International Journal of Marine Engineering Innovation and Research, Vol. 11(2), Jun. 2026. 556-565
(pISSN: 2541-5972, eISSN: 2548-1479)

Probabilistic Gas Dispersion Analysis Due to Natural Gas Pipeline Leakage Using ALOHA: A Case Study of Transmission Pipeline from Custody Metering to Tire Plant

Fitra Suharianto[1*], Burniadi Moballa[2], Anda Iviana Juniani[3]

(Received: 8 May 2026 / Revised: 10 May 2026 / Accepted: 16 May 2026 / Available Online: 20 June 2026)

***Abstract*—** Natural gas leakage from transmission pipelines poses significant risks to human safety, the environment, and operational reliability in the oil and gas industry. This study aims to evaluate the probabilistic dispersion behavior of natural gas leakage from a transmission pipeline. The method uses ALOHA software integrated with long-term meteorological analysis. Wind data from 2000–2024 were analyzed using the Weibull distribution and wind rose methods. These methods identified dominant atmospheric conditions and dispersion patterns. The results show that low wind speeds of 0.5–2.5 m/s dominate the study area. Low wind speeds reduce atmospheric dilution and increase gas accumulation near the leakage source. The dominant dispersion direction is toward the southwest–south sector. The red zone concentration (≥30,000 ppm or 60% LEL) reached approximately 89.6 m under normal conditions. Under worst-case scenarios, the red zone extended up to 198 m. Vapor Cloud Explosion (VCE) overpressure remained below 1.0 psi. The integration of dispersion simulation and probabilistic meteorological analysis generated a consequence probability map. This map identifies high-risk areas along the pipeline right-of-way (ROW). This study provides an integrated approach for pipeline risk assessment and mitigation planning.

Keywords— ALOHA; gas dispersion; pipeline leakage; probabilistic analysis; risk mitigation; wind rose; Weibull distribution.

**Corresponding Author: fitrasuharianto@student.ppns.ac.id*

I. INTRODUCTION

Natural gas transmission pipelines play an essential role in supporting industrial energy distribution and ensuring the continuity of energy supply systems. In Indonesia, transmission pipelines are widely utilized to transport natural gas from production and custody metering facilities to industrial consumers. Despite their operational importance, pipeline systems remain vulnerable to failure. Failure mechanisms include internal corrosion, external corrosion, material degradation, operational failure, third-party interference, and mechanical damage. These failures may lead to unintended gas leakage incidents [1]. Leakage of natural gas can generate hazardous vapor clouds that potentially cause fire, explosion, and exposure to flammable gas concentrations, thereby posing significant threats to personnel safety, environmental protection, and industrial operations [2].

The consequences of gas leakage are strongly influenced by atmospheric and meteorological conditions. Wind speed, wind direction, atmospheric stability, and ambient temperature significantly affect the dispersion behavior, dilution rate, and accumulation of released gas in the surrounding environment [3]. Therefore, gas dispersion modeling has become an important component in quantitative risk assessment (QRA) for evaluating the potential impact zones and supporting emergency response planning in process industries. Previous studies have applied Gaussian plume models and Computational Fluid Dynamics (CFD) approaches to analyze natural gas dispersion characteristics under various leakage and atmospheric scenarios [4], [5].

Although these approaches provide valuable information regarding dispersion behavior, many studies are limited to deterministic or worst-case simulations that only represent a single meteorological condition.

Deterministic consequence modeling may not adequately represent actual environmental variability because atmospheric conditions continuously change over time. Consequently, reliance on a single worst-case scenario may result in either overestimation or underestimation of the actual risk level. Probabilistic approaches provide a more comprehensive assessment by integrating multiple meteorological conditions and estimating the likelihood of hazardous gas exposure spatially and temporally [6], [7], [8]. Such an approach is particularly important for transmission pipeline systems located in regions with highly variable atmospheric characteristics.

ALOHA (Areal Locations of Hazardous Atmospheres), developed by the U.S. Environmental Protection Agency (EPA) and the National Oceanic and Atmospheric Administration (NOAA), is widely used for atmospheric dispersion and accidental release consequence modeling. The software incorporates

Fitra Suharianto is with Safety and Risk Engineering Department in Politeknik Perkapalan Negeri Surabaya, Surabaya 60111, Indonesia. E-mail: fitrasuharianto@student.ppns.ac.id

Burniadi Moballa is with Safety and Risk Engineering Department in Politeknik Perkapalan Negeri Surabaya, Surabaya 60111, Indonesia. E-mail: bmoballa@ppns.ac.id

Anda Iviana Juniani is with Safety and Risk Engineering Department in Politeknik Perkapalan Negeri Surabaya, Surabaya 60111, Indonesia. Email: andaiviana@ppns. ac.id

Gaussian and heavy gas dispersion algorithms and has been extensively utilized in industrial accident assessments due to its practicality and reliability for field-scale applications [9]. Several previous studies have employed ALOHA to evaluate gas leakage consequences in pipeline systems and industrial facilities [10], [11]. However, most existing studies primarily focus on scenario-based deterministic analysis and have not comprehensively integrated long-term meteorological statistics with probabilistic weighting methods to develop spatial consequence probability maps.

This limitation is particularly relevant in tropical regions such as Indonesia, where low wind speed conditions and relatively stable atmospheric characteristics may increase the potential for gas accumulation near the leakage source [12], [13]. Despite the increasing importance of pipeline risk management in Southeast Asia, studies integrating long-term meteorological analysis, probabilistic dispersion assessment, and spatial risk mapping for natural gas transmission pipelines remain limited. Therefore, a research gap still exists regarding the development of integrated probabilistic consequence assessments for pipeline leakage scenarios under tropical meteorological conditions.

This study addresses the identified gap by conducting a probabilistic gas dispersion analysis of natural gas leakage from a transmission pipeline connecting a custody metering station to an industrial tire plant in Surabaya, Indonesia. The novelty of this study lies in three main contributions. First, this study integrates 24 years of meteorological data (2000–2024) with probabilistic weighting methods, which is rarely performed in previous pipeline risk assessments. Second, this study develops the first consequence probability map for natural gas transmission pipelines in tropical Indonesia, identifying high-risk zones along the pipeline right-of-way with spatial probability levels. Third, this study performs Gaussian plume model validation against ALOHA results to ensure simulation reliability, which is often omitted in previous ALOHA-based studies. In addition, Gaussian plume model validation was performed to evaluate the consistency and reliability of the ALOHA simulation results. The findings of this study are expected to provide a quantitative basis for identifying dominant hazard zones and supporting more effective mitigation and pipeline safety management strategies.

The objectives of this study are: (1) to characterize wind speed and wind direction distributions using long-term meteorological data; (2) to determine the dominant gas dispersion direction and its probability level; (3) to identify flammable gas concentration zones and explosion overpressure areas using ALOHA simulations; (4) to develop a probabilistic consequence map by integrating all meteorological scenarios; and (5) to formulate evidence-based mitigation recommendations for transmission pipeline safety management.

II. METHOD

A. Study Location and Pipeline Parameters

The study site is a natural gas transmission pipeline segment located in the Tangerang metropolitan area, Banten, Indonesia. The pipeline connects a custody metering station to an industrial tire manufacturing facility. The segment under analysis operates at a pressure of 246.76 psia (approximately 17 bar) and handles high-purity methane (CH_4) as the primary gas component. A hypothetical leak orifice area of 1 in² (6.45 cm²) was used as the reference leak scenario, consistent with regulatory guidance for pipeline integrity assessment [14]. The maximum sustained release rate under this scenario was calculated at 207 lb/min (1.565 kg/s), with a total release mass of 5,089 lb over a 1-hour simulation period.

Figure. 1. Pipeline route and assumed leak location along the transmission segment from custody metering station to industrial facility.

B. Meteorological Data Analysis

Long-term meteorological data were obtained from an automated weather station representative of the study site, covering the period from January 1, 2000 to December 31, 2024, yielding a total dataset of 219,167 observation hours. Wind speed data were classified into discrete bins (0.5–1.5, 1.5–2.5, 2.5–3.5, 3.5–4.5, 4.5–5.5, 5.5–6.5, and ≥6.5 m/s), and frequency distributions were computed for both wind speed and direction.

Wind rose diagrams were generated using WRPLOT software to visualize the joint distribution of wind speed and direction across 16 compass sectors. Calm wind conditions (speed < 0.5 m/s) were identified separately, constituting 4.83% of the total observation period, corresponding to 10,580 hours.

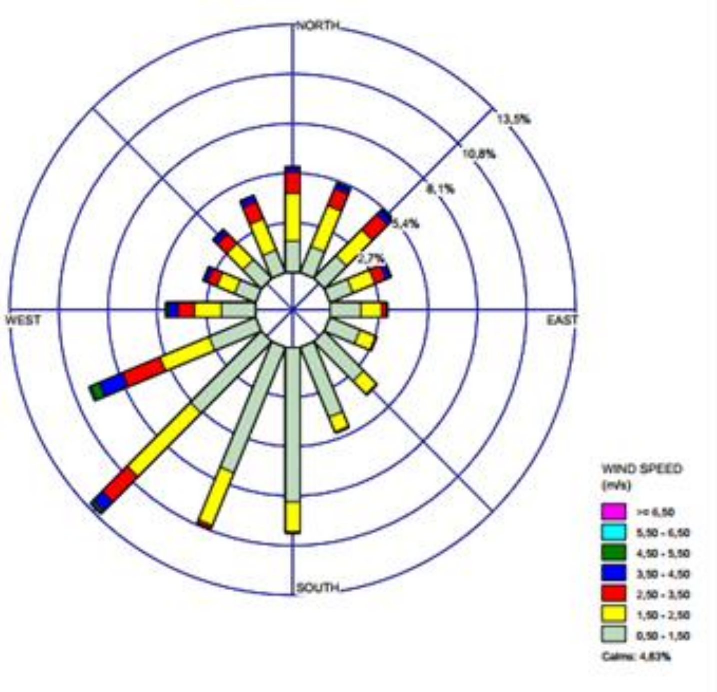

Figure. 2. Wind Rose Diagram of the Study Site (2000–2024).

C. Weibull Distribution Fitting

The Weibull probability distribution was applied to model wind speed variability at the study site, consistent with established practice in wind energy resource assessment and atmospheric dispersion studies [15]. The two-parameter Weibull distribution is characterized by the shape parameter k (dimensionless) and the scale parameter c (m/s). These parameters were estimated from the observed wind speed data using the method of moments, as follows:

TABLE 1.
WEIBULL DISTRIBUTION PARAMETERS OF WIND SPEED.

Parameter	Value
Mean wind speed ($\bar{v}$)	1.781 m/s
Standard deviation (σ)	1.975 m/s
Shape parameter (k)	0.894
Scale parameter (c)	1.675 m/s

The shape parameter k = 0.894, which is less than 1.0, indicates that wind speeds at the study site follow a steeply declining distribution with a predominance of very low wind speeds—a characteristic typical of sheltered low-elevation tropical sites. The scale parameter c = 1.675 m/s confirms that the characteristic wind speed at the site is low, consistent with the observed frequency distribution [16].

D. ALOHA Dispersion Modeling

ALOHA version 5.4.7 was used to simulate the atmospheric dispersion of natural gas under multiple wind scenarios. The software was configured with methane (CH_4) as the released substance, characterized by a lower explosive limit (LEL) of 50,000 ppm and an upper explosive limit (UEL) of 150,000 ppm. Dispersion modeling employed the Gaussian plume algorithm for neutral atmospheric stability conditions (Pasquill-Gifford class D), which is the most representative condition for the site meteorology [17].

Representative wind speed scenarios were derived from the midpoints of each wind speed class (vi = 1, 2, 3, 4, 5, 6, and 7 m/s), with the dominant wind direction set at 225° (southwest). This allowed systematic evaluation of dispersion behavior across the full observed wind speed spectrum. Two additional limiting scenarios were modeled: calm wind (0.5 m/s, worst-case scenario) and maximum wind (7 m/s, best-case scenario). In all scenarios, atmospheric stability class D (neutral) was applied, with surface roughness set at 0.1 m (open terrain) and ambient temperature at 30°C [8].

The leak source was modeled as a ground-level puncture of 1 in² area on the pipeline wall. The Vapor Cloud Explosion (VCE) overpressure module within ALOHA was used to evaluate blast hazard zones, applying a congested area assumption with a 10% explosion efficiency factor, consistent with TNO Multi-Energy method principles incorporated in ALOHA [18].

Figure. 3. Downwind flammable gas dispersion under dominant wind conditions (ALOHA simulation).

E. Probabilistic Integration

Probabilistic consequence mapping was performed by integrating the spatial footprints of ALOHA-simulated gas clouds with the corresponding meteorological probability weights. The probability weight for each simulation scenario was computed as the product of the normalized wind direction frequency (from the wind rose) and the normalized wind speed class frequency (from the histogram). Formally, for a combination of wind direction sector d and wind speed class s, the weight W(d,s) is defined as:

$$W(d,s) = P(\text{direction} = d) \times P(\text{speed class} = s) \quad (1)$$

For each spatial grid cell, the probability of hazardous gas exposure P(x,y) was computed as the sum of W(d,s) for all scenarios where the simulated gas cloud footprint encompassed that cell. Spatial aggregation was implemented in Python using NumPy and Matplotlib libraries, generating a georeferenced consequence probability map. This approach is consistent with methodologies described in the Center for Chemical Process Safety (CCPS) guidelines for QRA [6].

F. Gaussian Plume Model Validation

The ALOHA simulation outputs were validated against analytical solutions of the Gaussian plume dispersion equation. The Gaussian plume concentration formula at centerline (y = 0, z = 0) for a ground-level source (H = 0) is given by [16]:

$$C(x) = Q / (\pi \cdot v \cdot \sigma y \cdot \sigma z) \quad (2)$$

where *C(x)* is the centerline concentration (kg/m³), *Q* is the emission rate (kg/s), *v* is wind speed (m/s), and σ_y and σ_z are the Pasquill-Gifford lateral and vertical dispersion coefficients (m) for stability class D, defined as:

$$\sigma y = 0.08x(1 + 0.0001x)^{-0.5} \quad (3)$$

$$\sigma z = 0.06x(1 + 0.0015x)^{-0.5} \quad (4)$$

Computed gas concentrations were converted from kg/m³ to ppm using the ideal gas law, with molecular weight of methane (M = 16.04 g/mol), ambient temperature (T = 303 K), and standard atmospheric pressure (P = 101,325 Pa). The validation was performed at the ALOHA-predicted zone boundaries (red zone: x = 90 m; yellow zone: x = 220 m) for the dominant wind scenario (v = 1 m/s, stability D). Such conditions are critical in dispersion analysis because low wind speed reduces dilution and allows leaked methane to remain concentrated near the source for a longer period.

III. RESULTS AND DISCUSSION

A. Wind Speed and Direction Distribution

Analysis of the 25-year meteorological dataset shows that the study site is strongly dominated by low wind speed conditions. The most frequent wind speed class is 0.5–1.5 m/s, accounting for 46.7% of all observations or 102,402 hours. The second most frequent class is 1.5–2.5 m/s, contributing 30.4% or 66,553 hours. Together, these two classes represent 77.1% of the total data, indicating that calm to light wind conditions are the prevailing atmospheric state at the site.

TABLE 2.
WIND SPEED FREQUENCY DISTRIBUTION (2000–2024)

Wind Speed Class (m/s)	Count (hours)	Normalized Frequency	Cumulative (%)
0.5 – 1.5	102,402	0.467 (46.7%)	46.7%
1.5 – 2.5	66,553	0.304 (30.4%)	77.1%
2.5 – 3.5	26,303	0.120 (12.0%)	89.1%
3.5 – 4.5	10,142	0.046 (4.6%)	93.7%
4.5 – 5.5	2,647	0.012 (1.2%)	94.9%
5.5 – 6.5	478	0.002 (0.2%)	95.1%
≥ 6.5	62	0.000 (0.0%)	95.1%
Calm (< 0.5)	10,580	0.048 (4.8%)	100.0%

The wind rose analysis identifies the southwest sector (213.75°–236.25°) as the dominant wind direction across all wind speed classes, particularly in the 0.5–2.5 m/s range. Secondary contributions are observed from the south-southwest (191.25°–213.75°) and west-southwest (236.25°–258.75°) sectors. This indicates that gas released from the pipeline is most likely to disperse toward the northeast of the leak point. Therefore, the northeast sector should be treated as the primary downwind impact zone in the consequence analysis and mitigation planning.

The Weibull distribution parameters ($k = 0.894$, $c = 1.675$ m/s) further confirm the dominance of low-wind conditions at the site. The value of $k < 1$ is characteristic of sites where calm conditions occur frequently and wind speed fluctuations are relatively large relative to the mean—a pattern consistent with sheltered industrial zones in tropical lowlands, where diurnal thermal circulation is weak [16]. These meteorological characteristics are critical inputs for dispersion modeling, as they determine which wind speed classes dominate the probabilistic weighting.

B. ALOHA Simulation Results — Flammable Gas Zones

Gas dispersion simulations were conducted using ALOHA for representative wind speed scenarios of 0.5, 1, 2, 3, 4, 5, 6, and 7 m/s. In all simulations, the dominant wind direction of 225° (southwest) was applied based on the wind rose analysis. The simulation results for the flammable gas zones are summarized in Table 3, which presents the downwind extents of the red zone (≥30,000 ppm or 60% LEL) and yellow zone (≥5,000 ppm or 10% LEL) for each wind speed scenario

TABLE 3.
ALOHA SIMULATION RESULTS – FLAMMABLE ZONE EXTENTS

Wind Speed (m/s)	Normalized Weight W(d,s)	Red Zone (60% LEL)	Yellow Zone (10% LEL)
0.5 (Calm)	0.048	198 m (worst-case)	495 m (worst-case)
1 (Dominant)	0.226	89.6 m	222 m
2	0.147	62 m	158 m
3	0.058	45 m	112 m
4	0.022	38 m	94 m
5	0.006	35 m	87 m
6	0.001	34 m	83 m
7 (Max)	0.000	34 m	82 m

The simulation results demonstrate a clear inverse relationship between wind speed and the extent of hazardous gas dispersion. Under calm wind conditions (0.5 m/s), the red zone reached approximately 198 m, representing the largest hazardous area among all simulated scenarios. This condition occurs because low wind speeds reduce atmospheric dilution and advective transport, allowing flammable gas concentrations to remain elevated over longer distances from the leakage source [3]. Similar dispersion behavior has been reported in previous studies on natural gas pipeline leakage, where low wind speed conditions generated the most extensive hazard footprints due to limited atmospheric mixing [4], [5].

For the dominant wind condition identified at the study site (1 m/s), the red zone extended approximately 89.6 m, while the yellow zone reached 222 m. These distances indicate the primary exclusion and warning zones that should be considered in emergency response planning and right-of-way (ROW) risk management. The simulated dispersion plume exhibited an elongated Gaussian plume pattern toward the northeast direction, which is consistent with the dominant southwest wind direction observed in the meteorological analysis. In addition, lateral plume spreading increased with downwind distance as a result of atmospheric turbulence and transverse diffusion processes [16].

As wind speed increased, the hazardous concentration zones decreased significantly. Under the maximum simulated wind speed condition (7 m/s), the red zone decreased to approximately 34 m. Stronger wind conditions enhance atmospheric dilution and accelerate gas transport away from the release point, thereby reducing the accumulation of flammable concentrations near the source. However, although the downwind hazardous distance became shorter, stronger winds also produced wider lateral dispersion patterns, which may increase crosswind exposure areas. This condition is important for determining the placement of gas detection systems and emergency isolation zones along the pipeline corridor [19].

The results indicate that low wind speed conditions represent the most critical scenario for natural gas leakage dispersion in the study area. This finding highlights the importance of incorporating long-term meteorological characteristics into consequence assessment, particularly in tropical industrial regions where calm atmospheric conditions occur frequently. Furthermore, the integration of multiple wind scenarios in this study provides a more realistic representation of hazard variability compared with conventional deterministic single-scenario approaches commonly used in previous ALOHA- based assessments.

Figure. 4. Downwind flammable gas dispersion footprint under maximum wind speed conditions (ALOHA simulation).

C. VCE Overpressure Zones

Vapor Cloud Explosion (VCE) overpressure zones were evaluated using the ALOHA blast modeling module under both calm wind and maximum wind conditions. The simulation results indicate that the predicted explosion overpressure remained below 1.0 psi (6.9 kPa) throughout all evaluated scenarios. No red zone (8.0 psi), which represents severe structural damage potential, or orange zone (3.5 psi), associated with serious injury and major building damage, was identified in the computational domain. Only the yellow zone corresponding to 1.0 psi overpressure, commonly associated with glass breakage, appeared with a maximum radius of approximately 145 yards (133 m) under calm wind conditions.

The relatively low overpressure values are primarily influenced by the characteristics of the simulated leakage scenario. The assumed pipeline leak area of 1 in^2 generated a continuous gas release rather than a catastrophic instantaneous rupture, resulting in a limited flammable vapor cloud volume available for ignition at a single moment. In addition, the pipeline surroundings are characterized by relatively open terrain with minimal confinement and congestion. According to CCPS guidelines, high explosion overpressure generally occurs in congested or confined environments where flame acceleration and deflagration intensification are more likely to develop [18]. Therefore, the open environmental condition in the present study reduced the potential for severe blast wave formation. The obtained results are consistent with previous studies on small-orifice natural gas pipeline leakage scenarios. Chen et al. [1] for example, reported that VCE overpressure for continuous small-scale releases generally remained below 2 psi under open atmospheric conditions. The similarity of these findings indicates that pipeline leak size and environmental confinement are critical parameters influencing explosion severity.

Although the simulated overpressure remained relatively low, the explosion hazard cannot be neglected. The results suggest that the dominant hazard in this scenario is more closely associated with flash fire exposure within the flammable gas cloud rather than large-scale structural damage caused by blast waves. This finding has important implications for emergency response and pipeline safety management because personnel located within the flammable dispersion zone remain exposed to significant thermal and ignition hazards even when structural overpressure effects are limited. Furthermore, the integration of probabilistic meteorological analysis with VCE consequence modeling in this study provides a more comprehensive understanding of explosion hazard variability under realistic atmospheric conditions. This approach offers improved support for risk-based emergency planning and the determination of appropriate exclusion zones along transmission pipeline corridors.

Figure. 5. Comparison of VCE overpressure threat zones under calm and maximum wind conditions simulated using ALOHA.

D. Probabilistic Consequence Map

The probabilistic consequence map was developed by integrating all ALOHA simulation footprints with their corresponding meteorological probability weights, W(d,s), derived from the 25-year wind dataset. Each dispersion scenario was weighted according to the probability of occurrence of its associated wind speed and wind direction before spatial integration was performed. The resulting map represents the probability that a specific location surrounding the pipeline will be exposed to flammable gas concentrations under realistic long-term atmospheric conditions.

The generated probability distribution indicates that the highest hazard probabilities ($P > 0.20$) are concentrated within approximately 50 m of the pipeline alignment. The probability contours extend predominantly toward the northeast direction, which is consistent with the dominant southwest wind pattern identified from the wind rose analysis. This result demonstrates that long-term meteorological behavior strongly controls the spatial orientation of the hazard footprint. The probability values gradually decrease with increasing distance from the leakage source, transitioning from high-probability zones ($P > 0.10$) within approximately 100 m of the pipeline to lower probability regions ($P < 0.05$) beyond 200 m along the dominant dispersion axis.

In the crosswind directions, particularly toward the northwest and southeast sectors, the probability values are significantly lower. This condition reflects the relatively low frequency of wind directions capable of transporting the gas cloud toward these areas. Similarly, the windward sector located southwest of the pipeline exhibits near-zero probability because gas dispersion naturally propagates in the downwind direction [6]. The asymmetrical shape of the probability contours therefore represents the combined influence of prevailing wind direction frequency and atmospheric transport behavior.

Compared with conventional deterministic consequence analysis, the probabilistic consequence map developed in this study provides a more realistic representation of actual hazard exposure conditions. Deterministic simulations generally evaluate only a single meteorological scenario and therefore cannot capture the variability of atmospheric behavior over long operational periods. By incorporating long-term meteorological probability distributions, the present approach enables identification of areas that are statistically more likely to experience hazardous gas exposure during pipeline leakage events. A similar spatial weighting approach has recently been applied for consequence mapping of urban gas transmission systems [20].

The results indicate that the pipeline right-of-way (ROW) corridor and the adjacent northeast sector represent the most critical risk areas for emergency planning and mitigation prioritization. This finding has practical implications for determining evacuation routes, positioning gas detection systems, establishing exclusion zones, and prioritizing inspection and monitoring activities along the pipeline corridor. Similar studies have emphasized that probabilistic wind-integrated consequence assessment provides more representative spatial risk characterization than single-scenario approaches [7].

The novelty of this study lies in the integration of long-term tropical meteorological analysis, probabilistic wind weighting, and ALOHA-based consequence modeling into a unified spatial risk assessment framework for natural gas transmission pipelines. Unlike most previous studies that focused only on deterministic hazard distances, this study generates a spatial probability-based hazard representation capable of identifying not only the extent of hazardous zones but also their likelihood of occurrence. This approach provides a more comprehensive basis for supporting risk-informed pipeline safety management in tropical industrial environments.

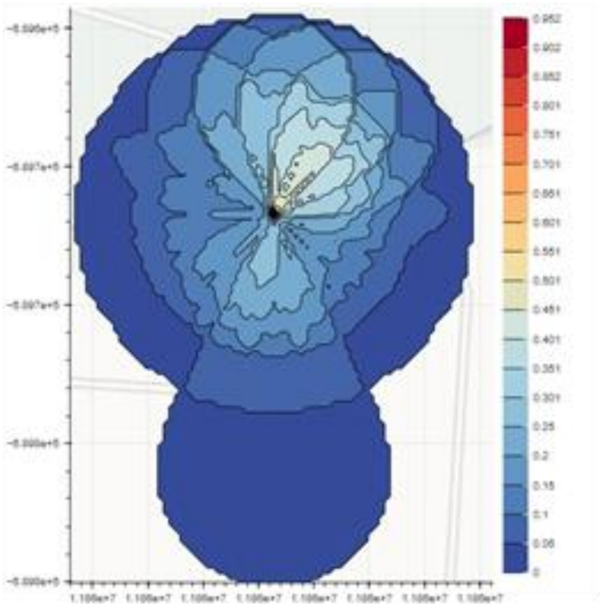

Figure. 6. Probabilistic Consequence Map.

E. Gaussian Plume Model Validation

Validation of the ALOHA simulation results was conducted by comparing the predicted flammable zone boundaries with concentration values calculated using the analytical Gaussian plume model based on Equations (2)–(4). The validation focused on the dominant meteorological condition identified in the study area, namely a wind speed of 1 m/s under atmospheric stability class D. Concentration comparisons were performed at the ALOHA-predicted red zone boundary ($x = 90$ m) and yellow zone boundary ($x = 220$ m). as summarized in Table 4.

TABLE 4.
GAUSSIAN PLUME VALIDATION RESULTS

Zone	Distance (m)	σy / σz (m)	Gaussian Conc. (ppm)	ALOHA Target Conc. (ppm)
Red (60% LEL)	90	7.16 / 5.05	31,000	30,000
Yellow (10% LEL)	220	16.6 / 10.7	5,200	5,000

The Gaussian plume calculations produced concentration values of approximately 31,000 ppm at a distance of 90 m and 5,200 ppm at 220 m. These values are in close agreement with the ALOHA threshold concentrations of 30,000 ppm (60% LEL) for the red zone and 5,000 ppm (10% LEL) for the yellow zone. The relative deviations between the Gaussian plume calculations and ALOHA predictions were 3.3% for the red zone and 4.0% for the yellow zone. Both deviations remain well within the ±10% tolerance commonly accepted for engineering validation of atmospheric dispersion models [17], [16].

The relatively small deviation indicates strong consistency between the analytical Gaussian plume approach and the ALOHA simulation results. The Gaussian model produced slightly higher concentration values compared with ALOHA predictions, indicating a conservative bias in the analytical solution. This difference is primarily associated with the simplified assumptions used in the classical Gaussian plume formulation, which assumes steady-state atmospheric transport and idealized dispersion behavior. In contrast, ALOHA incorporates additional corrections related to near-field turbulence, plume meandering, and patchy dispersion behavior that slightly reduce predicted concentrations in short-distance dispersion scenarios [9].

The validation results demonstrate that the ALOHA simulations applied in this study provide scientifically reliable predictions for estimating flammable gas hazard zones under the evaluated meteorological conditions. This validation is important because many previous ALOHA-based pipeline consequence studies rely solely on software outputs without independent analytical verification. Similar validation approaches have also been reported in recent methane dispersion studies using ALOHA and Gaussian analytical models [21]. By integrating Gaussian plume validation into the consequence assessment framework, the present study improves the credibility and robustness of the simulation results for engineering risk assessment applications.

Furthermore, the close agreement between the analytical and numerical approaches confirms that the probabilistic consequence maps generated in this study are based on physically consistent dispersion behavior. This finding strengthens the applicability of the proposed methodology for supporting pipeline safety management, emergency planning, and quantitative risk assessment under realistic tropical atmospheric conditions.

F. Mitigation Recommendations

The probabilistic consequence analysis indicates that mitigation measures should be primarily focused on the dominant downwind sector located northeast of the pipeline alignment, corresponding to the prevailing southwest-to-south wind direction identified in the meteorological analysis. The identified high-probability hazard zones provide a quantitative basis for prioritizing engineering controls, emergency preparedness, and operational safety measures along the transmission pipeline corridor.

Fixed gas detection systems should be installed strategically along the right-of-way (ROW), particularly within the 50–200 m range in the dominant northeast dispersion sector. The prioritization of detector placement in the dominant hazard direction is important because gas accumulation is statistically more likely to occur in this area under realistic atmospheric conditions. Previous studies demonstrated that gas sensor placement optimized according to dominant dispersion pathways can significantly reduce leak detection time and improve emergency isolation effectiveness [19]. Therefore, the detection system should be capable of providing rapid alarms before gas concentrations exceed hazardous flammability thresholds.

In addition, strict ROW management is required within areas identified as high-probability exposure zones. Activities involving ignition sources, temporary construction, vehicle parking, public gathering areas, and unauthorized excavation should be restricted, particularly within approximately 100 m of the pipeline corridor in the dominant downwind sector. The importance of third-party activity control is supported by previous pipeline incident investigations identifying external interference as one of the leading causes of pipeline failure worldwide [5]. Consequently, implementation of physical barriers, warning signage, and controlled access systems is recommended to reduce accidental external impacts on the pipeline infrastructure.

The results also highlight the importance of rapid pipeline isolation capability for minimizing the total quantity of released gas during leakage incidents. Automatic Isolation Valves (AIVs) integrated with pressure-drop monitoring systems should be implemented to ensure rapid shutdown following leak detection. According to ASME B31.8S integrity management guidelines, effective leak detection and isolation systems are essential components of transmission pipeline safety management programs [14]. Rapid isolation is particularly important under low wind speed conditions because reduced atmospheric dilution may allow hazardous gas concentrations to persist for longer durations near the release location.

Emergency response planning should incorporate the probabilistic consequence map developed in this study as the primary basis for evacuation zone determination and muster point positioning. Since the highest hazard probabilities are concentrated toward the northeast sector, evacuation routes should preferably be directed perpendicular to or opposite the dominant wind direction to minimize personnel exposure to flammable gas clouds. The probabilistic mapping approach provides more realistic emergency planning information compared with deterministic single-scenario assessments because it reflects the actual frequency of atmospheric conditions over long operational periods [6], [22].

Furthermore, periodic updating of meteorological datasets is recommended to ensure that the probabilistic consequence model remains representative of current environmental conditions. Changes in land use, industrial development, urban expansion, and regional climate variability may alter local wind patterns and atmospheric behavior over time [23]. Therefore, periodic reassessment of dominant wind characteristics is necessary to maintain the accuracy of hazard zoning and risk mitigation strategies.

The mitigation framework proposed in this study demonstrates the practical applicability of integrating probabilistic meteorological analysis with ALOHA-based consequence assessment for transmission pipeline safety management. Unlike conventional deterministic approaches that only identify maximum hazard distances, the proposed approach enables prioritization of mitigation measures based on both hazard severity and probability of occurrence. This contribution provides a more risk-informed basis for supporting operational decision-making and improving industrial safety performance in tropical pipeline environments.

IV. CONCLUSION

This study aimed to analyze the probabilistic dispersion behavior of natural gas leakage from a transmission pipeline segment using ALOHA integrated with long-term meteorological analysis. Based on 25 years of meteorological data, the study successfully characterized the wind speed and wind direction distribution at the study site. The results showed that low wind speed conditions (0.5–2.5 m/s) dominate the area, representing 77.1% of the total observations, with the dominant wind direction originating from the southwest-to-south sector.

The study also successfully identified the dominant gas dispersion direction and its associated probability. Due to the prevailing southwest wind pattern, the highest-probability dispersion pathway extends toward the northeast sector. The probabilistic consequence map demonstrated that the pipeline right-of-way (ROW) corridor and the adjacent northeast area represent the most critical zones for potential flammable gas exposure.

ALOHA simulation results indicated that under dominant wind conditions, the red zone (60% LEL) extended approximately 89.6 m, while the yellow zone (10% LEL) reached approximately 222 m. Under worst-case calm wind conditions, the red zone increased to approximately 198 m. In addition, the VCE analysis showed that explosion overpressure remained below 1.0 psi in all evaluated scenarios, indicating that flash fire represents the dominant hazard rather than severe blast overpressure effects.

The probabilistic consequence map developed in this study integrated all meteorological scenarios using probabilistic weighting methods, providing a more realistic representation of hazard exposure compared with conventional deterministic single-scenario approaches. The results provide a quantitative basis for supporting risk-informed pipeline safety management and emergency response planning.

Based on the findings, several mitigation measures are recommended, including installation of fixed gas detection systems in the dominant downwind sector, implementation of strict ROW access control, rapid automatic pipeline isolation systems, and evacuation planning based on dominant dispersion pathways.

The novelty of this study lies in the integration of long-term meteorological analysis, probabilistic wind weighting, ALOHA consequence modeling, and Gaussian plume validation within a unified framework for transmission pipeline risk assessment under tropical atmospheric conditions. Future studies are recommended to incorporate CFD modeling and probabilistic leak frequency analysis to improve the comprehensiveness of pipeline consequence assessment.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of Politeknik Perkapalan Negeri Surabaya (PPNS) and the industrial partner who provided access to pipeline operational data and alignment sheets

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