Modeling Inner City Traffic Generated Air Pollution

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Abstract

Rapid urban development in many cities in Malaysia has given rise to traffic congestions during peak hours. To overcome this congestion foe, more roads are being planned and built to help ease traffic away from the city centers. Hence city outer ring roads are being constructed to divert the traffic flow. The outer ring roads may, however, cut right through some parts of inner city with high concentration of population. Traffic generated air pollution may pose hazards to the health of the people living in the vicinity of the roads. The air pollutants include carbon monoxide, sulphur dioxide, nitrogen dioxide and particulate matters PM_{10} and $PM_{2.5}$. The air pollution model ISCST3EM developed by the US Environmental Protection Agency, USEPA, is used to simulate potential levels of air pollution due to traffic flows. Several air quality standards for various countries, Malaysia included, are used as benchmark to assess the potential hazards posed by the air pollutants generated. Alignments of roads in relation to predominant wind directions and other atmospheric conditions may play a significant impact on the levels of air pollution at receptors sites within the city centers. The model may be used to formulate alternatives and suggestions to reduce air pollution to safe levels, working within the constraints of budget and other restraining circumstances.

Introduction

The increase usage of vehicles in Malaysia has not only caused traffic congestion but has also caused the release of harmful chemicals such as nitrogen dioxide, carbon monoxide and other pollutants which are categorized as classical pollutants. The emissions from individual vehicles might appear to be relatively low, if compared to the smokestack image associated with air pollution. But the truth, according to the United States Protection Agency (USEPA), is that when the emissions of thousands or millions of personal vehicles on the roads or highways are added up, personal automobiles, as a whole is the highest air pollution contributor in many cities. Therefore, highway construction in inner cities has aroused some concerns especially for those who live near the highway.

In order to ensure that the pollution level is within the safety limits, many countries have set up regulatory controls on pollution emissions for transportation vehicles and industries. This is usually done through a variety of coordinating agencies, which monitor the vehicle emission, air quality and the environment. At the United Nations, the Atmosphere Management Program carries out world wide environmental projects to help save the atmosphere. In the United States, the primary federal agency is the Environmental Protection Agency, which is the counter part of the Department of Environment in Malaysia.

Prevention is a key to controlling air pollution. The regulatory agencies mentioned above play an essential role in reducing and preventing air pollution in the environment. To achieve these goals, guidelines and standards for air pollutants are formulated to prevent further destruction of the atmosphere. These air quality standards are formulated by governmental agencies, which include the World Health Organization (WHO) and U.S. Environmental Protection Agency (USEPA) and DOE of Malaysia. The Malaysian standards are adapted from these standards.

Air dispersion modeling is needed to predict and analyze the changes in ambient air quality arising from various sources. In this paper, air dispersion modeling is used to simulate the air quality in the vicinity of the local residents following the construction and usage of roadway to ensure that they are indeed breathing safe air and, if needed, perhaps find alternatives to minimize the damage. Although many air quality models are available, the USEPA model, known as the Industrial Source Complex (ISCST3) model is used in this paper.

Methodology

The ISCST3 was developed by the USEPA in 1970s (1, 2). It is based on a steady-state Gaussian plume model and is a widely used technique for estimating the impacts of air pollutants from various types of sources. ISCST3 model accounts for settling and dry deposition of particulates; building obstruction wake effects; plume rise as a function of downwind distance; multiple, but separate, point, area and volume sources. It has the ability to analyze concentrations in several type of terrain, both urban and rural. It can estimate hourly and annual average pollutant concentrations as well as those with various sampling durations. It has previously been used to study air pollution dispersion locally (3) and in Sudan (4). For a steady-state Gaussian plume, the hourly concentration at downwind distance x (m) and crosswind distance y (m) is given by (2):

$$\chi = \frac{QKVD}{2\pi u_s \sigma_y \sigma_z} \exp\left[-0.5\left(\frac{y}{\sigma_y}\right)^2\right] \qquad (1)$$

where:

Q = pollutant emission rate (mass per unit time)
K = a scaling coefficient to convert calculated concentrations to desired units (default value of 1×10^6 for Q in gs^{-1} and concentration in μgm^{-3})
V = vertical term
D = decay term
σ_y, σ_z = standard deviation of lateral and vertical concentration distribution (m)
u_s = mean wind speed (ms^{-1}) at release height

The equation (1) is a basic formula of the model for point sources, examples of which are chimney and smokestacks. However in the case of mobile source, models based upon area and line sources would be better since a single area source can simulate hundreds of point sources. Since there would be thousands of vehicle on the roadway, it is illogical and time consuming for the user to input thousands of data, one source for each vehicle, in the input file of ISCST3. Therefore, models based upon area source are developed. Emissions from area sources are assumed to be of neutral buoyancy. Therefore, plume phenomena such as downwash and impaction on elevated terrain features are not considered relevant for modeling area sources. The emission rate for area sources is in units of mass per unit time per unit area (e.g., $gs^{-1}m^{-2}$). It is an emission flux rather than an emission rate.

The ISCST area source model is based on a numerical integration over the area in the downwind and crosswind directions of the Gaussian point source plume formula given in equation (1). Individual area sources may be represented as rectangles with aspect ratios (length/width) not exceeding 10. The rectangle may also be rotated relative to a north-south and east-west orientation. Irregularly shaped area can be simulated by dividing the area source into multiple rectangular areas. Therefore, the ISCST area source algorithm may also be useful for modeling certain types of line sources due to its flexibility in specifying elongated area sources up to an aspect ratio of 10.

The ground-level concentration at a receptor located downwind of the source area is given by a double integral in the downwind (x) and crosswind (y) directions as follows:

$$\chi = \frac{Q_A K}{2\pi u_s} \int_x \frac{VD}{\sigma_y \sigma_z}\left(\int_y \exp\left[-0.5\left(\frac{y}{\sigma_y}\right)^2\right] dy\right) dx \qquad (2)$$

where:

Q_A = area source emission rate (mass per unit area per unit time, $gs^{-1}m^{-2}$)
K = units scaling coefficient (Equation (1))
V = vertical term
D = decay term as a function of x.

Line sources are typically used to represent roadways. In ISCST3, toxic pollutants from line sources are simply modeled as a series of area or volume sources. Previous model evaluation studies with roadways have shown that ISCST3 results are similar between modeling roads as volume sources and modeling them as area sources (5). However, modeling based upon area sources is more resource efficient. Additional studies (12) show that the aspect ratios might be increased from the previously recommended 10 to 100 without degrading model performance. The ISCST3 model user's guide, Volume I – User Instruction (1) may be consulted for additional information on how to use the ISCST3 model. For more information about the numerical algorithms of the ISCST3 model, the ISC3 user's guide, Volume II – Description of Model Algorithms (2) may be referred. The area and line source approach for mobile sources has been used by the USEPA for simulating air pollution due to traffic flow in highways in Houston, United States (6).

Even though the ISCST3 model is critically acclaimed, there are limitations and uncertainties because of some assumptions and constraints in its calculations. For more details, please refer to www.air-dispersion.com (7).

Preliminary Case Study

This section will present some simple preliminary applications of ISCST3 by using the area and line sources approach. Both straight and curve roadways with different elevations and different receptor sites may be analyzed. The concentrations of carbon monoxide and nitrogen oxide will be estimated for averaging period of 1 hour.

Meteorological Parameters

It is assumed throughout this section that the ambient air temperature is 298 K and the wind speed is constant at 4 m/s. The mixing height is assumed to be 100 m. It is also assumed that the apartment and the city center are in the downwind direction to simulate worst-case scenario, with the atmospheric condition of Class D. Sensitivity analysis will not be reported in this paper due to limitation of space.

a. Straight Roadway

Consider a straight roadway with width of 15 m and length of 15km without elevation. The traffic density along the roadway is 10000 vehicles h^{-1} while the average vehicle speed is 50 mile h^{-1}. The average emission rate of carbon monoxide is 21.20 g $mile^{-1}$ for each vehicle. There is an apartment located at 100m from the side of the roadway. The model will assess if the pollution level of carbon monoxide (CO) is within the safety limits under the worst-case scenario for the 1-hour averaging time.

Area Source Parameters

Some mathematical calculations are performed to obtain the emission flux ($gs^{-1}m^{-2}$), based upon the number of vehicles, the width of the roadway and the vehicles' speed and emission rates (J.D. Butler, 1979). We divide the roadway into a series of area sources, each source having an aspect ratio of 10 (width/length), as discussed in Section 2. Since the focus of this problem is the apartment, we will only include the roadway near the apartment instead of the whole roadway. This is because the emission from vehicles far away from the apartment would not contribute to CO levels at the apartment.

b. Curved Roadway

We now have a curve roadway with other data remaining the same as in section 3.1. Figure 1 shows the shape of the road and the location of the apartment. ISCST3 will be used to determine the pollution level of carbon monoxide under the worst-case scenario for the 1-hour averaging time.

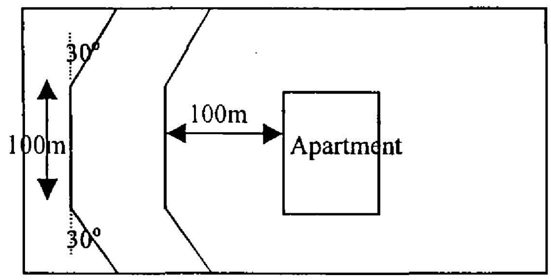

Figure 1 Map o f the Conceptual Case Study for Curve Roadway

Area Source Parameter

The emission rates of carbon monoxide remain the same as in previous case. However, the curved road segments must be rotated by an appropriate angle (e.g. -30°, 30°). This angle rotation is measured clockwise from the North.

c. Jalan Lahat, Ipoh

Figure 2 shows the location of Jalan Lahat in Ipoh. It is a 4-lane roadway, which is located near the city center of Ipoh. The objective of this study is to estimate the pollution level around the local neighborhoods (the circulated area in the map) contributed by vehicles on Jalan Lahat. The main focus is to estimate the level of carbon monoxide released by vehicles on the road when the wind is blowing south-east towards the city centre. Modeling of carbon monoxide by other methods have been conducted for roads in Penang (9).

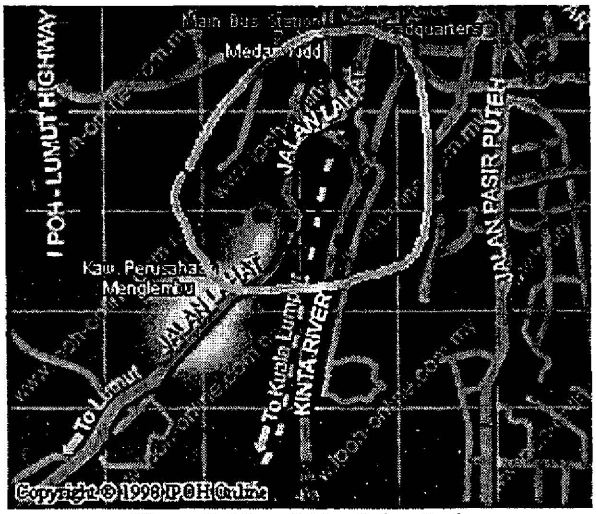

Figure 2 Map of Jalan Lahat, Ipoh

Area Source Parameters

Since emissions data of vehicles in Malaysia are not available, the emission rates indicated in Table 1, available from the United States Department of Transportation (10) is used. The normal traffic volumes on Jalan Lahat, Ipoh is adopted (11). The road has 4 lanes, with an estimated width of 10m (2.5m for each lane). The elevation of Jalan Lahat is assumed at ground level. Table 2 provides data regarding the amount, category and the emission rate of hydrocarbon, carbon monoxide and nitrogen oxide of these vehicles.

Table 1 Amount, Category, Pollutant Types and Emission Rates of Different Vehicles

Vehicle Types	vehicle per hour	Category	Pollutant Types	[a]Emission Rates (g mile^{-1} vehicle^{-1})
Car	6134	LDV-G	Exhaust and nonexhaust HC	2.16
			Exhaust CO	19.28
			Exhaust NOx	1.38
Trucks	1241	[b]LDT-D	Exhaust HC	0.84
			Exhaust CO	1.73
			Exhaust NOx	1.46
Lorry	195	[b]HDV-D	Exhaust HC	2.22
			Exhaust CO	11.53
			Exhaust NOx	11.24
Bus	243	[b]HDV-D	Exhaust HC	2.22
			Exhaust CO	11.53
			Exhaust NOx	11.24
Van	901	[c]LDT-G	Exhaust and nonexhaust HC	2.85
			Exhaust CO	24.99
			Exhaust NOx	1.80
Motorcycle	1353	Motorcycle	Exhaust and nonexhaust HC	4.26
			Exhaust CO	20.35
			Exhaust NOx	0.83

*KEY: CO = carbon monoxide HC = hydrocarbon NOx = nitrogen oxide LDV-G = light-duty vehicles (Gasoline) LDT-D = light-duty trucks (Diesel) HDV-D = heavy-duty vehicle (Diesel) LDT-G = light-duty trucks (Gasoline)

[a] Assumptions: ambient temperature 75°F, daily temperature range 60-84°F, average traffic speed 19.6mph (representative of overall traffic in urban areas)

[b] Data for nonexhaust HC is negligible for diesel fuel vehicles.

[c] Even though some vans use diesel as fuel, we assume they all use gasoline in this case.

As can be seen in the footnotes accompanying Table 1, the assumptions regarding climate conditions relevant to this data (e.g. temperature) are different from the local climate. According to the USEPA, emissions tend to be higher in very hot weather, especially for HC, or in very cold weather, notably for CO (12). However, this data uncertainty that might affect the simulation results will not be discussed here.

The length of the highway that contributes to air pollution at the apartment is estimated at 1500m. Therefore, it is divided into 15 area sources, each with a width of 10 m and a length of 100 m to create a line source with aspect ratio of 10 for each segment.

Results and Discussion

The simulated air pollutants concentrations will be presented and compared with some standards as shown in Table 2 to ascertain if they are within safety limits. The Pollutants listed in Table 2 are some classic example of chemicals released by vehicles.

Table 2 Ambient Air Quality Standards from WHO, USEPA, UK and Malaysian

Pollutant	Averaging Time	WHO Standards	US EPA Standards	UK Standards	Malaysian Standards
Carbon monoxide (CO)	24 hour				
	8 hour	10mg/m^3	9ppm 10 mg/m^3	10ppm 11.6mg/m^3	10mg/m^3
	1 hour	30mg/m^3	35ppm 40mg/m^3		35mg/m^3
Nitrogen dioxide (NO_2)	Annual	40μg/m^3	0.053ppm 100μg/m^3	40μg/m^3 21ppb	320μg/m^3
	24 hour	200μg/m^3			
	1 hour	418μg/m^3		150ppb 287μg/m^3	
PM_{10}	Annual	60μg/m^3	50μg/m^3	40μg/m^3	50μg/m^3
	24 hour	150μg/m^3	150 μg/m^3	50μg/m^3	150μg/m^3
	1 hour				
Sulfur dioxide (SO_2)	Annual	50μg/m^3	0.03ppm 80μg/m^3	20μg/m^3 8ppb	105μg/m^3
	24 hour	125μg/m^3	0.14ppm 365μg/m^3	125μg/m^3 47ppb	
	1 hour			350μg/m^3 132ppb	350μg/m^3

a. Straight Roadway

Figure 3 depicts the dispersion of carbon monoxide on the ground level around the apartment for case study 3.1. With emission flux of $2.4*10^{-3}gs^{-1}m^{-2}$ for area source, carbon monoxide exhibits a peak concentration of 9028 μgm^{-3} within the highway, but drops to around 1000μgm^{-3} when it is 50m away from the road, and around 530μgm^{-3} at the apartment (100m away) and around 260μgm^{-3} at the distance of 200μgm^{-3} away. These concentrations are well within the air quality standards of USEPA for carbon monoxide (1 hour average) listed in Table 2.

b. Curve Roadway

Figure 4 shows the dispersion of carbon monoxide, corresponding to input of section 3.2, on the ground level of the apartment and near the highway. With a total emission flux of $2.4*10^{-3}gs^{-1}m^{-2}$, carbon monoxide exhibits a peak concentration of 10016μgm^{-3} at the highway, but drops to around 4000μgm^{-3} 50m away from the roadway, and to 1000μgm^{-3} at the apartment (100m away) and further drops to around 500μgm^{-3} at a distance of 200m away from the roadway. These concentrations are well within the air quality standards of USEPA for carbon monoxide (1 hour average) listed in Table 2.

The maximum concentration in this case is slightly higher than in the previous case even though the emission rate of both cases is equivalent. This is mainly because of overlapping of segments when the curved line sources are created (ISC area source models only accept rectangular area) with area sources of different angles. In order to have more accurate results, we may subdivide the area into smaller areas.

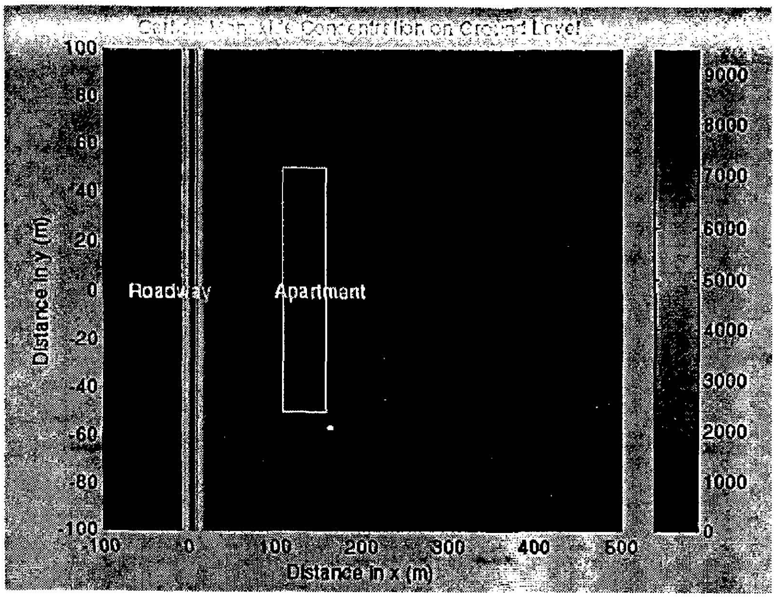

Figure 3 Contour plot for carbon monoxide concentrations in μgm^{-3} on ground level due to mobile sources (Straight Roadway)

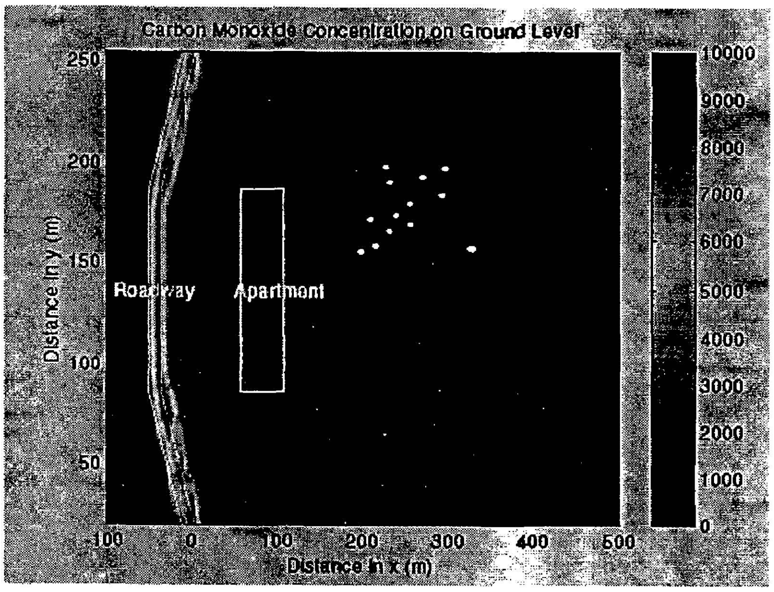

Figure 4 Contour plot for carbon monoxide concentrations in μgm^{-3} on ground level due to mobile sources (Curve Roadway)

c. Jalan Lahat, Ipoh

The maximum concentrations occur within the highway. This maximum concentration for 1-hour averaging period simulated by ISCST3 model for carbon monoxide is around 21422μgm^{-3}. However, at distances of 50m, 100m and 200m away from the road, the pollutant concentrations drop to around 1500μgm^{-3}, 700μgm^{-3} and 350μgm^{-3} respectively. This level of concentrations is well within the safety limit (Table 2). Figure 5 depicts the dispersion pattern of carbon monoxide for 1-hour averaging period. Dispersion patterns are similar for hydrocarbon and nitrogen oxide, which will not be presented in this paper due to lack of space. However, the maximum concentrations for hydrocarbon and nitrogen oxide at the roadway are elevated but they drop abruptly with increased distance from the road.

The simulations performed above are based upon worst-case scenarios in which it is assumed the wind blows directly towards the receptor sites. The actual scenario would have air pollution levels significantly lower than what have been presented above since the predominant wind directions for Ipoh are not towards the receptor sites. Figure 6 clearly shows that the percentage occurrence of the wind blowing towards southeast (namely towards the receptor) is very low. Therefore, we may conclude that the level of carbon monoxide is safe for the local neighborhood near the roadway, based upon the above simulations.

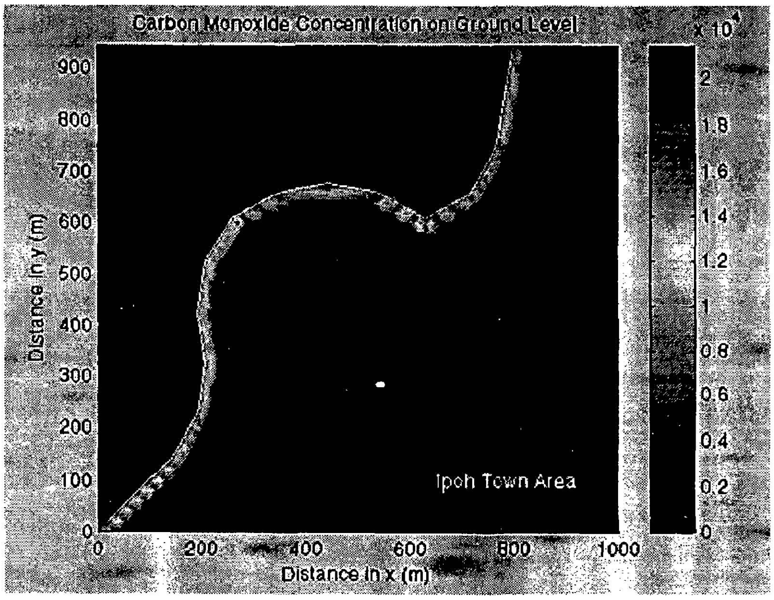

Figure 5 Contour plot for carbon monoxide concentrations in μgm^{-3} on ground level due to mobile sources (Jalan Lahat)

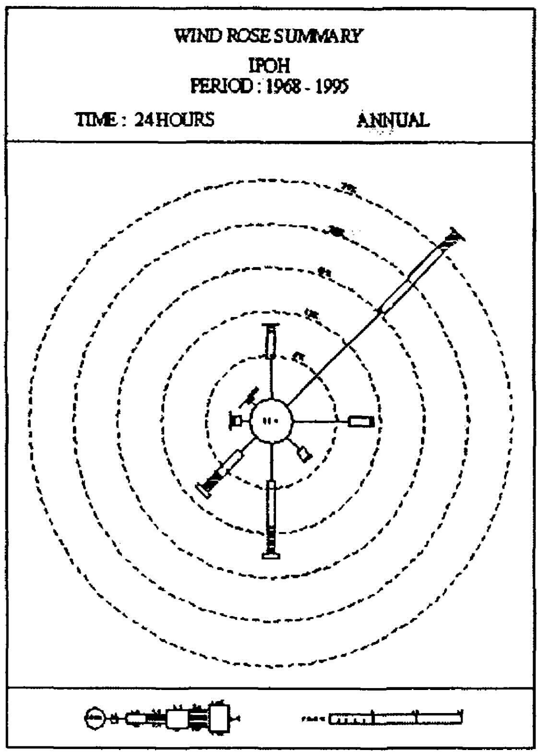

Figure 6 Wind Rose Summary for Ipoh, 1968-1995

Conclusion

Mobile sources are considered a major contributor to air pollution. Therefore, legislation is developed in order to control emission rates of the vehicles. For example, the US Federal Clean Air Act requires the USEPA to prescribe standards for any class of vehicle causing or contributing to air pollution that may reasonably be anticipated to endanger public health or welfare. Recently, the EPA has proposed new standards for nitrogen oxide, carbon monoxide and hydrocarbon emissions for several types of vehicles.

These new emission standards will begin to take effect in the year 2007. There is a need to reduce the use of fueled vehicle. Some Europe countries like Netherlands have encouraged their residents to ride the bicycle instead of using the car. Meanwhile, air pollution modeling is a useful tool that may be used to simulate air pollution scenarios to ensure safe air quality. This paper attempts to present an analysis of such an effort in Malaysia.

Acknowledgement

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