OPEN ACCESS

Saudi Journal of Civil Engineering
Abbreviated Key Title: Saudi J Civ Eng
ISSN 2523-2657 (Print) |ISSN 2523-2231 (Online)
Scholars Middle East Publishers, Dubai, United Arab Emirates
Journal homepage: https://saudijournals.com/journal/sjce/home

Original Research Article

Towards Global Optimal, High-Performance, Sustainable Maintenance of Highway Projects: Prisma

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DOI: https://doi.org/10.36348/sjce.2026.v10i08.001 | **Received:** 28.05.2026 | **Accepted:** 17.07.2026 | **Published:** 04.08.2026

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Abstract

The last few decades have witnessed considerable competition between developed countries to implement innovative digital advancements. This step is actually important for utility-scale highway construction enterprises, which are characterised by significant uncertainties, complex tasks, budget forecasting fluctuations, delays, cost overruns, and litigation. Nonetheless, the construction sector across all lands faces various hurdles to adopting 5G technologies. Thereby, it is substantial to highlight their instrumental benefits. Additionally, it is essential to illuminate the major risks of these projects. Actually, the global literature has few discussions of breakthrough approaches to mitigate the significant risks posed by these massive projects. Accordingly, this paper conducts a PRISMA-based data collection and analysis to bridge these knowledge gaps. This systematic review is noteworthy because it provides practical evidence and practices on the feasibility of digital tools for smart highway construction procedures and intelligent traffic management. It contributes to the available literature through valuable risk evaluation tools, contributions, and the imperative applications of the latest cutting-edge sensors.

Keywords: Highway Construction and Maintenance Enterprises; PRISMA; Systematic Review; Efficiency; Sustainability; Safety.

INTRODUCTION

Strategic, large road network facilities are considered the core element of economic, social, and political growth of any land by facilitating the transfer of people and commodities [1-5]. The reason is that highways can provide international competitiveness, according to the World Economic Forum, by offering sufficient access, efficient traffic transfer, and connections to important facilities, including tourist monuments, healthcare and therapeutic institutions, education, and different businesses and jobs for both local and international citizens [6-10]. A famous example of a country that benefits from all these critical relevant key strengths of highway infrastructure facilities is Jordan. This land has a strategic, pivotal location near Arab, neighbouring countries. It has its well-recognised credit and prominent reputation on ultra scales of performance and service in medicine, tourism, and education [11-14].

These relevant benefits and rationale can, for this reason, encourage government bodies worldwide to heavily invest in various Highway Infrastructure Construction, Maintenance, and Rehabilitation (HICM&R) approaches. China is rated as a prominent land, which has taken into account not less than 5.8% of its Gross Domestic Product (GDP) in HICM&R, particularly in 2020. Referring to the World Bank statistics, the private sector has shown remarkable interest in HICM&R activities, corresponding to an approximate investment value of 76.2 billion USD in 2021 [15].

Nonetheless, implementing and executing such large projects is challenging due to the high capital investment and the scarcity of holistic approaches to the characterisation and planning of these facilities' construction and maintenance [16].

Currently, the public construction sector faces many limitations to supervise and manage such kinds of projects because these utility-scale enterprises do necessitate ultra scales of accuracy in budget forecasting, risk control, engineering skills, talents, and experience in many construction-related disciplines, swift response to local users' complaints and registered notes and feedback, flexibility in the adoption of innovative Project Management (PM) strategies, enhanced adoption of cutting-edge technologies, notably Artificial Intelligence (AI), Machine Learning (ML), Deep Learning (DL), and Internet of Things (IoT) tools, and the adoption of efficient bidding strategies, incentives, and driving engineering legislations [17-20].

Unfortunately, none of these necessities and conditions exists in the public sector. In comparison, the private sector does contain most of these critical competencies. However, local engineering regulations and bidding strategies for carrying out large-scale HICM&R activities remain a challenge for the private sector. Additionally, specific advanced maintenance strategies, like predictive maintenance and repair diagnosis forecasting tools, are rarely harnessed in both sectors. As a result, the rates of safety, sustainability, efficiency, serviceability, and durability of these strategic infrastructure amenities would deteriorate.

In this context, it is crucial to implement innovative, comprehensive, workable, practical frameworks, like Public-Private Partnership (PPP), which was found to be very beneficial, valuable, and advantageous after its application in many lands [21]. Nevertheless, according to this author, the adoption of the PPP framework may encounter certain obstacles, manifested mainly as instability related to government legislation, dissatisfaction among individuals in the private sector regarding specific responsibilities, a shortage of technical expertise, and financial risk.

In addition, Chang et al. [22] reported that optimal scales of efficiency for critical urban system components, such as highways, are crucial to ensuring the provision of improved Quality of Life (QoL). However, these large-scale urban facilities are subject to constant ageing, degradation, and damage, contributing to accidents, inadequate safety measures, and risks if they are not regularly repaired and maintained [23].

Also, the public sector does not take into account a variety of complaints, reported problems, and feedback from local users regarding damage to highway amenities across diverse lands. Statistically elucidating, over 75% of local users in Korea have perceived their lower satisfaction and below the average levels of service and safety of their country's urban infrastructure and large road nodes [22]. Amidst these challenges, the main Research Questions (RQs) of this study can be formulated below:

- **RQ-1:** What are the key challenges of handling large-scale HICM&R projects supported by new technologies and the latest styles of PM tools?
- **RQ-2:** How could these bounding limitations and restrictions be resolved or at least alleviated?

To provide sufficient answers to these RQs, the current work relies on a systematic review. It involves a specialised review and analysis of noteworthy statistics to strengthen the main research evidence. Therefore, the global secondary data are reviewed to highlight critical benefits, factors, driving tools and limitations of HICM&R strategies, besides illuminating traditional and latest risk estimation approaches utilised worldwide in highway construction and maintenance activities.

Accordingly, the overall work content has been organised in the following sequence:

- Section 2 indicates the Materials and Methods of this study,
- Section 3 expresses data on Limitations and Restrictions to Completing HICM&R Projects,
- Section 4 displays Cutting-Edge Technologies and Innovations for HICM&R,
- Section 5 displays Renewable Energy and Sustainability Metrics for HICM&R,
- Section 6 indicates Relevant HICM&R Risk Control and Management Strategies,
- Section 7 shows Classic and Latest PM Tools of HICM&R Projects,
- Section 8 indicates the whole Conclusions of this research,
- Section 9 shows relevant Future Work Recommendations, essential to perform more enhancements on the overall research outputs.

MATERIALS AND METHODS

The current research has relied on a systematic methodology to collect necessary secondary data from the global literature, whose major objective is to shed light on primary benefits and advantageous influences of smart maintenance procedures, premature diagnosis strategies, and predictive repairing approaches to conduct efficient conservation activities for highways and large road infrastructure projects, which play pivotal roles in connecting local citizens to principal facilities, like healthcare institutions, schools and universities, public organizations, factories, groceries, etc. Also, this method is necessary to answer the RQs of this work.

To achieve the primary goal of this study, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) information collection and analysis style was chosen. Unlike other review tactics, PRISMA takes into account in-depth statistics, numeric figures, real-world insights, and case studies to strengthen the evidence of the research from the secondary data in the accessible worldwide literature. The primary steps considered and adopted in PRISMA are illustrated in Figure 1(a). Systematic reviews, as shown in Figure 1(b), are characterised by greater contribution, greater relevance, and more rigorous insights than other types of reviews.

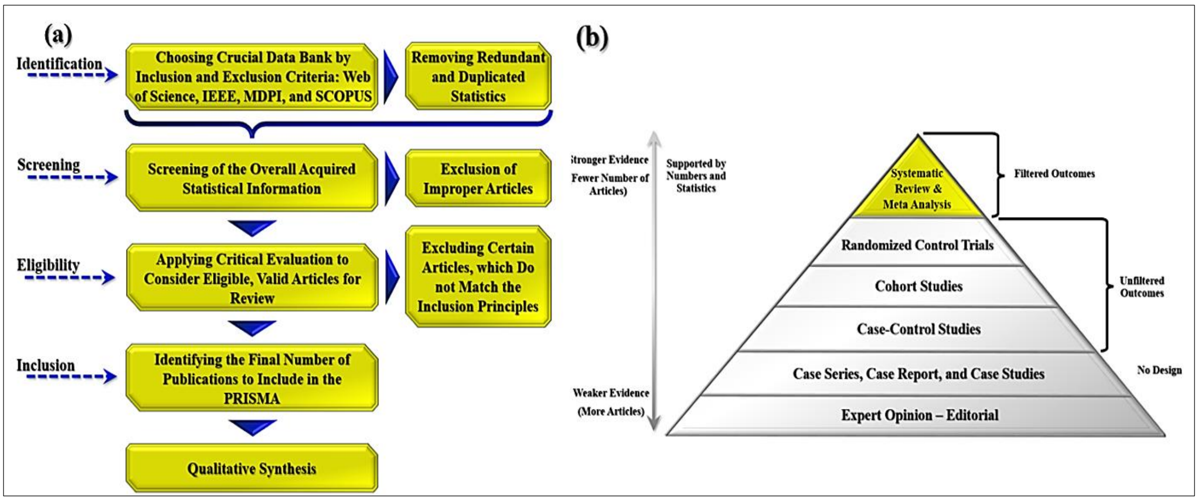

Figure 1: (a) The PRISMA procedure flowchart, and (b) Critical characteristics of the systematic review compared to other review types (Author, 2026)

To bound the overall collected data and exclude unrelated statistics and information from the total acquired data, some inclusion criteria have been applied, as can be seen on the left side of Figure 2, which summarises the main methodological steps of this research.

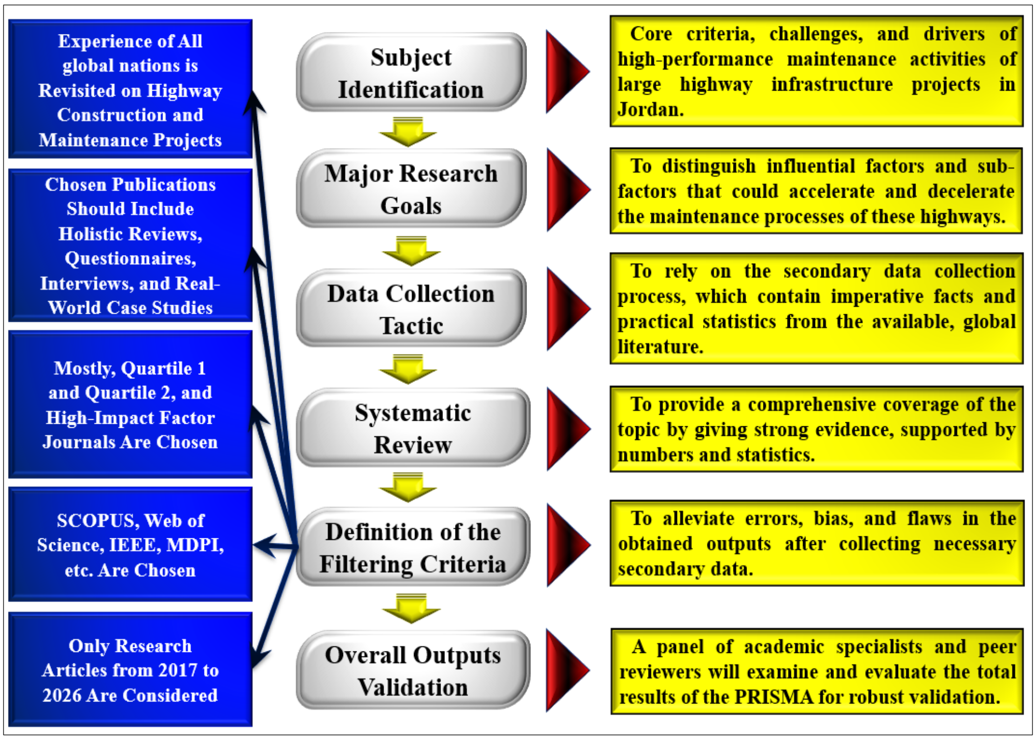

Figure 2: A flowchart of the major research methodology (Author, 2026)

To supply the crucial data bank of this research, a collection of scientific global search engines has been utilised, mainly IEEE, MDPI, ScienceDirect/ Elsevier, Web of Science (WoS), SCOPUS, and some other web engines to offer higher impact journals and Q1 and Q2 papers for most collected works, whose publication year ranges from 2006 to 2026 (two decades). After applying the five main PRISMA steps, the overall outputs have been refined, validated, and reviewed by several academicians, field experts, and engineering professionals with extensive experience in highway construction and maintenance, sustainability, and peer review.

LIMITATIONS AND RESTRICTIONS TO COMPLETING HICM&R PROJECTS

Unlike the construction of domestic facilities and business buildings, HICM&R projects are highly complex, as they involve multiple tasks and long-term activities that must be completed within the planned schedule. Nevertheless, accomplishing such an objective is considered very challenging because these large-scale projects may encounter many kinds of bounding restrictions, like severe weather working conditions, unpredictable soil properties, and substantial difficulties in forecasting the needed large project funding costs. On the other hand, local citizens may feel annoyed or exposed to minimal safety measures at HICM&R work sites. Active traffic management, in this context, is considered essential since road closures may hinder local citizens from reaching urgent places.

Conclusively, HICM&R project managers, chief engineers, and professionals may find many types of problems and hurdles to manage these projects due to increasing corresponding rates of uncertainties and unpredictable working constraints. Therefore, completing these utility-scale infrastructure projects on time is arduous, taking into account ultimate rates of quality, functionality, efficiency, reliability, performance, sustainability, precision, and customer satisfaction. Also, as has been confirmed by many authors, many construction stakeholders face a common issue continually, reflected in frequent registration of submission delays, cost overruns, and litigation. Similarly, Change Requirements (CRs) and Change Orders (COs) happen frequently. These CRs and COs are very problematic, as variations in design and execution can occur, forcing project managers to neglect many criteria and focus on satisfying owners' requirements.

In this respect, Alhawatmeh et al. [24] have shed light on some challenges encountered by project managers in Jordan in completing their HICM&R projects on time. They found that Jordanian laws and regulations are not sufficiently supportive or efficient to enable construction professionals to submit their projects flexibly. Besides, the construction private and public sectors face a record of frequent public COs. Additionally, they confront the shortage of adequate funding for their projects. In addition, in some circumstances, the prices of highway construction materials may fluctuate globally, putting these projects at various risks.

Simultaneously, Alkhawaja and Varouqa [25] conducted a survey questionnaire, involving around 300 construction professionals in Jordan. The critical objective of the questionnaire was to identify their instrumental standpoints regarding the limitations and restrictions that prevented HICM&R projects from being completed. The authors noted that the shortage of adequate infrastructure ranked highest among the obstacles threatening successful HICM&R project submission, with a rate of 86.2%. At the same time, they observed that the contract itself may contain some issues, triggering clashes between stakeholders. This risk has contributed to 85.8%. The latter ratios were recorded for certain risks related to highway infrastructure nodes, notably public regulations, structural concerns within construction companies regarding required responsibilities and procedures, and the lower adoption of safety and protection metrics, which led to elevated rates of injuries and accidents.

More importantly, the research by Al-Hazim et al. [26] has identified 19 main causes of risk and difficulty in completing HICM&R projects in Jordan. Approximately all reports and documents related to Jordanian highway infrastructure construction projects were critically revised between 2000 and 2008. The revision has supplied noteworthy causes of challenges and risks in these large projects, summarized in terrain constraints, extreme climatic situations and irregular weather events, COs, lower availability of labor, mistakes in the design, different values of planned costs, lower availability of necessary resources, greater fluctuations in the price of materials, variations in the planned time, labor fatigue because of emergency work duties and extra labor commitment, lower quality of raw materials, tools, and/ or equipment, delays in payments, excessive costs of COs, political issues, tough governmental restrictions, frequent rework problems due to lower laborers experience, delays in taking crucial decisions, management issues of laborers, and challenges in work sequencing referring to the schedule.

In a longitudinal, comparative analysis conducted by Wu et al. [27], the authors aimed to identify the key strengths and limitations of strategic, actionable plans and holistic approaches utilised in highway construction projects. A special focus was given to those frameworks that are connected to environmental protocols for highways. From their analysis, it was realised that both lands lack diversity and variation in environmental protection strategies and highway systems. Moreover, it was noticed that the USA exhibited an explanatory-related tendency to adopt ecologically friendly approaches, highlighting the impacts on human health.

Additionally, it was observed that those two developed nations have implemented enhanced environmental decision-making procedures to foster the sustainability of the local environment, since large expressway infrastructure projects can pose significant physical threats. Their analysis considered a comprehensive analysis of historical strategies and cutting-edge programs applied to protect and secure the environment, specifically between 1960 and 2018. Also, they utilised mining-related estimation materials published between 2009 and 2019. In addition, it was found that Chinese policies have focused on minimising pollution, while US strategies have taken into account the effects on human health.

CUTTING-EDGE TECHNOLOGIES AND INNOVATIONS FOR HICM&R

Lately, AI, ML, DL, and many other innovative technologies have entered nearly every discipline, including manufacturing, medicine, agriculture, education, computer and information technology (IT), and more. However, the adoption of these advancements is still scarce in the construction sector. This is not due to their initial capital costs. Conversely, these tools, such as smart IoT sensors, are widely available and inexpensive, and can be attached to many real-world subjects to collect Big Data. Nonetheless, as previously stated, and as will be discussed in later pages of this work, project managers and chief engineers cannot take into account sufficient time to analyse these data and implement these advanced instruments due to their primary focus on responding to CRs and COs of customers, and achieving all project tasks on time, which are all considered complex duties.

Therefore, those consultants can typically prioritise other project needs and tasks over implementing these technologies in their project. As a result, a practical knowledge gap exists, translating into a lack of sufficient global evidence-based practices for AI, ML, DL, IoT, and other technologies in the construction sector, including HICM&R projects.

In this respect, Zhang et al. [28] have remarked on the practicality, functionality, and contributions of recent 5G technologies to digitalise many amenities in the highway infrastructure, including railways, urban nodes, highway networks, and pipelines, making them smart by connecting them to governmental official management and control facilities. Those authors have also affirmed the latest technological advances in traffic monitoring and in flexibly reducing accidents and emissions. For this reason, local environment protection, citizens' safety, and transportation efficiency can be promoted. Countries such as Europe, the USA, Japan, China, and others implement these efforts. Also, connected automated vehicles (CAVs) and automated vehicles (AVs) have been adopted in some countries, such as Italy, contributing to smart, efficient highways.

By comparison, China is investing substantial capital to construct smart motorcycle lanes to facilitate individual travel between locations. The same country is investing in 5G to connect many infrastructure components to the Internet, therefore, offering flexible control and management. One of the crucial characteristics of smart transportation, according to the same authors, is its capability to address common errors and limitations of traditional transportation systems and to enhance the decision-making process by offering real-time data and predicting abnormalities and accidents to repair them swiftly, thereby ensuring smoother traffic throughout the day. Cyber-physical systems have also been innovated in Industrial Revolution (IR) 4.0, to protect Big Data from unauthorised access. Latest smart traffic management (STM) systems leverage intelligent sensing tools, advanced control equipment, and innovative detection instruments to reliably and efficiently address abnormal conditions on the road. The major process flowchart through which data is collected, stored, and analysed for necessary decision-making is shown in Figure 3(a). In addition, Figure 3(b) illustrates the IoT architecture for computing distribution utilised in smart traffic management systems.

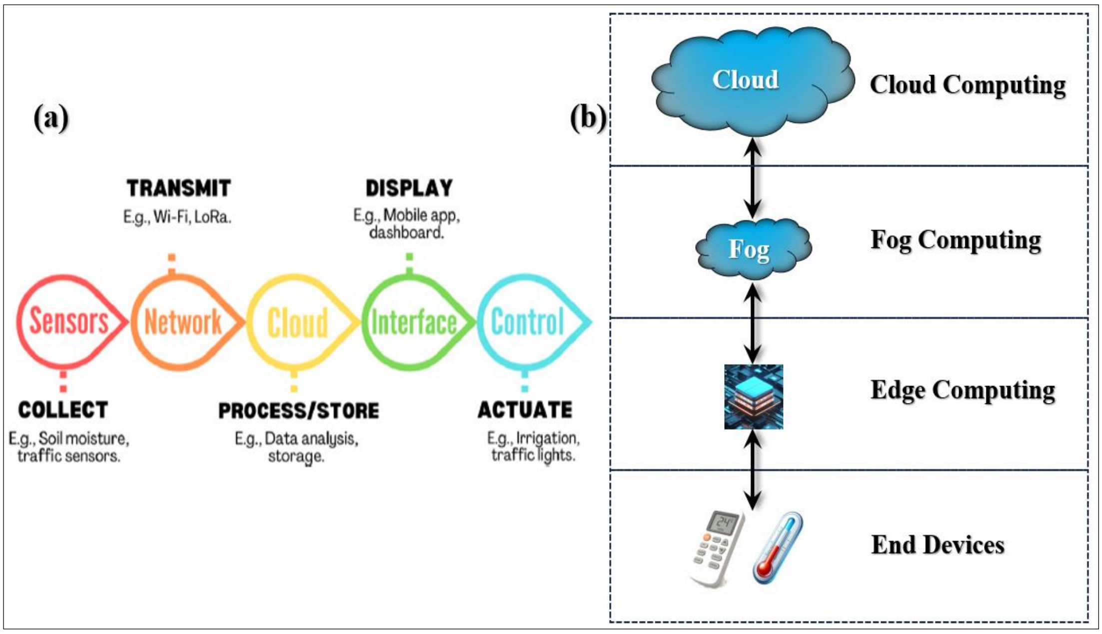

Figure 3: (a) The smart traffic management system decision-making process flowchart and (b) the IoT architecture related to computing distribution [17] [20]

The smart innovations crucial for intelligent highway construction and maintenance also include other technologies, such as unmanned ground vehicles (UGVs), and those expressed in Figure 4.

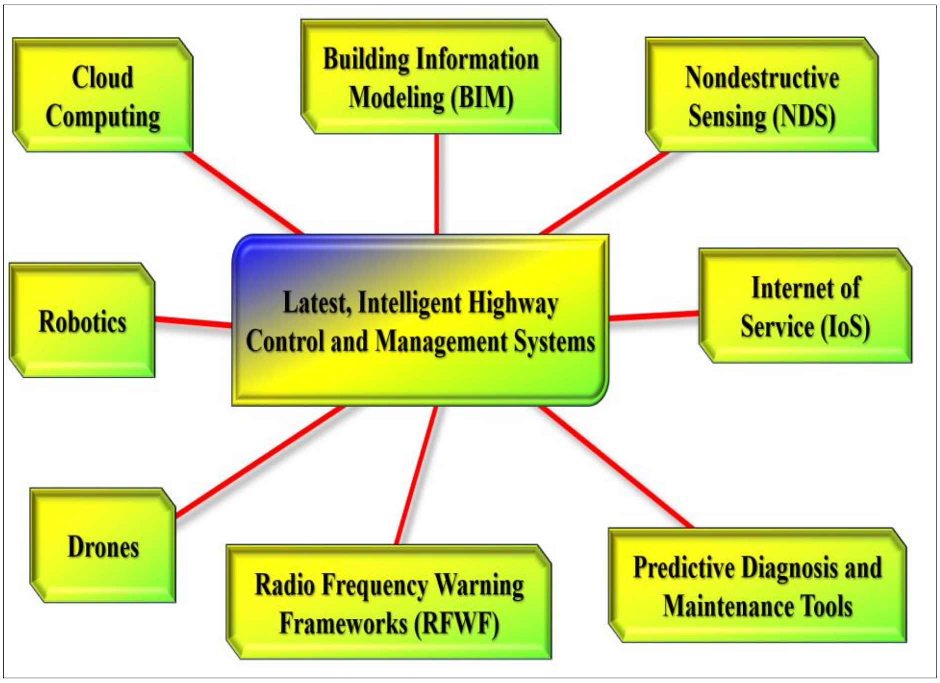

Figure 4: Other innovative equipment and advancements for smart highway and traffic management systems [17] [19] [29]

These IoT frameworks can support governmental officials and traffic consultants in identifying fluctuations, uncertainties, and irregular events, providing structural integrity, responding to current environmental conditions, and existing operating loads. Accordingly, these advanced tools can issue crucial alerts and facilitate automatic responding solutions to overcome any challenge [19]. These facts have also been confirmed by Natan et al. [30] and Rehman and Islam [31].

Also, Micko et al. [29] have classified the main sensor tools and detection instruments that can record the necessary real-time data for analysis from highway infrastructure amenities. A taxonomy of these sensors can be displayed in Figure 5.

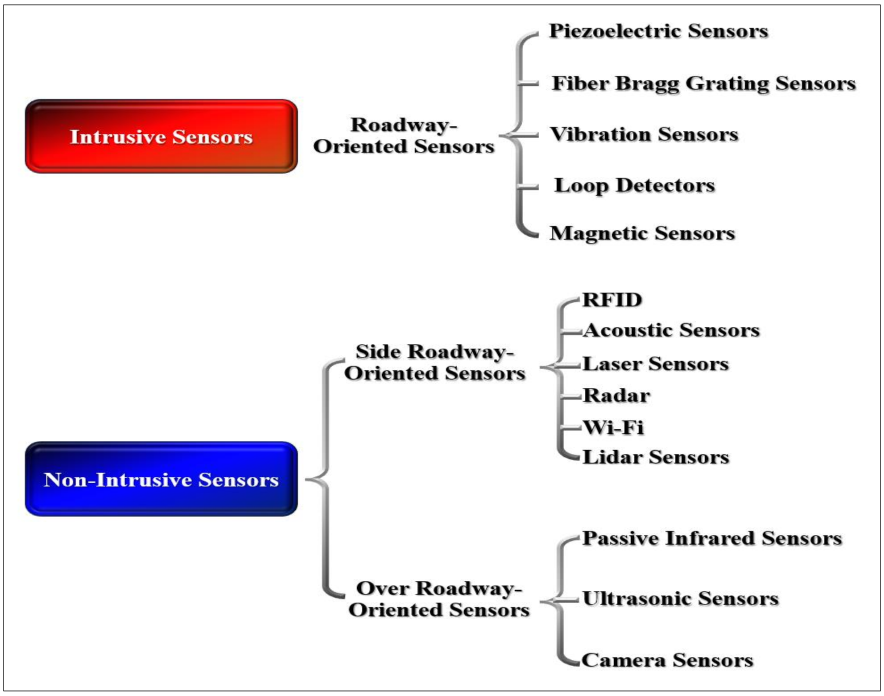

Figure 5: A taxonomy of main sensing technologies and detecting devices for recording real-time data from highways [20]

RENEWABLE ENERGY AND SUSTAINABILITY METRICS FOR HICM&R

Nowadays, based on a review of most global publications, it can be observed that academics and practitioners across many engineering disciplines have linked their research outcomes and objectives to renewable energy (RE) codes and sustainability metrics. For example, the annual US Department of Transportation (DOT) report (2024) has remarked on some recent trends, explaining that the US transportation sector has accounted for approximately 33% of the overall GHG emissions in the USA, which is considered the greatest share compared to other sectors, as can be seen in Figure 6. By 2017, the US transportation sector had surpassed the electricity sector, becoming the dominant source of GHG emissions. Also, the report noted that GHG emissions from US transportation rose steadily from 1990 to 2005. After GHG emissions from transportation reached their peak, the ultimate value in 2005, they declined throughout the recession between 2007 and 2009. It was also noted that these emissions increased during 2019. Then, their amount did fall obviously during the Coronavirus Disease 2019 (COVID-19) Pandemic. So did the GHG emissions from the transportation sector in many countries, due to global quarantine and movement restrictions. Then, US GHG emissions have risen again, but are still lower than 2005 levels.

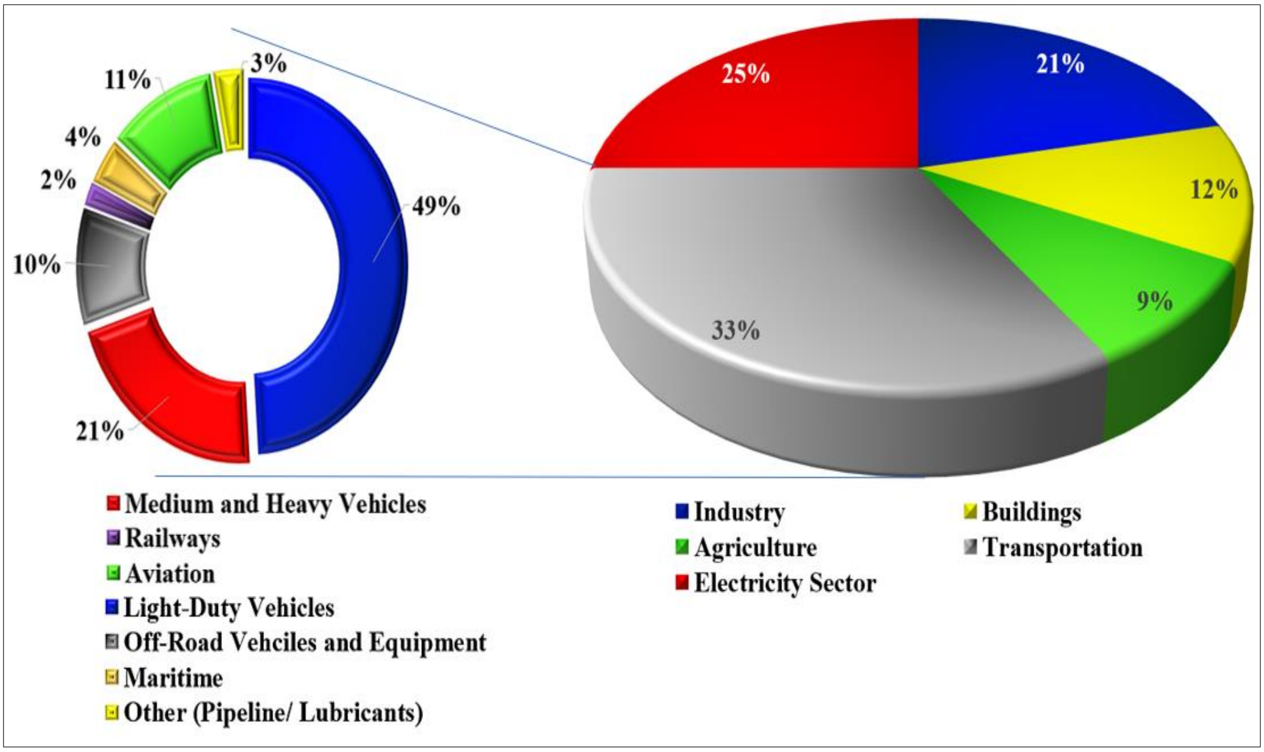

Figure 6: Share of GHG emissions in the USA by sector in 2022 [32]

Besides, the US construction, energy, and transportation engineers have adopted a collection of comprehensive, strategic plans of action to minimise the annual production of GHG emissions in the USA. These approaches are reflected in improvements to the planning of society, design, and land use. Also, US engineers have expanded the range of options for efficient transfer. Moreover, they adopted a transition system to zero emissions by manufacturing, marketing, and enabling local citizens to utilise hybrid and battery-electric vehicles (BEVs), as can be shown in Figure 7.

In addition, the US energy, construction, and transportation engineers have conceptualised a strategic energy plan and GHG emission reduction tactic, whose aim is to record very low amounts of emissions and pollution by 2050, as can be clarified in Figure 8.

As can be inferred from Figure 8, the US transportation sector, along with other sectors, would record approximately zero emissions by 2050 despite the dramatic rates of urbanisation and global population growth. Speaking in terms of crucial environmental metrics, which are heavily recognised these days, namely sustainability, in a PhD work, Odibat [33] has pointed out the importance of applying recent renewable energy (RE) management advancements and practising value engineering (VE) to support engineering in minimising the total energy consumption and excessive costs spent in HICM&R projects in Jordan. Also, Odibat [33] has elucidated the massive capability of Jordan's natural resources, especially solar radiation and a higher annual temperature profile, to provide favourable RE production to replace fossil fuels and minimise GHG emissions.

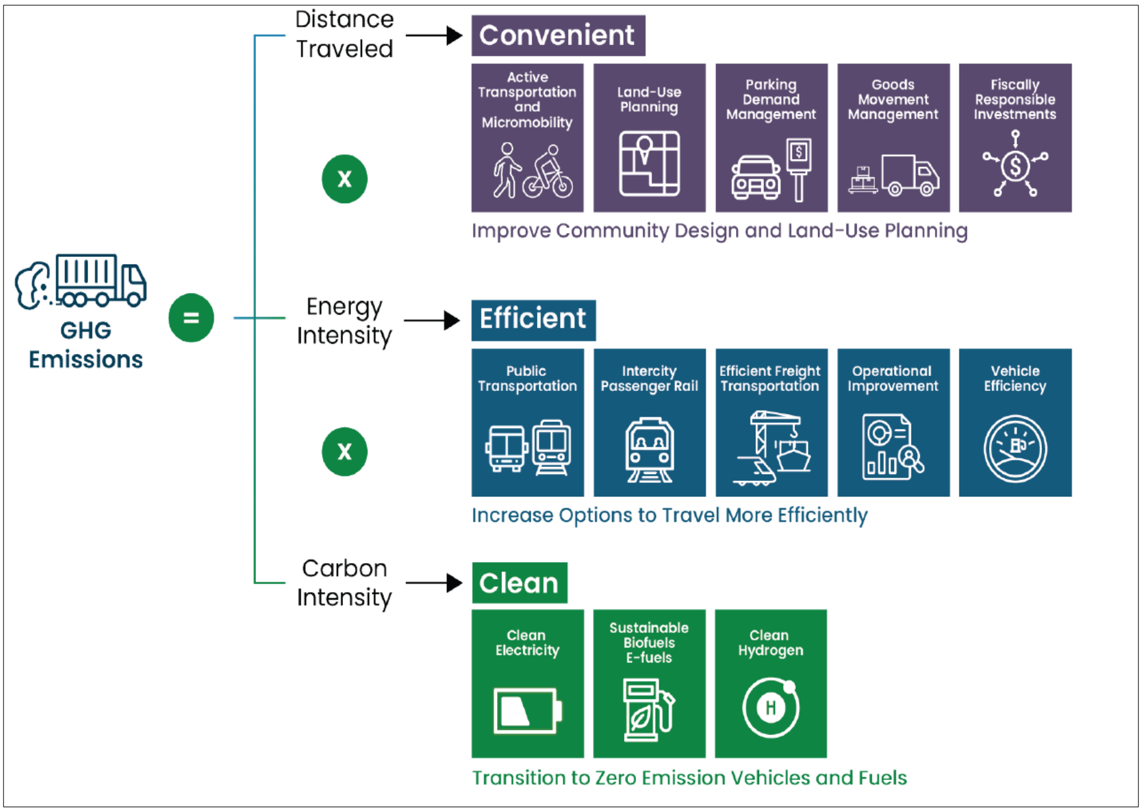

Figure 7: Different strategies to transfer into a safe, sustainable, high-efficiency US transportation sector [32]

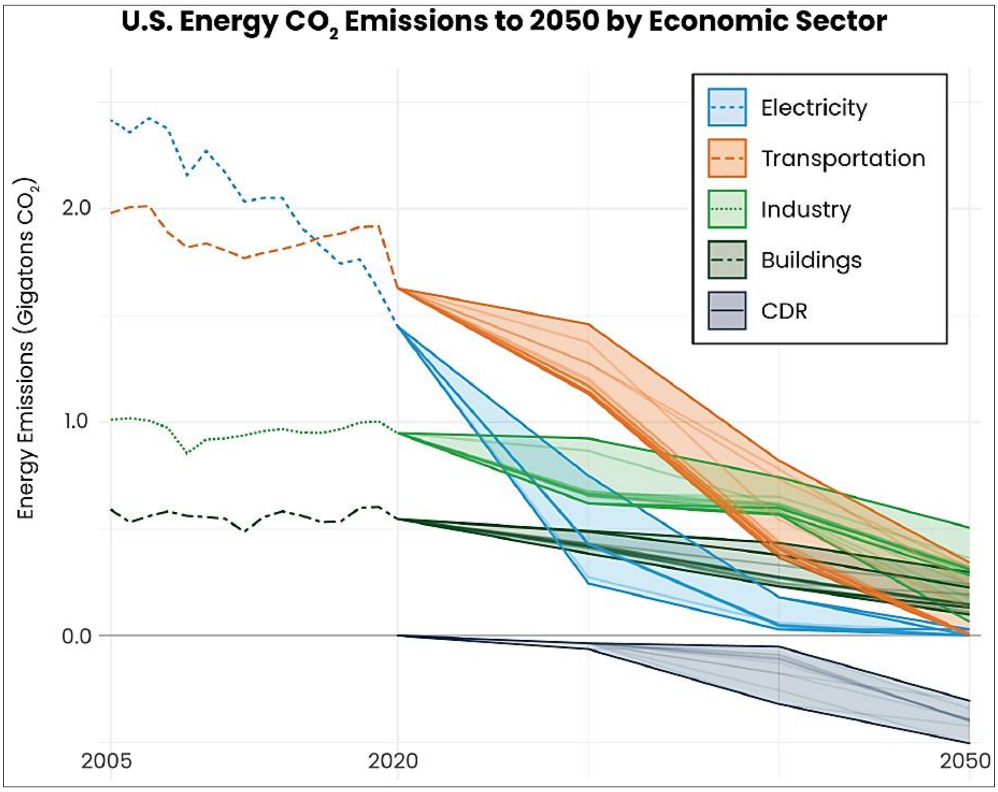

Figure 8: The US future roadmap to transition into an energy-efficient, sustainable, and safe transportation sector [32]

Additionally, the author has clarified the high viability and promising outputs of solar photovoltaics (PV) projects to alleviate the substantial costs required to achieve optimal levels of safety, reliability, performance, sustainability, durability, and efficacy at many Jordanian highway nodes. Besides, it was realised that VE and RE adoption could help accomplish preferable levels of economic savings to the total consumed energy (up to

24.43%), and a proactive alleviation in carbon dioxide emissions (22.30%), as well as improved energy stability (up to 19.18%).

Another PhD study was conducted by Alhawatmeh [34]; the author evaluated critical, influential benefits of supply chain management (SCM) to optimise the effectiveness of HICM&R projects, thereby minimising a prevalent problem: delays in project completion. Many scholars have explored this annoying issue for more than four decades due to weaker highway infrastructure. Also, it was realised that public bidding systems are not currently adequate or well-formulated to provide flexible choice, oversight, and execution of HICM&R projects. The author utilised semi-structured interviews (SSIs), covering various construction consultants from the public and private sectors. SSIs revealed that major obstacles to complete HICM&R projects timely include (1) the shortage of proactive laws and regulations, (2) the significant frequency of public CRs and COs, the scarcity of funding resources, (3) the shortage of laborers in this sector, and (4) issues between local contractors, reflected in low experience in HICM&R projects that lead in costly rework mistakes, besides other errors in precisely predicting the overall project budget to supply sufficient capital for the project. Simultaneously, it was noticed that (5) contractors could encounter different challenging hurdles because of varied prices and shortages in the supply of necessary materials.

Aljboor *et al.,* [13] utilised a survey questionnaire, a critical overview, and a case study to identify major drivers and challenges of sustainable HICM&R projects in Jordan. Rankings have been conducted by experts on each risk that was chosen from the literature. These risks involved (1) the shortage of education among engineers on crucial sustainability principles, (2) the deficiency of the engineering curricula since it does not consider sufficient skills, criteria, and content on sustainability, (3) the lack of talents, knowledge, familiarity, and skills among project managers, senior engineers, and laborers in adopting sustainability, (3) the shortage of practical evaluation tools to estimate sustainability, (4) most engineering and academic communities consider sustainability criteria as a complementary subject not a principal theme, (5) the scarcity of experience, case studies, and real-world HICM&R projects, which implement crucial sustainability standards, (6) significant scales of unawareness, hesitancy, and lower understanding pertaining to the application and relevance of core sustainability rationale, (7) the deficiency of consistent coordination, communication, collaboration, and consolidation between different HICM&R project stakeholders to facilitate sustainability adoption, (8) the resulting costly expenses of various types of resources utilized to apply sustainability standards, (9) At most times, priorities are given for troubleshooting many issues and flaws in the project, neglecting the crucial application of sustainability, (10) limited availability of platforms and worldwide software packages that implement sustainability, and (11) uncertainties, vague scenarios, and difficulties in predicting future risks that may emerge when applying major principles of sustainability.

RELEVANT HICM&R RISK CONTROL AND MANAGEMENT STRATEGIES

Developing and developed countries, like the USA, all face frequent events of risky accidents and fatal injuries among drivers and pedestrians, which have been recorded in many HICM&R projects [35]. Through a critical review of numerous reports issued by the Fatality Assessment and Control Evaluation (FACE) division, the authors, i.e., Al-Bayati et al. [35], have explored key risk factors recorded during HICM&R projects in the USA. It was found that the main factors that could cause fatal injuries and risks would include (1) the lack of active traffic management, corresponding to serious accidents around the highway working zones, (B) the shortage of adoption of suitable tools and equipment (like speed reduction signs and traffic shading) to regulate traffic within the HICM&R projects even with the prevalence of necessary traffic and pedestrian control laws, (C) unsuitable infrastructure around the HICM&R project (e.g. repetitive accidents recorded in two-lane highway project work areas), (D) drivers, taking alcohol and drugs, and (E) implementation of old-style traffic control and management approaches.

Given these consequences, it is crucial to adopt practical approaches and the latest risk evaluation tools for use at the sites of HICM&R projects. In this context, Zhasmukhambetova et al. [36] have identified functional, qualitative risk estimation frameworks, whose application can be efficient and advantageous to provide high-precision estimations and categorisation of the scales of danger and hazards of each risk at these sites. The kinds of practical risk estimation approaches and their corresponding roles can be clarified in Table 1.

Table 1: Instrumental approaches to risk evaluation for highway construction and maintenance projects [36]

#	Type of Risk Evaluation Strategy	Explanation	Citation
1	HAZOP (Hazard and Operability Estimation)	A structured approach to risk and hazard estimation.	[37]
2	Risk Breakdown Structure (RBS)	A hierarchical organisation of risks.	[38]
3	Risk Classification	Categorisation is made to distinguish a collection of risks.	[39]

#	Type of Risk Evaluation Strategy	Explanation	Citation
4	Failure Mode and Influences Analysis	An evaluation given for corresponding impacts that may emerge from certain risks.	[40]
5	Risk Scenario Analysis	An analysis was conducted to identify potential risks by presuming dangerous situations.	[41]
6	Risk Root Cause Analysis	A structured strategy to distinguish principal kinds of hazards.	[42]
7	Cause-and-Effect Schematic	A diagram that clarifies the root causes of risks.	[43]
8	Brainstorming	A group of individuals who collaborate to provide estimates of risk.	[44]
9	Expert Judgement	Enabling specialists to give their opinion to estimate the hazard level.	[45]
10	Delphi Strategy	An iterative-oriented risk identification referring to the experts' viewpoint.	[18]
11	Checklists	A predefined, guiding risk list to assess the scale of risk.	[46]
12	SWOT Analysis	An analysis strategy, consisting of four tactics: 1) Strengths, 2) Weaknesses, 3) Opportunities, and 4) Threats.	[47]
13	Risk Matrix	A matrix that categorises all types of hazards through likelihood and corresponding impacts.	[48]
Explanation of risk evaluation strategy No. 13, i.e., risk matrix, can be found in Appendix B.			

In comparison, the same scholars have identified other classes of risk estimation procedures, which are mainly linked to the provision of probabilistic figures and statistical facts that best indicate the extent to which highway hazards at HICM&R projects would create uncertainties. Table 2 displays these styles of risk evaluation strategies along with their roles.

Table 2: Practical classes of statistics-oriented risk estimation for highway construction and maintenance projects [36]

#	Type of Risk Evaluation Strategy	Explanation	Citation
1	Markov Chains	It utilises probabilistic models to identify system changes referring to existing state conditions.	[49]
2	Network Theory	A strategy that relies on models' dependencies and hazards within connected systems.	[50]
3	Bayesian Networks	Bayes' theory is used to estimate conditional probabilities based on related models' variables.	[51]
4	Cost Hazard Estimation	An approach that quantifies uncertainties and variability in the project budget to predict cost overruns.	[52]
5	Fuzzy Set Theory	It can manage vague, missing, and uncertain information to provide precise predictions on hazards.	[51]
6	Sensitivity Analysis	An estimation whose application can help provide the pattern of outputs referring to the values of inputs.	[41]
7	Analytic Hierarchy Process	A structured procedure that exploits pairwise comparisons to give priorities to each risk.	[40]
8	Decision Tree Estimation (DTE)	An analysis that plots a diagram of current risks and their corresponding decisions.	[53]
9	Event Tree Evaluation (ETE)	An analysis that plots various existing scenarios and their predicted outcomes.	[36]
10	Fault Tree Estimation (FTE)	A top-down logical schematic for estimating failures associated with each type of risk.	[54]
11	Probability-Effect	A strategy that assigns impact scores and interdependencies to quantify risks.	[55]
12	Expected Financial Value	An approach that computed the weighted average of expected monetary outputs referring to hazard probabilities.	[53]
13	Monte Carlo Simulations (MCS)	Random sampling is utilised to model uncertainties, thereby producing probability distributions.	[41]
An illustration regarding the risk estimation approach No. 8 can be clarified in Appendix B.			

From the US Department of Transportation statistical report, issued by the Federal Highway Administration by Ashley et al. [48], which considered a conceptual risk estimation process, as indicated in Figure (4) (a) and allocation for highway construction management, the authors have reported that the risk management process of HICM&R projects can refer to six-step method, which can be illustrated in Figure 4 (b). Ashley et al. [48] have also introduced a configuration that elucidates the five major steps of the risk management process, as shown in Figure 4(c). Additionally, they explained the risk management and cost validation processes adopted by the Washington State Department of Transportation (WSDOT). The US highway community has also created the Cost Estimation and Validation Process® (CEVP), whose configuration and principles can be illustrated in Figure 4 (d). In addition, Tables 3 and 4 in Appendix A present a table for estimating and analysing HICM&R project risks, referring to the project phase and the main responsibilities related to the risk analysis activities credited to the same author. The same authors have introduced a top-level cost-risk estimation diagram, which is shown in Figure 10.

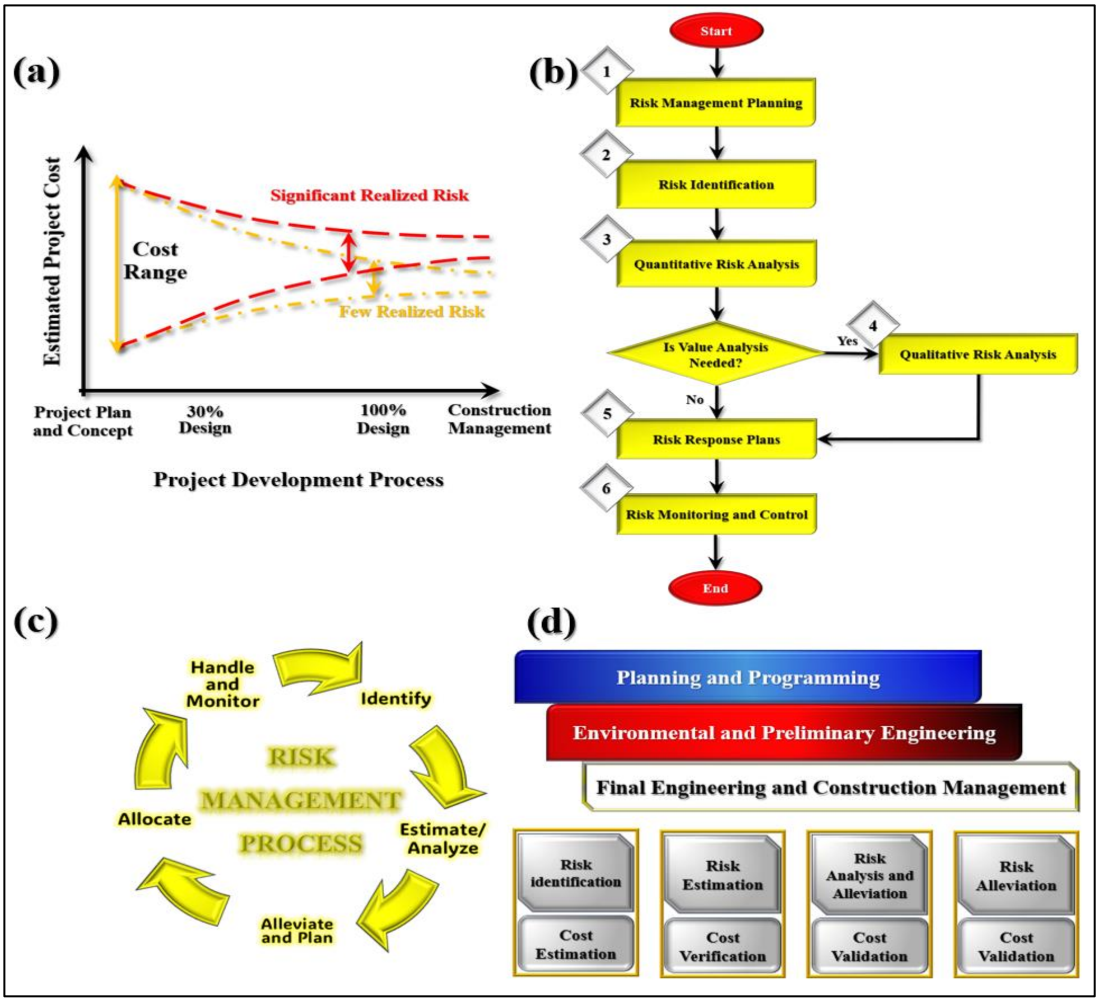

Figure 9: (a) A flowchart of a six-step risk control procedure, (b) conceptual refinement related to the cost estimation process, (c) the risk management process, and (d) the Cost Estimation and Validation Process® (CEVP) [48]

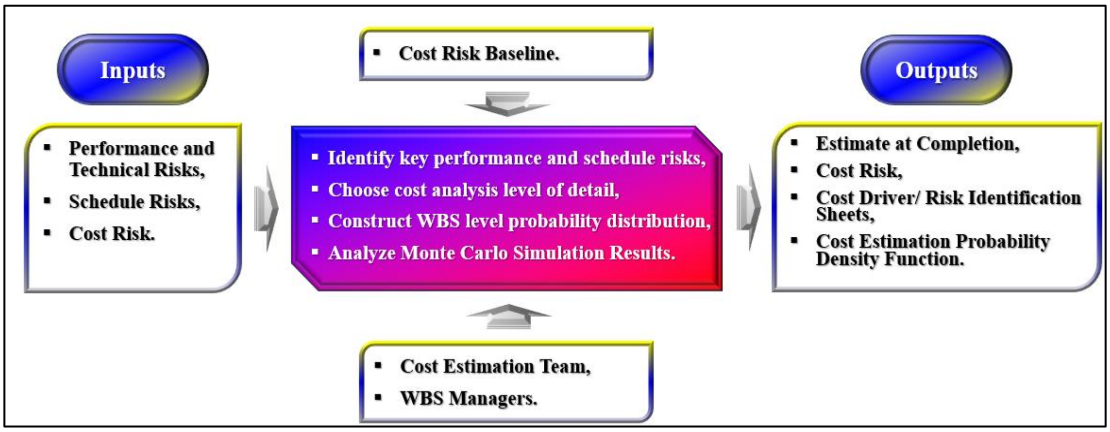

Figure 10: Top-level cost risk estimation diagram [48]

Besides, Ashley *et al.,* [48] have introduced mathematical correlations and models for various risk variables in highway construction projects. For example, the summation of risk variables, Y, can be expressed in the following:

$$Y = \sum_{i=1}^{N} x_i = x_1 + x_2 + x_3 + \cdots + x_N, \quad (1)$$

where x is the risk variable, and i is the risk index. N is the number of the overall risks. In addition, they modelled the average value of risks, such that [48]:

$$E(Y) = \sum_{i=1}^{N} E(Y) = \sum_{i=1}^{N} E(x_i) = E(x_1) + E(x_2) + E(x_3) + \cdots + E(x_N), \quad (2)$$

To estimate the variance of the total risky variable, the following equation can be harnessed [48]:

$$\sigma_Y^2 = \sum_{i=1}^{N} \sigma_{x_i}^2 = \sigma_1^2 + \sigma_2^2 + \sigma_3^2 + \cdots + \sigma_N^2, \quad (3)$$

When another risk estimation procedure is conducted to distinguish the impacts of some risks on others, the mathematical product can be utilised. So [48]:

$$Z = x_1 * x_2 * x_3 * \ldots * x_N, \quad (4)$$

Similarly, the corresponding average value can be evaluated relying on the following formula [48]:

$$E(Z) = E(x_1) * E(x_2) * E(x_3) * \ldots * E(x_N), \quad (5)$$

And therefore, the variance can equal [48]:

$$\sigma_Z^2 = \left[E(x_1)^2 * \sigma_{x_2}^2\right] + \left[E(x_2)^2 * \sigma_{x_1}^2\right] + \cdots + \left[E(x_{N-1})^2 * \sigma_{x_N}^2\right], \quad (6)$$

At the same time, Castañeda et al. [15] have provided a quantitative ranking of major causes and influential factors of scheduling risks, PM challenges, and deficiencies, which have taken place in HICM&R projects. This quantitative estimation was examined through three critical equations. The first and second formulas express the Relative Frequency Index (RFI) and the Relative Severity Index (RSI). The correlations of both indices can be expressed as follows [15]:

$$RFI = \left(\frac{\sum_{i-1}^{N} f_i}{N\ x\ f_{Max}}\right) \quad (7)$$

$$RSI = \left(\frac{\sum_{i-1}^{N} s_i}{N\ x\ s_{Max}}\right) \quad (8)$$

where f_i and s_i indicate the corresponding weights of frequency and severity, respectively. While f_{Max} and s_{Max} are the ultimate probable weights of the frequency and severity, respectively. *N* is the overall number of valid responses from the survey questionnaire forms, distributed to identify these factors, and *i* is the evaluator value.

To offer insights into the impact of each cause by integrating its occurrence frequency and perceived severity, the RII index, which expresses the Relative Composite Index, can be introduced. It can support supplying a ranking of each rank, along with its relative importance. The given ranking value can aid scholars and engineers in identifying the major reasons, factors, and causes that necessitate greater attention, awareness, and specialised management to enhance the planning, control, and prevention of challenges in these HICM&R projects. The *RII* can be calculated relying on the following formula [15]:

$$RII = RFI * RSI \quad (9)$$

In addition, the RII rate can provide a better idea of the effect of each problem/factor and its relationship to other factors/causes.

CLASSIC AND LATEST PM TOOLS OF HICM&R PROJECTS

To distinguish the extent to which the latest scheduling and PM approaches are practical, workable, and efficient, like agile PM (APM), lean management, Kanban, and SCRUM, it is essential to cite the major old-fashioned PM, scheduling, and time arrangement strategies. Therefore, project managers and construction consultants can gain a better understanding of how they can overcome many uncertainties and complexities in HICM&R projects.

In this regard, Figure 3 shows old-style scheduling tools that may hinder planners and engineers from efficiently tracking and managing project tasks. As shown in Figure 3, CPM focuses on identifying the longest path to minimise duration. PERT utilises 3-point estimates to determine probabilistic intervals. In comparison, Gantt charts can be created to present bar diagrams, showing activities, their corresponding intervals, and progress. Simultaneously, LoB facilitates the graphical display of repetitive tasks to ensure continuity. Likewise, PDM utilizes graphical shapes to express project tasks. In parallel, heuristic scheduling procedures are also employed to provide rule-oriented, swift organisation of project activities and resources. Yet, it is well-suited for projects with simple tasks and activities of greater time sensitivity.

In a similar context, Sultan et al. [56] have critically reviewed various traditional PM tools (including those shown in Figure 11) and the latest PM and scheduling strategies. They explained that conventional scheduling mechanisms, such as CPM, often struggle to adequately handle complex tasks. Additionally, the LoB strategy can supply limited scheduling flexibility and performance when it is implemented in geographically-dispersed highway construction and maintenance projects with elevated nonlinearities. As a result, achieving effective resource allocation in Scattered Repetitive Projects (SRPs) would be an arduous challenge.

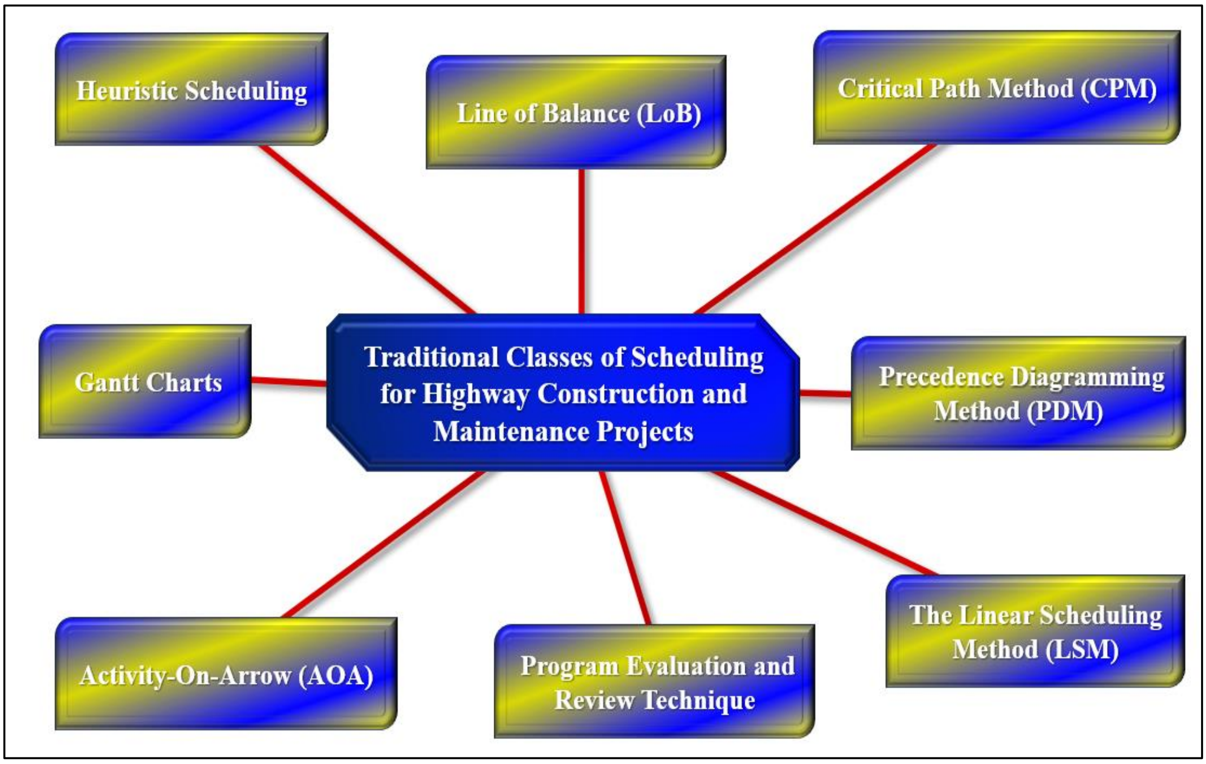

Figure 11: Old-style schedule management tools in HICM&R projects [36]

Moreover, Sultan *et al*. [56] have classified the major PM approaches into three major categories: (A) mathematical optimisation models, (B) heuristic planning tactics, and (C) metaheuristic/ hybrid strategies. They evaluated them using explicit criteria that included decision variables and captured constraints (such as crew continuity, travel times, hard/soft logic, multi-crew correlations) and solution characteristics (which can optimally confirm effectiveness in relation to scalability). They also considered management of uncertainties, including reactive, fuzzy, robust, and stochastic complexities. They investigated adoption readiness, considering information requirements and technology integration.

From Figure 3, it can be noted that the Linear Scheduling Method (LSM) is another PM tool utilised in HICM&R projects. This approach is primarily used for linear projects, such as highways and pipelines, especially those with frequent, sequential tasks. Yogesh and Rao [57] have also investigated the use of LSM for road construction projects. Their critical findings confirmed the advantageous impacts of LSM in performing efficient and optimal project scheduling of these large-scale highway projects through project duration forecasting. The scholars also noted that LSM can minimise idle resource time and deliver greater efficiency than other PM styles. In addition, Figure 3 indicates that Activity-On-Arrow (AOA) uses arrows to organise activities and provides corresponding nodes for each milestone. Actually, AOA is considered a kind of CPM model. However, it has been largely replaced by the PDM-oriented CPM in the latest project scheduling activities across many projects owing to its greater efficiency and flexibility.

CONCLUSIONS

Highways and large road infrastructure nodes play various practical roles in facilitating the economic and social growth of each land. Therefore, constructing high-performance road facilities is pivotal. Nonetheless, these large amenities are subject to various forms of permanent degradation, annual decay, and damage due to rapid urbanisation, excessive numbers of vehicles on the routes, and associated factors such as GHG emissions, which can cause faster deterioration of road materials and stress on the current highway infrastructure.

In this respect, it is essential and influential to ensure the provision and adoption of adaptive, efficacious, workable, and functional HICM&R tactics. Nevertheless, many lands face various common boundaries and arduous obstacles that hinder them from adopting sufficient HICM&R measures. Therefore, this PRISMA research was conducted to highlight the most significant constraints and challenges, enabling stakeholders, construction and maintenance consultants, and project managers of highway networks to propose appropriate solutions and comprehensive, strategic plans of action to eliminate most of these problems. The summary of the overall PRISMA work can be elucidated in the following points:

- The worldwide literature confirms the importance of enabling the global construction sector to adopt recent technologies, innovations, and cutting-edge tools to accelerate HICM&R activities, since the levels of quality, serviceability, durability, reliability, performance, and efficacy of large road networks should be optimal. Unfortunately, the prevalence of these state-of-the-art tools is still slowly growing in this sector,

- The recent global literature contains new styles of risk evaluation approaches that have overcome the bounding restrictions prevalent in traditional risk estimation mechanisms, namely probabilistic and statistical risk tools. These latest tools have helped project managers and HICM&R consultants supply ultimate precision, statistical data, and reliability in predicting expected risk scenarios when the current HICM&R projects face certain constraints,
- Organisation of normal-day traffic is considered very imperative to alleviate extra costs needed for maintenance of highway road networks since higher traffic density can accelerate excessive wear, degradation, consumption of fuel, and GHG emissions,
- Frequently, it has been reported that many lands do not commit to the ultimate proportions of PM standards, guidelines, and frameworks, resulting in many accidents, low performance of traffic management, and injuries around the HICM&R work areas,
- HICM&R encounter funding gaps. For this reason, a bottom-up multi-goal HICM&R decision-making procedure is crucial to optimise regular HICM&R expenses, user expenses, which include costs of fuel and tyre replacement, and environmental protection costs due to GHG emissions,

The literature affirms the importance and relevance of PPP frameworks because they can enable the following:

a) Enhanced communication, consistent coordination, collaboration, consolidation, and exchange of multiple experiences from both public and private construction sectors about HICM&R,

b) Active management of limitations existing in the public sector (e.g. the shortage of funding and the lack of implementation of cutting-edge, latest technologies and breakthrough innovations in HICM&R, such as AI, ML, DL, IoT, etc., the shortage of engineering experience, and more), and those obstacles frequent in the private sector (like the lack of active, sufficient, practical legislations and incentives). The reason is due to efficient win-win strategies and two-sided collaboration,

c) A balanced risk-sharing can be attained, preventing either public or private construction companies from enduring greater scales of risky situations, especially those that are common, like cost overruns and submission delays in these large-scale HICM&R projects,

d) PPP can enable long-term provision of innovation, creativity, success, and advancements because of permanent collaboration between those two sectors in HICM&R,

- The available literature cites, referring to the standpoints of many surveyed and interviewed consultants, and publications' authors, that the public sector in many lands does not take seriously different kinds of feedback, reported complaints, frequent comments, and notes into account, which are recorded from local users of highways and pavements regarding the occurring damage to these amenities. This issue has corresponded to degraded satisfaction,
- Currently, fewer lands implement recent, proactive predictive diagnosis strategies and premature repair and maintenance technologies regularly, which can remarkably minimise corresponding maintenance activities and very costly HICM&R tasks,
- Many countries lack the use of the latest testing instruments and equipment for pavement and road facilities, such as concrete and asphalt. As a result, this may pose challenges to maximising the lifespan, performance, reliability, durability, and serviceability of these large road networks. It would also result in high costs in future repair procedures.

FUTURE WORK RECOMMENDATIONS

Relying on the total PRISMA outputs of this work, the latter does suggest a set of future work recommendations and specific, practical suggestions that could be considered and adopted by scholars and stakeholders in the same discipline to further amend the current rationale and contributions of this research. These suggested recommendations contain the following affairs:

- To explore key drivers and restricting limitations that can largely influence the adoption and practice of newly-emergent technologies, latest solutions, and innovative advancements in the construction sector to accelerate and facilitate HICM&R activities in developed and developing lands,
- To investigate practical strategies and efficient methods that can enable the public sector to respond, take into account, and handle frequent complaints, problems, notes, and reported issues on damage and hazards existing in the available road and highway networks,
- To conduct a comparative analysis between multiple case studies of HICM&R procedures from many nations to shed light on success

factors and critical restrictions that could limit and decelerate the HICM&R tasks,

- To highlight new PM approaches, such as APM, which is rarely discussed in the available literature as a new PM strategy, and to explain its relevance for HICM&R projects.

Author Contributions: Al-Ahdab: Systematic Review, PRISMA, Methodology, Overview, Construction, Highway Maintenance Investigation, Project Management, Statistical Analysis, Conceptualisation, Comparative Analysis, Materials and Methods, Examination, and Writing.

All authors have viewed and accepted the published version related to the manuscript.

Funding: This study has not received any type of external funding.

Data Availability: The overall survey questionnaire data and corresponding statistical analysis can be provided by the authors upon request.

Conflicts of Interest: The authors of this study declare no known competing financial interests or personal relationships that may adversely affect the results of this research.

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