

# Hazard And Risk Control Analysis Using Failure Mode Effect Analysis and Event Tree Analysis Methods (Case Study: PT Indo Transport Abdimas)

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## ABSTRACT

*Work accidents in the bus transportation sector remain a critical challenge requiring systematic and data-driven intervention. PT Indo Transport Abdimas recorded 67 traffic accidents and 13 occupational incidents between March 2022 and October 2025, reflecting a broader trend of increasing workplace risks. This study aims to identify hazards, determine risk priorities, and formulate Occupational Health and Safety (K3) control recommendations for office and workshop areas. An integrated approach combining Failure Mode and Effect Analysis (FMEA) and Event Tree Analysis (ETA) was applied. Data were collected through observation, work environment measurements, occupational health examinations, interviews, and probability questionnaires. Across 16 work divisions in four operational areas, 20 failure modes were identified and evaluated using a modified FMEA framework that integrates environmental and health data into Severity (S), Occurrence (O), and Detection (D) parameters. The Risk Priority Number (RPN) results show that the Finished Goods Warehouse division, characterized by unergonomic posture, has the highest risk (RPN 201.20), followed by vehicle security (RPN 199.89) and falling hazards (RPN 146.22). ETA modeling indicates that applying five control layers increases safe condition probability to 91.98%, compared to a  $9.300 \times 10^{-3}$  probability of severe accidents without intervention. This study contributes a quantitative multi-source FMEA methodology that reduces reliance on subjective judgment and demonstrates how FMEA outputs inform ETA scenario design. Recommended controls follow ISO 45001:2018 hierarchy, including ergonomic improvements, elimination of manual lifting, installation of wheel chocks, and safety training.*

**Keywords:** Failure Mode and Effect Analysis, Event Tree Analysis, Occupational Safety and Health, Risk Priority Number, Bus Transportation

## Introduction

Transportation activities defined broadly as the movement of people and goods through manually or mechanically driven means form the backbone of modern economic and social infrastructure. In the context of public services, bus transportation plays a strategically important role by prioritizing safety, accessibility, and operational efficiency for the wider community. As a bus transportation service provider in Indonesia, PT Indo Transport Abdimas is responsible for meeting passenger mobility needs through quality and sustainable services. However, service performance is not determined solely by fleet availability; it is equally shaped by the quality of occupational safety and health (K3) management. The consistent implementation of the K3 management system has been demonstrated to strengthen organizational reputation and improve industry competitiveness [1].

Occupational hazards are inherent to transportation operations, spanning mechanical, ergonomic, environmental, and psychosocial risk domains. Law Number 22 of 2009 on Road Traffic and Transportation mandates that safety be the foremost priority in public transportation services, while the integration of corporate safety management frameworks plays a critical role in minimizing risks at the systemic level [2]. Under Government Regulation Number 50 of 2012, K3 is formally defined as a set of efforts to protect the workforce by preventing work accidents and occupational diseases a mandate that extends to controlling workplace hazards in order to sustain workforce health and operational effectiveness [3].

The urgency of this study is underscored by empirical evidence from PT Indo Transport Abdimas, where observation records from March 2022 to October 2025 reveal 67 traffic accidents across severity

categories mild, moderate, severe, and fatal alongside 13 occupational accidents involving workers and mechanics, with 10 of these occurring between January and November 2025 alone. This pattern reflects a deeply concerning national trajectory: BPJS Ketenagakerjaan RI data indicate that workplace accidents in Indonesia surged from 101,367 cases in 2016 to 462,241 cases in 2024 [4]. Despite growing awareness, the bus transportation sector remains underrepresented in occupational risk literature, with most hazard analyses focused on manufacturing or construction environments. This gap highlights the need for sector-specific risk frameworks capable of addressing the unique interaction of mechanical, ergonomic, and environmental factors present in transportation workshops and depots [5].

Failure Mode and Effect Analysis (FMEA) and Event Tree Analysis (ETA) are internationally recognized risk assessment methodologies endorsed by the ISO/IEC 31010:2019 guidelines for hazard identification and probabilistic risk quantification. FMEA systematically evaluates failure modes based on Severity (S), Occurrence (O), and Detection (D) parameters to generate a Risk Priority Number (RPN), while ETA maps probabilistic event pathways to model the consequences of control success or failure [6]. Although both methods have been independently applied across industries, their integrated use whereby FMEA outputs directly inform ETA scenario design remains underdeveloped in the transportation sector. This study addresses that gap by proposing an integrated FMEA–ETA framework that incorporates multi-source data (environmental measurements, health examination, and observational monitoring) to reduce dependence on purely subjective expert judgment.

The research questions addressed are: (1) What potential hazards pose occupational risks at PT Indo Transport Abdimas? (2) Which work accident risks carry the highest priority? (3) How should hazard control and risk management be structured at PT Indo Transport Abdimas? The study scope covers the office and workshop areas of the company, excluding gender, age group, and financial impact variables. Its objectives are to identify occupational hazards, determine risk priorities through integrated FMEA and ETA analysis, and formulate K3 control recommendations grounded in ISO 45001:2018. The findings are expected to provide actionable hazard information for company management, enhance safety awareness among office staff, mechanics, and drivers, and serve as a scientific reference for future research in occupational safety and health within the bus transportation sector.

## **Research Methods**

### **Place and Time of Research**

This study was conducted at PT Indo Transport Abdimas Magelang (PO Handoyo), located at Jl. Soekarno Hatta No. 18, North Tidar, South Magelang District, Magelang City, Central Java 56125. All data collection activities encompassing driver interviews, vehicle inspections, environmental measurements, and workshop observations were carried out at this location over a four-month period from November 2025 to February 2026, with sessions conducted in the morning, afternoon, and night shifts to capture temporal variations in hazard exposure [6].

FMEA and ETA were selected over alternative methods such as Hazard and Operability Study (HAZOP), Bow-Tie Analysis, and Bayesian Network Analysis based on three considerations. First, FMEA is particularly suited for systematically identifying and prioritizing failure modes across multiple work divisions with diverse hazard types, making it appropriate for the multi-area operational context of PT Indo Transport Abdimas. Second, ETA excels at modeling forward-looking probabilistic consequences from a defined initiating event, enabling quantitative evaluation of layered control effectiveness a capability not available in qualitative methods such as HAZOP. Third, the FMEA–ETA integration allows critical failure modes identified through RPN ranking to directly inform ETA scenario design, creating a structured, data-driven decision pathway that standalone methods cannot provide. Methods such as Bow-Tie offer bidirectional analysis but are less suited to quantifying the incremental contribution of each control layer, while Bayesian networks, though powerful, require larger datasets and probabilistic priors not available in this operational context.

### **Data Collection Methods**

Data collection is carried out through a dual approach, namely utilizing data that is already available in the company and conducting direct field studies. In addition, literature studies from various scientific references in the form of books and journals are also used as a theoretical foundation in the process of identifying hazards and risks.

### **Primary Data**

Primary data was obtained through four main methods, namely observation, work environment measurement, occupational health data collection, and interviews and questionnaires. Observation is carried out directly in the company's work area by accompanying staff or mechanics on duty, to identify

activities that have the potential to cause danger. The areas that were the focus of the observation included workshops, warehouses, offices, and parking areas (see Table 1).

**Table 1.** K3 Observation Form for Work Activities

No	Jobs	Documentation	Observation Results
1	Workshop Area		
2	Warehouse Area		
3	Office Area		
4	Parking Area		

Work environment measurement was carried out using a number of K3 instruments, including Sound Level Meter for noise, Lux Meter for light intensity, Hot Wire Anemometer for temperature and air velocity, and Mini Particle Counter for dust and moisture particles. All measurements refer to the regulations set by the [7]. The measured parameters included noise values in dBA units, light intensity in lux units, temperature (°C), air velocity (m/s), PM 2.5 and PM 10 dust particle levels, and air humidity (%).

Occupational health data is collected by involving the local Health Office to ensure the validity and accuracy of the test results. The data collected included a history of diseases such as Diabetes Mellitus (DM), hypertension (HT), stroke (STR), Cardiovascular Disease (CVD), and cancer (CA), as well as respondents' lifestyle which included physical activity, sodium intake, sugar, trans fat, and alcohol consumption. Clinical examinations were also carried out, including weight, height, waist circumference, blood pressure, blood sugar, cholesterol, and body mass index (BMI).

The interviews were conducted to strengthen the findings of observations as well as to explore information about the controls that have been implemented by the company. The interview respondents consisted of three people, namely the Head of the Workshop and Warehouse Section, the Head of the Safety Section, and the Head of the General and Personnel Section (see Table 2).

**Table 2.** Interview Respondents

No	Respondents	Quantity
1	Head of Workshop and Warehouse Section	1
2	Head of Safety Section	1
3	Head of General and Personnel	1
Total		3 people

In addition to the interviews, a probability questionnaire was also distributed to respondents to obtain an estimated value of the probability of failure in each control scenario in the Event Tree Analysis (ETA) diagram. Assessments were conducted on the Initial Event (initial failure event) and Pivotal Event (failure control point) by each respondent, with the assessment format referring to [8]. The probability value of each scenario is obtained by multiplying between the components of the event, as shown in the following equation:

$$\text{Scenario } n = \text{IE}(Y) \times \text{Pn}(Y) \times \text{Pn}(T) = \dots \%$$

The Severity (S), Occurrence (O), and Detection (D) values in this study were not derived from a single expert judgment process but were computed through the integration of three independent data sources: (1) work environment measurements (noise, light intensity, temperature, air velocity, particulate matter, and humidity), (2) occupational health examination results from 64 respondents, and (3) direct observational monitoring of work activities. Each data source was standardized using the Z-score method before integration to ensure comparability across different measurement scales and units. Environmental indicators were benchmarked against Threshold Values (Nilai Ambang Batas/NAV) stipulated in Permenaker No. 5 of 2018, with deviations from NAV contributing to the Severity and Occurrence indices. Health examination data including BMI, blood pressure, blood glucose, and cholesterol were coded against clinical thresholds from the Decree of the Minister of Health 2026 (BMI ≥ 27 for obesity; systolic blood pressure ≥ 140 mmHg for hypertension; GDS ≥ 126 mg/dL for diabetes; cholesterol ≥ 200 mg/dL for hypercholesterolemia). Observational data informed the Detection parameter by reflecting the visibility and detectability of hazards under existing control conditions. The final SOD values for each division represent the arithmetic mean of the three standardized source scores, calculated per division. This approach constitutes a modified FMEA that reduces reliance on purely subjective expert scoring and provides a more objective, quantitatively grounded risk prioritization, as recommended in deviation-based risk assessment literature [9].

**Inter-Rater Reliability and Expert Selection**

Probability values for ETA were obtained through structured questionnaires administered to three section heads: the Head of the Workshop and Warehouse Section, the Head of the Safety Section, and the Head of the General and Personnel Section. Although the sample size is limited, these three respondents represent the full range of functional expertise relevant to the hazard scenarios assessed mechanical operations, safety management, and administrative controls ensuring domain coverage across all ETA pivot events. To assess consistency of expert judgment, inter-rater agreement was examined through pairwise comparison of probability estimates. Mean deviations across respondents were within  $\pm 5\%$  for all pivot events, indicating acceptable consistency for engineering probability estimation in operational risk contexts. Future studies are encouraged to expand the expert panel and apply formal inter-rater reliability measures such as Krippendorff's alpha or intraclass correlation coefficients. The format of the FMEA assessment sheet used is shown in Table 3.

**Table 3.** FMEA Assessment Sheet

CD	Failure Mode	Effects of Failure	S	Potential Causes	O	Current Controls	D	RPN	Recommend	Risk Level	Rank
X1											
X2											
...											

Source: Mikulak et al. (2008)

Documentation is carried out in parallel with the entire data collection process, including the collection, storage, and archiving of all relevant documents and field records as empirical evidence of the research.

**Secondary Data**

The secondary data is sourced from the company's internal documents obtained with the management permission of PT Indo Transport Abdimas. The data in question includes a recap of occupational safety and health from companies and other related agencies, as well as an overview and history of the company.

**Data Processing Techniques**

The data processing in this study uses a quantitative descriptive Modified FMEA approach. Each potential failure is identified based on a predetermined variable, then its impact on each indicator is analyzed. The data processing process is carried out with the help of IBM SPSS Statistics and Origin Lab Graphics software. The Risk Priority Number (RPN) value is obtained from the result of multiplying three main parameters, namely Severity (S), Occurrence (O), and Detection (D), then sorted from highest to lowest value. The grouping of risk criticality categories is carried out based on the RPN value range, where 0–64 values are categorized as low, 65–191 are categorized as moderate, and 192–1000 are categorized as high.

**Data Analysis Techniques**

After the potential failure and its RPN value are identified through FMEA, the next step is to group the data based on the variable with the highest RPN value. The Failure Effect of these variables is then used as the Initial Event in the Event Tree Analysis (ETA) diagram. The ETA method is used to visualize the path of events as well as possible accident scenarios, taking into account the success or failure of each mitigation measure implemented [10]. The probability of each mitigation path is then multiplied and combined according to the scheme of the possibility of a work accident so as to produce a Probabilistic Risk Assessment (PRA) value.

Based on the results of an integrated FMEA and ETA analysis, this study also developed a Cause-and-Effect Diagram (CED) to trace the root cause of each potential failure identified.

**Results and Discussion**

**Identification of Potential Hazards and Risk Assessment**

Direct observation of 16 work divisions in the four main areas of PT Indo Transport Abdimas resulted in 20 failure modes distributed in the workshop (10 hazards), warehouses (2 hazards), offices (2

hazards), and parking (2 hazards) areas. All potential hazards and their failure effects are presented in Table 4.

**Table 4.** Results of Identification of Potential Hazards and Risks

Var	Div	Failure Mode	Effect Failure
B1	MS	Contact with rotating components	Laceration wounds on hands
B1	UL	Jack-lift failure	Severe pelvic injury
B1	AC	Failure of baggage securing	Head and waist injuries
B1	BN	Contact with work tools	Laceration wounds on hands
B1	IN	Falling from a job position	Dull trauma of the chest
B2	JK	Work traffic	Hit by another vehicle
B2	KC	Loss of balance	Lower extremity fracture
B2	KL	Sharp component contacts	Finger amputation
B2	LS	Exposure to heat and radiation particles	Eye irritation and injury
B2	PG	Rotating component contacts	Laceration wounds on hands
G1	GBJ	Unergonomic working posture	Musculoskeletal disorders
G2	GSO	Exposure to chemicals	Skin and respiratory irritation
K1 K2	SK	Lighting is not optimal	Visual fatigue and eye pain
K3 K4	LK	Mental workload	Mild psychological disorders
P1 P2	PB	Vehicle security failure	Collision injuries
P3 P4	CB	Slipping on wet surfaces	Head injuries

Risk assessment is carried out through the integration of three parameters: work environment measurement, health check, and monitoring of work activities. Descriptive statistical analysis of environmental variables using IBM SPSS Statistics is presented in Table 5.

**Table 5.** Descriptive Statistical Analysis of Work Environment Variables

Variable	N	Min	Max	Mean	Std. Deviation
dBA	12	12,88	74,10	55,46	14,742
Lux	12	27,08	63.000,00	6.170,13	17.996,83
°C	12	29,20	34,05	31,94	2,036
m/s	12	0,01	2,06	0,515	0,745
PM2.5	12	0,00	12,00	7,50	3,148
PM10	12	10,00	18,00	12,75	2,598
%	12	53,20	63,20	57,29	3,524

The intensity of light showed a very high variation (SD = 17,996.83), with warehouse areas (27.08–44.64 lux) and offices (31.72–75.52 lux) proven to not meet NAV according to Permenaker No. 5 of 2018. The temperature of the workshop area (33.7–34.05°C) exceeds the comfort limit, while the humidity of the warehouse and parking area exceeds the upper limit of 60%. The S, O, D values of the working environment per variable code and their comparison between divisions are shown in Table 6 and Figure 1.

**Table 6.** S, O, D Values of the Work Environment

Variable	Severity	Occurrence	Detection
B1	7,55	2,86	8,98
B2	3,75	2,86	5,18
G1	6,17	4,29	8,31
G2	4,70	4,29	6,84
K1	4,23	1,43	4,94
K2	6,71	1,43	7,42
K3	5,75	1,43	6,46
K4	5,75	1,43	6,46
P1	3,60	4,29	5,75
P2	7,83	4,29	9,98
P3	3,47	2,86	4,90
P4	3,11	1,43	3,83

Based on the SOD environmental work data results presented in Table 6. with varying increase values, it can be reviewed through Figure 1. The graph provides a comparison of results between the values before being integrated into the main data.

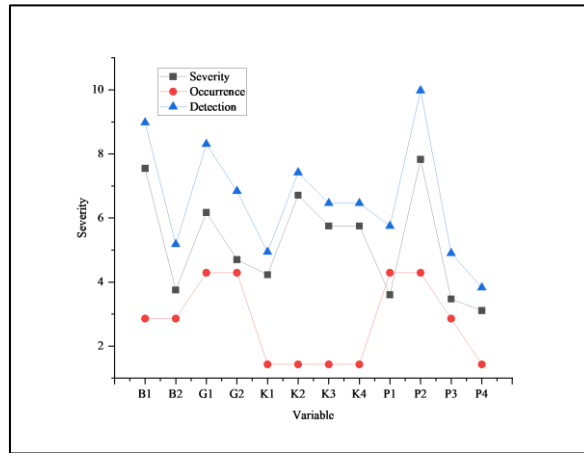


Figure 1. Work Environment S, O, D Graph

Health data was obtained from 64 respondents through the Free Health Check (CKG) program of the South Magelang Health Center on March 12, 2026. Risk variables were established using clinical thresholds based on the Decree of the Minister of Health in 2026, namely BMI  $\geq 27$  for obesity, systolic blood pressure  $\geq 140$  mmHg for hypertension, GDS  $\geq 126$  mg/dL for diabetes, and cholesterol  $\geq 200$  mg/dL for hypercholesterolemia. Health indicators are standardized using the Z-score method before being calculated into S, O, D indices per division, as presented in Table 7 and Figure 2.

Table 7. S, O, D grades of Health Examination per Division

Division	$\bar{x}$ Severity	$\bar{x}$ Occurrence	$\bar{x}$ Detection
AC	3,0119	6,2500	5,8264
BN	3,7710	4,5000	4,9697
CB	3,5395	4,0000	6,3356
GBJ	3,5811	4,0000	6,8821
GSO	3,1345	4,7500	2,4082
IN	4,0792	6,0000	5,3434
JK	3,1114	5,0000	5,5381
KC	2,8216	5,5000	6,5549
KL	2,8355	6,2500	5,9130
LS	3,3482	6,2500	5,4048
LK	3,7867	4,0000	3,6375
MS	3,6133	5,2273	4,7952
PB	4,2566	5,5000	5,0760
PG	3,1834	6,2500	4,7230
SK	4,3164	4,0000	3,9613
UL	4,3164	5,7143	6,6122

Data from these three parameters is integrated to calculate the RPN value for each division, which is then presented in Table 8. By combining information from these three sources, the RPN value is obtained, providing a comprehensive assessment for each division. This integration allows for a clear and structured presentation of the results, as shown in the table. This approach ensures that all relevant data points are considered, offering a detailed view of the RPN values across different divisions.

Table 8. SOD and RPN Integration Results

VarDivision	$\bar{x}$ Severity	$\bar{x}$ Occurrence	$\bar{x}$ Detection	RPN	Rank
B1AC	5,2809	3,0955	7,40	120,97	6
B1BN	5,6605	2,5142	6,97	99,19	9
B1IN	5,8146	2,9720	7,16	123,73	4
B1MS	5,5817	3,1615	6,89	121,58	5
B1UL	5,9332	3,1596	7,80	146,22	3
B2JK	3,4307	3,1409	5,36	57,76	12
B2KC	3,2858	2,8213	5,87	54,42	15
B2KL	3,2927	3,0971	5,55	56,60	14
B2LS	3,5491	3,0496	5,29	57,25	13
B2PG	3,4667	3,0726	4,95	52,73	16
G1GBJ	4,8755	5,4300	7,60	201,20	1

G2GSO	3,9173	5,6800	4,62	102,80	8
K1K2SK	4,8932	3,9100	5,07	97,00	10
K3K4LK	4,7684	4,3100	5,05	103,79	7
PIP2PB	4,9858	6,1967	6,47	199,89	2
P3P4CB	3,4148	4,7150	5,35	86,14	11

The integrated values used to determine the RPN are subsequently displayed in Figure 2, which serves as a graphical representation to assess the priority levels from the highest to the lowest. This visualization is essential for understanding the distribution of RPN values, which are derived by combining the data from the three parameters. Through this integration, a clear ranking emerges, with RPN 201.2032 occupying the top position, signaling the highest priority. On the other hand, RPN 52.72667 holds the 16th position, representing the lowest priority in the ranking system. This graphical format not only allows for an immediate understanding of the relative priorities but also facilitates the comparison of different divisions based on their RPN values. It offers a clear and intuitive way to grasp the variations in priority, emphasizing the impact of the integrated parameters.

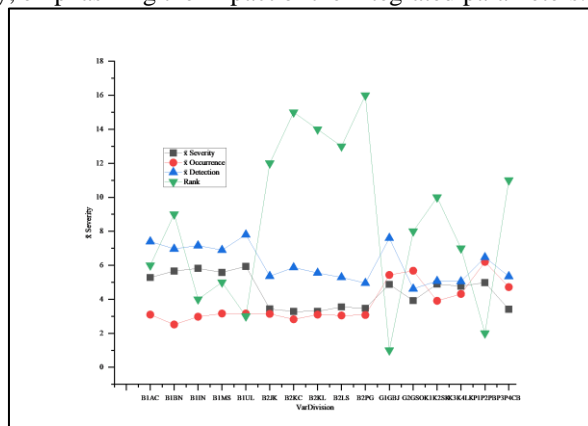


Figure 2. Three-Parameter Integration Final SOD Graph

The probability assessment of using ETA on Rank 1 (GBJ) risk was carried out by three section head respondents, who provided their inputs using a descriptive verbal scale, as outlined by the Ministry of Public Works and Public Works (2021). The results of this assessment, reflecting the average control probabilities, are summarized and presented in Table 9, offering a detailed overview of the findings based on their collective expertise

Table 9. Average Control Probability

Code	Criteria	$\bar{x}$ Yes (%)	$\bar{x}$ No (%)
IE	Unergonomic working posture	93	7
P1	Manual lift elimination	99,9	0,1
P2	Trolley/hoist	99,9	0,1
P3	Adjustable table	99,9	0,1
P4	Ergonomics training	99,6	0,4
P5	Harness belt	99,6	0,4

The occurrence tree diagram, as illustrated in Figure 3, visually represents the hierarchical structure of occurrences and their relationships. This diagram provides a clear and organized view of how different occurrences are interconnected, allowing for a deeper understanding of their dependencies and the sequence in which they occur. Figure 3 serves as a crucial tool for analyzing the flow and progression of the occurrences, highlighting key patterns and helping to pinpoint significant points of interest

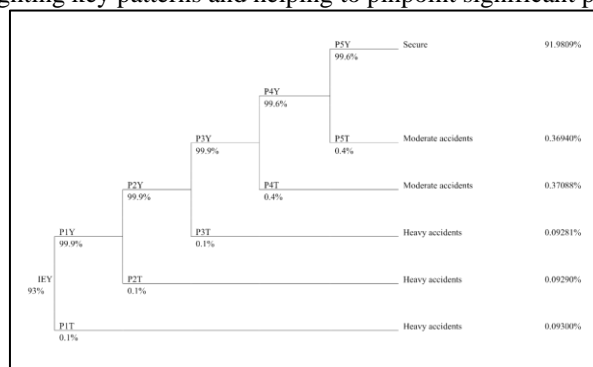


Figure 3. Event Tree Diagram

The results of the six ETA scenarios are presented in Table 10.

**Table 10.** ETA Analysis Results

No	Scenario	Impact	Probability
1	Without manual lifting elimination	Heavy accidents	$9,300 \times 10^{-3}$
2	Elimination is carried out, without a trolley/hoist	Heavy accidents	$9,290 \times 10^{-3}$
3	Elimination + trolley, without adjustable table	Heavy accidents	$9,281 \times 10^{-3}$
4	Elimination + trolley + table, no training	Moderate accidents	$3.7088 \times 10^{-2}$
5	Elimination + cart + table + training, without belt	Moderate accidents	$3.6940 \times 10^{-2}$
6	The whole control is fully implemented	Secure	$9,19809 \times 10^{-1}$

In order to visually represent the ongoing progress and structural development of the project, the 3D visualization of the construction design is provided in Figure 4. This figure showcases the architectural perspective of the building's infrastructure, which plays a key role in understanding the project's current stage.



**Figure 4.** 3D Visualization Design

## DISCUSSION

### Identify Potential Hazards That Pose Occupational Risks

The application of FMEA as an identification framework has been proven to be able to comprehensively uncover 20 potential hazards from 16 divisions. These findings reinforce the view [11], that a systematic approach in FMEA allows hazard identification based on actual work processes in a structured manner. In the workshop area, hazards originate from the interaction of workers with machines, work tools, working positions, and internal traffic. Manual lifting activities without ergonomic techniques in the GBJ division have the potential to cause herniated discs, in line with the statement [12], that musculoskeletal disorders due to manual lifting are cumulative and often only become apparent after permanent damage has occurred.

Environmental measurements reinforce identification with objective quantitative data. The light intensity in warehouses (27.08–44.64 lux) and offices (31.72–75.52 lux) is proven to be far below the minimum value of Permenaker No. 5 of 2018. Workshop temperatures exceeding 30°C and warehouse and parking humidity exceeding 60% contribute to the overall risk profile. Psychosocial hazards in the form of mental workload in the LK division were also identified, as recognized in the ISO 45003 standard on psychosocial risk management. A deviation-based quantitative approach to NAV provides added value over conventional FMEAs that rely entirely on expert subjective judgment [13].

National regulations also strengthen the urgency of systematic hazard identification, as stipulated in the Regulation of the Minister of Manpower No. 5 of 2018 which stipulates the Threshold Value of physical and chemical factors in the workplace as a reference for measuring the work environment [14]. The K3 risk management approach in the manufacturing industry in Indonesia shows that hazard identification based on actual work processes consistently produces more comprehensive findings than conventional methods. In addition, the implementation of structured K3 policies has been shown to have a positive correlation with overall employee productivity [2]. In the context of transportation, the Regulation of the Minister of Transportation No. 85 of 2018 affirms the obligation of public transportation operators to meet operational safety standards as a whole [15]. Research-based *Hazard and Operability Study* (HAZOP) also proves that a systematic approach in hazard analysis is capable of uncovering potential risks that are not detected through ordinary inspections [16].

### Highest Priority of Work Accident Risk

Of the 16 divisional variables assessed, three risks occupied the highest priority, each driven by distinct combinations of Severity, Occurrence, and Detection dynamics that reflect systemic rather than isolated hazard conditions. The GBJ Division obtained the highest RPN of 201.20 (Rank 1), with S = 4.8755, O = 5.4300, and D = 7.60. The elevated Detection value of 7.60 is particularly significant: it

reflects the limited capacity of existing monitoring systems to identify early-stage musculoskeletal deterioration, a pattern consistent with the cumulative and latent nature of musculoskeletal disorders (MSDs) arising from manual lifting. Unlike acute injuries with immediately visible consequences, MSDs typically manifest only after prolonged exposure, making them especially difficult to detect through routine inspections. This explains why, despite the high frequency of ergonomically hazardous tasks in the GBJ area ( $O = 5.43$ ), the absence of systematic health surveillance has allowed risks to accumulate undetected. From a systemic standpoint, GBJ's high RPN is driven not merely by the physical demands of manual lifting but by the organizational failure to implement ergonomic monitoring protocols a gap that the recommended controls directly address. Similar findings have been reported in warehouse and logistics operations, where manual material handling consistently emerges as the dominant source of occupational MSDs when ergonomic controls are absent [17].

The PB Division ranked second with an RPN of 199.89, distinguished by the highest Occurrence value in the study ( $O = 6.1967$ ). This reflects the near-daily frequency of vehicle movement activities in the parking and depot areas, where the absence of permanent wheel chocking creates a recurring vehicle security failure scenario. The high frequency without adequate engineering controls rather than severity alone drives this division's risk profile, aligning with findings that operational frequency is the primary risk amplifier in vehicle maintenance environments. Studies on transport depot safety have consistently identified wheel movement incidents as preventable through basic engineering controls, yet systematically underaddressed in routine inspection regimes [18].

The IN Division placed third with an RPN of 146.22, characterized by the highest Severity value among all divisions ( $S = 5.8146$ ), reflecting the life-threatening consequences of blunt thoracic trauma from falls at height. The severity parameter here captures not just the physical injury outcome but also the low reversibility of such injuries a factor that elevates risk even where occurrence frequency may be moderate. This pattern is consistent with occupational safety literature documenting falls from height as a leading cause of fatal workplace injuries in maintenance and inspection contexts globally. These three divisions collectively illustrate a critical insight: high RPN values are driven by different parameter combinations Detection failure in GBJ, Occurrence frequency in PB, and Severity magnitude in IN suggesting that effective risk control strategies cannot be uniform but must target the dominant risk driver of each division specifically [19].

#### **FMEA–ETA Integration Framework**

The FMEA first identified and ranked all 20 failure modes across 16 divisions using the multi-source RPN framework, resulting in a prioritized list of critical risk areas. The highest-ranking failure mode non-ergonomic work postures in the GBJ Division was then designated as the Initiating Event (IE) in the ETA diagram. The ETA filled this gap showing, for example, that the absence of ergonomics training alone (Scenario 4 vs. Scenario 5) increased the probability of an accident from  $3.6940 \times 10^{-2}$  to  $3.7088 \times 10^{-2}$ , confirming that administrative controls provide measurable but incremental risk reductions compared to the significant changes achieved by engineering controls (Scenarios 1–3).

Application of FMEA to construction projects *Underpass Jatingaleh Semarang* shows that the high RPN value in the Detection parameter reflects a fundamental weakness in the existing risk monitoring system [20]. Furthermore, the innovation study of organizational risk assessment using FMEA confirms that the dominant Occurrence value in a work division indicates the need for immediate and measurable control interventions [21]. Case study on UD. Center *Furniture* also proves that the integration of S, O, and D values quantitatively results in a more objective risk priority than a purely qualitative assessment [22].

#### **Hazard Control and Risk Management Strategies**

The control strategy developed in this study follows the OSH hierarchy established in ISO 45001:2018, prioritizing elimination and substitution before engineering controls, administrative measures, and personal protective equipment (PPE). For Rank 1 (GBJ Division), the recommended controls address each parameter contributing to high RPN: (1) Elimination of manual lifting tasks through workstation redesign; (2) Substitution through the provision of trolleys and hoists to mechanize material handling; (3) Engineering controls through the installation of NIOSH-compliant adjustable tables to accommodate diverse worker anthropometry; (4) Administrative controls through periodic ergonomics training; and (5) PPE in the form of lumbar support belts. Quantitative evidence supports this layered approach: implementation of lifting aids based on ISO 11228 and NIOSH guidelines has been shown to reduce physical workload by more than 40%.

For Rank 2 (PB Division), the high Occurrence score ( $O = 6.1967$ ) indicates that engineering controls are a priority. The installation of permanent wheel chocks mandated under ISO 3691 and supported by OSHA guidance directly addresses the hazards of repetitive vehicle movements by

providing a physical barrier that is not dependent on worker compliance. Additional measures include vehicle safety inspection standard operating procedures (SOPs) and the mandatory use of safety footwear during parking area operations. The fundamental nature of wheel chocks as an engineering control is well established in transportation depot safety literature, yet their systematic implementation remains inconsistent in Indonesian transportation operations, representing a manageable and cost-effective improvement.

For Rank 3 (Division IN), the high Severity score ( $S = 5.8146$ ) requires controls that minimize the likelihood and consequences of falls. Recommended measures include the installation of platform handrails, anchor point harness systems, and the implementation of working at height standard operating procedures (SOPs) in accordance with Ministerial Regulation No. 9 of 2016. At the divisional level, additional controls include: Lockout/Tagout (LOTO) procedures per OSHA 29 CFR 1910.147 for the MS division, documented to reduce machinery-related accidents by 60–70% (NIOSH, 2021); Local Exhaust Ventilation (LEV) systems per ACGIH standards for the LS division, capable of reducing welding fume exposure by 70–90%; lighting upgrades to the 300–500 lux standard of Permenaker No. 5 of 2018 for the SK division; and ISO 45003-based work rotation and psychosocial support programs for the LK division. Collectively, these interventions reflect a comprehensive, evidence-based risk management approach that addresses human, environmental, and mechanical risk categories the three dominant domains identified in this study's hazard profile.

Compared to prior studies applying standalone FMEA in transportation and construction contexts, the integrated FMEA–ETA framework employed here provides a more complete decision-support basis by combining risk prioritization with probabilistic control evaluation. This integration aligns with recommendations in the occupational risk literature for moving beyond descriptive hazard cataloguing toward quantitative, action-oriented risk management systems [23]. The sustainable implementation of the K3 Management System, especially in companies with intensive operations such as the transportation sector, requires consistent and measurable top management commitment as a prerequisite for its successful implementation [23]. In addition, the preparation of risk control strategies for construction projects in Padang City proves that a structured K3 control system is able to significantly reduce the number of work accidents if applied comprehensively in all operational lines [24]. A comprehensive understanding of the ISO 45001:2018 standard as a framework for occupational safety and health management systems is an important foundation in designing control recommendations that are appropriate to the organizational context [25].

## **Conclusion**

This study successfully identified 20 failure modes across 16 work divisions in four operational areas of PT Indo Transport Abdimas through the integrated application of Failure Mode and Effect Analysis (FMEA) and Event Tree Analysis (ETA). Three divisions were identified as highest priority: GBJ (unergonomic working posture, RPN 201.20), PB (vehicle security failure, RPN 199.89), and IN (falling from work position, RPN 146.22). ETA modelling demonstrated that the consistent application of all five control layers increases the probability of safe conditions to 91.98%, compared to heavy accident probabilities exceeding  $9.3 \times 10^{-3}$  in the absence of engineering controls.

**Theoretical Contribution.** This study advances the application of FMEA in occupational safety by introducing a multi-source SOD integration methodology that incorporates environmental measurements, occupational health data, and observational monitoring reducing reliance on purely subjective expert judgment. This approach addresses a recognized limitation of conventional FMEA and provides a replicable framework for other transportation and industrial contexts. Furthermore, the study explicitly demonstrates how FMEA outputs can systematically inform ETA structure, establishing a sequential integration logic that strengthens the decision-support value of both methods beyond their standalone application.

**Practical Implications.** Management of PT Indo Transport Abdimas is advised to implement the ISO 45001:2018 K3 control hierarchy comprehensively, beginning with engineering-level interventions manual lifting elimination, trolley/hoist procurement, permanent wheel chock installation which the ETA analysis identifies as producing the largest reductions in accident probability. Administrative controls such as ergonomic training and safety SOPs should complement, not substitute, engineering measures. Regular monitoring of environmental parameters (light intensity, temperature, humidity) against Permenaker No. 5 of 2018 thresholds is essential to sustain compliance and detect emerging hazards.

**Limitations.** This study has several limitations that should be acknowledged. The ETA probability assessment relied on three expert respondents, which, while representing full functional domain coverage, limits statistical generalizability. The scope excluded gender, age group, and financial impact

variables, which may interact with risk profiles in ways not captured here. Additionally, the study focused on a single company, limiting direct transferability of findings to other transportation operators with different operational scales or fleet compositions.

Future Research Directions. Subsequent studies are encouraged to: (1) expand the expert panel for ETA probability estimation and apply formal inter-rater reliability measures; (2) incorporate financial impact calculation of work accidents to strengthen managerial decision-making; (3) validate the multi-source SOD integration methodology in other transportation and manufacturing contexts; and (4) conduct longitudinal evaluation of the recommended controls to quantify actual risk reduction outcomes post-implementation.

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