Doctoral Thesis in Machine Design

Application of Integrated Vehicle Health Management in Automated Decision-making for Driverless Vehicles

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Abstract

Vehicles are becoming increasingly complex and are prone to faults and failures, which threaten the dependability of vehicles in terms of availability, reliability, safety, and security. When vehicles are detected with certain types of faults and get into alarm situations, human drivers play a vital role in deciding what strategies and actions to take. Once driverless vehicles are introduced, human drivers’ roles in decision-making will no longer exist, which urges new solutions on both technological and managerial levels.

This thesis depicts the current human decision-making process by analyzing field study data in the truck industry, which contributes to gaining domain knowledge and identifying research gaps. An integrated vehicle health management scheme is applied to automate this decision-making process by integrating vehicle health state estimation and prediction, resource utilization, and self-adaptive management. To implement this scheme, fault diagnosis and decision-making methods are proposed, and a decision support system is designed.

Fault diagnosis is a critical functional module for providing reliable vehicle health state information for decision-making. To address the influence of uncertainties in fault diagnosis, we propose an uncertainty analysis framework and a fault diagnosis method using Bayesian inference. Simulation experiments validate that the proposed method could effectively diagnose the root cause of fault symptoms under environmental uncertainty.

A risk-based automated decision-making method is presented, which imitates the human decision-making process. On this basis, a collaborative decision-making method is proposed by considering traffic congestion, which is a currently neglected public concern. Experiment results show that the proposed methods could effectively reduce the economic risk and the risk of traffic congestion.

In the end, a decision support system is designed to provide decision information to its human users. Besides, reviewing and learning functions are considered for gaining knowledge and achieving full automation in the long run. Additional system stakeholders from the public sector regarding safety, traffic, and the environment are considered. A transparent, interactive, and adaptive graphical user interface of the system is designed to enhance user experience and trust.

This thesis shows the potential of automated decision-making and technical system design in increasing corporate profits, catalyzing public-private partnerships, enabling technological transformation, and achieving a more sustainable transportation system.

Keywords: Driverless vehicles, Integrated vehicle health management, Automated decision-making, Fault diagnosis, Public-private partnership.
Sammanfattning

Fordon blir allt mer komplexa och är benägna att få fler felkällor, vilket hotar fordonens pålitlighet när det gäller tillgänglighet, tillförlitlighet och säkerhet. När fordon upptäcks med vissa typer av fel och hamnar i larmsituationer spelar mänskliga förare en avgörande roll när det gäller att bestämma vilka åtgärder som ska vidtas. När förarlösa fordon väl har introducerats kommer mänskliga förare roller i beslutsfattandet inte längre vara tillgängligt, vilket kräver nya lösningar på både teknisk nivå och på ledningsnivå.

Denna avhandling skildrar den nuvarande mänskliga beslutsprocessen genom att analysera fältstudiedata i lastbilsindustrin, vilket bidrar till mer kunskap om området och att identifiera forskningsluckor. Ett integrerat system för fordonshälsa används för att automatisera denna beslutsprocess genom att integrera uppskattning och förutsägelse av fordonets hälsotillstånd, resursanvändning och fordonets möjlighet att själva anpassa sig för att hantera fel. För att implementera detta schema föreslås feldiagnostik och beslutsmetoder, och ett beslutsstödssystem utformas.

Feldiagnos är en kritisk funktionsmodul för att tillhandahålla tillförlitlig information om fordonets hälsotillstånd för beslutsfattande. För att hantera osäkerheter i feldiagnostik, föreslår vi ett ramverk för osäkerhetsanalys och en feldiagnosmetod som använder Bayesiansk slutledning. Simuleringsexperiment bekräftar att den föreslagna metoden effektivt kan diagnostisera grundorsaken till felsymptom, även vid osäkerhet om fordonets kontext.

En riskbaserad automatiserad beslutsmetod presenteras, som imiterar den mänskliga beslutsprocessen. På grundval av detta föreslås en samarbetsmetod för beslutstödande genom att överväga trafikstockningar, som är ett stort allmänt problem. Experimentresultat visar att de föreslagna metoderna effektivt kan minska den ekonomiska risken och risken för trafikstockningar.


Denna avhandling visar potentialen hos automatiserat beslutsfattande och teknisk systemdesign för att öka företagens vinster, ökad möjligheten till partnerskap mellan offentlig och privata aktörer samt möjliggöra teknisk transformation och för att uppnå ett mer hållbart transportsystem.

Nyckelord: Förarlösa fordon, Integrerad fordonshälsohantering, Automatiserat beslutsfattande, Feldiagnostik, Offentligt-privat partnerskap.
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Chapter 1

Introduction

1.1 Background

Vehicles, or automotive systems, are highly complex systems consisting of mechanical, hydraulic, software, and hardware components. Vehicles are increasingly automated, electrified, and digitized, so their functionalities rely on more sensors, software, and hardware components. All these components can contain defects that lead to functional failures of vehicles, such as anomalous sensors [1] [2], faulty actuators [3], battery issues [4] and others. These impairments, including failures, faults, and errors, threaten the dependability of vehicles in aspects of availability, reliability, safety, and security [5].

There are four fundamental means to increase system dependability: fault prevention, fault tolerance, fault removal, and fault forecasting [5], [6]. These means are usually combined to attain dependability [7]. Fault-tolerant techniques, achieved by using redundancy, are essential for vehicles to continue operating in the presence of faults, which has drawn massive intention [6], [8], [9]. Fault forecasting techniques estimate faults’ presence, possible future occurrences, and consequences. It includes fault detection, diagnosis, and prognosis techniques that contribute to fault-tolerant and fault removal techniques [10]–[12]. Among these four means, fault removal is the only one that reduces the number of faults presented in the system by replacing or repairing the faulty components. Fault removal is usually part of the maintenance process. There are several maintenance strategies, such as reactive maintenance, preventive maintenance, and predictive maintenance. Among them, predictive maintenance has attracted considerable attention in recent years. Once faults are presented, unless fault removal is conducted, vehicles are still exposed to the risk of functional failures, leading to a vehicle breakdown.

The high occurrence of vehicle breakdowns and their negative impacts on aspects such as safety, economy, and operation have been spotted and highlighted. According to an annual report [13], vehicle breakdown is one of the most prolific incidents occurring in the road network in the UK, with 15,000 vehicle breakdowns recorded in 2018. It is reported that 69 million vehicle breakdowns happen in the US each year, which cause a high economic cost of $41 billion and other high society impacts, including lost working days, congestion delays, and cost of injuries and fatalities [14]. A report assigned the critical reason to malfunctioning
vehicles in an estimated 44,000 crashes comprising about 2 percent of the crashes in total in the US \cite{15}. The number of road accidents in Russia due to the operation of malfunctioning vehicles is even higher and amounts to 3.6 percent of the total number of road accidents \cite{16}. As a typical cause of traffic bottlenecks, a vehicle breakdown may expose public transport to traffic congestion. Statistics showed that vehicle breakdowns accounted for about 30\% of all types of road incidents in New South Wales in Australia \cite{17} and 64\% of all incidents on a motorway in the United Kingdom \cite{18}. In \cite{17}, a steep rise in vehicle breakdown frequency on motorways was disclosed in a case study in New South Wales. These pieces of evidence urge the importance of taking proper actions to mitigate the negative impacts of malfunctioning vehicles.

When a fault is presented on the vehicle, depending on the fault properties, various actions or operations can be taken, such as automated protection \cite{19}, \cite{20} and onboard engine control \cite{21}, \cite{22}. A figure from Rolls-Royce provided a framework that categorizes the operations of vehicles under fault conditions based on two fault properties, namely, the impact or consequence of failure and the remaining time to functional failure \cite{23}. The impact or consequences of a functional failure of a vehicle can be low, economic, operational, or SHEL (safety, health, environment, and legislative compliance). By plotting these two properties, several quadrant areas emerge, corresponding to different ways of operation, shown in Figure 1.1.

![Figure 1.1: Fault handling strategies of vehicles. Redraw from Fig.4.2 in \cite{23}.](image)

Among these quadrants, our interest lies in the green area, which refers to the
situation where 1) the remaining time to functional failure is between the response
time of the vehicle operator and one mission or minor maintenance cycle, and 2) if
a failure happens, there will be economical, operational or SHEL impacts. In this
situation, the operator takes mitigating action after being informed by alarms and
warnings. For conciseness, this situation is referred to as an *alarm situation* in the
rest of the thesis. A series of field studies in [24] thoroughly investigated the hu-
man decision-making and action-taking process in this alarm situation. According
to these studies, in today’s truck industry practice, an onboard driver plays a critical
role for a truck in an alarm situation, including collecting information, informa-
tion exchange with remote personnel, and decision-making. However, deciding
what actions to take for the vehicle in an alarm situation becomes challenging if a
vehicle becomes driverless.

Driverless vehicles are also referred to as fully automated vehicles, autonomous
vehicles, or self-driving vehicles, and have various definitions provided by differ-
ent organizations [25]–[28]. The SAE Standards J3016 defines fully automated
vehicles (Level 5 automation) featuring 'can navigate and handle all sorts of driv-
ing modes, different driving conditions and roads autonomously without the need
for human driver interaction’ [27]. According to a regulation of the European Par-
lament, a fully automated vehicle refers to a motor vehicle that has been designed
and constructed to move autonomously without any driver supervision [28]. De-
spite the different emphasis of these definitions, removing the conventional human
driver’s roles is a common ground. In this thesis, the term *driverless vehicles* is
used to highlight the absence of an onboard human driver, and *autonomous driving*
is used in contexts that highlight the driving mode.

For a driverless vehicle in an alarm situation, there will no longer be a human
driver to make decisions and take action. Therefore, a problem with driverless
vehicles emerges: *How to decide what action to take for a driverless vehicle in an
alarm situation that a human driver currently handles?* This problem gives rise
to a reconstruction opportunity of the decision-making process so that a driverless
vehicle can handle such an alarm situation. Since the driverless vehicle is a highly
automated system, an intuitively sensible way would be to automate this decision-
making process.

Experiences of automated solutions are already well captured in Figure 1.1, in-
cluding automated protection, onboard engine controller, preventive maintenance,
or integrated vehicle health management (IVHM). However, not all of them are
appropriate strategies for the addressed problem. Automated protection is mainly
targeted for safety-critical faults that may abruptly result in a functional failure
and endanger people’s lives. The onboard engine controller, or engine control
module/unit, is specifically for controlling actuators on an internal combustion
engine to ensure optimal engine performance. These two strategies are not gener-
ally adaptable to an alarm situation since the faults considered are not necessarily
safety-critical or occur in the engine system. Preventive maintenance is perform-
CHAPTER 1. INTRODUCTION

ing regularly scheduled maintenance activities to help prevent unexpected failures in the future, which does not consider the failures that may happen due to unexpected faults of a vehicle during the mission. IVHM, on the other hand, provides a fundamental and general scheme to automate the addressed decision-making problem.

There is no unanimously or generally accepted definition of IVHM [29]. The IVHM definitions were summarized in [30]. According to SAE International, IVHM is defined as 'The unified ability of a system of systems to assess the current or future state of the health of the membership system and to integrate that image of the health of the system within a framework of available resources and operational demand.' [23]. Among various definitions, this definition emphasizes the unified ability of health state assessment and resource integration of vehicle assets or fleets. In 2018, the SAE Surface Vehicle and Aerospace Recommended Practice JA6268 [31] provides best practices and a methodology to implement IVHM functionality, with a capability model with maturity levels 0 to 5. In this model, the highest level (level 5) of IVHM capability is 'Self-adaptive management, where conventional IVHM capability is integrated with self-adaptive control and optimization to extend vehicle operation and enhance safety in the presence of potential or actual failures.' In summary, the core ideas of an IVHM scheme lie in the integration of health state estimation and prediction, resource utilization, and self-adaptive management.

With the development of sensing and fault diagnosis technologies, it is promising that vehicle health states can be obtained automatically by modules on driverless vehicles in the future. Meanwhile, availability and utilization of resources and information can be improved mainly with the support of advanced technologies, including sensor technology, communications technology, big data, and cloud Computing [32], digital twins [33], artificial intelligence and reasoning technologies [34] etc. Based on this anticipated technological development, in this thesis, an IVHM scheme is applied to automate the decision-making process of driverless vehicles in an alarm situation that a human driver currently handles. This work mainly addresses the self-adaptive management and integration functionalities, which belong to the highest level of IVHM functionality according to [31].

1.2 Research questions

The challenge addressed in this thesis is deciding what action to take for a driverless vehicle in an alarm situation. This challenge is motivated by the concept of driverless vehicles and the absence of human drivers, with which the current human decision-making solutions are no longer applicable. A disruptive transition from manual solutions to automated solutions is involved in addressing this challenge, which requires innovations on both technological and managerial levels. However, technologies of driverless vehicles are still under intensive exploration,
as well as its technological transitions and business models [35]–[37]. Furthermore, this challenge is rather a problem caused by driverless vehicles instead of being its key enabler, at least in the current stage. Therefore, relevant research on this topic in the field of autonomous driving is still being determined. To conclude, this challenge is broad, conceptual, and neglected by the research community.

The underlying research gaps need to be unraveled first to tackle this challenge constructively. Here research gaps mean *unsolved problems in established research areas that need to be solved to advance in particular directions*. In Paper D, a gap analysis was performed regarding the post-diagnosis decision-making problem between the current industry practices with human-driven trucks and a potential futuristic solution for highly automated trucks. This gap analysis identified three significant research perspectives gaps: information, decision-making model, and system actors. These perspectives can be further reflected in an IVHM scheme, which sets the foundation of the problem formulation of this thesis.

The IVHM scheme has been defined and concretized with designs and architectures in considerable research works [23], [30], [33], [38], [39]. Some work has narrowed down or restricted an IVHM scheme to a large extent. For example, in [33], it was stated that IVHM is a technology that offers a paradigm shift in support of condition-based maintenance. However, condition-based maintenance is one type of maintenance strategy among many and is not necessarily a property that defines IVHM. This thesis keeps the core idea of IVHM, i.e., the integration of health state estimation and prediction, resource utilization, and self-adaptive management, which can be depicted with a typical IVHM framework shown in Figure 1.2.

![Figure 1.2: An IVHM Framework. This figure is redrawn from [23]](image-url)
tection, diagnosis, and prognosis of highly automated vehicles are also constantly challenged and under active exploration [41]–[43]. One of the prominent challenges is managing the uncertainties arising from the increasing complexity of driving environments, tasks, and automated driving systems. If not properly managed, these uncertainties may lead to false detection of the actual fault condition of a system, which in turn may affect decision-making and potentially cause fatal consequences. Therefore, the first research question of this thesis is:

Q1: How to infer the fault condition of highly automated vehicles under uncertainty to enable more reliable decision-making?

The core of an IVHM framework is the advisory generation module, which is the main focus of this thesis. This module is like an artificial brain that takes in various information from several other modules, reasons about decisions, and makes automated decisions. For intuitiveness, the advisory generation module is referred to as the decision-making module in the rest of the thesis. It is further clarified that in this framework, applying an IVHM scheme means the process of automated decision-making by an integrated utilization of various information from state detection, diagnosis, prognosis, mission profile, and operational process.

The core of the decision-making module lies in developing decision-making models, on which there are massive research and literature [44], [45]. The relevant decisions to be made consist of mission plans, maintenance plans, resource allocation, and route plans. While these different types of decisions are interconnected, maintenance planning is the main focus of the initial step of designing this decision-making module. In the context of this thesis, the first automated decision-making scheme is to replicate the way how human drivers make decisions today. Such a replication mainly lies in two aspects, including the choice of decision alternatives and concern of economic risk. The decision alternatives are mainly about whether to maintain the vehicle in a workshop before the delivery or not. As for the concern of economic risk, two aspects are considered, including the availability loss and maintenance cost. In short, the second research question is

Q2: How to make a short-term maintenance decision that minimizes the economic risk for a driverless vehicle in an alarm situation?

Regarding the concerned decision-making problem, it is a common practice today to consider the economic risk of the private company caused by mission delay. However, a vehicle breakdown may also bring high risk to the public. In Paper D, an impact analysis was performed, which identified various risks that might be caused by a vehicle breakdown. Among them, traffic congestion is a direct and significant impact on the public. Considering this impact in the decision-making process could reduce the risk of public time loss, thus achieving a more sustainable transport system. What’s more, the decisions for an alarmed vehicle involve not only its maintenance plan but also its route plan. Therefore, the third research question is
Q3: How to make maintenance and routing decisions for a driverless vehicle in an alarm situation so that both the risk of mission delay and the risk of public time loss are considered?

The two research questions above are mainly about developing decision-making models, which are the core of the decision-making module. In addition, the interaction and integration of the decision-making module with other system modules or potential human users are also crucial for its applicability in practice. According to the field studies in [24], to adopt an automated solution at an early stage, the stakeholders, in this case, the truck company, still expect humans to take control and make the final decision remotely. Therefore, a decision support system that facilitates humans to make use of a massive amount of information and make a decision is needed. To this end, the last research question is

Q4: How to design a decision support system to facilitate remote decision-making?

1.3 Scope and delimitations

In this section, the scope and delimitations of this thesis are presented, with details of how in-depth the thesis is in exploring the research questions. Some scopes and delimitations have been aforementioned and are further discussed here.

First of all, the challenge of the thesis is mainly motivated by the absence of onboard human drivers of driverless vehicles. Therefore, driverless vehicles can be regarded as one of the scopes of the thesis. However, it does not necessarily mean that automated decision-making of vehicles in an alarm situation is only applicable to driverless vehicles. Suppose a claim that automated decision-making can outperform human decision-making in some aspects. In that case, it can serve as a motivation for this research and apply to human-driven vehicles. However, in this thesis, we do not make this claim, and automated decision-making is not compared to human decision-making. Instead, this research on automated decision-making can primarily support human decision-making and improve human-driven vehicles’ functionality as well.

The decision-making problem caused by removing human drivers applies to vehicles in general. Therefore, this thesis aims to study vehicles in general instead of those with specific functions, such as private cars, buses, taxis, and trucks. However, for the decision-making problem to be relevant and solvable, some conditions need to be satisfied. For the relevance of the problem, the vehicle’s remaining operating time until functional failure is expected to be less than one mission or minor maintenance cycle, which has been discussed in Chapter 1 with Figure. [1.1] In other words, it should be likely that the vehicle has a functional failure
before the transport mission is finished. In this case, long-distance transport mission takes a longer time to finish and are more likely to satisfy this condition than short-distance ones.

To solve the problem with computer-based systems, the transport missions, penalty mechanisms, and decision criteria need to be explicit. Explicit transport missions mean that mission information, including the origin, the destination, the departure time, and the expected arrival time, is available. Explicit penalty mechanisms here refer to the methods that can evaluate and quantify the loss if the mission is not fulfilled. The transport mission goals and penalty mechanisms are generally explicit for commercial vehicles, such as trucks, taxis, and buses. However, the mission target and the penalty mechanism can be explicit or implicit for non-commercial vehicles, such as private cars. For example, the mission is implicit if the car owner drives without a time schedule. Or if the car driver drives with a schedule but would not get any concrete loss other than a bad experience, the penalty mechanism is implicit. Explicit decision criteria refer to principles, guidelines, or requirements that can be reflected with measurable or quantifiable variables. For example, the criterion of arriving at the destination on time is explicit since it can be reflected in the arrival time. However, a criterion of having a good view along the route might be an implicit criterion if a good view is regarded as subjective. Considering these three requirements, commercial vehicles are more likely to encounter the addressed decision-making problem in this thesis than non-commercial ones.

Trucks for long-distance freight transport combine commercial vehicles with long-distance transport missions, thus very likely to be the target vehicle types for the addressed problem. Furthermore, there is consensus among industry experts that autonomous trucks are likely to become commercially available first \[46\], and there is a rapidly growing research interest in autonomous trucks \[47\]. Therefore, in this thesis, trucks for long-distance freight transport are selected as the targeted scenario when needed, such as in case studies and system design. However, this does not mean that the research in this thesis only applies to trucks or trucks for long-distance freight transport. Instead, this study generally applies to vehicles satisfying the conditions explained above.

In this thesis, a driverless vehicle being in an alarm situation is a major scope where automated decision-making is investigated. In Chapter[?] an alarm situation is defined with two fault properties: 1) the remaining time to functional failure is between the response time of the vehicle operator and one mission or minor maintenance cycle, and 2) if a failure happens, there will be economical, operational, or SELH impacts. Therefore, a delimitation of this thesis is the focus on faults with these two properties instead of certain types of faults. For the applicability of the studies in this thesis, it is necessary to identify the particular faults with these properties, which is not the scope of this thesis.
1.4 List of appended papers

To answer the research questions, the following papers A-D are included in this thesis:


Xin Tao performed the research and wrote the paper. Jinzhi Lu guided Simulink model tuning and implementation and provided feedback on the paper draft. Dejiu Chen was involved in the discussion of the research and provided feedback on the paper draft. Martin Törngren provided feedback on the paper drafts and paper revision.


Xin Tao performed the research and wrote the paper. Jonas Mårtensson provided feedback on the paper draft and revision. Håkan Warnquist was involved in the discussion and provided feedback on the paper draft and revision. Anna Pernestål helped develop the idea, was involved in the discussion, and provided feedback on the paper draft and revision.


Xin Tao performed the research and wrote the paper. Mladen Čičić was involved in the development of the public time loss model and wrote the model. Jonas Mårtensson was involved in the discussion of the research and provided feedback on the paper drafts.


Xin Tao performed the research and wrote the paper. Lina Rylander conducted the field studies, was involved in the discussion of the industry practice analysis, and provided feedback on the paper draft. Jonas Mårtensson was involved in the discussion of the research and provided feedback on the paper draft.
Other contributions by the author not included in the thesis:


iii. Xin Tao, Zhao Yuan. "Real-time decision-making for autonomous vehicles under faults." Accepted for publication in IEEE 9th International Conference on Industrial Engineering and Applications. DOI.


1.5 Thesis outline

The remainder of this thesis is as follows. Chapter 2 introduces the research design of the thesis, including the information systems design in general and the application of design science in this thesis. Chapter 3 presents a brief literature review on the state-of-the-art of the relevant fields and the preliminaries of theories. In Chapter 4, a reading guide of the appended papers is provided, followed by a summary of the contributions, validation, and limitations of each appended paper. Chapter 5 first answers the research questions and provides discussions and future research directions afterward. In the end, appended papers A-D are attached.
Chapter 2

Research Design

A research design is an action plan that guides research from the questions to the conclusions and includes steps for collecting, analyzing, and interpreting evidence [48]. A good research design is critical for correctly utilizing research methods, ensuring the consistency of the research methods and goals, and drawing valid and trustworthy conclusions. This thesis is a compilation of four appended papers. Each paper contains a description of its research design. In this chapter, we provide a research design on a high level that motivates and describes the overall strategy utilized to carry out the research in this thesis.

2.1 Information systems design

This study aims to apply an IVHM scheme to automate the decision-making process of driverless vehicles in an alarm situation. A context-specific IVHM system is designed with a design research methodology to reach this goal.

There are various studies on design research methodology in the engineering field [49]–[51]. For example, in [51], a framework for conducting engineering design research was proposed, suggesting an iteration process of descriptive and prescriptive studies. These research methodologies and frameworks have provided a rich source of inspiration for the research in this thesis. Nevertheless, they lack a specific application context, consequently being too broad and conceptual to support structuring the research design of this thesis.

In this study, since the core of an IVHM system is an integrated utilization of various information resources, an information system design methodology is taken. An information system is defined as 'interrelated components working together to collect, process, store, and disseminate information to support decision-making, coordination, control, analysis, and visualization' [52]. An influential study performed in 2004 characterized information systems research with two paradigms, i.e., the behavioral science paradigm and the design science paradigm [53]. The former is about 'truth-revealing’ and seeks to develop and verify theories that explain or predict human or organizational behavior. The latter is about 'problem-solving’ and seeks to extend the boundaries of human and organizational capabilities by creating new and innovative artifacts. Complementary research cycles between these two paradigms are engaged to address fundamental problems in information systems research.
CHAPTER 2. RESEARCH DESIGN

The study in this thesis is mainly about problem-solving, thus taking on the design-science paradigm. The design science paradigm of an information systems research framework proposed in [53] is shown in Figure 2.1. The red arrows and texts refine the framework based on my understanding during the study. Below is an explanation of this framework and the correspondence between this framework and the research in this thesis.

Figure 2.1: An information systems research framework, adapted from [53].

The design-science paradigm of information systems research includes two design processes, **building IT artifacts** and **evaluation**. IT here refers to information technology. The IT artifacts can be constructs (vocabulary and symbols), models, methods, and instantiations. The designed artifacts are evaluated with respect to their utility in problem-solving by analytical means, case studies, experiments, etc. The evaluation, in return, contributes to refining the designed artifacts. The design research contributions can be applied to the environment or added to the knowledge base for further research and practice.

For **research relevance**, the design should satisfy the business needs, which are derived from the environment. The environment is composed of people, organizations, and technology and can be further instantiated, as shown in the figure. Here the term ‘societal needs’ is added to this framework as another type of need. Due to the complex relationship between business and society, it is intractable to strictly distinguish between business and societal needs. Business needs are more toward increasing corporate or individual profits, while societal needs emphasize the public’s well-being, especially the sustainable development of society. Business needs are intuitively crucial for the studied problem, such as saving time and
2.1. INFORMATION SYSTEMS DESIGN

energy and increasing mission profit, while societal needs are less concerned in the current practice. Nonetheless, the fundamental problem of a driverless vehicle in an alarm situation on public roads also threatens society regarding safety, traffic, and so on. Therefore, the potential to consider societal needs during the design process is an essential part of research and an important idea to convey in this study.

The rigor of the design is achieved by applying knowledge composed of existing foundations and methodologies, which are explicit and well-established. Here, an added arrow connects the environment to the knowledge base with tacit knowledge. Explicit and tacit knowledge are two distinctive types of knowledge that comprise a knowledge base. Explicit knowledge can be easily formulated with symbols, digitized, transferred, and utilized. Tacit knowledge, on the other hand, is highly subjective insights and intuitions learned and gained through practice, which is challenging to capture, express, and share with words [54], [55]. The problem this thesis tackles, vehicles’ decision-making in an alarm situation, is currently handled by humans. In the human decision-making process, tacit knowledge is gained through field practice and experience sharing, which is valuable but need to be investigated more. During my Ph.D. study, research was performed on investigating the current industry practice of the concerned problem, not only for identifying needs but also for gaining tacit knowledge. This study was presented as part of [Paper D]. The knowledge gained in this process is part of our knowledge base and is further utilized in the design process. Therefore, we highlight it as a tacit knowledge-gaining process from the environment to the knowledge base in this framework.

The contents of each part of the framework corresponding to the design in this thesis are specified in Figure 2.2. Note that in the 'build' block, the listed IT artifacts are the major designed IT artifacts, while other accessory designs are not listed for the conciseness of the figure. For example, in Paper D, the decision support system design includes the system architecture design, graphical user interfaces, etc. The contributions of the appended papers to the design science are marked with red circles and their appended alphabets. These contents are further used in the next section for presenting the application of design science in this thesis.
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Figure 2.2: Design science of this thesis within an information system research framework adapted from [53]

2.2 Application of Design Science in this thesis

The previous section introduces the design-science paradigm of an information systems research framework. Based on this framework, seven design-science research guidelines were proposed in [53], including design as an artifact, problem relevance, design evaluation, research contributions, research rigor, design as a search process, and communication of research. In this section, the application of these guidelines in the studies of this thesis is presented.

2.2.1 Design as an artifact

In this thesis, an IVHM scheme is applied to automate the decision-making process of driverless vehicles in an alarm situation. This automated solution is mainly enabled by the following methods:

- fault detection and diagnosis to obtain the health state information of vehicles in an uncertain driving environment (Paper A);
- maintenance planning to minimize the economic risk of the truck companies considering availability loss and maintenance cost (Paper B);
- multi-criteria decision-making to achieve a trade-off between the risk of mission delay and the risk of public time loss (Paper C);
2.2. APPLICATION OF DESIGN SCIENCE IN THIS THESIS

- decision support to enable remote control of driverless vehicles in an alarm situation (Paper D).

Various models and system designs are built to implement these methods, which are the design artifacts of this study.

2.2.2 Problem relevance

The amount of interest and needs in the industry ensures the relevance of the research in this thesis. Autonomous driving is disrupting the automotive industry, with lots of ongoing commercial tests, especially in the truck industry [56], [57]. Despite the benefits of autonomous driving, problems arise from removing the functionalities of human drivers, especially in decision-making. Decision-making in an alarm situation is a nontrivial task for autonomous vehicles to ensure safety and efficiency. Therefore, the overall research background of this thesis has a solid industry interest and needs.

To ensure the relevance of the specific research questions, a gap analysis was conducted regarding the decision-making process between the current practices and a potential futuristic solution for highly automated trucks. Gap analysis is a technique used to define the difference between the current state and the proposed state of any business and its functionalities [58]. The current state of industry practice was obtained through field studies, including field trips, interviews, and workshops supported by Scania AB, a major Swedish manufacturer focusing on commercial vehicles. These field studies were conducted from 2019 to 2021 to gather information on the fault handling process of a vehicle, with details provided in [24]. The proposed future states were derived from technological development and general principles to make decision-making more reliable, sustainable, and intelligent. The current states, desired future states, and the gap analysis results were presented in Paper D. The problems investigated in this thesis are derived from the identified research gaps, ensuring the relevance of the research questions.

2.2.3 Design evaluation

Evaluation regarding the utility, quality, and efficiency of a design artifact with well-executed evaluation methods is an important part of the design process. This thesis mainly involves two types of design artifacts, i.e., models and systems. Their evaluation is presented below in two aspects, evaluation criteria and evaluation methods.

Evaluation criteria

In Paper A, a fault diagnosis model is built to cope with environmental uncertainty by combining the sensing information with prior knowledge and environmental
information. The evaluation criterion of the design is the performance of the model in improving fault diagnosis accuracy, which is a well-adopted criterion in the fault diagnosis domain and well reflects the aim of the design. The model is compared to a baseline model that only considers the sensing information of components.

In Paper B, a maintenance planning model is built to minimize the economic risk of vehicle breakdown. The evaluation criteria of the design are the performance of the model in reducing economic risk, which is very straightforward. In the current practice, human drivers are mainly responsible for making decisions. Based on field studies, the attitudes of drivers toward risks play a vital role in the decision-making process. Therefore, the model is compared to two baseline models representing two types of human decision-makers, i.e., risk seeking and risk aversion.

In Paper C, a multi-criteria decision-making model is built to make a trade-off between the risk of mission delay and the risk of public time loss caused by traffic congestion. Reducing traffic congestion is not considered in the current human decision-making process. Therefore, the evaluation criterion is the reduction of the risk of public time loss with a limited increase in the risk of mission delay. The model is compared to a baseline model that represents the current practice of minimizing the risk of private companies.

In Paper D, a decision support system is designed to provide decision information and recommendations to enable remote decision-making and control of autonomous vehicles by humans. The evaluation criterion of the design is the feasibility of the system in solving the identified gaps of adopting such a system in practice. These gaps are identified based on field studies.

Evaluation method

Case study

All the studies in this thesis are based on particular industry contexts and solve contemporary problems within these contexts. Therefore, the case study is used as a fundamental method in the evaluation process to build the use case scenarios. A case study is an empirical inquiry that investigates one or a few instances of a contemporary phenomenon within its real-life context [48], [59]. The cases in this thesis include a fault diagnosis case of a highly automated vehicle in a driving scenario (Paper A) and three automated decision-making cases of driverless trucks in long-distance freight delivery scenarios (Paper B, C, and D).

Several data collection methods are deployed in the case studies to gather information, build scenarios, and configure the models. The collected data include simulation, open-source, and expert data. In Paper A, the data used for fault detection and diagnosis are generated by simulation, specifically by fault injection of a Simulink model of an accelerator in Matlab. In papers B, C, and D, open source data are used, including Swedish traffic data [60] and speed limit data [61]. Data
2.2. APPLICATION OF DESIGN SCIENCE IN THIS THESIS

from experts are also used, such as the maintenance time and cost. Since these data depend on the specific case and may vary in a large range, data recommended by experts provide a valid reference value for the case study.

**Numerical simulation**

Numerical simulation is used instead of field experiments to evaluate the fault diagnosis model and the decision-making models. In field experiments, it is hard to control environment variables to obtain the data that characterize certain types of uncertainty. However, in simulation experiments, control and interventions are done on pre-built models rather than entities in the real world, thus providing an efficient solution for evaluation. Another consideration of using numerical simulation is that due to the forward-looking nature of this study, it is difficult to build real-world freight-delivery experiments with driverless trucks in alarm situations.

In paper A, a Simulink model of an accelerometer was built to model the physical properties of a real accelerometer. Simulation experiments of fault injection were performed on this model to obtain sensor data, which were further used as inputs to the fault diagnosis model. In papers B and C, the decision-making models are hard to be solved analytically since they contain many variables and complex operations like integrals. Therefore, numerical experiments were used to approximate the outputs of the models to evaluate their performance.

**Informed Argument**

Informed Argument is a descriptive evaluation method that uses information from the knowledge base to build a convincing argument for the artifact’s utility. In paper D, a decision support system is designed, including a system infrastructure, system information flows and contents, and three user interfaces. To evaluate the feasibility of the design, information from the knowledge base is used, which is the tacit knowledge obtained from the field studies about the users’ requirements and expectations of such a system.

**Scenarios development**

Scenario development is another descriptive method that constructs detailed scenarios around the artifact to demonstrate its utility. In paper D, a use case scenario is developed containing several system actors and action steps to accomplish a specific task, which serves as an evaluation of the feasibility of the system design.

2.2.4 Research contribution

The research contributions of this thesis to the design-science paradigm of information systems research mainly include two aspects:

- The design artifacts, including the models and the decision support system. These artifacts solve various problems caused by vehicle automation. They
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apply existing knowledge in new and innovative ways, thus extending the current knowledge base.

• Methodology. In Paper C, a new evaluation metric was proposed: the decrease of the risk of public time loss with a limited increase in the risk of mission delay. This evaluation metric provides a quantitative measure of the performance of the decision-making model, which represents a private-public partnership mechanism. Paper D presents a gap analysis of the industry practice and the desired future based on the field studies. Although this research contribution is not a design itself, it supplements the knowledge base and provides metrics by which a designed information system can be evaluated. These aspects provide design-science research contribution according to the guidelines.

2.2.5 Research rigor

Design-science research relies on the application of rigorous methods in both the construction and evaluation of the design artifact.

Research rigor in constructing design artifacts

In constructing IT artifacts, research rigor is ensured by the effective use of the knowledge base, including theoretical foundations and research methodologies. A rich knowledge base has been used for the research in this thesis. The studies in papers A, B, and C are mostly about building mathematical models, including a fault diagnosis model, a risk evaluation model, a public time loss model, and two decision-making models. For this purpose, well-established mathematical foundations, including theories and methods, are selected and utilized since they can be easily understood, approved by other researchers, and supported by existing tools. These mathematical foundations include probability theory, decision theory, optimization theory, Bayesian inference model, risk quantification model, macroscopic traffic model, etc. These rigorous mathematical techniques have had a long history of being applied to solve problems in fault detection and diagnosis, maintenance planning, and decision-making.

Besides mathematical foundations, foundations and methodologies for system design are also essential for the research rigor of this thesis, especially for Paper D. Well-known and influential frameworks and models in relevant research communities are preferred for better understanding and approval. In Paper D, well-known frameworks and methodologies are adopted, including the IVHM framework, rational decision-making framework, decision support system framework, software system development model, etc.

Another aspect of research rigor in constructing IT artifacts is the clarification and justification of the external validity of the design artifacts. External validity refers to the extent to which the results of a study can be generalized and applied to
the real world. In Chapter 4, the contents of each appended paper are summarized, where a discussion of the external validity of the design is provided.

**Research rigor in evaluating design artifacts**

Research rigor in evaluation is ensured by constructing effective evaluation metrics and selecting appropriate evaluation methods. The evaluation criteria and methods are presented in Subsection 2.2.3 above. The selected evaluation metrics directly reflect the research problems and contributions, including the increase in fault diagnosis accuracy, the reduction of economic risk, and the reduction of the risk of public time loss. The evaluation methods of models, including case studies and numerical simulation, are well-known and adopted methods in the relevant domain. Evaluation methods, including informed argument and scenario development, build a convincing argument for the system design’s utility. They serve the validation purpose well, especially when more rigorous methods such as building prototypes and user tests are not allowed due to limited resources.

Evaluating design artifacts regarding **internal validity** also contributes to the research rigor. **Internal validity** refers to the degree to which the results are attributable to the independent variable and not some other rival explanation. In Paper C and Paper D, the maintenance planning and decision-making models are internally validated by **sensitivity analysis**, which quantifies how the uncertainty in the outputs of a model is related to the uncertainty in its inputs. The sensitivity analyses were implemented by varying important model inputs and parameters and analyzing the correlation between these variations and their effects on the model outputs.

### 2.2.6 Design as a search process

The design in this thesis is essentially an iterative search process. Analyses of the current industry practice based on field studies were conducted in the first place, which provided a rich library of domain knowledge and a foundation of research gaps. On this basis, in Paper B, an initial step was taken to design a short-term maintenance planning model, which replicated a rational human decision-making process. Afterward, by building use cases and evaluating the current model, limitations of the design were identified, and the idea of extending the research to a larger road network emerged. New concerns and decision criteria were considered important by revisiting the identified research gaps and performing an impact analysis of vehicle breakdown activity. These ideas led to the research in Paper C. By further searching for opinions on the applicability of the models, the idea of developing a decision-support system that is transparent, adjustable, and interactive was proposed and studied in Paper D. To conclude, the design in this thesis presents a search and iteration process that continuously finds problems, addresses problems, evaluates methods, and improves the established methods.
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2.2.7 Communication of research

It is necessary to effectively present and communicate research works to both technology and management-oriented audiences. The research work done in this thesis has been demonstrated in various circumstances to various audiences, including

• Presentations towards industry partners, including technical experts and managers from Bosch Germany, Scania AB, etc.

• Presentations and discussions with researchers in the relevant field in meetings, seminars, and conferences.

• Papers submitted to international conferences and journals.
Chapter 3

Literature review

In this chapter, the state of the art in the relevant research domains is provided, followed by the mathematical preliminaries that build the theoretical foundation of this study.

3.1 State of the art

This thesis addresses the challenge of automated decision-making for driverless vehicles through cross-disciplinary research across several domains, including fault diagnosis, fault prognosis, maintenance planning, logistics planning, and traffic congestion management. Except for traffic congestion management, all these research domains are currently part of or closely connected to the concept of an IVHM system. As a main technological scheme applied in this thesis, IVHM has been introduced in the first chapter, including its relevant standards, concepts, and frameworks. The core ideas of IVHM lie in integrating health state estimation and prediction, resource utilization, and self-adaptive management of vehicle assets or fleets. Fault diagnosis and prognosis are the main techniques to obtain vehicle health states. Maintenance planning and logistics planning are the major decision-making tasks to improve resource utilization and realize self-adaptive management. This chapter provides a comprehensive overview of the state of the art of these domains. Some of the references and materials from the literature review sections of the appended papers are reused.

3.1.1 Fault diagnosis and prognosis

In reliability and safety engineering, fault diagnosis and prognosis play critical roles in condition monitoring and health management of complex systems. Fault diagnosis is the process of identifying the root cause of faults, while fault prognosis predicts the evolution of the faults and estimates the remaining useful life of components or systems. They have been widely applied in the automotive industry for decades [62], [63]. Fault diagnosis and prognosis technologies can be broadly classified into three categories: model-based, data-driven, and hybrid approaches. Model-based approaches use mathematical models to represent the system’s behavior and analyze the data to identify faults through mapping rules such as Dependency Matrix [64]. Many conventional fault detection methods are based
on this type of model [65]–[67], which is effective when accurate fault models are developed. However, they require a thorough understanding of the monitored systems and are unsuitable for complex or nonlinear systems. In the recent year, due to the development of machine learning, big data, and cloud computing, data-driven approaches are gaining momentum by using machine learning techniques, such as decision trees, support vector machines, and convolutional neural networks [68]–[70]. Data-driven approaches do not require a priori knowledge of the system and can handle complex or nonlinear systems. However, they depend on the availability and accessibility of a large amount of training data, and their performance may degrade in the presence of noisy or incomplete data. Hybrid approaches combine the advantages of model-based and data-driven approaches to overcome their limitations, such as lack of data and missing data [71], [72].

With the rapid development of vehicle automation, vehicular systems are becoming increasingly complex with lots of sensors, hardware, and software, which makes the fault diagnosis and prognosis of vehicles more challenging. One of the critical challenges is dealing with the uncertainty associated with data, models, and vehicular systems. Particularly, fault diagnosis and prognosis models built from field data and empirical data may not perform well due to uncertainties arising from specific systems and complex operational environments. Research on uncertainty management in technical systems has been conducted in recent years, especially in safety-critical systems and cyber-physical systems, where the automotive system is a common application. Research in these domains has highlighted the need for comprehensive uncertainty treatment [73] and proposed various taxonomies, measurements, models, and analysis methods of uncertainty [74]–[77]. Despite these efforts, uncertainty modeling, quantification, and propagation in fault diagnosis and prognosis are still challenging due to complex operational environments and limited system knowledge, especially for highly automated driving systems.

To tackle this challenge, there are extensive and increasing research efforts into quantitative uncertainty management in fault diagnosis and prognosis. In [78], board-level fault diagnosis was conducted using Bayesian inference for pattern analysis and classification. In [79], Bayesian networks and causal modeling were used in decision-making under uncertainty. In these works, fault detection accuracy was improved by integrating information from off-line fault-insertion tests using Bayesian inference, but uncertainties from the dynamically changing environment are not considered. The Hidden Markov Model (HMM), with good performance in time-varying dynamic systems, also gains increasing attention. In [80], an HMM-based algorithm was developed for online fault detection with partial and imperfect tests. These test uncertainties are handled to find the best inference of fault conditions and to identify the dynamic changes in fault conditions. A simulation-based approach was introduced in [81], using Discrete Time Markov Chains and a probabilistic model accommodating a diverse set of param-
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Parameter range distributions for software architecture evaluation. These methods based on Markov Chains had a common assumption that the evolution of system failure modes could be approximated by a parametric random process with Gaussian distribution. Multi-sensor fusion method based on deep learning algorithms, such as artificial neural networks and convolutional neural networks, is another technique that has caught a broad research interest [12], [82], [83]. This type of method has excellent learning ability and nonlinear mapping capabilities, thus building a unique advantage in identifying the uncertainty of the operating state of the researched system and significantly improving the accuracy of fault identification [82]. Such a data-driven approach requires large amounts of data to train the model and can be computationally intensive. Based on the literature review, it is a common practice to take one kind of uncertainty as an example to illustrate the application of various methods. Although uncertainties are widely considered, systematic analysis and reasoning of uncertainties in a quantitative way in the fault diagnosis and prognosis process are still lacking.

3.1.2 Maintenance planning

Maintenance planning is an established research area with a lot of engineering applications, especially in complex industrial systems like infrastructure [84], manufacturing [85], transport [86], [87], and electricity [88]. The maintenance plan is considered one of the primary outcomes of a decision-making module of a prognosis and health management system [89], [90]. The decision-making in an IVHM system may refer to decisions on mission plans, maintenance plans, resource allocation, and route plans. However, the maintenance need caused by a change in the vehicle’s health state is the fundamental problem that brings about other operational decision-making and planning problems. It was highlighted in [33], [91] that it is important to utilize the capabilities of IVHM to enable effective and efficient maintenance and operation of the vehicle.

As the automotive industry evolves, the challenges and opportunities of vehicle maintenance are gaining increasing attention in research communities, especially with the development of AV technologies. A recent literature review of maintenance approaches revealed the need for detailed quantitative analyses to properly choose the maintenance strategy [92]. Analyses in [93] showed that scientific research that deals with heavy vehicle maintenance, especially modern truck maintenance guidelines, is lacking. In [86], the necessity to study the use of emerging technologies in vehicle maintenance was identified, especially data processing and communications technologies. According to [94], the effects of full automation on maintenance and repair are poorly understood. With these research demands and challenges identified, effective solutions and maintenance strategies utilizing new technologies are still in high demand.

There are several typical types of maintenance planning strategies, includ-
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ing corrective, preventive, condition-based, predictive, and proactive maintenance [86], [92], [95]. Corrective maintenance is performed after a failure, which may cause a high cost for critical and complex components and systems. Preventive maintenance is a scheduled maintenance approach where maintenance tasks are performed regularly, regardless of whether the equipment or system shows signs of wear or failure. This approach lacks the flexibility to adapt to the actual condition of the components. Condition-based maintenance involves monitoring the condition of the equipment or system through sensors or other methods and performing maintenance tasks when the equipment or system shows signs of wear or impending failure [96]. In this approach, maintenance is performed based on the current condition of the equipment or system. This can make it more challenging to plan maintenance activities and ensure that maintenance tasks are completed on time. Predictive maintenance takes condition-based maintenance further by using advanced analytical and machine-learning algorithms to predict when maintenance is needed. This approach uses historical data and real-time sensor data to detect patterns that can indicate when equipment or systems are likely to fail, allowing maintenance to be performed just in time, reducing downtime, and improving reliability. Proactive maintenance brings predictive maintenance to the next level by incorporating the principles of continuous improvements method, such as adjusting equipment settings or operating procedures and updating predictive analytical models [97]. These four maintenance planning strategies correspond to a gradual transition from reactive to proactive ones. In recent years, benefiting from the development of sensing and prognosis technologies, maintenance strategies are transitioning from reactive to proactive ones and becoming more adaptive and intelligent [98]. As a typical and fast-developing proactive strategy, predictive maintenance takes advantage of real-time condition monitoring and prognosis of equipment and provides more accurate maintenance plans [99] [100]. Predictive maintenance has received wide attention and is becoming the common practice for critical and costly components in the vehicle industry [11]. As a key enabler of predictive maintenance, prognosis technology can predict the development of the fault and estimate the remaining useful life of the equipment [11] [101]. It is becoming increasingly advanced with the support of various data-driven methods, especially machine learning methods [98].

Research on the maintenance planning of vehicles has been conducted with different problem formulations and solved by various methods. In [96], an optimization of grouping maintenance operations for a heavy commercial vehicle was addressed to reduce the global maintenance cost of the system. In [102], a vehicle fleet maintenance scheduling optimization problem was solved by a multi-objective evolutionary algorithm. [103] used constraint programming for flexible maintenance planning and route optimization for fleet utilization optimization for heavy trucks. In [104], a multi-objective optimization problem was formulated for maintenance planning based on unavailability and cost criteria. An intelli-
gent decision-making method, particle swarm optimization, was utilized in [105] to solve the high-level maintenance planning problem of the electric multiple-unit train. Deep reinforcement learning is used in [106] for condition-based maintenance planning of multi-component systems. Among various methods, risk-based maintenance methodology provides a tool for maintenance planning and decision-making to reduce the probability of failure of equipment and the consequences of failure [84], [107], [108]. Despite these efforts, these studies mostly considered known vehicle health states and focused on the global maintenance performance of vehicle fleets. In other words, unexpected faults and the risk of vehicle breakdown during a transport mission are rarely considered. Accordingly, the mobility and the vehicle routing problem of vehicles at risk of breakdowns in a road network are not considered, which limits the applicability of predictive maintenance for long-freight delivery vehicles with high availability requirements.

Maintenance planning can be classified into long-term and short-term, depending on the time span. Long-term planning is commonly considered, especially the life cycle of the system [84], [109], [110]. There were also researches on short-term maintenance planning [107], [108], which were less up-to-date and have attracted much less attention than long-term ones. However, in the context of maintenance planning for autonomous vehicles, the need for short-term maintenance may increase due to more intensive and non-stop driving. Short time horizons, such as hourly or daily maintenance schedules, require new maintenance planning strategies that can effectively detect and predict faults in real-time.

3.1.3 Logistics planning

For commercial vehicles in a freight transportation context, logistics planning is closely related to IVHM as it involves the efficient planning and execution of vehicle routing and scheduling. IVHM systems are designed to optimize vehicle performance and reduce maintenance costs. Incorporating logistics planning into maintenance planning can help optimize vehicle routing and scheduling, reduce downtime, and improve efficiency. The IVHM system can anticipate breakdowns and plan maintenance tasks in advance by considering logistics planning in maintenance planning. However, according to the literature review, logistics planning and maintenance planning usually take each other as preconditions instead of being considered holistically.

In logistics engineering, vehicle breakdown is considered one of the four main types of disruptions and is considered in disrupted vehicle routing problems (DVRP). DVRP is a problem considered in logistics planning that involves the optimization of vehicle routing and scheduling in the event of a breakdown. In the scope of this thesis, DVRP is very relevant since the thesis considers vehicle breakdowns and replanning of delivery missions and maintenance. The review in [111] showed that DVRP for road freight transport had been a widely studied area for years.
Various types of breakdown disruption are considered in DVRP, including determined, dynamic, and random breakdowns. In [112], a location-routing problem in a supply-chain network was considered where the vehicles involved in the distribution system were disrupted randomly. In [113], a multilayered agent-based heuristic system was developed for vehicle routing problems under random vehicle breakdown. While DVRP is a useful tool for planning vehicle routing and scheduling in the event of a breakdown, it has limitations in considering the situation where a vehicle is at risk of a breakdown. DVRP assumes the breakdown has already occurred and focuses on optimizing the remaining route. However, this approach does not consider the situation where a vehicle is at risk of a breakdown. Incorporating risk factors into DVRP can help the IVHM system anticipate breakdowns and plan for maintenance tasks in advance, leading to improved efficiency and reduced downtime.

Furthermore, in DVRP, a spare vehicle is usually used to take over the delivery mission of the broken down vehicle, while vehicle maintenance before delivery is not considered [111]. In [114], although maintenance was considered in a DVRP, it focused on rescheduling the supply plan in case of planned preventive maintenance instead of maintenance itself. However, at risk of breakdown, getting maintenance and delivering afterward is a strategy used in practice [24]. In the end, most of the targets of planning and decision-making in DVRP are related to the private sector’s profit, while the impact of vehicle disruption on the public has not been considered [111].

To conclude, logistics planning is a relevant factor in the operational decision-making of vehicles. However, it is often not considered in maintenance planning, despite its potential to optimize vehicle routing and scheduling. In the scope of this thesis, DVRP is a relevant tool for optimizing vehicle routing and scheduling in the event of a breakdown, which, however, is limited in considering alarm situations, flexible maintenance plans, and the impact on road traffic.

3.1.4 Traffic congestion management

Traffic congestion management is essential to transportation planning to improve traffic flow and reduce delays. In traffic congestion management, vehicle breakdowns and slow vehicles are typical road incidents that may significantly impact traffic flow, leading to increased congestion and delays. Therefore, this research domain has a natural connection to the research of this thesis. There are extensive and profound studies on how traffic bottlenecks are formed [115] and on how traffic congestion can be estimated [116] and relieved [117]. The time-space diagram is at the core of many traffic flow theory innovations. It is a comprehensive diagram containing all the information required to estimate the microscopic and macroscopic characteristics of the traffic stream [118]. However, according to [119], many previous studies have not differentiated the road incident types, and
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studies that focus on the specific type of vehicle breakdown are rare.

Despite this, the risk of the breakdown of a single vehicle is usually not considered in the traffic congestion management domain. As a result, the impact of these incidents on traffic flow is often underestimated, leading to increased congestion and delays. Furthermore, according to our literature review, there have not been studies on how a single vehicle at risk of breakdown impact traffic flows or how to evaluate this impact. Meanwhile, the impact on traffic flow is usually not considered in maintenance planning and logistics planning. This mutual ignorance between traffic congestion management, maintenance planning, and logistics domains can lead to inefficiencies and delays in the transportation system.

3.1.5 Summary of gaps based on the state of the art

Based on the analysis of the relevant literature and state-of-the-art presented above, the research gaps between the relevant research domains are summarized below.

- In the fault diagnosis and prognosis domain, quantitative uncertainty management to handle complex automated driving systems and driving environments is still lacking.

- In IVHM, the integration of real-time and uncertain fault diagnosis and prognosis information into operational decision-making is still lacking.

- Maintenance planning of vehicles is usually considered for a longer time span, and maintenance during a transport mission is usually not considered.

- In logistics planning, especially in disrupted vehicle routing problems, maintenance is usually planned forehand. On the other hand, unexpected and uncertain vehicle breakdown disruption and maintenance during a mission are usually not part of the consideration.

- In maintenance planning and logistics planning, the primary concern is the profit of the private company, and the impact on the public regarding traffic congestion is usually not considered.

- In traffic congestion management, although traffic congestion caused by road incidents is a widely considered concern, the risk of traffic congestion brought about by a vehicle at the risk of breakdown is not considered.

- There is a mutual lack of consideration between the maintenance planning, logistics planning, and traffic congestion management domains, although they are interconnected.

These research gaps motivate a holistic IVHM implementation with effective information utilization and integrated decision-making and planning, which makes up this thesis as a whole.
CHAPTER 3. LITERATURE REVIEW

3.2 Preliminaries

This thesis is a comprehensive research work comprising technical and non-technical components. The technical aspects of the thesis involve developing and implementing mathematical models and algorithms, while the non-technical components primarily focus on system analysis and design. The technical parts of the research are founded on fundamental mathematical tools that are widely recognized within the relevant domain. Below, the preliminaries of two major mathematical tools and their relevance to the thesis are introduced, providing a foundation for the technical aspects of the study.

3.2.1 Bayesian Inference

Bayesian Inference is a method of statistical inference in which Bayes’ theorem is used to update the probability of a hypothesis as more evidence or information becomes available. Bayes’ theorem, also known as Bayes’ rule, is named after English statistician Thomas Bayes, who discovered the formula in 1763. More knowledge on Bayes’ theorem can be found in [120], [121]. Bayes’ theorem is expressed as:

\[
P(H|E) = P(E|H) \cdot P(H)/P(E),
\]

where in general, \(H\) and \(E\) refer to two events. In the context of Bayesian inference, \(H\) refers to a hypothesis that can be true or false. \(E\) refers to the evidence which can be observed and can be present or absent. The probability that \(H\) is true depends on the observation of \(E\). Often, there are multiple competing hypotheses, and Bayesian inference aims to determine which hypothesis is the most probable.

Other important concepts in Bayes’ theorem include

- \(P(H|E)\) is the posterior probability of hypothesis \(H\) given evidence \(E\) is present. This is the probability to be computed to decide which hypothesis is most probable.

- \(P(E|H)\) is the likelihood, the probability of observing \(E\) given hypothesis \(H\) is true. It indicates the compatibility of the evidence with the given hypothesis.

- \(P(H)\) is the prior probability of \(H\) without considering any observation information of \(E\).

- \(P(E)\) is the prior probability of observation of \(E\) without considering any hypothesis. \(P(E)\) is also referred to as the marginal probability. Given that there are in total \(I\) mutually exclusive and collectively exhaustive hypotheses in the hypothesis space \(H\), \(P(E)\) can be expressed by the law of total probability as:
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\[ P(E) = \sum_{i \in I} P(E \cap H_i) = \sum_i P(E|H_i) \cdot P(H_i). \] (3.2)

Bayesian inference allows one to make probabilistic predictions about the system’s health state by considering all available data and prior knowledge and updating them as new information becomes available, making it a powerful tool for fault diagnosis and prognosis. In this context, \( H \) refers to hypotheses of root causes of fault symptoms, while \( E \) refers to the observations of fault symptoms. A probability distribution for the system’s health state \( P(H) \) can be established based on the prior knowledge of the monitored system, including both its normal operating conditions and faulty conditions. As new sensor data is collected and fault symptoms are observed, the posterior probability \( P(H|E) \) is updated. Any significant changes in the distribution can indicate a potential fault. There are considerate studies that use Bayesian inference in fault detection and diagnosis [122]–[124]. It is also a mathematical tool used in this thesis to deal with uncertainties in the fault diagnosis process.

3.2.2 Probabilistic risk assessment

Probabilistic Risk Assessment (PRA) is a systematic approach to evaluating the risks associated with complex technological systems. PRA combines probability theory and engineering analysis to assess the likelihood and consequences of potential accidents or failures.

The expected value equation is a fundamental tool in PRA that helps quantify the likelihood and consequences of potential accidents or failures. The equation is expressed as

\[ R = \int \int \int c(x_1, x_2, \ldots, x_m) f_X(x_1, x_2, \ldots, x_m) \cdot dx_1 \cdot dx_2 \ldots dx_m, \] (3.3)

where:
- \( R \) represents the expected value of the risk associated with a particular event or outcome.
- \( c(x_1, x_2, \ldots, x_m) \) is a function that quantifies the consequences of the event or outcome, taking into account various factors such as property damage, human injury, and environmental impact.
- \( f_X(x_1, x_2, \ldots, x_m) \) is the joint probability density function of the uncertain variables that contribute to the risk, such as the failure rates of components in a system.

The expected value equation integrates the consequences of potential accidents or failures over all possible outcomes, weighted by their probability of occurrence. This quantitatively measures the overall risk associated with a particular event or outcome.

When dealing with discrete events and probabilities, the integral can be replaced by a sum over all possible values of the random variables. In this case, the
total risk is expressed as

\[ R = \sum \sum \sum c(x_1, x_2, ..., x_m)P(x_1, x_2, ..., x_m), \quad (3.4) \]

where:

- \( c(x_1, x_2, ..., x_m) \) is the consequence or cost associated with a particular combination of events \( x_1, x_2, ..., x_m \).
- \( P(x_1, x_2, ..., x_m) \) is the joint probability of events \( x_1, x_2, ..., x_m \) occurring simultaneously.

PRA is widely used in nuclear power, aerospace, chemical, and transportation industries to inform decision-making, improve safety, and minimize risks. More theories and applications about PRA can be found in [125]–[127]. This probabilistic risk quantification is a complex process that requires a detailed understanding of the system being analyzed and the potential failure modes, their likelihood, and potential consequences. Therefore, it is usually used with other risk assessment and management methods, such as safety and hazard analyses, to make more informed decisions.

In the context of this thesis, an alarmed vehicle on the road intuitively puts various stakeholders in a risky situation, such as the logistics company at risk of mission failure and the traffic flow at the traffic of congestion. Therefore, PRA is used as a fundamental tool to quantify various risks for further decision-making.
Chapter 4

Summary of appended papers

In this chapter, a brief reading guide is provided by first introducing how the contents of the appended papers are reflected in an IVHM scheme. Then a reading order of the papers is suggested for better reading consistency. Afterward, each paper’s research topics, contributions, evaluation, and delimitation are presented.

4.1 Reading guide

As introduced in Chapter 1, this thesis studies how to apply an IVHM scheme to automate the decision-making process of driverless vehicles in an alarm situation that a human driver currently handles. Therefore, all four appended papers are related to an IVHM system design and focus on different aspects. The relation between the appended papers, an IVHM system framework, and the application environments is illustrated in Figure 4.1.

![Figure 4.1: The relation between the appended papers, an IVHM system framework, and the application environments.](image)

As shown in the figure, the industry application contexts of this study comprise four major parts, including the IVHM system, the complex vehicle system,
CHAPTER 4. SUMMARY OF APPENDED PAPERS

the driving environment, and the business environment. Among them, the IVHM system can be regarded as part of the functionality of a complex vehicle system. The driving environment is a physical environment characterized by various factors, such as road conditions, weather, and traffic condition. On the other hand, the business environment is a conceptual environment comprised of people, organizations, and business content. The IVHM system interacts with the other three parts by taking information from them and, in return, affecting them by providing advice on changing mission plans, maintenance plans, resource allocation, etc.

Among the four appended papers, Paper A investigates fault detection and diagnosis under uncertainty, providing essential decision-making information. Paper B and Paper C have the same research focus on developing decision-making models, while Paper D focuses on designing a decision support system design. Papers A, B, and C all present complete research works and do not depend on other appended papers. However, the background and motivation of the studies of these three papers can be more thoroughly retrieved in Paper D. In terms of Paper D, in the case study, the graphical user interface design takes the results of the numerical study of Paper C.

Based on the above considerations and a comprehensive understanding of this thesis, a reading order of the appended papers is suggested below.

• Paper D. The first half of this paper presents the current industry practice of the addressed problem and a gap analysis between the industry practices and a potential futuristic solution. By reading this part of the paper, the readers can get an overview of the industry practice and the challenges, which are the foundation of the other appended papers and the latter half of paper D.

• Paper A. In an IVHM system, Paper A focuses on the condition monitoring and diagnosis modules, which provide information for decision-making. This paper helps the readers to understand the challenges and importance of obtaining this information for decision-making.

• Paper B and Paper C. These two papers both focus on the decision-making part of an IVHM system. Although they target addressing similar research problems, Paper B provides a preliminary solution replicating how a rational manual solution currently works. On the other hand, Paper C considers the societal needs on top of the current business needs and aims to provide a more sustainable solution. Therefore, we suggest reading Paper B and Paper C sequentially.

• Paper D. The latter half of this paper focuses on designing a decision support system as a software service. As shown in figure 4.1, it involves both automated decision-making and interaction with the business environment through graphical user interfaces. This paper helps readers to understand
4.2 Paper A

Paper A contributes to the thesis by addressing the first research question, "How to infer the fault condition of highly automated vehicles under uncertainty to enable more reliable decision-making?". In this paper, Cyber-physical systems (CPS) are set as the studied system, while highly automated vehicles are a representative system of CPS in the case study. CPS is an integration of computation and physical processes, a typical application of which is autonomous driving. Monitoring, anomaly detection, self-diagnostics, and comprehensive uncertainty treatments are critical functionalities for CPS operations. In this paper, two major contributions are made to address the research question, including

- performing a structured uncertainty analysis of a fault detection and diagnosis process;
- developing a fault diagnosis model based on Bayesian inference.

Uncertainty management, including its characterization and modeling, has been actively explored in research communities with various theory foundations such as probability, evidence theory, and possibility theory. However, uncertainty modeling, quantification, and propagation in CPS remain challenging due to the complexity of the system itself and the operational environment. The first contribution of paper A is performing a structured uncertainty analysis of a fault diagnosis process. By analyzing a typical feature-based fault diagnosis process, four types of uncertainties that may cause false fault diagnosis are identified: 1) the uncertainty of the operational environment, 2) the uncertainty of algorithm performance, 3) the uncertainty of causal relations between faults, and features, and 4) the uncertainty of the causal relation between environment uncertainties and features. The symbolic or mathematical characterizations of these uncertainties are also presented in the paper.

Based on the first contribution, the second contribution is developing a fault diagnosis model that provides probabilistic inference of fault conditions based on Bayesian inference. Bayesian inference uses Bayes’ theorem to update the probability of a hypothesis as more evidence or information becomes available. The preliminaries of Bayesian Inference are introduced in Section 3.2. Hypotheses in this paper are made that a fault-related feature can have one of the following four causes, including 1) system faults, 2) uncertainties, 3) both system faults and uncertainties, and 4) neither system faults nor uncertainties. The calculation of the posterior probability of a hypothesis involves prior probabilities, likelihoods, and marginal probability. In this paper, the prior probabilities are obtained in various
ways, including empirical knowledge, other monitoring services, and simulations. The likelihoods are obtained by simulations based on the law of large numbers. The marginal probability is obtained by using the law of total probability. By executing the proposed fault diagnosis algorithm in the runtime, the cause of the fault-related signal features can be inferred in the existence of uncertainties.

A case study is conducted to validate the proposed fault diagnosis model. In this case study, a use case scenario is built in which a vehicle equipped with an accelerometer is driving on a road with uncertain road conditions. The accelerometer is a micro-electro-mechanical system (MEMS) representing a CPS component. Simulink models of the accelerometer and the operational environment are built in Matlab. Faults and uncertainties are modeled, coded, and injected into the Simulink models for generating data, which are further collected and used for extracting relevant signal features, as presented in [128]. The root causes of the fault-related features can be inferred by running the proposed fault diagnosis algorithm.

The validation of the proposed method has three aspects:

- Validation of the assumption that uncertainties rather than system faults potentially cause the detected feature;

- Validation of the feasibility of the proposed uncertainty quantification and parameter acquisition methods;

- Validation of the performance of the fault diagnosis model.

The simulation results show that the proposed fault diagnosis model can effectively distinguish system faults and uncertainties arising from environmental disturbances. As a result, the fault diagnosis accuracy increases significantly from 64% to 83% in one of the specific cases.

The generalization, in other words, the external validity, of the proposed method in this paper can be limited due to the following aspects:

- Firstly, in developing the fault diagnosis model, the assumption is made that the system faults and uncertainties are independent.

- In the uncertainty analysis process, four types of uncertainties are analyzed. However, in the case study, only the first type of uncertainty, environmental uncertainty, is studied.

- Thirdly, in the case study, the validation process only involves an accelerometer Simulink model, one system fault, and one feature, which might be too simple to represent a typical fault diagnosis process.

The independence assumption of system faults and uncertainties might be invalid for certain uncertainties, such as the uncertainty of the causal relationship
between the system faults and the generation of the corresponding feature. However, this assumption is valid specifically for environmental uncertainty, which is considered in the case study. The second limitation exactly refers to considering only the environmental uncertainty in the case study. Despite these two limitations, the first contribution of uncertainty analysis is still valid and can be generalized to any fault detection and diagnosis process. The second contribution of developing a fault diagnosis model can be generally applied in cases where the system fault and the uncertainty are independent.

Regarding the third limitation, in the case study, the validation process involves multiple aspects, from problem formulation to parameter acquisition to model performance evaluation. Therefore, the case setup itself is relatively simple, and the validity of the performance of the proposed model in increasing fault diagnosis accuracy is limited. However, the proposed model generally applies to more complex systems, including multiple system faults, uncertainties, and signal features. In the future, the proposed model can be tested with more complex use cases to obtain a more valid result of the model performance.

4.3 Paper B

Paper B contributes to the thesis by addressing the second research question, ‘How to make a short-term maintenance decision that minimizes the economic risk for a driverless vehicle in an alarm situation?’ The alarm situation considered in this paper is defined with two fault properties. One is that the vehicle’s remaining time to functional failure is less than one mission or minor maintenance cycle. In this situation, a maintenance decision is the most significant decision to make. The maintenance may be conducted during the transport mission or afterward within a minor maintenance cycle. The other property is that there will be economic, operational, or safety impacts if a failure happens. According to the field study analysis presented in Paper D, in the current practice, the economic risk of failure is the most concerning impact for non-safety-critical faults.

Paper B focuses on proposing a preliminary solution that replicates and automates the current practice. The current practice is reflected in two aspects: 1) the decision is about whether to drive to a workshop immediately or not; 2) the goal is to minimize economic risk. For the relevance of the problem, the business context is set as a driverless truck on a long-distance freight transport mission, which is discussed in Section 1.3. This paper addresses the proposed problem with the following contributions:

- identifying the required information and information flow;
- developing a maintenance planning model;
- performing sensitivity analyses of model parameters.
CHAPTER 4. SUMMARY OF APPENDED PAPERS

In the current industry practice, this short-term maintenance planning task is performed by humans. In this process, information is obtained from different providers and utilized differently. Some information is documented offline, such as a business contract. Some can be obtained in real-time by computers or computerized devices, such as fault diagnosis information. However, some may be obtained by experience and exchanged verbally and are not officially documented, such as the workshop information and the confidence level of fault information. To automate this process, it is essential to identify the relevant information and how the information flows in this process, which is the first contribution of this paper. Four major types of information are identified based on an IVHM system design and an evaluation-based maintenance planning scheme, including fault information, workshop information, maintenance information, and delivery information. The provider of these types of information and their detailed contents are also described.

By utilizing the identified information and information flow, the second contribution is developing a maintenance planning model using a risk-based decision-making method. This model evaluates the economic risk of different maintenance decisions and identifies the decision with minimal risk. The risk evaluation model is based on probability theory and utility theory. Based on these theories, risk can be measured as the expected value of the loss, which combines the probabilities and consequences of the occurrence of hazardous events into a single value. The preliminaries of risk quantification are provided in Section 3.2. The economic risk is comprised of the economic utility of the risk of availability loss and the risk of maintenance costs. Availability loss is modeled as the mission delay caused by maintenance time and travel time, which is converted into economic loss by a utility function. The utility function is derived from the business contract on the penalty of mission delay. The maintenance cost is modeled as the sum of the maintenance cost in the workshop and the tow truck service fee. This model essentially replicates a rational evaluation-based human decision-making process.

The third contribution of this paper lies in performing sensitivity analyses of the proposed maintenance planning model. The investigated model variables include:

- the variance of the probability density function of remaining useful life;
- the maximal allowed time of delivery delay and the penalty of order cancellation of the economic utility function of availability loss;
- the number of workshops,

which represent different types of critical information identified in the first contribution. Among them, the variance of remaining useful life is a variable that reflects the estimation accuracy of the remaining operating time of the vehicle, which is a typical type of fault prognosis information provided in real-time. The
4.3. PAPER B

Economic utility of availability loss represents the penalty mechanism of mission delay, which reflects the business contract between the logistics company and the customer. The number of workshops represents the available maintenance resources, which is also a critical consideration in decision-making. In the sensitivity analysis, one variable is changed at one time, and the impact of the change is studied on the model output.

The proposed model is validated with case studies and numerical experiments. The use case is inspired by Swedish freight transport practices and set as intercity delivery, where the truck mostly runs on the highway. Data on model parameters and inputs are obtained from various sources, including public data and expert recommendations. Public data includes vehicle velocities, workshop location, data on road topology, etc. Some data are recommended by industry experts combined with an online search, such as the local tow truck service fee. Some data have no specific resource, while others have a wide range of possible values. In this case, the principle is that the data value should be consistent with common sense and reflect the situations the experiment investigates. For example, the maintenance time of vehicles in alarm situations and that of breakdown vehicles can take a wide range of values and are assumed in the paper. Their values are selected so that the former is much shorter than the latter, which is consistent with common sense. In case of the expected remaining useful life, the value is set so that the vehicle is likely to break down before delivery, reflecting the problem’s basic setup.

Three baseline methods are set up that reflect three different strategies a human decision-maker may have. These decision strategies correspond to three typical risk attitudes: risk-seeking, risk-neutral, and risk-aversion. In the numerical experiments, compared to the three baseline methods, the expected economic risk of the proposed method is reduced by up to 47%, which validates the effectiveness of the proposed method.

As for the sensitivity analyses, the numerical experiment results show that the economic risk is closely correlated to the value of the selected variables, contributing to the model’s internal validity. Specifically, the results indicate that the economic risk significantly decreases when the estimation accuracy of remaining useful life, the maximal allowed time of delivery delay before order cancellation or the number of workshops increases. These results contribute to identifying future research and development attention of autonomous trucks from an economic perspective.

As a preliminary study, this paper manually defines a decision alternative set containing three decisions for simplification. Although these three decisions reflect different vehicle operations and risk attitudes, they are limited and manually selected, making the maintenance planning process not fully automated. Furthermore, regarding the risk factors, this paper considers the economic risk caused by availability loss and maintenance costs. Although it reflects the practical consideration to a large extent, it is not determined by reasoning but more a mimic of
CHAPTER 4. SUMMARY OF APPENDED PAPERS

the current practice. Despite these limitations, the proposed maintenance planning model uses a generic risk quantification model and builds a universal framework that can be easily generalized and applied to cases with more decision alternatives and risk factors.

4.4 Paper C

Paper C contributes to the thesis by addressing the third research question, *'How to make maintenance and routing decisions for a driverless vehicle in an alarm situation that considers both the risk of mission delay and the risk of public time loss?*’ The overall research problem this paper investigates is similar to that of Paper B, i.e., the maintenance planning of a driverless vehicle in an alarm situation. It explicitly targets two significant limitations of Paper B, including the decision alternatives and the risk factors. Relaxing or eliminating these limitations is not trivial, which involves changing both the business model and the techniques. This paper addresses the research question with the following contributions:

- formulating a multi-criteria decision-making problem;
- developing a multi-criteria decision-making model considering both the risk of mission delay and the risk of public time loss;
- developing a public time loss model that quantifies and estimates the impact of vehicle breakdown on traffic flow;
- building a decision-alternative generator;
- performing sensitivity analyses of model parameters.

Except for improving Paper B, this paper has highlighted the shift of mindset to consider a public concern in a private business context, which brings about the first contribution. As common practice today, economic risk is the most important risk factor to consider in human decision-making when the situation is not safety-critical. However, a vehicle breakdown may also bring high risks to society, especially the risk of traffic congestion. While economic risk is a private concern mainly to the truck company, the risk of traffic congestion is a public concern that the road authorities and the public are interested in. Ignoring this type of concern in the decision-making process will harm the benefit and well-being of the public. The potential of collaborative decision-making between traffic management authorities and autonomous vehicles in enhancing safety and reducing traffic congestion has been recognized and attracted increasing attention [129], [130]. This paper addresses the importance of considering the risk of traffic congestion in the decision-making process. Currently, no standard or reference method exists to compare or combine the two distinctive types of risks. Therefore, they are considered independent decision criteria and constitute a multi-criteria decision-making problem considering both the public and private sector’s concerns.
4.4. PAPER C

The second contribution of this paper is developing a multi-criteria decision-making model considering both the risk of mission delay and the risk of public time loss. This model contains a risk evaluation model and a decision selection model. The risk evaluation model has the same theoretical foundation of risk quantification as Paper B. Compared to paper B, this paper refines the risk evaluation model to enable the independent development of low-level loss models. Independence development here means that the value of variables in the risk evaluation model does not affect the development of low-level loss models. As for the decision selection model, currently, there is no standard or reference to compare the public time loss and the private loss of mission delay. Therefore, a trade-off strategy is proposed to select the final decision from the Pareto front set if there is more than one Pareto front decision. The strategy, in principle, identifies the decision that maximizes the reduction of the risk of public time loss while preserving an acceptable increase of the risk of mission delay.

In this paper, there are two low-level loss models, i.e., a mission delay model and a public time loss model. The former characterizes the logistics company’s main concern and is well-built in Paper B. The latter is for quantitatively evaluating the traffic congestion caused by a vehicle breakdown, which is the primary concern of the road authorities and the public. Building this public time loss model is the third contribution of this paper. The main theoretical foundation of this model is the macroscopic traffic flow model, which is introduced in Section ???. Public time loss is selected to represent the severity of traffic congestion since it involves both the spatial and temporal properties of traffic congestion. The proposed public time loss model captures both the dynamics of the traffic flow and the towing process of the vehicle, which exemplifies a cross-disciplinary tryout between traffic management and maintenance planning domains.

The fourth contribution of this paper addresses the limitation of decision alternatives in paper B. In paper B, decision alternatives are simplified and manually defined, not considering real road networks and consequent vehicle routing problems. With oversimplification, the globally optimal decision may be excluded from the pre-defined decision set. By manually defining the decision set, the maintenance planning method is not fully automated, thus restricted in applying it to real-world scenarios. This paper considers a generic road network with multiple workshops located within to eliminate this limitation. A decision-alternative generator that automatically generates maintenance decisions by route searching in road networks is developed. This generalization improves the level of automation and the applicability of the proposed method in practice.

The last contribution of this paper is performing a sensitivity analysis of the proposed model. Five important variables are selected, including the alarm time, the alarm location, the mean and variance of the probability density function of remaining useful life, and the maintenance time. The values of all the variables are changed at the same time. In total, 4860 variable configurations are generated,
and the impacts of the changes in the model output are studied.

The proposed method in this paper is evaluated by case studies and numerical experiments. The case scenario of the experiments is similar to that of Paper B. In this paper, the road network is derived from real Swedish highway networks, where intersections, motorways, country roads, and multiple workshops are considered. Relevant traffic flow parameters are derived based on public data from Swedish road authorities, such as [60]. The experiment results show that neglecting the risk of vehicle breakdown on public roads can cause a high risk of public time loss of 175 hours at most in dense traffic flow, which validates the relevance of the problem formulation. With the proposed method, alternate decisions can be derived to reduce the risks of public time loss by 99% at most, which validates the effectiveness of the proposed method.

The sensitivity analysis results show that the proposed problem is relevant in a wide range of situations. The proposed method can effectively reduce the risk of public time loss as high as 341 h with an increase in the risk of mission delay of less than 1 h. The relevance of the problem and the effectiveness of the proposed method are prominent in specific scenarios, especially when the alarm occurs in the dense traffic flow, the remaining driving distance of the vehicle is relatively long and uncertain, and the time of workshop maintenance is short. Furthermore, they are also influenced by the topology of the road network, including the alarm location, the location of workshops and the customer, and the road types. These results further validate the relevance of the problem formulation, the effectiveness of the proposed method, and the correlation between key model variables and the model output.

Despite a comprehensive modeling and validation process, the generalization and applicability of the proposed method in practice can be reduced due to the lack of computation efficiency and the generality of the public time loss model. In the numerical experiments, the road network is derived from real ones but simplified by only keeping the major roads. If more details of an entire road network are considered, the size of the decision space, i.e., the number of decision alternatives, will increase drastically, thus being computationally expensive. To solve this problem, the computation model can be further optimized, and additional constraints on the decision-alternative generation can be added, which can be an extension of the proposed model. As for the public time loss model, it is still preliminary and does not consider some complexities in traffic modeling, such as traffic flow overloading and traffic control. However, the one developed in this paper serves its purpose of building the connection between maintenance planning and traffic management. It is built on a generic microscopic traffic model and can be extended to more complex and detailed traffic situations with minor efforts.
4.5 Paper D

Paper D contributes to the thesis by addressing the fourth research question, ‘How to design a decision support system to facilitate remote decision-making?’ The design follows the procedures of a Waterfall model, which is the earliest systems development life cycle approach used for software development [131]. Following this model, the design in this paper starts with requirement analysis, then a system design, and ends with a case study of implementation. The contributions of the paper include:

- depicting the industry practice;
- conducting a gap analysis;
- performing stakeholder analysis;
- designing a decision support system architecture;
- specifying the contents of the system modules in the architecture;
- designing a graphical user interface.

Among them, the first two contributions found the basis of the background, motivation, and domain knowledge of the thesis. As has been introduced, the concerned decision-making process in this thesis is currently handled by human drivers. To automate this process, knowledge of how it works today and what gaps prevent it from working in the future is needed. For this purpose, the current decision-making process in the truck industry is depicted based on a series of field studies. Afterward, a systematic gap analysis is conducted between the current practice and the desired future in a highly automated context. This gap analysis identifies the business and societal needs to be satisfied regarding information, decision-making models, and system actors.

The stakeholder analysis contributes to identifying the potential user of the designed system, which is a critical step for a system design. As has been introduced, the mission profit or the economic risk is the main decision criteria, representing the private sector’s concern. However, through the stakeholder analysis, public concerns are identified, such as traffic congestion, safety, and environmental issues, the stakeholders of which are public representatives, such as road authorities.

The fourth to sixth contributions are itemization of an overall contribution, i.e., a decision support system design. Based on the stakeholder analysis, a decision support system architecture is designed, including decision-making, reviewing, and learning processes. The reviewing and learning process is lacking in the current practice and is critical for achieving the long-term goal of fully automated decision-making. This process supports such a goal by collecting different types of data from the decision support system and the users. Over a long time horizon, these data will accumulate to an adequate size that can be further utilized for
reviewing and learning. On this basis, the contents of the modules in this architecture are specified within the context of this thesis, including decision-making, information input, and graphical user interface modules. For a decision support system, the graphical user interface is an important channel for communication between the computerized system and its human users. Before designing such an interface, the decision-making and information input modules need to be specified and implemented. A concrete graphical user interface is designed based on the information utilized or generated by the decision-making module, which is the last contribution of this paper. This design illustrates the idea of making the decision support system more adaptive, interactive, and transparent, thus gaining the trust and acceptability of its users.

The evaluation of this system design is conducted with a case study. The case scenario is the same as that of Paper C, and the decision-making model developed in Paper C serves as the technical input of this design. In this case study, the contents of each module in the decision support system are specified. Three graphical user interfaces are designed to showcase the interaction between the system and the user. An informed argument is made to evaluate the feasibility of the design based on the tacit knowledge obtained from the field studies about the users’ requirements and expectations of such a system. A use case scenario is developed to exemplify the usage of the system step-by-step.

This paper serves well for conveying knowledge, provoking ideas, and solving problems. As comprehensive as it is, it may need lots of elaboration to clarify details, which is not the focus of this paper. A limitation of this work can be that the designed system is not validated by real-world human users. This limitation is common when the time and resource of the project is limited, which is the case in this paper. Building a prototype of this decision-support system and testing it with humans require a big effort on various technological levels and management levels, which is not applicable to this project. However, the decision support system design in this paper has been well validated by informed argumentation and scenario development. The knowledge base of the arguments is based on the field studies performed at the beginning of this project, which can be considered convincing.

4.6 Summary of contributions

Based on the appended papers, the contributions of this thesis can be summarized as follows.

- C1: Perform a structured uncertainty analysis of a fault detection and diagnosis process.
- C2: Develop a fault diagnosis model based on Bayesian inference.
- C3: Develop a short-term maintenance planning model for an alarmed driverless vehicle that minimizes economic risk.
4.6. SUMMARY OF CONTRIBUTIONS

- C4: Perform sensitivity analyses of model parameters.
- C5: Formulate a multi-criteria decision-making problem.
- C6: Develop a multi-criteria decision-making model for an alarmed driver-less vehicle that considers both the risk of mission delay and the risk of public time loss.
- C7: Develop a public time loss model that quantifies and estimates the impact of vehicle breakdown on traffic flow.
- C8: Build a decision-alternative generator;
- C9: Depict the industry practice of the post-diagnosis decision-making process of human-driven trucks.
- C10: Conduct a gap analysis between the industry practice and the future demands and requirements.
- C11: Perform stakeholder analysis to identify potential users of the DSS.
- C12: Design a post-diagnosis decision support system (DSS) architecture for highly automated trucks that include both the decision-making process and the reviewing and learning process;
- C13: Specify the contents of the system modules in the architecture.
- C14: Design the graphical user interface of an intelligent DSS with adaptive, interactive, and transparent decision-making solutions.

The correlation between the appended papers, the research questions, and the contributions are listed in Table 4.1.

Table 4.1: The correlation between the appended papers, the research questions, and the contributions.

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Chapter 5

Conclusion

In this chapter, the answers to the research questions are presented. In addition, the studies in the appended papers have generated additional insights into this research topic. Therefore, a discussion of these insights and possible directions for future work is presented afterward.

5.1 Answers to the research questions

Research question Q1: How to infer the fault condition of highly automated vehicles under uncertainty to enable more reliable decision-making?

This research question is mainly addressed in Paper A with contributions C1 and C2. The question itself can be ambiguous unless the meaning of uncertainty is further specified. Therefore, concretizing, structuring, and modeling uncertainties and analyzing their resources and influence on fault detection and diagnosis process are the initial steps to address this research question. In a typical feature-based fault diagnosis process, uncertainties mainly arise from the operational environment, the fault detection algorithm, and the causal relations between faults, features, and environment uncertainties. These different types of uncertainties can be modeled in different ways. For example, the uncertainties of the operational environment, such as road and weather conditions, can be modeled with the specific domain knowledge and statistics of these environments. The uncertainties of algorithm performance and causal relationships can be modeled by experimental tests. Having formalized and modeled uncertainties in a structured way, they can be used as prior information in the fault detection and diagnosis process. The Bayesian inference method is a useful tool to take this prior information and the operational information to infer the posterior probability of a hypothesis, which assumes particular root causes of the fault. In this way, the vehicle’s health condition under uncertainties can be obtained and further used in decision-making.

Research question Q2: How to make a short-term maintenance decision that minimizes the economic risk for a driverless vehicle in an alarm situation?

This research question is mainly addressed in Paper B with contributions C3, C4, and C5. Information and its utilization are essential for a computerized system to make a decision. Therefore, the first step to addressing this research question
CHAPTER 5. CONCLUSION

is identifying the required information and information flow. The required information can be categorized into fault, workshop, maintenance, and delivery information. These different types of information are used for building a maintenance planning model, which is the key to answering this research question.

A decision-making model has three major aspects: the decision criteria, the decision variables, and the method. As a preliminary study, the first two aspects are predefined by the research question to some extent. The decision-making criterion is the economic risk, which mainly includes the economic risk caused by mission delay and the risk of maintenance cost. To replicate the current practice of human decision-making, the decision alternatives include driving to the nearest workshop at a normal speed, driving to the nearest workshop at a reduced speed, and continuing driving to the customer. Regarding the method, a classical evaluation-based decision-making model is adopted, which evaluates the risk of all the decision alternatives, essentially replicating a rational human decision-making process. As an initial attempt to automate a decision-making process, this method is more transparent and easier to interpret, which is essential for human users to comprehend and adopt.

Research question Q3: How to make maintenance and routing decisions for a driverless vehicle in an alarm situation so that both the risk of mission delay and the risk of public time loss are considered?

This research question is mainly addressed in Paper C with contributions C4 to C8. This research question is an upgrade of the previous research question, which ends up being addressed with several new perspectives. The main work to address this question is developing a decision-making model. Therefore, the question is answered from three aspects, the decision criteria, the decision alternatives, and the method.

The highlight of this research question is considering the risk of public time loss as a decision criterion. Currently, there is no standard or reference method to compare or combine public time loss and private time loss. Therefore, this question is formulated as a multi-criteria decision-making problem by considering the two criteria independently.

In this research question, maintenance and routing decisions are considered instead of simple maintenance decisions. In a real-world scenario, these two types of decisions exist simultaneously and depend on each other. In a human decision-making process, the capability of evaluating all possible decisions is limited, which, on the other hand, is the strength of computerized systems. Therefore, a decision-alternative generator is developed to automatically generate all decisions by route searching in road networks with all available workshops and routes.

Same as in the last research question, an evaluation-based method is adopted for explainability and transparency, which evaluates the risk of mission delay and the risk of public time loss of each decision alternative. Since these two criteria
can not be compared, a decision selection model is built, representing a trade-off strategy for the two types of risks. With this strategy, if there is more than one Pareto front decision, the decision that maximizes the reduction of the risk of public time loss while preserving an acceptable increase of the risk of mission delay is selected. This strategy essentially keeps the risk of private business low and aims at minimizing the risk to the public. An important part of the decision-making model is a public time loss model built based on macroscopic traffic flow modeling theories. Unlike conventional traffic flow modeling for traffic congestion management, this model correlates traffic congestion with a typical vehicle towing process, requiring cross-disciplinary knowledge from both domains.

**Research question Q4: How to design a decision support system (DSS) to facilitate remote decision-making?**

This research question was addressed in Paper D with contributions C9 to C14. In a remote decision-making setting for a driverless vehicle, a DSS can be considered a software service that connects the computing system to remote human users. Following a software design process, three procedures are conducted to answer this research question: requirement analysis, system design, and implementation. The system design contains architecture design, specification of system modules, graphical user interface design, etc. Among them, specifying the decision-making module with decision-making models is mainly addressed by answering the previous two questions. This question is answered mainly from a system design perspective. Considering the richness of Paper D, a selected collection of highlights is presented to answer this question.

The requirement analysis is used to determine the needs and expectations of the system, which is done by analyzing the current industry practice based on field studies. Afterward, a systematic gap analysis is conducted between the current practice and the desired future in a highly automated context. This gap analysis identifies the business and societal needs to be satisfied regarding information, decision-making models, and system actors. While considerable distinctive gaps are identified, only part of them is addressed in this thesis due to the limited time and resources. However, this requirement analysis provides thorough analysis and insights into this research topic.

In the system design, a stakeholder analysis is performed to identify the main stakeholders and their concerns, which is vital for determining the decision criteria and the system users. For the addressed problem, in the current industry practice with a freight transport context, the mission profit or the economic risk is the primary concern, and the logistics company is the main stakeholder. However, public concerns, such as traffic congestion, safety, and environmental issues, are also relevant, and the corresponding stakeholders are public representatives, such as road authorities. While transitioning from manual solutions to automated ones, innovations on both technological-level and organizational levels can be considered. In
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this case, an organizational-level innovation would be considering stakeholders’ concerns from the public sector in designing the DSS.

While the main functionality of a DSS is to support decision-making, it can also serve for reviewing and learning purposes. By reviewing, the performance and consequences of a decision can be evaluated after it is selected and executed. Such evaluation is missing in the current practice and could be valuable for explicitly gaining experience and knowledge for decision-making. Regarding learning purposes, at the starting phase, the DSS mainly provides advisory decisions and relevant information to human users while humans still make the final decision. With this trade-off of keeping the authority of humans, human users get to know about and trust the system, which contributes to a smooth transition from a conventional manual solution to an automated one. When human users interact with a DSS, their inputs to the system can be obtained and stored. Other relevant information utilized and generated by the DSS and the reviewing results are also valuable and should be stored. Over a long time horizon, these data will accumulate to an adequate size and be utilized for learning the experiences and preferences of human users. This contributes to upgrading the DSS toward a fully automated version.

At the starting phase, the human users of the DSS may want to preserve the right to make the final decision due to their limited trust in this computerized system. In this case, the DSS mainly supports human decision-makers by providing useful information. For this purpose, the graphical user interface is an important communication channel between the system and its human users. To improve the user experience and enhance the users’ trust of human users, the interface design should be transparent, interactive, and adaptive. To be transparent, the DSS can provide not only the advisory decision to the users but also other information, including the inputs to the system and the intermediate information generated by the decision-making model. In this way, the users can check what information is being utilized and how the final recommended decisions are derived. By being interactive and adaptive, the interface enables the users to navigate, check different types of information, and adjust the value of some information being used. As a result, the users can make maximum use of the intelligence of the DSS and, in return, provide information about their experiences and preferences.

5.2 Discussion and future work

Although the studies in the appended paper have provided insights and solutions to the research questions, more questions than answers have arisen in this research process, which I believe is a matter of course in a PhD-pursuing process. In Chapter 4, the limitations of every appended paper are presented, together with a discussion on the external validity of the study contributions. In Paper A, many research gaps of this research topics are identified, while only part of them are addressed
in this paper. Some of them are worthy of continuing to be studied. Below is a
discussion on some of them, which can be studied in the future.

The research in this thesis has a concrete industry application context. There-
fore, employing its results in practice is the best way to maximize the efforts. In
Paper D, a decision support system is designed, which can be further developed
into a software service and used in practice. Therefore, a future step is to develop
prototypes of the system and test it with human users. In this way, user experiences
and opinions can be collected and used for improvement and commercial applica-
tion. As discussed in Section 1.3, commercial vehicles with long-distance freight
transport missions are more likely to be the targeted platform for this service, thus
being a preferred vehicle type for testing and application.

When developing decision-making models and designing a DSS, clarifications
are made that the research was focused on automated decision-making instead of
fault diagnosis and prognosis. Therefore, in these studies, the contents of fault
type, diagnosis, and prognosis information are assumed, and the methods to ob-
tain these contents are not specified. However, in communicating these studies
with industry and academic experts, the fault diagnosis and prognosis information
is found to be one of their key concerns, despite their interest in the decision-
making problem. This concern consists of several aspects, including the specific
fault types, how to obtain fault prognosis information from real data, how to use
machine learning methods in fault prognosis, what are the form of prognosis infor-
mation, and how to consider different forms of prognosis information in decision-
making. On the other hand, this validates my opinion that we should have a global
view and integrate fault detection, diagnosis, and prognosis with decision-making
to address our research goal. Therefore, a potential future research direction would
be further studying how to comprehensively consider fault detection, diagnosis,
prognosis, and the decision-making processes and integrate them as a whole.

An innovative tryout of public-private partnership in decision-making is con-
sidered in paper C, which conveys an important message from this work of this
thesis. This tryout is motivated by providing statistics on the negative impacts of
malfunctioning vehicles on society regarding safety, traffic, and the environment.
However, this motivation is not enough for the output of this research to be im-
plemented in practice. To be explicit, private companies may need more business
motivation to take the idea and consider public concerns in a conventional pri-
vate decision-making process. Direct business motivation could be new policies
or regulations from the public authorities. However, for the public authorities to
establish and implement a new policy or regulation, its societal impacts must be
comprehensively assessed and validated. In the context of this thesis, validation
is needed regarding the performance of the proposed method in reducing traffic
congestion by considering all the vehicles in a larger region and a longer time
horizon, which could be another future research direction.

In the last chapter, one of the contributions of Paper C is eliminating the lim-
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itation of oversimplified decision alternatives by considering real road networks
and consequent vehicle routing problems. However, even if this limitation was
addressed in this way, it was relieved instead of eliminated. In other words, the
decision alternatives are still simplified in some aspects. For example, the option
of using spare trucks to take over the transport mission was not considered. Fur-
thermore, if the vehicle is in a fleet, the other vehicles in the fleet could also take
over the mission. If these options are considered, the decision-making problem
will involve a multi-agent or large-scale optimization problem. Therefore, a future
research direction is to further generalize the proposed methods by considering
vehicle fleets or spare vehicles in generating decision alternatives.

There are various decision-making models for autonomous vehicles, which can
be categorized into two major types: classical and learning-based. Classical meth-
ods include rule-based methods, optimization methods, and probabilistic methods.
The learning-based methods can be static learning-based, deep learning-based, and
reinforcement learning-based, which have been gaining massive attention in re-
cent years. However, the decision-making models in implementing the DSS in
this thesis are selected by more than chasing the spotlight. As an initial attempt to
automate a decision-making process, the decision-making model must be easy to
interpret, and human users must approve the results. Therefore, in papers B and C,
a classical evaluation-based decision-making model was used, which evaluated the
risk of all the decision alternatives, replicating a rational human decision-making
process.

In the last section, the selection of an evaluation-based decision-making model
is justified. However, this method can be computationally expensive and has lim-
ited capability in dealing with more complex problems. Therefore, it is not neces-
sarily a good choice in the long run. In designing the DSS, reviewing and learning
functionalities are considered. Suppose that with these functionalities, the DSS
collects an adequate size of data on the historical performance of the DSS and
user preferences over a long time horizon. In this case, a future direction would
be to utilize machine learning methods to train decision-making models to make
the DSS more intelligent and towards full automation. Nonetheless, the trustwor-
thes of these artificial intelligence systems, especially using machine learning
methods, is critical for their real-world application to be approved.

In the end, it is worth mentioning that this thesis contributes to building a sus-
tainable society, especially a sustainable transportation system in various aspects,
including reducing the risk of traffic congestion, deaths, and injuries, catalyzing
public-private partnerships, promoting technological transformation, and fostering
innovation. However, for these contributions to take effect, corporate and public
authorities need to make joint efforts on technological and managerial innovations,
which would be a long-term process.


BIBLIOGRAPHY


Appended papers