POLITECNICO DI TORINO

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An innovative approach to maintenance for a bus fleet

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Abstract

This thesis work is the result of an internship at Arriva Italia Srl, that is a local public transport company and owns a fleet of about 2500 buses. Specifically, the internship has been carried out in Turin, where the company owns a fleet of about 215 buses. Among the various departments of the company, the section where I operated was the Technical Area, which focuses on vehicle maintenance. The role I filled was that of the Planner with the aim to support the planning of activities on the territory taking into account the needs of the Operation, maintenance plans, priorities and available resources and to actively participate in the periodic planning meeting between Operations and Maintenance. To better understand, it could be useful to introduce the definition of maintenance, according to legislation UNI 13306:2018, which states that "*Maintenance is the combination of all **technical, administrative, and managerial** actions, during the **life cycle** of an entity, intended to maintain it or return it to a state in which it can perform the required function*" [1]. The purpose is to find both technical and organisational solutions for large assets like factories or transportation vehicles, as well as for smaller assets such as hobby devices and consumer products, to function properly, in a cost-effective way, with low energy consumption, without polluting the environment and in a safe, controlled and predictable way. Poorly functioning production machines and unreliable products are not good for a company's business. As a result, maintenance is directly linked to competitiveness and profitability and thus to the future of a company [2]. Maintenance costs are a major part of the total operating costs of all manufacturing or production plants. Depending on the specific industry, maintenance costs can represent between 15 and 60 percent of the cost of goods produced. These expenses are not truly maintenance and should be allocated to non-maintenance cost centers; however, true maintenance costs are substantial and do represent a short-term improvement that can directly impact on plant profitability [3]. This involves that maintenance doesn't means just to fix something broken, but requires several activities such as planning, documentation management, budget management, etc. For this reason, it could be necessary to save costs, act in order to ensure safety and respect for the environment, increase the durability and quality of the asset to be maintained. Below are a few terms

that are useful for understanding the discussion. The "Life Cycle" of an asset is defined as "*The period of time from the beginning of the entity's design to the end of its disposal*" [1]. The "Useful Life" of the asset is a concept defined by the manufacturer, but it can be extended through some expedients. It is defined as "*The Time Interval that begins at a given instant and that ends when the failure rate is unacceptable, or when it is believed that the entity is not repairable as a result of failure or other relevant factors*" [1]. The above are general concepts of maintenance. Within this thesis when we talk about maintenance we refer to buses maintenance.

Regarding the goal of the thesis, currently the company performs maintenance activities in a planned or corrective manner; it means that interventions are planned in advance and in parallel the technicians take action when unexpected failures occur. In the following chapters, these types of maintenance will be discussed in detail with a focus on their respective advantages and disadvantages, as well as when to implement a certain type of maintenance instead of another. As technology and the quality of components and lubricants evolve, there is a tendency to leave behind the old maintenance plans with their fixed, pre-set deadlines and move towards predictive maintenance. The aim of this thesis is to renew the maintenance plans used so far in the company in order to reduce vehicle downtime and costs and to implement a predictive approach. Predictive maintenance means having systems that can use AI (Artificial Intelligence) and algorithms to process data collected on board in order to estimate the remaining life of the component and then take action just before the component fails. Data collection can be implemented by means of telediagnostic systems that collect the data of interest through the CAN line. The goal of this thesis was also to implement telediagnostic systems on a limited family of Arriva buses and monitoring of the data collected in order to analyze the boundary conditions of the occurrence of a failure and plan an action in a predictive manner. The future perspective is to replace maintenance plans imposed by the manufacturer or with fixed deadlines and to adopt only a predictive policy that step by step is able to plan maintenance activities.

It is now interesting to understand why maintenance is important and where the necessity to perform it derives from.

"To Gabriella,
The wonderful chapter of my life"

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Acronyms

AI

Artificial Intelligence

CBM

Condition Based Maintenance

TPM

Total Productive Maintenance

RCM

Reliability Centered Maintenance

DMV

Department of Motor Vehicles

MTBF

Mean Time Between Failure

MTTF

Mean Time To Failure

MTTR

Mean Time To Repair

TBM

Time Between Maintenance

PDCA

Plan Do Check Act

PDSA

Plan Do Study Act

JUSE

Japanese Union of Scientists and Engineers

RAMS

Reliability Availability Maintainability Safety

LPT

Local Public Transport

FMEA

Failure Mode Effects Analysis

FMECA

Failure Mode Effects and Criticality Analysis

TPMS

Tyre Pressure Monitoring System

CMMS

Computerised Maintenance Management Systems

GT

Gran Turismo

CNG

Compressed Natural Gas

OEM

Original Equipment Manufacturer

ABS

Anti-Blocking System

CAN

Controller Area Network

BCM

Body Control Module

VeNICE

Vehicle Network Integration Component Electronics

ITxPT

Information Technology for Public Transportation

GNSS

Global Navigation Satellite System

GSM

Global System for Mobile

KPI

Key Performance Indicators

EMF

Electric and Magnetic Field

CCA

Cold Cranking Amps

Chapter 1

An introduction to Maintenance

Maintenance is a very ancient activity. It started with the first tools and instruments that man created to dominate nature and develop his own well-being, constituting the very history of civilization: sharpening the blades of stone or metal weapons is a maintenance activity, as well as repairing fishing nets, repairing a boat or a means of transport on land. In the past, the same user of the tool or means of transport performed the maintenance, until the complexity of the equipment and the demand for a specific skill did not lead to the specialization of people to perform repair operations and, more generally, maintenance [4]. In the 1940s-1950s it was good practise to replace utilities when they failed. According to legislation, failure is the *"State of an entity characterized by its inability to perform the required function"*. Breakdown, instead, is the *"Cessation of the ability of an entity to perform the required function"* [4]. For a better understanding, we could define a failure when the equipment condition reaches an unacceptable level. Whatever it may be, when it reaches an unacceptable level, it's still operating or could be operating. That failure would then develop into breakdown. Breakdown means that it's going to stop functioning. So it's a time period from when you have a failure to a breakdown. To refer to the asset, machine, equipment, or facility (production or service) that is the subject of the maintenance activity we will use the general term "Entity". Starting from the 70's instead, it began to replace utilities at scheduled times and was also introduced Life Extension concept and Availability about utility.

Concerning the nature of maintenance, it should be something that improves, meaning you need to get to the root of the failure and understand why it occurs, not just fix it. The maintenance organization is responsible for defining the maintenance strategy based on three main criteria:

1. Ensure the availability of the entity for the required function, often at the optimal cost;

2. Consider the safety requirements associated with the entity for both maintenance and user personnel and, if necessary, any impacts on the environment;

3. Improve the durability of the entity and/or the quality of the product or service provided while considering cost, if applicable.

Maintenance is not limited to technical actions, but includes all activities such as planning, documentation management and many others [1]. In general terms, maintenance can be divided into two types:

- Ordinary Maintenance: It includes all those activities that, during the life cycle of the asset, aim to repair it, maintain the original integrity of the asset, maintain or restore efficiency, contain normal deterioration, face accidental events and minimize the duration of downtime;

- Extra-ordinary Maintenance: It includes, on the other hand, high-cost activities that can extend the useful life and improve efficiency, reliability, productivity, maintainability and inspectability. It do not involve changes in the intended use of the asset and seek to minimize the frequency of downtime and asset's duration [5].

In this thesis work, when we mention maintenance, we refer to the maintenance of public transport buses. For this reason, a third type of maintenance appears which includes Shunter Activities. This is a type of maintenance peculiar to means of transport.

- Shunter Activities: It is a type of maintenance on the same level as Ordinary and Extra-ordinary Maintenance, as it does not fall under either of the two mentioned above. It is not a mandatory type of maintenance to be performed but it brings many benefits. It can be performed by the Maintenance Area or by Operation. Usually for urban transport vehicles it is performed by the Maintenance Area as the work is guaranteed 24 hours a day; on the other hand, for extra-urban public transport vehicles shunter activities are performed by the Operation.

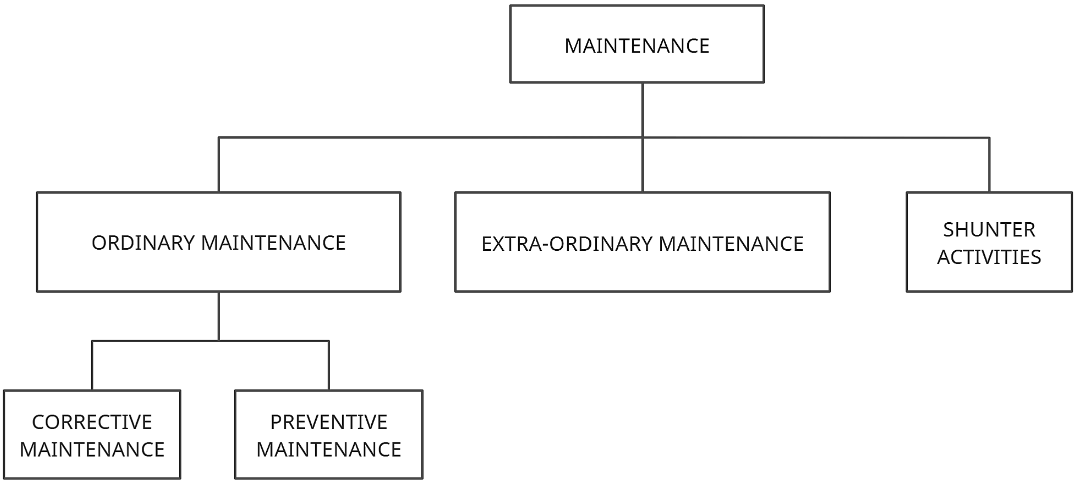

Figure 1.1: Maintenance classification - By My own work

1.1 Ordinary Maintenance

Ordinary maintenance can be further divided into Corrective Maintenance and Preventive Maintenance.

1.1.1 Corrective Maintenance

It is also known as Run-to-failure maintenance. It is performed as a result of fault detection in order to restore the functionality of the asset. The logic of run-to-failure management is simple and straightforward. When an asset breaks, fix it. This "If it ain't broke, don't fix it" method of maintaining asset has been a major part of maintenance operations. A company using run-to-failure management does not spend any money on maintenance until a machine or component fails to operate and a failure develop into a breakdown. Run-to-failure is a reactive management technique that wait for component failure before any maintenance action is taken:

however, it is actually a "no-maintenance" approach of management. It is also the most expensive method of maintenance management, especially in the long run. The major expenses associated with this type of maintenance management are high spare parts inventory cost or at least all major components of all critical vehicle equipment, high overtime labor costs, high machine downtime, and low service availability. The alternative is to rely on equipment suppliers who can provide immediate delivery of all required spare parts, but of course the premiums for quick delivery substantially increase the cost of repair parts and the downtime required to correct failures. The net result of this reactive type of maintenance management is higher maintenance cost and lower availability of service. Analysis of maintenance costs indicates that a repair performed in the reactive mode will average about three times higher than the same repair made within a scheduled or preventive mode. Scheduling the repair minimizes the repair time and associated labor costs. It also reduces the negative impact of expedited shipments and lost service [3].
People have realised that the strategy to wait to repair equipment until it fails is often not a good solution. The breakdown may come at an inconvenient time and the sudden and unexpected stoppage can be very expensive. The breakdown may even become a source of problem for nearby equipment (secondary damage), the environment (pollution) and may even pose health and safety problems to nearby personnel. One solution is to use scheduled maintenance, stopping the equipment regularly for checking and service. The problem with this approach is that the equipment is stopped also in unnecessary cases, and sometimes the stop and unnecessary service action may causes increased disservice and costs due to downtime. [6].
To summarize, this kind of maintenance involves:

- Exploitation of the component until breakage and thus for its entire life;
- Expensive maintenance cost in the long term;
- Resource planning not simple;
- Acting in emergency scenarios;
- Large number of spare parts are needed.

This type of maintenance can always be applied, but it is expensive and has negative impact on safety and environment [4]. In some cases, corrective maintenance may be the best option. For example, let's imagine we have an end-of-life bus that will soon be scrapped. It would not be wise to perform preventive maintenance but wait until a failure occurs and then take action. On the other hand, if we decided to perform only corrective maintenance, we still have to consider environmental and safety impacts. Therefore, at least one preventive maintenance action per year should be implemented. This is a pull system, meaning maintenance is "pulled" by what happens, i.e., failures.

1.1.2 Preventive Maintenance

There are many definitions of preventive maintenance, but all preventive maintenance management programs are time or mileage driven and actions are performed before a failure has occurred, just to avoid its occurrence. Since we are dealing with buses, the deadlines will be time or engine hours or mileage driven. Preventive maintenance requires widespread commitment in the production organization because it requires weekly or monthly inspections, monitoring of control equipment signals, and immediate restoration of facilities when a malfunction occurs, in order to resume their use. Preventive maintenance includes scheduled maintenance - or systematic maintenance - which is performed at regular intervals (Time-based Maintenance), timed according to the type of asset: daily, weekly, monthly and even annually [5],[3].
According to legislation, it is defined as *"Maintenance performed at predetermined intervals or according to predetermined criteria and intended to reduce the probability of failure or degradation of an entity's operation."* [1]
It may be divided into:

- Cyclic Maintenance: Actions are based on elapsed time regardless of the state of the asset. Time intervals between one action and the next one are decided on the basis of predetermined parameters or experience. It is performed without inspection of component conditions;

- Condition based Maintenance (CBM): It is maintenance related to the condition and reliability of the asset, is one of the forms of preventive maintenance at non-regular intervals and includes preventive actions contingent upon the verification of a specific condition of a system, ascertained on the basis of operating variables such as, for example, the mileage, average and maximum temperature, engine hours. It requires inspections, monitoring and testing to define the consequent maintenance actions. Thereby there could be some component to be replaced according to cyclic maintenance and not to maintenance by condition, and vice versa. Its purpose is to reduce the probability of a failure occurring when the deadline for cyclical maintenance has not yet been reached, or vice versa, to postpone cyclical maintenance when a certain threshold is not reached. To do it requires the competent use of several diagnostic techniques.

- Predictive Maintenance: It is a kind of maintenance that monitors the performance and condition of equipment during normal operation with the aim to reduce the likelihood of failures. It is the most complicated type and involves an accurate evaluation of key parameters in order to estimate the residual life of the components and plan the replacement. Estimation of component lifetime is done through algorithms and AI.

It is important not to confuse condition based maintenance with predictive one, which involves consideration of the remaining life of the asset. Both maintenance are related to degradation of the asset but the by-condition maintenance is based on reaching a user-defined threshold that is reflected in receiving an alert, while the predictive one must be able to assess the remaining life of the system.
During preventive maintenance is used to do activities required by regulations and laws, equipment care, lubricating and greasing mechanical parts. As a result, costs can be reduced on the long run, resources can be planned in the best way, major deterioration and failures are avoided, number of spare parts is reduced. On the other hand, cyclic maintenance could require to do activities not necessary without exploiting the life of component. The benefit is that safety is better preserved. Defining the frequency with which preventive maintenance should be performed is not easy. The point in the life of the component at which there is a significant increase in the failure rate should be identified but it is not always evident. If the point in the life of the component where there is an increased failure rate is not obvious, we could perform corrective maintenance or a mix of both. Performing only corrective maintenance is not a good solution.
Below is an example in which the increase of failure rate is evident and it is easy to plan for preventive replacement or corrective action. The example shown in the

figure is the result of a study done in 2008 on the failure rate of an Iveco model 491 engine used in an urban bus. The plot can be achieved by analyzing the number of failures in a given time interval or mileage, precisely as stated in the definition of Failure Rate that will be discussed in subsection 1.6.1. Otherwise failures happen randomly and it is not easy to plan for replacement. As shown in Figure 1.2, where the failure rate is plotted on mileage, after about 290 000 Km there is a significant increase in the failure rate and it may be wise to perform a corrective action on the engine. The graphic does not clearly mention what the fault is, only that it is inherent in the engine.

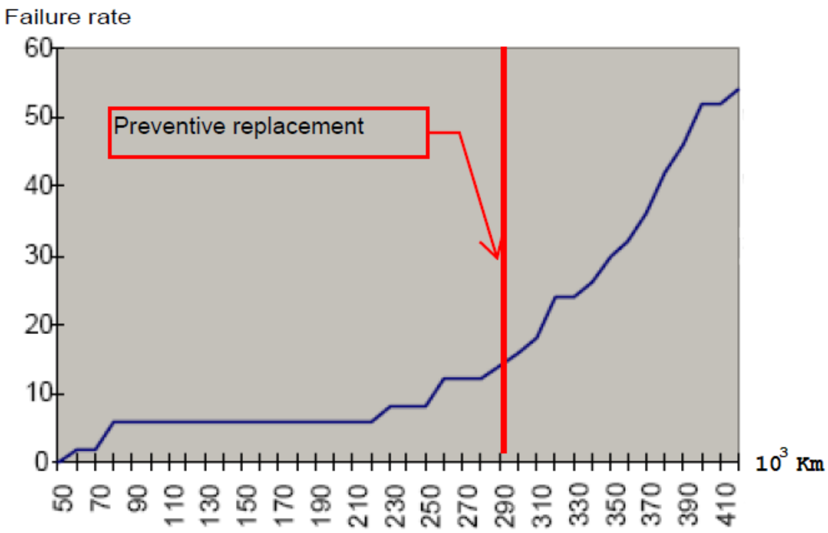

Figure 1.2: Cumulative failure rate of an Iveco engine 491 - By Arriva Italia 2008

1.2 Extra-Ordinary Maintenance

In addition to ordinary maintenance, there is one more type of maintenance that can be performed at any time and is defined as "Improvement Maintenance". This is the combination of improvement actions or minor modification undertaken with the purpose of improving reliability (through the elimination of the causes of systematic failures and/or the reduction in the probability of occurrence of other failures) and the maintainability of the asset. It should be noted that "minor" changes are

defined as not increasing the asset value of the entity. Maintenance Improvement derives from the principles of TPM (Total Productive Maintenance) and aims at continuous improvement. It therefore deals with the identification of potential improvement actions, both with the use of methodologies and analytical techniques, but especially with the involvement and motivation of the people who work in close contact with the asset. TPM is an approach that also includes a chapter on Maintenance Engineering. TPM does not mean extra-ordinary maintenance but this one can be understood as an effect of TPM, i.e. to perform maintenance on the asset in order to improve it over time and extend its useful life. During my internship experience at Arriva Italia Srl, I had the opportunity to take part in initiatives of small changes in order to make improvements to the components. A quick example would be the construction of support brackets for the coolant tank. Some types of vehicles are initially equipped with a metal tank. This has a higher cost, higher weight and avoid to detect coolant level from outside. For this reason, improvement maintenance was performed by installing a translucent plastic tank. This means lower costs, less stress on the brackets due to the lower weight and detection of the coolant level in a short time. As a result, downtime to check the coolant level and the likelihood of tank breaking is reduced. Obviously, each activity is followed by a Technical Note that is an official document signed by the Engineering Director and distributed to all depots so that everyone can implement that action.
A substantial difference between ordinary and extraordinary maintenance is that the costs of the latter may be amortisable. When you buy a bus, you create an asset. Extraordinary maintenance increases the value of the asset. The asset can be depreciated over 8 to 12 years or over its entire useful life (15 years for buses). If the bus has already reached a certain age, activities can be performed to extend its life and these can be depreciated.

1.3 Shunter Activities

Another type of maintenance is defined as Run Out Maintenance and includes:

- Movement of vehicles and reorganization of the depot;
- Vehicle refueling (oil, diesel, coolant, ecc.);

- Preparation of the bus exit in the morning;
- Exit assistance;
- Cleaning.

This type of maintenance is often underestimated and people tend to consider it as not a real maintenance. In depth, refueling is essential to ensure service, exit assistance is necessary to guarantee regular service and cleaning is a way to ensure comfort. Support must also be provided by drivers and passengers.
The former have to perform the so-called "First Use Checks", i.e. quick checks on the bus before starting their daily work. These checks will be discussed in more detail in the following chapters. Passengers can, however, contribute not in a direct sense to maintenance but certainly reduce the workload of maintenance activities. It is easy to understand how damage to the seats, bus windows or even the external bodywork requires more work from the technicians to restore them. At this point we are no longer dealing with accidental failures but with intentional damage in which the passengers are responsible. Passengers should therefore be made aware that they should only use the buses as a transport service without causing damage.

1.4 RCM and TPM

In the last decades several organisational approaches to arrange the maintenance work as efficiently as possible have been developed. Such methods are, e.g., Total Productive Maintenance (TPM), Reliability-Centered Maintenance (RCM) and Condition-Based Maintenance (CBM). These methods have been implemented in the industry with mainly very good results. [7]

1.4.1 RCM - Reliability-Centered Maintenance

RCM is a unique tool used by reliability, safety, and/or maintenance engineers for developing optimum maintenance plans which define requirements and tasks to be performed in achieving, restoring, or maintaining the operational capability of a system or equipment. Implementing the RCM process requires the application of a decision logic that enables systematic analysis of failure mode, rate, and criticality

data to determine the most effective maintenance requirements for maintenance-important items. It is through this process that the scheduled maintenance burden and support costs are reduced while sustaining the necessary readiness state.
RCM benefits include:

- The development of high quality maintenance plans in less time and at lower cost;
- The availability of a maintenance history for each system; one is able to correlate this experience with specific parts and their failure modes and criticalities;
- The assurance that all maintenance-important parts and their failure modes and criticality are considered in the development of maintenance requirements;
- The increased probability that the level and content of the maintenance requirement is optimally specified;
- The basis for routine, on-line information exchange among the engineering staff and management even in a widely dispersed organization. [8]

1.4.2 TPM - Total Productive Maintenance

TPM is an advanced manufacturing technique that focuses on maximizing the overall equipment effectiveness of any asset utilized in the production of services. TPM involves everyone in the organization from operators to senior management in equipment improvement [9]. In today's world, modern maintenance should no longer be regarded as a hepisodic reaction to failures and malfunctions, but an activity that must be conceived as a new "company service" aimed not only at maintaining the living conditions of the productive organisation and market, but also to improving the efficiency and quality of all business processes. For this reason, this new "corporate service" must be "pervasive" and "ubiquitous": it must not be the responsibility of a few appointed operators, or of a specialised office or intervention department, but must extend to the whole organisation and monitor every aspect of it which, over time, may reveal some likelihood of malfunctioning or some form of "decay". This new maintenance function is called Total Productive Maintenance (TPM). TPM combines the “Western method” of

preventive maintenance with the “Japanese” method of Total Quality Management, which involves personnel at every business level and provides that the “control” of the efficiency of machinery and systems is not the function of a single specialized office but is implemented by entire organization. It requires that each member of the organisation must acquire the motivation to maintain and improve corporate integrity and must be equipped with the appropriate cognitive and operational tools. The goal of the TPM program is to markedly increase production while, at the same time, increasing employee morale and job satisfaction.
The adjective "Total" has three meanings:

- Total efficiency: indicates the search for productive efficiency, but also economic and financial efficiency;

- Total maintenance system: includes reactive, corrective, preventive and proactive maintenance;

- Participation of all employees and includes autonomous maintenance, performed by operators in small groups.

The ideal situation that assumes that a system can remain immune to failures and breakdowns throughout its useful life seems unachievable; however, the need to minimise the temporary unavailability of machinery and the costs resulting from both malfunctioning and repairs makes it necessary and urgent to adopt increasingly sophisticated and integrated maintenance policies and techniques both within the maintenance function itself and throughout the company. Maintenance, therefore, is not synonymous with "repair" but must be understood as a "process" aimed, first of all, at understanding the technical and human causes that produce failures and, consequently, at deciding and planning actions to prevent the failures themselves and maximise the overall efficiency and economic effectiveness of the production system. Therefore, great importance is being attached to the personnel aspect, not only in terms of preparation but also team spirit. Indeed, in maintenance it is necessary to combat individualism, which allows neither collective growth nor development. This problem can be solved through greater communicativeness and greater involvement in the processes that govern the company. This is precisely the logic of TPM [5].

1.5 Which maintenance approach to choose?

Real-world scheduling problems are usually complex and involve many approaches to find sub-optimal rather than optimal solutions using reasonable computing resources. The bus maintenance scheduling problem, which is distributed and dynamic in nature, has received less attention compared to scheduling problems in manufacturing. There is no unique answer to the question because the choice depends on some different aspects:

- Corrective maintenance is the easiest and cheapest on the short time because it doesn't require planning, but it is characterized by huge number of failure, greater degradation of the asset and expensive costs on the long term. When we talk about transport we need to take into account that it is a service offered to passengers and therefore it is necessary to plan in the best way the number of vehicles to be taken out of service for maintenance activities, in order to ensure ordinary service without having lack of work buses;

- Preventive maintenance is moreover enforced by legislation (i.e. DMV Department of Motor Vehicles test).

Significant importance is given to costs:

- Cyclic maintenance is the most expensive because involves costs of planning and job preparation, has a systematic approach about replacing with the risk of replacing components that have not reached the end of their life;

- Maintenance by condition involves costs of planning and job preparation, but also costs of inspection and monitoring of conditions and sometimes requires subjective decisions;

- Predictive maintenance is the solution to optimize replacements but requires additional costs beyond those listed above.

In summary, the best solution is to use a maintenance plan consisting of a mix of different approaches. Usually in Italy, it is used a mix composed of scheduled maintenance for 25%, predictive-by condition maintenance for 25% and corrective maintenance for 50%.

1.6 Asset design

Maintenance is an activity performed on an asset that has been previously designed. For this reason, we can think to maintain an asset efficiently and effectively, but it is necessary that asset must be designed to be maintainable. It is also appropriate to keep in touch with the manufacturer so as to involve him in case of invasive improvement activities. Another important aspect is that at least in the first years of life the asset is in warranty and therefore it is necessary to observe the policies of the manufacturer. If we wanted to represent in a graph the trend of the failure rate versus time, the shape would be similar to a bathtub.
The vertical axis is the failure rate at each point in time and the horizontal axis is the test time. The bathtub curve is the result of the sum of three components:

1. The red curve is "Infant Mortality". It is the early failure (or break-in) stage. During this period failures typically occur because products were not designed properly or manufacturing flaws occurred. Failure rates at the beginning of the early failure stage are high, but then they decrease with time as the early failures are removed;

2. The yellow curve is due to "Wear Out Failures". This is the final stage where the failure rate increases as the products begin to wear out and break down due to asset's age. When the failure rate becomes high after a long period of use, repair or replacement of parts should be performed. For transport, the failure rate rises to 8-9 years because the gearbox and differential require maintenance. The years of life considered are 15, for tram 30 or even more;

3. The green curve is representative of "Random Failures" and it is characterized by a constant failure rate. This stage is the most significant for prediction and reliability assessment activities.

One of the most important goals is to extend the life of components prior to the onset of wear out. Remarkable strides have been made in this direction. Thus, we can consider the bathtub curve composed of three regions: early failure, useful life, and wear out. Actually, many systems do not readily fail, but rather become obsolete as a result of design changes and introduction of new technology [10].

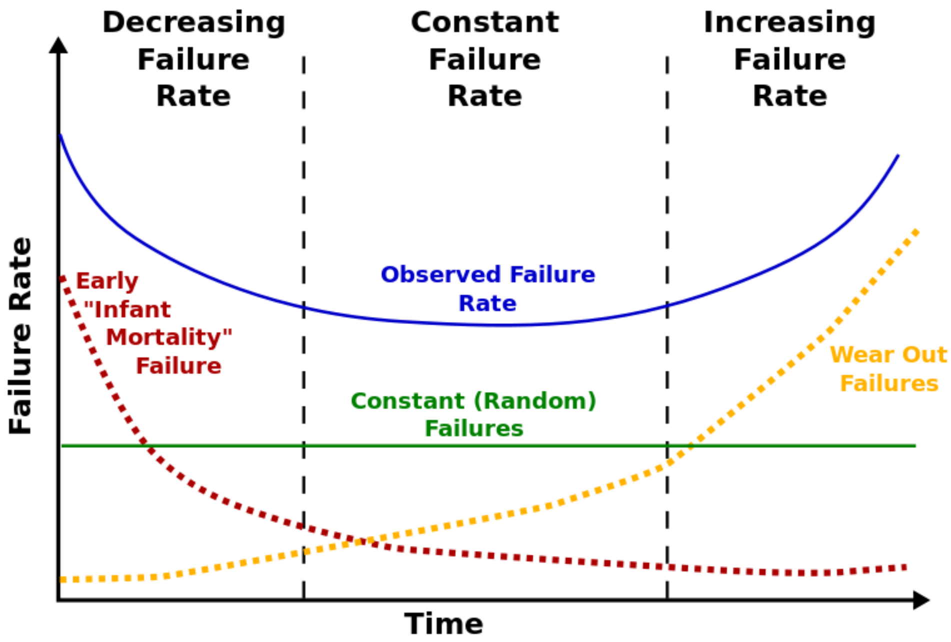

Figure 1.3: Bathtub curve - By Wyatts and McSush

The useful life of a bus is estimated at 15 years and that of a tram at around 30 years. The useful life can be extended by extraordinary maintenance. However, this requires a cost-benefit analysis to find out whether the costs can really be balanced against the benefits. This analysis then has to be cross-referenced with financing. In the LPT world, the purchase of new buses is done either by external financing or by the company itself. Given the high cost of a bus, if the company does not have the resources to buy a bus, it can request financing or perform extraordinary maintenance that would extend the useful life of the bus that would have to be scrapped. These activities are usually bodywork, both internal and external, such as underframe repair or interior coating to make the bus comfortable and suitable for service. The concept of the bathtub is all the more true when the item analysed derives from mass production with an assembly line. The more we move towards handmade production, the more the bathtub concept is less respected. Therefore, since buses are not built by an assembly line but by assembling several components, it is necessary to take into account how each individual component was made. As far as buses are concerned, the bathtub would present two peaks: the first after about 9 years because of "major replacements" and the second one at the end of its life at about 15 years. Therefore, we can consider the bathtub model as consisting of two adjacent bathtubs.

1.6.1 Failure Rate

The Failure Rate $\lambda(t)$ of a component at time t is defined as the probability of a component failing at time t. It is usually denoted by the Greek letter λ (lambda). According to legislation, failure rate is defined as *"Number of failures of an entity in a given time interval divided by the interval itself"* [1].
Let assume N_F = number of components that failed during the time interval $t+\ \Delta t$ and N_S = number of components that have NOT failed by time t. If Δt is small and the failure rate does not change during this time interval, then the failure rate at time t can be calculated as:

$$\lambda(t) = \frac{\text{Number of component failures between } t \text{ and } t{+}\Delta t}{(\text{Number of component that have NOT failed by time } t) \times \Delta t} = \frac{N_F}{N_S \times \Delta t} \tag{1.1}$$

While it is relatively easy to define failure rates for individual product components such as springs or gears, it becomes more difficult for complex products like cars or buses. For example, a failure in a complex product can be complete breakdown (a catastrophic failure) to a relatively minor, easily repaired failure. While failures in complex products may be repairable, they may not be repairable for individual product components [10].

1.6.2 Reliability

An important concept is Reliability R(t), which is, according to legislation, *"The probability of the entity to perform the required function with the set conditions for an established time"* [1] i.e., at least, for the intended mission prior to return to the depot if we consider buses. It is not required to never fail. For example if a bus has a breakdown when it returns to the depot it is acceptable because it has already performed its service. If we have a large number of a certain component that we can test over time, then the reliability of that component at time t is given by:

$$R(t) = \frac{\text{Number of components that have NOT failed by time } t}{\text{Total number of components being tested at time } t{=}0} \tag{1.2}$$

At time t=0, the number of components that have not failed is equal to number of components being tested. Therefore, the reliability at t=0 is R(0)=1=100%.

Note that the reliability, R(t), will continuously decline as t increases and components fail. When the failure rate is constant, the reliability graph is a straight horizontal line and represents the middle phase of a bathtub curve. When there is little break-in failure (early failure), a constant failure rate can be effectively used to predict the reliability of a product to a particular time. If the failure rate $\lambda(t)$ is a constant (i.e., independent of t so then we can set $\lambda(t) = \lambda$), then the reliability R(t) at time t is given by:

$$R(t) = e^{-\lambda t} \qquad \text{where } \lambda = \text{ constant failure rate} \tag{1.3}$$

For example, if there are initially 1000 components and their failure rate is constant at $\lambda = 10\%$ per hour, then using Eq. 1.3 the reliability after 3 hours, with $\lambda =$ 0.1/h, is:

$$R(t) = e^{-0.3} = 0.741 = 74.1\% \tag{1.4}$$

In order to describe reliability, two markers could be used: **MTTF** and **MTBF**. The Mean Time to Failure (MTTF) is the average time an asset may be expected to function before failure and this concept is applied to non-repairable items, i.e spare parts. "An entity is considered non-repairable if, as a result of the failure, it cannot be brought back to its normal operating condition and therefore a new entity must be provided for that purpose. Vice versa, a repairable entity can be brought back, through a maintenance intervention, to its original functionality" [4]. The Mean Time Between Failures (MTBF) applies to repairable items.
Since this refers to the mean time between failures it is defined as

$$\text{Mean Time Between Failure=MTBF} = \frac{\sum \text{Time in operation,T}}{\text{Total number of failures during time T}} \tag{1.5}$$

A sequence of failure events is shown in Fig. 1.4.

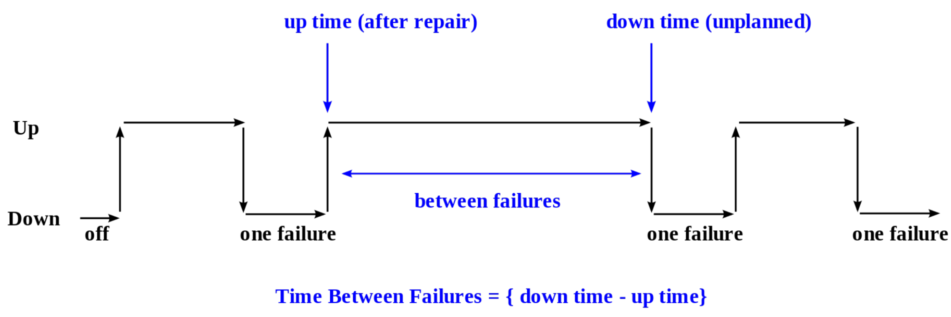

Figure 1.4: Time Between Failures, By Ferdna Andjohn 2000

The time between the beginning of the failure and the end of the failure corresponds to the unavailability time of the asset. The time between the end of the previous failure (within which the previous failure is repaired) and the beginning of the new failure (next failure) is called TBF (Time Between Failure). Given a longer period of time, such as a year, there would be a sequence of failures and repairs. After all respective TBFs have been calculated, the MTBF value can be calculated as a sample average of the TBF values.
For example, if an asset has failed five times over a period of exactly 10000 hours then its MTBF is 10000/5 = 2000 hours. Notice that the MTTF is the same as the MTBF. Thus, for a constant failure rate, $\lambda(t)=\frac{1}{MTBF}=\frac{1}{MTTF}$. For example, the item above fails, on average, once every 2000 hours, so the probability of failure for each hour is obviously 1/2000. This result depends on the failure rate being constant. Accordingly, MTBF (or MTTF) = 1/F. For example, if the failure rate $\lambda = 0.0002$ per hour, then MTBF (or MTTF) = 1/0.0002 = 5000 hours. The reason for the preferred use for MTBF numbers is that the use of large positive numbers (such as 2000 hours) is more intuitive and easier to remember than very small numbers (such as 0.0005 per hour) [10].
The MTTF is simply the average of all the times to failure. It is used for non-repairable components and the failure time is the time between when the component goes into service and when it fails.

$$\text{Mean Time To Failure=MTTF} = \frac{\sum \text{Time in operation,T}}{\text{Total number of failures during time T}} \tag{1.6}$$

For example, if four items are tested to failure and have lasted for exactly 3900, 4100, 4300, and 3700 hours respectively, then the MTTF is:

$$\text{MTTF}=\frac{3900+4100+4300+3700}{\text{4 failures}} = \frac{\text{16000hours}}{\text{failures}} = \text{4000hours per failure}$$

Similar to the calculation of TBF and TTF, it is possible to consider the time interval between two successive maintenance actions. Given a certain time interval, in addition to accidental failures and therefore replacement, preventive maintenance will also be planned. It is possible to calculate the TBM (Time Between Maintenance) as the average time between two successive maintenance interventions, whether they are preventive or corrective. The MTBM index will be calculated as a sample average of all maintenance interventions:

$$\text{Mean Time Between Maintenance=MTBM} = \frac{\sum \text{Time in operation,T}}{\text{Total number of maintenances during time T}} \tag{1.7}$$

1.7 Deming Cycle Plan-Do-Check-Act

Different organizations use different methodologies, approaches and tools for implementing a quality management and programmes for continuous quality improvement. Most of these tools, approaches and techniques are used worldwide and simple to understand and can be used by a large number of people of the company, e.g. PDCA cycle or Deming's circle. It is very important that tools, approaches and techniques should be selected for the appropriate team and applied correctly to the appropriate process. The successful implementation of approaches, tools and techniques depends on their understanding, knowledge and proper application in organizational processes. In a central process, the actual results of an action are compared with a target or a set point. The difference between the two is then mentioned and corrective measures are adopted if the disparity becomes large. The repeated and continuous nature of continuous improvement follows this usual definition of control and is represented by the PDCA (Plan-Do-Check-Act) cycle. This is also referred to as the Deming circle, named after W. E. Deming. Another variation of PDCA is PDSA (Plan, Do, Study, Act). PDCA was not the first tool to be introduced.

Dr. Walter A. Shewhart displayed the first version of the "Shewhart Cycle" in 1939. It was composed of three steps: Specification, Production and Inspection. To be specific it was not a circle but a straight line. They corresponded respectively to making a hypothesis, carrying out an experiment, and testing the hypothesis. The three steps constituted a dynamic scientific process of acquiring knowledge. Shewhart's 1939 book was edited by a 39-year-old W. Edwards Deming. In 1950, Deming modified the Shewhart "cycle". His straight line: Step 1- Design, Step 2 – Produce, Step 3 - Sell was converted to a circle with a fourth step added: Step 4 - Redesign through marketing research. Deming stressed the importance of constant interaction among design, production, sales, and research and that the four steps should be rotated constantly, with quality of product and service as the aim. Deming's Shewhart cycle was modified slightly in 1951. The Japanese called this the "Deming wheel". Imai, a Japanese economist, stated the Japanese executives recast the Deming wheel from the 1950 JUSE (Union of Japanese Scientists and Engineers) seminar into the Plan-Do-Check-Act (PDCA) cycle.

Imai shows the correlation between the Deming wheel and the PDCA cycle.

- P - Planning: Product design corresponds to the planning phase of management. It is important to establish the goals and processes necessary to deliver results consistent with those expected, through the creation of production expectations, completeness, and accuracy of specific choices. Whenever possible, it is recommended to start small, to test possible effects;
- D - Doing: Production corresponds to doing-making, or working on the product that was designed. Thus, the second phase is the execution of the program, first in limited contexts. It need to implement the plan, execute the process and offer a service in our case. It is useful collecting data for the creation of graphs and analyzes to be allocated to the "Check" and "Act" phases;
- C - Control: Sales figures confirm whether the customer is satisfied. Test and control, study and collect results and feedback. It is necessary to study the results, measured and collected in the "Doing" phase, comparing them with the expected results, objectives of the "Plan", to check for any differences. Looking for deviations in the implementation of the plan and focus on its adequacy and completeness to enable implementation. Data graphs can make this much easier, as you can see trends across multiple PDCA cycles, converting collected data into information;
- A - Act: The last phase is acting to make definitive and/or improve the process. It requires corrective action on significant differences between actual and projected results. In our case it is not enough to repair a failure or compensate a fault, but it is important to determine their causes and where to apply changes to achieve the predetermined results.

When a process, through these four steps, does not involve the need to improve the scope to which it is applied, the PDCA cycle can be refined to plan and improve the next iteration in greater detail, or the focus must be placed in a different phase of the process. The resulting PDCA cycle is shown in figure 1.5.

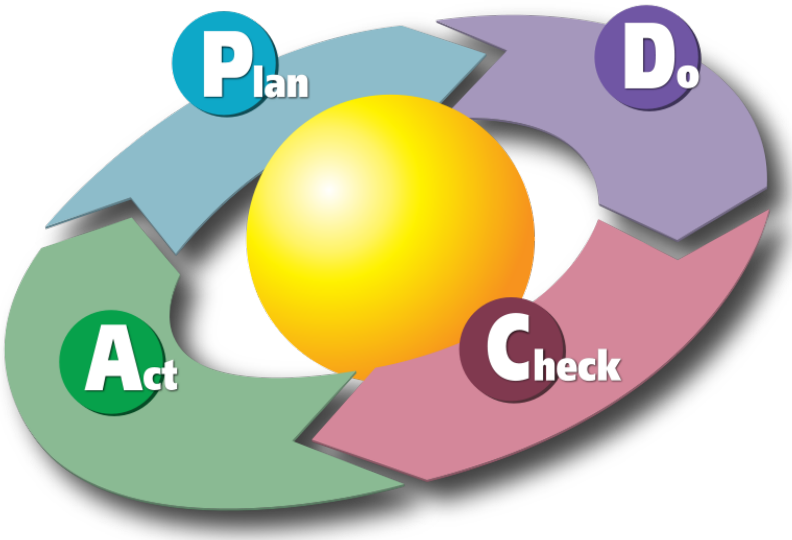

Figure 1.5: PDCA cycle - By Karn Bulsuk

The PDCA cycle enables two types of corrective action: temporary and permanent. The temporary action is aimed at results by practically tackling and fixing the problem. The permanent corrective action, on the other hand, consists of investigation and eliminating the root causes and thus targets the sustainability of the improved process. In 1987 Moen and Nolan presented an overall strategy for process improvement with a modified version of Deming's cycle of 1986. The planning step of the improvement cycle required prediction and associated theory. The third step compared the observed data to the prediction as a basis for learning. Langley and Nolan refined the improvement cycle and called it the PDSA Cycle. The use of the word "study" in the third phase of the cycle emphasizes that the purpose of this phase is to build new knowledge. It is not enough to determine that a change resulted in improvement during a particular test. As you build your knowledge, you will need to be able to predict whether a change will result in improvement under the different conditions you will face in the future. The PDCA and PDSA have their roots in the scientific method and the philosophy of science that has evolved for more than 400 years. In order to improve quality and satisfy the customer, it is necessary to go through all four phases constantly, with quality as the main criteria. This strategy can be applied in any industry, so this includes the transportation sector.

1.8 RAMS Analysis

In the design and determining frequent failure of large engineering systems, their engineering integrity needs to be determined. Engineering integrity includes *Reliability, Availability, Maintainability* and *Safety* of inherent systems functions and their related equipment. The overall combination of these four topics constitutes a methodology that ensures good engineering design with the desired engineering integrity. This methodology provides the means by which complex engineering designs can be properly analysed and reviewed, and is termed a RAMS analysis [11].

1.8.1 Reliability

The concept of reliability has been discussed in subsection 1.6.2. The failures of an entity are caused by phenomena that also affect its reliability. These phenomena also increase the degree of wear of the asset and progressively reduce the time between one failure and the next one (MTBF,MTTF). Maintenance has the objective of contrasting these phenomena, reducing or eliminating them, with preventive or improvement actions. To do this, it is necessary to study the history of the entity failures and analyze that data. A first step is the calculation of reliability parameters [4]. Reliability can be regarded as the probability of successful operation or performance of systems and their related equipment, with minimum risk of loss or disaster or of system failure. Designing for reliability requires an evaluation of the effects of failure of the inherent systems and equipment.

1.8.2 Availability

According to current legislation, "*Availability is the aptitude of an entity to be able to perform a required function, under certain conditions, at a particular instant or during a given period of time, assuming that the necessary external resources are provided.*"[1] For instance, if we consider public transport, it is required availability of a precise number of buses in order to ensure daily service. But it is not enough to have buses available in the morning, because if the vehicles break down as soon as they cross the threshold of the depots, we have not done our job, which is to take passengers to work rather than to school. Buses must perform the required service during a certain period and additional reserve buses must also be provided. For this reason, the bus fleet must be larger than the buses required by the service because reserve vehicles must also be considered. In the ideal world it is not necessary to have a reserve, in real world it is. A fair compromise is to have a 10-20% reserve, but it is not a unique number. The lower the reserve, the lower the costs. But if a service is very variable, for example buses of different lengths or different missions, it would be appropriate to have many different vehicles and very different reserves. If the buses are spread out over the territory, the greater the reserve I need. For example, if a depot is on the high mountains, it is necessary to guarantee a reserve because we can not send a long bus from a depot in the plains to another one on the mountains. The increase in vehicle reserve can be forced. The reserve may be variable over time because missions may change.

1.8.3 Maintainability

The first two concepts could not exist without the concept of *Maintainability*, which is, according to legislation, *"The aptitude of an entity, under certain conditions of use, to be maintained or restored to a state in which it can perform the required function, when maintenance is performed under given conditions and the prescribed procedures and resources are adopted"* [1]. Another way of expressing the concept of maintainability is "How easy is it to maintain the asset". To better understand the concept we can add words like: accessibility, extractability, manipulability and interchangeability. For example, if we wanted to take access to a component or a valve, there might be cases in which we are forced to remove other components in front or cases where we can take access to the component easily. In the first case the component has low maintainability, in the second one high. Maintainability is a consequence of the asset design. Since the initial stages of designing a component, the designer has to take into account its disassembly, replacement and reassembly in order to ensure high maintainability.

1.8.4 Safety

Safety can be categorized into three main areas, one related to personal protection, another related to the equipment protection, and yet another related to the protection of the environment. In this context, Safety's purpose is to "not involve risk", where risk is defined as "the chance of loss or disaster". Designing for Safety is inherent in the development of design for reliability and maintainability of systems and their associated equipment. Environmental protection in engineering design, relates to the prevention of failure of the inherent process systems resulting in environmental problems associated predominantly with the treatment of wastes and emissions. For instance, during maintenance activities performed in the LPT sector, it is important not to dispose of waste oil into the environment, wear and tear materials such as brake pads, and ensure that exhaust after-treatment systems are working efficiently. The purpose of risk analysis techniques is to estimate all risks present and evaluate them in order to make them acceptable. These techniques therefore allow, if carried out correctly in the initial phases of design, to eliminate criticality before commissioning or placing the component on service, reducing costs. RAMS is started early in the conceptual stages of design and must continue throughout the life of the product or service. The overall combination of these four topics constitutes a methodology that ensures good engineering design with the desired engineering integrity. Such an analysis and review is conducted not only with a focus upon individual inherent systems but also with a perspective of the critical combination and complex integration of all the systems and related equipment, in order to achieve the required reliability, availability, maintainability and safety. This analysis is often termed a RAMS Analysis [11].

1.9 FMEA - Failure Mode Effects Analysis

The manufacturer does the RAMS analysis through FMEA (Failure Mode Effects Analysis) which is a technique for estimating the four terms listed in the section 1.8. It is applied to each system, subsystem and component linked to the main system. Specifically, the failures and causes are predicted and the effects that these failures may have are estimated in order to eliminate these weaknesses early in the development cycle where it is easier to take actions to mitigate the failures, starting with those with the highest priority. As a corrective action, we could redesign, install a sensor, or put in something of redundant. A failure could be little serious as effect but maybe it keeps the vehicle out of service for a long time and creates high unavailability. The manufacturer does feasibility study, design, project development. Already in the vehicle construction phase it is possible to predict if the product will present problems during its life.
The FMEA deals with each system function and all possible failures. Then examines the consequences of failure to determine what effect failure has on the mission or operation, on the system. In spite of the fact that there are more than one mode of failure, often the effects of failure are the same or very close in nature. From the perspective of system function, the result of any component failure can lead to the degradation of the system. Often similar systems and machines will have the same failure modes, but the use of the system will determine the consequences of the failure, which can then be quite different. A failure mode in an equipment item or component could also be the failure cause of a system failure. Since a failure mode may have more than one cause, all potential independent causes for each failure mode shall be identified.
The fault characteristic for the failure mode should be identified as follows and already discussed in the section 1.6:

- Infant mortality: shall be used for failures associated with manufacturing defects and installation, maintenance or commissioning errors or even errors in the design phase;

- Random Failure: shall be used for failures associated with random breakdowns caused by sudden stresses, extreme conditions, random human errors, or any failure that is not predictable over time;

- Wear failure shall be used for failures related with end-of-life issues for components.

Another very similar term used in this context is FMECA (Failure Mode Effects and Criticality Analysis). Both are two methodologies; FMECA is an extension of FMEA with an extra section of criticality analysis. The purpose is to identify system failures, the reasons for the failures, and the subsequent impact of those failures on the system. As a result, studying the system's criticalities also leads to greater reliability, improved safety, better quality and saving of costs [12].
It is very important to make these analyses in the early stages of design because it is very common for the maintenance phase to be more demanding than the design phase itself, so it is considered useful to make a greater effort in the early stages and then benefit from it in the later stages.

1.9.1 Differences between FMEA and FMECA

It can be argued that FMEA and FMECA are two very similar methodologies and that the second one is an extension of the first one. However in many texts and sources, the terms FMEA and FMECA are used to explain the same methodology and usually both include the criticality analysis. Below are some key differences to better understand the two methods:

- FMECA is an extension of FMEA. Therefore, it is necessary to perform FMEA first and then by adding criticality analysis it be possible to obtain FMECA;
- The FMEA method provides only qualitative information, while FMECA provides quantitative information in addition to qualitative ones. The latter assigns a level of criticality to failure modes;
- FMEA determines the failure modes of a product or process and their effects, while Criticality Analysis ranks those failure modes in order of importance considering the failure rate.

Chapter 2

A deep dive into Bus Maintenance

The scheduling of maintenance activities is an important component in bus transit operations planning process. The other components include network route design, setting timetables, scheduling vehicles, and assignment of drivers [13]. In bus transportation companies, buses are maintained regularly in fixed time or mileage intervals in geographically distributed maintenance depots. A depot performs maintenance jobs occurring and arriving dynamically.
The problem is dynamic in nature due to certain events:

1. The unexpected breakdowns of buses;

2. Changes in the assignment of buses;

3. Daily incoming maintenance tasks;

4. The change in availability of maintenance resources.

Normally, a bus transit company schedules its incoming maintenance orders in advance to take place in a specific time period. Such a time period is regarded as the scheduling horizon and can be sub-divided into time slots. Each maintenance job can be scheduled into one or several time slots. However, this predictive schedule is subject to change during execution due to unforeseen events. Hence, bus maintenance scheduling is comprised of two different parts: devising an initial schedule based on all known information about orders and their constraints, which is referred to as predictive scheduling, and adapting the schedule to dynamic events in real time, or the so called reactive scheduling problem. Ideally, managers of bus transit companies aim to maintain buses during their idle time to avoid extracting them from service (street time). In practice, this ideal situation is subject to constraints such as the availability of maintenance bays and buses. A maintenance bay is capable of handling only certain types of maintenance work; a bus is not available to be worked on for a particular maintenance type when in an alternative bay, receiving another form of maintenance, or when in service. Given a set of bus maintenance tasks, of interest is finding good schedules for all jobs to minimize the total out-of-service time and maximize the utilization of maintenance resources, and to simultaneously accommodate the four aforementioned dynamic events [14]. Fleet maintenance is another major component in bus transit operations and is one of the major problems with which the public transit agencies are faced. The reliability, safety, and vehicle life in bus transit systems depend on the maintenance system employed by the agencies. Maintenance costs are the second highest expense category after vehicle operations. They account for approximately 21% of the total operating expenses in a typical transit system. These facts make maintenance one of the most important and substantial elements of transit systems. Considering that maintenance costs have increased 33% faster than vehicle operating costs, and four times faster than general/administrative costs in recent years [15], providers of public transportation are being challenged by high costs, dwindling sources of support funds, and pressures to improve services. Therefore, transit agencies make capital investments in maintenance systems with the objective of having a reliable, safe and attractive transit system. There are numerous papers, articles, and scientific reports that document the results of studies in the bus maintenance area. Some of these studies try to identify different maintenance systems and their components, some focus on maintenance cost characteristics under different conditions, some attempt to offer maintenance performance indicators, and some evaluate different policies and strategies in maintenance systems. These studies can help maintenance managers in planning, managing, and controlling different aspects of the maintenance system. In most bus transit agencies' operations, buses are not assigned a fixed daily service schedule. To meet the daily route service requirements, buses are assigned to a scheduled route service on a daily basis. The entire fleet can be basically viewed as a pool of buses from which buses can be drawn either for daily service or for maintenance. In most agencies, the routine inspections and maintenance are performed in fixed time or mileage intervals. Buses go on a list as the deadline for their next inspection or routine maintenance approaches, and the list is processed generally in order of the due dates and crew availability for the inspection or maintenance that is needed. When buses have unexpected mechanical anomalies and breakdowns, they are pulled out of service, and depending on the type of repair needed, they are either sent to a major repair facility, or are scheduled for repair along with the buses that need routine inspection and maintenance [13].

2.1 Arriva Italia overview

Arriva Italia is one of the main local public transport operators in Italy. Since 2002 it has been present in the Italian market, of which it holds about 5%, providing passenger transport services both at urban and interurban level, mainly in northern Italy, as well as connecting services to the airports of Turin and Milan. Arriva Italia currently operates in Valle d'Aosta, in the provinces of Turin, Brescia, Bergamo, Lecco and Cremona, as well as owning majority stakes in Arriva Udine and Arriva Veneto and minority stakes in ASF Autolinee and Trieste Trasporti. Overall, the company provides public transport services for about 100 million bus/km per year, with 2500 vehicles and a total of 3500 employees. In 2012 Arriva Italia Rail, a company dedicated to railway services, was established.
The thesis work was carried out at the Turin site, therefore all considerations refer to the Turin fleet. Arriva Italia-Torino owns a fleet of about 215 vehicles, buses that are different in terms of length and mission and are located in various depots in order to have a homogeneous coverage over the whole territory.

Lenght	**Number of vehicles**	**Type of service**
< 10m	16	Interurban and suburban
>10m <12m	177	Interurban and suburban
>12m	21	Interurban, rental and GT

Table 2.1: Arriva TO fleet distribution

As shown in table 2.1, the 214 buses are different in terms of length and the type of service they are intended to provide. In particular, the company has vehicles with a length of less than 10m (also called "short"), between 10m and 12m (called "long") and more than 12m (called "extra-long"). "Short" buses are mainly used for mountainous or urban routes; "long" or "extra-long" buses are used in plains or on suburban routes where the length of the bus is not relevant. Of course, the length of the bus is also chosen according to the number of passengers it has to take. The type of service buses offer is also synonymous with the mission they perform: a bus operating in the mountains will work under more stressful conditions, while a bus operating on the flat, with constant engine speed, will work under less stressful conditions. Consequently, scheduled maintenance can be planned taking into account the type of service provided.

2.2 Arriva Italia Maintenance approach

As discussed in Chapter 1, Arriva Italia performs preventive, run-to-failure and extraordinary maintenance. In particular, the company have to find a compromise between the maintenance plans dictated by the manufacturer and the company's own internal policy. The company policy is a set of rules, established by each respective company, in order to implement maintenance actions and ensure the longevity of the vehicles. Usually the company policy is the result of many years of experience, tests and a trade-off in terms of cost-benefit regarding the lifespan of components and their replacement. When a new vehicle is sold to a public transportation company, the manufacturer guarantees a certain warranty period, usually 5 or 10 years. The vehicle, depending on the type of engine or on the environmental emission class or more generally on its characteristics (e.g. if it is normal floor or low entry) is provided with a user and maintenance manual. The manual indicates all maintenance operations to be performed and their respective deadlines and also the proper way in which the operations should be performed. Maintenance activities that have the same deadline are grouped together and are called Service or Maintenance Services. The set of services or maintenance services is called Maintenance Class. Therefore, it follows that each family of vehicles is associated with a maintenance class and consequently a set of services to which the vehicles must be subjected. This implies that the customer must strictly adhere to the requirements of the maintenance manual in order to meet the warranty.

Should the customer fail to meet the deadlines for a maintenance service, the vehicle supplier may retaliate against the customer and terminate the warranty period. This is the reason for which it is very important to plan maintenance activities appropriately and to prevent maintenance services from exceeding the manufacturer's schedule. In some cases, the maintenance customer may have a different policy, but at least for the warranty period of the vehicle, they are required to comply with the manufacturer's requirements.

2.2.1 Preventive Maintenance in Arriva Italia

The "Maintenance" section of Arriva Italia, like all LPT companies, performs preventive maintenance activities. For preventive purpose, services are carried out in compliance with the scheduled deadlines, as well as inspection activities. In particular, the inspection consists of a series of Mechanical, Electrical and Bodywork checks in order to identify any anomalies. These are mainly visual checks, but for the mechanical part there are other tests such as brake and steering test, steering to the left or to the right to see if the steering tie rod touches to the wheel, hand brake on/off, foot brake on/off to highlight any pneumatic leaks of the brake system. The inspection, as defined by company policy, is conducted at least twice a year. More than the required number of inspections is acceptable, less than two is not. Purpose of inspections is to find the fault in order to plan and schedule to do the corrective action before it develop into a breakdown. The inspection is performed, in a special inspection room, by an inspector who has attended a dedicated course in order to perform it properly. He has a dossier with the required check list, and for each one he reports whether they are compliant or non-compliant. At the end of the inspection, all non-compliance are collected and the dossier converted into an anomaly report. The workshop manager can decide to take immediate action and eliminate the anomaly or wait. Taking action immediately means putting the vehicle out of service for a longer period of time or, on the other hand, the repair of the anomaly detected during the inspection can be combined with the next closest service and thus avoid stopping the vehicle several times.

Until around 20 years ago, Arriva only performed maintenance in accordance with its policy, without reference to the manufacturer's requirements. With the introduction of warranties, the company is forced to comply with the manufacturer's requirements, but only for vehicles that are less than 5-10 years old; for all other vehicles, the company is free to implement the maintenance plan it deems most appropriate. In particular, Arriva categorises the types of service into three maintenance classes, simply called CM30, CM45 and CM60. The number indicates how often the engine oil should be replaced. All other work will be in multiples of the oil change, so a vehicle in maintenance class CM30 will be serviced every 30 000 kilometres, a vehicle in maintenance class CM60 will be serviced every 60 000 kilometres, and so on. In addition to engine oil replacement, other relevant operations are gearbox oil replacement and differential oil replacement. Therefore, these deadlines are also carefully defined. The choice of a vehicle's maintenance class depends on the type of mission it is required to perform. As regards the Turin site, the vehicles provide both suburban and interurban service. A further difference, which is not insignificant, is the difference in altitude they cover during their daily service: there are vehicles that operate on the plain and vehicles that travel on mountain roads. It is straightforward to see that vehicles travelling over mountainous terrain work under more severe conditions, which means greater stress on mechanical components. Consequently, more frequent oil replacements are expected for these vehicles. In addition to the "heaviness" of the type of mission, it is also important to assess the estimated average kilometres driven each year. Engine oil, as well as gearbox and differential oil, tends to degrade over the time and the number of kilometres driven by the vehicle (mileage). These two variables (time and km) must be taken into account in the cyclical maintenance, as described in section 1.1.2.

2.2.2 Unplanned maintenance in Arriva Italia

As discussed at the beginning of Chapter 2, preventive maintenance is always characterized by a dynamic aspect due to unforeseen events. Therefore, it is very important to adapt the schedule to the dynamic real-time events. For this reason, maintenance, even when scheduled in advance, must be reactive.
One of the responsibilities of the driver is to make a rapid check before starting the daily service. These checks are described in depth in section 2.2.4. If the driver discovers a fault, he is responsible for notifying the workshop manager immediately.

He has essentially two ways of doing this:

1. Verbally report the fault to the workshop manager, giving full details;
2. Fill in a report at the digital totem, mentioning the vehicle number and all the details of the fault detected.

As a result of the communication of the fault by the driver, the workshop manager is aware of the fault, regardless of whether it is reported in one way or another. This happens because all reports inserted into the digital totem reaches the workshop manager. At this point, the workshop manager decides if he should stop the vehicle immediately and take action; if the fault is not significant, it is stored and action is taken at the closest scheduled maintenance. Undoubtedly, a very important aspect of maintenance is reactivity. As discussed in the previous chapter, part of the maintenance is based on elapsed time or mileage, but there will always be a rate of corrective maintenance. Considering a workshop with X bays, assuming they are all equal, it is important to plan the scheduled maintenance so that there will always be a few bays available in case of corrective maintenance.

2.2.3 CMMS and Totem

The increased complexity of maintenance management and its processes has led to a considerable volume of information that needs to be collected and exchanged in order to govern events. For this reason, it is necessary to have an information system that is aimed at managing continuous improvement in all aspects of maintenance effectiveness and efficiency. CMMS is, according to legislation, *"A set of rules, procedures and instruments to collect and process the information necessary for the management of maintenance activities and for monitoring the activity of the installations"* [16]. The type and quantity of information to be processed and its interrelationships is such that the CMMS can only be managed effectively and efficiently using a computer support consisting of a data archive (database) and a program (software package) both installed on a computer. Hence the extended definition of "Computerised Maintenance Management System" (CMMS).

The maintenance information system can be divided into the following subsystems:

- Environment;
- Management;
- Control;
- Improvement;

The CMMS environment consists of a set of general company information, the physical elements, or assets (plant, machines, etc.), subject to maintenance and the type elements, or parts, into which these can be catalogued, the parts managed as stock in the warehouse and the normal overhaul and repair work cycles. The information on the maintenance objects shall be coded. Coding plans must be implemented with a long-term projection.
The CMMS environment comprises the following processes:

a) Management of technical archive;

b) Management of the physical structure;

c) Management of the warehouse master data;

d) Management of normal work cycles: the typical example is the scheduled maintenance cycles where all the work to be carried out will already be entered. Having this information available makes it possible to prepare a schedule so that workloads, spare parts, equipment and other requirements can be planned. It is also a very useful tool for budgeting.

The management of the maintenance system is realised with the cooperation of the following processes:

a) Report of defects: paper document or request made through electronic supports or verbal request, asking for the maintenance work to be performed. Normally it can derive from the operation or in any case from the user of the asset;

b) Management of work order: paper document or request made through electronic supports or verbal request, which triggers the maintenance intervention following a work request;

c) Management of companies;

d) Management of the schedule;

e) Management of warehouses register: sheet containing, for spare parts managed in stock, the following information: procurement criteria, possible suppliers, price and whether there are already existing contracts to be used;

f) Management of technical maintenance indicators.[17]

The CMMS is a support tool. The data uploaded into the software must be reliable, otherwise garbage in-garbage out. The work order must be signed by the technician who actually carries out the work, because in the event of major damage, the judiciary requires the work order to be consulted on the information system but also on paper.
Even the **Totem** requires special mention. The totem is a device for digital reporting of an anomaly. Contrary to what happens in other parts of the world, in Italy this device is quite widespread. It is a station consisting of a monitor, a mouse and a keyboard, or the monitor can be a touchscreen. The reporter, having reached the totem station, follows the guidelines presented in the monitor. The monitor shows a series of "sectors" that identify the category in which the fault occurred. The reporter, after selecting a category, must choose a "block". As the selection continues, the field in which the fault occurred becomes increasingly narrow. This information is not to be underestimated as it is very important detail for the workshop manager so that he can quickly identify where the fault has occurred and then communicate it to the operator to whom he assigns the repair. The initial view of the totem from which a sector can be selected is shown in figure 2.1. By selecting the sector of interest, a series of reference blocks will appear and so on.

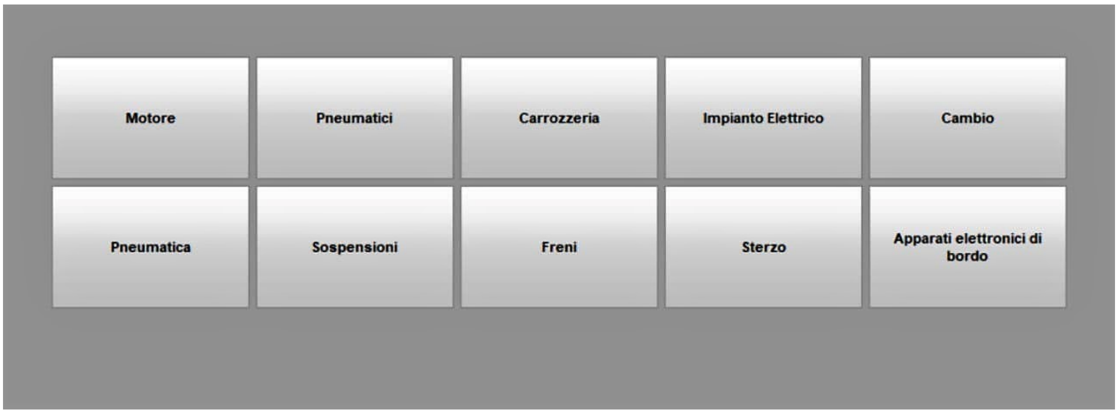

Figure 2.1: Totem layout - By CMMS Software

An illustration of a sector - block - anomaly description could be:

- Engine ⟶ Cooling ⟶ Engine coolant leakage
- Boodywork ⟶ Interiors ⟶ Damaged driver's seat
- Pneumatics ⟶ Brakes ⟶ Air leakage under braking

One of the tasks carried out during my internship was to identify the sectors, blocks and anomaly descriptions to be implemented within the totem. The next step was to define, for each anomaly, a potential default repair. In this way, when the warning arrives to the workshop manager, he can quickly create a work order with a work proposal to be performed. Obviously, the workshop manager has the faculty to modify this proposed work if he does not consider it appropriate. In order to identify the most suitable repair request, an analysis was carried out on the CMMS. In other parts of the world, reporting a fault is done by filling in a manually typed report. The driver, or more generally the reporter who detects the fault, must be careful to enter all the data in the report, i.e. the vehicle identification number, its registration number, date and time of detection and must list all the details in such a way as to accurately describe the fault. By entering the alert at the totem, all these data are requested automatically and it is not possible to go on if some data are missing. Below are the most frequent reports and in combination the potential repair to be performed:

- Electrical system - External lighting - Faulty sidelights ⟶ Replacing sidelights

- Engine - Generic - Oil leakage ⟶ Oil leak repair
- Gearbox - Generic - Retarder not working ⟶ Retarder review

2.2.4 Shunter Activities and First Use Checks in Arriva Italia

As described in the section 1.3, performing shunter activities is very important in order to ensure that the service is provided appropriately and to reduce the number of vehicle failures (and consequently the number of downtime).
To summarize, shunter activity requires to:

- Cleaning the buses and coaches externally and internally;
- Fuelling the buses and coaches ready for the next day;
- Driving the buses within the yard and parking them up;
- Other duties such as internal depot cleaning.

When the driver takes the bus, before starting the trip, he is required to carry out some quick operations, also known as First Use Checks, that consist in checking:

- the engine oil level;
- the coolant level;
- the wiper fluid level;
- the operation of internal and external lighting (sidelights, low and high beams);
- for any warning lights that are ON before driving;
- that the bodywork is not damaged as a result of impacts;
- tyre pressure using the TPMS display;
- all components and features for damage.

If he detects any low level, he is required to restore it or report to the workshop manager if there is any indicator lamp on. When the vehicle ends its daily service and returns back to the depot, the driver is responsible for refueling and parking the vehicle appropriately in the marked areas. With regard to parking, in some cases they may be asked to park in a buffer area and then there will be a shunter who moves the bus into the yard so that the first ones out are closer to the exit. In other cases, if the yard is large enough and there are enough parking, buses are parked randomly, in order of arrival, and are picked up randomly. The shunter has the role of cleaning the vehicle internally and externally after the work carried out by the workshop. Often repairs may be carried out on the inside of the vehicle and therefore the floor or seats, etc. may be dirty. The shunter proceeds with the cleaning in order to guarantee a comfortable journey for the passengers. Another duty the shunter has is to assist with the exit of the bus in the morning. The company provides service from the early hours of the morning, when the workshop is still not working. The shunter provides support and first assistance when needed. If the breakdown is serious, the vehicle will be repaired in the workshop.

Chapter 3

Towards Predictive Maintenance

Predictive maintenance can be explained through different definitions. According to legislation it is defined as: *"Condition-based maintenance performed following a forecast derived from the analysis and subsequent evaluation of significant parameters relating to the degradation of the entity* [1]. Although there are many definitions, the common premise of predictive maintenance is that regular monitoring of the actual mechanical condition, operating efficiency, and other indicators of the operating condition of machine-trains and process systems will provide the data required to ensure the maximum interval between repairs and minimize the number and cost of unscheduled outages created by machine-train failures. Predictive maintenance is much more, however. It is the means of improving productivity, product quality, and overall effectiveness of manufacturing and production plants. Predictive maintenance is not vibration monitoring or thermal imaging or lubricating oil analysis or any of the other nondestructive testing techniques that are being marketed as predictive maintenance tools. Predictive maintenance is a philosophy or attitude that, simply stated, uses the actual operating condition of asset equipment and systems to optimize total asset operation. A comprehensive predictive maintenance management program uses the most cost-effective tools to obtain the actual operating condition of critical asset systems and based on this actual data schedules all maintenance activities on an as-needed basis. Including predictive maintenance in a comprehensive maintenance management program optimizes the availability of process machinery and greatly reduces the cost of maintenance. It also improves the product quality, productivity, and profitability of manufacturing and production plants. Predictive maintenance is a condition-driven preventive maintenance program. Instead of relying on industrial or in-plant average-life statistics (i.e., mean-time-to-failure) to schedule maintenance activities, predictive maintenance uses direct monitoring of the mechanical condition, system efficiency for each machine-train and system in the plant. At best, traditional time-driven methods provide a guideline to "normal" machine-train life spans. The final decision in preventive or run-to-failure programs on repair or rebuild schedules must be made on the basis of intuition and the personal experience of the maintenance manager. The addition of a comprehensive predictive maintenance program can and will provide factual data on the actual mechanical condition of each machine-train and the operating efficiency of each process system. This data provides the maintenance manager with actual data for scheduling maintenance activities. [3].

3.1 Successfull application related to oil analysis

Although predictive maintenance does not rely exclusively on vibration monitoring or thermal imaging or lubricating oil analysis or any other non-destructive testing technique, but uses the data obtained through these tests to make considerations about the remaining life of the component under investigation, this thesis will discuss analyses conducted on engine oil. Indeed, one of the main activities I managed was the definition of maintenance plans for the vehicles that joined Arriva's fleet in 2022. These vehicles were delivered to Turin, Bergamo, Brescia and Aosta. As mentioned in the previous sections, new vehicles have a certain warranty period in which the user is forced to strictly adhere to the policies set by the manufacturer. In general, vehicles are divided into batches according to their characteristics (e.g. diesel or CNG, normal floor or low entry vehicles). Each batch is associated with a maintenance plan consisting of a certain number of service, which in turn includes a certain number of activities to be performed. The bus user, who purchases vehicles from a provider, essentially has two alternatives:

- Completely adhere to the maintenance schedules required by the manufacturer and strictly meet all imposed deadlines. This may lead to maintenance activities being performed at sub-optimal intervals due to the variability of missions performed by vehicles. In fact, it may happen that the manufacturer suggests a specific time or mileage deadline, but if the bus is operated under heavy-duty conditions, it may be very wide to comply with those time or mileage intervals because lubricants and components in general are submitted to greater stress that turns into premature wear;

- Implement more restrictive plans that require inspections and replacement of components on shorter schedules. It should be noted that in order to respect the warranty offered by the manufacturer, the user can implement a greater number of interventions required by the manufacturer but always ensuring the minimum number imposed by the maintenance manual.

In this task of implementing maintenance plans on new vehicles, it was decided to use the second approach, which means modifying the plan suggested by the manufacturer in a more restrictive way. The activities to be performed and consequently the deadlines with which to execute them, must be established critically in order to reduce vehicle downtime, minimize unexpected failures and costs. In order to reduce vehicle downtime, it would be wise to merge similar service intervals as much as possible. For example, the manufacturer may require that some components should be replaced every 60,000 km and others every year. These activities, due to the mileage and time deadlines, belong to cyclical maintenance. If a vehicle has an average annual mileage of about 70,000 km, it means stopping the vehicle when it reaches 60,000 km and then stopping it again after about 30 days to perform the time operations. Because of this, it is possible to combine the two services in such a way as to stop the vehicle only once, despite the fact that components with an annual deadline are replaced a little bit earlier and is not fully exploited.
Another aspect not to be undervalued is that a portion of the activities required by the manufacturer within the service may already be included in the inspection activities, according to company policy. Referring to Arriva, and as already reported in this chapter, the company policy foresees at least two inspection activities per year. If the activities required by the manufacturer and those foreseen by the inspections were the same, it would mean carrying out redundant activities in brief time intervals. In this regard, the activity I conducted was to first analyse the inspection activities required by the manufacturer and compare them with

the activities carried out in the inspections required by the company policy. If the activities were the same, they were removed from the cycle proposed by the manufacturer. In this way, the workload of the service imposed by the supplier was reduced and redundant checks at short intervals were avoided. After obtaining the new list of services, an attempt was made to combine them so as to reduce the number of services after having already reduced the number of activities. During the development of this new maintenance plan, three main activities related to the replacement of lubricating oils for the engine, gearbox and differential were used as reference. Below are the manufacturer's guidelines for oil changes for a diesel engine:

- Engine oil and filter change: 120 000 Km or 2 years;
- Automatic gearbox oil and filter change: 180 000 Km;
- Differential oil change: 240 000 Km.

In the past, these operations were required at much more stringent intervals because of the high degradation of the oil. Nowadays, due to the use of synthetic oils and no longer mineral oils, oil degradation is less pronounced and therefore oil change intervals have been extended. It is therefore for this reason that the manufacturer, on the basis of numerous analyses with the OEMs (Original Equipment Manufacturer), sets very large deadlines, whether in terms of time or mileage. Although the manufacturer requested this, and despite the fact that the vehicles are covered by a 10-year warranty and the manufacturer is therefore liable in the event of a breakdown, these deadlines were considered to be not suitable because of the hard conditions in which the vehicles of the Turin depot operate. With the aim of identifying new deadlines, oil analyses carried out in the past were analysed. Specifically, in 2020, the company Arriva conducted a study on engine oil degradation in collaboration with the oil company itself, which will not be mentioned in this thesis work. The purpose was to perform engine oil analysis after different mileages by extracting small oil samples. For this reason, three vehicles with different starting mileage were selected. To simplify, these vehicles will be identified as v1, v2 and v3. All vehicles were equipped with Cursor 8 engines and the type of oil used for the three vehicles was the same, whose identification code is omitted.

- Vehicle v1 analysis:

$Km_0 = 82\ 960$	$Km_1 = 145\ 929$
$\Delta_0 = 62\ 969$ Km	
Cu = 31 ppm	
Pb = 54 ppm	

Table 3.1: Vehicle v1 overview data

Table 3.1 shows some salient data for the vehicle under consideration, specifically Km_0 indicates the mileage of the vehicle at which the oil was inserted and Km_1 the mileage at the time the oil was removed. Consequently, Δ_0 is the duration in km for which the oil under consideration worked. The vehicle used was about 2 years old at the time of testing, so it can be considered quite "young". This is also evidenced by the low mileage. Upon reaching approximately 63 000 Km (Δ_0) the oil was removed and analyzed. As reported in the document below, the analysis detects the physical characteristics, potential presence of wear metals, any possible contamination and presence of additives. In this case a deviation from the nominal values was highlighted by the presence of Lead (Pb) and Copper (Cu), synonymous with wear of the engine components due to inefficient lubrication. In fact, the diagnosis suggests an oil change. The consideration that can be drawn from this analysis is that replacing an oil beyond 63,000 km would result in the loss of proper lubrication of engine components.

Apparecchiatura-
Componente
Motore Iveco Irisbus Matricola [redacted] - Motore - diesel Motore Iveco

Costruttore - Modello
Iveco (CNH Industrial) - Cursor 8

Action

Diagnosi

Non risulta contaminazione anormale del campione (acqua, silicio...)
Il contenuto di metalli da usura è superiore alla norma.
Si raccomanda un cambio dell'olio.
Controllare e verificare che il sistema stia operando correttamente
Fare molta attenzione ai trend di Piombo (Pb) e Rame (Cu)

Informazioni del campione	
Numero del campione	[redacted]
Condizione del Campione	✖
Data del Campione	**29/Jun/2020**
Campione ricevuto	01/Jul/2020
Campione Completato	01/Jul/2020
Lubrificante in uso	[redacted] 5W-30
Durata dell'apparecchiatura	145929 (Chilometri)
Durata lubrificante	62969 (Chilometri)
Volume rabbocchi	
Caratteristiche fisiche	
Visc 100°C cSt	11.9
Punto di infiammabilità (Passa/Non Passa) °C	>180
Usura	
Ferro (Fe) ppm	35
Cromo(Cr) ppm	2
Stagno (Sn) ppm	4
Piombo (Pb) ppm	✖ 54
Rame (Cu) ppm	! 31
Nickel (Ni) ppm	0
Alluminio (Al) ppm	7
Vanadio (V) ppm	0
Argento (Ag) ppm	0
Titanio (Ti) ppm	0
Manganese (Mn) ppm	0
Contaminazione	
Contenuto Acqua (Aquatest) %	0.00
Glicole (In House) % vol	0
Indice di contaminazione (IC) %	1.60
Disperdibilità (MD)	97
Demerito Ponderato (DP)	4.8
Sodio (Na) ppm	5
Litio (Li) ppm	0
Silicio (Si) ppm	4
Potassio (K) ppm	12
Additivi	
Calcio (Ca) ppm	2528
Zinco (Zn) ppm	851
Fosforo (P) ppm	716
Bario (Ba) ppm	0
Molibdeno (Mo) ppm	6
Magnesio (Mg) ppm	94
Boro (B) ppm	12

- Vehicle v2 analysis:

Km_0 = 75 617	Km_1 = 138 766	Km_2 = 142 655	Km_3 = 146 395
Δ_0 = 63 149 Km	Δ_1 = 67 038 Km	Δ_2 = 70 778 Km	
Cu = 26 ppm	Cu = 26 ppm	Cu = 27 ppm	
	Pb = 20 ppm	Pb = 21 ppm	

Table 3.2: Vehicle v2 overview data

Vehicle v2, at the time of the first oil insertion had a very similar mileage to vehicle v1, i.e. 75 617 Km. However, in this case the oil was changed after 70 778 Km. In reality, however, a sample was withdrawn in two intermediate steps, without draining all the engine oil. In this way it was possible to carry out the analysis also at intermediate mileages, to be exact after 63 149 Km and 67 038Km. All summary data are reported in the table 3.2. Specifically, at the time of the first sampling, an abnormal presence of Cu greater than the nominal value was found. Again, this is synonymous with mechanical component wear. Moreover, the second sampling confirmed the abnormal presence of Cu but also found a quantity of Pb higher than the nominal value. Intuitively, on the third sampling both the amount of Cu and Pb increased. This demonstrates that with increasing mileage the oil loses its lubricity and consequently the wear of metal components increases. The analysis carried out states that already after the first sampling, i.e. after only 63 149 Km, it was advisable to replace the oil. Despite the diagnosis, for experimental purposes it was decided to continue without replacing it.

Apparecchiatura-
Componente
Motore Iveco Irisbus Matricola [redacted] - Motore - diesel Motore Iveco

Costruttore - Modello

Iveco (CNH Industrial) - Cursor 8

Attention

Diagnosi

Non risulta contaminazione anormale del campione (acqua, silicio...)
Il contenuto di metalli da usura è superiore alla norma.
Si raccomanda un cambio dell'olio.
Monitorare l'andamento al prossimo campione.
Il "numero di basicità totale" (TBN) è diminuito rispetto a quello dell'olio nuovo.
Fare molta attenzione ai trend di Piombo (Pb) e Rame (Cu)

Informazioni del campione			
Numero del campione	[redacted]	[redacted]	[redacted]
Condizione del Campione	!	!	!
Data del Campione	**10/Aug/2020**	**20/Jul/2020**	**02/Jul/2020**
Campione ricevuto	13/Aug/2020	22/Jul/2020	07/Jul/2020
Campione Completato	13/Aug/2020	23/Jul/2020	07/Jul/2020
Lubrificante in uso	[redacted] 5W-30	[redacted] 5W-30	[redacted] 5W-30
Durata dell'apparecchiatura	146395 (Chilometri)	142655 (Chilometri)	138766 (Chilometri)
Durata lubrificante	70778 (Chilometri)	67038 (Chilometri)	63149 (Chilometri)
Volume rabbocchi			
Caratteristiche fisiche			
Visc 100°C cSt	12.1	12.2	12.1
Punto di infiammabilità (Passa/Non Passa) °C	>180	>180	>180
TBN (D 4739) mg KOH/g	! 5.3		
Usura			
Ferro (Fe) ppm	32	31	30
Cromo(Cr) ppm	1	1	1
Stagno (Sn) ppm	5	5	4
Piombo (Pb) ppm	! 21	! 20	14
Rame (Cu) ppm	! 27	! 26	! 26
Nickel (Ni) ppm	0	0	0
Alluminio (Al) ppm	5	5	5
Vanadio (V) ppm	0	0	0
Indice di usura (PQ) Index	2		
Argento (Ag) ppm	0	0	0
Titanio (Ti) ppm	0	0	0
Manganese (Mn) ppm	0	0	0
Contaminazione			
Contenuto Acqua (Aquatest) %	0.00	0.00	0.00
Glicole (FTIR) %	0		
Indice di contaminazione (IC) %	1.70	1.70	1.70
Disperdibilità (MD)	100	98	99
Demerito Ponderato (DP)	0.0	3.4	1.7
Sodio (Na) ppm	5	5	5
Litio (Li) ppm	0	0	0
Silicio (Si) ppm	5	5	5
Potassio (K) ppm	6	6	5
Carburante (FTIR) %	UTT*		
Fuliggine (FTIR) Abs/0.1mm	0.9		
Additivi			
Calcio (Ca) ppm	2644	2511	2395
Zinco (Zn) ppm	904	882	814
Fosforo (P) ppm	767	791	721
Bario (Ba) ppm	0	0	0
Molibdeno (Mo) ppm	5	6	5
Magnesio (Mg) ppm	92	100	81
Boro (B) ppm	12	13	14
Condizioni dell'olio			
Ossidazione (FTIR) Abs/0.1mm	6.8		
Nitrazione (FTIR) Abs/0.1mm	6.4		

- Vehicle v3 analysis:

Km_0 = 751 796	Km_1 = 801 187	Km_2 = 811 092	Km_3 = 817 113
Δ_0 = 49 391 Km	Δ_1 = 59 296 Km	Δ_2 = 65 317 Km	
Visc = 12.5 cSt	Visc = 12.7 cSt	Visc = 12.6 cSt	
Fe = 60 ppm	Fe = 66 ppm	Fe = 74 ppm	

Table 3.3: Vehicle v3 overview data

In contrast to vehicle v1 and v2, vehicle v3 already had a very high mileage of 751 796 km at the start. Vehicle v3 was selected to highlight any critical issues due to the high mileage. In this analysis the engine oil was completely drained after 65 317 Km but two intermediate samplings were made, after 49 391 Km and 59 296 Km respectively. The first sampling found a quantity of Fe slightly higher than the nominal value and a kinematic viscosity of 12.5 cSt (centistokes mm^2/s). For the oil under consideration, the kinematic viscosity must be $3.8cSt < Visc < 12.5cSt$. The diagnosis, despite these anomalies, did not deem it necessary to request the replacement of the oil, therefore the oil was still effective in carrying out its lubricating function. After 59,296 Km, the amount of Fe increased to 66 ppm and the kinematic viscosity to 12.7 cSt and these discrepancies from the nominal value suggested the replacement of the oil. At the third step, these values increased further to a kinematic viscosity of 12.6 cSt and a Fe presence of 74 ppm.

Apparecchiatura-
Componente
Motore Iveco Irisbus Matricola [redacted] - Motore - diesel Motore
Iveco

Costruttore - Modello
Iveco (CNH Industrial) - Cursor 8

Attention

Diagnosi

Non risulta contaminazione anormale del campione (acqua, silicio...)
Il contenuto di metalli da usura è superiore alla norma.
La viscosità è aumentata lievemente rispetto al valore dell'olio fresco.
Si raccomanda un cambio dell'olio.
Monitorare l'andamento al prossimo campione.

Informazioni del campione			
Numero del campione	[redacted]	[redacted]	[redacted]
Condizione del Campione	!	!	✓
Data del Campione	**12/Jun/2020**	**26/May/2020**	**22/Apr/2020**
Campione ricevuto	16/Jun/2020	28/May/2020	28/Apr/2020
Campione Completato	16/Jun/2020	28/May/2020	28/Apr/2020
Lubrificante in uso	[redacted] 5W-30	[redacted] 5W-30	[redacted] 5W-30
Durata dell'apparecchiatura	817113 (Chilometri)	811092 (Chilometri)	801187 (Chilometri)
Durata lubrificante	65317 (Chilometri)	59296 (Chilometri)	49391 (Chilometri)
Volume rabbocchi			
Caratteristiche fisiche			
Visc 100°C cSt	! 12.6	! 12.7	! 12.5
Punto di infiammabilità (Passa/Non Passa) °C	>180	>180	>180
Usura			
Ferro (Fe) ppm	! 74	! 66	! 60
Cromo(Cr) ppm	2	2	2
Stagno (Sn) ppm	0	0	0
Piombo (Pb) ppm	13	11	8
Rame (Cu) ppm	2	2	2
Nickel (Ni) ppm	0	0	0
Alluminio (Al) ppm	7	5	4
Vanadio (V) ppm	0	0	0
Argento (Ag) ppm	0	0	0
Titanio (Ti) ppm	0	0	0
Manganese (Mn) ppm	0	0	0
Contaminazione			
Contenuto Acqua (Aquatest) %	0.00	0.00	0.00
Glicole (In House) % vol	0	0	0
Indice di contaminazione (IC) %	0.50	0.50	0.50
Disperdibilità (MD)	99	98	96
Demerito Ponderato (DP)	0.5	1.0	2.0
Sodio (Na) ppm	4	4	4
Litio (Li) ppm	0	0	0
Silicio (Si) ppm	4	5	5
Potassio (K) ppm	8	7	5
Additivi			
Calcio (Ca) ppm	3029	2998	2795
Zinco (Zn) ppm	982	1047	902
Fosforo (P) ppm	807	827	732
Bario (Ba) ppm	0	0	0
Molibdeno (Mo) ppm	1	1	0
Magnesio (Mg) ppm	24	27	25
Boro (B) ppm	8	7	6

In conclusion, although it is undisputed that an analysis of only three vehicles and only seven samples analysed may be unrepresentative of an entire fleet, it seems clear that at around 60 000 km there begin to be abnormal traces of Fe, Cu and Pb in the oil and the kinematic viscosity increases. In addition, it should be borne in mind that the vehicles used for the tests are usually in service on mountain roads and therefore the engine is subjected to greater stress. It is probable that an analysis carried out on vehicles with a mission on flat roads would have asserted a longer mileage so that the oil would be able to perform its function as a lubricant. As the vehicles for which the new maintenance plans were to be drawn up are used on both flat and mountain roads, the deadlines have been updated and modified as follows:

- Engine oil and filter change: 60 000 Km or 2 years - 90 000 Km or 2 years;
- Automatic gearbox oil and filter change: 180 000 Km or 3 years;
- Differential oil change: 240 000 Km or 4 years.

In particular, it was considered appropriate to further split the vehicles into two categories:

- For those vehicles that provide extra-urban service on mainly plain roads and for which the engine speed is almost constant, oil changes are carried out every 90 000 km or 2 years;
- For vehicles that operate in urban areas or on mainly mountainous roads and where the engine speed switches repeatedly, oil changes are carried out every 60 000 km or 2 years.

In conclusion, engine oil change has been reduced to 90 000 km or 60 000 km from the initial 120 000 km. On the other hand, for changing the gearbox and differential oil, a time deadline of 3 or 4 years has been added respectively. In this way, should the vehicles drive less than 60 000 km per year, the time deadline is reached earlier and the replacement is carried out in advance of the mileage deadline. The analysis of the lubricating oil and especially the considerations that led to the reduction of the replacement intervals cannot be defined as predictive maintenance but is only an approach. Predictive maintenance would have provided indications of oil replacement as operating conditions change and therefore not a fixed deadline for all vehicles and for the whole vehicle life. In contrast, predictive maintenance would have been able to adapt the various schedules to take full advantage of the oil's properties but without incurring failures due to lack of lubrication. The approach used in this study made it possible to establish the replacement interval with an experimental criterion based on the evidence of oil degradation. In the future, the idea would be to replace the oil when it has become depleted of its lubricating properties and therefore to take action at different intervals from vehicle to vehicle in order to reduce vehicle downtime for maintenance that is not strictly necessary, make full use of the oil, reduce breakdowns due to lack of lubrication and save costs.

3.2 A closer look into Telediagnostic

The implementation of a predictive approach in maintenance cannot do without remote monitoring of bus operating parameters. In truth, remote monitoring of parameters is already available for tyres. In particular, systems to monitor tyre pressure and temperature through sensors embedded in the tyre have been available for some years now. These battery-powered sensors are encased in a sheath of the same material as the tyre and then bonded by a curing process to the tyre casing. In this way, the sensor can be replaced without removing the casing, but simply pulled off, or if the casing also needs to be replaced, the whole thing can be removed. The sensors are interchangeable from one tyre to another.

Figure 3.1: TPMS sensor assembly - By Continental

Figure 3.1 shows the three stages of the sensor: on the right is the bare sensor, very small in size, in the centre is what the sheath looks like before incorporating the sensor, on the left is the sensor encapsulated in the sheath before being cured into the inside of the tyre. When curing the sheath on the tyre, it is important to allow that the accelerometer will switch on the sensor by keeping a certain distance from the tyre sidewall and positioning the sensor with the arrows pointing in the direction of rotation of the tyre and not crosswise. This ensures accurate acquisition of the parameters we need to monitor. The 6/8 sensors (depending on whether the vehicle has 2 or 3 axles) continuously monitor the tyre pressure and temperature in real time. The detected data is encoded and transmitted via radiofrequency to a receiver with a high-frequency signal located in a compartment of the vehicle. Dedicated software installed in the controller elaborates the information and displays it on the vehicle's dashboard so that it can be read by the driver. The control unit also communicates with the satellite, so the same data made available to the driver is also transmitted to an online platform for remote monitoring. In this way the TPMS alerts the driver if the pressure drops below a certain level before the situation becomes critical, fuel consumption and therefore CO_2 are reduced because the tyre is always working in optimal conditions and the life cycle of the tyre is increased. Older controllers would detect a p or T fault in one of the tyres but were unable to identify the position of the tyre. With today's technology, the system is able to precisely locate the tyre, as shown in figure 3.2. Tyre pressure and temperature data are displayed on the vehicle's dashboard but are also available on an online platform that authorised users can consult or receive notifications in real time. Figure 3.2 illustrates the birdview of the tyres with their pressures and temperatures compared to nominal values. In addition to the numerical values, a colour legend is also used so that any deviations from the nominal values can be quickly identified.

The nominal pressure value is shown in the middle, while the real time value is shown on the respective tyre. In order to receive alerts, the user can set acceptance thresholds. In this case a threshold of -20% has been set for very low pressure and a threshold of -10% for low pressure. On the other hand, over-inflation is not acceptable either and therefore a threshold of +15% has been set. Unacceptable T values are set at 115°C. In the example shown, the right outer rear wheel has a pressure lower than the acceptable threshold and therefore requires inflation.

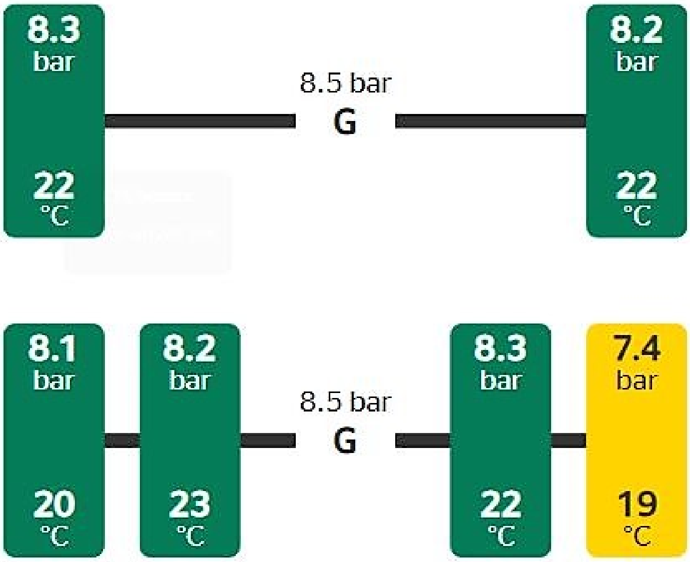

Figure 3.2: Birdview of real-time tyre status - By ContiConnect

With these systems, the driver immediately notices a tyre malfunction and has to report it to the workshop manager to decide whether he can continue the trip, return to the depot immediately or request a service on the ride. If the driver does not detect a tyre fault, the operator who monitor the web platform receives an alert and can call the driver who is currently operating the bus. In addition to the tyre sensors, a data set can be obtained via CAN line.

3.2.1 CAN Bus

Modern vehicles are equipped with a large number of control units. Each control unit is responsible for detecting a certain parameter. A single control unit can use more than one sensor, and therefore more than one wiring harness. In practice, the electrical system consists of a large number of control units and even more sensors and wiring. An example is the ABS (Anti-blocking system) system, which requires a control unit, four sensors and four cables, one for each wheel. The key point is that several control units may need the same data, so they will calculate redundant parameters already calculated by other control units. Vehicles equipped with a CAN (Controller Area Network) line include a BCM (Body Control Module) that distributes information to all control units that require that parameter. This greatly reduces the number of sensors and wiring because all individual parameters are measured once. This system was initially called *VeNICE* (Vehicle Network Integration Component Electronics). The first chip for CAN networks was developed in 1987 in cooperation with Bosch. In 1195 the standard for the extended CAN 2.0 B protocol was developed. All the vehicle's on-board control units are connected to each other via a twisted pair that works as a bus and they can exchange information with each other. The CAN line consists of two lines on which the high CAN H signal and the low CAN L signal travel. This type of network connection works in multimaster-multislave mode. If the units connected to the bus through the nodes work as masters, they can both send and receive information. If they work as slaves, they can only receive information and supply it on demand. The control units can be connected to each other in series or in parallel. In the first case, the control units form an integral part of the electrical circuit. This implies that if a fault occurs in any one control unit, the communication of the entire line will be lost. In the second case, on the other hand, the circuit is developed without passing through the individual control units, so that in the event of a fault in a single control unit, only the communication of that control unit would be lost.

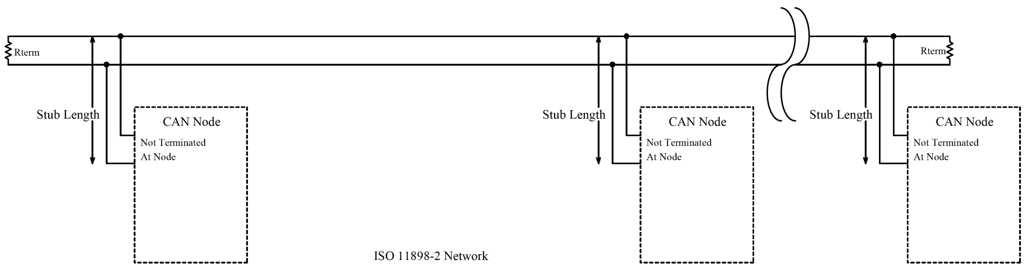

Figure 3.3: CAN network ISO 11898-2, By EE JRW

Shown is an example of a network with parallel connection. The entire circuit has two termination resistors of 120 Ω each, placed in parallel, for an equivalent value of 60 Ω. The two resistors are located into two control units, so if one of these two control units fails, communication is unavoidable. The installation of telediagnostic devices intercepts data travelling on the CAN line. However, installing aftermarket devices is sometimes not straightforward. This is because some issues can arise, such as:

- The devices to be installed may not all be suitable for the various brands of vehicle;
- Different types of vehicles, even those built by the same manufacturer, may have different equipment and therefore be compatible with only some devices;
- The manufacturer, for vehicles under warranty, may require not to install devices not produced by itself.

The context in which LPT companies operate is sometimes complex and variegated and therefore companies are forced to install devices produced by the same vehicle manufacturer, which means having different devices for each brand of vehicle, or installing universal devices suitable for several vehicles. Furthermore, installing devices produced by different manufacturers means having as many dashboards to monitor parameters as there are types of vehicle, because devices can communicate information according to different protocols, and sometimes creating a single database is not straightforward.

3.2.2 ITxPT - Information Technology for Public Transportation

In addition to telediagnostics systems that collect information on engine and equipment functioning, the vehicles are equipped with systems that manage tariff payment, information on passengers on board and fleet management. However, these systems communicate with each other through non-standard communication protocols. Even if systems and devices from different manufacturers are compatible with each other, installing these devices may create conflicts. Previously, vehicles had to be equipped with multiple redundant on-board systems, taking up space and complicating installation and maintenance access. More importantly, a lot of space that could have been dedicated to passengers and their comfort was taken up by on-board equipment. Recently, international standards have been developed so that companies producing intelligent transport technologies can ensure the proper management of the infrastructure and avoid conflicts. This standard is referred to as Information Technology for Public Transportation (ITxPT). However, the standard is still developing and will evolve in the coming years [18]. ITxPT is a non-profit association that provides open architecture, data accessibility and interoperability between information systems. ITxPT members develop the architecture for public transport. It is based on standards and good practices from implementations and running projects. With ITxPT, on-board modules and systems can be combined and work together even if they are produced by different suppliers. Their distribution in a vehicle is planned in such a way as not to take up unnecessary space and to allow easy access for maintenance and servicing. The need for customisation in each vehicle is virtually eliminated and system integration can be done in the same standard way across the entire bus fleet. ITxPT fully supports the development and implementation of plug-and-play mechanisms, which also simplifies back-office installations and allows wireless software updates.

3.2.3 Condition-based monitoring and Predictive Maintenance initiative

Currently, manufacturers are exploiting the installation of diagnostics to their advantage by offering self-installation and introducing ever higher levels of authorisation. As a result, LPT companies are forced to buy potentially more and more expensive subscription packages over time. One ploy used by manufacturers is to equip vehicles with these systems as standard, offer the monitoring service free of charge for the warranty period and then charge an annual subscription. In the long run, the result would be to give up their maintenance know-how, as all the data collected is available to both the LPT companies and the vehicle manufacturer. The aim of this thesis is to implement telediagnostic systems on a small number of Arriva's entire fleet.
The whole project can be structured in several steps:

- **Step 1**: The first period was characterised by in-depth research into a system capable of allowing the acquisition of operating parameters but free from the installation and commercial constraints imposed by the vehicle manufacturer. In fact, the vehicle manufacturer only allowed the installation of devices produced by itself or the use of vehicles no longer under warranty, since the installation of devices produced by third parties would have caused the warranty on the vehicles to lapse. Analysing Arriva's fleet and due to the presence of more recent vehicles still under warranty, it was decided to install non-warranty vehicles in this pilot project and therefore the focus was shifted to a supplier able to provide a cross-system. After an intensive period of interfacing with various suppliers, Stratio Automotive was deemed to meet our requirements. It is a Portuguese provider offering remote diagnostics, predictive maintenance and other services such as ecodriving and real-time fleet monitoring for both buses, coaches and trucks. Stratio Databox connects to the vehicles and is compatible with all brands, models and ages, regardless of the interface used. The system consists of a Databox, a GNSS (Global Navigation Satellite System) antenna for satellite tracking and a GSM (Global System for Mobile) antenna that communicates with the platform via a SIM card for remote data monitoring. Ideally, the GNSS antenna should be mounted parallel to the horizon where a 360° unobstructed clear view of the sky is available to enable a connection to visible GNSS satellites. The databox location is on the right side of the tachograph compartment. The Databox is connected to the tachograph via a Stratio y-cable shown in the figure. This cable has a bypass function. One end of the cable connects to the databox, another end to the original connector removed from the tachograph and the other end to the tachograph. In addition, the Stratio y-cable has two lines that connect via schotchlocks to the 30-pin socket to detect brake and instruments data.

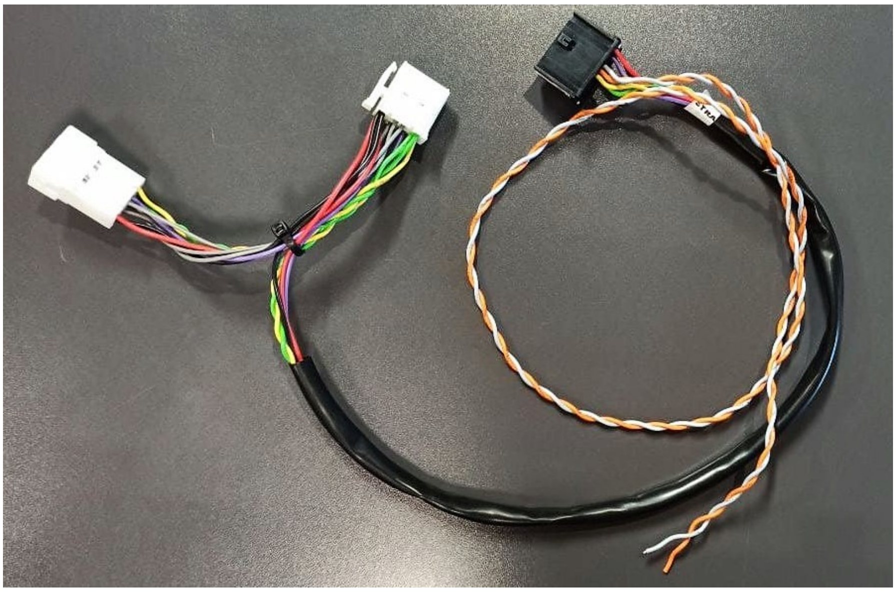

Figure 3.4: Stratio y-cable

In order to monitor vehicles that belong to the same family and perform the same daily mission, 19 vehicles were selected for this pilot project. Of these vehicles, 10 vehicles are in service in Turin and 9 vehicles are in service in Aosta. In this way it is interesting to highlight the differences in the type of mission the vehicles fulfil, and consequently the effect of the more or less severe conditions in which they work. On the other hand, the vehicles installed, not being under warranty, have an average age of about 10 years, a EURO 5 environmental class, and a number of sensors that can provide less information than the system would be able to detect.

- **Step 2**: The second phase was an initial monitoring period to determine what data the system was actually able to collect, due to the small number of sensors on the vehicle euro 5, how it was processed and the default thresholds set. The system is able to provide real-time data on the engine (e.g. engine load %, engine oil pressure, engine intake manifold temperature and pressure, engine speed, engine coolant temperature, engine coolant load increase, ...), on the gearbox (gearbox oil temperature, current transmission gear, ...), accelerator pedal position %, maximum retarder available, vehicle speed tachograph, battery voltage, service brake circuit air pressure 1-2, etc.

Below is a series of alerts issued by the system and then verified by the workshop.

– **Insufficient oil pressure - 0.6 bar**: The first alert provided by the system stated insufficient oil pressure for a proper engine work. It is well known that correct engine oil pressure is essential for proper lubrication and therefore for proper engine operation. The system, in order to communicate the alert, compares the measured pressure value with reference values, which for the case in point are:

  * Rpm 200 - Bar 0.0;
  * Rpm 550 - Bar 1.5;
  * Rpm 1200 - Bar 3.0;
  * Rpm 1500 - Bar 3.5;
  * Rpm 2000 - Bar 4.5;

  These parameters are for reference and values with a certain tolerance are acceptable. However, the system detected a discrepancy between the reference values and the values actually measured and consequently issued an alert.

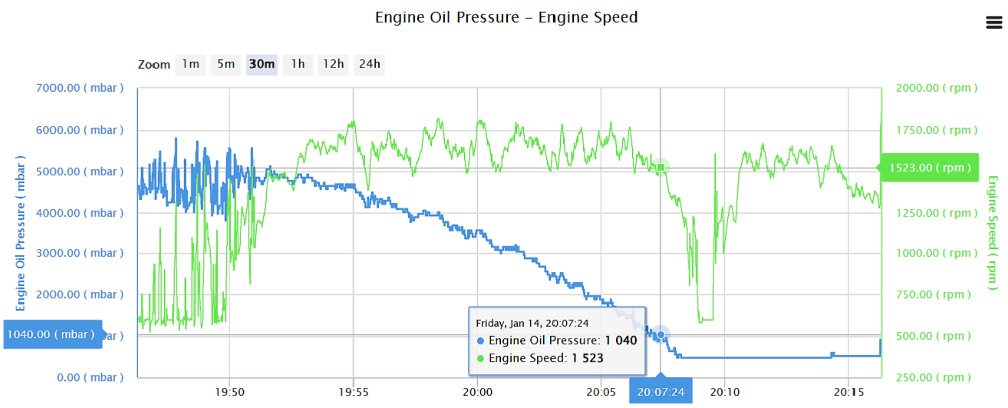

Figure 3.5: Insufficient oil pressure

Figure 3.5 shows a sudden decrease in the engine oil pressure value. In blue is the engine oil pressure in mbar and in green the engine speed in rpm. In the initial part of the graph, an engine speed of approximately 1250 rpm corresponds to a relative pressure of approximately 4.5 bar. The values are, on the whole, in accordance with the reference values. After 19:50 on 14 January, a sharp drop in pressure was observed. In fact, as shown on the right-hand side of the graph, although the engine speed continues to assume values around 1500 rpm, the relative pressure decreases from about 5 bar to 1 bar. A potential cause could be oil pump failure or oil leaks in the engine lubrication circuit, or an incorrect functioning of the pressure sensor. In this particular case, there was not a fault in the engine oil circuit but in the sensor, which detected an incorrect pressure. As a preventive measure, the vehicle was stopped immediately in order to avoid major breakdowns. In fact, potential consequences could have been increase of engine wear due to lack of lubrication between components and possibility of engine seizing.

– **High gearbox oil temperature**: Another widely received alert is about the gearbox oil temperature. The gearbox installed in these vehicles is a four-speed automatic. For efficient lubrication, the oil temperature must not exceed 100°C. However, this can happen if the gearbox is stressed in particularly heavy road conditions where retarder use is accentuated. The retarder is a wear-free auxiliary retarder system capable of generating a torque resistant to rotation above a certain number of rpm. It is usually installed on heavy vehicles where the braking power required is very high and frequent use of the service brakes could lead to excessive wear and overheating of the braking system. The retarder uses some of the kinetic energy from the vehicle to convert it into heat and acts on the drive shaft. The retarder can exploit an electromagnetic or hydraulic principle. In the first case, an electric field is created around a stator that impedes the free rotation of a rotor clamped on the drive shaft, which is consequently slowed down by Foucault currents. The second type, on the other hand, exploits the incompressibility of liquids so that the dynamic fluid friction between the vanes of an impeller clamped on the transmission shaft tends to slow it down depending on the amount of viscous fluid available. If the retarder is a hydraulic type, prolonged use will result in overheating of the oil itself. This implies that a detection of high gearbox oil temperature does not necessarily mean that there is a fault, but perhaps that the retarder has been used heavily. For instance, the following figure shows an example of gearbox oil operation at temperatures very close to the set threshold. In particular, a Warning Limit threshold has been defined when 110 °C is reached and a Critical Limit threshold when 120 °C is reached. In this case the oil temperature exceeds the critical limit threshold and reaches peaks of 138 °C. This was caused by excessive use of the retarder due to continuous downhill runs and a clutch that is no longer efficient, which contributes to an increase in oil temperature.

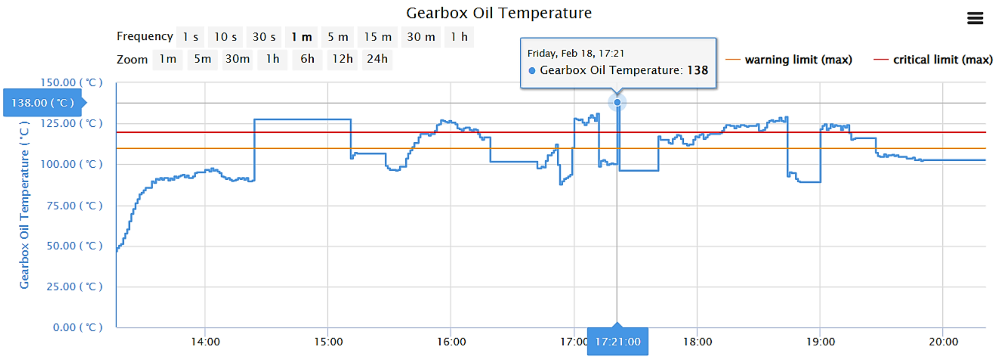

Figure 3.6: High gearbox oil temperature - By Stratio Dashboard

In conclusion, it is necessary to analyze the context of the alert received, as an increase in oil temperature can be caused by several factors. In this case, the frequency with which the temperature exceeds the threshold is due to the road conditions and therefore the use of the retarder, but also to the clutch that needs to be replaced.
As a demonstration of the above, figure 3.7 shows another example of exceeding the gearbox oil temperature threshold. Analysing the gearbox oil temperature trend of this vehicle, it can be noted that the values are close to the Warning Limit threshold. As explained, this is not an anomaly but may be due to the use of the retarder. However, a concentrated peak in T can be observed.

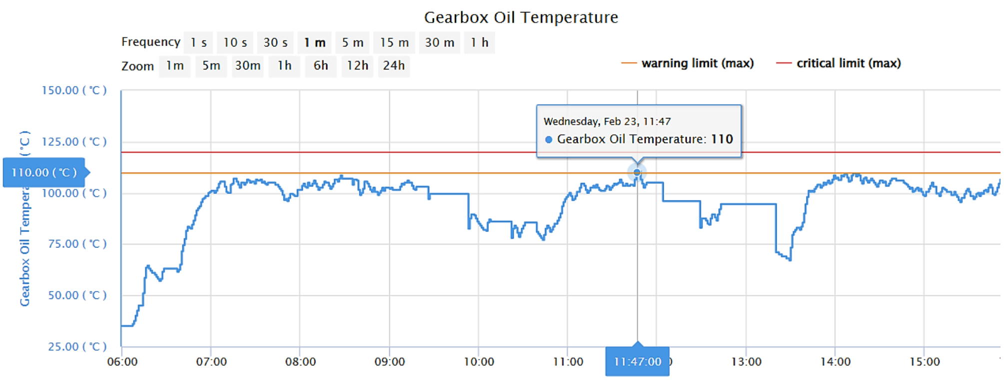

Figure 3.7: High gearbox oil temperature - By Stratio Dashboard

Figure 3.8 shows a zoom of the area of interest. It is evident the temperature increase and then it return to acceptable values.

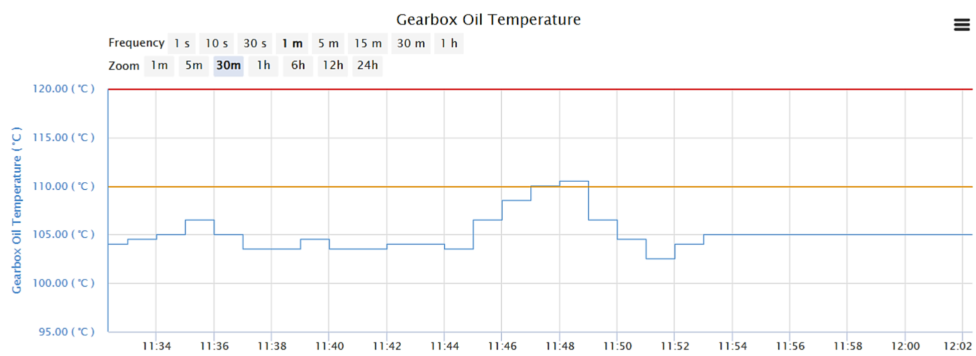

Figure 3.8: High gearbox oil temperature - By Stratio Dashboard

In order to understand the causes that led to the increase in temperature, the gearbox oil temperature is compared with the engine rpm. Figure 3.9 shows that the increase in T corresponds to a reduction in engine rpm: in particular, the peak of T is reached when the engine is idling.

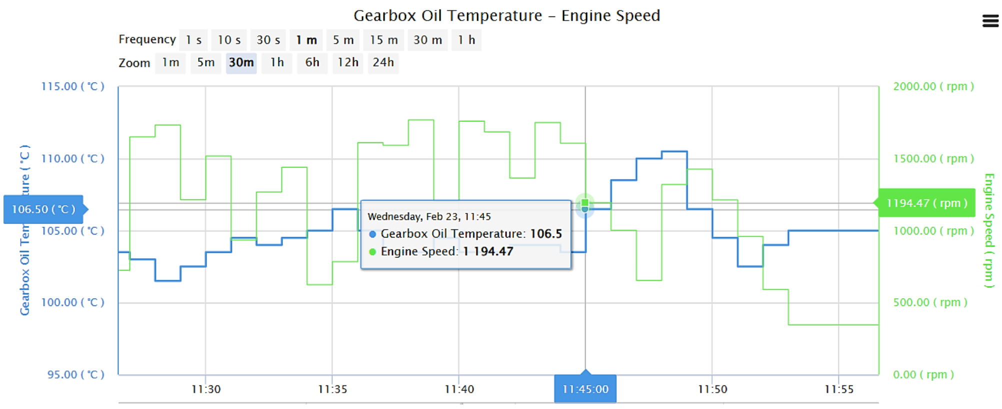

Figure 3.9: High gearbox oil temperature - By Stratio Dashboard

As the engine is idling, the use of the retarder can be excluded as a reason. A potential cause, however, could be gear shifting. In order to rule this out, the engine speed is plotted with the transmission current gear.

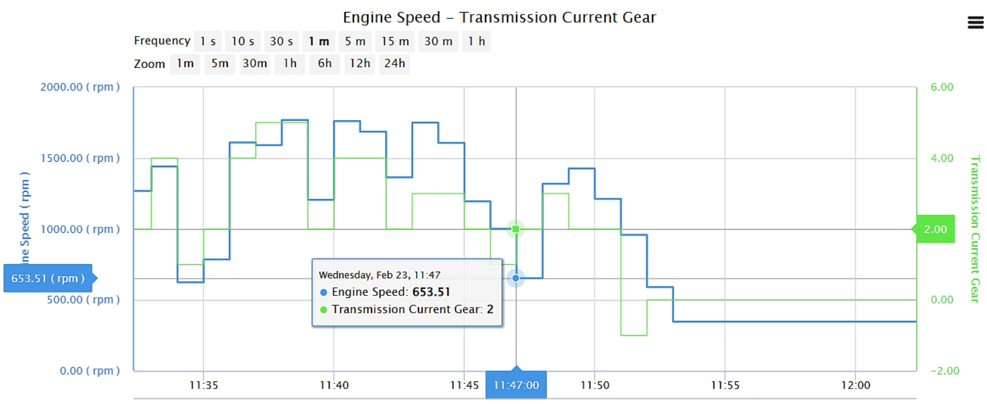

Figure 3.10: High gearbox oil temperature - By Stratio Dashboard

In effect, graph 3.10 shows that as engine speed decreases, the current gear also decreases. Since the vehicle is equipped with an automatic transmission, one would expect it to be in N (Neutral) when the engine is idling. On the contrary, however, as the graph shows, the vehicle was idling (653.51 rpm) but the gear was 2 and not in Neutral. As a general rule, when the vehicle is stationary and therefore idling, the gear selector should be set to Neutral and not D (Drive). In this case, the vehicle was stationary but the driver had engaged the gear, which caused the gearbox oil temperature to rise. Fortunately, this only lasted for three minutes, after which the vehicle was able to continue the trip without the gearbox oil overheating. Remote monitoring and, above all, the ability to compare different parameters at the same time, made it possible to detect the "anomaly" and, above all, to trace the cause, thereby ruling out major faults.

– **Engine coolant temperature**: Another type of alert that the system is able to provide is inherent to the coolant temperature. In fact, the system is capable of providing information on engine coolant load and engine coolant temperature. In this case, the system indicated that the engine coolant temperature exceeded the maximum recommended by the manufacturer. In this case, too, a Warning Limit threshold of 100 °C and a Critical Limit threshold of 105 °C were set. These thresholds were chosen because the coolant should operate at temperatures around 90 °C. A potential cause could be low coolant level, thermostat or water pump malfunction, the cooling system radiator is clogged inside or outside, the intercooler is blocked from the outside or the liquid temperature sensor is faulty. Figure 3.11 shows an increase in coolant temperature to a peak of 120 °C. The coolant is forced through a pump and circulates in the engine cavities whit the aim of cooling it. In turn, it is cooled by air from a radiator, which receives air from a fan. Excessive coolant T leads to a lack of engine cooling and thus to a subsequent increase in T and eventual engine failure, since the coolant temperature is also related to the engine oil T.

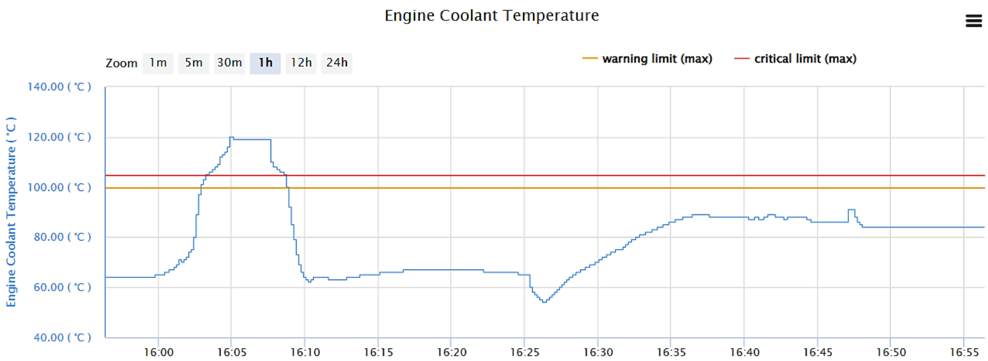

Figure 3.11: Engine coolant temperature - By Stratio Dashboard

Figure 3.11 shows an excess of T over the threshold. In this case, after the system provided the alert, the vehicle was stopped and checked by the workshop. The technicians found that the water pump had broken, preventing the coolant from being recirculated. As a result of the remote diagnostics system, it was possible to take early action to prevent the high temperature from turning into a serious fault.
The faults described so far have all been reported by the diagnostic system and subsequently confirmed by the mechanics. Telediagnostics made it possible to take action in good time to prevent the most serious fault from occurring.
However, there was one fault that occurred but was **not detected** by the system. In particular, there was a coolant leak. As described in subsection 2.2.4, the driver has the task of performing some visual checks before starting the daily service. As a result of the first use checks he found a coolant leak from a pipe. However, the leak was not detected by the system, probably due to the fact that it was not a huge leak and, above all, due to the lack of a sensor capable of detecting the level of liquid in the tank. If the driver had not detected the leak, the vehicle would have started the trip and the loss of coolant would probably have led to a sudden increase in the temperature of the coolant remaining in the tank and only then would the alert have been received. On this subject, it would be advisable to equip the vehicle with sensors capable of detecting the level of liquid in the tank and ensure that the telediagnostics system is able to predict the loss of coolant in advance, not by taking into account thresholds but perhaps by the amount of heat absorbed by the fluid, which is synonymous with the efficiency of the coolant function. Instead of monitoring the excess of a value over a preset threshold, this would move towards a predictive approach. The system is currently able to provide coolant temperature overviews specifying in time or percentage terms the rate of operation at T below 75 °C, at T between 75-85 °C and at T above 105 °C.

Vehicle	Operation Time	< 75 °C	75-85 °C	85-95 °C	95-105 °C	> 105 °C
Vehicle 1	52h 56m	19%	28%	53%	0%	0%
Vehicle 2	36h 41m	20%	51%	29%	0%	0%
Vehicle 3	28h 41m	30%	44%	25%	0%	0%
Vehicle 4	33h 44m	27%	50%	23%	0%	0%
Vehicle 5	45h 44m	44%	36%	21%	0%	0%
Vehicle 6	37h 59m	32%	48%	19%	0%	0%
Vehicle 7	29h 56m	46%	35%	19%	0%	0%
Vehicle 8	27h 36m	35%	53%	12%	0%	0%
Vehicle 9	3h 49m	68%	21%	11%	0%	0%

Figure 3.12: Engine coolant temperature - By Stratio Dashboard

From this overview, vehicle 1 stands out, characterised by 53% of the operating time at T between 85-95 °C. This does not mean that there is a fault since the values are below the 105 °C threshold. However, if we take into consideration the fact that all these vehicles have the same mission and therefore drive almost the same itinerary, we can see that almost all of them spend about 20% of their operating time at a T between 85-95 °C while vehicle 1 spends more time. In order to explain why this value was out of range, the cooling system was checked. Although the system did not show any particular anomalies, the technicians found a clog in the cooling system. This clogging was not completely occluding the coolant recirculation, which was in fact able to fulfil its function, but it was causing the coolant to always work at temperatures close to the threshold due to inefficient cooling with the air from the intercooler.

– **Battery voltage**: The Stratio device, reading data from the CAN line, is able to receive information about the battery voltage. It has been set a warning limit (min and max) and a critical limit (min and max) beyond which the system issues an alert. Potential causes could be prolonged shutdown of the vehicle or the existence of relevant electrical consumers that lead to a high battery discharge. It is advisable to check the battery condition, the existence of relevant electrical consumers, the condition of the generator, connectors and the wiring harness. Anyway, it is not strictly necessary to replace the battery but it may only be necessary to recharge it. It is really helpful to receive this kind of alert because reaching this value, the battery may not be able to put the engine running and this may cause disservice to public transportation. Figure 3.13 shows an example of a battery malfunction warning due to the fact that an abnormal discharge of the battery was detected, even though it was working properly when the engine was running.

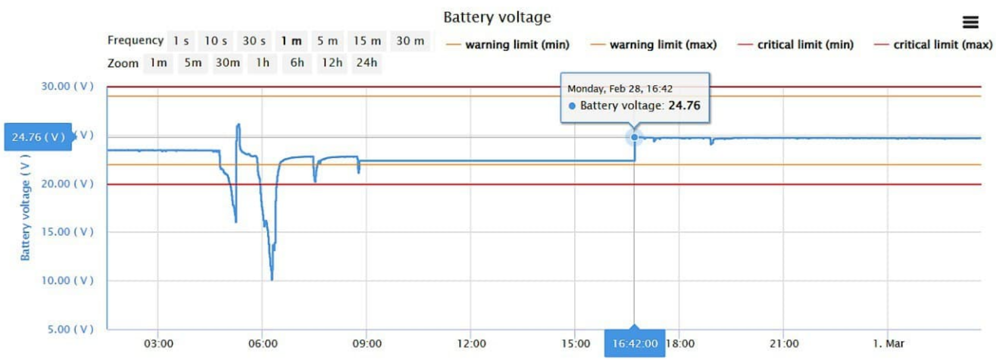

Figure 3.13: High battery discharge - By Stratio Dashboard

As Figure 3.13 shows, when the vehicle is turned off the battery voltage drops. When the vehicle is then started voltage is restored by the alternators. Obviously, if this anomaly had not been detected immediately, it is probable that after a few days the batteries would no longer be able to start the engine and this would have caused inefficiency in public transport. In this case, however, the batteries were replaced as a precautionary measure and the voltage was restored to nominal values. This is a clear example of how interesting telediagnostics is from the point of view of detecting future faults.
To confirm the fact that a low battery voltage does not necessarily imply a malfunction of the electrical system but maybe a high downtime, figure 3.14 shows the state of the battery after a period of about 10 days in the bodywork shop for a crashed vehicle.

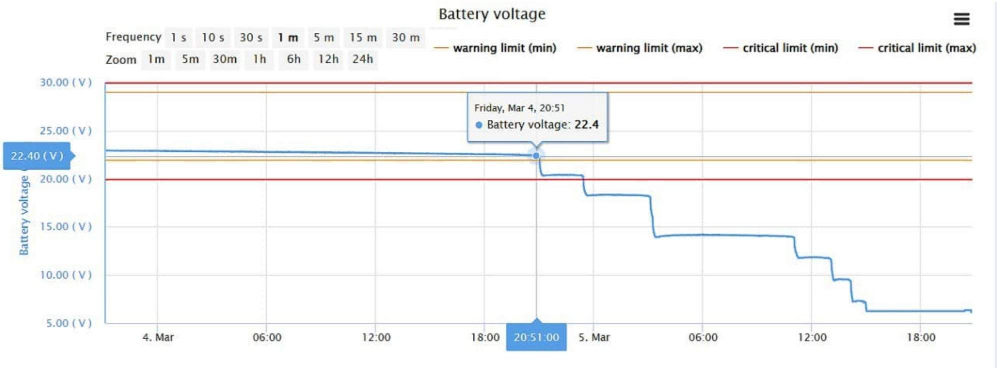

Figure 3.14: Battery voltage too low - By Stratio Dashboard

A purely telediagnostic system is capable of comparing the measured data with preset thresholds in real time, but not of making considerations. For such considerations, it is necessary to implement algorithms that make use of artificial intelligence.

- **Step 3**: In accordance with what the system is able to offer, analyses were conducted using the CMMS in order to estimate which were the categories characterised by a higher number of faults. For this purpose, the faults were divided into 12 categories and the number of faults in each month for the years 2020 and 2021 was reported. It should be noted that the analysis does not refer to the company's entire fleet, but only to the vehicles on which the Databox has been installed. A number of KPIs (Key Performance Indicators) were calculated for these 19 vehicles with the intention of making a comparison over time and making considerations about possible reductions in downtime, breakdowns and costs.
  The calculated KPIs are shown below:
  - **Breakdowns**: Failure is the loss of the ability of the asset to perform the required function. This indicator therefore takes into account those events that give rise to corrective maintenance and thus to corrective downtime. After having identified the events, and therefore the number of failures, the kilometres travelled in that time interval were also taken into account in order to normalise the data and to be able to compare vehicles with different mileage. More precisely, the aim was to find out how many breakdowns a vehicle suffers every 10 000 km travelled. The BPK data (Breakdown per Km) is obtained by means of a proportion starting from the breakdowns and the km travelled. It would have been possible to consider the total number of breakdowns during the year and divide it by the total number of kilometres travelled, but since we are interested in finding out the trend, the calculation was made monthly for the 10 vehicles in Turin and 9 in Aosta.
    Starting with the situation in Turin, graph 3.15 shows the monthly trend in breakdowns, normalised for kilometres travelled.
    The year 2018 was characterised by a value of approximately 2 breakdowns per 10 000 km for all months except May, which was affected by approximately 3 breakdowns per 10 000 km. In summary, the normalised value in relation to the kilometres travelled remains constant at around 2. 2019, on the other hand, shows a trend marked by breakdowns of less than 1 per 10 000 km, but also by peaks of more than 4 breakdowns. It should be said, however, that 2019, compared to the other 3 years taken

into consideration, was the one with 20% more kilometres travelled than all the other years. Therefore, although the value shown has already been normalised with respect to the mileage covered, the increase in this value may be due to the high mileage covered in this year.

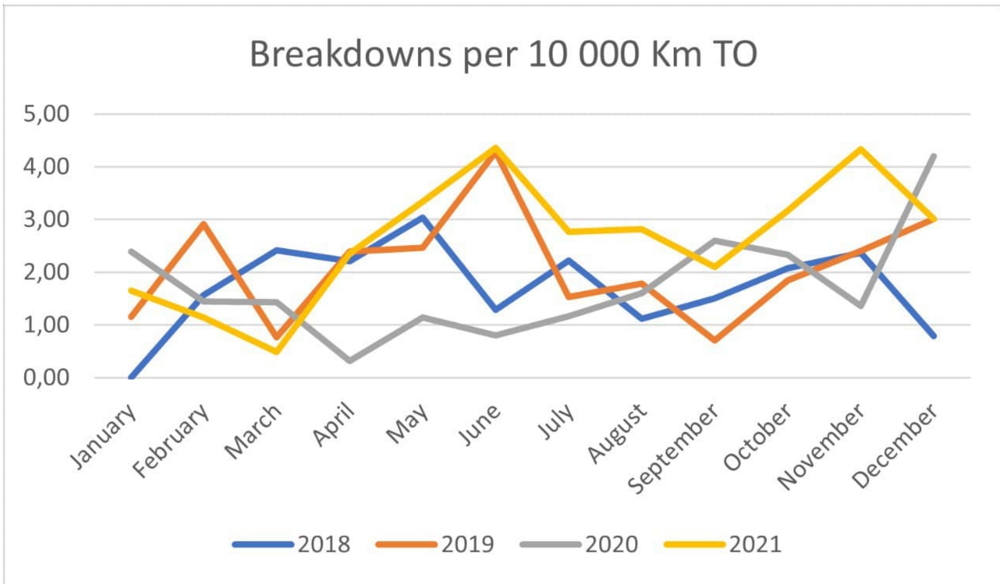

Figure 3.15: Breakdowns every 10 000 Km TO

The year 2020 shows a very low number of breakdowns, with the lowest number occurring during the pandemic months of March to May. In addition, there is an increase in failures at the beginning of the year and at the end of the year. This could highlight an increase in failures occurring at the turn of two consecutive years. On the other hand, 2021 will mark a very high number of breakdowns, as confirmed by the following indicators. More than four breakdowns are reported for every 10 000 km travelled. This data is not to be underestimated and efforts must be made to change the maintenance approach in order to minimise vehicle downtime.

Analysing the 9 vehicles in Aosta, one could intuitively affirm that 2018 was the year characterised by the highest number of breakdowns, with the peak in the month of July. In truth, however, and this is the reason for that the breakdowns have been normalised with the kilometres travelled, the year with the highest number of breakdowns is 2019, with 152 breakdowns

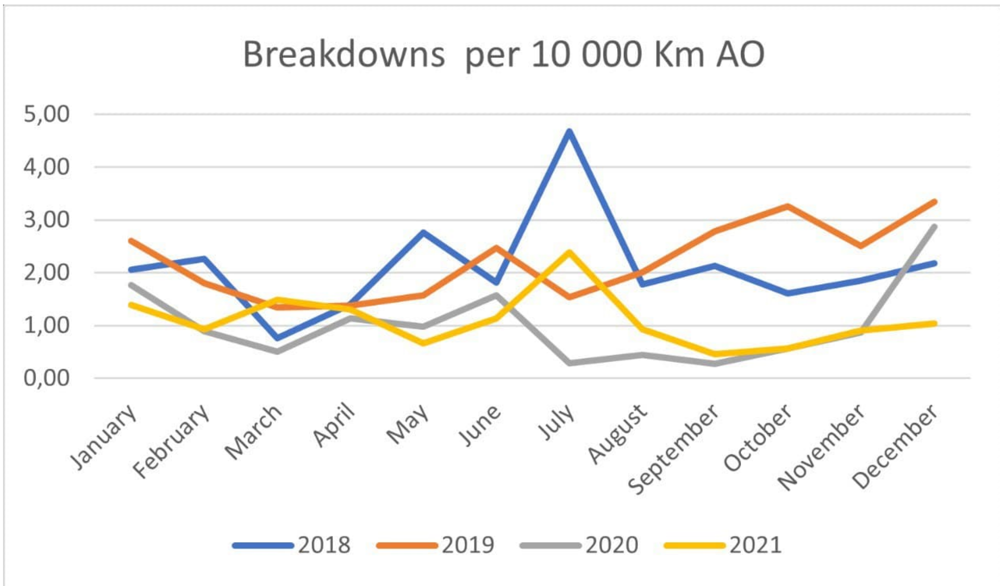

Figure 3.16: Breakdowns every 10 000 Km AO

compared to 123 in 2018. In conclusion, the July peak in 2018 represents the fact that there were many faults in relation to the kilometres travelled, but not that there were many in absolute terms. Nevertheless, although 2019 was the year with the highest number of breakdowns, these were balanced by the high number of kilometres travelled, so the indicator has a value of around 3 breakdowns per 10 000 km travelled.

– **Average vehicle downtime**: The purpose of this indicator is to show the rate of total downtime due to unplanned downtime. Total downtime is defined as all downtime occurring during the reporting period, in this case monthly, whether due to planned maintenance or corrective maintenance. In the ideal world, all downtime should only be caused by preventive maintenance and not by corrective one. This would mean that all planned maintenance would serve to avoid corrective intervents. In reality, however, as explained in the previous chapters, it is unavoidable that a share of the maintenance is due to corrective maintenance. With this indicator it is possible to make considerations about the share that most predominates vehicle downtime. Even in this case, the analysis was carried out month by month, for the years 2020 and 2021, with a distinction between vehicles in Aosta and Turin on which the telediagnostic device was installed. The duration of downtimes is expressed in days and the term UD refers to Unplanned Downtimes and TD to Total Downtimes. Naturally, since the vehicles analysed offer a public transport service, the fewer downtime the better. But since having a zero number of downtime is impossible because otherwise there would be no maintenance, if the vehicle had to be stopped it would be preferable to do it for preventive and not for corrective maintenance.

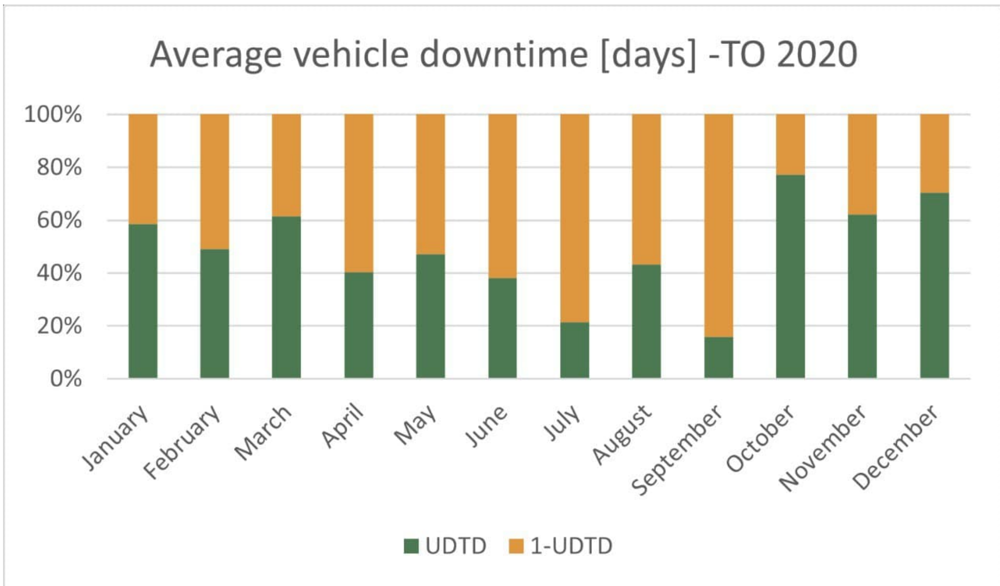

Figure 3.17: Average vehicle downtime TO 2020

Starting from the situation in 2020 for the Turin site, it is possible to say that there is nothing relevant in the graph. The bars in figure 3.17 indicate for each month the percentage of unplanned downtime out of the total downtime in green and in orange the downtime for planned maintenance. When the green bar exceeds 50%, it means that the corrective downtime has been greater than the planned downtime. This situation should be minimised. In this specific case, the last three months of the year were characterised by an excess of unplanned downtime compared to planned ones.

Moving to 2021, the situation looks much more critical. Obviously, the relative percentage of planned and unplanned downtime would be related to the absolute number of downtime. In fact, a very low number of downtime due to unplanned failures would still be acceptable. Figure 3.18 shows that only February and March were characterised by fewer unplanned downtimes than planned. For all other months, however, unplanned downtime predominated. It is unavoidable that the situation in 2021 should not be underestimated. Indeed, these indicators provide an indication, although a qualitative one, of the causes that led to the vehicle being stationary.

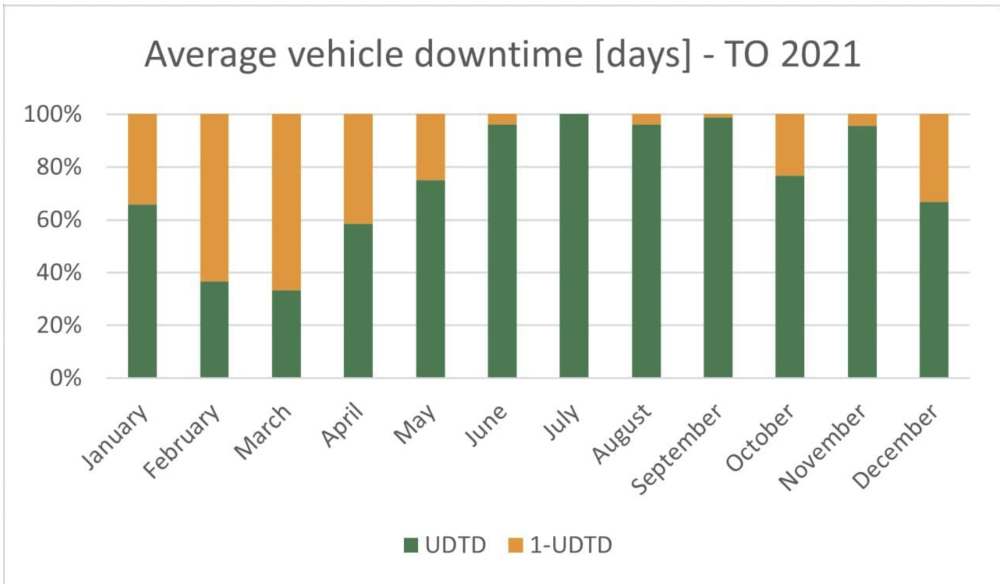

Figure 3.18: Average vehicle downtime TO 2021

Similarly, the indicator was also calculated for Aosta vehicles for the years 2020 and 2021 respectively. Graph 3.19 shows the situation in 2020. In contrast to what happened to vehicles in Turin in 2020, in Aosta the first few months of the year were characterised almost exclusively by planned downtime for preventive maintenance or inspection. The last few months of the year, on the other hand, were characterised almost entirely by unscheduled shutdowns. This is explained by the fact that during the first months of 2020, the pandemic reduced the service of the vehicles and consequently also the breakdowns: this resulted in only preventive activities and not accidental breakdowns during that period.

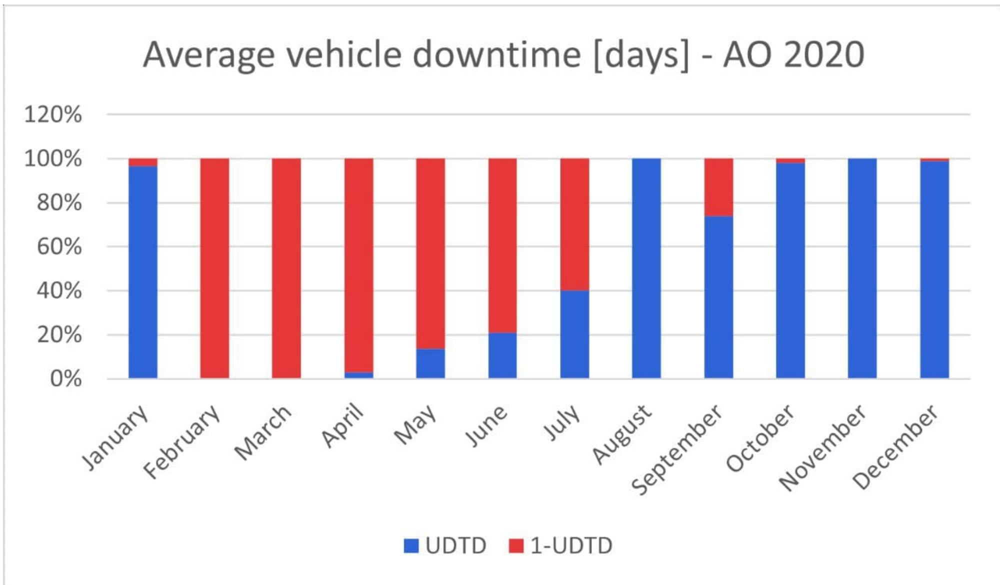

Figure 3.19: Average vehicle downtime AO 2020

As far as the year 2021 is concerned, similarly to what happened with the vehicles in Turin, the number of unplanned downtimes has taken over from the planned downtimes. In this case, this is not optimal, but it is necessary to try to reduce the number of unplanned downtimes, also because this implies that preventive maintenance activities have been inefficient.

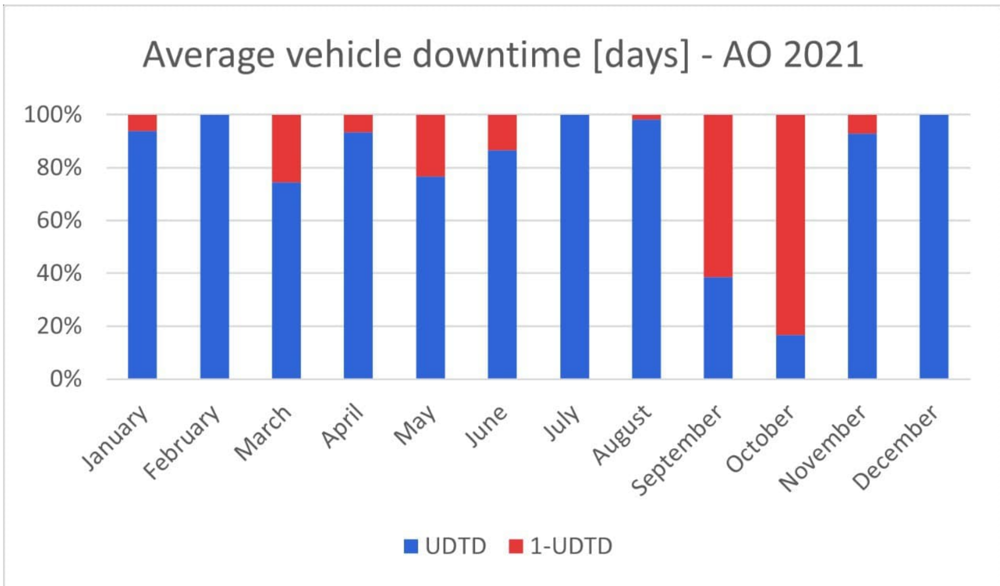

Figure 3.20: Average vehicle downtime AO 2021

- **Breakdowns by category**: The calculation of this KPI aims to identify the categories of faults that occur most frequently during a certain time interval. Also in this case, failures occurring in 2020 and 2021 were analysed, with a distinction between vehicles in Turin and Aosta. The faults have been divided into 12 macro categories. The following are some of the examples of faults for each category:
    - Bodywork: chipped windscreen, damaged seat covers, dented bodywork due to impact;
    - Braking System: brake pads to be replaced, brake cylinder to be replaced, brake caliper to be replaced;
    - Chassis: rusting chassis, cracks on chassis;
    - Tires: tire replacement due to puncture;
    - Pneumatic System: air leakage pneumatic system, brake system air leakage;
    - Suspensions: exhaust damper, inefficient silentblock;
    - Engine: injector replacement, engine oil leak, pump belt breakage;
    - Cooling system: coolant leak, broken alternator cooling pipe;
    - Electrical System: alternator to be replaced, external lights out;
    - Heating System: inefficient preheater, diesel leakage from preheater;
    - Transmission: gearbox oil leak, noisy differential;
    - Steering: steering bar to be fixed, power steering oil leak.

For each vehicle belonging to the Turin depot in which the telediagnostics device was installed, and for each month, the number of faults relating to one of the 12 chosen categories was reported. What stands out overall from the analysis is that the number of failures in 2021 was around 100 times higher than in 2020. The reason may be the lockdown period caused by the pandemic that affected Italy from March to May. The pandemic undoubtedly reduced bus services to a minimum and thus the number of kilometres travelled. Consequently, the number of breakdowns during this period was also reduced. This is demonstrated by the fact that before March and after April the number of breakdowns started to rise again, but overall 2020 is characterised by a lower number of breakdowns than 2021, since the vehicles were stationary for three months.

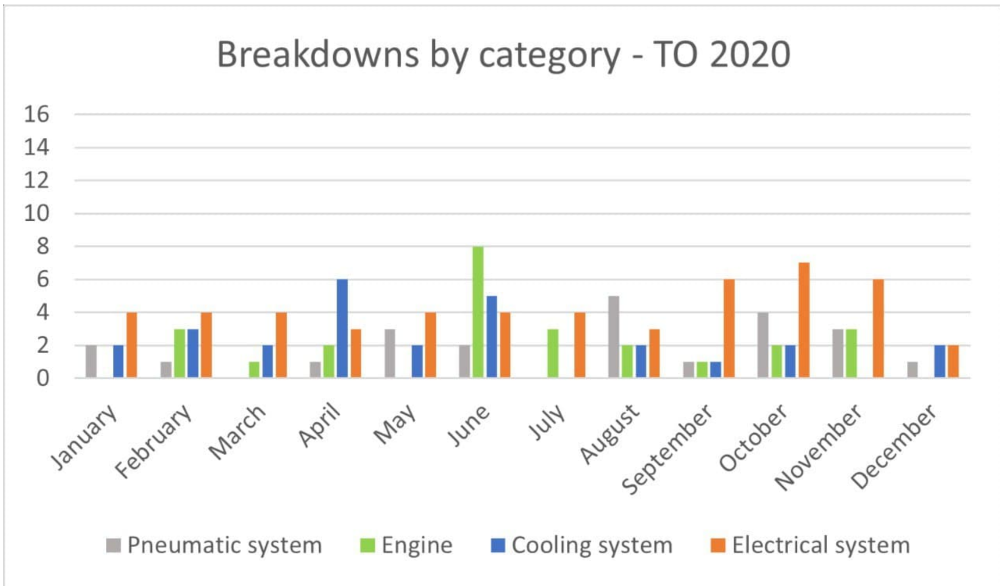

Figure 3.21: Breakdowns by category TO 2020

In detail, Figure 3.21 shows the four most significant failure categories in 2020. As shown, the failures are related to the pneumatic system, the coolant system, the electrical system and everything directly connected to the engine. The total number of failures was 236, of which 126 were related to these four categories, so these categories took up more than 53% of the total. By the way, the month with the most faults was June; probably because faults found in the pandemic months were accumulated due to lack of workshop technicians and then repaired in June.

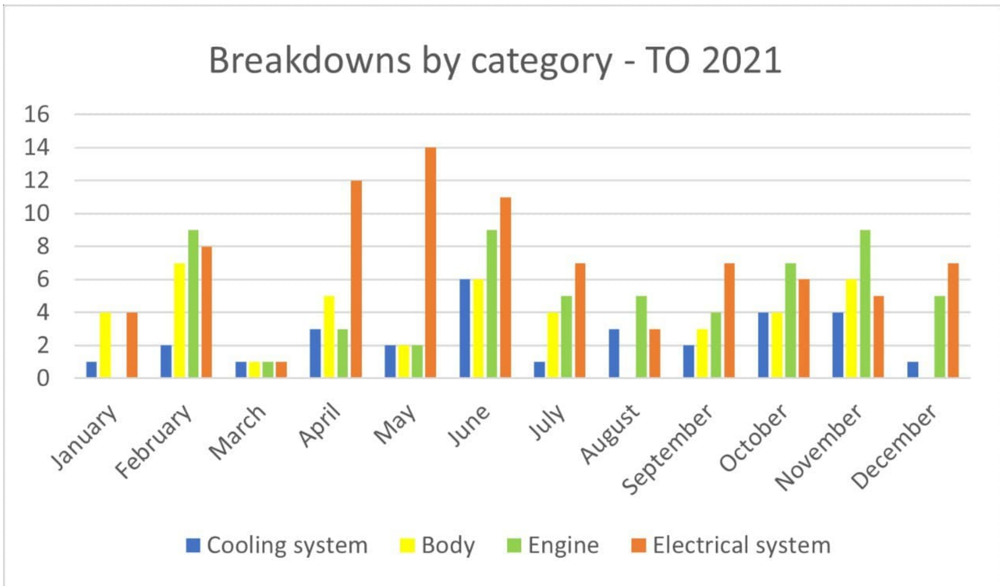

Figure 3.22: Breakdowns by category TO 2021

The year 2021 was characterised by as many as 341 failures, i.e. an increase of 44% compared to 2020. In this reporting year, the categories with the highest number of failures were cooling system, bodywork, electrical system and everything directly related to the engine. The total number of failures was 341, of which 216 related to these four categories, so these categories took up more than 64% of the total.
The same analysis conducted for vehicles in Turin was carried out for vehicles in Aosta. In this case, only 120 faults were detected in Aosta in 2020. Compared with the number of breakdowns in Turin in the same year, the number of breakdowns is almost 100% lower. The five categories with the highest number of failures are the electrical system, the bodywork, and then the cooling system, suspension and everything directly related to the engine with the same number of events. These five categories accounted for 72% of total failures, i.e. 86 out of 120. The four most relevant categories in 2021 were bodywork, electrical system, cooling system and everything directly related to the engine. In this case, these categories accounted for 68% of the total faults, i.e. 107 out of 158. Taking the year 2021 as a reference but for vehicles in Turin, the number of breakdowns found in Aosta is more than 100% lower than in Turin.

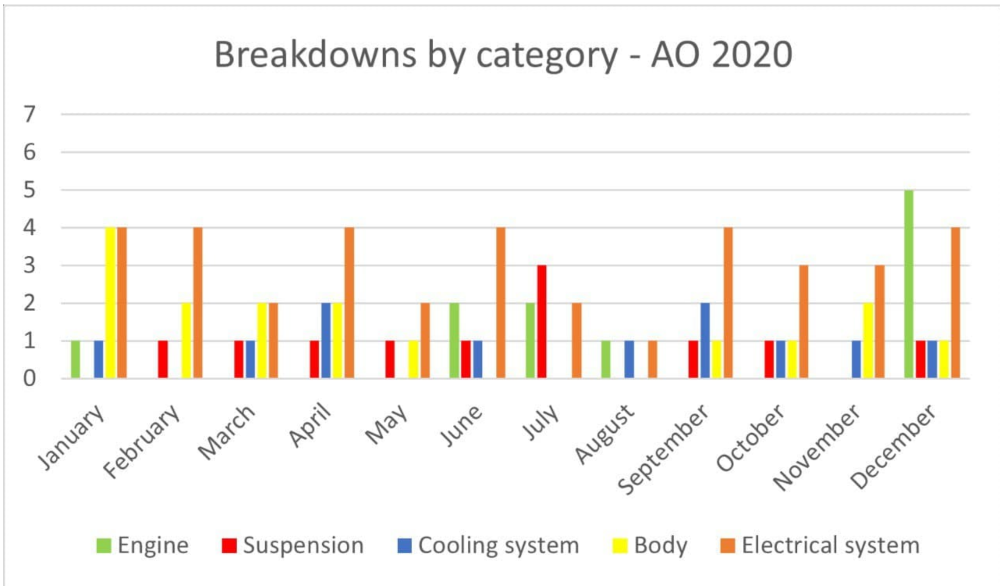

Figure 3.23: Breakdowns by category AO 2020

Intuitively, it is possible to say that, although the vehicles in Aosta had comparable mileage to those in Turin, they were affected by far fewer breakdowns during the year. This consideration becomes even more relevant if one notes that the analysis was carried out on 10 vehicles from Turin and only 9 from Aosta, and despite the lower number of vehicles, those from Aosta travelled about 500 000 km more. In conclusion, this difference in values is due to the fact that the Aosta depot performs more restrictive scheduled maintenance than the Turin depot. This is because the mission carried out by the vehicles in Aosta is more stressful and therefore the periodicity with which maintenance is performed in Aosta is shorter and therefore the results in terms of breakdowns are better.

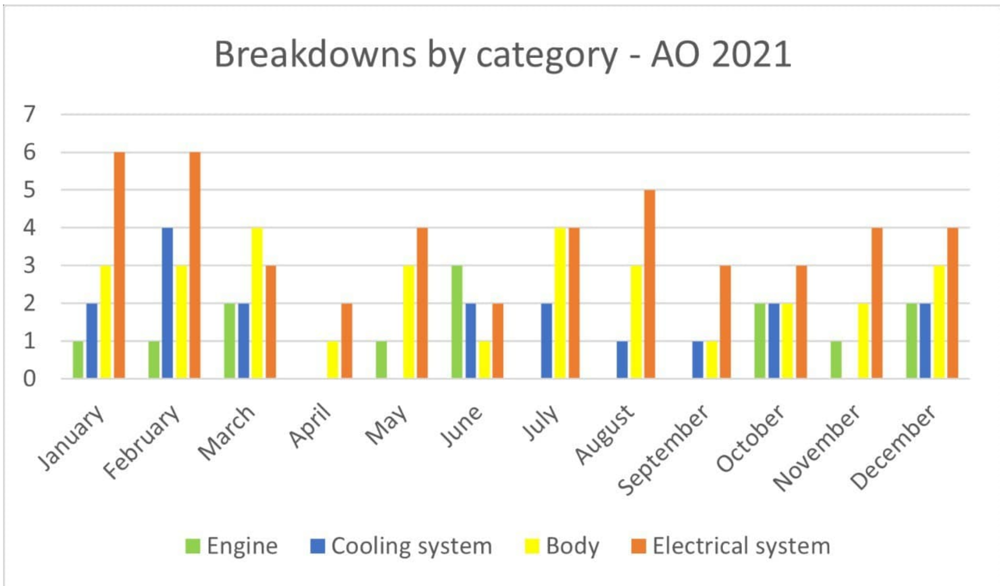

Figure 3.24: Breakdowns by category AO 2021

Aosta's vehicles were subject to more breakdowns than in the previous year, i.e. there was a 32% increase from 120 breakdowns to 158. Again, it is assumed that the reduced number of failures in 2020 is due to the period in which vehicles were stationary during the pandemic.

- **Step 4**: The fourth step consisted of configuring the alerts after analysing the most frequent fault categories and the alerts provided by the system. To this purpose, more attention was given to **Engine, Transmission** and **Electric System**. The purpose of this step was to ensure that alerts were received when there was a real anomaly and not just when a value exceeded a preset threshold. For this reason, we tried to interpret the real conditions in which an anomaly could occur.

  With regard to exceeding the **Gearbox** oil temperature threshold, it was found that this could be due to incorrect driver behaviour or excessive use of the retarder. Consequently, two alerts have been configured:

  - Gearbox oil temperature above 110 °C;
  - Vehicle speed = 0 kph;
  - Gear engaged;

- Time elapsed 15 mins.

If all these conditions occur, it means that the increase in oil temperature is due to incorrect behaviour of the driver, who left the gear engaged during the stop and did not switch the gear selector to Neutral.
In order to eliminate the possibility of receiving an alert when it is certain that the increase in T is due exclusively to the use of the retarder, an alert has been configured as below:

- Gearbox oil temperature above 110 °C;
- Vehicle speed = 10 kph;
- Retarder switched from on to off;
- Time elapsed 1 min.

The occurrence of these conditions excludes the possibility that the increase of T is due to the gear engaged when the vehicle is stationary, since 10 kph is required as vehicle speed. On the other hand, in order to avoid that the increase in T is due to the use of the retarder, one minute is required to elapse from when the retarder is switched off. In this way the increase in T is related to gearbox anomaly or malfunctioning.

As far as the **Engine** is concerned, since there is no direct indication of intercooler operation, an alert has been configured to highlight a potential fault. The function of the intercooler is to maintain the coolant circulating in the engine cavity at a constant temperature, as well as the oil used to lubricate the engine components, but also to lower the temperature of the intake air. At high engine loads, more fuel has to be burned and consequently more combustion air is required. In order to intake more air, this is compressed and then the temperature is lowered to increase volumetric efficiency. The intercooler is an air exchanger. It consists of a radiator in which the fluid or the air to be cooled circulates, and a fan which forces the outside air onto the radiator. The fan can be driven mechanically via a belt, hydraulically via an oil pump or driven by a viscostatic joint. The fan in the vehicles analysed is hydraulically controlled. The circuit consists of two oil pumps, the second of which is regulated by a solenoid valve. Oil is constantly sent under pressure from the first pump to the second one; when the solenoid valve is closed there is a recirculation of oil, when it is open the oil fills a chamber and by viscous action sets the fan in motion. The higher the temperature of the coolant, the greater the opening of the solenoid valve and consequently the higher the fan speed. Therefore a higher fan speed is expected at high engine speeds and similarly a lower fan speed when the engine is idling. In order to identify potential anomalies in the cooling circuit, the system was required to check the parameters every minute and mark t=0 when:

– Intake manifold temperature > 50 °C & engine speed <= 600 rpm;

when time elapsed 1 min check if:

– Engine speed > 600 rpm & intake manifold temperature > 50 °C.

In the event that the intake manifold temperature does not drop with increasing engine speed, this could indicate a malfunction in the air exchanger. This is a complex alert, but it allows to get an indication of the functioning of the intercooler despite not being able to get a direct indication of the parameters.

The third largest category of failures is the **Electrical System**. In particular, on this kind of vehicle we have indications only on the state of the battery. A huge number of alerts have been received on the battery voltage, but sometimes this is not due to a malfunction of the alternators but rather to the high rate of inactivity of the vehicle (e.g. a vehicle that has been at the bodywork shop for several weeks or a vehicle that has been stopped waiting for repair due to lack of parts). The goal now is to better understand when the system issues a battery voltage alert. The system evaluates the health of the battery by taking into consideration the Crank profile which is the voltage need for the starter motor to start the gasoline combustion engine and to which the battery drops during cranking the engine. As a result, a lower voltage means less torque for the starter motor which causes it to run slower, less back EMF (Electric and Magnetic Field), more heating, and slower engine starting. However, the most important part in starting an engine is amperage, not just voltage. An average bus battery produces 800 to 1300 cold crank amperes to start the vehicle. Cold crank amperes are a unit of measurement that show the amount of amperes a battery can discharge in 30 seconds at 0 degrees Fahrenheit. Cold cranking amps is an industry standard referring to a battery's capacity to start a vehicle in cold temperatures. A battery with a high CCA (Cold Cranking Amps) rating has a higher starting power. This indicator highlights that starting at low temperatures should be more difficult than starting at elevated temperatures. Below are two pictures representing how battery works and the influence of external temperature.

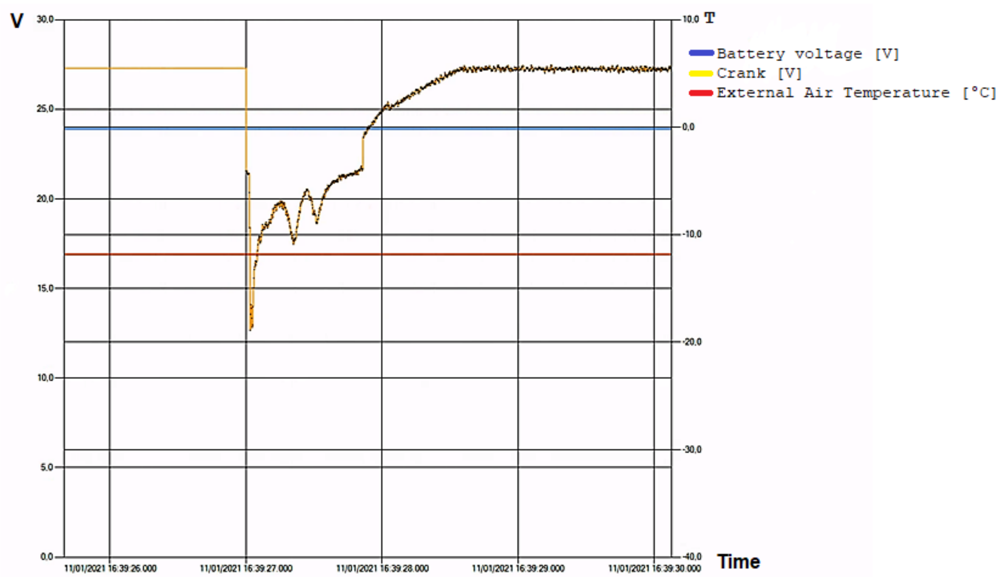

Figure 3.25: Crank profile with -12 °C

Figure 3.25 shows that the nominal battery voltage is about 24 volts with an external temperature of -12 °C. The crank voltage trend shows a rapid decrease in voltage to 13 V starting from about 27 V and then the alternator restores the voltage. Starting the engine involves a high voltage absorption. Similarly, figure 3.26 shows that the battery voltage is about 24 volts with an external temperature of 10°C.

The crank voltage trend shows an early decrease in voltage starting from a value of about 27 V and arriving at about 13 V and then the alternator restores the voltage. Also here the starting of the engine involves a high voltage absorption.

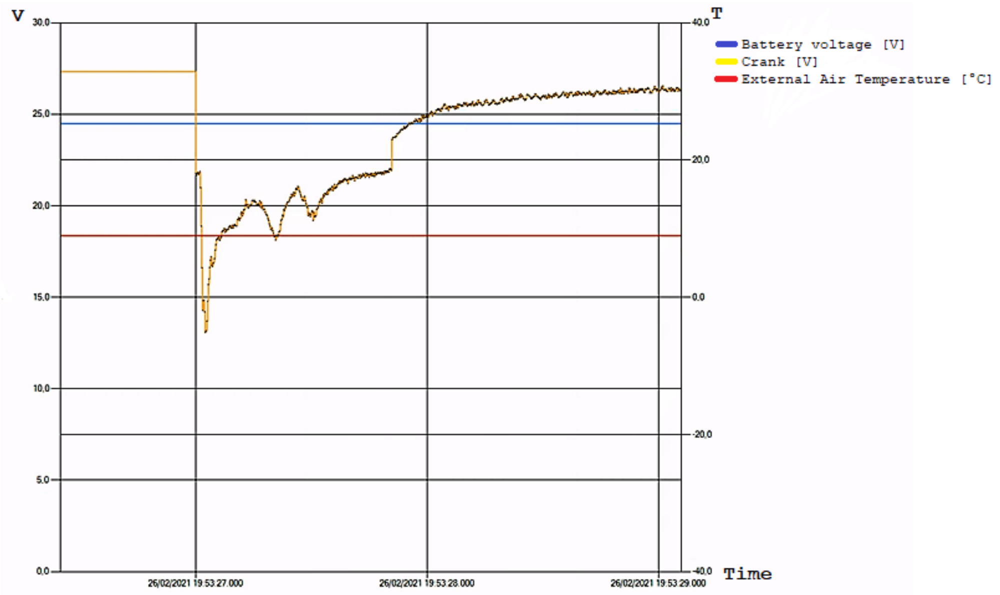

Figure 3.26: Crank profile with 10 °C

The two vehicles had the same battery and what emerges is that the external temperature has a small impact on the minimum battery voltage but the crank profile remains the same, just a bit lower on the scale although it takes in both cases about 1 s to restore the voltage.

On the other hand, when a battery is faulty the crank pattern changes, for example:

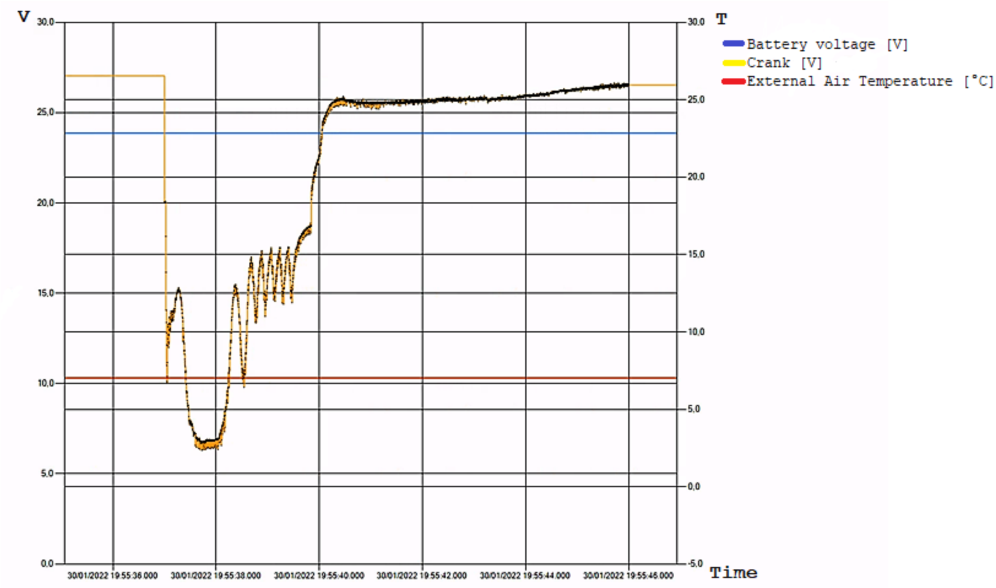

Figure 3.27: Crank profile with a faulty battery

In this case, although the initial voltage is always 27 V, after starting the engine the voltage drops to about 6 V and takes about 5 seconds to be restored. Such a pattern indicates a battery failure.
After crank detection, the model analyzes the profile and translates it to a score: the lower the score the better the battery status is. In this way, the battery's end of life could be detected more than 15 days before the change.

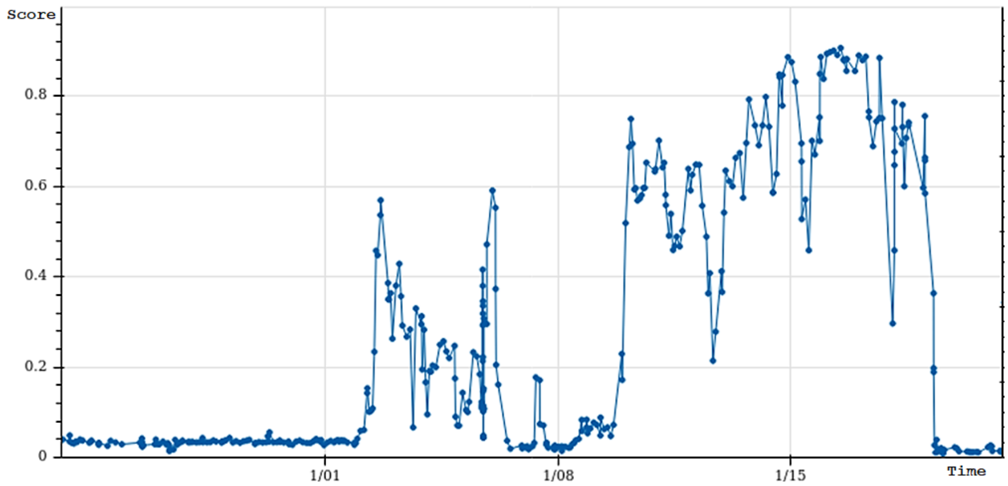

Figure 3.28: Battery status score model

Figure 3.28 shows the trend in battery status score over time. In particular, four weeks are shown here. As can be seen, the scores are initially very low, which means that the battery is in good condition. Later on, the scores start to become higher, which means that the battery is losing efficiency. When the values reach around 1.0, the battery is almost at the end of its life and needs to be replaced. In the last part of the graph, on the right, it can be seen that the values become very low again after battery replacement.

The aim of this step of the Pilot Project is to go beyond simply receiving alerts when a threshold is exceeded and to configure more complex alerts.

Chapter 4

Conclusion and Future Insights

4.1 Conclusion

These alarms are transmitted in real time via e-mail notifications or sms when the previously defined conditions occur. This also makes it possible to determine the position of the vehicle at the time of the event; the maintenance operator, and eventually also the movement coordinators, can thus make important initial considerations based on the position of the vehicle. They can therefore promptly determine the best 360° intervention strategy: type of fault/failure, severity, type of vehicle and its map position, type of vehicle power supply, availability of resources and means etc.
This thesis work has highlighted how it is possible to detect a multitude of signals relating to the operating parameters of the most diverse systems, assemblies and components present on local public transport vehicles. Due to time constraints, the experimentation focused only on a small portion of the fleet. Moreover, the vehicles were not of the latest generation, which meant that only limited parameters could be extracted. Unfortunately, at least as concerns public transport in Italy, many manufacturers focus their attention on remote monitoring but have not yet reached the maturity to implement a predictive system. At the moment the emphasis is on collecting all data available and processing them through algorithms in order to be able to implement a predictive maintenance system that leaves behind as far as

possible the predefined deadlines required by traditional maintenance plans. With reference to what I described in the previous chapters, one limit of telediagnostics is the need for a Control Room composed of one or more operators who have the task of monitoring alerts received 24 hours a day and communicating them to the technicians. In fact, despite the short monitoring time after the installation of these devices, a large number of alerts were received by e-mail and communicated in real time to the workshop manager. This would undoubtedly be an advantage for public transport companies as the number of breakdowns is reduced, it is possible to plan in advance when the vehicle will be stopped and it is possible to minimise vehicle downtime in the workshop thanks to the pre-diagnosis performed by these systems. This last point is not to be underestimated since in the absence of diagnosis the workshop operator has to carry out several tests before determining the problem. With telediagnostics, on the other hand, it is possible to identify the component that caused the fault precisely. On the other side, in day-to-day activities, receiving dozens of alerts due to exceeding a threshold does not fit in with the idea of predictive maintenance, but more with condition-based maintenance.

4.2 Future Insights

Although the systems installed are telediagnostic, the idea still remains to move towards a predictive approach. The analysis was carried out on heavy-duty vehicles, in particular public transport buses, which also appears to be the market segment that can benefit most, given the high mileage they cover and the amount of time they run. However, it should not be excluded that remote monitoring can also be implemented on private vehicles, perhaps with lesser benefits. In view of increasingly stringent emission regulations, the fleet will be renewed with fully electric vehicles in the next few years. The architecture here is much simpler than that of a conventionally powered vehicle, so all parameters will be easier to monitor. At the moment, unfortunately, considering only failures with their associated boundary conditions is not sufficient to prevent all possible breakdowns of a vehicle. In addition, some of the alerts issued are already critical at the first occurrence and/or represent a failure that has already generated a breakdown: consequently the possibility of preventive intervention is lost.
On the other hand, however, relying on mileage to prevent failure when using

classic maintenance schedules is a rather limited concept given the huge number of random variables that come into play when determining the life of a component. From these concepts stems the need to move to predictive maintenance which is based on collecting and monitoring all CAN signals related to each component during the normal use of the vehicle and establish, through back-end algorithms, the useful life of the components themselves. New digital technologies such as Machine Learning, Connectivity, Big Data, Cloud Computing will play a key role in the success of this strategy. The new generation vehicles, in particular Euro 6 - Step E, will be equipped with telediagnostics systems as standard. These vehicles will be powered on an experimental basis with HVO - Diesel (Hydrotreated Vegetable Oil) that is a high quality 100% plant-based biofuel. It has a completely hydrocarbon nature (it does not contain oxygen) and a high cetane number which allows excellent combustion, especially in cold starts, and reduces engine noise. It is also free of aromatics and polyaromatics. Thanks to its nature it can be added to fossil diesel in high percentages. The result is a biofuel of renewable origin capable of polluting up to 90% less than traditional fossil diesel: fewer greenhouse gases and particulate. Aiming to monitor the performance of this new fuel and collect data to move towards predictive maintenance, these vehicles will be equipped with telediagnostics systems. In the next few years, suppliers will probably offer dedicated packages at the moment of vehicle sales with predictive maintenance support. The company Arriva Italia, in order to take a direction towards predictive maintenance, will continue this remote monitoring project and also carry out the installation of further vehicles with a monitoring system provided by the manufacturer itself. The aim is to define any differences between a system provided by the manufacturer and a cross-system one. Certainly, with the system offered by the manufacturer itself, there will be access to a greater amount of data as there are no constraints. What has been analysed so far was only based on the occurrence of a fault and for time limitations it was not possible to make considerations in terms of reductions in vehicle downtime. It would also be interesting to analyse whether the cost of installing the diagnostic system was covered by the cost savings resulting from no longer performing traditional maintenance.

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