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Research Article

Risk Analysis Related to the Possibility of Using CNG in Trans Jogja Buses

Analisis Risiko Kemungkinan Penggunaan CNG di Bus Trans Jogja

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Abstract

One of the issues in urban areas such as DI Yogyakarta province is air pollution. The pollution level is high, as shown by the quality index value of about 85.25 in 2019. Vehicle emissions are the most significant source of this pollution in urban areas and can be decreased by using fuel with minimum carbon emission. Compressed Natural Gas (CNG) is an environmentally friendly fuel. However, a safety study is required because CNG is stored under high pressure. Therefore, this research aims to analyze the risk of using CNG in the Trans Jogja bus. The research method collects secondary data and then processes them using FTA, ETA, ALOHA software, and a risk matrix. The result shows that the risk value for CNG usage in the Trans Jogja bus is low to a moderate level or acceptable.

Keywords: CNG; ETA; FTA; risk matrix; Trans Jogja

Abstrak

Polusi udara menjadi salah satu permasalahan di daerah perkotaan seperti di provinsi DI Yogyakarta. Tingkat polusi di DIY cukup tinggi yang ditunjukkan dari nilai indeks kualitas udara sebesar 85,25 pada tahun 2019. Penyumbang terbesar dari polusi udara di perkotaan adalah kendaraan bermotor.Oleh karena itu polusi udara dapat diturunkan dengan menggunakan bahan bakar yang rendah emisi karbon. Compressed Natural Gas (CNG) adalah bahan bakar yang ramah lingkungan. CNG disimpan dalam tekanan tinggi, maka kajian keselamtan ketika menggunakan CNG perlu dilakukan. Penelitian ini bertujuan untuk menganalisa resiko apabila CNG digunakan pada bus Trans Jogja. Metode penelitian dilakukan dengan mengumpulkan data-data sekunder kemudian mengolahnya menggunakan FTA, ETA, ALOHA software dan matriks resiko. Berdasarkan hasil analisa, nilai resiko dari penggunaan CNG pada bus Trans Jogja berada di tingkat rendah hingga sedang atau dapat diterima.

Kata kunci*: CNG; ETA; FTA; matriks resiko; Trans Jogja*

1. Introduction

Air pollution has become one of the environmental issues in urban areas. The source of the pollution comes from the combustion process of industries, vehicles, and waste. DI Yogyakarta, one of the provinces in Indonesia with a population of about 3,842,932 people in 2019 [1], has an air quality index (AQI) of 85.25, below the minimum target of 87.73 [2]. The cause for insufficient air quality is pollution from the fuel combustion of vehicles. The number of vehicles in 2019 was 1,575,074 units, according to data from the Department of Transportation [3]. This figure will be increased as the population of DI Yogyakarta grows. Therefore, a clean transportation system with minimum CO_2 and pollutant emissions is needed. The alternative solution is to use Compressed Natural Gas (CNG) as fuel, which is considered the solution for fossil fuel substitution. This is because of its several advantages, such as showing great promise in reducing emissions [4], low maintenance costs [5], its inherent clean nature of combustion [6], ready availability, and low fuel cost [7].

CNG was first introduced in the late nineties as an alternative to mineral oil. It contains methane as the main component, ethane, propane, butane, pentane, and other gas impurities [8]. It is made by compressing methane at 18-20 Mega Pascal (MPa) pressure and then stored in a metallic or composite cylinder tube at a 200–250 bar [9]. The design and testing pressure are usually 30 MPa, the tube does not explode at less than 46 MPa, and the working pressure is 20 MPa [10]. CNG's physical properties provide some benefits over gasoline and diesel fuel, such as 120 to 130 octane/cetane number, 47.5 MJ/kg Lower Heating Value (LHV), 0.41 m/s flame propagation speed, and 24.6 MJ/m^3 combustion energy [11].

In Indonesia, CNG was first introduced as the fuel for Trans Jakarta BRT (Bus Rapid Transit) in 2005. Trans Jakarta BRT had 373 CNG buses in 2017, and based on the former research, the amount will increase to 800 in 2021[12]. Therefore, the possibility of using CNG as fuel in Trans Jogja can be the solution for increasing the air quality in DI Yogyakarta. However, attention should be paid to CNG use as fuel, especially in the safety aspect. For example, 55 road accidents related to vehicles in Pakistan from 2008 to 2014 caused over 250 casualties [13].

Buses using compressed natural gas (CNG) should have their cylinder tanks inspected for fire hazards during operation. This is because a large quantity of mechanical and chemical energy is stored in the tanks. Theoretically, the pneumatic burst of a 130-liter tank at a pressure of 200 bar releases an energy equivalent to the detonation of about 1.85 kg of TNT (8.7 MJ) [14]. The other causes of fire or ignition sources are engine compartment and exhaust system, hydraulic system, turbocharger, electrical system short circuits, operator error (brake or tire fire), mechanical (road accident), low voltage battery, heaters, garages, interior, etc. [15]. Methods for determining the cause of fires include fault and event tree analyses.

Fault Tree Analysis (FTA) is commonly used to identify the failures within certain systems [16]. Also, it can be used to determine the causes of previous accidents. FTA is a combination of qualitative and quantitative methods. The root cause of the main event and the probability of its occurrences can be discovered using the logical relationship. In contrast, Event Tree Analysis (ETA) is a constructive and modeling way of detecting and analyzing the different events of pragmatic accident possibilities with safety features. In addition, it shows the sequences of events related to success or failure. ETA is a quantitative method for analyzing the possible outcomes of the event in FTA. The probability of the sequences of events following a primary incident can be calculated using this method [17].

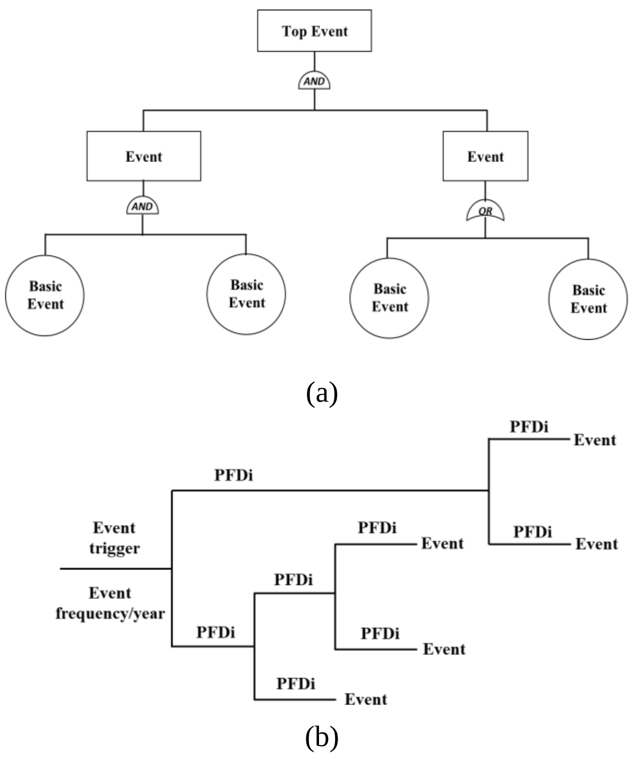

Figure 1. FTA (a) and ETA Diagram (b) [18]

Further research into the risk of CNG buses in DI Yogyakarta is required to avoid the same accident as Trans Jakarta. Using FTA, ETA, and risk matrix, the risk rank for the probability of fire appearing in CNG bus during operation can be analyzed. This research will use Trans Jogja routes in Sleman District, which has heavy traffic and many accidents.

2. Materials and Methods

2.1. Materials

The research needs secondary data to be simulated to achieve its goal. These include the traffic accident data from 2016 until 2020 in Sleman District from Sleman District Police Station, the data of vehicles that pass through the entrance of Yogyakarta per day from May 6 to 21, 2021, from the Department of Transportation D.I. Yogyakarta, properties of CNG, CNG buses system from HINO's CNG buses, and weather data from Indonesian Agency for Meteorological, Climatological, and Geophysics.

2.2. Methods

2.2.1. Determination of Accident Frequency

Using accident data from Sleman Resort Police, the accident frequency of buses was calculated. The steps are shown in equation (1).

$$\text{Frequency } (f_0) = \frac{x}{s} \quad \text{.....................................(1)}$$

Where x is the amount of accidents and s is the number of vehicles that pass through the street.

2.2.2. Consequences Analysis

The analysis started by deciding the event scenarios from historical accident data for vehicles with CNG fuel. The second step was using FTA and ETA to determine the probability and frequency of consequences. Finally, the severity of each consequence was analyzed using qualitative and quantitative methods, and ALOHA software was used as a quantitative method.

2.2.3. Risk Analysis

Risk analysis combines the frequency and the likelihood of the incident occurring and the severity value of the possible consequences [19].

The condition and the likelihood can be seen in Table 2, where the value is from 1 to 5, with the highest value for the most incident occurring per year. While Table 3 shows the condition and the severity from 1 to 5, with the highest value for the catastrophic damage such as fatality or multiple fatalities.

The value obtained from multiplying the likelihood with the severity is read in Table 1 as risk rank. The risk category in Table 1 are ranked 1 to 2, 3 to 8, 9 to 15, and 16 to 25 for low, moderate, medium, and high risk [19].

Table 1. Risk Matrix [19]

MICOPERI RISK MATRIX			PROBABILITY				
			1	**2**	**3**	**4**	**5**
			Very Unlikely	**Unlikely**	**Possible**	**Likely**	**Frequent**
SEVERITY	**1**	**Minor**	1	2	3	4	5
	2	**Moderate**	2	4	6	8	10
	3	**Significant**	3	6	9	12	15
	4	**Serious**	4	8	12	16	20
	5	**Catastrophic**	5	10	15	20	25

Table 2. The Category of Frequency (Likelihood) [19]

LIKELIHOOD		
Rank	**Description**	**Probability**
1	**Very Unlikely:** Could only occur under a freak combination of factors	$< 10^{-5}$
2	**Unlikely:** May occur only in exceptional circumstances	10^{-5} - 10^{-4}
3	**Possible:** Could occur in some time	10^{-4} - 10^{-2}
4	**Likely:** Would not require extraordinary factors to occur at some time	10^{-2} - 10^{-1}
5	**Frequent:** Almost certain to happen if conditions remain unchanged	10^{-1} - 1

Table 3. The Category of Severity [19]

SEVERITY		
Rank	**Severity**	**Description**
1	Trivial	Minor injury / no internal disruption
2	Minor	Injury which requires medical attention/minor internal disruption
3	Lost Time	Potentially life-threatening injury causing temporary disability and requiring medevac/disruption possibly requiring corrective action
4	Major	Major life-threatening injury or causing permanent disability /incomplete recovery/pollution with significant impact/very serious disruption which may cause performance degraded
5	Fatal	Fatality or multiple fatalities or multiple life-threatening injuries causing permanent disabilities/total loss

2.2.4. Simulation Procedure

This research procedure was conducted using several steps seen in Figure 1.

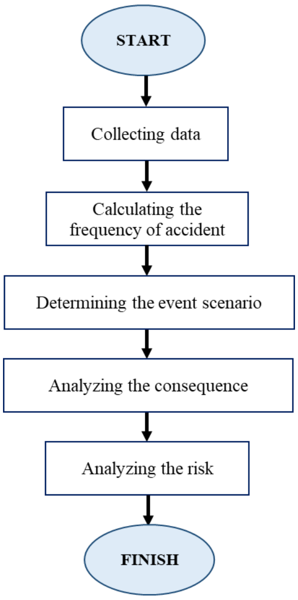

Figure 1. The Research Diagram

3. Results and Discussion

3.1. Accident Frequency

Table 4 provides data for the amount of accidents in the Sleman district in the scope of Trans Jogja routes. The data was obtained from the traffic accident from 2016 until 2020 from Sleman District Police Station. Whereas Table 5 provides the number of vehicles that pass through the Sleman district, assuming there are no extra from the outside area. The data was obtained from vehicles that pass through the entrance of Yogyakarta per day from May 6 to 21, 2021, from the Department of Transportation D.I. Yogyakarta. It is for the location with the accident amount of more than once per year.

Tables 4 and 5 can calculate the frequency of accidents in both streets. The frequency of accidents in Jogja-Solo and Wates Street is 1.04 x 10^{-6} and 0.623 x 10^{-6} per year.

Based on the calculation above, Jogja-Solo street has a higher accident frequency than Wates street. Therefore, Jogja-Solo street will be used as the sample street for further analysis.

Table 4. The Traffic Accident Data for Bus in Sleman District from 2016 until 2020

Location	The Accident Amount per year					The Average Amount per year
	2016	2017	2018	2019	2020	
Jogja- Solo Street	6	8	2	4	1	4
Laksda Adisucipto Street	1	1	2	0	0	1
Wates Street	5	1	4	2	1	3
Kaliurang Street	0	1	0	1	0	0
Senturan Raya Street	0	0	1	0	1	0
Padjajaran Street	0	0	0	1	0	0
Janti Street	0	0	1	0	0	0

Table 5. The Data of Vehicles that Pass Through per day

Location	The Average Vehicles that Pass Through	
	(Vehicles per month)	(Vehicles per year)
Jogja-Solo Street	318,987	3,827,844
Wates Street	402,149	4,825,788

3.2. Consequence Analysis

3.2.1. Determination of Event Frequency

The two scenarios, with fire and explosion, will be investigated. The first scenario was CNG release from a cylinder tube because of an accident and overpressure.

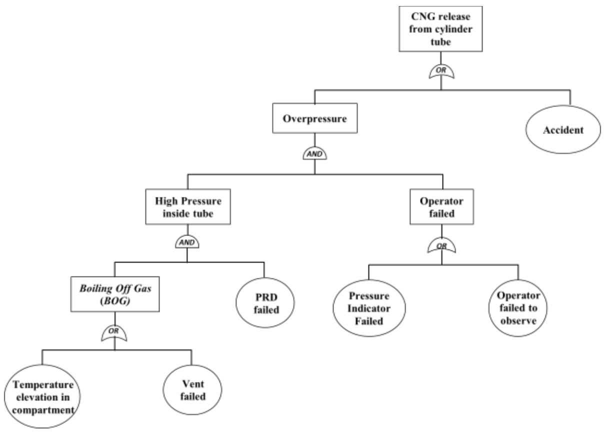

Figure 2. FTA for CNG release from cylinder tube scenario

Table 6. Frequency of Event

Code	Event	Frequency of Event (per year)
A1	Temperature elevation in compartment	1×10^{-6} [20]
A2	Vent valve failed to open	1.14×10^{-3} [20]
A3	Safety valve failed or PRD failed	3.5×10^{-3} [21]
A4	Pressure Indicator Failed	1.24×10^{-2} [20]
A5	Operator failed to observe	0.1 [22]
B1	Accident in Jogja-Solo Street	1.04×10^{-6} (the data from Sleman District Police Station)
SS1	Boiling Off Gas (BOG)	
SS2	High pressure inside tube	
SS3	Operator failed	
SS4	Overpressure	

The probability of the top event can be calculated from the frequency values given to the basic events, as follows:

Boiling Off Gas **(BOG)**

$P(SS1) = P(A1 \cup A2)$

$= P(A1) + P(A2) – P(A1 \cap A2)$

$= 1 \times 10^{-6} + 1.14 \times 10^{-3} - (1 \times 10^{-6} \times 1.14 \times 10^{-3})$

$= 0.001141 = 1.141 \times 10^{-3}$

High pressure inside tube

$P(SS2) = P(SS1 \cap A3)$

$= 1.141 \times 10^{-3} \times 3.5 \times 10^{-3}$

$= 0.00000399 = 3.99 \times 10^{-6}$

Operator failed

$P(SS3) = P(A4 \cup A5)$

$= P(A4) + P(A5) – P(A4 \cap A5)$

$= 1.24 \times 10^{-2} + 0.1 - (1.24 \times 10^{-2} \times 0.1)$

$= 0.11116 = 1.112 \times 10^{-1}$

Overpressure

$P(SS4) = P(SS2 \cap SS3)$

$= 3.99 \times 10^{-6} \times 1.112 \times 10^{-1}$

$= 0.00000044368 = 4.437 \times 10^{-7}$

Thus, the probability of the top event is,

$P(\textit{Top Event}) = P(SS4 \cup B1)$

$= P(SS4) + P(B1) – P(SS4 \cap B1)$

$= 4.437 \times 10^{-7} + 1.04 \times 10^{-6} - (4.437 \times 10^{-7} \times 1.04 \times 10^{-6})$

$= 1.484 \times 10^{-6}$

Based on the calculation above, the frequency for scenario 1 was 1.484×10^{-6} events per year. Thus value was close to Berghmans and Vanierschot's research, where the probability of leaks in enclosed car parking buildings was 1.68 x 10^{-6} events per year [23].

The second was an oil spill in the hot component around the engine because of turbocharger failure and a leak in a hydraulic system.

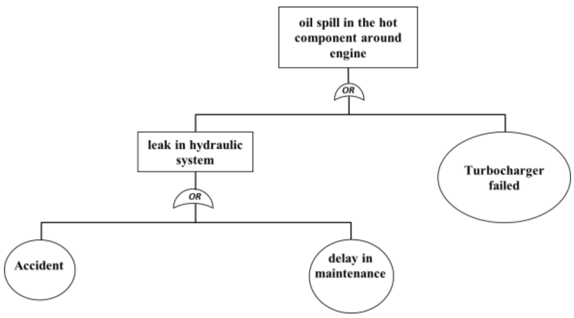

Figure 3. FTA for the oil spill in the hot component around the engine scenario

Table 7. Frequency of Event

Code	Event	Frequency of Event (per year)
A1	Accident in Jogja-Solo Street	1.04 x 10^{-6} (the data from Sleman District Police Station)
A2	Delay in maintenance because of human error	4 x 10^{-2} [21]
A3	Turbocharger Failed	6.7 x 10^{-2} [24]
SS1	Leak in hydraulic system	

Based on data in Table 7, the probability of the top event can be calculated as follows:

Leak in hydraulic system

P(SS1) = P(A1 U A2)

= P(A1) + P(A2) – P(A1 ∩ A2)

= $1.04 \times 10^{-6} + 4 \times 10^{-2} - (1.04 \times 10^{-6} \times 4 \times 10^{-2})$

= 0.0400009984 = 4 x 10^{-2}

The probability of oil spill in the hot component around engine is,

P (*Top Event*) = P(SS1 U A3)

= P(SS1) + P(A3) – P(SS1 ∩ A3)

= $4 \times 10^{-2} + 6.7 \times 10^{-2} - (4 \times 10^{-2} \times 6.7 \times 10^{-2})$

= 0.10432 = 1.043 x 10^{-1}

Based on the calculation above, the frequency for scenario 2 was 1.043 x 10^{-1} event per year. The frequency was high, appropriate with the data of bus fires in New South Wales in 2018, where the cause of the fire and thermal incidents was 33 percent from fluid leakage [25].

3.2.2. Determination of Probability and Frequency of Consequences

The probability of consequence in each scenario was calculated using ETA. For example, Figure 4 is the ETA diagram for scenario 1.

The probability data that delayed ignition for continuous gas release and explosion based on Bevi [26] were 0.2, 0.8, and 0.4. At the same time, the probability of fireball and delayed ignition for spontaneous gas release based on research from Ko and Kim were 0.25 and 0.9 [27]. Therefore, the total value of P and P* should be one. Figure 5 is the ETA diagram for scenario 2. The value of probability in the diagram, based on The Purple Book, was 0.065 for direct ignition, 0.065 for delayed ignition, and 0.1 for vapor cloud explosion [28].

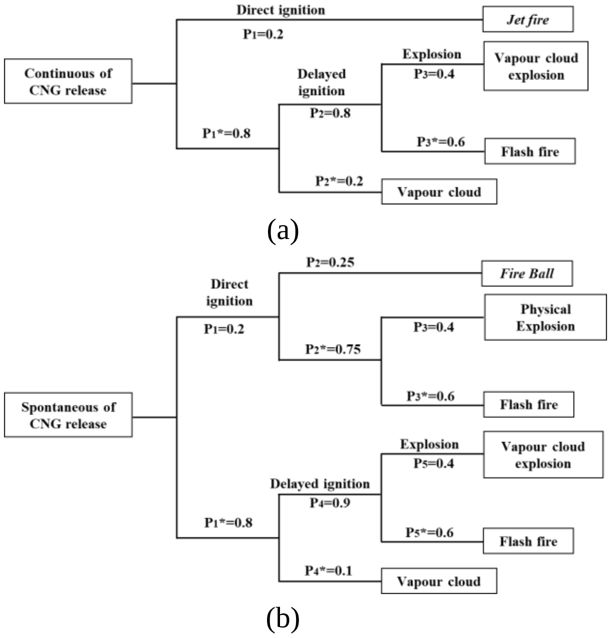

Figure 4. ETA for Continuous CNG release (a) and Spontaneous CNG release (b) scenarios

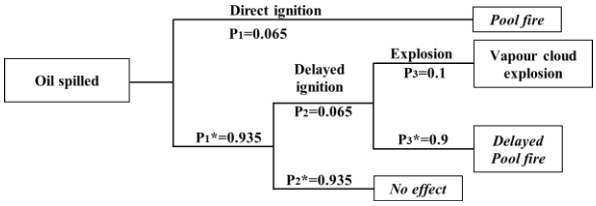

Figure 5. ETA for oil spilled scenario

The frequency of consequence for each scenario can be seen in Table 8, where the probability of consequence can be calculated using the formulation below,

$P_{(Consequence)} = P_n \times P_{(n+1)} \times P_{(n+2)} \times \ldots$ **(1),**

or

$P_{(Consequence)} = P^*_n \times P_{(n+1)} \times P^*_{(n+2)} \times \ldots$ **(2)**

Where, n= the number of probability (1, 2, etc).

The consequence frequency was calculated by multiplying the value of the event frequency with the probability of consequence.

Table 8. The Frequency of Consequence for each scenario

Scenario	Consequence	Frequency of event (per year)	Probability of consequence	Frequency of consequence (per year)
Continuous of CNG release	Jet fire	1.484×10^{-6}	0.2	2.968×10^{-7}
	Vapour cloud explosion	1.484×10^{-6}	0.256	3.799×10^{-7}
	Flash fire	1.484×10^{-6}	0.384	5.699×10^{-7}
	Vapour cloud	1.484×10^{-6}	0.16	2.374×10^{-7}
Spontaneous of CNG release	Fire ball	1.484×10^{-6}	0.05	0.742×10^{-7}
	Physical Explosion	1.484×10^{-6}	0.06	0.890×10^{-7}
	Flash fire	1.484×10^{-6}	0.09	1.336×10^{-7}
	Vapour cloud explosion	1.484×10^{-6}	0.288	4.274×10^{-7}
	Flash fire	1.484×10^{-6}	0.432	6.411×10^{-7}
	Vapour cloud	1.484×10^{-6}	0.08	1.187×10^{-7}
Oil spilled	Pool fire	1.043×10^{-1}	0.065	6.779×10^{-3}
	Vapour cloud explosion	1.043×10^{-1}	0.0068	0.709×10^{-3}
	Delayed pool fire	1.043×10^{-1}	0.0547	5.705×10^{-3}
	No effect	1.043×10^{-1}	0.874	9.116×10^{-2}

From Table 8, the frequency of consequence for continuous CNG release was close to that of spontaneous. The societal risk assessment unloading of CNG receiving terminal stated that the frequency of consequence ranged from 10^{-6} to 10^{-8} per year [29].

3.2.3. Determination of the Severity of Consequences

The severity of consequence was determined in qualitative and quantitative using ALOHA software. Furthermore, the severity of the jet fire and flash fire was assumed similar. The data used in the calculation were 0.5 inches for the diameter of leakage, 8.9408 meters/second for wind speed, 72% for relative humidity, 80 liters for CNG tube volume, and 60 seconds for burn duration.

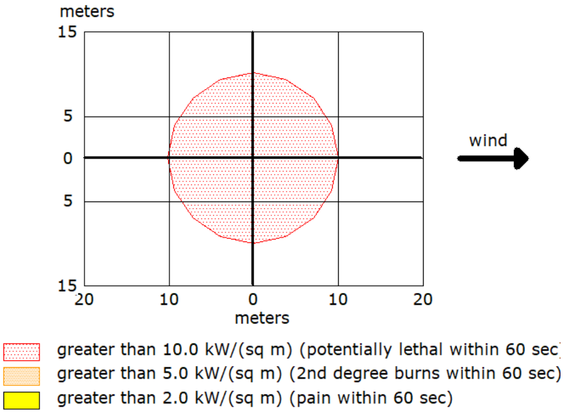

Figure 6. Threat Zone for Heat Flux Radiation of Jet fire and Flash Fire

Figure 6 shows that the severity of heat flux radiation from jet fire and flash fire is third-degree burns for fewer than 10 meters. The severity of the burn can lead to fatality, therefore, the value for both consequences is 5 [19]. Perwitasari et al. stated that 14.8706 kW/m^2 heat flux radiation in the distance from 1 to 8.8 meters can cause third-degree burns of more than 50% and may lead to death [30].

Based on Figure 7, the severity of heat flux radiation from the fireball is third-degree burns for a distance of fewer than 35 meters, with a value of 5 [19]. However, the radius distance was large, and operating the CNG bus on a busy road could be dangerous.

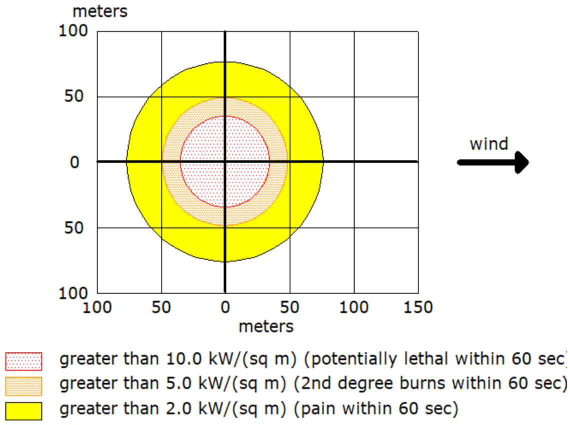

Figure 7. Threat Zone for Heat Flux Radiation of Fire Ball

According to Figure 8, there are consequences for overpressure that can cause shattered glass around the source for distances less than 18 meters. Therefore, the severity value for vapor cloud explosion is 4 [19]. This can also be used for the severity of a physical explosion.

Perwitasari et al. stated that overpressure for a radius less than 10 meters was 1566.439 kPa or 15.459 atm. It can give 100% minor and major damages, leading to a building's collapse [30].

The severity value for the consequences in the oil spilled scenario is 2. Thus cause the amount of oil that spilt was small so the fire that occurred was not big.

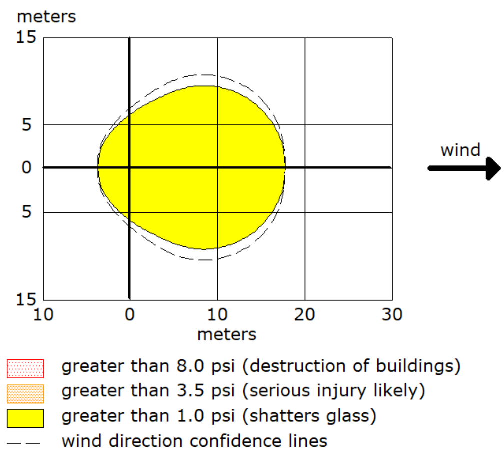

Figure 8. Threat Zone for Overpressure of Vapour Cloud Explosion

3.3. Risk Analysis

Risk analysis was conducted using a 5x5 matrix. As a result, the resume for the frequency (likelihood) and the severity of consequence in each scenario can be seen in Table 9. Based on Table 9, the risk rank for each incident on CNG buses was in moderate or acceptable risk rank [19].

Table 9. The Frequency and The Severity of Consequence for each scenario

Scenario	Consequence	Frequency of consequence (per year)	*Likelihood*	*Severity*	*Risk Rank*
Continuous CNG release	Jet fire	2.968×10^{-7}	1	5	5
	Vapour cloud explosion	3.799×10^{-7}	1	4	4
	Flashfire	5.699×10^{-7}	1	5	5
	Vapor cloud	2.374×10^{-7}	1	3	3
	Physical Explosion	0.742×10^{-7}	1	4	4
Spontaneous CNG release	Flashfire	0.890×10^{-7}	1	5	5
	Vapour cloud explosion	1.336×10^{-7}	1	4	4
	Flashfire	4.274×10^{-7}	1	5	5
	Vapor cloud	6.411×10^{-7}	1	3	3
	Physical Explosion	1.187×10^{-7}	1	4	4
Oil spilled	Pool fire	6.779×10^{-3}	3	2	6
	Vapour cloud explosion	0.709×10^{-3}	3	2	6
	Delayed pool fire	5.705×10^{-3}	3	2	6
	No effect	9.116×10^{-2}	5	1	5

4. Conclusion

The risk rank for CNG release from the cylinder tube and oil spilled in the hot component around the engine was below 6. It means that the risk was acceptable or can be tolerated. Therefore, using CNG as a substitute for diesel fuel in the Trans Jogja bus can reduce the pollution in DI Yogyakarta.

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