Project Work
Maintenance

Subject
Modern maintenance strategies in the automotive and machinery industry

Supervisor
Prof. Dr.-Ing. Tobias Leopold

Short description
Maintenance strategies for complex technical products are of great importance to users and manufacturers. In addition to economic aspects, the service life should be ensured as easily as possible. In addition to a characterization of different maintenance strategies and their comparison, the requirements for reliability engineering in particular are to be analysed. The resulting possibilities for users and manufacturers will in turn be considered.

Tasks of the project
- Research and evaluation of various maintenance strategies
- Description of selected examples from the perspective of technology, user and manufacturer
- Reliability engineering challenges of modern maintenance strategies
- Technical challenges of modern maintenance strategies
- Business case (qualitative) of modern maintenance strategies

Team
Mert Avsar 772134
Patrik Janak 772194
Jheng-Da Huang 772183
Saiparth Shingaram 772206

Table of Content:

HOCHSCHULE ESSLINGEN

1. What is maintenance in Mechanical Engineering……………………………2
2. Maintenance Types…………………………………………………………...2
3. Relationship between different maintenance strategies………………………3
4. Application of Different Maintenance Strategies……………………………3
5. Relationship between Asset Health, Cost and Time in maintenance………..4
6. Application of Different Maintenance Strategies……………………………5
7. Relationship between Time and Increasing Data Volume, Variety, and Complexity…………………………………………………………………...5
8. Evolution of Maintenance Paradigms………………………………………..6
9. Preventive Maintenance……………………………………………………...6
10. Preventive maintenance in automotive industry……………………………..7
11. Predictive Maintenance in the Automotive Industry………………………...29
12. Corrective Maintenance……………………………………………………...43
13. Reliability Engineering in the Automotive and Machinery Industry: Maintenance Strategies……………………………………………………46
14. Additional Maintenance Strategies for Reliability Enhancement……………46
15. Total Productive Maintenance (TPM)...48
16. Condition-Based Maintenance (CBM)..49
17. Major challenges in the automotive and machinery industry………………..50
18. Maintenance of ML-based automotive systems………………………………52
19. Predictive Maintenance for Autonomous Vehicles…………………………...53
20. Business Case…………………………………………………………………54
21. Conclusion……………………………………………………………………59
22. Sources………………………………………………………………………...61

1. What is maintenance in Mechanical Engineering?

In mechanical engineering, maintenance describes the tasks necessary to guarantee the durability, safety, and appropriate operation of mechanical systems, machinery, and equipment. It includes a variety of actions meant to keep mechanical systems operating at optimum reliability and effectiveness, reduce interruption, and avoid malfunctions.

In mechanical engineering, maintenance is essential to guarantee the efficiency, reliability, and safety of manufacturing processes, transportation systems, power plants, and other mechanical systems. It contributes to extending equipment life, reducing the chance of accidents and malfunctions, and maximising operating expenses.

2. Maintenance Types:

a. **Preventive Maintenance:** This involves scheduling routine maintenance, repairs, and part replacements to stop equipment failure before it starts. It covers maintenance duties like lubrication, cleaning, calibration, and component replacement according to equipment conditions or scheduled times.

b. **Predictive Maintenance:** With this strategy, equipment failure may be predicted using data and analytics, allowing for just-in-time repair to minimise downtime and save money. Techniques like condition monitoring, vibration analysis, thermography, and oil analysis are all part of maintenance planning.

c. **Corrective Maintenance:** This strategy is fixing equipment after it has broken down. Although it can lead to expensive downtime, it's often less desirable than predictive or preventive maintenance, however, it may be needed to prevent catastrophic failures.

d. **Routine Maintenance:** These are routine, ongoing duties that guarantee machinery keeps operating at peak efficiency. These could involve things like cleaning, little modifications, and daily inspections.

e. **Shutdown Maintenance:** This refers to scheduled maintenance tasks that necessitate a long-term downtime of equipment. It is frequently carried out during planned maintenance shutdowns or outages.

3. Relationship between different maintenance strategies:

Relationship between Time and Machine Condition:
It shows the optimal points for applying predictive, condition-based, and preventive maintenance strategies based on the machine's condition over time.

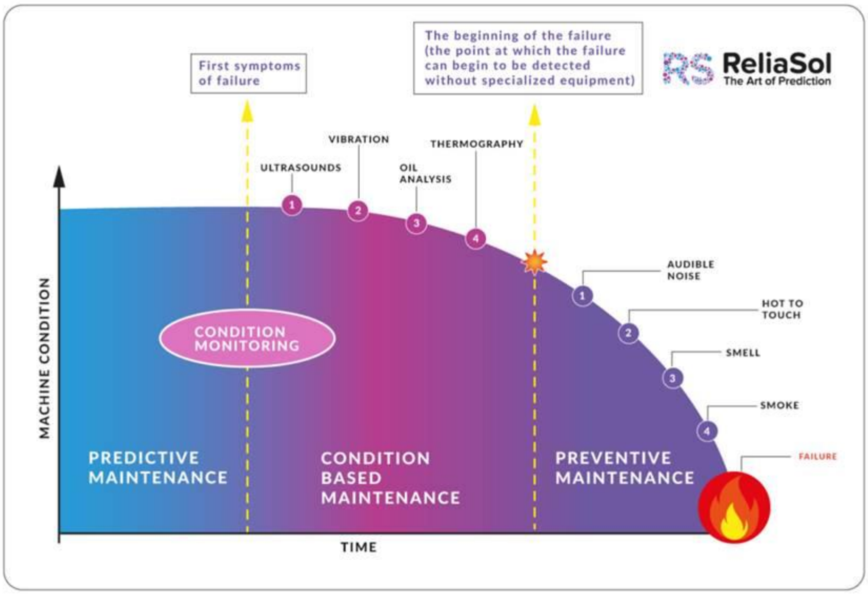


Fig. Relationship between Time and Machine Condition

- **X-axis (Time):** Shows the operational timeline of the machine.
- **Y-axis (Machine Condition):** Indicates the health status of the machine, from good condition to failure.
- Represents the deterioration of machine condition over time, eventually leading to failure

4. Application of Different Maintenance Strategies:

Predictive Maintenance: Conducted before the first symptoms of failure appear, using techniques like ultrasounds to predict issues.

Condition-Based Maintenance: Performed as the machine condition starts to deteriorate, using methods such as vibration analysis, oil analysis, and thermography to monitor the condition and make maintenance decisions.

Preventive Maintenance: Carried out when the beginning of failure can be detected without specialised equipment, including obvious symptoms like audible noise, the machine being hot to touch, strange smells, and smoke.

Condition Monitoring: Throughout the deterioration process, various techniques (ultrasounds, vibration analysis, oil analysis, thermography) are used to continuously monitor the machine's condition. This allows for early detection and intervention before the machine reaches a critical failure point.

5. **Relationship between Asset Health, Cost and Time in maintenance:**
The diagram underscores the importance of timely and appropriate maintenance to reduce repair costs and prevent asset failure. It also shows the optimal points for applying different maintenance strategies based on the asset's health deterioration curve.

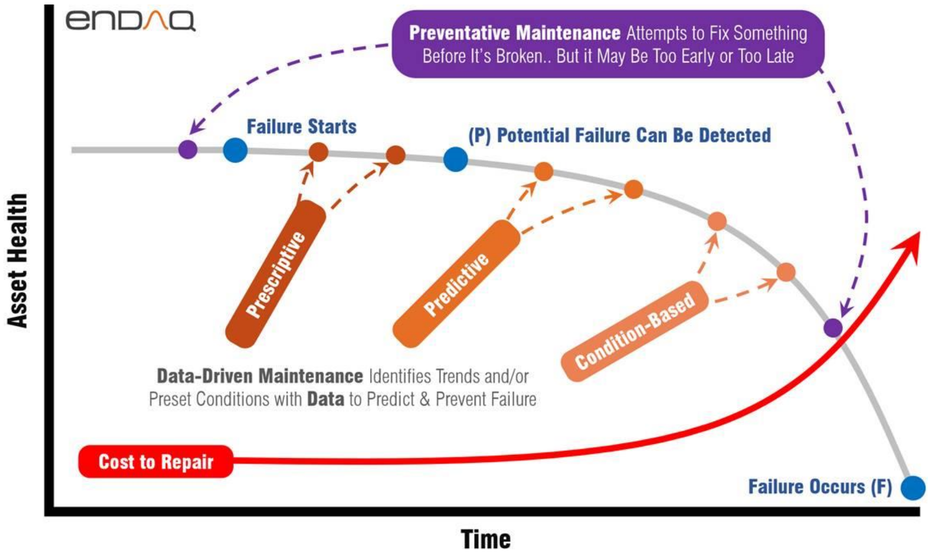


Fig. Relationship between Asset Health, Cost and Time in maintenance (Hanly, n.d.)

- **X-axis (Time):** Shows the operational timeline of the asset.
- **Y-axis (Asset Health):** Indicates the health status of the asset, from good to failure.
- Represents the deterioration of asset health over time, eventually leading to failure
- Repair costs rise as time progresses, especially near the point of asset failure.

6. **Application of Different Maintenance Strategies:**
   - **Preventative Maintenance:** Attempts to fix something before it breaks, but may occur too early or too late.

- **Prescriptive Maintenance:** Conducted before failure starts (Failure Starts).
- **Predictive Maintenance:** Performed when potential failure (P) can be detected.
- **Condition-Based Maintenance:** Based on the actual condition of the asset.

7. **Relationship between Time and Increasing Data Volume, Variety, and Complexity:**
   This diagram highlights the evolution of maintenance paradigms, showing the shift from reactive to prescriptive maintenance. It underscores that as technology advances and data becomes more abundant, maintenance strategies evolve towards highly intelligent and self-optimising approaches.

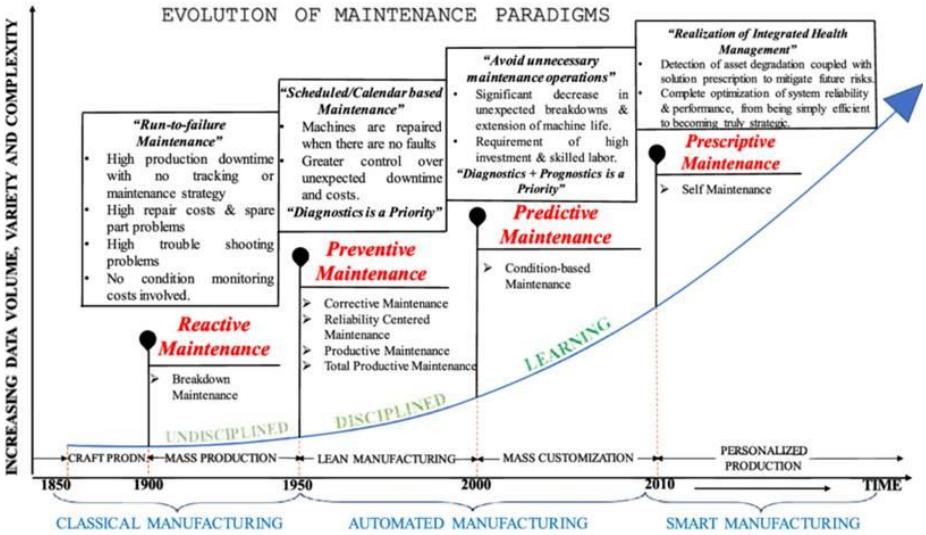


Fig. Relationship between Time and Increasing Data Volume, Variety, and Complexity

- **X-axis (Time):** Displays the evolution of maintenance paradigms over time, from craft production, mass production, automated manufacturing, mass customization, to smart manufacturing.
- **Y-axis (Increasing Data Volume, Variety, and Complexity):** Indicates that as time progresses, the volume, variety, and complexity of data increase.

8. **Evolution of Maintenance Paradigms**:

I. **Reactive Maintenance (1850-1950):** Also known as "Run-to-Failure Maintenance," characterized by high production downtime, no tracking or maintenance strategy, high repair costs, troubleshooting problems, and no condition monitoring costs.

II. **Preventive Maintenance (1950-2000):** Scheduled or calendar-based maintenance, where machines are repaired when there are no faults, allowing greater control over unplanned downtime and costs. Diagnostics are a priority. This includes corrective maintenance, reliability-centered maintenance, predictive maintenance, and total productive maintenance.

III. **Predictive Maintenance (2000-2010):** Condition-based maintenance aimed at avoiding unnecessary maintenance operations, with a significant decrease in unexpected breakdowns and extension of machine life. Diagnostics and prognostics are a priority, relying on high investment and skilled labor.

IV. **Prescriptive Maintenance (2010-Now):** Focuses on the realization of integrated health management, with detection of asset degradation coupled with solution prescriptions to mitigate future risks. This represents the complete optimization of system reliability and performance, moving from being simply efficient to becoming truly strategic.

9. Preventive Maintenance:

Preventive Maintenance (PM) is based on the fundamental principle that regularly scheduled inspection and maintenance of the asset provides a number of benefits to the ongoing performance of the asset. These include extending the life of the equipment, anticipating future need for major service or replacement, ensuring optimum levels of performance, preventing downtime due to malfunction or breakdown, minimising repair costs and ensuring the safety of the equipment by preventing potential hazards that can occur when it is run outside its normal operating condition. Carrying out PM also provides an opportunity to address minor repairs not included in the original PM plan and to identify additional action items. Effective implementation requires technicians who can go beyond simply following prescribed work orders. Equipment longevity may be primarily a financial concern, as premature failure necessitates equipment replacement. However, it can also be a safety issue, depending on the circumstances and timing of failure. Proper performance is critical for both comfort and safety, with safety taking precedence, particularly when performance degradation is subtle and could negatively impact the outcomes. In certain cases, the failure of one device can lead to subsequent faults in other devices, adding to the impact and cost.

A. Two major types of preventive maintenance:

- **Time-based preventive maintenance:**

  This form of preventive maintenance is carried out at regular intervals according to a schedule, often facilitated by preventive maintenance software. While all critical equipment should undergo PM, focusing on equipment that is vital to production can help minimise breakdowns. A fleet of vehicles could be scheduled for maintenance every four months as a prime example of preventive maintenance in action.

- **Usage-based preventive maintenance**

  Another type of preventive maintenance is usage-based, where a machine's operating data informs maintenance actions. Data metrics can include cycle counts, run time, distance travelled or hours of operation. For example, an industrial maintenance technician might evaluate machine usage statistics and then schedule maintenance based on the gathered measurements and usage patterns.

10.Preventive maintenance in automotive industry

Lubrication:

Using a lubricant to minimize wear and friction between moving surfaces in touch with one another is known as lubrication. By creating a thin layer or film between the surfaces, the lubricant reduces frictional forces and avoids direct metal-to-metal contact. Lubricants come in a variety of forms, including oils, greases, and solid lubricants. The type of lubricant chosen depends on a number of variables, including temperature, load, speed, and operating circumstances.

Importance of Lubrication:

Reduced Friction and Wear: By reducing friction between moving parts, lubrication helps machinery and equipment last longer and sustain less wear.

Heat Dissipation: Lubricants act as a barrier between surfaces, which helps disperse heat produced during operation. This minimize the chance of component thermal damage and overheating.

Corrosion Protection: Lubricants work as a barrier against particles and moisture, preventing corrosion on metal surfaces.

Improved Efficiency: Machine functioning is smoothed out and energy savings and efficiency are increased with proper lubrication.

Noise Reduction: Because lubrication softens and dampens the movement of mechanical components, it can help minimise noise and vibration.

Applications of Lubrications as Maintenance Strategies in the Automotive Industry:

Past:

Animal Fat: During the carriage era, animal fat was a common lubricant used to lubricate wooden wheel bearings and other moving parts.
Olive Oil: In some early steam cars, olive oil was used as a lubricant for moving engine parts such as pistons and crankshafts.
Grease and Mineral Oil: For parts with higher lubrication requirements such as gears and transmission chains, some types of grease and mineral oil may have been used to provide lasting lubrication.

Now:

Engine Oil:
The most common and essential form of lubricant for automobiles is engine oil. By lowering the friction of moving parts, engine oil is in charge of completely lubricating the engine's combustion chambers. The engine oil's ability to maintain its viscosity even at greater operating temperatures is crucial. To extend the life of the engine parts, engine oils often include a variety of chemicals, including dispersants, detergents,

and anti-wear compounds. Manufacturers frequently advise doing routine engine oil changes.

What is the changing time period of the engine oil?

The intervals vary between 5000 to 15,000 kilometers for a passenger car, pickup truck, SUV, and plug-in hybrid vehicle (PPV), contingent on the engine oil quality used. A high-grade oil designed specifically for this purpose can last up to 15,000 kilometers. The frequency of automobile usage also affects the interval.

Gear Oil:

Vehicle differentials, transmission boxes, and manual transmissions are the principal applications for gear oils. To handle the high-pressure motions, they often have extremely high viscosities and incorporate severe pressure additives with phosphorus sulfur compounds. Though it has a far longer lifespan than engine oil and is often replaced after 100,000 kilometers, gear oil does not need to be changed as frequently. To prolong the lifetime of the gear oil, it's necessary to choose high-quality oil, observe driving behaviour, prevent frequent rapid acceleration and sudden braking, regularly inspect the engine and oil system of the vehicle to ensure smooth oil flow.

Greases:

Thickener, extra additives, and petroleum or synthetic chemicals can be used to make greases. It is comparable to oil, but because of its thickness, it is perfect for lubricating linkages, gears, and bearings. Some of the most recent high-performance lubricants, such silicone-based synthetic greases, have been effectively employed in applications requiring high mechanical pressure, like torque gearboxes.

Penetration Lubricant:

These fluids are low viscosity because they are highly purified and flowing. Usually, they are in containers similar to aerosols. They are applied to rusty and difficult-to-loosen nuts and bolts. When they are sprayed and given time to absorb, they work best. Penetration lubricants sometimes require frequent reapplication due to their rapid wear.

Dry Lubricant:

They are a mess-free, simple-to-use lubricant. They are composed of dry lubricating particles, alcohol, and liquids like water. Typically, they are packaged in an aerosol spray canister. The liquid evaporates once it is sprayed, leaving behind a coating of dry lubricant. They work best on tiny components that might otherwise get blocked with grease, such as hinges and threaded rods.

Future:

The future of lubrication will be defined by technological advancements and sustainability. Innovations in nanotechnology will enhance performance, while biodegradable and eco-friendly lubricants will address environmental concerns. Smart lubricants will adapt in real-time to optimize performance. IoT and advanced sensors will enable real-time monitoring and predictive maintenance, supported by AI and machine learning. Sustainable practices like recycling and re-refining will reduce waste. Specialized lubricants will cater to electric vehicles and robotics. Advanced application methods, such as additive manufacturing and micro-dispensing, will improve efficiency. Additionally, non-toxic and fire-resistant lubricants will enhance safety, making the future of lubrication innovative, responsible, and efficient.

Suspension System

The suspension system is a critical component of a vehicle, responsible for providing a smooth and comfortable ride while maintaining control and stability. Proper maintenance of the suspension system is essential to ensure its longevity and optimal performance.

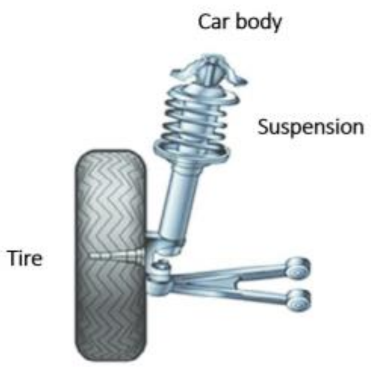


Figure 1: Quarter-car suspension system [1]

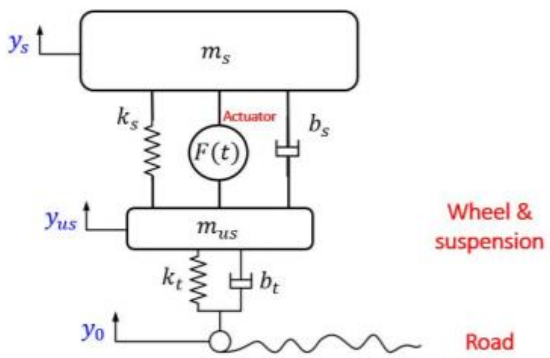


Figure 2: Lumped-parameter suspension model [2]

When a vehicle encounters a pothole, its suspension system may sustain significant damage almost instantly. Suspension systems must effectively handle various road conditions while providing support to the wheels, seats, and vehicle frame. To assess the functionality of a vehicle's suspension system, researchers often employ multibody analyses and simplified lumped models of mechanical systems.

Suspension System Maintenance

Tire Maintenance:

- Tire inflation should be checked monthly and adjusted to the recommended pressure, which can vary depending on the vehicle and driving conditions.
- Tires should be rotated every 6,000-10,000 miles to ensure even wear.
- Wheel alignment should be checked every 6,000-10,000 miles or as needed to prevent uneven tire wear.

Shock and Strut Replacement:

- Shocks and struts typically need to be replaced every 50,000 miles, but this can vary depending on the vehicle and driving conditions.
- Excessive bouncing, sagging, or clunking noises may indicate the need for shock or strut replacement.

Bushing and Ball Joint Inspection:

- Control arm bushings and ball joints should be inspected every 15,000 miles for wear and damage.
- Worn bushings can cause vibrations, rattling, and imprecise steering, while damaged ball joints can lead to suspension instability and increased risk of accidents.

Regular Inspections:

A comprehensive suspension system inspection should be performed by a qualified mechanic during regular maintenance intervals, typically every 12,000-15,000 miles.This inspection should include a thorough examination of all suspension components, including springs, shocks, struts, control arms, and related hardware.

Common Suspension Problems and Failures

Wear and Tear:

Over time, shocks, struts, and bushings undergo wear and tear due to constant use, leading to a decline in suspension performance. Shocks and struts may lose their ability to absorb impacts effectively, while bushings can become brittle or cracked. Regular inspection and timely replacement of these components are essential to maintaining optimal vehicle performance and safety.

Leaks:

Shocks and struts contain hydraulic fluids that can leak, reducing their damping effectiveness. A leak can lead to a bouncy or unstable ride, compromising vehicle handling. Regularly checking for fluid leaks during maintenance inspections and promptly replacing any leaking parts is crucial to ensure the suspension system functions properly.

Corrosion:

Suspension components exposed to harsh environmental conditions, such as moisture and road salt, can corrode over time. Corrosion weakens these parts, potentially leading to failure. Regular cleaning, protection of suspension components, and inspections for rust and corrosion are necessary to prevent these issues and extend the lifespan of the suspension system.

Misalignment:

Hitting potholes or curbs can misalign the suspension, leading to uneven tire wear and poor handling. Misalignment affects the tire-road contact angle, causing uneven wear patterns and reducing tire lifespan. Regular wheel alignments and careful driving can prevent misalignment, ensuring the vehicle maintains optimal performance and safety.

Failure and Prevention

Shock and Strut Failure:

Symptoms of shock and strut failure include excessive bouncing, poor handling, and uneven tire wear. These components are crucial for absorbing road impacts and providing vehicle stability. To prevent failure, replace shocks and struts at recommended intervals and at the first sign of wear to maintain optimal vehicle control and safety.

Bushing Wear:

Worn bushings can cause vibrations, rattling noises, and imprecise steering, affecting the comfort and control of the vehicle. Regular inspection of bushings and prompt replacement at the first signs of wear are essential to prevent these issues and ensure smooth and precise steering.

Ball Joint Failure:

Ball joint failure is often indicated by clunking noises, poor handling, and uneven tire wear. These joints are critical for steering and suspension control. Regular inspection and timely replacement of ball joints when they start to wear out are necessary to maintain safe handling and prevent further damage to the suspension system.

Spring Breakage:

Symptoms of spring breakage include sagging suspensions, uneven ride height, and poor handling. Springs support the vehicle's weight and absorb road shocks. Periodic inspection of springs and replacement when necessary are crucial to ensure a stable and comfortable ride, preventing further suspension issues.

The lumped model of the vehicle suspension system has three main components:

1. Wheels
2. Seats
3. Body

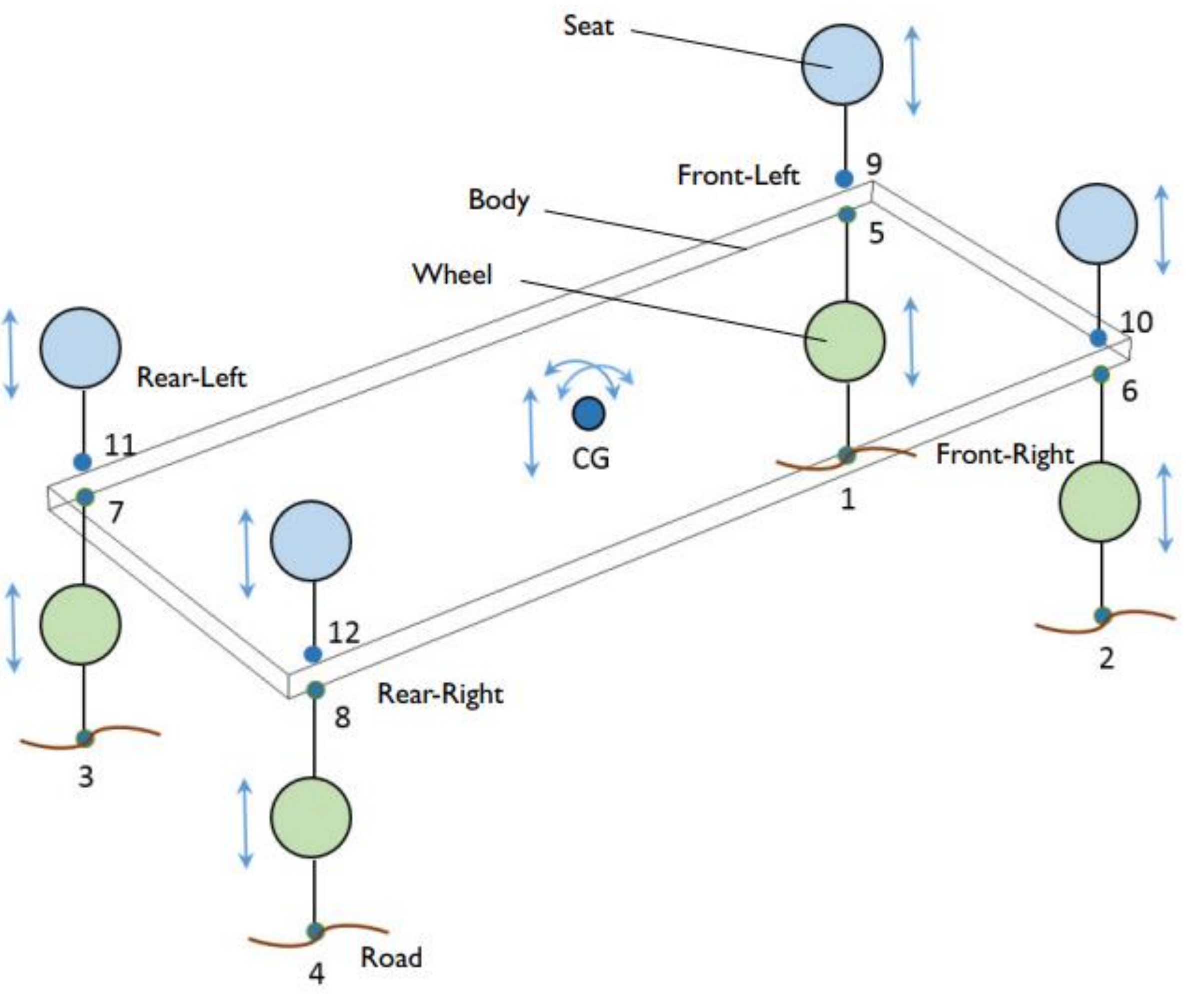


Fig. The lumped model of a vehicle suspension system with three main components

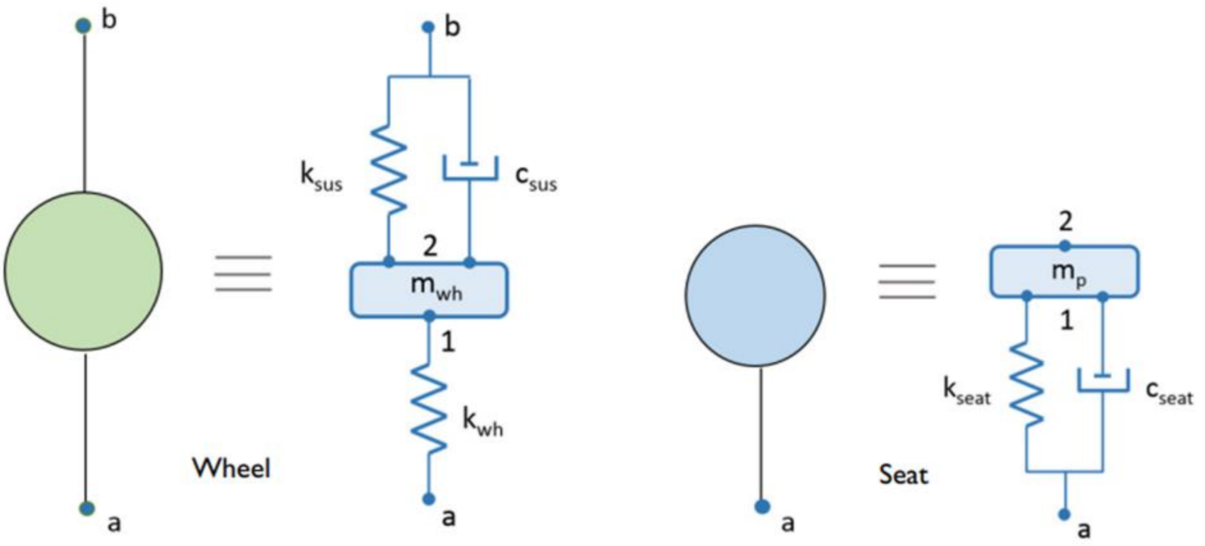


Fig. The lumped model of a wheel and seat

To determine how soft or hard the suspension is and modify it accordingly, we want to find out what the forces are in the springsThe results show that the force magnitude in the spring and damper of a wheel is much larger than that of a seat. This is because the force is absorbed by the inertia of the wheels and the vehicle body, so only a fraction of the force is transmitted from the wheel to the seat. Additionally, the frequency of vibration is much lower for the forces in the seat compared to the forces in the wheel — making for a smoother ride.

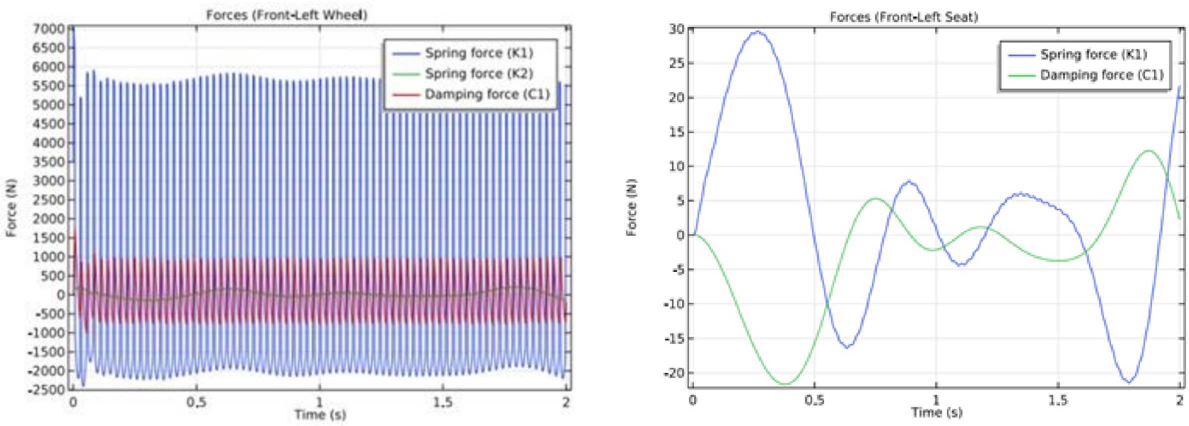


Fig. Forces in the springs and damper of the front-left wheel (left) and front-left seat (right).

Suspension System Lifetime

Proper maintenance of the suspension system can significantly extend its lifespan. Studies show that vehicles with well-maintained suspension systems can last over 100,000 miles, compared to around 50,000 miles for those with neglected systems. Regular inspections, timely replacements, and addressing issues promptly can prevent failures and ensure a smooth, safe ride

TIRES:

Tire Pressure: For both safety and fuel economy, tires must be inflated to the recommended pressure. Underinflated tires can cause early wear on the tire edges, reduce fuel economy, and increase rolling resistance. Tires that are overinflated may have less grip, uneven wear, and a more difficult ride. It is important to consistently monitor and modify tire pressure in accordance with the manufacturer's guidelines.

Fig. Example of wrong-inflated tires

Preventive Solution: Tire Pressure Monitoring Systems

According to FMVSS No. 138, at least one tire on 12.4 percent of passenger cars in the US from model years 2004 to 2011 is seriously underinflated (at least 25 percent below the cold tire pressure advised by the vehicle manufacturer). Additionally, the poll discovered that 23.1% there was at least one seriously underinflated tire on the MY 2004–2007 vehicles without TPMS, but only 11.8 percent of the MY 2004–2007 vehicles with TPMS, and only 5.7 percent of the more current.

Although TPMS's main objective is to lessen underinflation to increase vehicle safety, reducing underinflation also improves fuel efficiency. Estimates of decreased underinflation brought on by TPMS and estimates of increased fuel efficiency as a result of tire

pressure, it is possible to calculate how much gasoline TPMS will save the typical car over a specific length of time. According to estimates, TPMS will save an average passenger vehicle 9.32 gallons of gasoline and an average LTV 27.89 gallons of fuel during the course of the first eight years of operation. By using less gasoline, TPMS is thought to have saved $511 million on the fleet of vehicles in 2011. This estimate excludes any potential extra savings from longer tire life or from advantages related to preventing crashes.

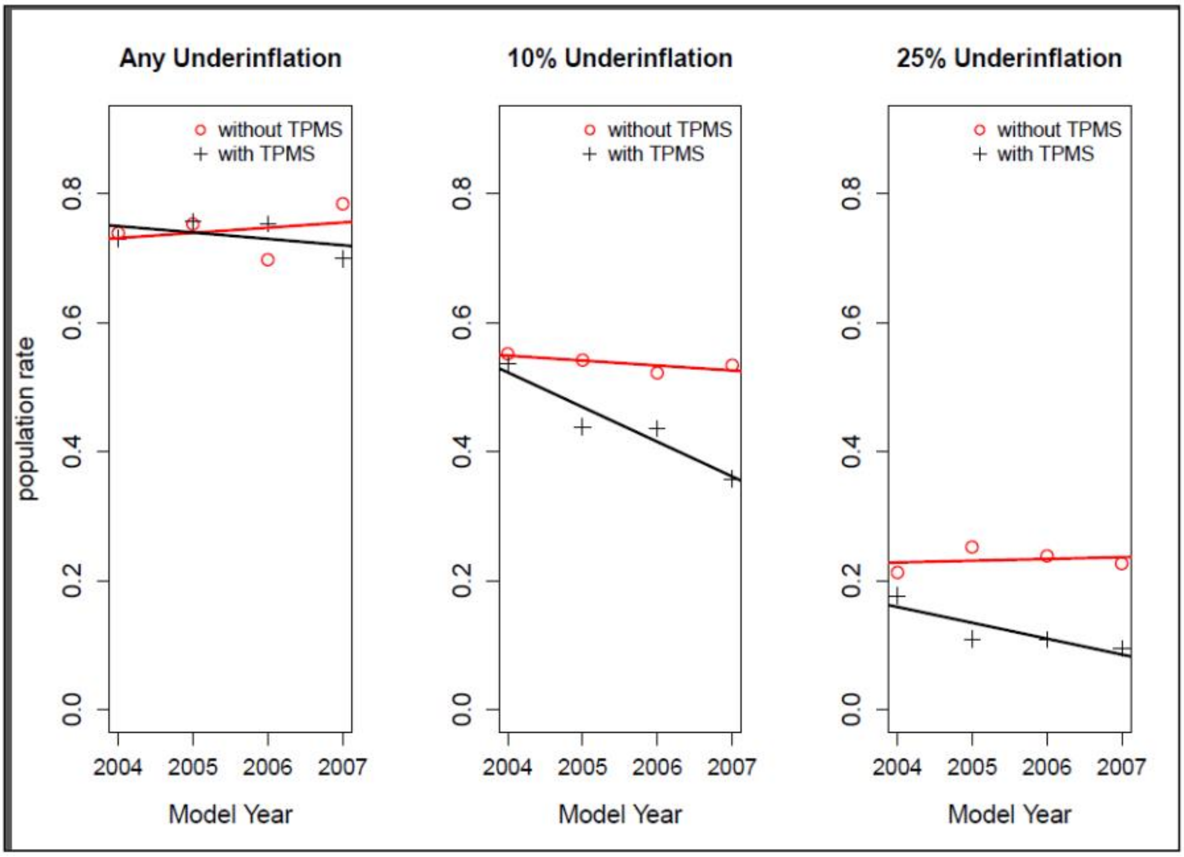


Fig. Population Underinflation Rates by Model Year and TPMS

Vehicles with TPMS are less likely to have one or more tires that are significantly or moderately underinflated, according to the data's graphical interpretation. Observe that the left graph, which displays the rate of "any" underinflation, shows little to no difference between vehicles equipped with and without TPMS systems. This is not surprising, as most TPMS systems only notify drivers of underinflation if it reaches 25% or much worse.

Tire Rotation: Because of differences in weight distribution and steering dynamics, tires wear differently depending on where they are located on the vehicle. Tires may be kept in peak performance and even wear by rotating them on a regular basis. Depending on the kind of vehicle, the type of tires, and the driving circumstances, there may be variations in the suggested rotation pattern.

Wheel Alignment: The wheels must be parallel to one another and perpendicular to the ground in order for proper wheel alignment to occur. Poor handling, uneven tire wear, and steering problems can all be brought on by misaligned wheels. Premature tire wear may be avoided and vehicle stability can be guaranteed with routine alignment inspections and adjustments.

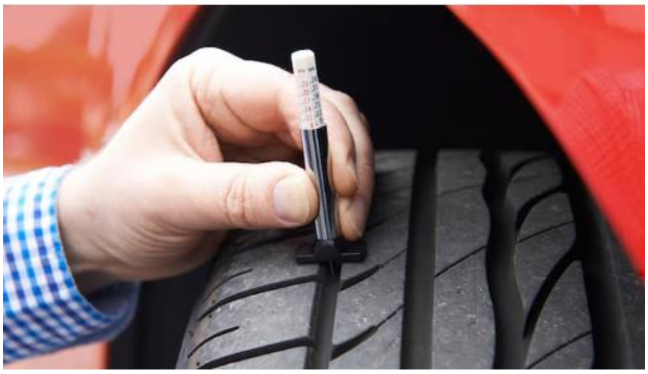


Fig. Tire Tread Depth measurement.

Tire Tread Depth: Traction is directly impacted by tire tread depth, particularly in slick or rainy circumstances. The risk of hydroplaning and losing control increases when treads are worn out because they decrease grip. For safety, it is crucial to regularly check the tread depth of tires and to replace them when they reach the manufacturer's minimum suggested tread depth.

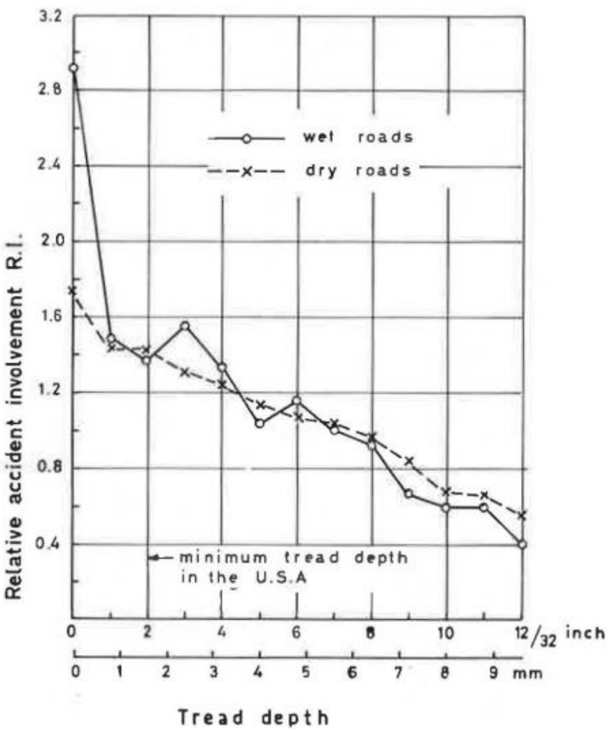


Fig. Accident involvement of low tread depth tires

Tire Balancing: Unbalanced tire wear, vibrations, and stress on suspension parts can all be caused by misaligned tires. To guarantee smooth functioning, balancing tires involves distributing weight across the tire and wheel assembly. Every time tires are put on wheels or rotated, balancing needs to be done.

Tire Inspections: It's crucial to visually examine tires on a regular basis for decreased indicators like cuts, bulges, and punctures in order to spot possible safety risks. In addition, maintaining correct tire inflation requires looking for embedded things like nails or screws that might cause air leakage.

Tire Replacement: Tires have a limited lifespan and will eventually have to be changed, even with appropriate care. When tires need to be replaced depends on a number of factors, including age, driving conditions, and tread wear. It's crucial to select tires that are appropriate for the vehicle and its intended use, as well as comply with the manufacturer's recommendations on tire replacement intervals.

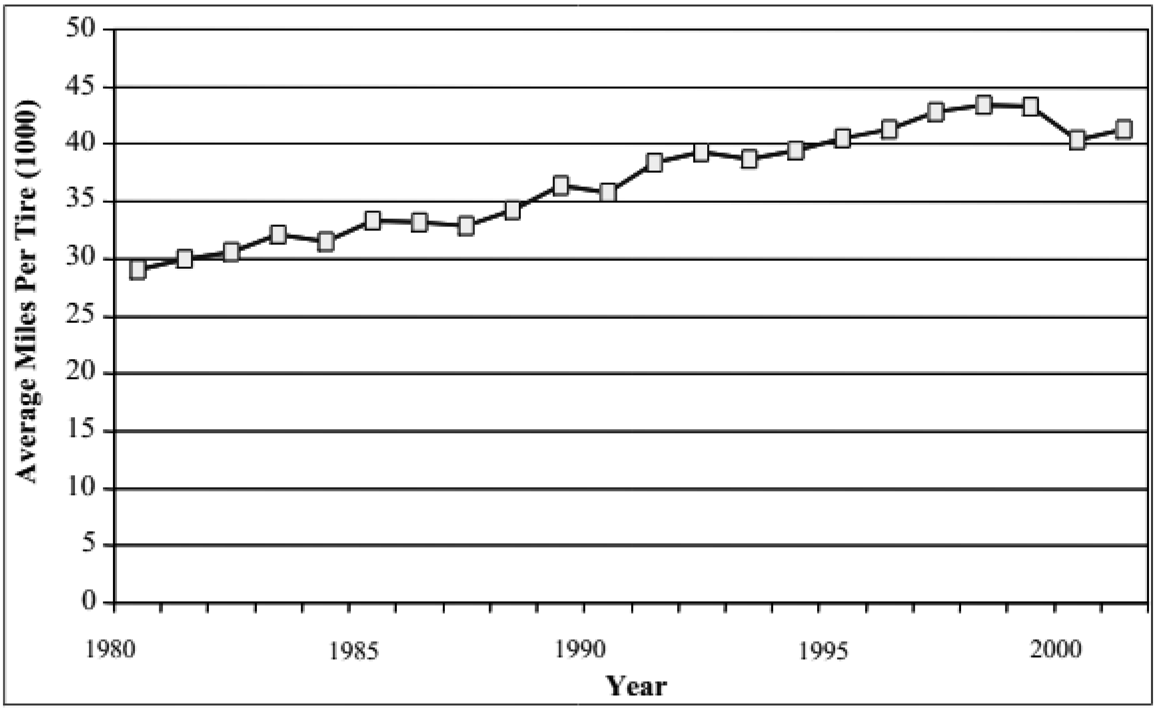


Fig. Average Tire Replacement Period 1980-2001

Although it's unclear how much these variables have changed over the past 20 years, customer choice in tire purchases and vehicle user tire maintenance habits are two aspects of tire technology that affect average tire life.

Determining the reasons for tire replacement and disposal on vehicles is crucial to comprehending tire life and distinguishing between tire practices and tire technologies that affect tire life. Based on a market assessment, the restricted tire warranties offered are between 30,000 and 80,000 miles. Numerous well-known tire manufactures provide warranties ranging from 50,000 to 60,000 miles. This guarantee is often dependent on the client providing proof that they have rotated the tires on a regular basis and have otherwise properly maintained the tires.

Cooling system maintenance:

Cars should go through major maintenance every 10000 km, including the cooling system maintenance. It can prevent engine overheating, coolant leaks, the damage to cooling system components and the decrease of engine performance.

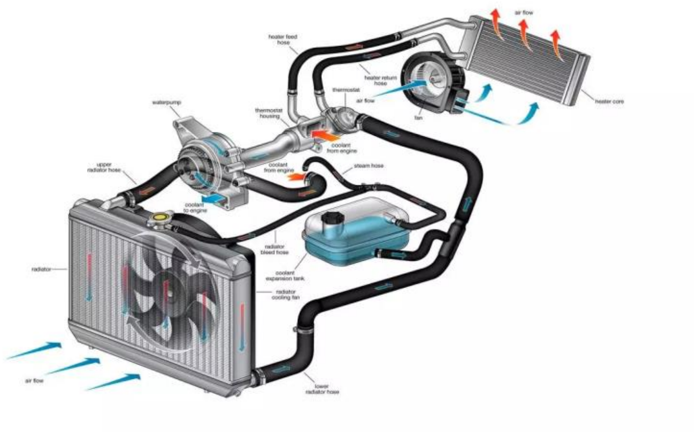


Fig. The diagram of cooling system structures in vehicles.

Fig. The colors of used coolant (left one) and new coolant (right one).

The cooling system maintenance including following items:

1. **Checking coolant level:** Ensure the coolant reservoir is filled to the recommended level.
2. **Inspecting for leaks:** Look for any signs of coolant leaks around hoses, connections, radiator, water pump, and thermostat housing.
3. **Flushing the coolant:** Periodically flush the cooling system to remove old coolant and contaminants.
4. **Testing the radiator cap:** Check the radiator cap for proper sealing and pressure release.
5. **Inspecting hoses and belts:** Look for any signs of wear or deterioration in coolant hoses and drive belts.
6. **Cleaning the radiator:** Remove debris and dirt from the radiator fins to maintain proper airflow.
7. **Checking the thermostat:** Test the thermostat to ensure it opens and closes correctly.
8. **Inspecting the water pump:** Look for any signs of leaks or bearing wear in the water pump.
9. **Checking the fan and fan clutch:** Ensure the cooling fan operates correctly and the fan clutch engages properly.
10. **Testing the temperature gauge:** Verify that the temperature gauge on the dashboard accurately reflects the engine temperature.

Cleaning the coolant is the major step in cooling system maintenance. The coolant is recommended to be cleaned every 20000 km. Neglecting this can reduce cooling efficiency, cause corrosion and blockages in the pipes, and ultimately lead to engine overheating.

The following research data shows the relationships of the coolant performance in different mileages. The effect of the cooler and coolant mileage on the cooler thermal performance was investigated in laboratory conditions. Coolant based on water and ethylene glycol G12+ (50:50) was investigated in terms of the mileages of 0 km, 50000 km, and 100000 km. The new cooler with 0 km mileage was compared with the used cooler with 100000 km mileage. (Lipnický & Brodnianská, 2023)

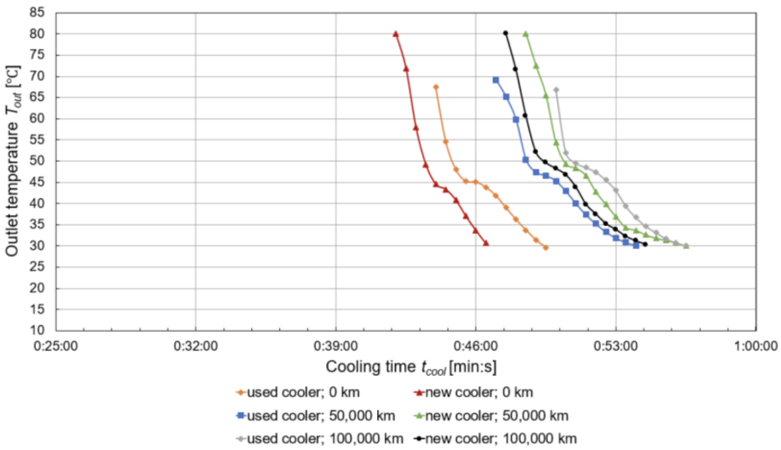


Fig. Comparison of the coolant cooling time of the new cooler and the used cooler when changing the coolant mileage.

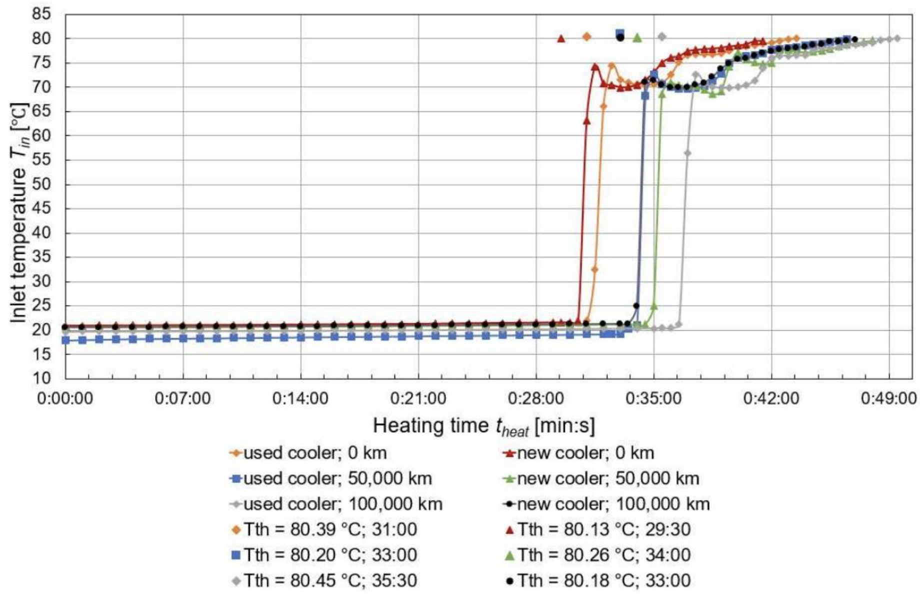


Fig. Comparison of the coolant heating time of the new cooler and the used cooler when changing the mileage of the coolant.

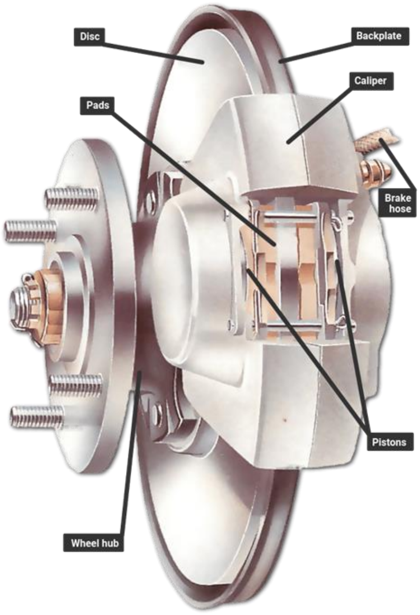
The research shows that the new coolant in the new cooler achieved the shortest heating time and cooling time and the highest values of thermal performance at the start and end of cooling. The coolant and cooler with higher mileage have no significant effect on the thermal performance of the cooler and the proper cooling function of the car engine.The correct heat transfer properties of the coolant are maintained, and the cooling process continues to run properly even after several years of mileage. Finally, it should be noted that the use of coolants is only possible if they are not contaminated with engine oils.

Obstacles faced by cooling systems in vehicles today:

I. **The increasing demand for higher performance and efficiency:** This can put additional strain on the cooling system. Especially with the rise of electric vehicles and hybrid vehicles, which generate heat differently than traditional internal combustion engine vehicles.
II. **The complexity of modern vehicle designs:** This can make it challenging to effectively cool all components, especially those located in confined spaces or with limited airflow.
III. **The ageing components of cooling systems:** In older vehicles, ageing components can lead to issues such as corrosion, leaks, and inefficient heat dissipation, requiring regular maintenance and potential upgrades.
IV. **Environmental concerns:** The coolant formulations and their impact on global warming potential can also pose challenges for cooling system designs and maintenance practices.

Future aspects:
Some potential cooling system maintenance for vehicles could be adapted.
Self-monitoring systems: Vehicles equipped with sensors and monitoring systems that can detect coolant levels, temperature fluctuations, and potential leaks in real-time, allowing for proactive maintenance.
Advanced coolant formulations: Development of more efficient and durable coolant formulations that require less frequent replacement and provide better protection against corrosion and overheating.
Improved cooling system materials: Integration of lightweight and corrosion-resistant materials in cooling system components to enhance durability and reduce maintenance needs.
Smart cooling system controls: Implementation of intelligent cooling system controls that optimise cooling performance based on driving conditions, engine load, and ambient temperature, reducing unnecessary strain on the system.
Predictive maintenance algorithms: Utilisation of predictive maintenance algorithms that analyse data from the vehicle's cooling system to anticipate potential failures and schedule maintenance before issues arise, improving reliability and reducing downtime.

Brake system



As the brake system of a passenger car is a crucial part for safety, preventive maintenance measures must be taking place regularly. These essentially ensure that the car performs the shortest braking distance and appropriate pedal feel for the driver in every situation as well as save the running costs extending longevity of components. Very common signs indicating a need for brake repair are squeaking or grinding noises when the brakes are applied, vibration or soft feel through the brake pedal, longer stopping response, uneven braking forces at each corner of a vehicle or finally, just a simple warning light at a dashboard. The typical braking system of a passenger car consists of a brake calliper, brake pads, which are pushed by pistons against a brake disc (rotor) and braking fluid which induces hydraulic forces to push the pistons.

Brake pads

Due to the wear and tear they are exposed to, brake pads need to be checked regularly to ensure that they meet standards. While the expected life of brake pads is sometimes estimated based on mileage, this overlooks driving habits. Passenger car use varies widely, such as urban driving with numerous stops, or motorway driving with fewer breaks over longer distances. Wear indicators, such as warning lights or acoustic signals, are often used to tell the driver when the pads have reached a certain thickness.

Thermal effects have a significant impact on brake components, increasing wear and reducing friction (brake fade). Brake fade requires more effort from the driver due to increased normal force, and wear escalates quickly with temperature. This poses difficulties during heavy braking, such as the rapid conversion of kinetic energy into heat, leading to potentially dangerous temperature spikes in a short period of time. The problem is magnified during continuous braking, such as downhill driving or on racetracks, where brakes have limited time to cool (Mulani et al., 2022).

Scientific article by Jensen et al., 2024 studied a useful lifetime of a passenger car brake pads according to the different driving conditions while using only data from on-board vehicle diagnostics (OBD), such as vehicle speed and engine speed to ensure applicability to a wide range of cars. The four characteristic scenarios, which were considered include highways consisting of long distance travel without frequent braking, country roads with a bit more frequent braking action and mixed, where different road types are considered. Their results in the Figure below show decreasing pad thickness with respect to time and characteristic situations as well as one extreme side of a spectrum called hard braking, which includes short distance drive with multiple sudden hard braking actions.

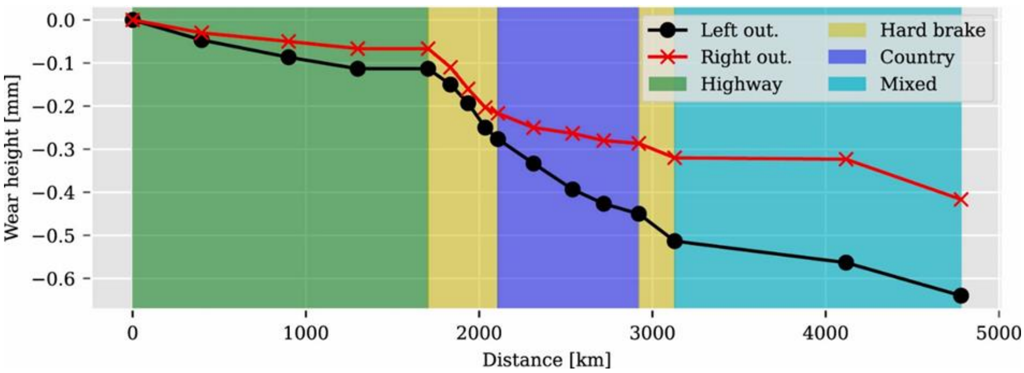


Figure XX – Wear of both front brake pads depending on driving environment

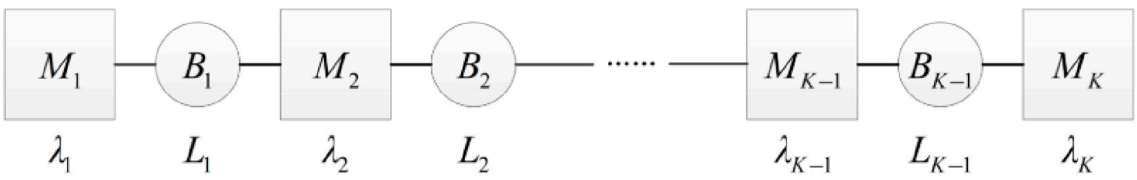
It was found that the highest possible lifetime is 20460 km, but only when taking into account highway driving. The most promising value taken as an average worked out to be 16552 km when most of the manufacturers recommend changing the brake pads once their thickness reaches to 3 mm. This mileage is however still underestimating the actual performance of brake pads in real conditions, but clearly indicating that if appropriate preventive measures such as cleaning pads from dirt, grease, rust, etc. as well as regular inspection of their thickness do not take place, the life time is drastically decreasing.

Preventive Maintenance Strategy for an Automatic Production Line (Machinery)

By creating a preventative maintenance strategy based on the group maintenance technique, automatic manufacturing lines with high maintenance costs and low dependability may be made more reliable. After a criticality assessment, the manufacturing line's machines were divided into three categories: most critical, secondary critical, and general. For every group, a different maintenance strategy was used, with general machinery receiving breakdown maintenance. Based on the Delay-time theory, a preventive maintenance model was developed for the most important equipment, with the least shutdown time serving as the decision target. Reliability and maintenance costs were taken into account in the secondary critical machine maintenance model. The suggested technique was tested through a case study on an automobile part manufacturing line, which showed how to achieve reliability standards while maintaining maintenance periods for important equipment.

Evaluation: One of the most crucial performance indicators for assessing the autonomous production line is the operating rate, which is determined by dividing the actual output by the theoretical output per unit of time. The primary variables that impact the manufacturing line's operating rate are the mean buffer capacity, manufacturing line balancing rate, and time to repair (MTTR). A clear analytical model linking all influencing elements and the operating rate is extremely challenging to build since the autonomous production line is frequently a complex manufacturing system. The failure and repair rates of the machines were directly impacted by the optimal maintenance strategy, which took maintainability into account. As a result, the machine failure rate was thought to be the primary factor influencing the operating rate. (Zhang, et al., 2018).

The standard structure and arrangement for an automated manufacturing line with K machines (M1, M2,..., MK) are displayed below.



the machine failure rate is represented by λi (i = 1, 2,... K)

the corresponding buffer capacity is Li (i = 1, 2,... K)

the buffer area is Bi (i = 1, 2,... K)

It is assumed that each machine's time between failure (TBF) follows a Weibull distribution.

The variables λj are independent of one another as the failure rates of the individual machines in the manufacturing line do not influence one another. As a result, the operating rate Y regression equation is as follows:

$$\hat{Y} = a + b_1\lambda_1 + b_2\lambda_2 + \cdots + b_K\lambda_K,$$

where the unknown parameters are denoted by a, b1, b2,..., bK.

For the N groups of samples (Yj), the minimal mean square error method fits the regression equation and is represented as:, λj1, λj2,..., λjK) (j = 1, 2,..., N)

$$\min M = E\left(Y_j - \hat{Y}_j\right)^2 = E\left(Y_j - a - b_1\lambda_{j1} - b_2\lambda_{j2} - \cdots - b_K\lambda_{jK}\right)^2.$$

The Activity Based Classification (ABC) analysis approach divides the production line's machines into three categories according to the criticality of each machine based on the parameter 􀀀􀀀 in Equation. The top 20% of machines are classified as the most crucial (A group), the next 30% as secondary critical (B group), and the other 50% as general machines (C group) in accordance with Pareto's principle. Due to their substantial influence on the performance of the production line, preventive maintenance is advised for the majority of equipment as well as secondary critical machines. Breakdown maintenance is considered appropriate for general machines, nevertheless, because it lessens the impact of the machine's failure on production line operations.

Preventive Maintenance Modeling for Most Critical Machines Based on Delay-Time Theory

The most important machines have a significant impact on the automatic production line's running rate, and if their downtime is prolonged, manufacturing companies will suffer significant financial losses. If each of the most important machines' preventative maintenance is done independently, this will result in frequent production line shutdowns. Consequently, in order to lower the frequency of preventative maintenance, all of the most important machines are maintained collectively in accordance with the synchronous maintenance principle.

The shortest shutdown time was considered in the current study as the decision target of synchronizing maintenance for the most essential equipment, and the balance between the preventative maintenance period and the shutdown time of failure was then determined, so as to reduce the complete shutdown duration. For the most important machines, the connection between the total expected value of shutdown time (ED(Tm)) per unit time and the preventative maintenance period (Tm) may be written as follows:

$$ED(T_m) = \frac{t_f EN_f(T_m) + t_p}{T_m},$$

tf are the average shutdown times for preventative maintenance and failure, respectively. (Tm) is the anticipated failure number during the preventative maintenance interval for all of the most important equipment. The most crucial machines' failure and maintenance data may be used to determine the tf and tp. When ED(Tm) is the shortest, the Tm is then obtained.

It is possible to compute the ideal interval for preventative maintenance on the most important machinery. In the meantime, the most important machine that might result in the lowest shutdown time has to have its dependability guaranteed throughout the preventative maintenance period. Weibull distribution applies to the manufacturing line's time between failure (TBF).

$$F_w(t) = 1 - \exp[-(t/\alpha)^{\beta}], t \geq 0.$$

The scale parameter (α) and shape parameter (β) of each machine may be solved using the maximum likelihood estimation approach. By entering the preventative maintenance period Tm into Equation (15), one may get the cumulative failure probability of each machine. To verify, the cumulative failure probabilities are then compared to experience values found in literature or given by the company.

11. Predictive Maintenance in the Automotive Industry

Predictive maintenance is a maintenance strategy that utilizes machine learning algorithms to analyze data from sensors, equipment logs, and other sources to predict when a machine, in this instance, an automotive vehicle, is likely to fail. Data analytics involves using historical data to generate insights into future outcomes with remarkable accuracy. Instead of relying on reactive maintenance practices or regular check-ups, predictive maintenance enables remote diagnosis of potential vehicle problems before they lead to significant breakdowns.

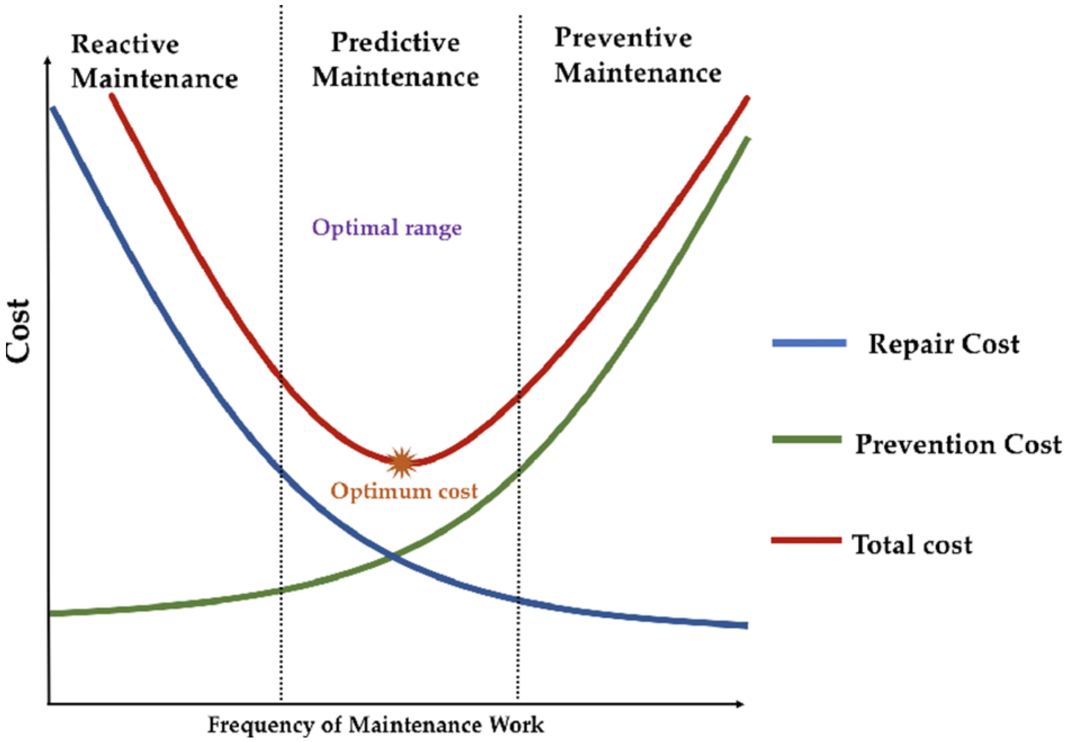


Fig. Comparison of reactive maintenance, preventive maintenance, and predictive maintenance on the cost and frequency of maintenance work

Why is Predictive Maintenance important for the Automotive Industry?

Predictive maintenance offers significant benefits to everyone involved in the automotive industry. For vehicle owners, fleet operators, and manufacturers, this proactive strategy leads to cost savings, as it identifies and rectifies possible issues before they lead to downtime and severe financial losses. By delivering real-time alerts and early warnings, predictive maintenance extends the lifespan of vehicle components.

Several automotive manufacturers have already implemented predictive maintenance solutions to optimise their operations and enhance customer experience.

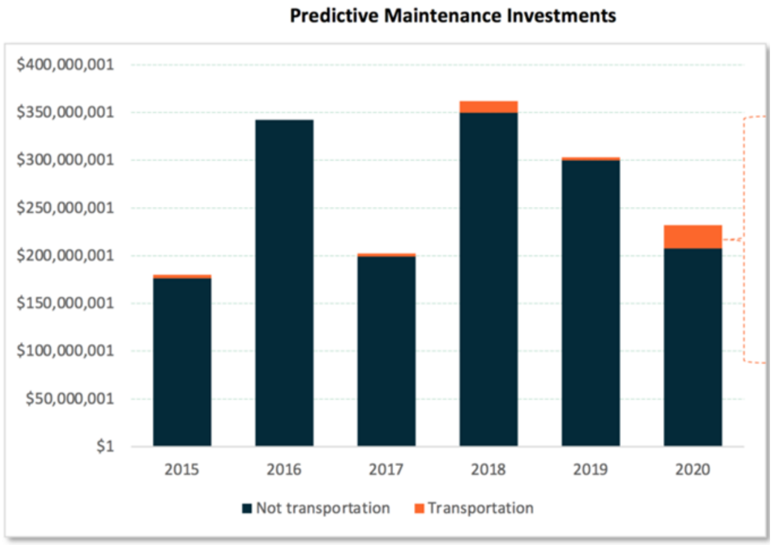


Fig. Investments in predictive maintenance.

Challenges in Adopting Predictive Maintenance for Automotive Vehicles.

When organizations consider adopting predictive maintenance (PdM) technology, they encounter several common challenges including:

- Need for modern sensors, intelligent devices, and advanced business analytics software.
- Integrating IoT security into the system to ensure data protection and privacy.
- Creating flawless communication between various components of the PdM solution poses a major obstacle.

The problem of high upfront expenditures provides a serious challenge for adopting predictive maintenance solution:

It is essential to thoroughly evaluate these problems and weigh them against the long-term benefits that the PdM solution can give. In the end, the investment in predictive maintenance shows to be well worth it due to its potential for better efficiency, reduced downtime, and cost savings.

Predictive Maintenance Techniques:

A) Condition Monitoring:

Vibration Analysis:

In order to find imbalances, misalignments, and wear in rotating parts including engines, gearboxes, and bearings, vibration analysis is an essential condition monitoring tool. To record vibration data, accelerometers and other vibration sensors are fixed on important parts. The sensors communicate the data to a central processing unit while continually monitoring the vibration levels. The vibration data is analyzed by sophisticated algorithms to find trends and departures from typical operating circumstances. These variations may be a sign of possible problems such as gear wear, misalignment, or bearing problems.

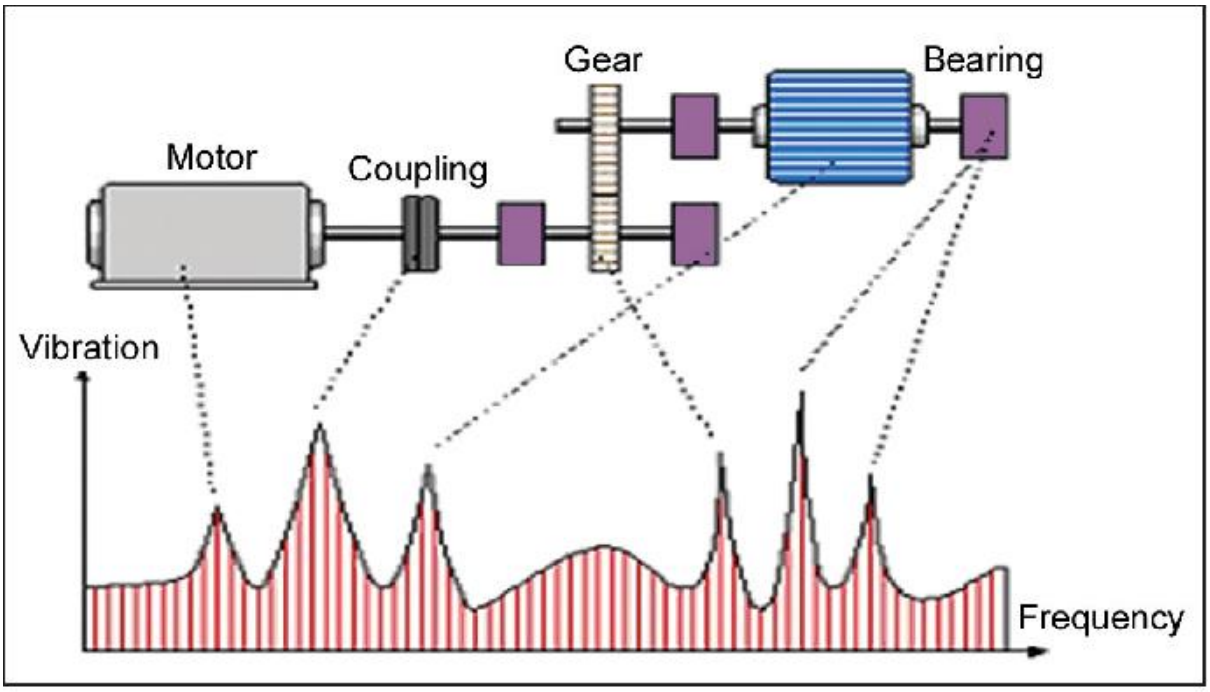


Fig. Typical vibration analysis FFT plot(magnitude vs. frequency).

Advantages are early defect identification lowers the possibility of catastrophic failures, prolongs the life of components by resolving problems before they cause serious harm, and increases the general safety and dependability of vehicles.

Thermography:

Thermography measures the temperature distribution of car parts with infrared cameras. It assists in locating overheated components, which may be a sign of electrical problems, excessive friction, or other problems. Thermal pictures of car components are captured using infrared cameras. The analysis of the thermal pictures identifies temperature abnormalities, such hotspots. This information can be used by engineers to identify hot spots, such as overheated brakes, electrical connections, or bearings.

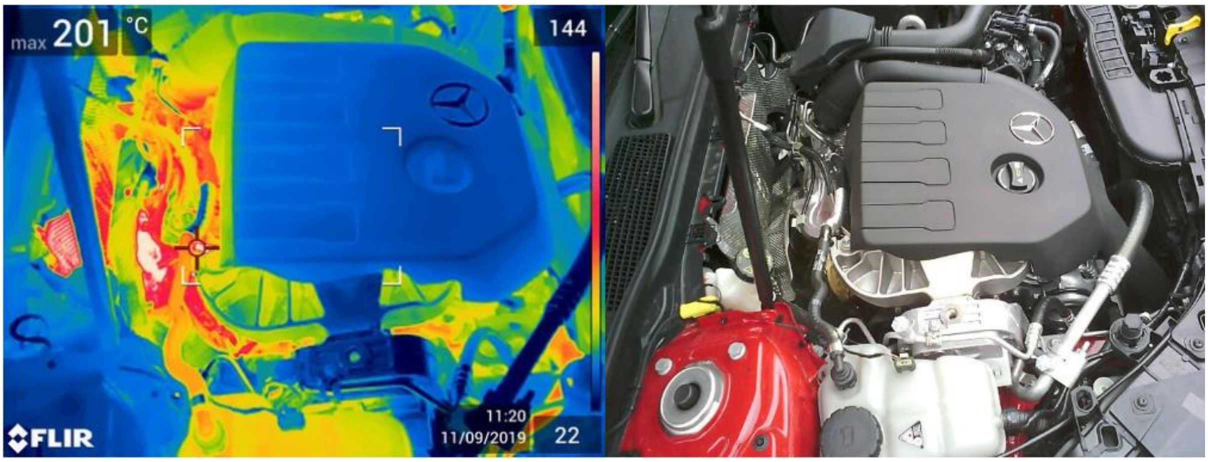


Fig. Automotive engine thermal imaging.

Advantages are a non-intrusive technique that allows continuous monitoring without interfering with vehicle operation; detect problems that are not immediately apparent; improves diagnostic capabilities; and helps in maintenance planning by identifying parts that are at risk of failure from heat stress.

Acoustic Emission:

The process of recording sound waves released by stressed components is known as acoustic emission monitoring. Unusual noises may be a sign of mechanical deterioration, leaks, or cracks. Sensors and microphones positioned close to important parts pick up sound waves; the sound information is then captured and examined to look for irregularities. To identify problems like fluid leaks, gear tooth flaws, or bearing defects, sound patterns are matched to established fault signatures.

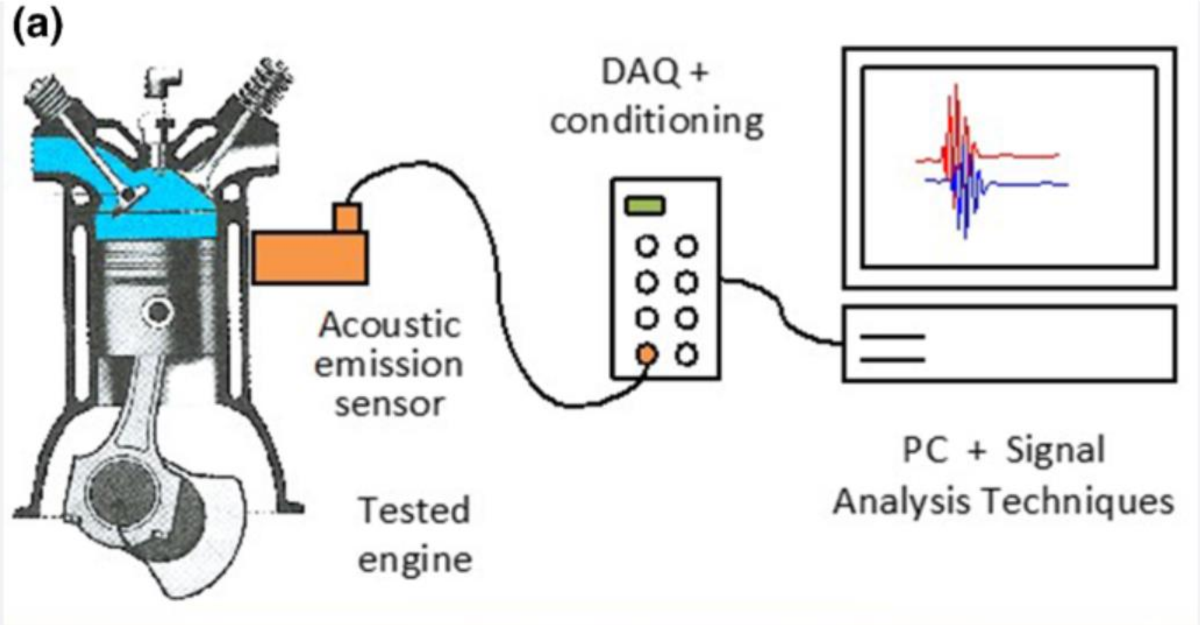


Fig. Measurement of Acoustic Emission.

Advantages are its early defect detection, ability to avert significant failures, ability to identify problems in inaccessible regions, and ability to be combined with other monitoring systems for full diagnostics.

B) Real-Time Monitoring:

Vehicle performance and condition data are collected and transmitted in real time via telematics systems. Large-scale operations and fleet management benefit greatly from their utilization. Telematic Tools installed in cars to gather information from different sensors. A central server receives data on variables including location, speed, fuel economy, and engine performance. Proactive maintenance is made possible by real-time data analysis, which assists in spotting departures from regular functioning.

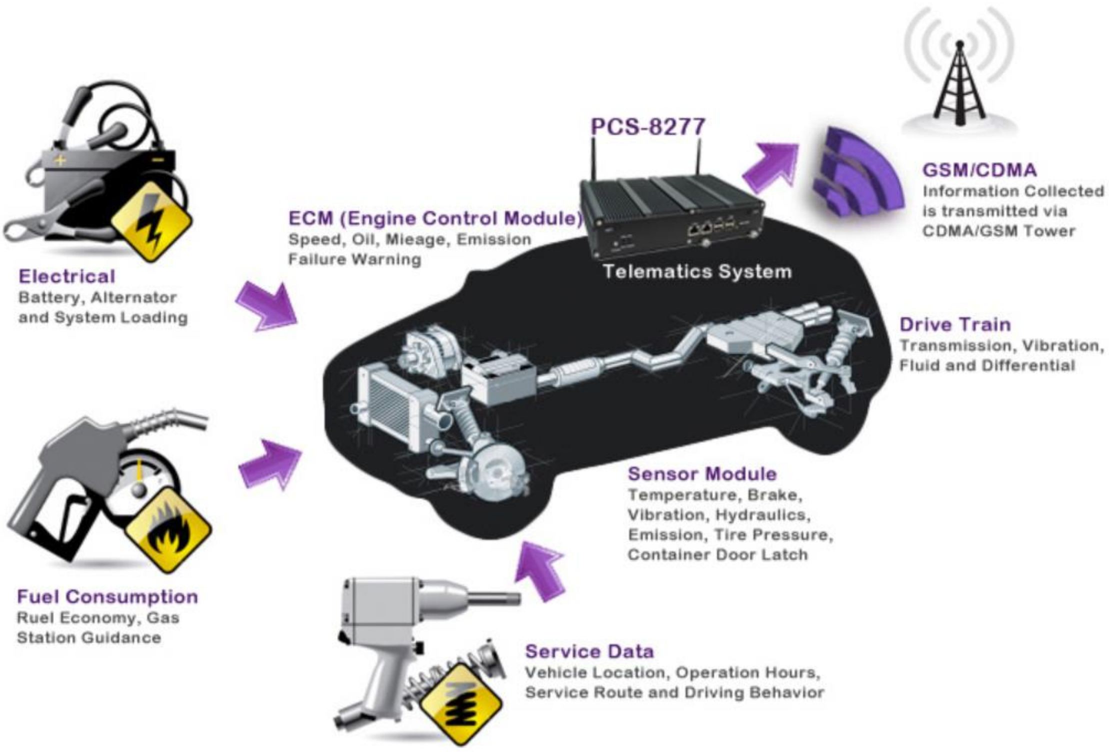


Fig. Example of Real-Time Monitoring.

Benefits include the ability to remotely monitor the health and performance of the vehicle, assistance in optimizing maintenance plans based on real usage and condition, and increased operational efficiency through the reduction of unplanned downtime and breakdowns.

Smart Sensors:

IoT devices and smart sensors provide thorough and ongoing monitoring of car parts. These sensors take measurements of fluid levels, pressure, and temperature. Numerous car systems have smart sensors installed to keep an eye on important metrics. Data is continually sent to IoT systems by sensors. IoT platforms examine the information to offer insights about the condition of car parts.

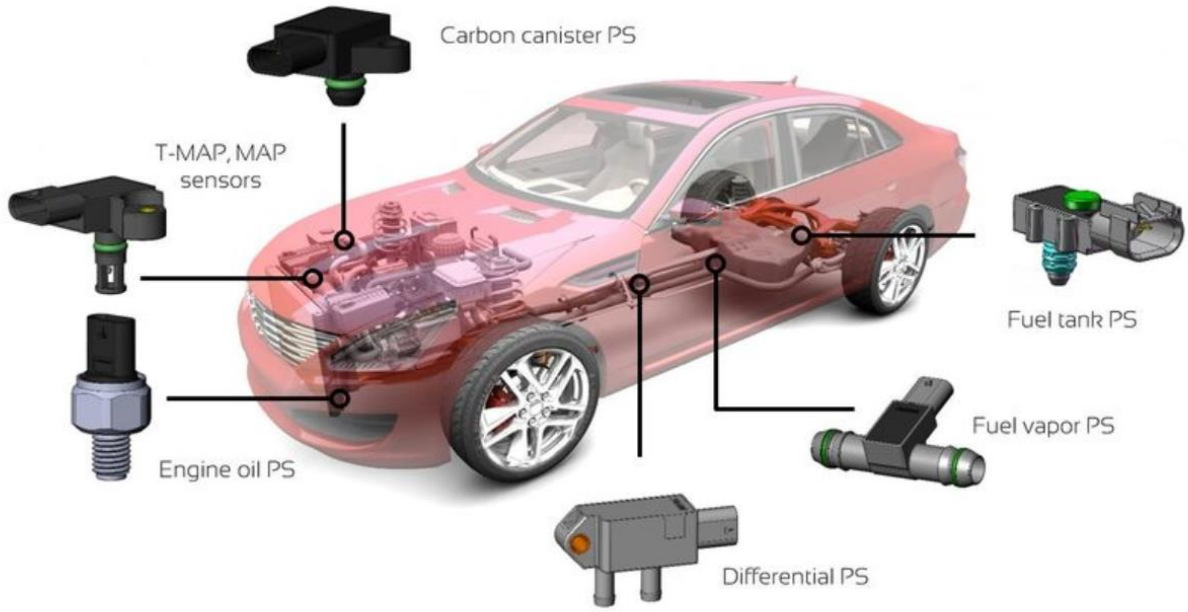


Fig. Example of Smart sensors.

The benefits include better decision-making through greater data analytics capabilities, better diagnostic and maintenance planning accuracy, and real-time monitoring and alerts for prompt action.

Future trends in predictive maintenance

In recent decades, the study of prognostics for complex engineering systems has garnered significant attention from researchers and industry professionals. The main drivers behind this interest are the goals of enhancing system safety, boosting machine reliability and availability, and cutting maintenance costs. The swift advancement in digital technologies — including 3D printing, robotics, artificial intelligence (AI), digital automation, cloud computing, the Internet of Things (IoT), digital twins, augmented reality (AR), and machine learning—has spurred the Fourth Industrial Revolution, commonly known as Industry 4.0. Within the framework of Industry 4.0, to meet the growing demand for functionality and quality, systems have become more interconnected and complex than ever before. Consequently, meticulous monitoring of system operations and devising suitable maintenance strategies have become crucial, as unexpected failures can lead to severe consequences. An effective maintenance strategy is essential to minimize unplanned downtime and ensure facilities operate at peak efficiency (Wen et al., 2022).

Machine learning

The high production costs associated with installing sensors on all engine components hinder the application of predictive maintenance across the board. To address this issue, machine learning-based predictors can be employed, which utilize data from indirect sensors to forecast potential faults. This approach requires collecting data that represent both normal and faulty conditions of the target component, which is then used to train machine learning models to detect defects before integrating them into the engine's electronic control unit software. However, acquiring such data can be costly, as it often involves multiple rounds of destructive testing across various driving cycles, performed in real time on instrumented vehicles using a dynamometer. Fortunately, machine learning models can tolerate some level of data noise, allowing for the use of simulated engine data for training purposes. This simulation-based approach eliminates the need for real-time testing and extensive vehicle instrumentation, thereby reducing overall data acquisition costs. The use of simulated data to train machine learning models has been validated across different applications, proving effective in scenarios where system modeling is feasible.

Fig. Machine learning.

Augmented reality (AR)

Augmented reality (AR) is revolutionizing the maintenance industry by providing an intuitive, engaging way to visualize complex data, making it particularly suitable for predictive maintenance. Incorporating AR into maintenance processes enhances efficiency, minimizes downtime, and boosts equipment uptime, leading to significant cost savings. AR allows maintenance technicians to view real-time machine health data clearly, enabling quick identification and resolution of potential issues before they escalate (Tessaro et al., 2020). Moreover, AR facilitates remote collaboration, enabling teams to share knowledge and work together from different locations. A key advantage of AR in maintenance is its ability to deliver immersive, interactive training for maintenance staff. This type of training can reduce onboarding time and improve training quality, leading to better performance and increased operational efficiency. AR simulations create realistic scenarios, providing a safe, controlled environment for hands-on learning.

Digital twins

When a vehicle is introduced to the market or undergoes testing or a recall, Digital Twin technology can simulate test data to assess quality and performance. This allows for testing new components under various conditions to implement design improvements and optimize performance. Changes can be made in real time to predict and determine the best configuration. By monitoring key components, Digital Twin technology can prevent mass recalls by identifying and addressing issues with specific consignments, such as corroded parts during transport.

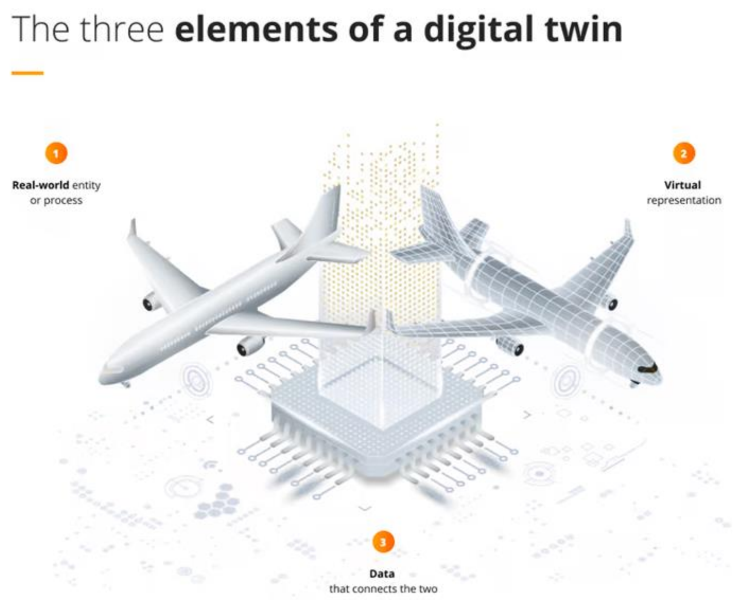


Fig. Three elements of digital twin.

Digital Twins are particularly valuable for electric vehicles. Each vehicle can be paired with a customised digital twin through IoT sensors that exchange data. This enables manufacturers to maintain a digital record of the car's condition and detect potential problems early to avoid repairs. For instance, Tesla uses Digital Twin technology in all its vehicles. Tesla's partner, Thinkwik, explains that real-time mechanical issues can be resolved via over-the-air (OTA) software updates. Continuous data transmission between the vehicles and the manufacturer enhances product quality (Piromalis & Kantaros, 2022).

Predictive Maintenance for Electrical System of Vehicle:

Traditional maintenance approaches are often reactive, but with the increasing number of vehicles, more effective methods are needed to maintain vehicle performance. Predictive maintenance is an emerging approach that predicts potential faults by analyzing the current state of vehicles, allowing for proactive measures. Modern vehicles consist of complex subsystems including engines, transmissions, and braking systems, requiring advanced diagnostic techniques and intelligent algorithms for remote monitoring and fault prediction. This approach is crucial for the development of future autonomous vehicles, ensuring the stability and safety of vehicle systems.(Shafi et al., 2018)

The main advantages of the proposed system are as follows:

1. A nontechnical person can get into the failure of any subsystem of vehicle as VMMS(Vehicle Remote Health Monitoring and Prognostic Maintenance System) provides all information of vehicle status and condition on smart phone which is connected to vehicle.
2. VMMS focuses on the real life solutions using machine learning techniques which can save money and time as well.
3. Autonomous vehicle needs continuous stream of sensory input of functioning part of vehicle; VMMS prediction will guide autonomous vehicles decision system from failure of any system part.
4. Vehicle life time is increased as when owner/driver knows all about internal conditions of systems; then driver can get some steps to get rid of any system failure
5. Accident risk decreases with the awareness of structure of systems.

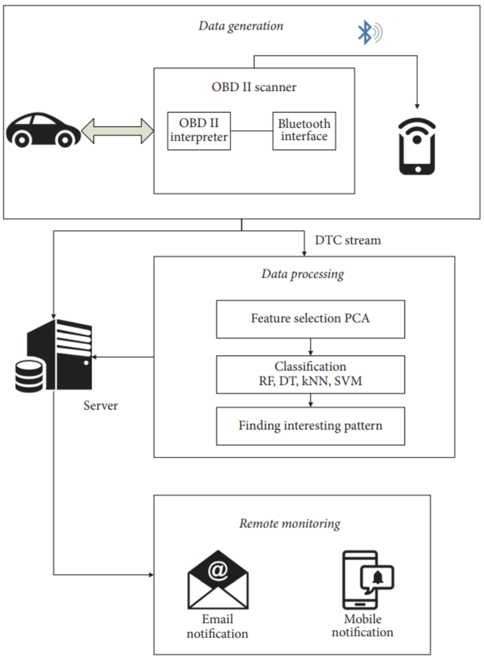


Fig. VMMS Architecture

VMMS system has three main layers, as shown in the above figure.

Data generation layer:

- An OBD2 scanner, such as the ELM 327 Bluetooth scanner, connects to the vehicle via the OBD2 port. This scanner, essentially a microcontroller, acts as a bridge between the vehicle and a portable device like a smartphone or laptop that supports Bluetooth.
- All sensor data is generated in the form of Diagnostic Trouble Codes (DTC) while the vehicle is in motion and sent to a smartphone continuously via Bluetooth.
- The smartphone communicates wirelessly with the Engine Control Unit (ECU), serving as a source to connect the vehicle to the backend server.

Data processing layer

- The first step involves feature selection, where the DTC data stream is filtered using expert suggestions.
- Principal Component Analysis (PCA) is then applied to the dataset for feature reduction.
- Four classification algorithms, including Decision Tree, Random Forest, K-Nearest Neighbor (K-NN), and Support Vector Machine (SVM), are used in the classification phase.
- Further processing is carried out on the server end, where these results are stored for fault prediction and remote monitoring.

Remote monitoring layer

- Vehicle owners or relevant personnel can remotely monitor the current condition of the vehicle, such as fuel status, speed, and current position.
- Automatic notifications are sent to the driver or vehicle owner in case of any subsystem failure.

There are four main vehicle systems:

- **ignition system**
- **fuel system**
- **exhaust system**
- **cooling system.**

These systems are monitored by sophisticated computer controls, with sensors providing false information to the Engine Control Unit (ECU). The ECU, a microcomputer with electronic components and circuits, receives input from sensors located throughout the engine and compares it with stored data in memory. Its primary function in the electric fuel injection system is to control pulse rate through the injector, idle speed, ignition timing, and fuel pump, aiming to maximise engine power while minimising exhaust emissions and fuel consumption.

OBD2 scanner tools download on-board trouble codes by communicating with the ECU to determine which sensor is malfunctioning. The communication protocol CAN (Controller Area Network) ensures effective communication between controllers, actuators, sensors, and the ECU.

During vehicle operation, the OBD2 scanning tool is connected to the vehicle, and real-time Diagnostic Trouble Codes (DTCs) are transmitted to a smartphone. Data from around 70 Toyota Corolla vehicles were collected, including normal operation and fault conditions in different subsystems. Each reading, taken at a sampling frequency of 1Hz, is considered as one example, with DTCs generated by sensors being the attributes or features. The dataset consists of 150 examples, with binary output class labels indicating safe operation or system fault.

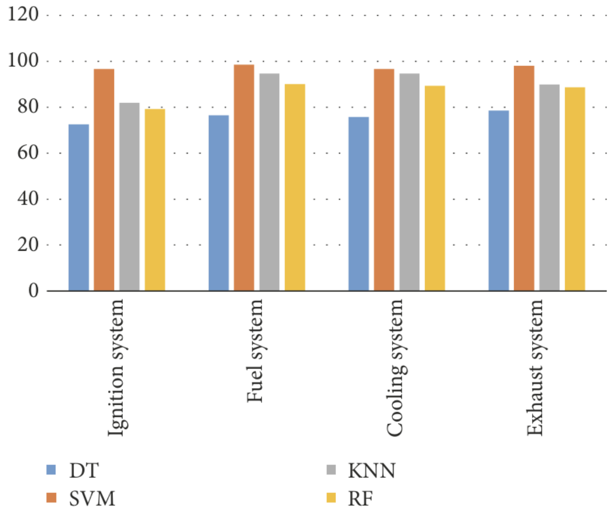


Fig. Accuracy comparison.

Systems VMMS	DT%	SVM%	kNN%	RF%
Ignition system	72.5	96.6	81.9	79.2
Fuel system	76.5	98.5	94.6	90.0
Exhaust system	78.5	98	89.9	88.6
Cooling system	75.8	96.6	94.6	89.3

Table. Comparison with existing systems.

Acronyms

DT: DecisionTree

SVM: SupportVectorMachine

□-NN:□-NearestNeighbor

RF: RandomForest

(These are four different predictive algorithms)

Figure 7 shows the comparison of accuracy in these four algorithms. And the comparison with existing systems can be found in Table 5.

With the widespread use of smartphones and wireless communication, it has become feasible to utilise these technologies for real-time solutions. Despite limited resources, these technologies are being employed along with machine learning approaches to address significant challenges in the automotive industry. This paper introduces a novel vehicle monitoring and fault prediction system, including the Vehicle Remote Health Monitoring System (VMMS). Four classifiers, including Decision Tree, Support Vector Machine, Random Forest, and K-Nearest Neighbour, have been used for fault prediction, considering the four main systems of vehicles. The primary objective of the proposed system is to reduce the frequency of faults in vehicle systems.

Future aspects:
There are several ways to extend the current results. Notably, refining classification performance is crucial. This paper employs four classification algorithms, but the accuracy can be further discussed by applying other prediction techniques and working on larger datasets. The data collected thus far comes from 70 Toyota Corolla vehicles, and future efforts will involve data collection from various vehicle types to continue improving results.

12. Corrective Maintenance:

The corrective maintenance describes the procedures used to get a car back in working order following a malfunction. Reactive maintenance is the kind that attends to unexpected faults and breakdowns. Corrective maintenance is described by the ISO 14224 standard as maintenance performed after a problem has been identified with the goal of restoring the item to a condition where it can carry out its intended function.

Types of Corrective Maintenance:
Immediate Corrective Maintenance:
Also referred to as "breakdown maintenance," urgent corrective maintenance is carried out as soon as possible following a failure to restore functioning. When a vehicle of this sort is non-operational, urgent repairs are frequently required.For instance, an abrupt alternator failure makes it impossible for the car to start.

Fig. Immediate Corrective Maintenance.

Deferred Corrective Maintenance:
Corrective maintenance that may wait and be planned for a later date without endangering the vehicle's performance right now is known as deferred corrective maintenance. This strategy is usually used when the car can still be driven, but it is less efficient or there may be safety issues. for instance, a little oil leak that may be fixed at the following service interval.

Fig. Deferred Corrective Maintenance.

Steps Used for Corrective Maintenance:

Determine the Problem:
Diagnostic methods are applied to determine the failure's primary cause. This calls for the employment of oscilloscopes, multimeters, On-Board Diagnostics (OBD) devices, and diagnostic software tools. The accuracy and speed of defect identification in diagnostic systems have greatly increased with the incorporation of artificial intelligence and machine learning. A methodical technique for identifying the several reasons behind a particular system failure is fault tree analysis. Understanding the logical connections between various components and their possible breakdowns is made easier with the use of FTA.

Repair:
Repairing components at the component level entails changing or repairing damaged parts. For example, a malfunctioning fuel injector can require cleaning or replacement, depending on the severity of the issue. Repairing the system at the system level is A more thorough strategy used when the breakdown impacts the entire system. This might entail taking complicated assemblies apart and putting them back together.

Test and Documentation:

Post-maintenance testing is that after repairs, cars are put through a thorough testing process to make sure all problems have been fixed. This covers emissions testing, electronic diagnostics, and road tests. Reliability testing involves simulating working circumstances and stress testing to ensure the long-term dependability of repairs.

Records for Maintenance is imperative that maintenance actions be meticulously documented. This involves keeping track of the symptoms, diagnostic processes, component replacement, labor costs, and repair times. Analyzing historical data is examining maintenance data over time to find patterns and provide guards against future problems.

Importance of the Corrective Maintenance:

- Making sure that after repairs, cars are safe to drive, hence reducing accidents brought on by mechanical failures, which constitute a sizable portion of traffic accidents
- For fleet management in particular, getting the car back to a dependable functioning state is essential for both operational efficiency and customer confidence.
- Even while corrective maintenance might be more expensive than preventative maintenance, timely fixes can prevent small problems from becoming larger, more costly ones.
- Reducing vehicle downtime and inconvenience through prompt and effective remedial maintenance increases customer satisfaction. This is essential for preserving reputation and brand loyalty.

13. Reliability Engineering in the Automotive and Machinery Industry: Maintenance Strategies

Reliability engineering is fundamental in the automotive and machinery industries, focusing on ensuring that systems and components operate consistently over their expected lifespans. Effective maintenance strategies are crucial for optimizing reliability, minimizing downtime, and reducing operational costs. The significance of reliability engineering and examines various maintenance strategies employed to enhance reliability in these sectors.

Importance of Reliability Engineering

Reliability engineering plays a pivotal role in the automotive and machinery industries by enhancing safety, ensuring cost efficiency, boosting customer satisfaction, and ensuring regulatory compliance. In the automotive sector, reliability engineering is essential for vehicle safety, preventing component failures that could lead to accidents and endanger lives. For machinery, it ensures that operations run smoothly, minimizing the risk of accidents and operational halts. Reliable systems reduce the frequency of repairs and replacements, translating to substantial cost savings for companies. This economic benefit extends to reducing production downtime and enhancing productivity. High reliability in products leads to customer satisfaction and loyalty, which are critical for maintaining a competitive edge in the market. Adherence to reliability standards also helps companies meet industry regulations and avoid potential legal penalties.

14. Additional Maintenance Strategies for Reliability Enhancement

Reliability-Centered Maintenance (RCM)

Reliability-Centered Maintenance (RCM) is a structured framework that focuses on identifying the most cost-effective maintenance strategies based on reliability data. It involves analyzing failure modes and their effects (FMEA) to prioritize maintenance tasks, ensuring that efforts are concentrated on critical components that have the highest impact on system reliability. RCM ensures that maintenance resources are used efficiently, targeting areas that will yield the greatest reliability improvements. However, RCM requires a thorough understanding of failure modes and can be time-consuming to implement due to the detailed analysis involved. An example of RCM in the aviation industry includes prioritizing maintenance tasks for aircraft systems based on their criticality and potential failure impacts, thereby enhancing safety and reliability.

The Bathtub Curve Fallacy

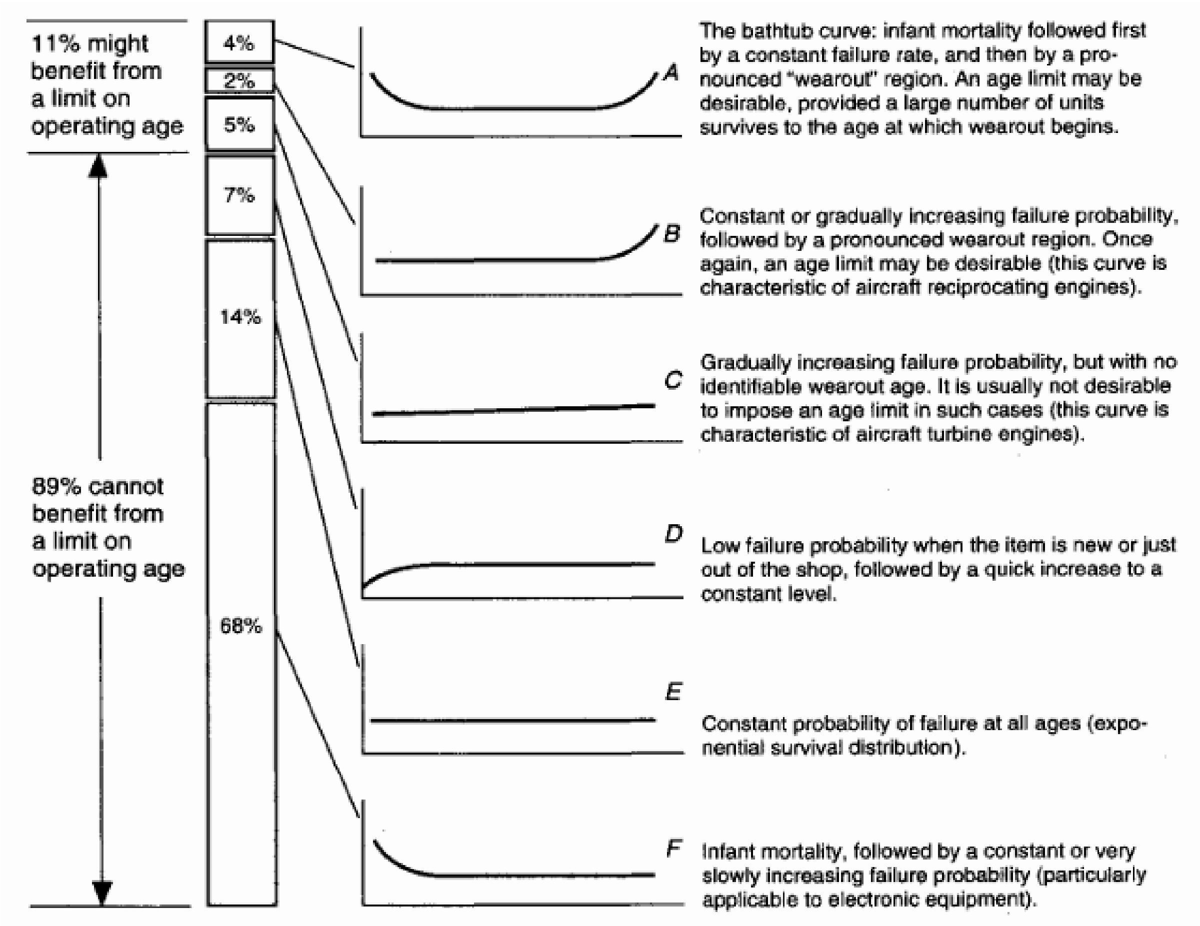


Fig. The Bathtub Curve Fallacy.

The bathtub curve method is mostly used in reliability engineering and lifecycle management techniques. It is a graphical representation of a system or a component to time and it has three different phases:

- **1. Early Failure (Infant Mortality):** At start, the failure rate is higher due to production/manufacturing defects, installation issues or different early life problems. Over time these early problems are identified and rectified, which results in a decrease in the failure rate.
- **2. Constant Failures (Useful Life):** After the initial high failure rate part, the system enters a phase of relatively constant and low failure rate. This is the "normal" operating phase where the system functions are expected with random failures occurring due to unexpected factors.
- **3. Wear-out Failure:** Finally, as the system ages, component wear out, and the failure rate increases again, This signifies the end of system useful life

15. Total Productive Maintenance (TPM)

Total Productive Maintenance (TPM) is a holistic approach to maintenance that involves all employees in proactive maintenance activities. TPM combines preventive maintenance, autonomous maintenance performed by operators, and continuous improvement initiatives. This strategy enhances equipment effectiveness, reduces downtime, and fosters a culture of continuous improvement within the organization. However, implementing TPM requires significant cultural change and comprehensive employee training. In a manufacturing plant, TPM might involve operators performing daily checks and minor repairs on their machines, supported by maintenance specialists for more complex issues, thereby improving overall equipment reliability and efficiency.

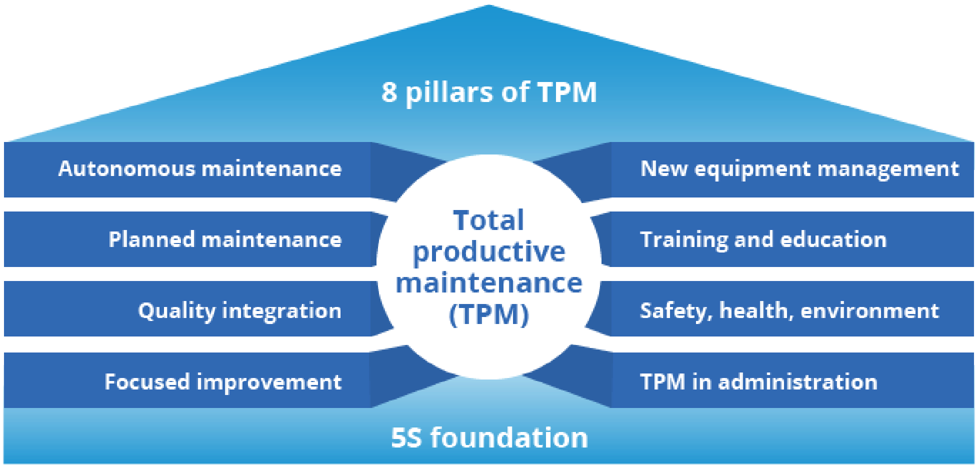


Fig. 5S foundation: Each of these five things should be actioned in order to stand up a TPM strategy (What Is Total Productive Maintenance (TPM)?, n.d.).

- **Sort:** Determine which items are used frequently and which are not. The ones used frequently should be kept closeby, others should be stored further away.
- **Systemize:** Each item should have one place—and one place only—to be stored.
- **Shine:** The workplace needs to be clean. Without it, problems will be more difficult to identify, and maintenance will be more difficult to perform.
- **Standardize:** The workplace should be standardized and labeled. This often means creating processes where none existed previously.
- **Sustain:** Efforts should be made to continually perform each of the other steps at all times.

16. Condition-Based Maintenance (CBM)

Condition-Based Maintenance (CBM) involves making maintenance decisions based on the real-time condition of equipment, rather than following a fixed schedule. This strategy uses sensors to continuously monitor parameters such as temperature, pressure, and vibration, providing real-time data to inform maintenance actions. The primary advantage of CBM is that it ensures maintenance is only performed when necessary, reducing unnecessary interventions and downtime. However, CBM implementation can be complex and costly, requiring robust data collection and analysis systems. An example of CBM in the wind energy sector includes real-time monitoring of gearbox oil quality in wind turbines to predict and prevent gear failures, ensuring continuous and efficient energy production.

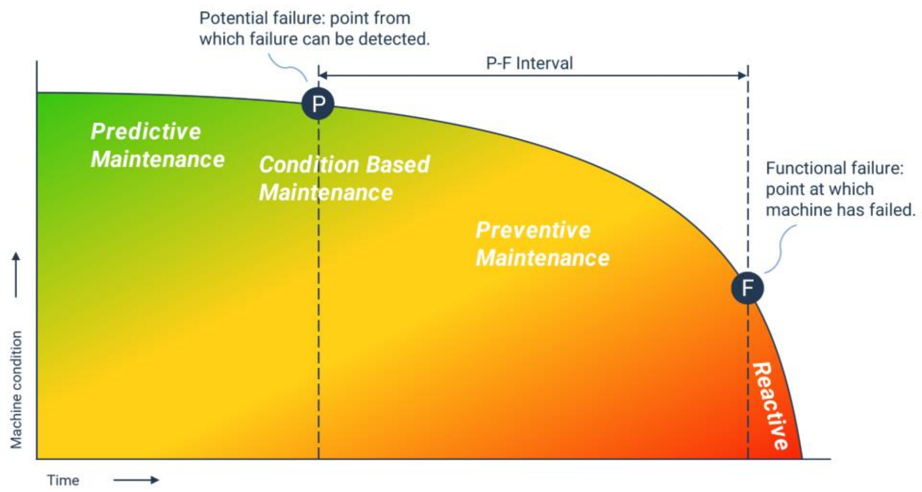


Fig. Relationship between machine condition and time.

17. Major challenges in the automotive and machinery industry

Random error:

Random errors in reliability engineering are unpredicted deviations from the expected performance of a system or component. Unlike systematic failures, which are predictable and typically result from design flaws or consistent manufacturing problems, random failures are inherently unpredictable and can occur occasionally. These errors are caused by multiple factors, such as manufacturing variability, extreme and uncertain environmental conditions (humidity, vibrations, etc.), unpredicted driver behaviour and operation of a vehicle as well as random wear rates of components (Hamid, 2019).

Several techniques to at least partially mitigate mentioned risks have evolved and especially for safety relevant parts and assemblies, for instance, fault simulation tool or some of many mentioned modern maintenance systems as real-time analysis and monitoring, feedback mechanisms, machine learning are used to help to overcome these unwanted issues (University of Ottawa, n.d.). Also, a different approach is implementing a FMEA (Failure modes and effects analysis) in order to target the failures and its consequences based on the proactive evaluation and on the experience of a particular company.

Non-availability of public real-word data sets:

- **Lack of Continuous Research Lines:** Due to the scarcity of public real-world automotive data, research typically relies on collaborations between academia and industry. However, once projects conclude, researchers often move on, leading to a discontinuation of research due to lost data access.(Theissler et al., 2021)
- **Inefficiency in Follow-up Research:** Researchers aiming to build on prior studies face challenges as they must repeat the costly process of acquiring new data, hindering progress and continuity in the field.
- **Lack of Reproducible Research:** Restricted data access prevents the replication and extension of published findings, limiting the advancement of automotive research.
- **Limitations in Research Rigour:** Existing research lacks robust comparisons with state-of-the-art results due to the unavailability of datasets used in previous studies, posing challenges for evaluating new methodologies.
- **High Cost of Data Acquisition:** Acquiring automotive data is resource-intensive, involving efforts to obtain confidential access or perform extensive measurements. Some researchers resort to simulated data due to these challenges.

Lack of labelled data:

Working with real-world data allows for practical evaluation of developed methods. However, real-world data is often unlabelled or partially labelled because annotating it is time-consuming and requires expert knowledge. While unsupervised methods can be used without labels, semi-supervised or supervised methods generally produce more robust results. At a minimum, labelled data is needed to test models, even if they are trained on unlabelled data.(Theissler et al., 2021)

Complexity of problem setting:

Several challenges can be traced back to the complex problem set ting caused by the fact that the automotive industry supplies long-term products for a wide range of application areas.(Theissler et al., 2021)

High number and variety of vehicles: Due to the large number and diversity of vehicles, it is challenging to obtain a representative data set for ML(Machine Learning) models. Vehicles also have long lifespans, with commercial vehicles potentially operating for 20-30 years, increasing data variability over time.

Research direction: Improving the representativeness of the training set. To enhance the training set, researchers can use simulated data from hardware- or software-in-the-loop systems alongside real-world data. Another approach is to create artificial data that mimics the original, a common technique in deep learning called data augmentation. This method can improve accuracy, but for predictive maintenance, care must be taken to avoid creating misleading data.

Rarity of faults and wear: Faults in vehicles are rare, and wear occurs only after long periods of operation. Consequently, data collected from vehicles is often highly imbalanced and may not include all possible faults and signs of wear.

Research direction: Developing methods for learning from imbalanced data. To address imbalanced data, researchers need to use ML models that are robust to class imbalances, implement cost functions that do not favour the majority class, and apply resampling methods to the data.**Increasing complexity due to transformations in the automotive industry:**

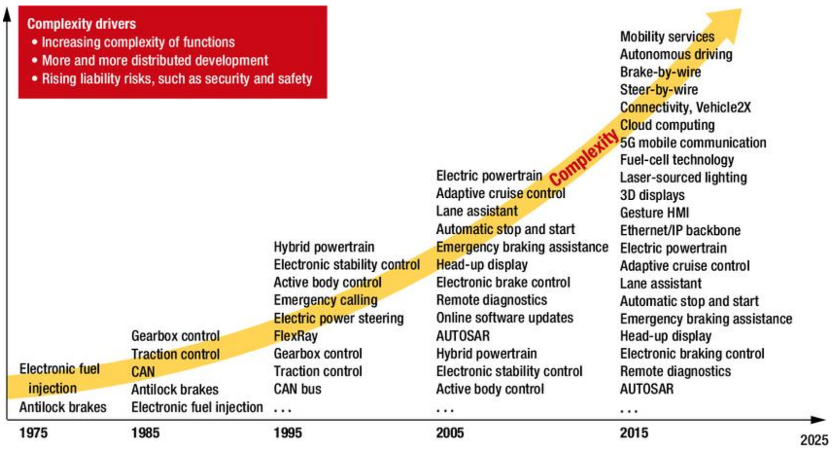


Fig. Software innovations fuel automotive and mobility advances but quickly increase complexity.

18. Maintenance of ML-based automotive systems:

Traditionally, predictive maintenance focused on mechanical and electrical parts (e.g., vee-belts, suspension systems). However, for ML-based advanced driver assistance and autonomous driving systems, the ML models themselves may also require predictive maintenance. This would likely occur at the fleet level for all vehicles with a specific version of an ML model. Reasons for updating or replacing ML models include improved accuracy, higher efficiency, lower latency, and better robustness against adversarial attacks.

Transformation of the drivetrain: The advent of alternative drive trains brings along new vehicle components requiring maintenance. Specifically for full electric vehicles, hybrid vehicles as well as fuel cell vehicles, the monitoring of batteries is crucial. Due to the ongoing transformation of the drivetrain, it is highly likely that this research direction will become increasingly important.

Data Privacy and Security:

Data Sensitivity: Automotive data often contains sensitive information related to vehicle performance and user behavior. Ensuring data privacy and security while sharing data for research and development purposes is a significant challenge.

Regulatory Compliance: Adhering to data protection regulations such as GDPR (General Data Protection Regulation) in Europe adds an additional layer of complexity to data handling and sharing.

Skill Gaps and Workforce Training:

Technical Expertise: Implementing and maintaining predictive maintenance systems requires specialized skills in data science, machine learning, and automotive engineering. Bridging the skill gap in the workforce is essential.

Continuous Learning: As technologies evolve, continuous training and upskilling of the workforce are necessary to keep pace with advancements in predictive maintenance.

Cost-Benefit Analysis:

Investment Justification: Convincing stakeholders to invest in predictive maintenance solutions requires demonstrating cost savings and operational benefits over traditional maintenance approaches.

Short-term vs. Long-term Benefits: Balancing the short-term costs of implementing predictive maintenance systems against the long-term benefits can be challenging, particularly for smaller organizations.

Technological Advancements:

Keeping predictive maintenance systems up-to-date with the latest technological advancements and integrating new features and capabilities is an ongoing challenge.

Continuously innovating and improving maintenance practices to leverage new technologies such as AI, IoT, and blockchain can provide a competitive edge but requires significant effort and investment.

19. Predictive Maintenance for Autonomous Vehicles:

Complexity of Autonomous Systems: Autonomous vehicles rely on a multitude of sensors, actuators, and ML models. Predicting maintenance needs for such complex systems involves understanding the interplay between hardware and software components.

Safety and Reliability: Ensuring the safety and reliability of autonomous vehicles through predictive maintenance is crucial, as failures can have severe consequences.

Scalability of Solutions:

Large-scale Deployment: Scaling predictive maintenance solutions across a large fleet of vehicles or machinery requires robust infrastructure and consistent data management practices.

Customization: Customizing predictive maintenance solutions to meet the specific needs of different types of vehicles and machinery adds to the complexity of large-scale deployment.

20. Business Case:

Tire Supply company Continental Founded in 1871, the technology company offers safe, efficient, intelligent and affordable solutions for vehicles, machines, traffic and transportation. As one of the biggest car tire manufacturers, service is provided in 56 different countries. Even Though it is hard to tell exactly how long a tire will last, the lifespan depends on a combination of factors including a driver’s habits, tire design, climate, road conditions, and service of the tire. Continental suggests that all tires that were manufactured more than ten years previous be removed from service and be replaced with new tires, even when tires appear to be usable from their external appearance. People drive between 20000 and 25000 km annually on average, so an excellent all-season tire should last three to five years, depending on weather, driving style, and maintenance.

Solution:

Steps for Business Cases:

Determining the advantages of predictive maintenance is the primary problem. There is a great deal of uncertainty here: it's unclear how frequently an item may malfunction, how accurate the predicting and what kind of maintenance technology will be used, whether an alteration will be made to increase the asset's lifespan, and so on.

Step 1:

Finding a Team who specialised on the predictive maintenance technology

Step 2:

Start with the obvious advantage of preventing failures. Breaking down the asset's failure into its failure modes is the most effective approach to do this. If an asset has ten potential failure modes, list them all and determine whether predictive maintenance is necessary for each one. The sensitivity will increase with technology.

1) Determine the Mean Time Between Failures. Your estimate may be supported by the manufacturer's handbook, current reliability data, professional opinion, or any combination of these.

2) Make use of the predictive maintenance system to estimate both the new and current sensitivity. To assess the sensitivity and associated costs, one can utilize both the optimal and minimal response times.
3) Calculate the expenses in the following two scenarios: (A) no failure was anticipated, and (B) a failure was anticipated. Add any expenses that are relevant to your case: the expenses associated with upkeep, the missed manufacturing opportunity costs, and the cost of ecological harm, and so forth.

Step 3:

Talk about the extra benefits you will receive from the new predictive maintenance system after that. How and to what degree will it impact, among other things, the expenses of operations, periodic maintenance, inspections, and so forth?

1) Minimizing the number of additional inspections if the new technology partially or completely replaces visual checks.
2) Extending the time between periodic maintenance checks in the event that they are missed whether the asset's state continues to be considered acceptable by the predictive maintenance system, or if routine maintenance is completely discontinued.
3) Lowering energy consumption, provided the new technology facilitates the early detection and resolution of energy waste.
4) Extending the asset's lifespan in the case that degradation is detected early and resolved, avoiding more degradation, or if the new technology produces information about the sources of degradation and allows for their mitigation.

Step 4:

Finally, talk about the price of alerts (false and genuine). What is the expected number of alerts per year? And how are you going to reply to them?

1) Alerts to prompt further investigation, either to confirm the warning or to identify the necessary repair. These diagnoses are considered supplemental expenses if they would not have been made otherwise.
2) alarms to set off maintenance activities, including unneeded ones—that is, premature maintenance—because without them, the value at step 2 is constrained. What proportion of alerts, upon validation (step 4a), still result in needless upkeep?

Business case for predictive maintenance

Tire supplier for a car manufacturer

The important value drivers for predictive maintenance are in this case the value of time, accuracy and decisions, which are always connected with the costs occurring at each stage. For complex assets such as tires that have various failure modes and degradation mechanisms, business case analysis should consider the likelihood of overlooking an impending failure and the chance of triggering a false alarm. Additionally, it is important to recognize that the existing accuracy of detecting issues prior to adopting new predictive maintenance technology, is almost zero. Current methods, as mentioned earlier, can already identify anomalies and impending failures, although these methods usually offer a shorter prediction horizon compared to predictive maintenance technologies. The following graph shows how vital it is to look for arising issues in the future and how easier it is to respond to the failures well-defined in advance.

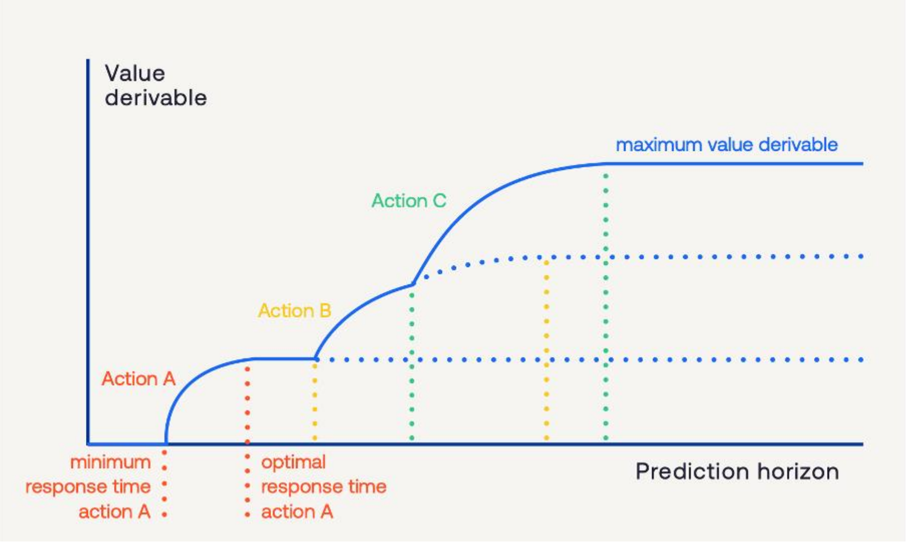


Fig. Schematic of predictive maintenance.

Challenges for the manufacturer:

Storage of the tires before selling. They state that any tire up to 5 years old can be sold as new. However, there are a lot of effects, which can change the properties or lifetime of the material such as temperature and humidity while storing them or changing the conditions during shipping. Also, car manufacturers must have a guarantee from the supplier about the age of a particular tire.

As it is recommended to at least visually check them from the user once a month and they must not be used for more than 10 years, consumers very often oversee these rules. They can also overinflate the tires for improved fuel consumption and thus risk premature failures. This corresponds to the technology aspects which will be mentioned later.

Trust and data shared with the car company. The car manufacturer can insist on a shorter replacement period to prevent a random errors and unnecessary claims from the users while gaining higher profit.

Disposal in an environmentally-friendly way is another issue, which the supplier is forced to ensure.

Challenges in terms of technology:

- Every new technological advancement has a higher probability of unexpected failure, therefore shorter maintenance periods and trained technicians are needed, which is increasing the costs for both manufacturers.
- Especially important for electric vehicles, which do not have such requirements for the regular inspections but their demands on high quality tires capable of withstanding higher loads while keeping the same standards and longevity are high.
- Cybersecurity is another issue concerning the predictive maintenance as the important database is shared between the supplier and manufacturer

Challenges for the user:

- Not sufficient information from the manufacturer (air pressure, …)
- Selection of a tire for different conditions and basic knowledge
- Warranty

Possible Solutions:

Tire predicted maintenance: Manufacturers can make educational videos to inform consumers about the importance of regular tire checks and proper inflation. Also, by monitoring the torque, temperature, air pressure while accelerating or decelerating to predict the wear and replacement time of a tire. Since artificial intelligence and machine learning technologies are growing tremendously, we can even put sensors in the tire, for instance, the digital tire management system from Continental tires (The Digital Tire Management of the Future: ContiConnect 2.0 – Data-Driven Decisions for Fleets, n.d.). With the data from tires, also including the data of the environment, it is possible to calculate the precise condition of the tire, as well as the time for the driver to maintain their tires.

By developing a new web portal and a multifunctional app, combined with above mentioned AI calculation and the big data of smart tiers, it is able to identify potential issues in advance, thereby reducing vehicle downtime and maintenance costs. Tire data provided by the sensors in the smart tires transferred to the Engine Control Unit then to the multifunctional app. This improves the availability of error, as well as the efficiency. Easier for drivers and repair shops to take action. Moreover, not only to predict the wear of tires, the broad pool of data and continuous analysis can improve the control of the car engine by providing the ideal data for vehicle controllers and the drivers, for instance, the recommended tire pressure, the torque and brake force, thus enhancing the accuracy of vehicle predictive maintenance.

Finally, the app can also transfer the data to the corporate repair shop to prepare the new tires earlier, this can also solve the problem of tire storage.

Trust and data shared with the car company: Manufacturers should develop clear and transparent data-sharing policies, ensuring that the data collected is used solely for maintenance and safety purposes. Establishing predictive maintenance agreements with car companies will help create a balanced tire replacement schedule that considers both safety and cost-effectiveness, avoiding unnecessary early replacements and gaining consumer trust while maintaining profitability.

Environmentally-Friendly disposal: Promoting tire recycling programs to consumers can increase awareness and participation in eco-friendly disposal practices. Additionally, combining the variety of tire data, it is possible to research and develop tires using more sustainable materials that are easier to recycle or decompose, and perhaps better structure and geometry can be used for making tires. These will contribute to environmental conservation and meet regulatory requirements.

21. Conclusion

In conclusion, our project provides a detailed analysis of modern maintenance strategies in the automotive and machinery industries. We looked at how maintenance strategies can ensure the longer life and reliability of complex technical products while addressing the different challenges.

We started by thoroughly researching and evaluating different maintenance strategies, such as preventive, predictive, and corrective maintenance. By comparing these strategies, we identified which approaches work best in different situations, helping to improve reliability and efficiency.

One of our key focuses was on reliability engineering. We analyzed what it takes to ensure that products last as long as possible and operate safely. Our insights into reliability engineering provide valuable information to implement maintenance strategies that can meet the requirements effectively.

We also tackled the technical challenges of modern maintenance. We explored advanced techniques like vibration analysis, thermography, and oil analysis. These methods help predict when maintenance is needed, reducing repair costs, and preventing failures.

In the automotive sector, we looked at the importance of preventive maintenance, especially lubrication. We detailed how proper lubrication minimizes wear and friction in car parts, extending their life. We covered the evolution of lubricants and stressed the need for regular maintenance of components like engine oil, gear oil, greases, and suspension systems.

Predictive maintenance was another critical area. We explored how using smart sensors, IoT devices, and machine learning algorithms can predict potential issues before they become serious problems. Despite the high initial costs and the need for advanced technology, the benefits of predictive maintenance, such as cost savings and longer component life, are significant.

Our research included real-world examples and case studies from various automotive manufacturers. We highlighted how technologies like augmented reality and digital twins can enhance maintenance practices. We also discussed future trends in predictive maintenance and their potential impact on the industry.

In analyzing the business case for predictive maintenance, especially for a tire we analyzed the data of a tire manufacturer. We studied and showed how predictive maintenance can prevent failures, optimize schedules, and improve overall efficiency. We also looked into the solutions to overcome the challenges faced by manufacturers and users.

Our work demonstrated how advanced technologies and data analytics are crucial for the future of maintenance. Despite the challenges, making a strong case for its adoption. Our research and practical insights contribute significantly to the advancement of maintenance strategies in the industry.

22. Sources:

Jensen, K. M., Santos, I. F., & Harry J.P. Corstens. (2024). Estimation of brake pad wear and remaining useful life from fused sensor system, statistical data processing, and passenger car longitudinal dynamics. *Wear*, *538-539*, 205220–205220. https://doi.org/10.1016/j.wear.2023.205220

Mulani, S. M., Kumar, A., Shaikh, H. N. E. A., Saurabh, A., Singh, P. K.,C. (2022).

A review on recent development and challenges in automotive brake pad-disc system. *Materials Today: Proceedings*. https://doi.org/10.1016/j.matpr.2022.01.410

Gupta, A., & Singh, P. (2021). Automotive vibration analysis for predictive maintenance. *Journal of Vehicle Engineering*, 45(3), 123-136.

Brown, R., & Taylor, M. (2020). Application of thermography in automotive predictive maintenance. *International Journal of Thermal Analysis*, 37(2), 98-110.

Harris, L., & Cooper, S. (2019). Using acoustic emission for condition monitoring in the automotive industry. *Journal of Acoustic Monitoring*, 22(1), 45-58.

Piromalis, D., & Kantaros, A. (2022). Digital Twins in the Automotive Industry: The Road toward Physical-Digital Convergence. *Applied System Innovation*, *5*(4), 65. https://doi.org/10.3390/asi5040065

Tessaro, I., Mariani, V. C., & Coelho, L. dos S. (2020). Machine Learning Models Applied to Predictive Maintenance in Automotive Engine Components. *Proceedings*, *64*(1), 26. https://doi.org/10.3390/IeCAT2020-08508

Wen, Y., Fashiar Rahman, Md., Xu, H., & Tseng, T.-L. B. (2022). Recent advances and trends of predictive maintenance from data-driven machine prognostics perspective. *Measurement*, *187*, 110276. https://doi.org/10.1016/j.measurement.2021.110276

Noria Corporation. (n.d.). Machinery Lubrication. Retrieved January 15, 2024, from https://www.noria.com/machinery-lubrication

Gandhar Oil Refinery (n.d.). Types of Automobile Lubricants. Gandhar Oil Refinery. https://gandharoil.com/blog/types-of-automobile-lubricants/
https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/811681

Singh, R., & Lallan, R. (2018). *Predictive maintenance for modern industry: Intelligent monitoring, prognosis, and optimization*. Springer.

Mobley, R. K. (2002). *An introduction to predictive maintenance*. Butterworth-Heinemann.

Wireman, T. (2005). *Developing performance indicators for managing maintenance*. Industrial Press Inc.

Hamid, A. (2019). *Accelerating Automotive Random Error Analysis Through PSS*. https://brekersystems.com/wp-content/uploads/2019/08/Breker-Random-Error-Analysis-8-5-2019.pdf

University of Ottawa. (n.d.). *ESTIMATION OF RELIABILITY OF RESULTS*. Retrieved June 17, 2024, from https://course.physics.uottawa.ca/Modern%20physics/ESTIMATION%20OF%20RELIABILITY%20OF%20RESULTS.pdf

Lipnický, M., & Brodnianská, Z. (2023). Research of Car Cooler Thermal Performance Depending on the Mileage of Cooler and Coolant. Machines, 11(2), 255. https://doi.org/10.3390/machines11020255

Shafi, U., Safi, A., Shahid, A. R., Ziauddin, S., & Saleem, M. Q. (2018). Vehicle Remote Health Monitoring and Prognostic Maintenance System.

Journal of Advanced Transportation, 2018, 1–10. https://doi.org/10.1155/2018/8061514

Theissler, A., Pérez-Velázquez, J., Kettelgerdes, M., & Elger, G. (2021). Predictive maintenance enabled by machine learning: Use cases and challenges in the automotive industry. Reliability Engineering & System Safety, 215, 107864. https://doi.org/10.1016/j.ress.2021.107864

Hanly, S. (n.d.). Differences Between Condition-Based, Predictive, and Prescriptive Maintenance. Blog.endaq.com. Retrieved June 25, 2024, from https://blog.endaq.com/differences-between-condition-based-predictive-and-prescriptive-maintenance#conclusion

The Digital Tire Management of the Future: ContiConnect 2.0 – Data-Driven Decisions for Fleets. (n.d.). Continental AG. Retrieved June 25, 2024, from https://www.continental.com/en/press/press-releases/20220224-conticonnect-20/

Li, G., Li, Y., Zhang, X., Hou, C., He, J., Xu, B., & Chen, J. (2018). Development of a preventive maintenance strategy for an automatic production line based on group maintenance method. *Sciences*. School of Mechanical and Aerospace

Engineering, Jilin University, Changchun 130025, China. Received: 22 August 2018; Accepted: 28 September 2018; Published: 30 September 2018.

Dubizzle.com. (2024).

Tips on maintenance of the suspension system.

https://www.dubizzle.com/blog/cars/tips-maintenance-suspension-system/

Cunha, M. L. D. (2020, April 28).

How often does the suspension system need maintenance? MotorHaus.