

Enhancing Infrastructure Reliability Through Risk Identification: A FMEA-based Failure Analysis in Indonesian Road Construction

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Abstract

The high failure rate of infrastructure projects, especially road construction projects in Indonesia, has reached an alarming level. The failure often originate during the planning, tendering, supervision, and construction phases. Many infrastructure projects fail to meet engineering standards and contracts requirement, leading to functional failures, reduced service life, safety issues, inconvenience, and high maintenance and operating costs. This paper presents a failure analysis using the Failure Mode and Effect Analysis (FMEA) approach, which is based on root cause failure analysis to identify all potential failures and their impact on the reliability of infrastructure construction. The findings from this analysis can serve as a basis for decision making to improve construction quality, safety, and comfort while reducing maintenance and operation costs. The FMEA method has been successfully applied in the aviation industry to achieve a zero-accident program. The results of the study indicate that the main causes of construction failure are corrupt practices, incompetent planning consultants, and weak supervision. The results of FMEA, measured through the Risk Priority Number (RPN), allow project owners to identify components that need to be improved, prioritize changes, to increase infrastructure service life, safety, comfort, and infrastructure reliability according to the selected budget.

Keywords : FMEA, failure, infrastructure, risk analysis, reliability

Abstrak

Tingginya tingkat kegagalan proyek infrastruktur, khususnya proyek pembangunan jalan di Indonesia, telah mencapai tingkat yang mengkhawatirkan. Kegagalan tersebut sering kali berawal pada tahap perencanaan, pelelangan, pengawasan, dan pelaksanaan konstruksi. Banyak proyek infrastruktur tidak memenuhi standar teknis dan persyaratan kontrak, sehingga menyebabkan kegagalan fungsi, berkurangnya umur layanan, permasalahan keselamatan, ketidaknyamanan, serta tingginya biaya pemeliharaan dan operasi. Penelitian ini menyajikan analisis kegagalan dengan menggunakan pendekatan Failure Mode and Effect Analysis (FMEA), yang didasarkan pada analisis akar penyebab kegagalan untuk mengidentifikasi seluruh potensi kegagalan beserta dampaknya terhadap keandalan konstruksi infrastruktur. Hasil analisis ini dapat digunakan sebagai dasar pengambilan keputusan dalam meningkatkan kualitas konstruksi, keselamatan, dan kenyamanan, sekaligus mengurangi biaya pemeliharaan dan operasi. Metode FMEA telah berhasil diterapkan dalam industri penerbangan untuk mendukung pencapaian program zero-accident program. Hasil penelitian menunjukkan bahwa penyebab utama kegagalan konstruksi adalah praktik korupsi, ketidakkompetenan konsultan perencanaan, serta lemahnya pengawasan. Hasil FMEA, yang diukur melalui Risk Priority Number (RPN), memungkinkan pemilik proyek untuk mengidentifikasi komponen yang perlu diperbaiki, menentukan prioritas perubahan, serta meningkatkan umur layanan infrastruktur, keselamatan, kenyamanan, dan keandalan infrastruktur sesuai dengan anggaran yang tersedia.

Kata-kata kunci : FMEA, kegagalan, infrastruktur, analisis risiko, keandalan

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1. Introduction

Failure in infrastructure projects can lead to other long-term failures that have a significant impact on expected performance, such as high maintenance costs, project delays, danger to humans, total failure, and possible litigation. Many infrastructure projects fail due to various factors, including poor design, low construction quality, funding constraints, and poor management. Weak regulatory enforcement, and lack of oversight, further exacerbate the problem. Additionally, non-technical factors such as corruption, weak regulatory enforcement, and lack of oversight which is common in the construction sector, also play a significant role in infrastructure failures.

Indonesia faces substantial challenges related to infrastructure failure. Notable structural failures include premature deterioration of roadways, bridge collapses, and other critical infrastructure breakdowns caused by both technical and non-technical factors. Beyond the immediate financial burden of repairs and maintenance, these failures can lead to loss of life and widespread social and economic disruption. The consequences extend far beyond physical damage, eroding public trust, undermining confidence in government institutions, discouraging investment, and hindering progress toward sustainable development.

Several studies have highlighted the numerous infrastructure and construction failures in Indonesia. Notable examples include the collapse of the Kutai Kartanegara Bridge, landslides along the Bogor-Ciawi-Sukabumi (Bocimi) Toll Road, and accident-prone locations on the Cikampek-Purwakarta-Padalarang (Cipularang) Toll Road (STA 92+000 - STA 100+000). Furthermore, cases of newly constructed infrastructure deteriorating shortly after handover due to poor workmanship - often linked to corrupt practices - are common. Investigations by law enforcement agencies have confirmed cases where infrastructure projects, funded by public funds, have suffered from substandard implementation [1].

Given these concerns, identifying and mitigating structural failures is imperative in infrastructure construction. By mapping potential risks, appropriate measures can be devised to address and prevent infrastructure failures. One effective method for quantifying failure causes is Failure Modes and Effects Analysis (FMEA). FMEA provides a systematic and reliable approach to identifying potential system failures and assessing their impact [2]. Initially developed in the manufacturing industry to map risks related to production and machinery operations, FMEA has demonstrated its effectiveness in risk assessment.

Despite its limited application in construction, FMEA presents significant potential for enhancing structural reliability and optimizing risk-based decision-making [3]. This paper explores the implementation of FMEA in road construction projects in Indonesia, aiming to provide insights into the method's effectiveness in identifying and mitigating structural failure risks.

2. Failure Mode and Effect Analysis (FMEA)

Failure Mode and Effect Analysis (FMEA) is a long-established method used to identify potential causes of failure. FMEA is a systematic methodology applied to examine product functions, potential failure modes, their underlying causes, and associated effects, including the elements influenced by such failures. Once a failure has been identified, its subsequent consequences must be thoroughly evaluated to inform risk mitigation strategies.

FMEA was initially developed by the United States military at the end of World War II as a strategy to reduce failures in production, operations, and the maintenance of wartime equipment and munitions. Its demonstrated effectiveness in minimizing failure rates within military applications later extended to the American aerospace and aviation industries, where it was adopted to drive reliability efforts toward zero-failure objectives [4]. Statistical data now indicate that air transportation has become one of the safest modes of travel globally, with accident rates approaching zero. The success of FMEA in aviation and aerospace subsequently influenced its adoption by Ford Motor Company, which applied the methodology to enhance product safety and reliability in the automotive sector. Although originally developed for military use, FMEA has since been widely adopted across various manufacturing industries, proving to be a highly effective tool for reducing failure rates in diverse technical domains.

As one form of Root Cause Failure Analysis (RCFA), FMEA serves as a systematic approach for understanding and mitigating risk in products or processes. According to [5], FMEA involves a structured set of activities aimed at: (a) recognizing and evaluating potential failures and their effects; (b) identifying actions that could eliminate or reduce the likelihood of such failures occurring; and (c) documenting the process. This method complements the broader design and process requirements necessary to meet customer expectations. Similarly, Ford Motor Company [6] define FMEA as a systematic technique for identifying and preventing product and process issues before they arise. The

approach is centered on defect prevention, safety improvement, and the enhancement of customer satisfaction.

FMEA involves a systematic inquiry for each asset under detailed evaluation, guided by the following sequence of diagnostic questions [7].

1. What is the intended function and performance standard of the asset within its operational context?
2. In what ways might the asset fail to fulfill its function?
3. What are the contributing factors to each potential failure mode?
4. What are the consequences of each identified failure?
5. What are the broader effects resulting from these failures?
6. What measures can be implemented to reduce the likelihood of failures, detect their early onset, or mitigate their impacts?

The application of Failure Mode and Effects Analysis (FMEA) in the construction industry remains relatively limited. Existing studies have

demonstrated its application in specific areas of construction, such as building [3] and railway infrastructure [7] projects. In addition, several studies have highlighted the valuable contribution and considerable potential of FMEA as a risk assessment and management tool for broader applications across the construction industry [3,17]. Accordingly, this paper seeks to further investigate the application of FMEA in construction projects and explore its potential to enhance risk identification and management practices.

2.1. FMEA elements

Failure Mode and Effects Analysis (FMEA) aims to systematically identify all potential failure modes in a process or product, acknowledging that even the simplest designs present numerous opportunities for functional inadequacies or malfunctions [8]. To ensure effectiveness of the FMEA, a structured procedural framework must be adhered to throughout its development. This framework provided in **Table 1.** yields a standardized set of output elements or components integral to the FMEA methodology, which serves as the foundation for consistent risk evaluation and mitigation practices.

Table 1. (Failure Mode and Effect Analysis) FMEA Element

FMEA Element	Description
FMEA Number	Identifies the FMEA documentation with a unique reference code for systematic tracking and retrieval.
Type	Specifies the system, subsystem, or component subject to FMEA evaluation.
FMEA Date	Indicates the date of completion along with the most recent revision, supporting version control and update traceability.
Function	Defines the operational performance and output tolerances expected within the asset's designated context.
Functional Failure	Describes conditions where the system or component is unable to meet its intended function.
Failure Mode	Refers to the specific breakdowns or malfunctions of equipment or components that result in system or subsystem functional failure.
Failure Effect	Outlines the consequences of a failure event across design, process, machinery, or tooling domains.
Cause of Failure	Describes the mechanisms through which a failure event may arise, typically associated with correctable conditions or deficiencies within the system or process.
Risk Priority Number (RPN)	Represents a numerical value that prioritizes risk based on the product of three factors: Severity, Occurrence, and Detection. This index serves as a key determinant in assessing the urgency and hierarchy of risk mitigation efforts
Recommended Actions	Refer to specific measures designed to resolve identified failure modes or mitigate their consequences. These actions must effectively address the underlying causes or reduce the severity of potential impacts.
Revised RPN	Following the identification of corrective measures, updated estimations of Severity, Occurrence, and Detection are recorded to calculate a new RPN. If no additional actions are taken, a corresponding note should be provided to document this decision.
Follow-Up	FMEA documentation is treated as a dynamic and iterative record, subject to continuous improvement and revision based on the evolving requirements and insights of the responsible team.

2.2. Calculating RPN

In implementing Failure Mode and Effects Analysis (FMEA), the prioritization of failure modes is guided by three critical parameters: the severity of the impact resulting from a specific failure mode, the frequency with which the causal factors lead to such failures, and the likelihood of detecting these causes before the failure occurs. Each parameter is quantitatively evaluated, and the aggregate score is represented by the Risk Priority Number (RPN) - a metric derived from the product of severity, occurrence, and detection values - serving as a basis for structured risk management decisions.

The overall assessment is quantified through a numerical index known as the Risk Priority Number (RPN), which is derived by multiplying the individual ratings assigned to severity, frequency of occurrence, and ease of detection.

$$RPN = S \times O \times D \quad (1)$$

To determine the priority level of a failure mode within the FMEA framework, it is necessary to define the values for severity, occurrence, and detection, which are then synthesized into a final value known as the Risk Priority Number (RPN). The RPN is obtained by multiplying the numerical ratings assigned to severity, occurrence, and detection as described on Equation (1). The criteria used to assign these ratings are outlined as follows.

2.2.1. Severity (S)

Severity (S) constitutes the initial step in risk analysis, whereby the extent or intensity of an event's impact on process output is assessed. The magnitude of impact is ranked on a scale from 1 to 10, with 10 indicating the most severe consequence. The detailed scoring system is presented in **Table 2**.

Table 2. Severity (S) Rating System

Category	Definition	Value
Hazardous without warning	Failure that is extremely dangerous to the system and occurs without warning	10
Hazardous with warning	Failure that is extremely dangerous to the system but occurs with warning	9
Very High	Failure that may cause the system to stop working and occur without warning	8
High	The system cannot operate and there is component damage	7
Medium	The system cannot operate and there is minor damage	6
Low	The system cannot operate despite the absence of damage	5
Very Low	The system can operate, but with significant performance deviation	4
Minor	The system can operate, but with minor performance deviation	3
Very Minor	The system can operate, but with slight performance deviation	2
Without impact	No impact at all	1

2.2.2. Occurrence (O)

Occurrence refers to the likelihood that a given cause will materialize and result in a specific mode of failure during the operational life of the roadway. This likelihood is estimated using a numerical scale ranging from 1 to 10. Error! Not a valid bookmark self-reference.. outlines the procedural framework for the occurrence rating system.

2.2.3. Detection (D)

The detection value is associated with the current supervision control mechanisms. Detection refers to the measurement of the system's ability to identify potential failures. The detection evaluation process is presented in **Table 4**. below.

2.3. Application of FMEA within the study context

This study employed the Failure Mode and Effect Analysis (FMEA) approach, utilizing field investigation data from road construction activities in Indonesia. The FMEA analysis was based on empirical data collected from forensic investigation of 10 infrastructure roadwork project packages across various regions. The selected projects represent a diverse range of road categories, including national, provincial, and local/regional roads, as well as both flexible and rigid pavement systems. Project lengths varied from approximately 5

Table 3. Occurrence (O) Rating System

Category	Definition	Value
Highest	Failure always occurs (100%)	10
Very High	Probability of failure is 20%, or very high likelihood of failure	9
High	Probability of failure is 10%, or high likelihood of failure	8
Medium High	Probability of failure is 5%, or moderately high likelihood of failure	7
Medium	Probability of failure is 3%, or moderate likelihood of failure	6
Medium Low	Probability of failure is 2.5%, or mid-moderate likelihood of failure	5
Low	Probability of failure is 2%, or moderately low likelihood of failure	4
Very Low	Probability of failure is 1.75%, or low likelihood of failure	3
Lowest	Probability of failure is 1.5%, or very low likelihood of failure	2
Zero Possibility	Failure is almost never expected to occur (<1%)	1

Table 4. Detection (D) Rating System

Category	Definition	Value
Highly uncertain	No control mechanism can detect the failure	10
Very rare	The current control mechanism has great difficulty detecting the failure mode or its cause	9
Rare	The current control mechanism has difficulty detecting both the failure mode and its cause	8
Very low	The control mechanism has very low ability to detect the failure mode and its cause	7
Low	The control mechanism has low ability to detect the failure mode and its cause	6
Moderate	The control mechanism has moderate ability to detect the failure mode and its cause	5
Moderately high	The control mechanism has moderate to high ability to detect the failure mode and its cause	4
High	The control mechanism has high ability to detect the failure mode and its cause	3
Very high	The control mechanism has very high ability to detect the failure mode and its cause	2
Almost certain	The control system will detect the failure cause when it occurs	1

5 km to 30 km, reflecting a range of construction scales commonly encountered in public road infrastructure development. Most projects were completed within a construction period of one to two years, providing a relatively comparable implementation timeframe. A key common characteristic among all projects is that they were financed through government budget allocations and executed under similar public procurement and construction management frameworks. To ensure compliance with legal and ethical requirements, detailed project identifiers, locations, and contract

information are not disclosed in this paper. Nevertheless, the diversity of project types and geographical distribution provides a sufficiently representative basis for identifying recurring risk factors and failure mechanisms in government-funded road construction projects.

Based on the investigation of the selected project packages, a compilation of observed failures was conducted. These identified failures were subsequently utilized as the foundation for the FMEA analysis. The results of the FMEA applied to

the 10 project packages yielded Risk Priority Numbers (RPNs), reflecting the risk levels associated with each failure cause. The initial S, O, D values to calculate the RPN are determined based on the definition and criteria mentioned in **Table 2.**, **Table 3.**, and **Table 4.** An analysis was then conducted to formulate recommendations addressing the identified failure causes. Following these recommendations, the initial RPN values were updated accordingly. The comparison between the initial and revised RPN values serves as a key reference in determining the priority of recommendations that require immediate implementation.

3. Failure definition

Failure is defined as the inability of a product to meet its quality and functional requirements as stipulated by applicable technical specifications and standards. In practice, the definition of failure is often complex, varying according to the reliability levels required. Two basic interpretations of failure may be described as follows:

1. The complete loss of a product's ability to perform its intended function, typically caused by substandard workmanship, inferior material quality, structural limitations, or a combination thereof; and
2. The failure of one or more components within a product to function as required, without compromising the overall operational capability of the product.

Such failures are further categorized into varying degrees, contingent on the analyst's evaluation, experience, and criteria. Problems in systems typically begin with the occurrence of a failure. This initial failure is followed by the identification of a Level 1 failure cause. Based on this Level 1 cause, further investigation is conducted to uncover a deeper contributing factor - designated as a Level 2 failure cause. Subsequently, an in-depth analysis of the Level 2 cause is carried out to determine the root cause of failure, referred to as the Level 3 failure cause.

It is important to note that a root cause is not always located at Level 3. If the Level 3 cause is deemed insufficient to represent the root cause, additional analysis can be pursued to identify the true origin of failure. On the other hand, if the Level 2 cause is already considered to be the root cause, the analytical process may conclude at that level. While these simplified definitions provide a general understanding, the reality is that failure can manifest in numerous forms, potentially without limit. Definitions may differ depending on the type of

product.

Across the manufacturing sector, high-quality manufacturers are expected to systematically track all potential failure modes to prevent product breakdowns. Accordingly, additional inquiry is necessary to establish precise definitions of failure. The implementation of Failure Mode and Effects Analysis (FMEA) assists engineers in mapping a comprehensive range of potential failures, encompassing both explicit and latent failure scenarios. This failure mapping approach is evidently also well-suited for application within the infrastructure domain, where systematic identification and analysis of failure modes can significantly enhance operational reliability and asset management.

3.1. Road infrastructure failure in Indonesia

According to Indonesia's Construction Services Act [9] No. 2, Article 1 Paragraph 10, structural failure is characterized by the collapse and/or non-functionality of a building following the final handover of construction services. Importantly, failure does not always manifest as physical collapse or destruction. It may also involve deviations from design specifications or inadequate performance, resulting in the infrastructure failing to operate as intended. In broader terms, failure can be interpreted as an unacceptable discrepancy between expected and actual performance outcomes.

Road infrastructure failure in Indonesia is a recurring phenomenon. The relatively high rate of traffic accident fatalities [10] indicates signs of systemic failure in road infrastructure. Roads play a vital role in societal mobility, facilitating movement from origin to destination at a designated speed while ensuring user safety. However, this functionality is compromised when roads fail to meet performance standard, either in terms of speed or safety. Common examples of such failure include potholes, uneven surfaces, water accumulation, and bridge damage, among others. Furthermore, severe road cracks, deformation caused by heavy vehicle loads, inadequate lighting [10], and insufficient traffic signage also contribute to the high incidence of accidents. These failures not only disrupt travel efficiency but also heighten risks for road users, thereby underscoring the need for improved infrastructure planning and maintenance to ensure safe and smooth transportation.

Constructed infrastructure frequently experiences failure due to insufficient diligence, limited technical knowledge, and inadequate professional experience. The potential for road failure may arise across multiple phases of project execution, as illustrated in the following **Table 5.**



Figure 1. Examples of road failure based on investigation findings conducted across Indonesia

Table 5. Percentage of road infrastructure component failure

Failure Characteristic on Each Phase of Road Construction	Probability (%)
Inherent failure due to design	5 – 15
Procurement failure in meeting quality standards	10 – 20
Failure due to equipment defect or malfunction	5 – 15
Failure caused by operator error	1 – 5
Damage during transportation to the site	1 – 2
Failure due to on-site material storage	5 – 10
Failure due to field installation	1 – 2

Identifying potential failure modes across various project stages constitutes a critical step toward implementing the necessary corrective measures. Following corrective actions targeting the root causes of failure, the failure rate was significantly reduced to levels well below the established threshold.

4. FMEA Study Case: Road Infrastructure in Indonesia

4.1. Function

Function delineates the expected performance attributes of a product and may encompass multiple elements, including its physical characteristics, operational behavior - such as output tolerance - and temporal requirements, such as continuous operation or specific availability windows. It is essential to systematically identify all critical functions relevant to the product's intended operational context. By articulating these functions with clarity and precision, the parameters for functional failure can likewise be rigorously defined, thereby facilitating

effective risk assessment and mitigation strategies.

Speed is a key indicator of road functionality. A well-constructed roadway typically facilitates average traffic speeds that closely align with the designated planning speed. Moreover, speed is recognized as one of the principal risk factors affecting road traffic safety and represents a persistent issue in many developing countries. Planning speeds vary across countries depending on infrastructure standards and traffic regulations. In Germany, the Autobahn is notably characterized by the absence of a maximum speed limit [11]. Japan sets planning speeds between 100 and 120 km/h for expressways [12], while Singapore enforces a speed limit of approximately 110 km/h on major roads [13].

In Indonesia, planning speeds are determined based on road classification and terrain conditions. Expressways are designed for speeds between 100–120 km/h, arterial roads for 80–100 km/h, and collector roads for 60–80 km/h [14]. However, actual travel speeds often fall significantly short of

these targets due to congestion, poor road conditions, and traffic density, particularly in urban areas where speeds may be limited to only 20-40 km/h [15]. The substantial gap between planned and actual speeds reveals systemic failures in road infrastructure, impacting both transportation efficiency and road user safety. Suboptimal infrastructure - such as potholes, inadequate drainage systems, and poor traffic management - contributes to these failures. Furthermore, driver behavior in Indonesia exacerbates the situation [16], underscoring the urgent need for a more integrated and effective transportation system.

In addition to speed performance, the functional attributes of road infrastructure are also determined by its planned service life. A roadway may be considered non-functional if it exhibits structural failure within a short period of operation. In Indonesia, the minimum design life for roads is 15 years [14]. Accordingly, the service life must be explicitly stated as one of the essential functions in road design assessments. Beyond this, road functionality also encompasses aspects such as resilience to climatic variations, non-degradative interaction with vehicle components, and other relevant operational criteria. A tabulated summary of road function example is presented in **Table 6.**

Table 6. Road infrastructure function

Project	: Construction
System	: Infrastructure
Sub-system	: Road
No.	Function
1	Capable of providing traffic access from the point of origin to the destination at a planned speed of 60 km/h under safe and secure conditions.
2	Has a minimum service life of 20 years with minimal maintenance required.
3	The road surface can be traversed by vehicles without causing damage to vehicle components
4	The road is resistant to extreme temperature fluctuations ranging from 5°C to 100°C, as well as other environmental factors.

4.2. Functional failure

Functional failure describes the various ways in which a system or subsystem can fail to meet the required functional needs. A system or subsystem operating in a degraded state but not impacting all system requirements and constraints does not experience functional failure. By clearly defining the necessary functions, the various failures of each function can be clearly identified.

For instance, one of the critical functions of a roadway is to facilitate safe and secure traffic flow at a designated speed of 60 km/h. Functional failure scenarios associated with this objective may include: (1) Certain segments of the roadway are not navigable at the designated operating speed of 60 km/h (or the prescribed design speed).; (2) The road is only passable at very low speeds (below 20 km/h).; or (3) the road is entirely inaccessible to traffic, etc. By precisely defining the functional parameters of the roadway, it becomes possible to systematically identify and categorize corresponding modes of functional failure for each operational expectation. An example for description of the functional failure of road infrastructures can be seen in **Table 7.**

4.3. Failure mode

Failure modes are specific failures of equipment and components that result in the functional failure of a system or subsystem. Dominant failure modes are those responsible for the majority of all item failures. These are the most frequently occurring failure modes in failure events. Not all knowledge about failure modes or causes of failure guarantees the success of a process, as failure events often go unnoticed, unconsidered, or have never occurred before.

As an illustrative example, we revisit the continuation of the previous analysis. The functional role of a roadway as infrastructure that provides traffic access from origin to destination at a designated speed of 60 km/h under safe and secure conditions may encounter functional failure, such as when the road can only be traversed at substantially reduced speeds (below 20 km/h). Such functional failure may arise from various failure modes, including: (1) traffic congestion that obstructs flow and reduces travel speed; (2) extensive pothole damage forcing users to operate vehicles at low speeds; and other related circumstances. Examples of functional failure modes illustrated in **Table 8.**

Table 7. Fncion and functional failure of road infrastructure

Proyek : Construction		
Sistem : Infrastructure		
Sub-sistem : Road		
No.	Function	Functional Failure
1	Capable of providing traffic access from the point of origin to the destination at a planned speed of 60 km/h under safe and secure conditions.	1.1. Certain segments of the roadway are not navigable at the designated operating speed of 60 km/h (or the prescribed design speed). 1.2. The road cannot be safely traversed at a speed of 60 km/h. 1.3. The road is only passable at very low speeds (below 20 km/h). 1.4. The road is entirely inaccessible to vehicular traffic.

Table 8. Function, functional failure, and failure modes of road infrastructure

Proyek : Construction			
Sistem : Infrastructure			
Sub-sistem : Road			
No.	Function	Functional Failure	Failure Mode
1	Capable of providing traffic access from the point of origin to the destination at a planned speed of 60 km/h under safe and secure conditions.	1.3 The road is only passable at very low speeds (below 20 km/h).	1.3.1 Traffic congestion has occurred, resulting in obstructed flow and reduced travel speeds. 1.3.2 Numerous potholes on the roadway force drivers to operate at low speeds.

4.4. Failure effect

Each identified failure mode is accompanied by a documented assessment of its corresponding effects. These may include operational disruptions such as downtime, degradation of product quality, evidence substantiating the occurrence of failure, potential corrective actions, and threats to safety or the environment. Such evaluations enable a structured determination of the extent to which each failure influences system performance and help establish the appropriate level of preventive measures

required.

Failure effects represent a critical component in determining the Risk Priority Number (RPN) within Failure Mode and Effects Analysis (FMEA). The greater the impact of a failure event, the higher the severity rating assigned in the RPN calculation. Illustrative descriptions of failure effects corresponding to each failure mode in road infrastructure systems are presented in **Table 9.**

Table 9. Function, functional failure, failure modes, and failure effects of road infrastructure

Proyek : Construction				
Sistem : Infrastructure				
Sub-sistem : Road				
No.	Function	Functional Failure	Failure Mode	Failure Effect
1	Capable of providing traffic access from the point of origin to the destination at a planned speed of 60 km/h under safe and secure conditions.	1.3 The road is only passable at very low speeds (below 20 km/h).	1.3.1 Traffic congestion has occurred, resulting in obstructed flow and reduced travel speeds.	- Road users experience delays in reaching their destinations. - Severe traffic congestion results in elevated levels of air pollution.

4.5. Cause of failures

Cause of Failure refers to the mechanism or condition through which a failure manifests. It is typically characterized as a correctable factor, representing an aspect of the system, process, or component that can be addressed or modified to prevent recurrence.

Wherever feasible, the cause of failure should be identified as the most terminal root condition that remains within the boundaries of the system or subsystem framework. This approach enables the formulation of precise and context-specific corrective recommendations aimed at effectively

addressing the corresponding functional failure modes. Examples of failure causes corresponding to each failure mode are presented in **Table 10.**

5. Result and discussion

5.1. RPN calculation

The outcome of the FMEA analysis is a prioritized mapping of failure mitigation strategies. Priority ranking is determined based on the calculated Risk Priority Number (RPN), which reflects the Severity (S), Occurrence (O), and Detection (D) ratings assigned to each defined and detailed failure cause, as exemplified in **Table 10.**

Table 10. Function, functional failure, failure modes, failure effects, casue of failure, and RPN of road infrastructure

Proyek : Construction		Sistem : Infrastructure		Sub-sistem : Road						
No.	Function	Functional Failure	Failure Mode	Failure Effect	Cause of Failure	Severity	Occurrence	Detection	RPN	
1	Capable of providing traffic access from the point of origin to the destination at a planned speed of 60 km/h under safe and secure conditions.	1.3 The road is only passable at very low speeds (below 20 km/h).	1.3.1 Traffic congestion has occurred, resulting in obstructed flow and reduced travel speeds.	- Road users experience delays in reaching their destinations. - Severe traffic congestion results in elevated levels of air pollution.	1.3.1.1 The design consultant did not conduct a traffic survey, resulting in a road traffic capacity inadequate of accommodating projected traffic volumes.	5	8	3	120	
					1.3.1.2 The planning consultant lacked expertise in traffic impact analysis.	5	9	9	405	

As demonstrated in the case study, the failure mode related to traffic congestion caused by the lack of expertise of the planning consultant yields a higher RPN than the failure mode stemming from the absence of a traffic survey. Accordingly, the issue of the planning consultant's insufficient competence warrants a higher priority in mitigation efforts.

5.2. Recommended action

Subsequent analysis following the initial ranking of failure causes based on their respective RPN values involves the development of recommendations and strategies aimed at preventing the recurrence of such failures. Upon implementing these recommendations, updated RPN values may be derived due to corresponding adjustments in the Severity (S), Occurrence (O), and Detection (D)

ratings for each identified failure cause.

As an example, consider a case in which the design capacity of the pavement foundation, as specified by the planning consultant, is lower than the actual load imposed. This discrepancy may result in surface undulations, leading to a functional failure wherein the road becomes unsafe for travel at 60 km/h. To address this, a fair and transparent bidding process for the selection of planning consultants is recommended to ensure the appointment of genuinely qualified experts. In this case, the proposed corrective measure contributes to a reduction in the severity, occurrence, and detection ratings associated with the failure cause, thereby lowering the RPN value from 504 to 175.

6. Conclusions

1. The case study-based FMEA conducted on road infrastructure in Indonesia revealed that high-risk failure modes are predominantly linked to the incompetence and negligence of planning consultants, contractors, and supervisory consultants. These factors contributed to substandard construction execution and ultimately yielded infrastructure that fails to meet the expected quality and service benchmarks. Addressing these critical cause of failure requires the implementation of transparent, accurate, and integrity-driven mechanisms for the selection and procurement of planning, construction, and supervisory service providers.
2. The FMEA analysis has proven effective in yielding actionable insights and uncovering novel perspectives, demonstrating that infrastructure failure is more significantly driven by negligence, dishonesty, and corruption. Therefore, the implementation of Failure Modes and Effects Analysis (FMEA) within infrastructure development has demonstrated considerable promise in enhancing both strategic planning and operational reliability. Through a systematic examination of potential failure modes, the method yields technical insights that surpass conventional assessment practices, enabling more accurate identification of vulnerabilities and informing targeted adjustments across design, construction, and maintenance phases. Moreover, the integration of interdisciplinary perspectives - drawing from engineering, environmental science, and regulatory compliance - fosters collaborative engagement among stakeholders and enhances the analytical robustness of decision-making processes. This multifaceted approach not only improves the overall efficacy of infrastructure systems but also contributes to cultivating a culture of continuous learning and shared accountability within project teams.

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understanding of the technical capabilities and integrity of the parties involved in the management and implementation of road infrastructure development in Indonesia.

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