Life Cycle Reliability and Safety Engineering (2021) 10:81–89
https://doi.org/10.1007/s41872-020-00130-3

REVIEW

Reliability, availability and maintainability aspects of automobiles

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Received: 24 February 2020 / Accepted: 11 May 2020 / Published online: 22 May 2020

Abstract
This paper presents a review on the recent advancements in the field of reliability, availability and maintainability (RAM) aspects of automobiles. The available literature is analyzed and categorically segregated by addressing various issues of RAM concerned with automobiles. The literature covered reliability aspects of mechanical, tribological and electrical and electronics elements, both at the system and component levels. An exclusive survey of literature on maintainability and maintenance aspects of automobile systems is included. The availability aspects of automobiles are also covered in detail. The research paper will be useful to researchers, maintenance professionals, academicians, designers and others concerned with automobile engineering field for updating their knowledge and exploring the research avenues in RAM aspects of automobile systems. The future scope of research pertaining to contemporary developments in automobiles, where RAM concepts have a great role, is also narrated in the concluding section.

Keywords Automobiles · Reliability · Maintenance · Maintainability · Availability

1 Introduction

Automobile usage is increasing each day all over the world. Although the vehicles being manufactured today are reliable and maintainable, yet there is consistent effort to further augment their performance. The recent customer surveys revealed that along with the cost, the reliability and maintainability are the critical decision factors that the customers are earnestly looking, while purchasing a vehicle. Since automobiles are machines with higher degree of risk, reliability is inevitable in its design, manufacture and operation. Manufacturers may be benefited by incorporating reliability and maintainability aspects at the conceptual design phase, which will minimize the failures. The expected reliability decreases with usage and passage of time; proper maintenance strategies needs to be planned for its restoration. Availability is another important factor in case of commercial fleet applications of automobiles and applications like ambulance or fire fighter as it has a direct bearing on the fleet revenues and on the criticality of its use. So, it is obvious that automobile, being a complex system, are subjected to lot of challenges throughout its useful lifecycle. These challenges can be minimized up to the maximum possible extent through RAM consideration at the design stage of a product.

The literature review carried out includes some of the contemporaray research in the areas related to RAM aspects of automobiles. The paper is organized with Sect. 2, narrating the reviews of available literature from journals, conferences and books; while Sect. 3 presents the research gaps that are identified from the study.

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2 Literature review

Dhillon and Choueiry (1987) presented a bibliography of literature published until 1987 on the reliability aspects of automobiles. The literature encompassed articles related to RAM concepts applied to design, tribology, systems, electronics, testing, failure data analysis, safety, fatigue life, failure probability distributions, diagnostics, maintenance, maintainability, etc. of automobiles. This review paper is a step ahead of the above work, by evaluating the most relevant articles from each category, which were published since 1987 and categorized into six segments as follows.

1. Reliability-based design of system/components.

2. Reliability of automobile tribological elements.
3. Reliability analysis and prediction of mechanical systems of automobiles.
4. Reliability analysis and prediction of electronics system and components.
5. Maintenance and maintainability of automobiles.
6. Availability aspects of automobiles.

2.1 Reliability-based design of system/components

Bertsche (2008) pointed out that the number of callbacks due to critical failures and defects in automotive components and systems has tripled in the last 10 years. This has increased call back costs by eight times and resulted in guarantee and warranty costs accounting for 8–12% of the turnover of companies. Such failures are mainly due to uncertainties in design variables, which were not considered during the conceptual design phase. Reliability-based design optimization (RBDO) techniques address such problems of various uncertainties in deterministic-based design and help in achieving flawless designs, characterized by low probability of failure. Agarwal (2004) proposed RBDO, which is a quantitative method for reliability-based design. This methodology represented uncertain variables using probability theory and the failure modes were replaced with constraints on probabilities of failure, corresponding to each of the failure driven modes. This concept had been adopted for reliability-based design of automobile system/components by several researchers. Rao and Tjandra (2004) developed a reliability-based design of automotive transmission systems, considering parameters such as power transmitted, dimensions of roller bearing, gear face widths, length of splines, length of keys, and material properties as random variables. They have also compared the reliability-based design with deterministic design procedure using normal, lognormal and exponential distributions. Zhang and Liu (2002) used techniques from the perturbation method, the second moment and reliability-based design theory for the reliable design of automobile axle and springs components. D'Ippolito et al. (2009) performed fatigue life prediction and RBDO for a vehicle knuckle using a probabilistic approach by considering the variations in the material characteristic parameters including Young's modulus and tensile strength. Grujicic et al. (2010) investigated the influence of processing- and manufacturing-induced uncertainties in material properties, shape and size and its effect on the reliability performance in a vehicle suspension system. They combined the concepts of RBDO and low-cycle fatigue durability for accomplishing this. Guo et al. (2010) performed RBDO of full-floating automobile semi-axle to minimize its weight, using evidence theory under the constraints of allowable torsional strength and rigidity. Acar and Solanki (2009) performed the RBDO of automobile structures for crashworthiness, considering variability in material properties and errors in FEA analysis. Zhu et al. (2011) came up with metamodeling development for RBDO of automotive body structure. Song and Lee (2011) also used metamodeling techniques with constraint feasible moving least squares method for RBDO of an automotive knuckle component under variable bump and brake loading conditions. The qualitative methods of incorporating reliability at design phase also had been used by researchers in this domain. Popovic and Ivanovic (2007) briefed the different procedures to be followed in the conceptual phase of design for reliability of vehicles. These included incorporation of quality function deployment (QFD), reliability specification, reliability block diagrams, reliability functions, reliability prediction and modelling, reliability allocation methods, Failure Modes, Effects and Criticality Analysis (FMECA), Fault Tree Analysis (FTA), stress–strength interference, reliability qualification testing, and design review evaluation. Ling et al. (2005) presented the reliability engineering practices in the design of light duty dodge ram truck chassis program using various tools like Design Failure Modes and Effects Analysis (DFMEA) and Finite Element Analysis (FEA). Brunner (2009) integrated computer aided engineering with Failure Modes and Effects Analysis (FMEA) for establishing the reliability requirements of design and testing of safety parts of automobiles. Arcidiacono and Campatelli (2004) formed a reliability tree by combining Axiomatic Design (AD), FMEA and FTA to design for reliability of an automotive heavy-duty diesel engine. Popovic et al. (2011) presented a comprehensive model for robust vehicle design, with improved reliability and quality incorporating FMEA, QFD, Design of experiments and the Taguchi method and applied it for design of a vehicle transmission system.

2.2 Reliability of automobile tribological elements

The reliability of tribological elements is necessary for ensuring the overall reliability of automobiles. Though, there are limited available publications in this domain, some are listed here. The most important concern of automobile tribology is the lubrication of automobile engines and other systems as it affects the reliability and functioning of entire automobile. The Original Equipment Manufacturer (OEM) of automobiles suggests engine lubricating oil and transmission oil changes based on mileage. Additionally, there are other factors like the age of engine, driving conditions, climate, load, etc. that do affect the oil changing schedule. Youngk (2000) expressed the life of automobile engine as a function of maintenance of its lubrication system after conducting survey on vehicle operator's oil changing pattern and engine tests. Naikan and Kapur (2006) performed the reliability analysis of automobile engine lubricating oil, when it was added as topping between replacements using a parametric and non-parametric approach with Weibull distribution model. It was concluded that the hazard rate of the oil was non-linear and the oil followed an increasing failure rate in comparison with a typical bathtub curve. The analysis proved to be helpful in predicting the next top-up time. Similar attempts were made by Sharma and Gandhi (2006, 2008) for evaluation of remaining useful life of lube oil used in vehicles by combining Analytic Hierarchy Process (AHP) with vector projection method and later by parameter profile approach. Both the methodologies were found to be helpful for planned oil replacement by evaluating the performance parameters periodically through sample analysis. This would be helpful in maximum usage of the lube oil, while maintaining its reliability. A more advanced work in this direction by Preethichandra and Shida (2000) narrated the designing of a multifunctional sensor that can measure viscosity, cleanliness, temperature and capacitance of automobile engine oil to monitor its condition and make decisions for oil change to maintain the engine reliability. A similar work by Jagannathan and Raju (2000) proposed the application of micro-electrical and mechanical systems, where both micro-sensors and mathematical models can be used in concurrence with neural network/fuzzy classification algorithm for prediction of the quality of engine oils and make replacement decisions. Eventually, Jun et al. (2006) developed a predictive algorithm to arbitrate the optimum replacement time of automotive engine oil, using the mission profile data obtained through oil sensors, engine control unit and on-board computers.

Apart from lubrication, the wear aspect of engine tribology needs attention. The reliability of components such as piston, cylinder and piston rings comes under this category. Prince et al. (2005) suggested a test methodology for estimating the future field reliability of head of engine cylinder. Du et al. (2003) introduced a new search algorithm titled Most Probable Point of Inverse Reliability (MPPIR) for achieving robust and reliability design of a vehicle combustion engine piston. Sherali and Ganesan (2007) also applied an inverse reliability-based approach for designing engine piston using the uncertainty conditions. Giorgio et al. (2007) presented an S-based methodology for condition-based estimation of liner reliability with reference to wear failure of marine engine cylinders. The authors postulated that this will help in condition-based maintenance of engines. Piątkowski and Matula (2012) applied a Weibull distribution model for estimating the reliability of a tribological cylinder-ring system. This, according to the authors, will help in the estimation of a theoretical failure-free running time of engine. Ejakov et al. (2003) conducted an analysis of reliability and robustness of engine ring-pack performance by integration of Computer Aided Engineering (CAE) tool with the design optimization and analytical robustness and reliability tool (iSIGHT). Koszalka et al. (2012) analyzed the engine reliability based on the reduction in combustion chamber tightness.

Some reliability issues related with automobile bearings were discussed by Sudhakar (2002), including failure analysis of automobile bimetal bearings by electron and optical microscopy. The early detection of fault in automotive ball bearings using the minimum variance spectrum was suggested by Park et al. (2013).

Brakes, which are another tribological element in automobile, should be reliable for ensuring the safety. Todorovic et al. (1995) developed a methodology based on Miner's hypothesis for wear prediction of automotive brakes. This was based on the test data of brake dynamometer wear and corresponding energy dissipation expressed as the work done by the brake. Fülep and Palkovics (2008) conducted a quantitative and functional reliability analysis of heavy-duty vehicles electronic brake systems. Mihalache et al. (2006) used a Petri net model to analyze the reliability issues coming out of the critical interactions between various elements in Antilock Braking System (ABS) of automobiles. Reliability of clutch, which is another tribological element, was analyzed by Teixeira and Cavalca (2008) that presented a case study on reliability as an added value factor in an automotive clutch system using combined methodology of KANO model, target cost and value analysis.

2.3 Reliability analysis and prediction of mechanical systems of automobiles

An automobile is a complex mechanical system with hierarchy levels, consisting of different sub-systems and components. The system reliability assurance can be accomplished by constructive and analytical methods. Bertsche (2008) suggested constructive methods that involve specification of exact design data, manufacturing guidelines, followed by early and broad testing procedures for ensuring reliability. The methodology of testing for reliability for automobile systems has been adopted by many researchers. Koo and Kim (2005) conducted an accelerated life test for the reliability assessment of automobile seat belt webbings under severe temperatures, ultraviolet irradiance and abrasion as stress factor for incorporating reliability in the process of webbing manufacture. Ke (2009) mentioned the procedures to be followed in reliability testing of automobiles, by introducing a concept called 'bogey'. The above concept had highlighted the requirements and objectives of test and instructed how to begin and complete after trialing for a finite period of time, cycles or mileage to make a decision with reliability measurements. Lin et al. (2010) used an accelerated durability analysis of motorcycle components involving field data acquisition, laboratory road simulation, fatigue life prediction and accelerated durability testing. The thermal aspects related to the reliability of automobile components were discussed by Aldridge (2004) with accelerated thermal test and cycles for components considering the heat generation at various places of automobile. Krolo et al. (2001) correlated the failure behavior of vehicle parts and components under taxi and field operating conditions. They have applied fatigue damage accumulation hypothesis and accelerated life testing data of a component under two operating conditions of taxis and field usage.

The analytical method of reliability assurance that involves determination and/or reliability prediction through quantitative and qualitative methods can be applied in conceptual design phase and during the field usage of automobiles. Its application in conceptual design phase has been explained by researchers, which involves the use of tools like ABC analysis, FMEA, FTA, Markov models, etc. A case study of causes and modes of failure of automobile cooling fan motors was conducted by Popovic et al. (2010) using FMEA, for the betterment in construction of cooling fan motors. Yang and Liu (2008) performed the failure analysis for an airbag inflator in automobiles using Stochastic Petri Nets. Jun et al. (2008) made a prediction of the fatigue life and reliability of an air suspension system in vehicles through the analysis of failure modes of the system, using computer simulation and actual running on Belgian road conditions. Jung et al. (2009) predicted the fatigue life for reliability of an automobile crank shaft through bending test and failure mode analysis, followed by Weibull analyses of data for the shape and scale parameters of crankshaft. Morello et al. (2008) used a modified FTA with the sensitivity analysis for reduction in fault tree of various components in the gear box of a commercial vehicle by considering the sensitivity to scale and shape factors for components. Neil et al. (2001) employed Bayesian belief networks for reliability prediction of military vehicle early in the life cycle through design and process capability evidence. Zuo et al. (2005) quantitatively analyzed the reliabilities of various design alternatives of steer-by-wire system of automobiles with numerical integration of the Markov diagrams based on realistic failure rate data.

The reliability analysis of components using field failure data of existing, similar or predecessor components had been a subject of research for many. Guidaa et al. (2009) explained the usefulness of data related to failure of predecessor components of automobiles, for evaluating the reliability of modified/successor components using a Bayesian procedure. Reliability analysis of transmission system of automobiles used by the Indian army was conducted by Kumar et al. (2006) with the failure data of components in the system considering a Weibull distribution. Krivtsov et al. (2002) estimated the reliability of automobile tire by performing a root-cause analysis of tire failure through tire life data obtained from laboratory test and its analysis using the Cox survival regression mode. The work also helped in identifying the elements that could affect the probability of tire failure. Constantin and Mircea (2011) analyzed the reliability of shock absorbers for a fleet of automobiles based on the failure data under different driving conditions using Weibull distribution. Dutta et al. (2010) conducted reliability analysis of gearbox assembly used in defence vehicle with Weibull model by incorporating the failure data collected from the logbooks. Lu (2008) developed a methodology for reliability prediction of automobile components, which have the probability to become actionable items. The components that are prone to recall decisions are referred as actionable items and they are sorted based on their early field failure data, which is assumed to be following a lognormal distribution. Hariprasad et al. (2009) estimated mission reliability of a fleet of vehicles with the field failure data using Weibull probability plots and its validation through Chi-Square test. Bohr et al. (2018) performed the reliability analysis of brake system of forklift trucks using exponential model.

Reliability prediction of automobile systems with the help of artificial intelligence has got momentum in the last decade. Emami et al. (2012) predicted the reliability of automobiles equipped with passive safety systems (PSS) and advanced driver assistance systems (ADAS) through reliability block diagram and mathematical models. Attempt for usage of expert system for reliability analysis was made by Srihari et al. (2010) through the development of an artificial neural networks-based fault detection system to enhance the reliability of gearbox of automobile. The application of artificial neural networks for vehicle reliability prediction was also presented by Hariprasad et al. (2012) and Lolas and Olatunbosun (2008). Their works involved collection, sorting and grouping of vehicle failure data that can be used for reliability prediction.

The automobile industry across the world is now focusing on developing vehicles that run on alternate fuels such as fuel cells, Liquified Petroleum Gas (LPG), Compressed Natural gas (CNG), Liquid Nitrogen Gas (LNG) and electricity. Since these are emerging fields, very few studies have been conducted on the reliability of such vehicles because of the limited reliability data (Chamberlain et al. 2009). However, some available work is listed here. A detailed analysis of reliability of fuel cell city car was conducted by Marchesoni and Savio (2005). The reliability analysis of fuel cell vehicles using of failure data and repair data was attempted by Wu and Li (2006). A probabilistic modelling using the physics of failure approach was used by Chamberlain et al. (2009) for predicting the reliability of fuel systems of CNG driven vehicles. Zhong and Yei performed the failure analysis of LNG cylinders of automobiles. Diesel–LNG dual fuel-driven truck was conducted Stefana et al (2016). They have used tools including, reliability block diagram, bow-tie analysis, Fault Tree Analysis (FTA), Failure Mode and Effects Analysis (FMEA) and likelihood and consequence analysis.

The assessment revealed that risk level of LNG–Diesel system and traditional diesel system is nearly same. Rodionov et al. (2011) conducted a study to identify and quantify risks associated with hydrogen explosions in the operation of a hydrogen-driven car. They have employed the methodologies of Event Tree and Fault Tree. The research revealed various initiators, contributors and consequences of the risk associated with the use of hydrogen as a fuel in cars.

2.4 Reliability analysis and prediction of electronics system and components

Automobile industry in the last decade had observed a phenomenal growth in the usage of electronics at various levels in an automobile system. The quality and reliability expectations from automotive electronics suppliers were described by Servais (2009) incorporating suggestions of Automotive Electronics Council (AEC) to homogenize on part qualification methods for the automotive industry. Kumpfmuller (2003) emphasized on the quality and reliability expectations from electronic components suppliers of automobiles and narrated the influence of electronic components on reliability of car with various tests for reliability. The use of failure data for reliability analysis in this domain had been attempted by Fieldler and Knoblauch (2003) for reliability analysis of electronic components in the Electronic Control Unit (ECU) of an automobile operating in the harsh conditions using Weibull distribution model. Angadi et al. (2009) estimated the reliability of a solenoid valve used in automobile transmissions through melding of theoretical and experimental approach, which correlated the results of accelerated life tests with finite element models. Reliability of electronic components in automobile applications was predicted by Coit et al. (2005) by developing a method for correlating field life degradation with reliability. Lee et al. (2011) introduced new method to assess the reliability and performance of automotive ECUs that involved the integration of hardware in loop simulation with requirement-based testing. A case study on the performance behavior of an articulated vehicle rigged with an all-wheel steering ECU was also conducted. The electronics reliability problems applied to the multi jet ECU of diesel engine control was discussed by Cassanelli et al. (2003) using FMEA and FTA. Yongfeng and Lingju (2007) exposed the concerns regarding the electromagnetic environments and the reliability issues coming out due to the interference between various electronic components under that electromagnetic field in an automobile system. Yang et al. (2011) analyzed the effects of high-temperature aging on the microstructure of the molding compounds, thermo-mechanical properties and the reliability issues of the packages related to electronic components used in automobile using experimental simulations and methods.

2.5 Maintenance and maintainability of automobiles

Automobile system reliability is much influenced by maintenance. Fault diagnosis is the primary task in vehicle maintenance. The application of the fault tree as a tool for diagnosis of vehicle performance problems has been suggested by many researchers including Mateyka et al. (1973), Teixeira and Cavalca (2008), Lu (2013), Wang (2013), Dobrivoje et al. (2013), Bogicevic et al. (2014) and James et al. (2018). A machine learning-based systematic approach for establishing online fault diagnosis for a hybrid-electric automobile considering the interrelations between all the sensor-based measurements was presented by Meckel et al. (2020). The maintenance strategies and maintenance scheduling are important for the reliability and, ultimately, the availability. Bouvard et al. (2011) developed a methodology for maintenance planning optimization for reducing maintenance cost of a commercial heavy vehicle. This was based on monitoring the component information and dynamic grouping of the maintenance operations. Dabell et al. (2009) narrated the use of onboard electronics hardware, software architecture for condition-based maintenance of automobile for automatic maintenance scheduling, service, and warranty cost reduction and optimization of design life. Grantner et al. (2010) presented the architecture of intelligent vehicle health management system (IVHMS) for condition-based maintenance of light trucks used in military applications by developing a fuzzy model to diagnose the axle fatigue of the vehicle. Chan et al. (2007) investigated the pattern of failures in radiators of the cooling system of different types of buses in a public fleet company through Weibull analysis and observed that overhaul is preferred over regular preventive maintenance for the radiators. The maintainability, which is a design attribute of vehicle, has a decisive role in maintenance. Bedewy et al. (2009) performed a comparative study of the reliability and maintainability of different models of public transport vehicles. Abdullah et al. (2006) presented a methodology to determine the maintainability index based on assembly criteria for the power window module of an automobile that involved the measurement of maintenance efficiency by considering the type of fasteners using a disassembly digraph. The disassemblability aspects of automobile systems for maintenance had been discussed by James et al. (2017a) and developed a framework for it considering the design aspects as well as the garage contextual factors. The quality and maintenance characteristics pertaining to an automobile service station were discussed by Valavi and Pramod (2013) for developing a framework for maintenance quality function deployment in automotive service industry. The occurrence of maintenance errors and its impact on automobile system failures had been discussed by James et al. (2017b). Maintainability evaluation of steering system of used automobiles was conducted by Onawumi et al. (2018) using Analysis of variance (ANOVA) and observed that maintainability of same system varies with the types of suspensions used. Chong et al. (2019) applied the concept of deep learning in conjunction with time between failure data of automobiles and geographic information system for the predictive maintenance of automobiles used in fleet. The insights from the study can be beneficial for fleet management organizations for optimizing their maintenance strategy.

2.6 Availability aspects of automobiles

Availability is pertinent for performance measurements systems in general (Loganathan et al. 2016) and automobiles are no exception. The availability aspects of automobiles and systems were discussed by few researchers. Xu and Qiao (2008) decided the optimum maintenance period of automobiles under the objective of maximum availability using renewal theory. Sharma et al. (2010) made the availability evaluation of a tractor with the help of Markov method. They considered constant failure and repair rates of different subsystems and found that the repair rate of gearbox significantly affects the system availability as compared to repair rates of other components. However, most of the automobile systems are mechanical components whose failure time follows Weibull distribution. Hence, Kumar et al. (2019) suggested Semi-Markov model that is suited for repairable mechanical systems. This can help in condition-based maintenance (CBM) of automobile systems as well (Kumar et al. 2018; Varghese and Kumar 2014). Kleyner and Volovoi (2010) applied stochastic Petri nets for calculating the availability of passenger safety systems of a car with partial detection and repair by calculating system availability with reference to system's probability of failure on demand.

3 Conclusions

The literature review provided an insight into the RAM aspects of automobiles in addition to the revelation of some gaps for future research. According to the author, there are few works reported on the reliability aspects of engine lubricating oil. However, none had been identified for transmission oil and coolant of automobiles, which is also important for overall reliability of engine and vehicle. There is ample scope of research in these domains. The maintainability-based design of automobile systems and its components is an area largely unexplored. The activity of automobile maintenance as a service business and its enhancement through performance measures, industrial engineering practices, etc. is a promising area for research. The human factors, safety and ergonomics associated with maintenance of automobiles are least discussed. The availability aspects were observed to be the least covered aspect of automobile systems. This is very significant in today's world, where shared mobility is getting momentum and car fleet services are emerging up. Such kind of fleet services should have diligent maintenance strategies to optimize the availability of fleet. One can dovetail the artificial intelligence techniques for the availability studies of such fleet systems. The reliability studies of mechatronics systems of automobiles are still at the primitive stages as these technologies have been developed very recently and have ample scope for future research. Lots of research has been conducted in the last twenty years in the development automobiles that runs on ethyl alcohol, LPG, CNG, LNG, biogas, hydrogen, solar power, electricity, hybrid mode etc. However, the literature revealed that RAM studies of such vehicles are still at the primitive stages. Hence, the researchers are also supposed to take into consideration the RAM aspects of such vehicles, which is again a new area for research. The application of big data analytics, artificial intelligence and machine learning for reliability and maintainability-based design of automobiles as well as for their maintenance and availability modeling has potential scope for future research.

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