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Research Paper

Enhancing Brake System Evaluation in Periodic Testing of Goods Transport Vehicles through FTA-FMEA Risk Analysis

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Abstract

Periodic testing of goods transport vehicle is very important in preventing traffic accidents, particularly in Indonesia. One of the leading factors contributing to these accidents is the malfunction of braking system. Despite the implementation of periodic testing, the incidence of accidents remains alarmingly high. Addressing this issue requires a proactive method to enhance and refine the Standard Operating Procedure (SOP) governing periodic vehicle testing. Therefore, this study aimed to introduce a methodology to revise and augment SOP regarding periodic testing of brake system. The method employed included a comprehensive risk assessment using the Fault Tree Analysis (FTA) and Failure Mode and Effect Analysis (FMEA) tools. These methods were grounded in accident investigation data compiled by the National Transportation Safety Committee (NTSC) spanning the years 2017 to 2022. FTA was employed to identify potential risk, while FMEA facilitated analysis of failure causes within brake system to pinpoint the most critical risk scenarios. Based on analysis, thirteen failure cases were identified and classified as Intolerable risk instances. For each of these cases, tailored SOP additions were recommended in order to offer valuable insights to stakeholders, enabling them to revise and refine the regulations governing periodic vehicle testing.

Keywords: Periodic testing; Braking system; Risk analysis; FTA; FMEA; Failure rate

1. Introduction

Accidents in transportation of goods are a leading cause of traffic incidents in Indonesia. According to data provided by the Indonesian National Police, motorcycle riders contribute significantly, accounting for as much as 73 percent of these accidents. Freight transportation follows, making up 12 percent of the total, as land transport remains dominant at around 90% [1]. In order to curtail this occurrence in goods transportation sector, the Ministry of Transportation has implemented a regimen of biannual vehicle assessments for both public and cargo vehicle [2]. However, data compiled from annual accident reports by the Indonesian Republic Police reveals a concerning uptick of 16.13% in transportation of goods between 2017 and 2020 [3]. This increase can be attributed to the current periodic vehicle assessments, which emphasize the comprehensive functionality of system rather than scrutinizing the performance of individual components within system. Interestingly, data from the NTSC (National Transportation Safety Committee) underscores that accidents often stem from component failure within the structure of vehicle [4]. Based on this scenario, it becomes essential to supplement system functionality test with examinations concentrating on pivotal components, such as the braking, drive, and steering system.

Braking system failure stand out as the primary contributing factors to accidents involving goods transport vehicle. This assertion

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is substantiated by data spanning the last five years from the NTSC [4]. A potential solution for mitigating the issue with braking system includes enhancing the quality of vehicle testing through modifications and additions to the Standard Operational Procedure (SOP). These adjustments to the SOP for periodic motorized vehicle testing hold the potential to diminish the occurrence of accidents in goods transport vehicle, particularly those arising from braking system failure.

To pinpoint which components within the braking system require urgent SOP improvements, a risk analysis method will be employed. This method will use the Fault Tree Analysis (FTA) and Failure Mode and Effects Analysis (FMEA) tools. FTA serves to identify potential risk, while FMEA provides a comprehensive analysis, spotlighting components with the highest risk levels.

Numerous studies focusing on risk analysis within the automotive and braking system domain, encompassing the advantages and disadvantages of each method, are outlined in sections 2.2 and 2.3. Consequently, a combined method employing FTA and FMEA has been implemented to address the limitations inherent in each method and to ascertain the reliability and maintenance tasks concerning vehicle system failure. Further insights into risk analysis concerning braking system, using the combined methods, are elucidated in section 2.4.

Among the various studies discussed in sections 2.2 to 2.4, it becomes evident that risk analysis method using FTA and FMEA tools has yet to be harnessed for the purpose of revising or enhancing SOP of periodic vehicle testing system. Most of the previous studies concentrating on FTA and FMEA have centered around individual vehicle components. As a result, this paper introduces recommendations, in the form of SOP additions and adjustments, targeting periodic testing of braking system in goods transport vehicle. These recommendations are drawn from risk identification and analysis method involving these tools.

2. Literature Review

2.1. *Periodic Vehicle Testing in Indonesia*

To establish safe and secure road traffic and transportation conditions, three crucial factors have to align in terms of eligibility. Firstly, the individual operating vehicle should possess the necessary driving skills. Secondly, the road needs to be suitable for travel, and lastly, the motorized vehicle used are expected to meet roadworthiness standards. Every motorized vehicle is required to adhere to the technical and roadworthiness criteria stipulated in Law Number 22 of 2009 concerning Road Traffic and Transportation [5]. Therefore, before its operation on the road, vehicle needs to unequivocally meet these prerequisites.

In fulfilling the mandatory roadworthiness requirements, regular testing of motorized vehicle is conducted. However, despite periodic nature of these tests, traffic accidents continue to occur due to technical issues associated with motorized vehicle. A potential shortcoming of periodic vehicle testing lies in the absence of comprehensive explanations and specifications for each component being tested. For example, concerning the braking system of vehicle, there is currently a lack of SOP or precise work instructions for testing individual braking system components. In a complex system, when one component fails to function optimally, it can adversely affect other braking components, leading to potential braking failure.

Another significant concern within periodic vehicle testing is that testing procedure does not encompass real-world conditions experienced by vehicle on the road. Factors such as vehicle load, road gradients (both uphill and downhill), brake fluid conditions, and variations in brake installation are not factored into testing process. Consequently, there is a need for established standards and protocols that encompass a range of conditions, enhancing the credibility and effectiveness of periodic motorized vehicle tests.

2.2. *Risk Assessment*

Risk assessment is a pivotal aspect of risk management, encompassing the identification of potential hazards and an analysis of potential outcomes when these hazards materialize. The ISO 31000:2009 standard outlines risk assessment process, comprising risk identification, risk analysis, and risk evaluation [6]. The risk assessment process is depicted in **Figure 1**. Several tools find utility in risk assessment, including FTA, FMEA, Preliminary Hazard Analysis, HAZOP, and Root Cause Analysis. In this paper, FTA and FMEA tools have been employed.

2.3. Maximum Likelihood Estimation (MLE)

MLE is a methodology that maximizes the likelihood function to derive parameter estimates with maximum accuracy. Furthermore, it employs an implicit and non-linear form suitable for solving the Newton-Raphson algorithm [7].

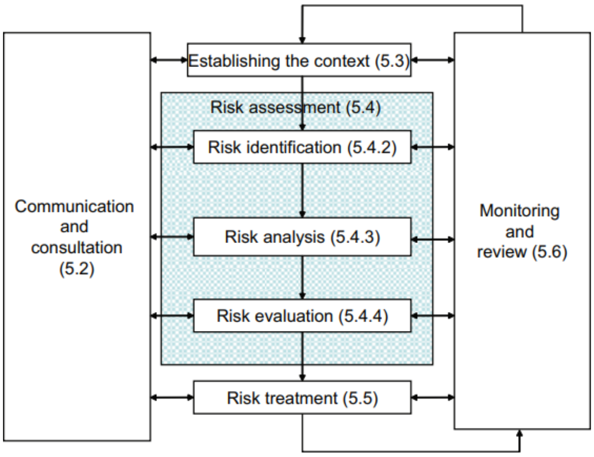

Figure 1. Process in Risk Management [6]

The Likelihood function is defined as follows:

$$f(x_1, x_2 \ldots, x_n; \theta) = f(x_1; \theta) f(x_2; \theta) \ldots f(x_n; \theta) \quad (1)$$

where $x_1, x_2, x_3 \ldots$ represent random variable size n from a distribution with $f(x;\ \theta)$, which depends on $\theta \in \Omega$, Ω denotes the universe of parameters. Equation (1) is used for determining the distribution for calculating failure rate of braking system components.

2.4. Fault Tree Analysis (FTA)

One of the most prevalent methods for effectively conducting risk analysis at system level is FTA, which is used to analyze, visually depict, and evaluate failure pathways within system [8]. The central feature of FTA lies in the use of a logic diagram to illustrate the correlation between system failure or accidents and the underlying causes, typically rooted in component failure [9].

FTA, when used qualitatively, employs two fundamental types of notations, namely events and logic gates. The event notation encompasses four symbols, including a Circle (representing basic events), a Square (for intermediate events), 4 Diamonds (denoting undeveloped events), and a Triangle (serving as a transfer symbol). Generally, two types of logic gates are employed, such as the AND-gate and the OR-gate [10], [11]. AND-gate is applicable when all input events from components contribute to system risk events, while the OR-gate is in a situation where one or more component input events lead to system risk events [12], [13]. FTA method assesses the reliability of system by determining failure rate of each component based on the logic gate [14]. This component failure rate subsequently influences failure rate of system, according to the specific logic gate employed in analysis. If the logic gate is an AND-gate, system failure rate is calculated by multiplying failure rate of individual components. On the other hand, when an OR-gate is used, system failure rate becomes the sum of failure rate of each component. FTA boasts several advantages (a) It aids in uncovering various failure scenarios necessitating the occurrence of at least two events prior to the top-level event [15]. (b) (b) It can be used both qualitatively and quantitatively, with the likelihood of the top event calculated if failure rate estimates for individual events are accessible [16], [17]. (c) The method offers a methodical method to problem-solving, accompanied by visual representation. Furthermore, qualitative FTA can be integrated with other methodologies. Studies have successfully combined FTA and Fuzzy analysis to enhance the quality of a model [18], [19]. In order to recognize the limitation of the method in expressing connections between basic events, efforts have been made to optimize it by integrating FTA with the Bayesian Network Model. These endeavors show that FTA-Bayesian effectively maps critical factors within the model [20], [21].

2.4.1. FTA on Automotive Application

Numerous studies have employed standalone FTA in the context of automotive applications to analyze component failure, particularly within braking system, and also investigate accidents. The method can be applied as a failure analysis of the braking system in light commercial vehicle. The development of two FTAs, supplemented by a reliability block diagram, led to the identification of brake system failure and the reduction of brake system performance as top events [22]. Furthermore, the method can be quantitatively employed to gauge the reliability of brake-by-wire system, integrating the probability importance index (PI). This study highlights the pivotal role of FTA in guiding vehicle system architecture design

[23], and explores the root causes of truck accidents in US mining activities from 1995 to 2011. The results showed that inadequate pre-operational checks and subpar truck maintenance were the primary culprits behind most accidents [24]. The automotive manufacturing sector has also embraced Dynamic FTA (DFT), which expanded the elements encompassing vehicle guidance system to 300 [25]. Additionally, the automotive industry has explored the integration of Fuzzy FTA and Bayesian networks to mitigate any drawbacks and enhance optimization [26].

2.5. *Failure Mode and Effect Analysis (FMEA)*

Another viable alternative for risk analysis is FMEA. Its core premise consists of identifying every potential failure mode for a given system, subsystem, or component through an inductive process. This method concurrently outlines potential failure causes and their consequences [12]. Given that FMEA is systemic analysis, it heavily relies on the expertise of professionals from diverse departments, including design, operation, maintenance, and safety. Increased collaboration among experts leads to more precise FMEA results (failure mode, effect, and causes) [27]. Primarily qualitative, the outcomes describe failure modes and their effects, which can be expanded into quantitative analyses through the incorporation of a criticality analysis (FMECA). Criticality is determined using a risk acceptance matrix as per the EN 50126 standard. Several standards dictate risk acceptance matrices based on specific purposes. The merits of FMEA studies include (a) A comprehensive assessment of potential failure and their effects on system, aiding in the identification of corrective measures [15]. ((b) Assistance in pinpointing critical facets of processes and products [12]. (c) The potential for results to serve as foundational technical analyses for formulating regulations and procedures. (d) FMEA places priority on prevention over detection. By detecting and understanding probable failure modes and causes, preemptive actions can be taken to avert or minimize the likelihood of these failure occurring, ultimately bolstering reliability and quality. Similar to FTA, FMEA can be quantitatively optimized by incorporating Bayesian Network and Fuzzy Method methods [28]. The Fuzzy method enhances FMEA by introducing a flexible Risk Priority Number (RPN) value [29].

2.5.1. *FMEA on Automotive Application*

FMEA has been previously employed as an individual analysis method for automotive applications, particularly in the assessment of braking system using automated model-based system technology. Furthermore, finite qualitative relationships among variables have been integrated. The results indicated that employing an automated model for FMEA yielded comparable outcomes to those produced by experts [30]–[32].

2.6. *FTA and FMEA*

Based on the explanations provided above, the primary differentiation between FTA and FMEA lies in their methods. FTA operates through an inductive methodology that links failure of system to the underlying causes of component failure. On the other hand, FMEA is deductive, focusing on evaluating the effects of a component failure cause [12]. The methods contribute significantly to risk analysis but also have some drawbacks. The core limitation of FTA is its inability to account for interdependencies among failure modes. Conducting this analysis individually for each failure mode can be challenging, specifically in complex system featuring various failure modes [15]. On the other hand, FMEA can prove to be time-consuming and complex when applied to intricate system with numerous components and multiple functions [33]. Its effectiveness necessitates costly expertise and skills, implying that the simultaneous use of FTA and FMEA in risk analysis can serve to counterbalance their limitations.

Studies have combined these methods in risk analyses, often using FTA as an initial guide for executing FMEA. In a broader engineering context, a combined method of using FTA to guide analysis of FMEA Aircraft Flaps has been proposed. The results showed that the structured nature of FTA facilitated a well-structured configuration in generating FMEA results [34]. Similarly, a combined use of the methods with PHA has been undertaken within the software. The results indicated that the method is particularly well-suited for iterative software processes [35]. FTA and FMEA have also been employed recursively, with analysis initially performed at system level, followed by quantitative FMEA. The highest RPN serves as the top event for FTA at the functional and even component levels [36]. Moreover, a critical weighing index was added to these methods in order to determine critical equipment for effective maintenance planning [37]. Several explorations have successfully developed a combined quantitative FTA and FMEA method to enhance risk analysis results [38]–[40]. Furthermore, the integration of the methods with Fuzzy Analysis has been employed to optimize qualitative analysis [41], [42].

2.6.1. *FTA and FMEA on Braking System Risk Analysis*

Considering that brake failure is a significant contributor to accidents, the combined FTA and FMEA method is anticipated to effectively identify potential hazards, risk, and associated failure modes within the braking system. FTA and FMEA were employed both qualitatively and quantitatively for braking system through reliability modeling. FTA estimated component failure rate, representing failure probability of brake system. Subsequently, FMEA introduced the RPN number and the results highlighted air brake malfunction as the highest RPN, emphasizing the need for monitoring the factors contributing to this failure [43]. The two methods were also used to address individual weaknesses, where FTA was structured based on fault probability and the calculation of each failure mode (FMEA). This FTA was further refined through the use of the Improved Analytic Hierarchy Process (IAHP), reliability index, and importance degree. This method was deemed more effective and feasible than conventional FTA [44].

2.7. *Principles of Air over Hydraulic (AOH) Braking system*

Figure 2 shows the braking system of goods transport vehicle featuring an AOH braking type. System is divided into two primary components, namely hydraulic and pneumatic. The hydraulic component encompasses a master cylinder, hydraulic pipes, and drum brake, while the pneumatic components include a compressor, oil-water separator, reservoir, and brake booster.

It is crucial to note that AOH braking system combines hydraulic and pressurized air brake. Compressed air engages the booster cylinder piston, which in turn pushes brake fluid into the wheel cylinders within the drum brake. This action also applies pressure to brake pads, enabling vehicle to decelerate or come to a complete stop. The advantage of this brake type lies in its superior performance compared to hydraulic brake. In terms of safety, AOH brake type is considered a notch above hydraulic brake.

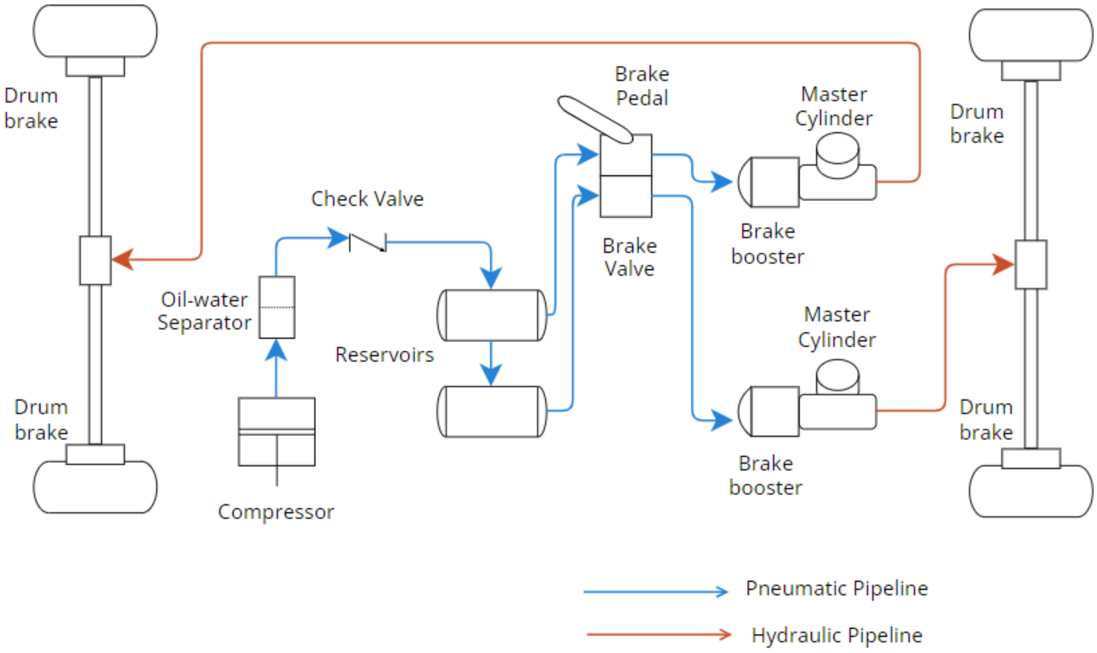

Figure 2. Diagram of braking system

3. Methodology

The selected methodology was broadly categorized into risk identification and analysis, as shown in **Figure 3**. This study combined risk assessment method from the ISO 31000 standard with the MLE method. MLE was employed to determine the parameters of the distribution for the NTSC data. These parameters were subsequently employed to compute failure rate for each underlying cause of failure in brake system of vehicle. The next step involved risk identification using FTA tools, which generated causes of failure for each instance of braking system failure in vehicle. These failure causes were then subjected to analysis using FMEA in order to ascertain risk category derived through an acceptance risk matrix, considering the severity of each failure and its frequency. The severity aspect was determined through expert judgment, while frequency was computed from a calculated failure rate. This risk category informed the evaluation of occurring risk and led to SOP recommendations for vehicle testing. Cases of component failure falling under the "Intolerable" risk category were prioritized. In this study, vehicle entering the test center were assumed to be similar as long as they belonged to goods vehicle category. Therefore, the SOP item for brake testing could be applied to all goods transport vehicle.

4. Results and Discussion

4.1. Collection of Vehicle Accident Data

Accident data stemming from braking failure between 2017 and 2022, as gathered by NTSC, served as a primary input for failure frequency in both FTA and FMEA. NTSC investigated accidents based on specific criteria a) incidents with a minimum of eight victims, b) widespread public attention, c) sparking polemic or controversy, d) inflicting substantial infrastructure damage, e) recurring incidents at a single location within a year, or f) causing environmental pollution due to hazardous waste or toxic materials during transportation. After compiling vehicle accident data over five years, it was found that 25 accidents were directly or indirectly linked to brake system failure.

4.2. Risk Identification using FTA

A braking system failure was defined as the inability of system to operate according to its intended function. Failure of individual components affected the entire performance of the braking system. For analytical purposes, it was assumed that all goods transport vehicle shared identical components. Prior to risk identification, the following boundary conditions were assumed for the braking system:

a. Vehicle equipped with AOH braking system were treated as a unified braking system.
b. The initial condition of a new vehicle complied with regulations, and all system except the braking system were considered to be in proper condition.
c. Vehicle operation was assumed to be 24 hours a day, resulting in 8760 hours of annual operation and 43800 hours of operation over a five-year observation period.
d. This study excluded considerations of road conditions and the environment. Based on these assumptions, the FTA was constructed by selecting braking system failure as the top event, as shown in **Figure 4**.

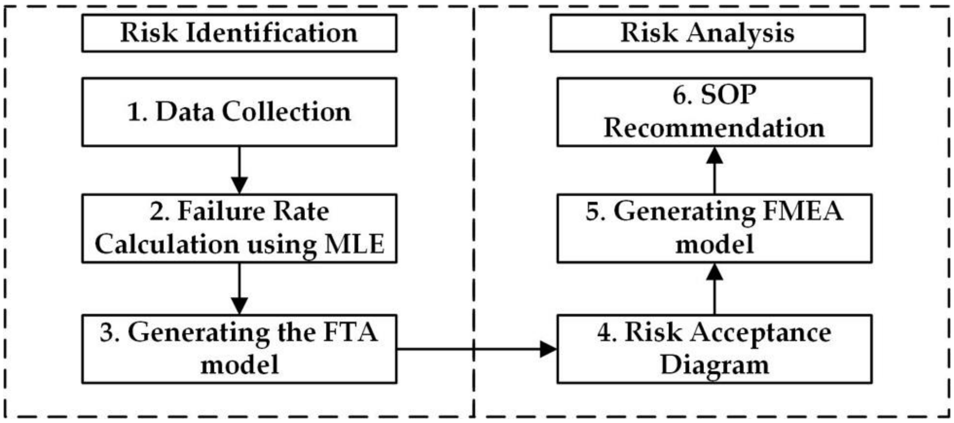

Figure 3. Flowchart for this study using FTA-FMEA

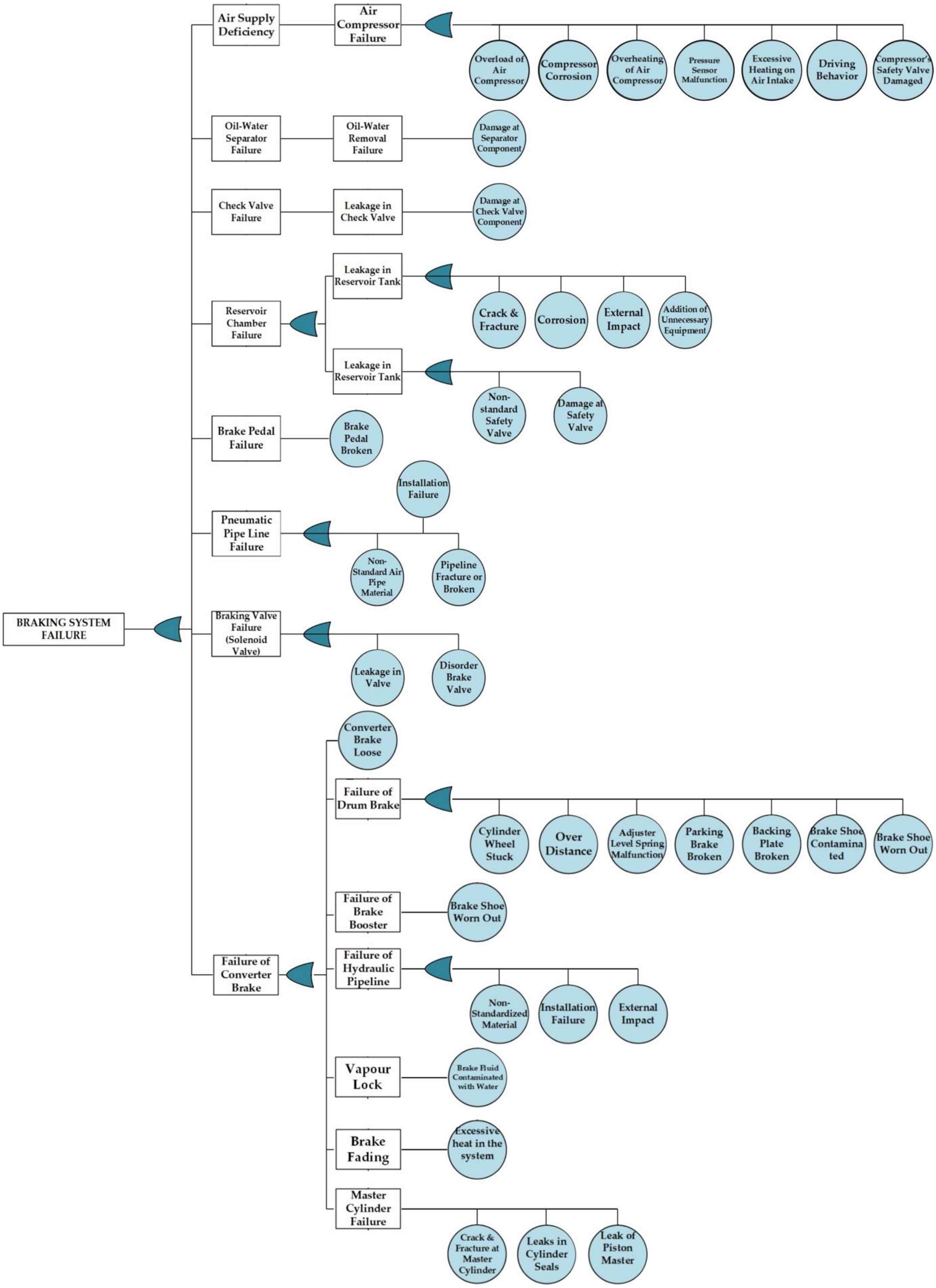

Figure 4. Fault Tree Analysis for braking system failure

Figure 4 showed the FTA diagram designed to identify the causes of brake system failure in goods transport vehicle. The method involved dissecting brake system into its constituent components and pinpointing failure causes that significantly contributed to braking system failure. These causes were determined through discussions with experts from the Bandung Institute of Technology (BRIN) and the NTSC, based on accident data over a specific period. Not all failure causes shown in FTA diagram served as references for changes to SOP for periodic vehicle testing. Further analysis using FMEA method, grounded in NTSC data, was required, as seen in **Table 1**. Based on failure causes derived from FTA, the corresponding failure rate were calculated using NTSC accident data. The calculation of failure rate (λ) employed the MLE method to determine an appropriate distribution. The parameters of the distribution were then used to compute failure rate (λ) with the assistance of Python 3.8.5 software. **Table 1** showed the results of failure rate calculations for each failure cause, indicating that no cases occurring between 2017 and 2022 were omitted.

Table 1. Failure rate calculation for failure causes

Failure Case	Number of Accidents	Distribution	Parameter	MTBF (hours)	Failure Rate
Driving Behavior	15	Gamma 3P	$\alpha = 5450.9693$ $\beta = 0.421$ $\gamma = 335.9999$	2630.8528	3.8E-04
Addition of unnecessary equipment	3	Exponential 1P	$\lambda = 0.000172$	5814	1.72E-04
Non-standard material air pipeline	4	Exponential 1P	$\lambda = 0.000243$	4116	2.43E-04
Installation Feature	5	Gamma 3P	$\alpha = 15059.8004$ $\beta = 0.2016$ $\gamma = 335.9999$	3372.0661	2.96E-04
Pipeline Fracture, Broken	3	Gamma 3P	$\alpha = 44324.4202$ $\beta = 0.207$ $\gamma = 95.9999$	9271.65	1.078E-04
Backing plate broken and Corrosion	5	Gumbel 2P	$\mu = 7956.0778$ $\boldsymbol{\delta} = 1761.5558$	6939.2802	1.4E-04
Brake shoe wear out and Broken	5	Gamma 3P	$\alpha = 15882.2694$ $\beta = 0.1418$ $\gamma = 6767.9999$	9019.51	1.1E-04
Distance between brake shoe and backing plate over limits	6	Gamma 3P	$\alpha = 35048.0748$ $\beta = 0.3357$ $\gamma = 383.9999$	12148.49	8.23148E-05
Parking Brake Broken	5	Gamma 3P	$\alpha = 53689.3006$ $\beta = 0.1697$ $\gamma = 95.9999$	9205.0644	1.086E-04
Brake shoe contaminated with impurities (dust, oil, grease, etc.)	3	Exponential 2P	$\lambda = 0.0002339$ $\gamma = 2903.999$	7179.4576	1.392E-04
Leaks in Cylinder Seals	6	Gamma 3P	$\alpha = 11192.2917$ $\beta = 0.2059$ $\gamma = 335.9999$	2640.7378	3.7868E-04
Water content was found in the brake fluid	6	Gamma 3p	$\alpha = 8896.7262$ $\beta = 0.2118$ $\gamma = 2591.9999$	4476.1165	2.2345E-04
Excessive heat in the system from repeatedly braking, under high loads, or at high speeds	7	Gamma 3p	$\alpha = 10670.0947$ $\beta = 0.2218$ $\gamma = 335.9999$	2702.3507	3.7004E-04

In **Table 1**, , specific failure cases that occurred three times over five years were detailed. The highest failure rate was attributed to accidents stemming from driving behavior, with a value of 3.8E-04. This behavior pertained to drivers repetitively pressing brake pedal, leading to decreased air pressure in the compressor and subsequently impaired braking functionality. The second highest failure rate corresponded to seal leaks in the cylinder, often occurring at the junction between hoses in the braking air tank. These failure rate values were used in frequency calculations to ascertain the frequency level of failure cases for subsequent FMEA analysis.

4.3. *Risk Analysis using FMEA*

FMEA referred to a method aimed at evaluating system design by considering various failure modes of system comprising components and analyzing their effects on system reliability. Specific critical items could be assessed by tracking the effects of component failure according to system level, and corrective actions were required to improve the design and eliminate or reduce the probability of critical failure modes.

During the evaluation, Risk Acceptance method, representing a critical value resulting from a matrix between event frequency and severity due to disturbances occurring in components/subsystem, was employed. The EN 50126 standard categorized severity levels as Catastrophic, Critical, Marginal, and Insignificant, each with consequences for people, environment, and service/property, as shown in **Table 2**. Event frequency comprised six levels, namely Frequent, Probable, Occasional, Rare, Improbable, and Highly Improbable, determined by the number of events within specific periods, as seen in **Table 3**. The magnitude of risk acceptance value determined whether the disturbance of failure modes was acceptable. Undesirable and intolerable outcomes on risk acceptance matrix indicated non-tolerance, necessitating prevention through evaluating and modifying the SOP for periodic motorized vehicle testing, specifically concerning the braking system.

Table 2. The severity of failure modes [45]

Severity Category	Consequences to Person or Environment	Consequences on service/property
Catastrophic	- Affecting a large number of peopleand resulting in multiple fatalities and/or - Extreme damage to the environment	Any of the below consequences in the presence of consequences topersons or environment
Critical	- Affecting a very small number of people and resulting in at least one fatality and/or - Large damage to the environment	Loss of a major system
Marginal	- No possibility of fatality, severe orminor injuries only, and/or - Minor damage to the environment	Severe system(s) damaged
Insignificant	Possible minor Injury	Minor system (s) damaged

Table 3. Frequency level of failure modes [45]

Frequency Level	Example of a frequency range based on a single item operating 24 h/day	Frequency value
Frequent	More than once within period of approximately six (6) weeks	$\frac{1}{\lambda nt} < \frac{6}{48}$
Probable	Approximately once per six (6) weeks to once per year	$\frac{1}{\lambda nt} > \frac{6}{48}$ and $\frac{1}{\lambda nt} < 1$
Occasional	Approximately once per one (1) year to once per ten (10) years	$\frac{1}{\lambda nt} > 1$ and $\frac{1}{\lambda nt} < 10$
Rare	Approximately once per 10 years to once per 1000 years	$\frac{1}{\lambda nt} > 10$ and $\frac{1}{\lambda nt} < 10^3$
Improbable	Approximately once per 1000 years to once per 100000 years	$\frac{1}{\lambda nt} > 10^3$ and $\frac{1}{\lambda nt} < 10^5$
Highly Improbable	Extremely unlikely to occur. It can be assumed that the event will not occur.	$\frac{1}{\lambda nt} > 10^5$

Table 4. Risk acceptance categories for failure modes of braking system [45]

Frequency of occurrence of an accident	**Risk Acceptance Categories**			
Frequent	Undesirable	Intolerable	Intolerable	Intolerable
Probable	Tolerable	Undesirable	Intolerable	Intolerable
Occasional	Tolerable	Undesirable	Undesirable	Intolerable
Rare	Negligible	Tolerable	Undesirable	Undesirable
Improbable	Negligible	Negligible	Tolerable	Undesirable
Highly Improbable	Negligible	Negligible	Negligible	Tolerable
	Insignificant	**Marginal**	**Critical**	**Catastrophic**
	Severity of an accident			

The severity value was obtained from the expert judgment of BRIN and NTSC based on the effect of the cause on the braking system. The frequency value is obtained from the calculated failure rate. Frequency values are based on Table 1 where λ = Failure rate, n = number of components, and t = Vehicle yearly Hours.

Table 4 featured a risk combination between the severity and frequency, shown in Table 2 and Table 3, respectively, according to the EN 50126 Standard. This type of risk was employed in FMEA table, and the outcome prioritized recommendations for vehicle testing SOP based on risk occurring in component failure causes. Failure mode component and causes were derived from FTA diagram as shown in Figure 4. Tolerable and Negligible risk were levels that would not cause harm or property losses if allowed to occur. It should be noted that the undesirable risk category required consideration. Although potential losses were not urgent, they could still result from failure. Intolerable risk necessitated immediate risk control. In the context of this study, an Intolerable risk case was a focus for updating concerning motor vehicle testing.

Table 5 showed FMEA results, with SOP recommendations from the method related to component failure causes significantly impacting braking system failure, particularly those categorized as "Intolerable" risk. The resulting failure effects were divided into "Local" effects impacting the component and "System" effects impacting the entire system. Failure effect data were sourced primarily from BRIN and NTSC experts, supplemented by secondary sources from relevant literature on braking system.

In Table 6 , the summary of risk level results for each subsystem in FTA and FMEA Braking System was provided. Brake Actuator was the subsystem with the highest number of Intolerable cases, followed by the Pneumatic Pipeline. This stemmed from brake role of Actuator in executing the braking mechanism, comprising various components, each with failure modes. For example, drum brake failure mainly resulted from wear, corrosion, and impurities that reduced braking performance. The table also indicated 13 cases categorized as "Intolerable," prompting the need for changes or additions to vehicle testing SOP.

4.4. SOP Recommendations for Periodic Vehicle Test

SOP recommendations were proposed for periodic vehicle testing of braking system with "Intolerable" risk levels, as detailed in Table 7. These recommendations aimed to decrease risk level of brake system failure in goods transport vehicle. Periodic testing estimates for each component were based on the Mean Time Between Failure (MTBF) value. MTBF values in Table 1 were in hours and needed conversion to days, weeks, or months (assuming vehicle operated for about 18 hours a day).

Table 7 showed the SOP requiring implementation in less than six months, such as checking air pressure in the reservoir tank, inspecting pipelines for air leaks, examining brake fluid seepage at the master cylinder, monitoring brake shoe and backing plate temperatures, and assessing vehicle load with an axle load tester. With these urgent parts and improved periodic vehicle testing SOP, the scope of periodic vehicle testing required consideration.

Apart from component failure factors, driver behavior significantly influenced brake system failure. NTSC accident investigation data revealed several braking system failure caused by driver behavior, such as not using the engine brake and exhaust brake when descending slopes, as well as

Table 5. FMEA of braking failure

Failure Mode	Failure Causes	Failure Effect		Risk		
		Local	System	Severity	Frequency	Risk Level
Air Compressor Failure	Driving Behavior	Reduce compressed air supply	Reduce braking performance	Critical	Probable	Intolerable
Leak in the reservoir tank	Addition of unnecessary equipment	Reduced compressed air supply	Reduce braking performance	Critical	Probable	Intolerable
Failure of pneumatic pipeline	Non-standard material air pipeline	Leak in pipeline	Reduce braking performance	Critical	Probable	Intolerable
	Installation failure	Leak in pipeline	Reduce braking performance	Critical	Probable	Intolerable
	Pipeline Fracture, Broken	Leak in pipeline	Reduce braking performance	Critical	Probable	Intolerable
Failure of Drum Brake	The backing plate is broken & corrosion	Reduce the friction between the brake pads and the backing plate	Reduce braking performance	Critical	Probable	Intolerable
	The brake shoe wear out & Broken.	Reduce the friction between the brake pads and the backing plate	Reduce braking performance	Critical	Probable	Intolerable
	Distance between brake shoe & backing plate over limits	Reduce the friction between the brake pads and the backing plate	Reduce braking performance	Critical	Probable	Intolerable
	Parking Brake broken	Reduce parking brake performance	The vehicle cannot stand still when parked	Critical	Probable	Intolerable
	Brake shoe contaminated with impurities (dust, oil, grease, etc.)	Reduce the friction between the brake pads and the backing plate	Braking system failure	Critical	Probable	Intolerable
Failure of the master cylinder	Leaks in cylinder seals	The hydraulic power of the brake system cannot be used to push the piston	Braking system failure	Critical	Probable	Intolerable
Vapor Lock	Water Content was found in the brake fluid	brake fluid boils	Braking system failure	Critical	Probable	Intolerable
Brake Fading	Excessive heat in the system from repeatedly braking, under high loads, or at high speeds	Temporary and sudden reduction in braking power	Reduce braking performance	Critical	Probable	Intolerable

Table 6. Risk Level's result from FMEA

Subsystem	Negligible	Tolerable	Undesirable	Intolerable
Air Compressor System	5	-	1	1
Oil Water Separator	1	-	-	-
Check Valve	-	-	1	-
Reservoir Chamber	3	-	2	1
Pneumatic Pipeline	-	-	1	2
Brake Pedal	1	-	-	-
Braking valve (solenoid)	2	-	-	-
Brake Actuator	4	-	4	9

Table 7. Periodic estimation for each SOP recommendation

Failure Cases	SOP recommendations	Estimation of Periodic vehicle test
Driving Behavior	Adequate Training for Drivers Check the air pressure in the reservoir tank	4 months 25 days
Addition of unnecessary equipment	Visual check at reservoir tank Check the reservoir tank for air leaks, and spray with soapy water if needed.	10 months 23 days
Non-standard material air pipeline	Check the pipeline for air leaks, and spray with soapy water if needed	7 months 17 days
Installation failure	Check the pipeline for air leaks. Spray with soapy water if needed	6 months 8 days
Pipeline Fracture, Broken	Check the pipeline for air leaks. Spray with soapy water if needed	17 months 5 days
The backing plate is broken and corroded.	Opens the drum brake and check the function of the drum brake component, especially the backing plate	12 months 15 days
The brake shoe is worn out and Broken.	Opens the drum brake and check the function of the drum brake component, especially the brake shoe condition	16 months 20 days
Distance between brake shoe & backing plate over limits	Opens the drum brake and check the distance between the brake shoe & backing plate	22 months 14 days
Parking Brake broken	Opens the drum brake and check the function of the drum brake component, especially the Parking Brake	17 months
Brake shoe contaminated with impurities (dust, oil, grease, etc.)	Opens the drum brake and check the condition of the brake shoes to see whether there are any impurities in them	13 months 8 days
Leaks in cylinder seals	Check for brake fluid seepage at the master cylinder	4 months 25 days
Water content was found in the brake fluid	Check the quality of brake fluid using a brake fluid tester	8 months 8 days
Excessive heat in the system from repeatedly braking, under high loads, or at high speeds	1. Check the temperature of the brake shoe and backing plate 2. Check vehicle load at axle load tester	5 months

putting excess load on the main brake. Additionally, repetitive use of the service brake caused rapid air pressure drops in the reservoir chamber, leading to reduced air pressure in brake actuator. Training for new drivers was essential to ensure proper brake system use. Some recommendations for new diver training consisted of (a) Acquiring knowledge of transported goods, (b) City driving training, including navigating traffic, and (c) Freeway or open-road training, encompassing diverse terrains such as uphill and downhill roads. Although these curriculums lacked specific regulation, drivers needed training to mitigate human errors causing brake system failure.

5. Conclusion

In conclusion, the study objective was to enhance SOP for periodic testing of vehicle, specifically focusing on braking system, using systematic risk analysis method. Analysis of risk was conducted based on data from transport vehicle accidents in Indonesia spanning from 2017 to 2022. This data was processed to determine failure distribution via MLE method, yielding failure rate data. Subsequently, this failure rate was employed to ascertain risk level and severity of component failure. The process involved the use of FTA to identify failure causes, followed by FMEA to determine risk levels associated with each cause of failure.

From the outcomes of FTA and FMEA methods applied to the braking system, thirteen failure causes were identified, with the most critical risk being classified as having an Intolerable risk level. In response to these failure causes, SOP was developed to prevent or mitigate the likelihood of recurring failure causes. It should be noted that this SOP was designed to be integrated into the existing protocols. Consequently, the recommended method to periodic vehicle testing emphasizes the evaluation of system performance and the examination of each component condition, with particular emphasis on the braking system.

In accordance with government regulations regarding periodic testing of motorized vehicle, it was stipulated that brake system testing involved assessing the braking performance under specific conditions, including empty cargo and favorable road conditions. The absence of testing precision could compromise the effectiveness of periodic vehicle testing. Therefore, in light of the failure causes associated with the Intolerable risk level, the recommended SOP prioritized testing and inspecting the condition and performance of braking system components, such as the Drum Brake, Air Compressor System, Pneumatic Pipeline, and Brake Chamber. It was advisable to supplement the SOP with training programs for drivers to equip them with the skills necessary for effective braking in goods vehicle.

This study comprehensively analyzed risk associated with braking system through the application of FTA and FMEA methods. However, FTA might not establish causal relationships between components that were not interconnected within the same gate. There was also a distinct need for risk analysis to uncover relationships between components within braking system that lacked correlation through FTA. This could potentially be achieved by employing Bayesian Network analysis, which would enhance risk calculations both quantitatively and qualitatively.

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Author's Declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript

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Competing interests

The authors declare no competing interest.

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