ISSN (O) 2321-2004, ISSN (P) 2321-5526

IJIREEICE

International Journal of Innovative Research in
Electrical, Electronics, Instrumentation and Control Engineering

Vol. 9, Issue 8, August 2021

DOI 10.17148/IJIREEICE.2021.9811

Intelligent Systems for Vehicle Reliability and Safety: Exploring AI in Predictive Failure Analysis

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Abstract: Given the complexity of automotive control systems, vehicles must exhibit high reliability in harsh environments. AI techniques for predictive failure analysis in vehicle safety have gained momentum. This document explores the concept of predictive failure analysis using AI about vehicle technology and safety. It focuses on early predicting failures in automotive microelectronic systems like electronic control units. The document introduces AI in vehicle technology and explores AI algorithms in autonomous driving. It discusses the impacts of predictive failure analysis and the movement toward autonomous systems. The document concludes with a summary of its contributions to predictive failure analysis. It serves as a channel to relate AI to reliable systems in automotive technology. It provides knowledge for researchers seeking newer methodologies for system automation and autonomy in vehicle designs. The document also provides an overview of AI technologies in autonomous driving and connected vehicles. It includes valuable comments, case studies, and an overview of AI applications in the automotive industry.

Keywords: Predictive Failure, Industry 4.0, Internet of Things (IoT), Artificial Intelligence (AI), Machine Learning (ML), Smart Manufacturing (SM)

I. INTRODUCTION

FIGURE 1. Introduction to AI and ML

To promote AI in the automotive domain, standards and regulations for safety and security are needed. The US National Highway Traffic Safety Administration has a lab for vehicle forensics and security research. The academic research community should shape the future of AI. Dr. Markus Hartmann emphasized the importance of validation and translation in AI research. IoT and vehicle connectivity can lead to more robust AI solutions for predictive failure analysis. However, genuine value must justify technological advancements. The application of AI methods and validation through real-world case studies is still under development. Predictive failure analysis can monitor vehicle dynamics, performance metrics, and driver behavior. AI is shifting towards more advanced predictive and prescriptive modeling. AI is widely used in the automotive industry to improve safety and driving experiences. Predictive failure analysis can identify deviations and schedule maintenance to prevent breakdowns and accidents.

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1.1. Overview of AI in Automotive Applications

Artificial intelligence (AI) is transforming the automotive industry. It enables vehicles to learn and make decisions from their surroundings. AI techniques such as autonomous driving, computer vision, and predictive maintenance are crucial in advanced automotive technology. This section explores these techniques and defines the levels of autonomy in vehicles. The automotive industry has evolved from basic driver assistance systems to fully autonomous vehicles, with big tech companies and startups investing in AI research. The US market is leading in automotive AI, with companies like Toyota, Ford, and General Motors incorporating AI in their vehicles. Moreover, AI is also revolutionizing car manufacturing and maintenance by enhancing productivity and reducing defects on the factory floor. This section focuses on autonomous driving and AI in-vehicle health monitoring, starting with explaining the different levels of autonomy in vehicles.

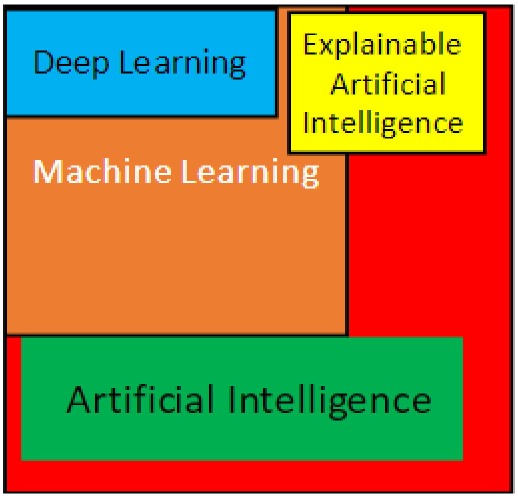

FIGURE 1.4. The connection between AI, ML, DL, and XAI.

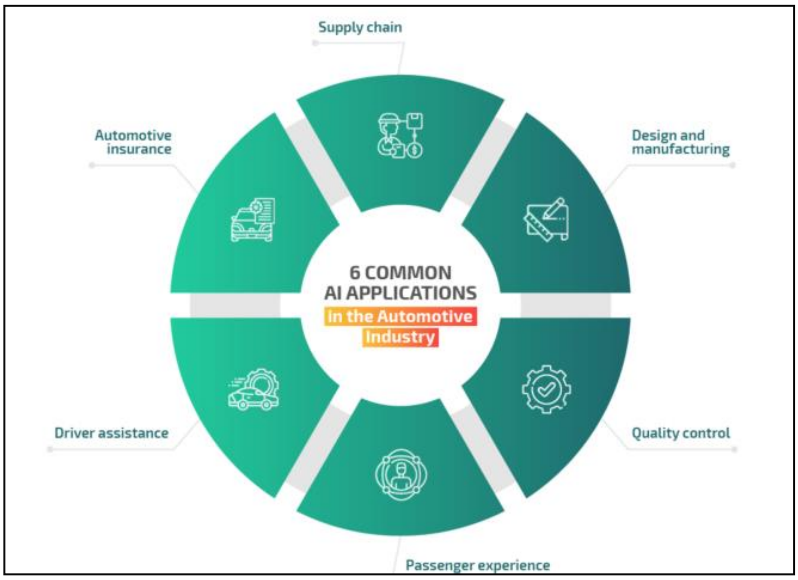

FIGURE 1.1. AI Applications in the Automotive Industry

1.2. Importance of Predictive Failure Analysis

Predictive maintenance is the key area where AI will play a significant role. As the global automotive industry moves towards a more connected world, increasing efficiency by analyzing system performance and foreseeing component failures in advance has become one of the main objectives for the automotive industry. This is mainly due to reducing costs and increasing the vehicle's uptime.

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Replacing archaic, reactionary methods with proactive, AI-driven insights enables the industry to shift from a 'fail and fix' model to a 'predict and prevent' approach, ultimately delivering significant benefits to the manufacturer, fleet owner, and, more importantly, the end user.

When a vehicle goes through predictive maintenance, you assume it will fail and take preemptive steps to prevent that from happening.

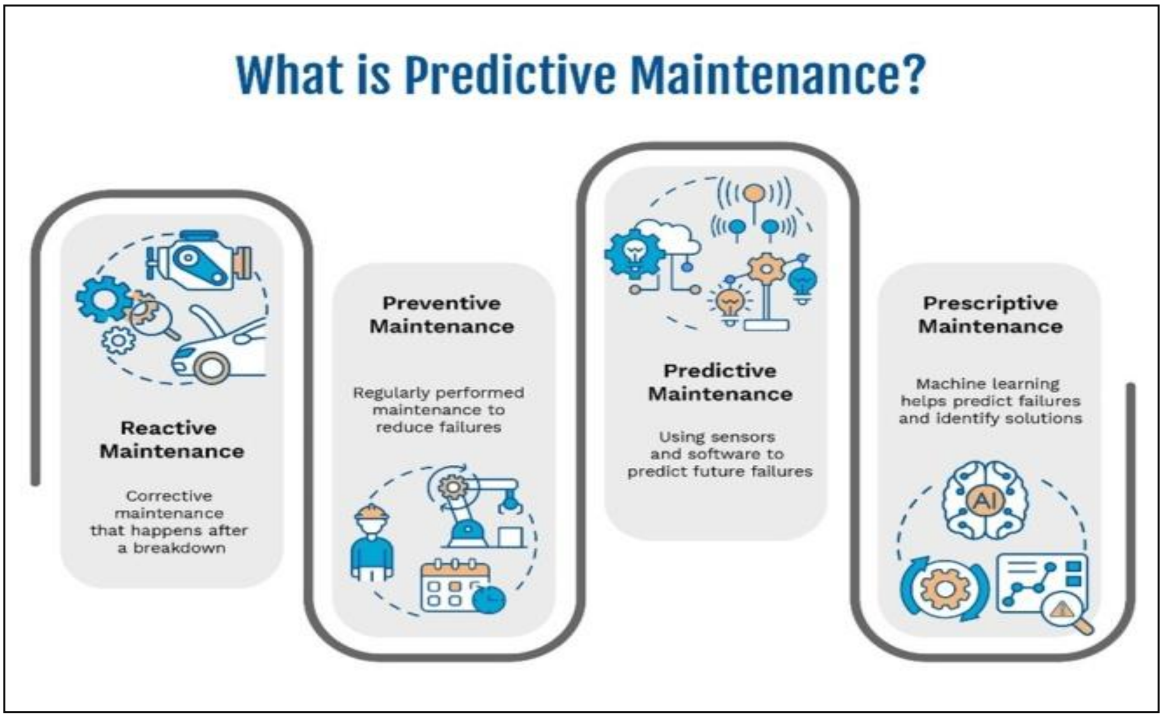

FIGURE 1.2. Predictive Maintenance

The commercial deployment of vehicle health prognostics can be seen in many places, such as the London Underground, which utilized a version of ABB's RCM software to automate predictive maintenance. Referring to the example of the London Underground, given the number of passengers who use the service every day and safety being the primary concern, the successful introduction of technology and the results show that predictive maintenance can be transferred across different industries.

It is about making good choices based on saving time and reducing organizational maintenance costs. By replacing inefficient 'run-to-failure' and time-based maintenance methods, the latest automatic condition monitoring systems and the introduction of predictive maintenance, coupled with AI, provide valuable insight into working plants – from individual assets to entire processes.

II. METHODOLOGY

The methodology section explains the data collection and preprocessing, AI algorithms for failure prediction, and performance evaluation metrics. A literature review identified gaps in failure prediction methodologies. SPS, maintenance logs, vehicle mileage, and start/stop times were viable data sources. AI's role in diagnosis, fault reasoning, and failure prediction was evaluated across domains.

Limited work exists on AI-driven predictive school bus maintenance. Data-driven techniques and their advantages were highlighted. Flexibility, adaptiveness, and intelligence in maintenance strategies were recommended. Discussions with domain experts provided real-world insights. Challenges included data collection barriers and implementing smart maintenance with AI. Real-world knowledge validated conclusions from the literature. Well-structured big data is necessary for AI-based failure prediction, but data management and preprocessing pose challenges.

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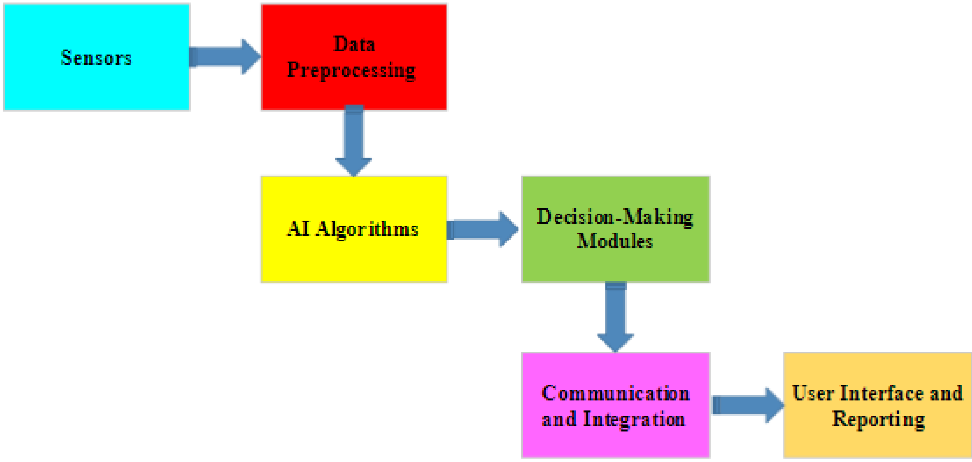

FIGURE 1.5. Key components of an AI-based PdM System

2.1. Data Collection and Preprocessing

After removing unsuitable features, data imbalance was resolved by synthesizing additional instances for failure cases using "SMOTE." Historical usage data and failure records were collected from vehicle fleets, including engine duty cycle, vehicle speed, engine speed, manifold temperature and pressure, exhaust gas recirculation, diesel particle filter, and selective catalytic reduction. The data was collected from different types and models of vehicles and was imported using the panda's library in CSV format. The timestamps' time zone was converted to Coordinated Universal Time (UTC) for standardized analysis. Traditional machine learning algorithms like k-Nearest Neighbour, Decision Tree, Random Forest, and Naïve Bayes were initially used for analysis. Later sections will introduce Modern deep learning algorithms to compare prediction accuracy and computation time.

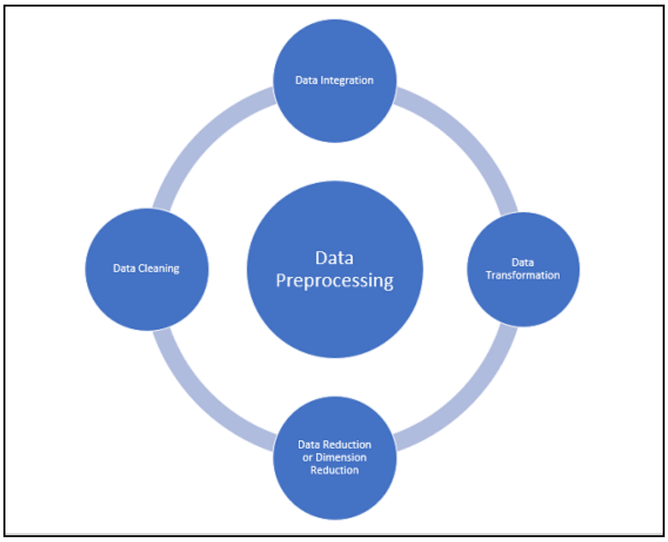

FIGURE 1.3. Data Processing

2.2. AI Algorithms for Failure Prediction

Different supervised and unsupervised learning algorithms fall under the broader category of AI. Supervised learning methods are applied to train the model using historical failures and operating conditions data and to learn the mapping function for predicting failures. A range of supervised learning algorithms, such as support vector machines, decision trees, naïve Bayes, and artificial neural networks, can be used for failure prediction. For example, support vector machines classify cases by finding the best line that separates data points into different classes. It creates a separation line that maximizes the distance to the nearest data point of any class. However, the choice of kernel and penalty parameters, which heavily influence the performance of the support vector machine model, usually have to be determined empirically.

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Decision tree builds classification or regression models as a tree structure. It breaks down a data set into smaller and smaller subsets while, at the same time, an associated decision tree is incrementally developed. The final result is a tree with decision nodes and leaf nodes.

On the other hand, unsupervised learning does not require historical failure data and failure labels, and the main task is to find the inherent structure in the data. Clustering analysis is one of the most used unsupervised learning algorithms for failure pattern recognition. It aims to partition a data set into clusters such that each data point in the subset is assigned to precisely one of the clusters. The K-means algorithm is a widely used clustering algorithm that partitions the data into K non-overlapping subsets. There are several different ways to initialize K-means, such as the Forgy method, the random partition method, and the choice of the initial clustering.

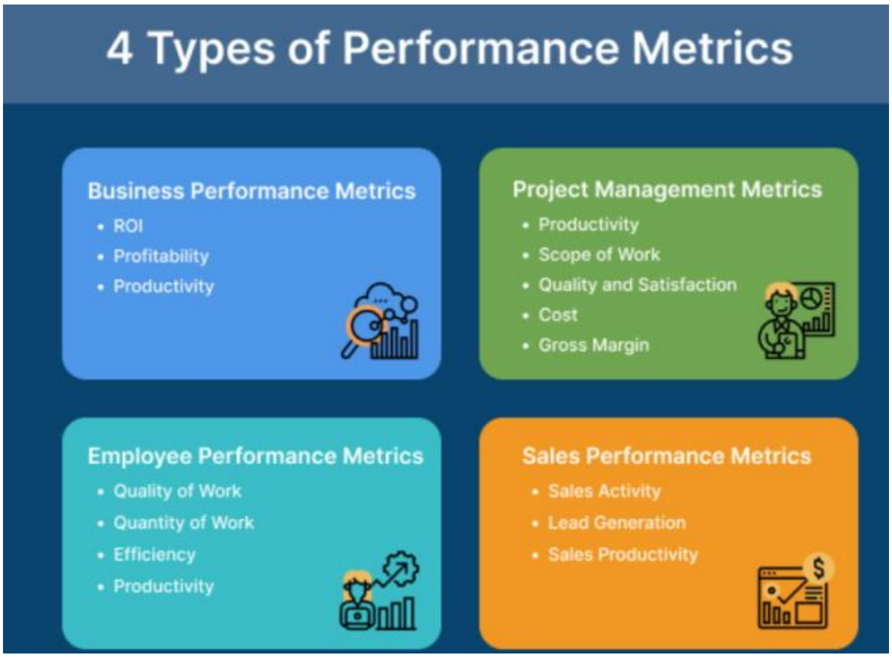

FIGURE 2.2. Types of Performance Metrics

2.3. Performance Evaluation Metrics

The F1 score is a metric that combines precision and recall into a single value between 0 and 1. Precision measures the accuracy of optimistic predictions, while recall measures the fraction of genuinely positive instances predicted correctly. The receiver operating characteristic (ROC) is another commonly used metric for binary classification, but it is unsuitable for imbalanced data. Other metrics like precision macro/micro and recall macro/micro are used in multi-class classification. Actual positive and false positive values are essential for evaluating performance for fault detection. *Sensitivity analysis* is a technique used to evaluate how results change with variations in assumptions or conditions. It can be used to test the response of algorithms to parameter variations. Other ways to evaluate machine learning algorithms include using training and testing datasets to assess prediction accuracy.

III. APPLICATION IN SCHOOL BUSES, TRUCKS, AND PASSENGER VEHICLES

3.1. Challenges in Predictive Failure Analysis for School Buses

Implementing predictive failure analysis in school buses is challenging due to their limited electronic systems and lack of infrastructure for advanced analysis. School buses have long times between failures and low probabilities of failure, making it difficult to study their health over time. Catastrophic failures are rare, making data collection challenging. Misbehavior, rather than underperformance, is often the cause of breakdowns. Data collection is limited, and privacy concerns may restrict access.

Implementing AI algorithms for school bus systems requires immense expertise. Interpretation and analysis of algorithm results are complex due to different failure modes. Safety and reliability considerations make it hard to introduce new techniques. Existing practices in other transportation modes cannot easily be transferred. Revolutionary methods like AI are difficult to implement, with only incremental upgrades allowed.

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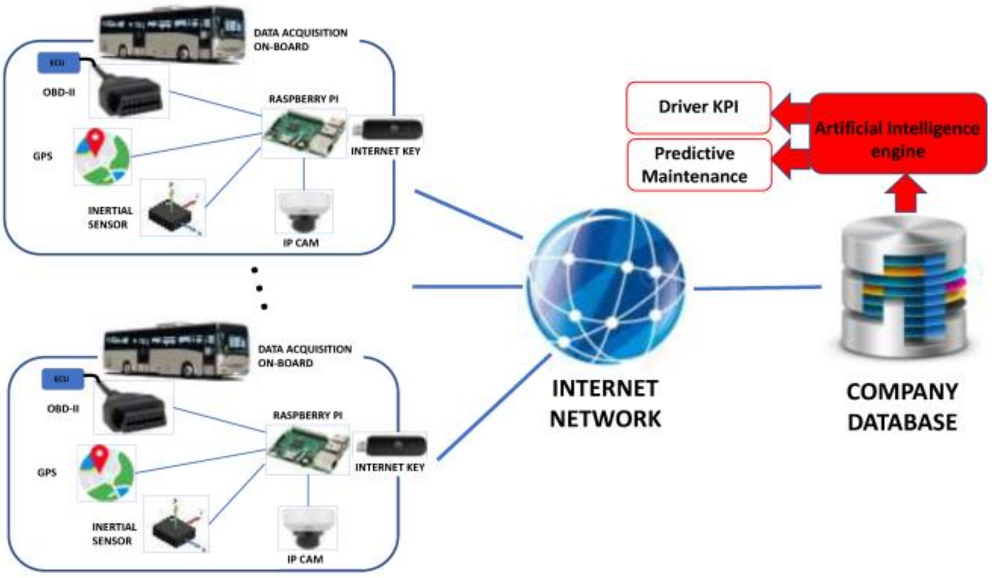

FIGURE 3. Application in School Buses, Trucks and Passenger Vehicles

3.2. Implementation in Trucks and Commercial Vehicles

Vehicle data is gathered and preprocessed using unsupervised learning algorithms to implement predictive failure analysis. Real-time data is extracted and cleaned, followed by statistical analysis to identify patterns and classify data types. Unsupervised learning can produce predictions without historical failure data, allowing immediate usage when installing a monitoring system. Each monitored vehicle is represented as a single point in a dataset, forming a complex structure continually analyzed by algorithms. As patterns or irregular behaviors emerge, they are categorized and processed by the AI program. This implementation allows for "deep learning," where the model adapts to unique structures and parameters in the datasets. With more data and understanding, prediction accuracy improves. Advertising funds our journalism!

3.3. Case Studies and Success Stories

Case studies and accomplishments in predictive failure analysis are discussed to showcase AI's practical applications in the automotive industry. One case study focuses on improving an intelligent vehicle maintenance system, while another highlights using "Mobius transformation" for aerial vehicle failure diagnosis. Success stories include a family-run bus company overcoming breakdowns with AI-based predictive maintenance and a European rail systems maintenance company achieving better service performance and cost reduction. These examples demonstrate the potential of AI and predictive failure analysis in the automotive industry.4. Future Directions and Conclusion.

During the last decade, AI algorithms have significantly advanced analysis and prediction. AI is now integrated into automotive engineering, evolving from basic driver-assistance systems to more complex ones that aim to reduce component failure. The automotive industry is benefiting from research in other fields, using techniques like deep learning to identify micro-cracks in suspension components. This research is establishing new best practices for predictive analysis. Before focusing on individual component relationships, we should explore how to transfer knowledge from other AI fields to automotive predictive analysis algorithms and consider identifying broader system failure trends. This revolutionary research would elevate AI-based predictive analysis in the automotive field and contribute to anticipatory vehicle health management. The following five to ten years are crucial for automotive AI evolution, promising widespread recognition of AI's role in vehicle health maintenance and increased safety and reliability for society.

IV. ADVANCEMENTS IN AI FOR AUTOMOTIVE APPLICATIONS

With the recent advancements in technology, automotive industries across the globe are striving to integrate AI in all the potential areas in which AI has been influencing to a greater extent and is bracing for much more significant advances. Many diverse and routine expert systems exist in artificial intelligence, and every system is confined to one area. For example, in various automotive applications, AI methodologies are being used in various tasks, from procedural steps of process planning to monitoring static and dynamic traffic signs in autonomous driving.

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However, with the recent advancements in machine learning and data mining, AI systems are being improved so that expert systems can be eliminated. With such technical improvement, the automotive sector is very enthusiastic that AI is turning into a reality where advanced products and services inherently more intelligent can be produced. This is due to the enormity of AI's potential benefits in unleashing better ways of doing jobs and even in designing new tools and methodologies, leading to higher quality output, practices, and efficiencies. Ergonomics is one of the prime aspects that AI dramatically enhances. For example, new advanced systems have been developed to allow the AI system to analyze vast amounts of data produced by economics analysis tools, and it will produce recommendations and solutions. In return, this minimizes the interaction time of the human factors specialists with the tool, and many of the time-consuming procedural steps can be eliminated.

FIGURE 4. Generative AI Use Cases in the Automotive Industry.

V. POTENTIAL INTEGRATION WITH CONNECTED VEHICLES

The authors propose potential use cases for AI failure prediction in automotive applications notably AI integration in passenger vehicle maintenance. With increasing drivers and IoT advancement, vehicle health monitoring and maintenance efficiency need enhancement. Connected vehicles continuously monitor conditions and process real-time data, such as fuel level, tire pressure, and engine temperature. Applying AI to historical records, current states, weather, and traffic conditions, the algorithm provides a predictive maintenance schedule. Car notifies the driver of predicted failures, severity level, and earliest booking time. This shifts from reactive to proactive maintenance. Vehicle downtime was minimized, and in-use efficiency was maximized. AI enables the move from preventative to predictive maintenance. Digital connectivity aids in implementing monitoring and optimizing bus systems and fleet management. Potential benefits for vehicle owners, manufacturers, and maintenance providers. Promising future for forecasting methodologies in the automotive industry.

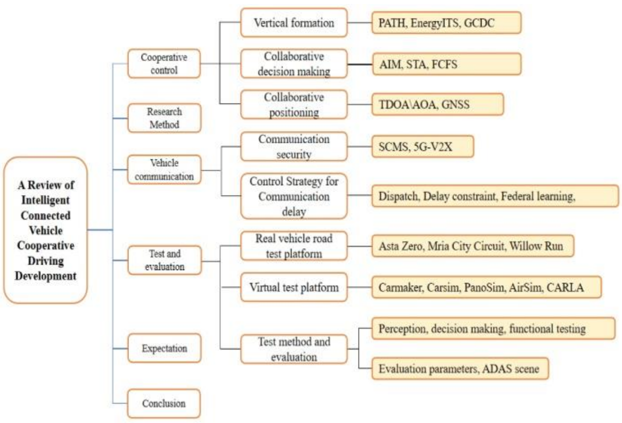

FIGURE 5. A Review of Intelligent Connected Vehicle Cooperative Driving Development

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VI. FUTURE SCOPE

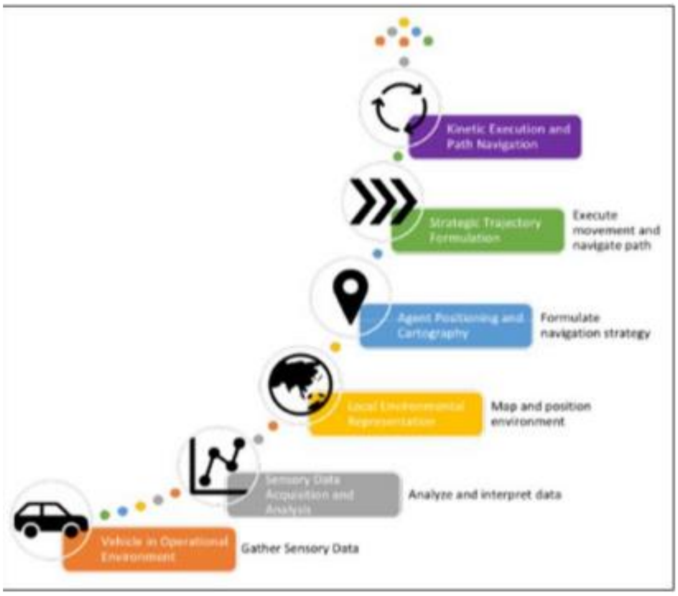

FIGURE 6. Schematic Representation of Vehicle Navigation Process

In recent days, AI is gradually moving towards deep learning. In the future, AI can explain the causes of different vehicle failures. Most car manufacturers are now shifting from traditional fossil fuel vehicles to electric vehicles, and electric vehicles have entirely different failure mechanisms and a new set of failure modes compared to traditional internal combustion engine vehicles. As electric vehicles are being widely used now, I believe that shortly, the upcoming researchers or people working with AI will mainly focus on the failure analysis of electric vehicles. Another potential area of research could be to study and compare a broad range of advanced AI and deep learning techniques. Most health monitoring and predictive maintenance tasks are carried out by advanced AI and machine learning techniques that provide solutions for a specific problem. However, future research will be conducted to analyze the different kinds of problem areas of the same failure analysis and provide various optimal solutions by studying the effectiveness of different kinds of AI methodologies.

Finally, another potential area of future work would be to develop and investigate using cloud-based prognostics. The rapid development of cloud computing and Industrial 4.0 would provide a better opportunity to use cloud-based vehicle prognostics, which can utilize real-time big data from same-day prognostics and historical maintenance records for better analysis and decision-making.

Using cloud-based prognostics would take advantage of same-day prognostics, which could help the vehicle plan maintenance and reduce downtime. In the future, I would consider investigating and studying the usage of Amazon Web Services or any other cloud platforms to develop a cloud-based vehicle health management and predictive maintenance system, provided it could digitalize the discovery and diagnosis of vehicle health problems successfully. The AI field is growing daily, and many improvements are pending in-vehicle health monitoring and predictive maintenance tasks. My work will contribute to using AI technologies more effectively to help and improve vehicle maintenance tasks shortly. I feel very proud to study and work in a field that can significantly impact society. Well, I am looking forward to seeing what is next.

VII. CONCLUSION

AI revolutionizes automotive technology by enabling predictive failure analysis to minimize vehicle breakdowns. Implementing this technology for larger vehicles like school buses presents challenges, but the benefits are clear. AI-powered failure prediction allows for early intervention, preventing costly failures and improving routine maintenance. By transitioning from pre-scheduled inspections to dynamic predictive strategies, resources can be used more effectively, and unnecessary maintenance activities can be eliminated. Comprehensive diagnostic systems may replace periodic maintenance for school buses.

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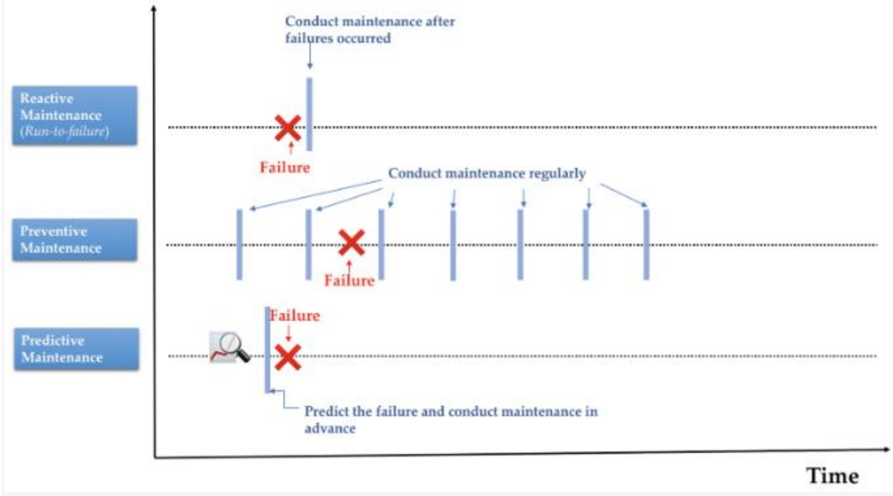

FIGURE 7. Maintenance strategies.

Moving beyond AI from a property or product of the individual vehicle to an integrated element of transportation systems and traffic management will be a significant milestone for AI in the automotive industry. "Connected vehicles" can communicate data with other vehicles and infrastructure systems and generate multidimensional data for real-time analysis. This can drive breakthrough technologies in traffic congestion and energy savings. Ced, AI will be present in various vehicles as technology advances and costs are reduced. The future of AI for predictive failure analysis in automotive is bright and promising, with potential applications across different vehicle types. This research showcases the usefulness of AI in failure prediction and inspires breakthroughs in this field. Utilizing AI for prediction analysis in automotive engineering would be a unique and necessary journey.

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BIOGRAPHY

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