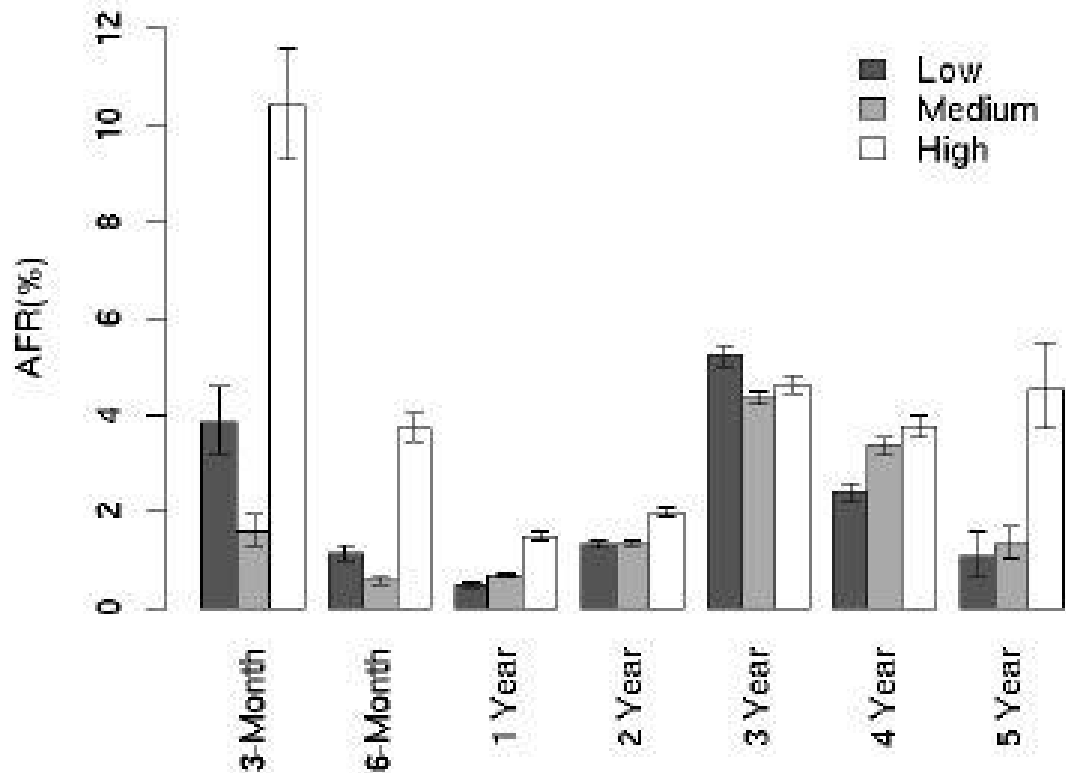


*Figure 5. Drive utilization's effect on failure rate [19].*

## 4.2   LED-modules

*Description*

LED displays consist of one or more LED-modules chained together. LED-modules are available in variety of sizes and pitches with each module having a varying number of LEDs to accommodate the various types of displays available. The LEDs in a module are arranged in a matrix where columns act as data inputs and a refresh pulse scans all the rows rapidly resulting in a still image for human perception. High brightness and by extension high luminance contrast are important for LED displays. Displays situated outside a vehicle must be readable with a quick glance from a fair distance away.

Most on-board LED displays manufactured by Teleste Corporation and used in rolling stock are monochrome displays using yellow LEDs [16]. The same type of LED is used in most displays, though the model was changed to a brighter one few years ago from the time of writing. Displays with the older LED type are still in use in the field but their number is diminishing. The manufacturer of the LED, the model, and its characteristics are confidential information and thus redacted from this thesis. Regardless, mechanisms behind lumen depreciation and final results presented are applicable for specific LED used in the company's displays.

*Failure condition:*

A failure of a single light-emitting diode is possible but it is a fairly rare occurrence and a certain number of dead LEDs in a display is tolerable. Instead it is more meaningful to look at the overall lumen depreciation of a display. A threshold is typically indicated as a percentage of LEDs able to output a certain percentage of the original brightness. For example, L50B50 would mean 50% of the LEDs are able to reach 50% of the original brightness [31].

L70 and L80 brightness values are also common. The choice of threshold depends on the application and desired brightness and contrast. A display covered by a glass might become difficult to read at L70B50, whereas an indoor display typically read at close distance could reasonably be used until L50B50.

Another thing to consider is the uneven utilization of the LED field. Depending on the text displayed, some parts of the field will see more use than others which will age the more utilized parts more quickly. Over time significant differences in brightness can form making the display unpleasant to look at. Whether or not such a "burn-in" look will happen depends on mission details and should be looked at case-by-case basis.

Human eyes are not good at distinguishing absolute luminance. If all the displays in a vehicle age approximately at the same rate, it becomes difficult to judge how much their absolute brightness has diminished without a reference. [21]

Additionally, as an example a display in direct sunlight would run at maximum brightness, and at half brightness in typical lighting. After a long time the display might still reach sufficient lumen output power at maximum brightness but under normal conditions would be far dimmer.

*Aging:*

The lumen maintenance curve of an LED is exponentially decreasing [5][10][20]. LEDs used in PIS displays are low-power ones. Such LEDs will be able to maintain their original brightness for a long time before they start rapidly declining. Utilization and ambient temperature have a major impact on the overall lifetime of an LED.

The overall brightness of an LED display is Pulse-Width Modulation (PWM)-controlled. When dimmed the LEDs are rapidly switched on and off which to a human eye seems as a constant intensity. A higher duty cycle, i.e. higher brightness therefore directly translates to a longer time the LED is on overall which will cause it to age more rapidly. Displays with automatic brightness control will run brighter in direct sunlight or in other bright conditions. Displays with glass covers might be operated at higher brightness on purpose to account for the glass absorbing some of the light output.

LED lumen depreciation is caused by a slow accumulation of damage in the LED package. There are several contributing reasons that together diminish the overall luminance output of an LED; cracks in the lens or encapsulation, illustrated in Figure 6, carbonization, yellowing of the encapsulation, shown in Figure 7, and package delamination. [9][10][35]



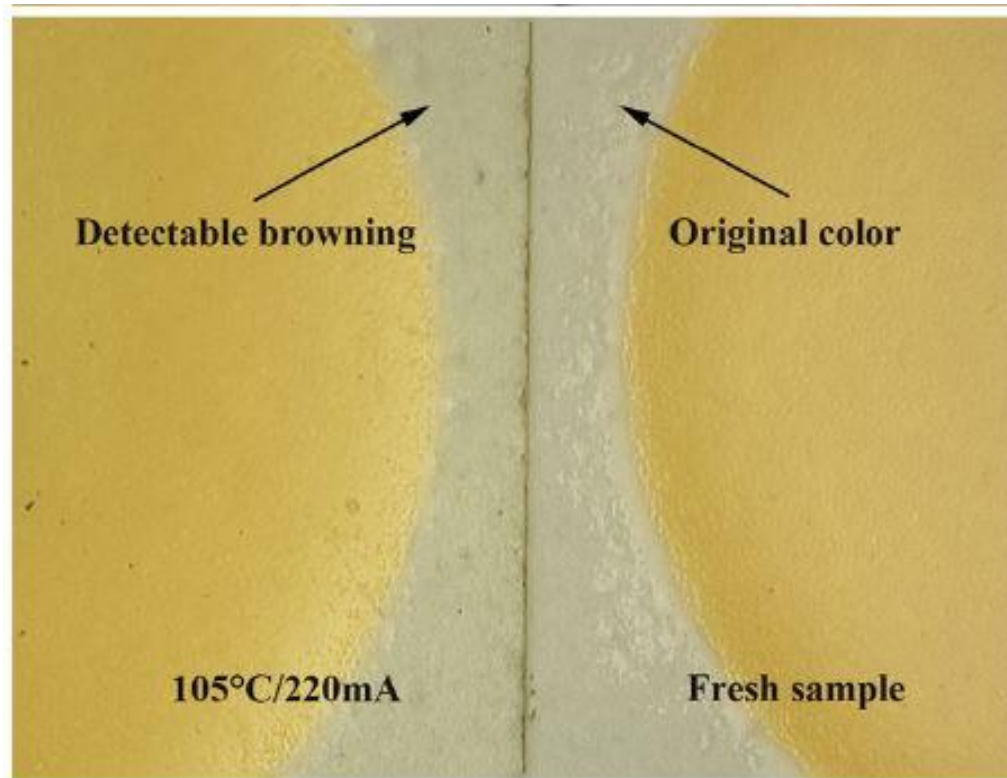*Figure 6. Crack formation in LED lens [35].*

*Figure 7. Yellowing of an LED package [10].*

Cracks are formed by slow creep strain rate of the LED package material. When an LED is turned on it produces heat which is immediately transferred to the surrounding package. This rise in temperature increases the material's viscoelasticity contributing to minor deformation of the LED package over time. Temperature cycling is fairly commonplace for display LEDs, especially with scrolling text, and can eventually lead to crack formation in the LEDs package and lens. Cracks disrupt the originally intended projection and reflection of light which in turn causes a reduction in the effective light power output [35].

LEDs require comparatively little power but since the light-emitting diode itself within the package is very small it has high power density and operates at high junction temperature. This heat dissipates to the LED package and circuit board. However, long periods of time can cause carbonization on the package's reflective surface and lens. Yellowing is a common effect in plastics and is caused by the material's reaction to ultraviolet light. Both effects reduce the reflective surface's effectiveness cause obstructions reducing light output power.

Ambient temperature is another factor that has a major effect on the LEDs overall lifetime. The rate of an LED's brightness degradation is inversely proportional to the ambient temperature within rated operational temperatures [5][31][35]. Therefore a warmer climate will have a detrimental effect on the LEDs lifetime. Sealed units with higher IP ratings are especially prone to the effects of higher temperatures as the air inside the unit

cannot circulate. The LEDs themselves along with other components will warm the inside air causing the display to run hotter compared to an "open" unit.

Mission profile is an important aspect to consider. The overall time a display is on and displaying text each day may vary, as it might be kept off when the vehicle is not being driven on route, or the displays might show text only at specific points along the journey. In practice this can be seen as a coefficient for the overall lifetime. For example, if a vehicle is driven 12 hours a day then the mission profile adds a coefficient of two compared to a 24 hour utilization, essentially doubling the effective lifetime.

## 4.3   LCD-panels and backlights

*Description*

The LCD-panel and backlight are treated as single replaceable unit. Failures on the LCD-panel itself are possible, such as dead pixels, but the brightness degradation of the backlight is considered to be a more important issue. Backlights come in two variants; Cold Cathode Fluorescent Lamps (CCFL) in older legacy panels, and LED backlighting in more recent panels. CCFL backlighting is essentially an obsolete technology and is no longer being developed. There are still CCFL backlit displays on the field at the time of writing but their number is diminishing.

LED panels are typically edge-lit, meaning the backlight is a combination of LEDs on the side of the panel and a light guide which extracts the light towards the LCD panel [3].

*Failure condition:*

Half-life is a term often used to describe the useful lifetime of an LCD-backlight implying that the end of lifetime has been reached when brightness is half of the original. However, because the backlight illumination is provided by LEDs the aging mechanisms and failure conditions of LCD-panels are fairly similar when compared to LED-displays. Thus, a similar lumen maintenance threshold such as L70B50 would be appropriate for LCD-displays as well.

The exact value is a fairly subjective choice. As was mentioned in the previous section with LED-displays, our visual system is not good at distinguishing absolute brightness which makes it difficult to determine when panel replacement would be needed. A new panel certainly has a "fresh" look when compared to ones that have been in use for a long time. Some differences between panel types are also possible due to their construction. Depending on the amount of LEDs and how effective the light guide is, a panel may develop noticeably darker areas, especially furthest away from the backlight source. Finally, luminance depreciation is perhaps more pronounced in LCD-displays because they are colored. As brightness decreases, color contrast suffers and the display will have a "washed out" look.

*Aging:*

LED-backlight brightness diminishes exponentially similarly to LED-displays and the same causes are applicable. Because there are many different panel types from several manufacturers used across all display models the characteristics of each are different. However, some qualities are shared by all panel types.

The TFT-layer along with polarizing films absorb up to 95% of the total light output produced by backlight LEDs [3]. Because of this the LEDs themselves have to be fairly powerful to provide sufficient output brightness which in turn causes the aging effects to be more pronounced. Driver's control panels have touch screens as an additional layer of obstruction. LCD-panels are also very tightly packaged which complicates heat dissipation.

In LED-panels the utilization of each individual LED depends on what is being shown on the display. LEDs in backlighting are all used uniformly which is both an advantage and a disadvantage. The luminance of backlight LEDs diminishes roughly at the same rate apart from minute differences between individual LEDs. However, if we draw a comparison with an LED-display that is "lucky" and experiences roughly even utilization across all of its LEDs. Such a display would experience a fairly low effective duty cycle, whereas LCD-display's backlight is on all the time. This is true even when the display is showing black color; the liquid crystals are in 'off'-position but the backlight is still on [3].

# 5. RESEARCH METHODS

This chapter presents the different research methods and approaches used in obtaining data and results. The research material for this thesis is gathered from three different sources; research publications, on subjects such as hard drive reliability, component datasheets, and historical data from the company's internal ERP system and collections of non-conformal components.

## 5.1 Data acquisition

Other scientific publications are the backbone of this thesis. Several papers on hard drive and flash memory reliability are referenced. These works, such as the one provided by Schroeder et al. [25] have several useful qualities: they have a large number of resources and access to a massive sample size. This given study alone had access to millions of drives from Google's datacenters. Such a large sample size provides good averages and diminishes the effects of any outliers. They have tools to extract detailed information from a population that is way too large to go through by hand. Detailed investigation is done on the aging mechanisms of semiconductor cells and on reasons behind error formation. These provide useful insights in terms of what conditions cause wear and tear. However, this thesis does not wish to get too detailed in any single area as the scope still includes several different devices based on totally different technologies. For LEDs several articles were found how brightness degradation actually manifests itself in the component package and how temperature plays a role.

Manufacturer datasheets were another important source of information. Values presented in datasheets, such as MTBF-values, are seemingly reliable as they are essentially a promise on the quality of a product from a manufacturer. However, as will be discussed in the next chapter, MTBF values for a lot of solid-state and hard drives do not correspond with research results from real world settings. This thesis does not try to disprove reliability calculation methods such as Telcordia sr-332, but does present skepticism towards manufacturer claims. Unfortunately device mechanics and specific components used are company confidential information and cannot be presented here. Substitute components will be used where appropriate.

Finally repair data was extracted from the company's database. The database holds all customer reclamations with a detailed repair report categorized by the type of repair action performed. For this work the extracted data has useful information on repairs performed due to mass memory failure. It does not help with LED and backlight brightness degradation investigation however, as no repairs have been performed solely for this reason. Many existing systems are not old enough yet so that the displays would have aged enough and customers have not requested maintenance actions on displays as of yet.

Since none of the above methods provides an accurate representation of real world aging on their own an estimation has to be performed based on all three methods.

## 5.2  Data validity

None of the methods presented in the previous section provide accurate results on their own. Each has their merits but also inaccuracies and hindrances in adapting results. This section describes the challenges in finding descriptive results and how the different methods incur error.

The first major obstacle in existing studies on mass storage is the difference in setting and application. Server rooms and data farms are the most common applications for mass storage drives, and researchers are happy to use them as they gain access to a large sample size. For this thesis this is a problem, as a server room and a train are two very different environments. Server rooms are static, climate controlled environments run around the clock, while a train is a moving platform with varying levels of temperature controls and is sometimes not in use. Application which the drives are used for is another unknown variable. Research papers do not specify what the drives are used for, either due to lack of information or it being confidential. Utilization levels are either not available at all or they are rough estimates. A drive used in PIS control unit that experiences mostly only read actions during its lifetime will most likely last longer than a drive that is being written to at full capacity all the time.

Finally, as mentioned in chapter 4, failure condition is fluid threshold and varies between studies. A drive that has a broken controller chip is universally considered failed but besides that conditions vary. An indifferent approach would consider a drive failed only after it has exhausted all its spare blocks or sectors and is no longer able to maintain data integrity. A stricter approach would consider a drive failed once it has developed its first bad sector or block. Some studies include drives in their results that have entered repairs due to software errors caused by an uncorrectable read error and have later been found not defective.

Repair data gathered from the company's database also has its own challenges and inaccuracies. For new rolling stock fleets the end customer receives vehicles as they are manufactured, and passenger information systems are delivered accordingly either one vehicle or few at a time. After being delivered the vehicle and PIS will undergo testing for varying amounts of time until they are finally commissioned and enter commercial operation. Commissioning dates are known and archived but it is unknown which device is installed in which train. Thus, for example if systems for five vehicles have been delivered at once, and those vehicles have been commissioned over half a year period there is already possibility for half a year error.

Customers often have a small amount of spare stock so that broken devices can be swiftly replaced with working ones. This presents another difficulty as there is no way of knowing how long a device have been kept as a spare, or how long it takes for a broken device to be sent for repairs. Because the systems are sold to customers and essentially become their property, they are under no obligation to trace the path of single devices.

# 6. RESULTS

Estimating the useful lifetime values of consumable components was one of the main goals of this thesis. The following subchapters describe how estimates for each type of component were obtained and reflects on different variables that have an effect.

## 6.1 Mass memory

Form factor does not really make a difference in terms of durability. Therefore, this sub-chapter can be presented with a simple division between solid-state and hard disk drives.

Mass memory failure rate follows a so called "bathtub curve". This is illustrated in Figure 8, adapted from the conference article by J. Yang et al. [34]. The beginning visualizes infant mortality; large number of failures early in lifecycle, while the end visualizes the wear-out period; components are past their useful lifetime and failures increase rapidly. The middle represents the useful life period, where failure rate is governed by natural aging.
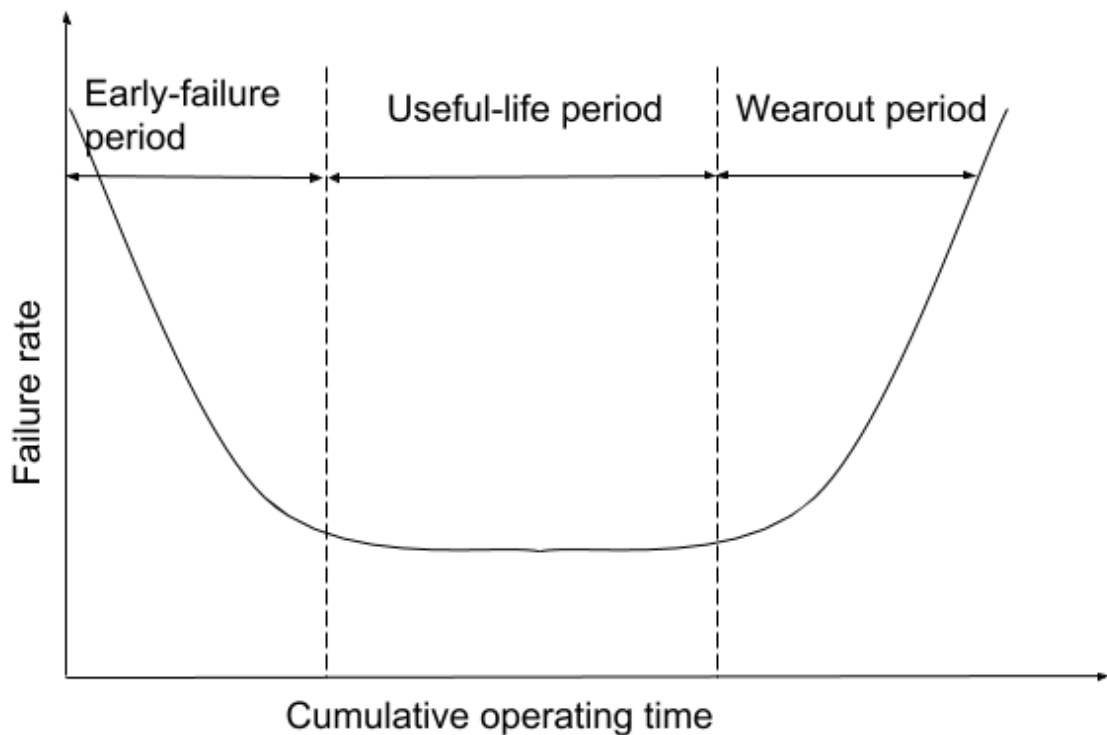


***Figure 8.*** *Bathtub curve of failure rate.*

A metric used to measure mass memory failure is called Annualized Failure Rate (AFR). Drive manufactures often provide an MTBF-value for their products, and AFR can be approximated from MTBF with the following formula:

$$AFR = \frac{8766}{MTBF} \tag{1}$$

8766 is the numbers of hours in a year. For example, an MTBF value of 1,000,000 hours would give an annualized failure rate of 0,88%, providing the fraction of drives that will fail of the entire drive population in one year. Sometimes a value of 8760 hours per year is used. However, the hours in formula 1 account for leap years. Bathtub curves often represent the failure rate as a constant over time. In reality failure rate does not stay constant but will increase instead as a drive population ages.

*SSDs:*

SSD drives comprise of 2,5" and Compact Flash form factors, both in SLC and MLC architectures. As described in chapter 4 there is no noticeable difference between SLC and MLC memories in terms of durability. SLC memory is used low-capacity drives and is primarily used to house an operating system. These type of drives experience mostly read operations with significantly less writes. Conversely, MLC drives are primarily used for data storage due to their larger capacities and they experience mostly write operations.

Theoretically a NAND-cell within the drives memory chip can only endure a certain amount of erase-and-write operations, and manufactures provide maximum amounts for sequential and random writes a drive can take, often in the region of tens or hundreds of terabytes. However, research shows that the most important metric for drive durability is actually the time used. Therefore, even though SSDs are used different tasks they can all be characterized similarly with fair amount of confidence.

The results provided here are of course only estimates. The largest variance is caused by different drive models and manufacturers used as the exact characteristics of each are largely unknown. Operational temperature also has a sizable effect as higher temperature are shown to directly correlate with higher failure rates.

Exact values and makes and models of drives used are confidential property of Teleste Corporation. The results provided here are examples that roughly correlate with the real results.

N. Mielke et al. had compiled results of SSD failures from several studies into a single chart shown in Figure 9. Their results show that SSDs are indeed fairly reliable, with annual failure rates ranging from just tenths of a percent to few percent. It is important to note that reasons why the studied drives had been deemed as failed varies between studies, and in some a failed drive was found to be not faulty after an inspection.
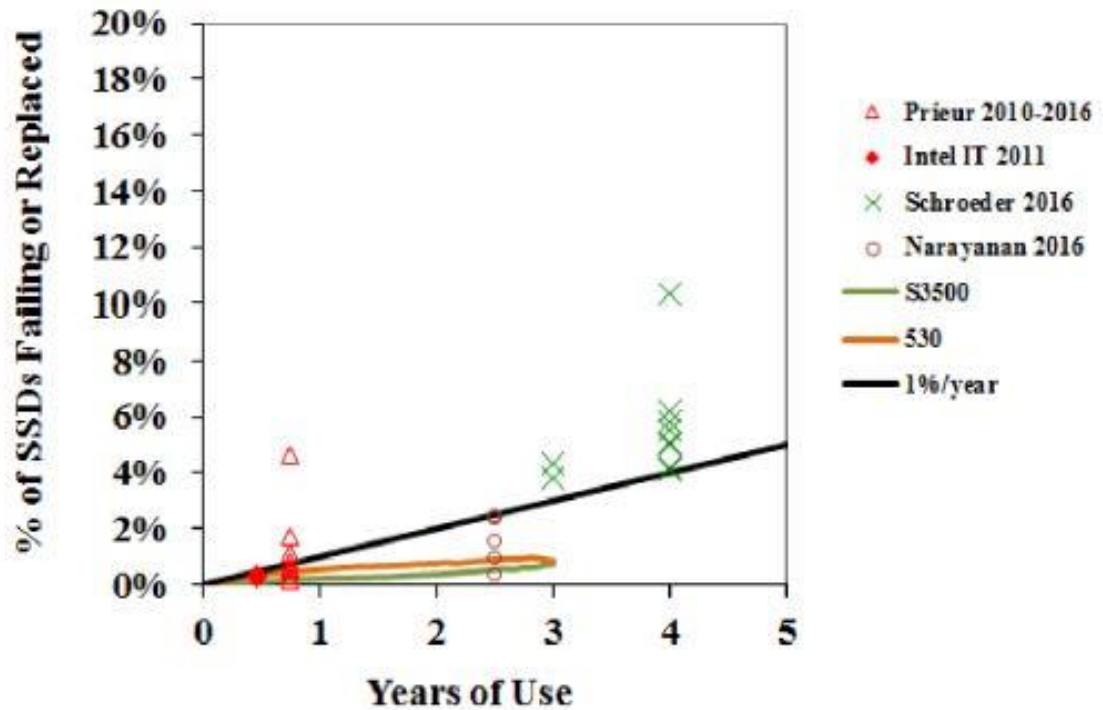
***Figure 9.*** *SSD failures from several studies [15].*

There is quite a bit of variance between different drive models but it is interesting to note that even in a static controlled environment the average annual failure rate is quite a bit higher than what is typically reported by SSD manufactures. Based on formula 1, MTBFs of one million and two million hours correspond to an AFRs of 0,88% and 0,44% respectively.

This study is mainly interested in failures caused by sector errors, or block errors as is the case with SSDs. It is often difficult to differentiate from studies the exact amount of failures that has been caused by block errors, as results often include failures that originate from uncorrectable bit errors. B. Schroeder's et al. study [25], also included in the previous figure, however does provide data on drives that had developed chip errors due to exceeding their spare block count. The values in Table 1 are derived from their study.

***Table 1.***   *Fraction of drives which exceeded their spare block counts.*

| Drive model | % of bad chips | % repaired | MTB repair (days) | % of drives repalced |
|---|---|---|---|---|
| MLC-A | 5.6 | 8.8 | 13,262 | 4.16 |
| MLC-B | 6.5 | 17.1 | 6,134 | 9.82 |
| MLC-C | 6.6 | 8.5 | 12,970 | 4.14 |
| MLC-D | 4.2 | 14.6 | 5,464 | 6.21 |
| SLC-A | 3.8 | 9.95 | 11,402 | 5.02 |
| SLC-B | 2.3 | 30.8 | 2,364 | 10.31 |
| SLC-C | 1.2 | 25.7 | 2,659 | 5.08 |
| SLC-D | 2.5 | 8.35 | 8,547 | 5.55 |
| eMLC-A | 1.4 | 10.9 | 8,547 | 4.37 |
| eMLC-B | 1.6 | 6.2 | 14,492 | 3.78 |

Their study found that between 1.2% and 6.6% of drives failed due to chip failures which translates to annual failure rates between 0.3% and 1.65%, assuming constant failure rate.

Figure 10 shows failure distribution of drives that were gathered from repairs performed on passenger information system control units. Drives included had experienced at least one sector error reported by their S.M.A.R.T attributes. Unfortunately, only one model of drive had sufficient sample size. One other model would have been available in large numbers but their S.M.A.R.T attributes did not record power-on hours. A third model would have also been available. However, large majority of failed drives also had corrupted attributes making them unsuitable for analysis.
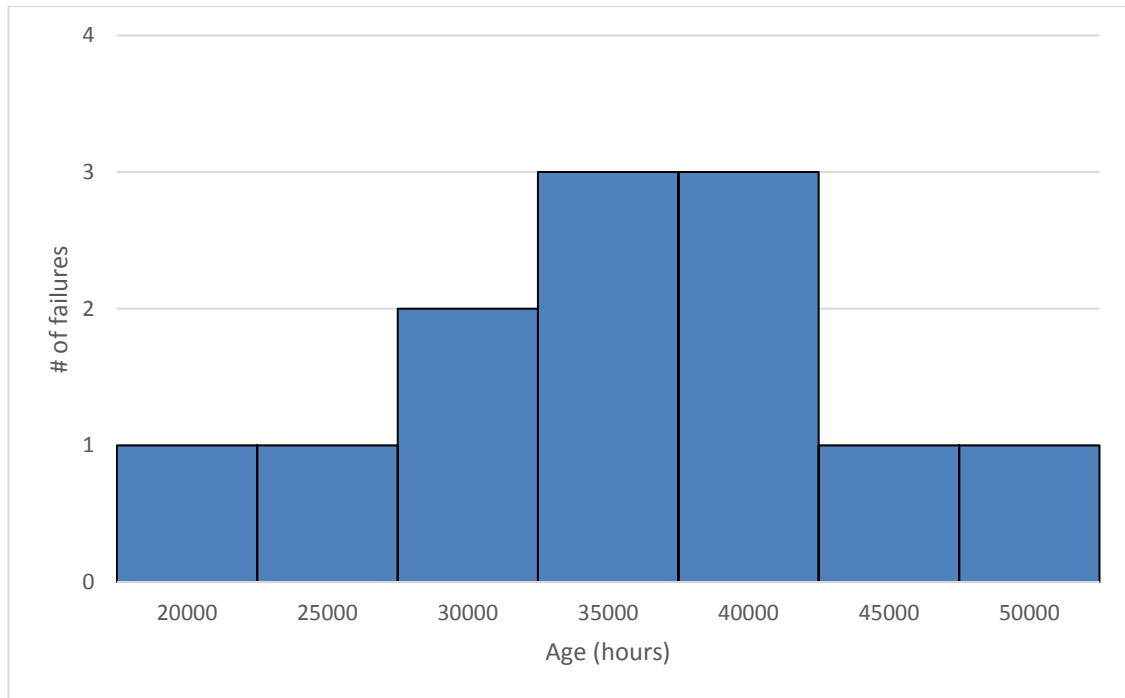
*Figure 10.*      *PIS control unit SSD failures, single model.*

It is important to note that the above figure presents only failed drives from several different systems. The amount of survivors or the size of the population is not known causing the graph to be biased towards earlier failure. In addition, the graph does not include drives that were completely dead as it is impossible to read their S.M.A.R.T. attributes. Neither does it include drives that were replaced for other reasons, such as drive reporting a large number of uncorrectable errors.

*Hard disks:*

Hard disks are used when large amounts of storage is required. They have the advantage of much lower cost per gigabyte with the drawback of being mechanically less durable compared to solid state drives. Hard drives in PIS applications can be described as "enterprise"-level, which are built to higher tolerances compared to ones targeted at consumer markets.

As with solid-state drives, real-world studies show that hard disks experience failure rates order of magnitude larger or even more than what is reported. It is important to note that research performed on large disk drive populations gathered from data farms can only be used as a guideline. Data farms are static, climate-controller environments, whereas hard disks within a passenger information system are on a moving platform. While dampening is employed drives still experience bumps and vibrations.

Figure 11 presents a compilation of hard drive failure rates gathered from several studies, done by N. Mielke et al [15]. Compared to Figure 9, which shows SSD failure rates, hard drives experience wildly varying levels of variance.
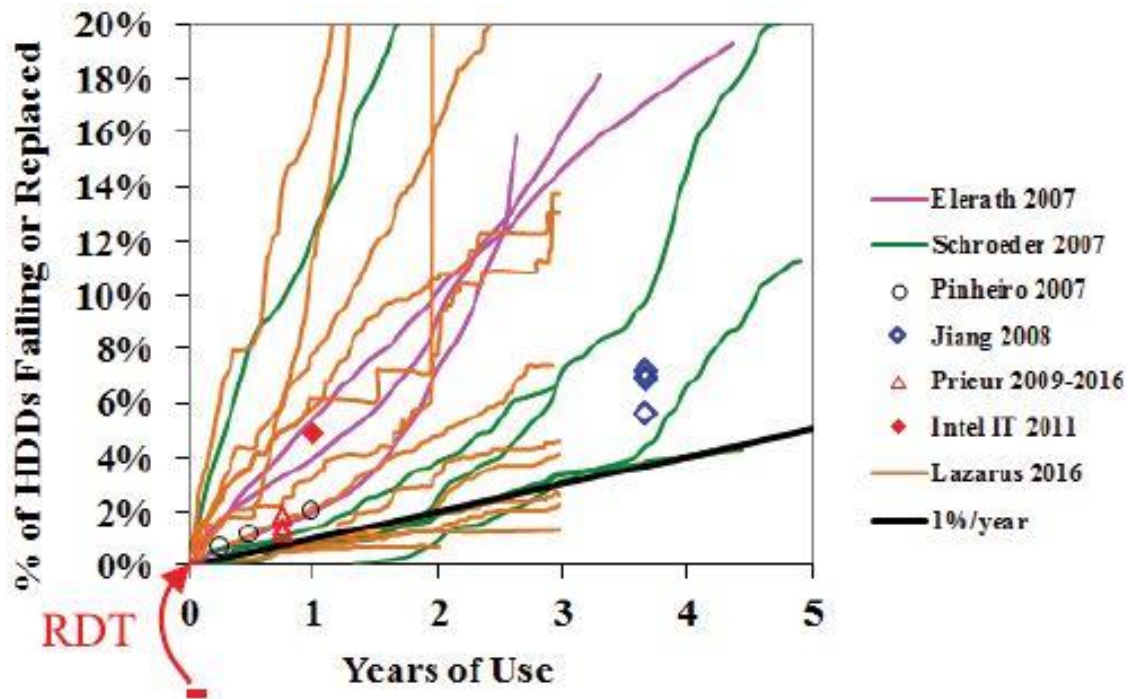
***Figure 11.*** *Hard drive failure rates from several studies [15].*

Some drives are able to achieve annual failure rates below 1%. Several curves are grouped around 4% AFR region while some report up to 10% or even 20% AFR. Again, exact failure conditions are unknown on the results presented here. Additionally, typical operating conditions are unknown. As was shown in chapter 3.1, hard drives do respond to increased utilization with higher infant and later-in-life mortality.

The source behind the 'Lazarus' data is interesting. It is a company providing cloud storage and the data on their drive database is freely available. The curves in figure 11 are from second quarter 2016, and they mention having replaced a large number of their drives the previous year. High failure rates seem to be caused by a combination of infant mortality and low sample size. A more recent overview is also available from second quarter 2018 [11]. They keep a record of lifetime failure rates, which averages 1.8% over 98,184 drives and over 87 million drive hours. Annualized failure rates vary from 0.3% to 5%. It is worth noting however, that the drives they are using have higher capacity than what is used in most PIS applications, and that the environment is vastly more stable.

They also keep a record on the most significant S.M.A.R.T attributes on failed drives. They report that of all the failed drives, 42.2% have reallocated sectors, 43.1% have currently pending sectors, and 33% have uncorrectable sectors. This would indicate that sector errors are a fairly common reason for failure but do not account for all cases.

A number of failed hard drives from recorder units were available for analysis, shown in Figure 12. The presented drives had experienced at least one sector error. Similarly to

Figure 10, this figure shows only failed drives; size of the entire drive population is unknown. Completely dead drives are not included, and neither are ones that had been replaced but report no sector errors
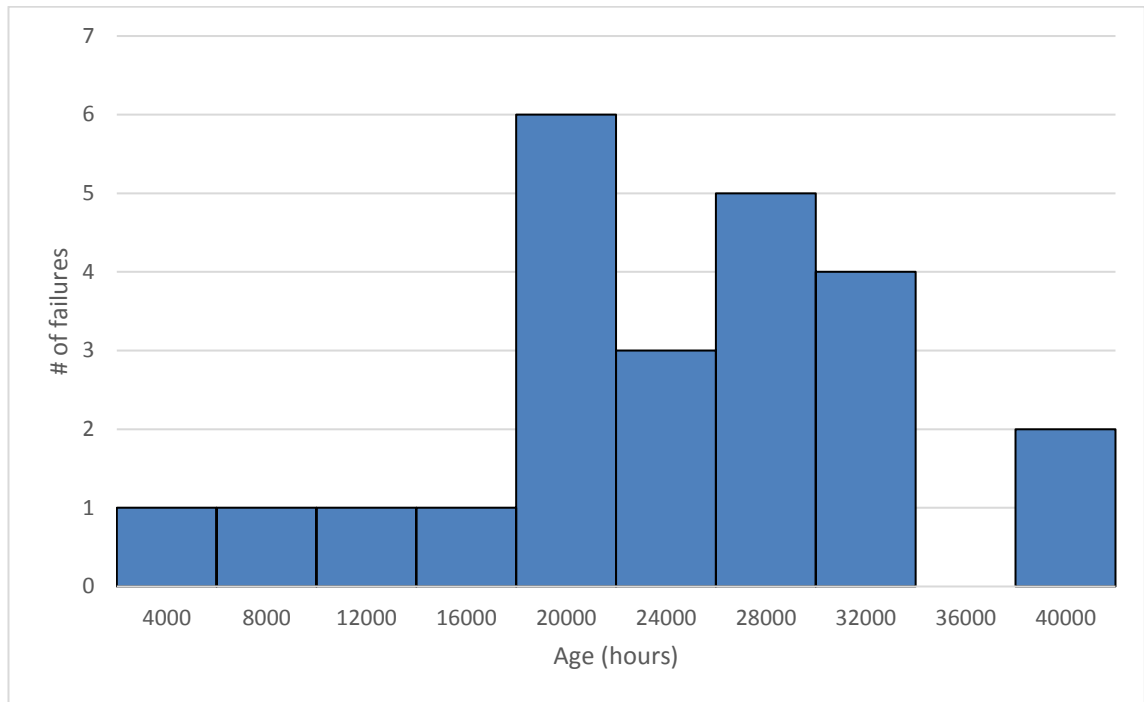


*Figure 12.*      *Recorder unit hard drive failures.*

Based on samples in Figure 10 and Figure 12 hard drives do seem to experience more early failures and fail earlier in general.

## 6.2 LED-modules

As described in chapter 4 LED brightness degradation is an exponential curve. The increase of the curve's derivative is largely determined by how bright and how warm the LEDs are run at. An approximation of lumen degradation is presented in Figure 13. This curve is based on existing research as well as on data provided by an LED manufacturer [5][10][20]. Unfortunately manufactures do not disclose the luminance degradation curves of their products, and any such documents would be under non-disclosure agreement.
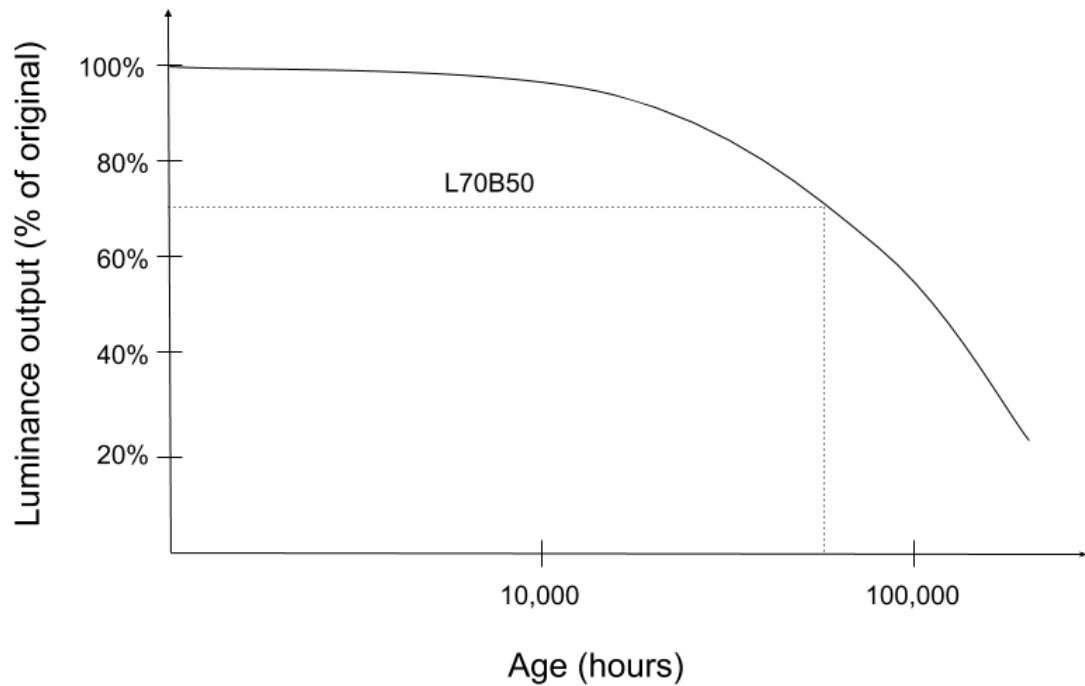
***Figure 13.*** *Example LED brightness degradation.*

An example for L70B50 value is given in the above figure. An L50B50 would take longer to reach but given the exponential nature of the curve the given benefits are diminishing. Ambient temperature (and by extension junction temperature) affects the rate of the curve. Higher temperature causes luminance degradation to start earlier and progress more rapidly. Conversely lower temperatures extend LED lifetime by slowing down the degradation. The effect of temperature becomes especially relevant in sealed displays as they inevitably run hotter due to lack of air circulation.

While the above image is used for illustrative purposes only, the light output curves and their response to temperature in the actual LEDs used in the company's displays behaves similarly. It is important to remember that the lifetime of a single LED depends on the text displayed and system utilization; a straightforward conclusion based on the above example would not be accurate.

Figure 14 shows LED degradation over time. The LED shown is the most common type used in Teleste Corporation's LED displays and is in the scope of this thesis. Upper left corner shows how a brand new unused LED. Upper right corner LED has been used for around a year. Bottom left corner is about three years old. Bottom right corner is approximately five years old.
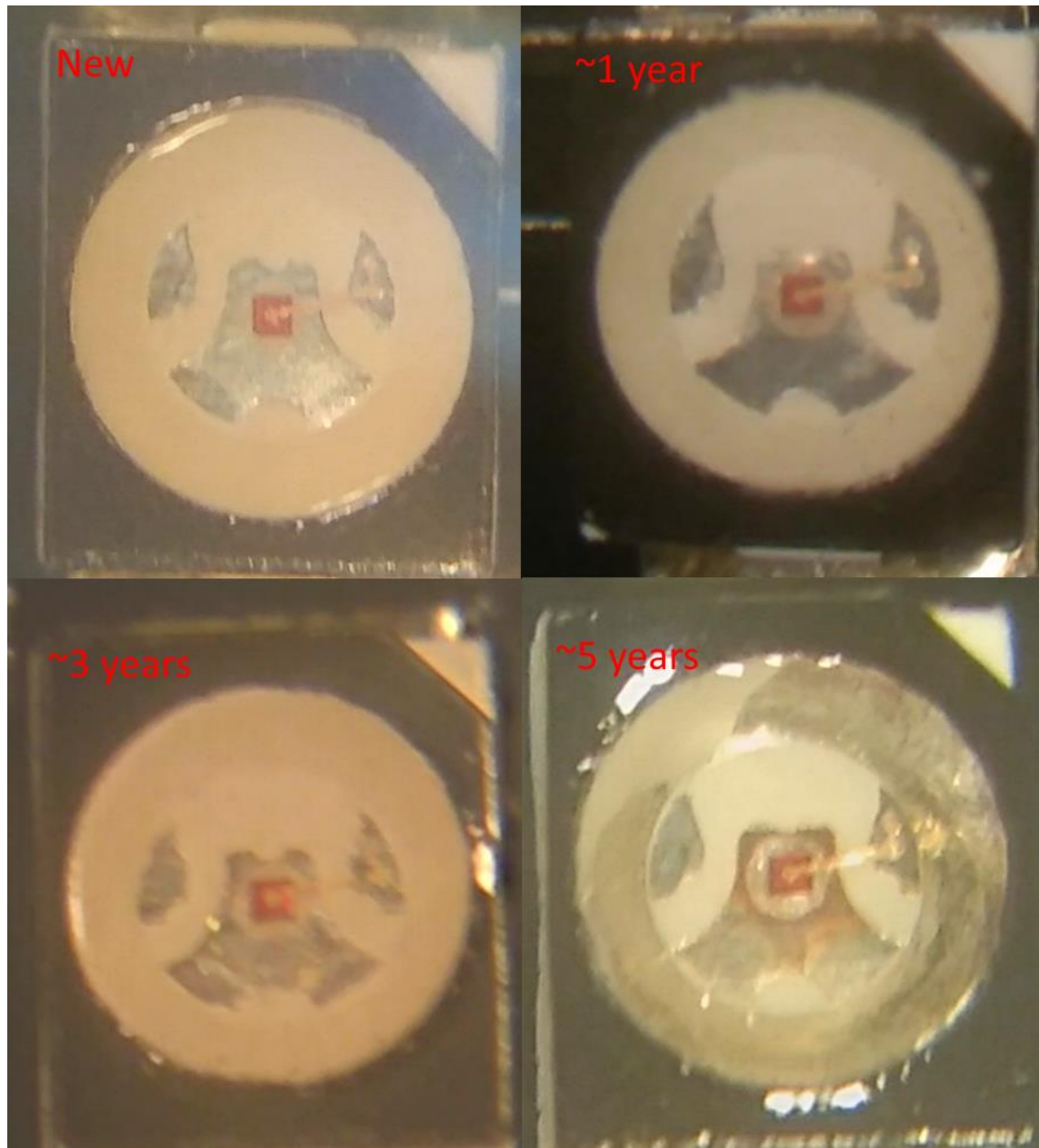
***Figure 14.*** *LED degradation over time.*

Not much difference can be seen between new and one year old LED. At three years, minor yellowing is perhaps visible along with minor carbonization immediately around the diode. Unfortunately there is some color distortion caused by the photo setup of microscope and camera. Five year old LED though shows significant signs of age. It is unclear if the paint on the reflective part has burned or peeled off but it has clearly suffered a lot of damage. There is also some carbonization visible around the diode itself. Both of these factors would result in reduced reflectiveness, and thus diminished overall brightness.

## 6.3   LCD-panels and backlights

LCD-panel backlights behave similarly as LEDs on LED-displays: their luminance decrease accelerates over time and they're susceptible to changes in temperature. Historically cold cathode tubes have been used and they are still found in some panel types. Because there are and have countless different types of TFT-panels on the market it is not possible to provide a comprehensive overview, but in general CCFL-tubes don't last quite as long as LED backlights [3]. Furthermore, LED backlights cannot directly be compared to LED displays. Backlights require high power LEDs to provide sufficient output brightness; up to 95% of the backlight output is absorbed by the TFT-panel and other material [3]. High power means large currents and heat production, and it is difficult to produce LEDs that would last a long time under such conditions.
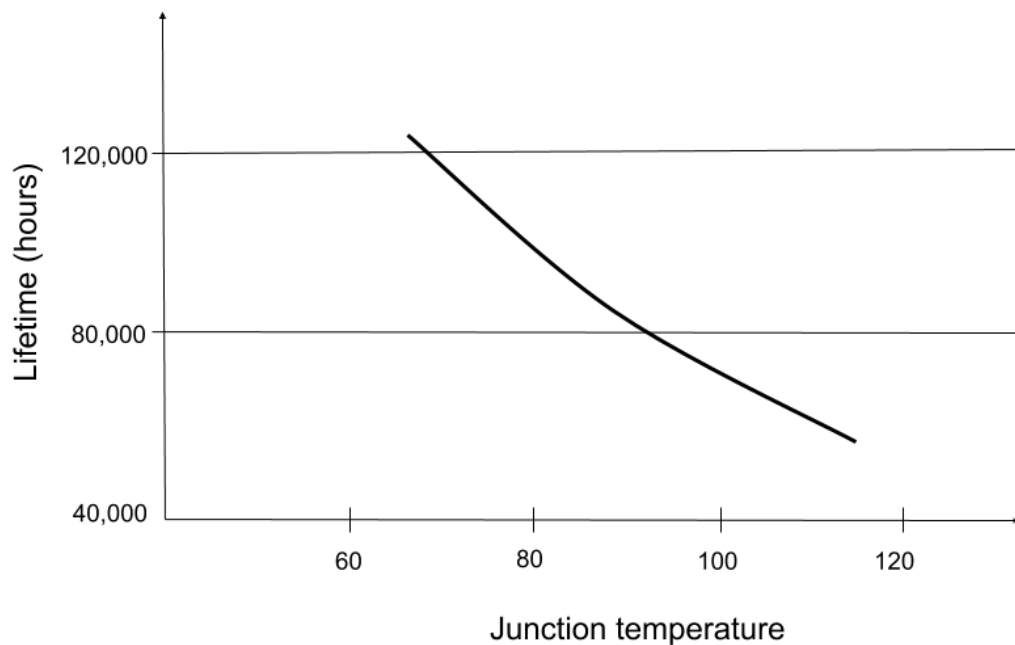


***Figure 15.***        *Junction temperature effect on LED lifetime.*

Figure 15 is an approximation for LED lifetime in response to its junction temperature. The curve is adapted from research done by F. K. Wang et al. [31] and by A. Poppe et al. [20]. Values presented are examples, exact values vary between products and are affected by the LED's current. However, the important take is that ambient temperature affects junction temperature which in turn has a direct impact on LEDs lifetime. Temperature plays a significant role when it comes to backlight aging for a couple of reasons. Firstly, LCD-panels are built to be very thin as manufactures want to build increasingly thin displays. This combined with how the panel is often integrated very tightly to the display mechanics, does not leave much surface area for cooling. Secondly, an LCD-display requires a processor unit of some kind to drive the display, which adds another source of heat. A tightly build display can have significantly higher internal temperature compared to ambient.

# 7.  SUMMARY OF RESULTS

It proved really difficult to obtain data from which representative results could be derived from. Passenger information systems are not server farms from which information could easily be extracted from. They are embedded systems onboard moving vehicles, and experience varying environments and climates from the scorching hot Mediterranean to the freezing cold of Nordic winters. As a supplier for one subsystem within a rolling stock vehicle we do not always have information available how the operator utilizes its vehicles. Information such as how many hours a day a vehicle is driven on route is critical when determining lifetimes of components. Useful lifetime is measured in effective hours of utilization but a gap needs to be bridged when trying to determine lifetime in a real-life scenario or trying to obtain said hours from historical data.

Research on mass storage reliability is plentiful as drive degradation is a major expense for large companies specializing in data storage, or who just need it by necessity. Unfortunately this information is not directly applicable on a specialty application such as passenger information systems. They did however provide a solid overview on failure trends concerning mass storage. Company's own ERP system does not provide very good data on its own as there is not a clear trail from deployment to failure and back to operation. Looking at failed material alone gives a biased view towards earlier failures. Trying to factor in the working population is also difficult as information on how long each device has been used is often lacking or completely unknown.

LED displays and LCD displays are sufficiently specialty equipment that it is difficult to find related research. Some studies have been done on lumen degradation in LED lighting which provided useful information especially on failure mechanisms. Still, LED lighting is quite different from an information display because its brightness is vastly higher. LCD displays are used in countless consumer electronics. However, typical lifetimes of consumer electronics are so short that the panel backlights are able to outlast them and there is not really any motivation to perform research on backlight lifetime.

Table 2 provides the best estimates on consumable component lifetimes based on the different approaches used by this thesis. It explains how different factors can either extend or diminish lifetimes. The table assumes PIS lifecycle to be 15 years. Thus SSD lifetime is given as 7.5 years so that they would be replaced once during the system's life, as an example.

***Table 2.*** *Results summary.*

|  | SSD | HDD | LED-module | LCD-panel and backlight |
|---|---|---|---|---|
| Failure condition | 10% annualized failure rate. | 10% annualized failure rate. | L50B50 | L50B50 |
| Suggested maintenance interval | 7.5 years. | Between 3 and 5 years. | Between 4 and 8 years depending on application. | Brand dependent, between 4 and 8 years. |
| Extending factors | Read-only applications. | Use of enterprise grade disks. RAID redundancy. | Even utilization of all LEDs. Low duty-cycle (low brightness). | Use of stand-by mode. Automatic brightness control. |
| Diminishing factors | High ambient temperature. | High or low ambient temperature. High utilization. Shock and vibration | High duty-cycle (high brightness). Uneven use. Poor air circulation. | High brightness. High ambient temperature |
| Variables | Drive models. Capacity. Utilization. | Drive models. Capacity. | Display structure. Display placement. | Brand and model. |

# 8.  CONCLUSIONS

An on-board passenger information system performs an important role in public rail transport by delivering travel information to passengers on their journey, while providing the vehicle operator with functions such as video surveillance and remote management. As an embedded system PIS is a component in a larger whole that makes up a rail transport vehicle. Reliability and high degree of availability are key; a system must work for long periods of time uninterrupted while a vehicle is transporting passengers. However, failures are an inevitability. Most failures are caused by consumable components which naturally degrade as they age. These components also make up the bulk of maintenance costs over a system's lifetime.

Purely corrective maintenance is still the most common type of maintenance performed. It is simple to execute and often times necessary when solving unexpected problems or eliminating issues present in new systems. Preventive actions are recommended to customers but they are rarely implemented in practice. In total they amount to a negligible amount when compared to all repairs. Predictive and condition-based maintenance plans are often discussed strategies when ideating the future of maintenance. Condition-based maintenance in particular would generate high quality data far exceeding what this thesis has to offer. Such data would be extremely valuable for quality assurance and maintenance cost calculation. In addition it could be useful when choosing which third-party components are used in the company's products. The move towards predictive/condition-based maintenance would be an extensive task. It would require significant initial investment and engineering work, and the results would not be discernible for years. Implementation would most likely concern future products only as retrofitting older versions would be difficult if not impossible.

As rolling stock manufacturers and railway operators calculate the costs of their investment they place passenger information systems under the same scrutiny. The systems will be in use for over a decade and have running costs. As a supplier we must understand the reliability of our own systems over a long period of time and what actions are needed to keep them working as efficiently as possible. This will help us remain competitive in an increasingly demanding market while providing customers with a service that will benefit both parties.

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