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Readiness and Influencing Factors for Disruptive Technologies Application in Malaysian Highway Maintenance: A Qualitative Study

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Abstract

The Fourth Industrial Revolution (IR 4.0) is transforming the construction industry through digitalisation and automation, offering opportunities for cost reduction and improved efficiency in infrastructure projects. This study investigates the readiness of Malaysian highway operators to adopt disruptive technologies during the operation and maintenance phases, identifying key influencing factors. A qualitative approach was employed, with semi-structured interviews conducted between June 2023 and March 2024 involving five experienced professionals from various highway concessionaires. Data analysis using NVivo 14 revealed that although operators show readiness for certain technologies, adoption levels vary across maintenance processes. Thematic analysis identified four critical factors influencing implementation: Discomfort, Innovativeness, Insecurity, and Optimism. The findings suggest that Innovativeness and Optimism drive adoption by potentially reducing labour dependency while enhancing efficiency and safety. In contrast, addressing Discomfort and Insecurity could lead to long-term time and cost savings. The study concludes that overcoming these barriers may accelerate technology integration in highway maintenance. Future research should examine emerging technologies such as machine learning, blockchain, and big data analytics to further enhance highway infrastructure management. This research contributes to a deeper understanding of the human factors influencing technology adoption in transportation infrastructure maintenance.

1. Introduction

The Fourth Industrial Revolution (IR 4.0) represents a major advancement of the digital revolution, integrating cyberspace, the physical world, and the biological domain. It has significantly impacted various economic sectors and aspects of society. Key technological megatrends driving IR 4.0 include the miniaturisation of supercomputers, advanced robotics, artificial intelligence (AI), the Internet of Things (IoT), blockchain, and 3D printing. The concept of IR 4.0 originated from Germany's Industry 4.0 initiative, which emphasises intelligent production systems in the manufacturing sector. In Malaysia, Industry 4.0 similarly refers to the adoption of these advanced technologies and forms a vital part of the broader IR 4.0 framework.

In a developing country like Malaysia, road infrastructure is a crucial component of the transport system. It comprises the essential facilities, services, and installations required for the smooth operation of highways, roads, and streets [1]. Highway maintenance is carried out by highway operators, specifically by their maintenance departments. These departments often struggle with limited resources, which can result in ineffective maintenance management, posing safety hazards and endangering lives [2]. Poor management remains a significant challenge in this area. Despite Malaysia's progress in modernising highway maintenance through computerised systems and electronic reporting and communication [3], [4], decision-making processes remain inefficient, with minimal improvement over time.

2. Review of Literature

This section provides a comprehensive review of the relevant literature on highway infrastructure, focusing on the challenges and advancements in highway infrastructure, especially in its operations and maintenance stages. Additionally, this section explores the role of disruptive technologies in the highway operation and maintenance stage, highlighting innovations and technologies that have been adopted in other countries or industries to address persistent issues.

2.1 Highway and Expressway Infrastructure

Highways and expressways are particularly important in this context as they serve as the backbone of a nation's transportation system. The development and maintenance of a robust road network are essential for the smooth flow of goods, services, and people, which directly contribute to national economic growth and regional development. However, there are a range of issues when operating and maintaining the highway infrastructure.

2.1.1 Operation and Maintenance Issues

According to Mohamed [5], the primary objective of highway maintenance is to ensure roads provide optimal service and maximum safety for users [6]. This is accomplished by eliminating disruptive physical defects such as potholes, cracked or broken pavement edges, loose gravel, uneven surfaces, and damaged bridge decks. Additionally, the maintenance of buildings and structures is essential to extending their lifespan through proper, ongoing, and efficient efforts. Inadequate maintenance can lead to costly repairs, renovations, or even reconstruction, ultimately increasing the overall life cycle cost of a project [6].

The total maintenance cost for state roads in 2000 was RM842 million, and this figure has steadily increased each year, in line with the growing road network, reaching RM4.33 billion in 2017, a more than 500% increase [7]. These substantial maintenance costs not only burden the government but also cause inconvenience to the public whenever refurbishment work is carried out. Maintenance work is assigned to concession companies and contractors, who act on behalf of the government to ensure road performance [7].

Meanwhile, Alaloul et al. [8] noted that the construction industry is on the brink of an innovative industrial era, with significant transformation underway through the initiation of IR 4.0. This shift is driving the industry toward more advanced digital practices, central to which is the concept of creating a "digital twin" for buildings and infrastructure. This approach enables accurate and well-informed decision-making throughout the project lifecycle. However, despite its early stages, IR 4.0 still finds the construction sector lagging behind other industries in terms of process automation and the degree of digitalisation [9].

2.2 Disruptive Technologies in Highway Operation and Maintenance Stage

In this research, disruptive technology primarily refers to the innovations driving the Fourth Industrial Revolution, such as artificial intelligence (AI), Internet of Things (IoT), blockchain technology, drones, 3D printing, and cloud computing. It is important to note that disruptiveness can be defined by various criteria, including the depth and scope of impact, the nature of effects, ethical considerations, the level of uncertainty, the pace of technological change, and the reversibility of outcomes [10]. The primary technological disruption of our time is digitalisation, which enhances the efficiency of infrastructure management [11]. Disruptive technologies such as digitalisation, algorithms, and automation not only reduce costs in the design, construction, and operation of infrastructure but also significantly boost efficiency.

Four (4) types of advanced technologies are focused on in this research, which are intelligent transport systems (ITS), drones, Internet of Things (IoT) and Connected and Autonomous Vehicles (CAVs) [12]. First of all, Intelligent Transport Systems (ITS) consist of transport infrastructure and operational systems designed to enhance road network safety, efficiency, and accessibility using advanced information technologies. This approach aims to minimise the need for costly large-scale road construction [13]. Besides that, IoT is regarded as a disruptive phase of the Internet revolution [14]. IoT encompasses physical objects equipped with network connectivity, processing abilities, and sensors, enabling them to record, process, and communicate data [15]. Likewise, Drones are increasingly utilised in the transport sector to boost operational efficiency and enhance safety. They are employed in inspecting bridges and tunnels, monitoring traffic, and logistics delivery [12]. Drones enable more frequent and precise infrastructure inspections through remote inspections and multispectral imagery. Last of all, CAVs, commonly known as self-driving vehicles, employ fully automated systems to perform driving tasks without human intervention [16]. CAVs are pivotal in the automotive sector, transforming global perspectives on vehicle evolution. These vehicles can enhance mobility, reduce resource consumption, lower carbon emissions, decrease parking demands, and improve traffic safety by mitigating human-driver errors, which are major contributors to traffic accidents [17]-[20].

2.2.1 Leveraging Disruptive Technologies to Overcome Highway Maintenance Challenges

Previous studies highlighted some impacts of disruptive technologies in overcoming the challenges in highway maintenance as follows:

- Reduce the cost of infrastructure management.
  First of all, efficiency in the infrastructure management can be enhanced with the assistance of technologies and resulting in reduced operational and maintenance costs [21]. Intelligent algorithms can analyse existing data to predict when maintenance will be required, facilitating the concept of "predictive maintenance" [22]. This approach allows maintenance activities to be carried out precisely when necessary, rather than relying on conservative theoretical estimates or waiting for costly breakdowns to occur. As a result, predictive maintenance can significantly reduce operational costs by preventing unnecessary interventions and avoiding expensive repairs caused by unforeseen failures. For instance, it is estimated that the adoption of advanced technologies could lead to an average reduction of 30% in capital expenditures in the road infrastructure industry [23]. This underscores the potential of predictive maintenance and other intelligent solutions to optimise resource allocation and enhance the efficiency of infrastructure management.
- Improve efficiency of road infrastructure maintenance
  Drones are increasingly being utilised in the transport and infrastructure sectors to improve operational efficiency, reduce costs, save time, and improve safety. This technology has found applications in various areas, including the inspection of bridges and tunnels, traffic monitoring, and logistics delivery. By enabling remote inspections and using multi-spectral imagery, drones offer a versatile platform that allows for more frequent and accurate assessments of infrastructure, ultimately making it more resilient. For example, inspecting a bridge with drones requires only two personnel, minimal equipment, and limited traffic control, which significantly simplifies the maintenance process. The entire inspection can be accomplished in around two hours, eliminating the need for heavy-duty machinery and extensive workforce involvement. This results in significant savings on labour and equipment while improving operational efficiency and safety [12]. Furthermore, the ability to perform inspections more frequently ensures early detection of potential issues, reducing the risk of structural failures and enabling more proactive maintenance.

2.2.2 Review of Existing Studies on Disruptive Technologies Application in Infrastructure Management

Lately, an increasing body of research has explored the application of disruptive technologies in infrastructure management, highlighting various implementations and outcomes across various countries, including both global and local contexts.

According to the United Nations Economic and Social Commission for Asia and the Pacific (2017) [24], China's expressway network had fully integrated Electronic Toll Collection System (ETCS) by 2015. This nationwide system spans 29 provinces and cities, with 12,772 dedicated ETCS lanes, 25.15 million users, and 23,187 service points. The ETCS has significantly reduced indirect costs, such as land acquisition and toll station construction, offering savings of up to 87% in toll station expansion expenses and approximately 20% in labour and operational costs. Similarly, Korea has introduced the Freeway Traffic Management System (FTMS), which is designed to improve the management of road congestion, respond to incidents, and handle natural disasters. This system enhances traffic management efficiency and allows for quicker emergency responses. Thereby ensuring smoother and safer freeway operations.

In the Malaysian context, several technologies have already been adopted to improve highway and expressway management, including the Intelligent Transportation System (ITS). Key applications of ITS in Malaysia include the Traffic Control and Surveillance System, Toll Collection System, and Emergency Response Plans [25]. These technologies are instrumental in enhancing transportation efficiency, particularly in highly urbanised areas such as Kuala Lumpur and the Klang Valley. By optimising traffic flow, improving toll management, and ensuring timely responses to emergencies, these systems play a crucial role in addressing the challenges of rapid urbanisation and congestion in Malaysia's major cities.

2.3 Technology Readiness Index (TRI)

The Technology Readiness Index (TRI) was first introduced by Parasuraman (2000) [26]. TRI suggests that an individual's perception of technology involves both positive and negative aspects, leading to the identification of four (4) key dimensions in technology readiness, which are Optimism, Innovativeness, Discomfort, and Insecurity. These dimensions collectively shape a person's overall readiness for technology. Optimism and Innovativeness dimensions act as mental enablers, which could encourage the acceptance and adoption of new technologies, while Discomfort and Insecurity dimensions serve as mental inhibitors, creating resistance to the implementation of new technologies.

2.3.1 Factors Influencing the Readiness of Technology Adoption

Concisely, the factors that shape an individual's readiness to adopt new technologies are classified into four (4) key constructs [27]:

a) Optimism - refers to a positive attitude toward technology, where individuals believe that technology enhances their control, flexibility, and efficiency in both personal and professional life. Optimism captures the favourable and proactive mindset toward technological advancements.
b) Innovativeness - reflects a person's tendency to be an early adopter in the use of new technologies. Innovativeness measures how willing participants are to experiment with new technologies and position themselves at the lead of technological change.
c) Discomfort - associates with feelings of a lack of control over technology, leading to anxiety or being overwhelmed by it. Discomfort gauges the extent to which participants feel uneasy or intimidated by technology, reflecting a reluctance to engage due to perceived complexity or frustration.
d) Insecurity - refers to the distrust individuals may have toward technology, characterised by concerns about its reliability and potential risks. This dimension assesses a negative disposition, where participants are sceptical about whether technology can function properly and worry about its unintended consequences, such as privacy issues or system failures.

In short, TRI reflects an individual's willingness to adopt and utilise new technologies to achieve their goals both at home and in the workplace [28].

2.3.2 Themes for the Thematic Analysis

The thematic analysis in this research is based on the constructs of the Technology Readiness Index (TRI) model, which are adapted to explore factors influencing the readiness of disruptive technology adoption. Both enabling and inhibiting factors can shape a person's overall readiness to adopt technology, such as personal experiences, technological exposure, and socio-cultural influences. These themes provide a structured framework to analyse participants' perceptions and behaviours regarding new technologies. The themes which aligned with the TRI constructs are Optimism, Innovativeness, Discomfort, and Insecurity. Moreover, these themes provide a comprehensive lens through which the data can be examined, offering insights into both the motivators and barriers that affect disruptive technology readiness, especially in highway infrastructure maintenance.

3. Methodology

This methodology section presents a comprehensive overview of the research design, data collection, and analysis techniques for the research. This research employs a qualitative method to explore the factors influencing the readiness of highway operators to adopt disruptive technologies for infrastructure operation and maintenance. A qualitative design was chosen for its ability to provide in-depth insights and capture the nuanced perspectives of participants, allowing for the identification of key themes emerging from their experiences and viewpoints.

Likewise, a semi-structured interview is the primary data collection method for this research. The semi-structured format ensures that all participants are asked a consistent set of core questions, while also providing the opportunity for deeper exploration of relevant issues as they arise. Thematic analysis is used to analyse the data collected from the interviews with the assistance of NVivo 14 software. This analysis method includes identifying, analysing, and reporting patterns or themes within the data and is widely applied in qualitative research studies.

3.1 Research Questions

The research question guiding this research is: How ready are highway operators, and what are the factors affecting the readiness of highway operators to adopt disruptive technologies in the road infrastructure operations and maintenance stage? Accordingly, this research aims to understand whether highway operators are ready for the application of disruptive technologies and to identify the factors influencing their readiness to adopt disruptive technologies such as ITS, IoT, drones, and autonomous and connected vehicles for mobility (AV) in highway infrastructure operations and maintenance practices.

3.2 Research Participants

The research targets highway operators involved in highway infrastructure, specifically focusing on highway and expressway projects across Malaysia. According to the Malaysian Highway Authority, there are presently 31 operational interurban and intraurban highways or expressways, with an additional 5 under construction. Therefore, the research encompasses a total of 36 participants. The participants selected for this study include top management personnel and decision-makers from highway operations and maintenance organisations.

A purposive sampling method was used to ensure that the selected participants were relevant to the study's focus. Additionally, snowball sampling was employed, where initial participants referred other suitable candidates to broaden the pool. Fig. 1 depicts the flow of participants' identification and selection in this research. Out of the thirty-six (36) potential participants, interview invitations were sent, followed by reminders. Unfortunately, thirty-one (31) of the potential participants either declined or did not respond. Seven (7) participants agreed to the interviews, but two (2) did not meet the inclusion criteria, which required participants to hold managerial positions with direct involvement in decision-making related to the adoption of disruptive technologies in highway operations and maintenance.

Additionally, participants needed to have related experience in the road infrastructure sector. Ultimately, semi-structured interviews were conducted with five (5) qualified respondents, and thematic analysis was performed on the data collected from these interviews.

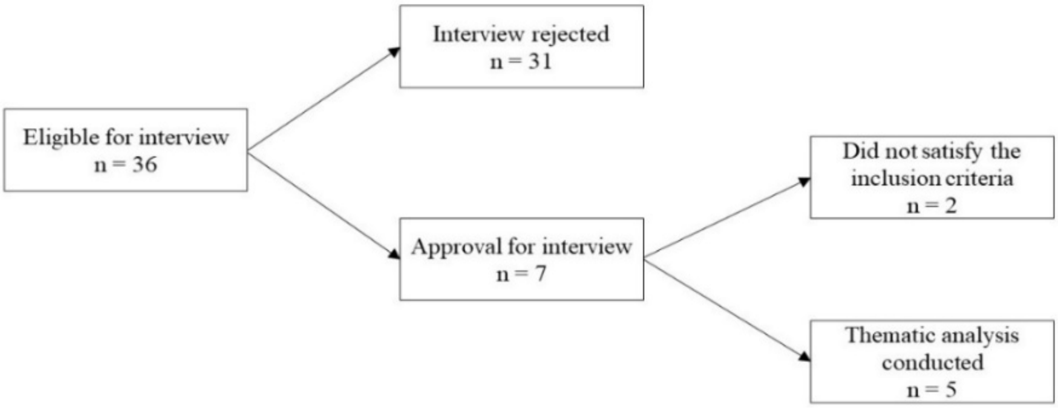

Fig. 1 *Flow diagram of participant identification and selection*

In this research, the estimation of the qualitative sample size is determined by assessing data saturation during the thematic analysis. Constantinou et al. [29] suggest that the sample size required to achieve saturation typically ranges from 5 to 24 interviews, with the minimum sample size being 5 interviews. Data saturation occurs when no new themes or insights emerge from the data, indicating that the collected information is sufficient to address the research questions. Therefore, the decision on the sample size is based on reaching this point of saturation, ensuring comprehensive coverage of relevant themes.

3.3 Method of Data Analysis

Thematic analysis is a method used to analyse qualitative data, and it is employed in this study to identify and interpret patterns or themes within the data, providing new insights and understanding [30], [31]. Braun & Clarke [32]-[34] introduced a six-phase process to streamline the thematic analysis method. This process aids researchers in identifying and focusing on the critical aspects of thematic analysis. Although the six phases are arranged in a logical sequence, but the analysis is not a straightforward, linear progression through these stages.

In this research, deductive thematic analysis is utilised. This top-down approach involves coding the data based on a pre-existing framework or aligning it with the researcher's theoretical perspectives and expectations [33]. NVivo software, version 14.23.1, is employed for qualitative data analysis in this study. Transcripts were created from the recorded audio during interview sessions. These transcripts were then analysed using NVivo, which facilitates an in-depth examination of qualitative data by organising and coding the information to identify patterns, themes, and insights.

3.4 Theoretical Underpinning of Factors Influencing Technology Readiness

The Technology Readiness Index (TRI) serves as the underpinning theory for this research, and the details of this theory are discussed in the literature review section. The TRI's four key constructs: "Discomfort," "Innovativeness," "Insecurity," and "Optimism", are adapted as the primary themes for the thematic analysis. During the analysis, interview transcripts are systematically coded and categorised under these relevant themes, enabling a structured approach to identifying patterns and insights related to the readiness of highway operators in adopting disruptive technologies. This process helps to uncover critical factors influencing their attitudes and preparedness for technological integration. The classification of codes to the related themes is shown in Table 1.

Table 1 *Classification of codes and corresponding themes*

Codes	Themes
Attitude of Workers	Discomfort
Generation Gap	
High Risk for Inspection Process	
Lack of Competent Staff	
Uncontrollable Weather Conditions	
Data and Server Storage Problems	Innovativeness
Necessary for Continuous Learning and Improvement	
Data Communication Issue	
Different Local Authority Regulations	Insecurity
System and Spare Parts Problems	
High Risk for Inspection Process	
Technology Malfunction	
Enhance Maintenance Performance	Optimism
Improve Workmanship Productivity	
Optimise Road Maintenance Process	

4. Results of Data Analysis

This section presents the outcomes from the data analysis, comprising demographic information of the respondents, a word cloud and themes regarding the readiness to adopt disruptive technologies in highway operation and maintenance stages.

4.1 Demographic Information of Respondents

The demographic information of the five (5) respondents offers valuable insight into their background and qualifications. Table 2 summarises key demographic characteristics, including education level, years of working experience, current job position/title, and field of specialisation.

Table 2 *Demographic statistics of respondents*

Personal Characteristics	Frequencies (N= 5)	Percentage (%)
Level of Education		
Bachelor's degree	3	60.00
Postgraduate (Master/PhD)	2	40.00
Working Experience (in Years)		
5-10 years	1	20.00
11-15 years	1	20.00
16-20 years	1	20.00
> 20 years	2	40.00
Job Position/Title		
Senior Manager	2	40.00
Project Manager	1	20.00
Technical Manager	1	20.00
Professionals in the firm	1	20.00
Field of Specialisation		
Construction Management	1	20.00
Civil and Structural	4	80.00

In terms of education, 60% hold a bachelor's degree, while the remaining 40% have postgraduate qualifications, including master's and PhD degrees. Their work experience is diverse, with 40% having over 20 years of experience, and the rest evenly distributed across the 5-10 years, 11-15 years, and 16-20 years categories.

With respect to job positions, 40% of respondents are Senior Managers, 20% serve as Project Managers, another 20% are Technical Managers, and the remaining 20% are professionals within their firms. The field of specialisation is predominantly in Civil and Structural engineering (80%), with only 20% specialising in Construction Management. This demographic profile suggests that the respondents are experienced professionals with significant expertise in civil and structural engineering, making them well-suited to provide insights into the adoption of disruptive technologies in highway infrastructure.

4.2 Results of Thematic Analysis

This section presents the results of the thematic analysis, highlighting the key codes and themes that emerged from the data.

4.2.1 Themes for Readiness to Adopt Disruptive Technologies

Four (4) themes are created from the thematic analysis, which are "Discomfort", "Innovativeness", "Insecurity" and "Optimism". The themes serve as the vital factors that influence the readiness of highway operators to adopt disruptive technologies in the highway maintenance process. The discussion for each theme is provided as follows:

4.2.1.1 Theme 1: Discomfort

The theme of discomfort primarily revolved around the challenges that workers face when adapting to new technologies. From the interviews, it became clear that generational differences significantly contribute to this discomfort. For example, older workers, particularly those from Generation X, often struggle more with learning and adapting to new technologies compared to their younger counterparts from Generations Y and Z. Interviewee 1 explained that: *The main issue is the generation gap. For example, Gen X finds it quite hard to learn new technologies, while Gen Y and Z find it easier; I found that it is easy for my young workers to adopt technologies. While younger workers also find it not so easy to adopt technologies, workers around 30 years old do better.*

This discomfort is further exacerbated by concerns about the reliability and ease of use of these technologies. Interviewees pointed out that workers might feel uneasy about potential technical failures, such as data transmission issues or power outages, which can disrupt operations and cause delays. As Interviewee 1 mentioned, the challenge is weather issues like heavy rain and lightning, which might cause power failures on *the highway. This will cause a problem, especially for the toll tower, when users enter and exit.*

Furthermore, discomfort underscores the need for comprehensive training and support systems to ease the transition for all employees, particularly those less familiar with new technological tools. Interviewee 4 said that: *Hire more workers in the near future, then provide training to become skilled and innovative workers*. At the same time, interviewee 5 also mentioned that: Always need to train the technical team, because staff *always quit. Prefer to appoint fresh graduates and young people, because there is a lower turnover rate. The old man is not easy to handle.*

4.2.1.2 Theme 2: Innovativeness

Innovativeness emerged as a crucial theme, with many interviewees highlighting how new technologies have transformed infrastructure management. For instance, Interviewee 1 mentioned that: *Data transmission problem, as the highway might have uncovered areas, so sometimes the data and signals received from the server/control rooms are limited, and sometimes it takes a longer time to receive the data.*

The adoption of drones, IoT devices, and big data analytics has significantly enhanced operational efficiency. For example, tasks that previously required multiple workers can now be completed by a single drone operator, reducing both time and labour costs. Furthermore, these technologies enable real-time monitoring and predictive maintenance, allowing for immediate intervention before issues escalate. Interviewee 5 said: *We need to have our own technical and maintenance team, always on standby for any incidents that happen. The maintenance team always check and clears the server room, only recording the important and critical data.*

At the same time, the interviewees also revealed that while the potential for innovation is high, it is often hampered by a lack of skilled personnel and the challenges of integrating new systems into existing workflows. This highlights the need for ongoing innovation, not just in technology, but also in training and process optimisation to fully leverage the benefits of these advancements. Interviewee 2 claimed that innovativeness can only be achieved when a need to always upgrade the knowledge of staff *regarding the technologies operating and control. The technical person must have related knowledge when using the technologies, and training is needed for a certain period to upgrade themselves.*

4.2.1.3 Theme 3: Insecurity

Insecurity was another significant theme, mainly focusing on the reliability and safety of new technologies. Interviewees expressed concerns about the accuracy and dependability of the systems being implemented. For example, issues like receiving incorrect data or the unavailability of spare parts for repairs can lead to operational setbacks, raising doubts about the overall reliability of the technology. As discussed by Interviewee 3: *System and spare parts problems, for technology instrument spare parts, need to buy from the contractors, quite expensive and also for some older parts might not be available and need to replace whole systems. Toll equipment is broken, and the supplier/contractor takes time to check and repair, forcing the lane to close, which will cause a slowdown in traffic flow.*

Additionally, the potential for job displacement due to automation also contributed to feelings of insecurity among employees. While the reduction in manpower needed for certain tasks, like surveying, was seen as a benefit, it also raised concerns about the long-term implications for employment. Interviewee 2 said that: *As fewer workforces are needed for the maintenance works, this can reduce the accidents that happen during maintenance works.*

This theme underscores the need to address both the technical and human aspects of technology adoption to build confidence and security within the workforce.

4.2.1.4 Theme 4: Optimism

Despite the challenges and discomfort issues, there was a strong sense of optimism about the potential of disruptive technologies to revolutionise infrastructure management. Many interviewees acknowledged the transformative impact of technologies like drones and IoT on their operations. Interviewee 1 mentioned that *preventive maintenance can be carried out with the assistance of big data. We use a road scanner to conduct the pavement condition assessment (PCA), which can understand the road conditions and prepare for the coming highway road maintenance. It can reduce workmanship by practising more in preventive maintenance. Repair works can be carried out immediately with the assistance of technologies.;* While Interviewee 2 claimed that: *For drone, own staffs can drone operator and carry out the survey works at any time whenever require to do so, only 2 workers are needed to carry out the survey works with the drone, 1 drone operator and another 1 to check conditions of the drone before flying, like, battery level, drone propellers and so on.*

As an example, the ability to conduct real-time monitoring and perform preventive maintenance was seen as a major advantage that could lead to more efficient and cost-effective management of infrastructure, for example, Interviewee 3 discussed that: *Another is IoT, top management of the concessionaire have the mobile app which linked with the highway smart system and can control and monitor the LED streetlight power efficiency.*

Additionally, there was optimism about the long-term benefits of these technologies in improving safety and reducing the risk of accidents during maintenance work. However, this optimism was tempered by the recognition that successful adoption would require ongoing investment in training and infrastructure. Interviewee 5 quoted that: *Motion detection equipment is installed at the second bridge, which is used to detect and prevent people from jumping off the bridge (suicide). AMS (ATMS) detects frequent accident spots on the bridge, then analyses them, finds out problems and comes up with rectification works.*

Overall, the interviews reflected a positive outlook on the future of technology in the industry, provided that the challenges could be effectively managed.

5. Discussions

The identified themes were enriched with specific codes to provide deeper insights into the readiness of highway operators to adopt disruptive technologies. Four (4) key themes, which are discomfort, innovativeness, insecurity, and optimism, are the vital factors which affect the readiness of disruptive technologies implementation. Each theme is associated with particular challenges and opportunities highlighted by the interviewees.

Discomfort factor reflects concerns regarding the attitude of workers, the generation gap, high risk for inspection processes, and a lack of competent staff. These codes mainly focus on the generational differences in adapting to new technologies and the risks involved in traditional inspection processes. In addition, uncontrollable weather conditions are another root of discomfort, presenting a significant challenge to technology execution in outdoor infrastructure management. The outcome aligns with a previous study by Khudzari et al. [35], suggesting that workers' competency plays a crucial role in the successful adoption of technologies in the construction industry. Organisations need knowledgeable, enthusiastic, and well-trained individuals to manage specific technologies effectively. For instance, assigning a dedicated person to oversee system updates, as well as maintaining data accuracy, is essential for ensuring smooth operation and maximising the benefits of technology integration [35].

The Innovativeness factor encompasses the readiness for continuous improvement and technological adaptation, represented by codes such as data and server storage problems, necessary for continuous learning and improvement, and data communication issues. These codes reflect the interviewees' recognition of the need for innovative solutions, like drones and IoT, to streamline maintenance processes and reduce reliance on manual labour. Similarly, Jafari & Ahmadvand [36] noted that strong organisational support and communication are essential for successfully implementing ITS technologies.

Insecurity factor focuses on the reliability of systems and the impact of external conditions on technology performance. Codes such as different local authority regulations, system and spare parts problems, technology malfunction, and high risk for inspection processes around implementing disruptive technologies. These insecurities stem from fears of inconsistent regulatory frameworks, the availability of spare parts, and the potential for technology failures, particularly during critical operations. Related studies also found that awareness and adherence to laws and regulations are one of the critical issues which will affect the infrastructure project [37]. Furthermore, the main aspects for an unsustainable rating were linked to negative assessments of the policy and regulatory environment, along with inadequate O&M policies and financing. In the transport and ICT sectors, insufficient funding for O&M contributed to low sustainability ratings, whereas strong institutional capacity and technical expertise were associated with higher sustainability ratings [38].

Lastly, the optimism factor covers the benefits of adopting disruptive technologies. The enhancement of maintenance performance, improvement in workmanship productivity, and the optimisation of road maintenance processes are codes linked to this theme. Interviewees expressed confidence in the ability of technologies to enhance efficiency, safety, and productivity, signalling a positive outlook on their eventual integration into infrastructure management practices. In short, Jafari & Ahmadvand [36] stated that supplier identification and selection, as well as information technology standards, are the management aspects that affect the implementation of ITS in road infrastructure management.

6. Conclusion and Recommendations

This research provides a comprehensive understanding of the factors affecting the readiness of highway operators in Malaysia to adopt disruptive technologies in highway operations and maintenance. Through qualitative analysis, four key factors were identified: discomfort, innovativeness, insecurity, and optimism. These factors highlight the complex attitudes and experiences of industry professionals as they navigate the integration of new technologies such as drones, IoT, and advanced ITS systems.

The findings suggest that addressing these factors can significantly improve maintenance processes, enhance efficiency, and ensure long-term sustainability. Stakeholders and highway operators should leverage optimism by making long-term investments in infrastructure and staff training, ensuring smooth transitions and maximising the benefits of innovation. Regarding innovativeness, operators should focus on both technology and workforce development for successful integration. For insecurity, policymakers and organisations must collaborate to ensure consistent regulations and resources are available for technology sustainability. Lastly, competency-building programs should be prioritised to reduce hesitation under the discomfort factor.

For further studies, it is recommended that future research explore the long-term impacts of disruptive technologies on employment within the highway infrastructure sector, particularly concerning job displacement and the evolving skill requirements. Additionally, quantitative studies could complement this qualitative research by measuring the actual impact of technology adoption on operational efficiency, cost reduction, and safety improvements over time. Expanding the scope of research to include a comparative analysis with other countries could also provide valuable insights into best practices and strategies for successful technology integration in highway operations and maintenance.

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Conflict of Interest

The authors declare no conflict of interest, personal circumstances or interests that could be perceived as inappropriately influencing the illustration or interpretation of the results of research presented in this study. Moreover, the funders had no role in the design of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results. All findings and conclusions are solely the responsibility of the authors and have been independently derived without any external influence or bias.

Author Contribution

The authors confirm contribution to the paper as follows: ***Study conception and design:*** *Zul Zakiyuddin Ahmad Rashid, Yong Ming Heng, Radzi Ismail, Mohd Hanizun Hanafi, Mohd Suhaimi Mohd Danuri;* ***Data collection:*** *Zul Zakiyuddin Ahmad Rashid, Yong Ming Heng;* ***Analysis and interpretation of results:*** *Yong Ming Heng;* ***Draft manuscript preparation:*** *Zul Zakiyuddin Ahmad Rashid, Yong Ming Heng, Radzi Ismail, Mohd Hanizun Hanafi, Mohd Suhaimi Mohd Danuri. All authors reviewed the results and approved the final version of the manuscript.*

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