A Zero-dimensional Mathematical Model of PM2.5 Measurement due to Daily Vehicle Density in Bangkok

Seree Khum-un, Nopparat Pochai

***Abstract*—Air pollution, particularly particulate matter smaller than 2.5 microns (PM2.5), has grown to be a serious issue that has an impact on people's health, especially the respiratory system. There are several studies that have found that the level of PM2.5 in the Bangkok region is high, as is how it affects individuals with respiratory illnesses. In this research, a numerical simulation of PM2.5 concentration was performed using a zero-dimensional model of PM2.5 measurement due to the daily vehicle density in Bangkok. It is evident that the wind speed and daily vehicle density have an impact on the simulated PM2.5 concentration in Bangkok. The daily density of vehicles greatly influences PM2.5 emissions. Wind speed was measured in this experiment. The hourly vehicle density in Bangkok, which was represented by calculating functions for wind speed and PM2.5 emission rate, is what produces the computed PM2.5 emission rate. The simulation includes three 24-hour scenarios: low vehicle density with medium wind speed, high vehicle density with low wind speed, and medium vehicle density with high wind speed. All of the models indicated that the PM2.5 level would drop as wind speed increased and vehicle density decreased. The daily vehicle density and wind speed are two factors that affect the PM2.5 level. Focusing, especially on wind speed, will not always lead to PM2.5 reductions. However, daily vehicle density also has a significant role in PM2.5 management. Wind speed and vehicle density influence PM2.5 concentrations, with three scenarios demonstrating that higher wind speed and lower vehicle density reduce PM2.5 levels. While wind speed helps to reduce PM2.5 levels, vehicle density also has a substantial impact on emissions. Managing PM2.5 requires addressing both daily vehicle density and wind speed, as focusing on only wind speed may not always result in reductions.**

***Index Terms*— Bangkok, air pollution, PM2.5, Euler point-slope method, mathematical model**

I. Introduction

When we talk about pollution these days, this is sure to be one of them sources of pollution to which we are exposed and which have a significant impact on society is "air pollution". Air Pollution Affects More Than One Person Society is also a matter of human life and the environment Everyone around the world should realize that. air pollution Harmful to health as it releases pollutants Dirty air causes asthma, lung cancer and cancer. beyond, is an important factor affecting environmental resources and man-made structures and installations and contribute to about climate change.

Air pollution can be categorized into two main types: natural and human-made. Natural sources include events like volcanic eruptions, wildfires, biological decomposition, pollen dispersion, swamps, and the release of radioactive materials. In contrast, human-made sources stem from activities such as emissions from thermal power plants, vehicles, burning of fossil fuels, and agricultural practices. Air pollution appears in different forms, primarily as gaseous and particulate pollutants. Common gaseous pollutants are carbon monoxide (CO), nitrogen oxides (NOx), sulfur dioxide (SO_2), ozone (O_3), and other similar substances.

At present, in Bangkok, Thailand, the particulate matter in the exhaust of cars on the streets, especially the air pollution caused by the exhaust of old or diesel vehicles, is harmful to health. Scientists are concerned that the particles may contain harmful chemicals like nitrous oxide and carbon monoxide, which could be dangerous if inhaled in large amounts.

Air pollution, particularly particulate matter smaller than 2.5 microns (PM2.5), has grown to be a serious issue that has an impact on people's health, especially the respiratory system. In [6], the level of PM2.5 in the Bangkok region has been studied, as has how it affects individuals with respiratory illnesses. Along with the average number of respiratory patients throughout the same periods (years 2011–2021), they also evaluated statistics on the average level of PM2.5 in the Bangkok area on an annual, monthly, and seasonal basis. According to a seasonal investigation, the average quantity of PM2.5 was found to be highest in the winter (29.51 micrograms per cubic meter) and lowest in the rainy season (21.86 micrograms per cubic meter). Regarding respiratory illness patients, the findings showed that the winter had the largest average number of patients, while the rainy season had the lowest average number of respiratory disease patients. There was little correlation between the quantity of PM2.5 and the number of patients with respiratory diseases, according to the correlation analysis. The corresponding R2 values for 2019 and 2020 were 0.2069 and 0.0047.

Nowadays, the growing population leads to road traffic congestion and air pollution. Then if we know the possible pollution concentration value of the existing pollution The accumulation of air pollution may be caused by emission

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sources such as vehicle exhaust. We may be able to control the concentration of air pollution in this area so that it does not exceed the standard.

In 2010, [1] in this study, the three-dimensional advection-diffusion equations of air pollutants are applied to a highway tunnel configuration. In 2011, [2] a mathematical model was studied to analyze the dispersion of smoke from two sources, with one source being affected by a structural obstacle. In 2016, [3] Mathematical models that represent the spread of air pollutants emitted from sources into the atmosphere were examined using a three-dimensional partial step approach. In 2017, [4] The issue of air pollution beneath the Bangkok Skytrain platform, caused by pollutants at the tunnel entrance, has been examined. The air quality model for the area is governed by three-dimensional advection-diffusion equations with a time-dependent component. To approximate these equations, finite difference methods are employed. The model is then solved using the explicit forward time central space (FTCS) scheme. In 2019, Numerical simulation of the two-dimensional atmospheric diffusion equation for an air pollution measurement model was proposed in [5]. The area considered is divided into two parts: industrial and urban areas. Comparisons and simulations are performed by releasing pollutants from multiple point sources above one industrial area to another industrial area. The governing partial differential equations for the concentrations of air pollutants are approximated using the finite difference method. In addition, the impact of multiple point sources on the concentrations of air pollutants is analyzed. In 2022, [7] considered the air pollution measurement in a street canyon using the numerical simulations of a two-dimensional vertically averaged. The air pollution was considered to be a regional problem caused largely by domestic heating and industrial emissions, both of which are now well under control. The research is focused on detecting air pollution in a street canyon. And the model of air pollutant concentration is approximated using a finite difference technique. In 2012, [10] considered about a three-dimensional time-dependent air pollutant concentration measurement in several types of high traffic street canyons. They used the Explicit finite difference techniques to visualize the considered model solution. In 2021, [11] presented a neural network modeling, which is using a genetic algorithm to apply an optimization method, applied to predict monthly ozone and carbon dioxide concentration time series. In 2013, The effects of air pollution exposure on cardiovascular morbidity and mortality are well documented by [12]. They used nonlinear time series analysis of blood pressure, heart rate and indoor air quality from the survey of health and living status of the general population. In 2011, [13] studied conduct research on an area related to pollution control and cloud computing, in global warming, green house Effects and pollution control. In 2013, [14] presented about the effect of CO_2 purity on improvement of indoor air quality (IAQ) through indoor vertical greening. They first measured the transpiration rates of 50 test plants, then selected the nest fern (Asplenium nidus) as the test object to measure the CO_2 absorption, and built an indoor green wall consisting of 189 pots continuously before, during and after the test.

The purpose of this paper is to approximate the concentration of air pollutants using a zero-dimensional model of PM2.5 measurement due to the daily vehicle density in Bangkok.

II. Governing Equation

The model is useful to predict the behavior of systems which are too complex to be amenable to exact analysis, for example, models can help to decide when agricultural burning should be allowed. The most controversial application of modeling has arisen as a result of the section of the Clean Air Act, which requires the EPA to determine whether a state's implementation plan will bring air quality within Federal Primary Standards. The following model is one of the simplest for relating emissions to air quality and is call the box model.

Consider a city whose rectangular boundary forms the base of a box shaped air shed. The height of the box is equal to the mixing height above the city. We assume pollutants are, being emitted from the city and also that the wind blows fresh air into one side of the box causing polluted air to be blown out the opposite side as shown in Fig.1. We then make the grossly simplifying assumption that pollutants instantly distribute themselves uniformly throughout the box. Let V is box volumn, C is pollution concentration in the box and leaving the box, v is wind speed, P is pollutant emission rate, Q is air flow rate, L is base dimension of box and h is mixing height.

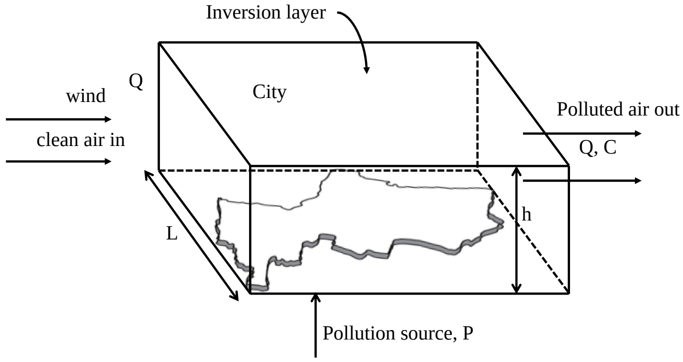

Fig. 1. The box model for relating emissions to air quality.

A simple mass balance equation is [8],

$$V\frac{dC}{dt}=P-QC. \tag{1}$$

In this research, we will introduce a zero-dimensional model of PM2.5 measurement due to vehicle density in Bangkok by,

$$V\frac{dC}{dt}=P(t)-Q(t)C, \tag{2}$$

where $P(t)$ is a PM2.5 emission rate due to vehicle density. The quantity $Q(t)$ is a measure of the amount of ventilation that the Bangkok box receives and is equal to the wind speed times the cross-sectional area of the Bangkok box as below,

$$Q(t)=v(t)Lh, \tag{3}$$

Initial condition is assumed by the given available PM2.5 concentration C_0,

$$C(0)=C_0. \tag{4}$$

III. Numerical Techniques

A. A quadratic regression for PM2.5 emission rate due to vehicle density representation

The least-squares procedure is used to approximate the solutions of the zero-dimensional form of PM2.5 density in Bangkok from daily vehicle. In this paper, the vehicle density and wind speed representation by using the least-squares procedure to fit a second -order polynomial.

In this case, a quadratic polynomial regression is [9],

$$P(t)=a_0+a_1t+a_2t^2. \tag{5}$$

To produce a least squares fit, we take the derivative of Eq. (5) for each unknown coefficients of the polynomial as follows,

$$\begin{aligned}\frac{\partial S_r}{\partial a_0}&=-2\sum\left(P_i-a_0-a_1t_i-a_2t_i^2\right),\\ \frac{\partial S_r}{\partial a_1}&=-2\sum t_i\left(P_i-a_0-a_1t_i-a_2t_i^2\right),\\ \frac{\partial S_r}{\partial a_2}&=-2\sum t_i^2\left(P_i-a_0-a_1t_i-a_2t_i^2\right).\end{aligned} \tag{6}$$

These equations can be zeroed out and rearranged to give the following set of normal equations:

$$\begin{aligned}(n)a_0+\left(\sum t_i\right)a_1+\left(\sum t_i^2\right)a_2&=\sum P_i,\\ \left(\sum t_i\right)a_0+\left(\sum t_i^2\right)a_1+\left(\sum t_i^3\right)a_2&=\sum t_iP_i,\\ \left(\sum t_i^2\right)a_0+\left(\sum t_i^3\right)a_1+\left(\sum t_i^4\right)a_2&=\sum t_i^2P_i.\end{aligned} \tag{7}$$

where all summations occur in the range from $i=1$ to n. Note that the first three equations are linear and have three unknowns: a_0, a_1 and a_2. The coefficients of the unknowns can be calculated directly from the observed data.

For this case, we see that the problem of determining a second-order least squares polynomial amounts to solving a system of three simultaneous linear equations. The two-dimensional case can be easily extended to polynomials of order m, as

$$P(t)=a_0+a_1t+a_2t^2+...+a_m^m. \tag{8}$$

B. A Euler point-slope method

The first derivative provides a direct estimate of the slope at t_i [9],

$$\phi=f(t_i,C_i), \tag{9}$$

where $f(t_i,C_i)$ is the differential equation evaluated at t_i and C_i. We get

$$C_{i+1}=C_i+f(t_i,C_i)h. \tag{10}$$

This formula is referred to as Euler's. A new value of C is predicted using the slope to extrapolate linearly over the step size h.

IV. Numerical Experiments

In this experiment, Bangkok is covered by a rectangular boundary box. Assuming that the mixing height is 183 m, the considered left length of the city is 42,173 m, the wind speed range is 0.50-3.20 km/hr, the PM2.5 emissions rate from the vehicle density is 35.44×10^3-215.55×10^3 μg/hr. Their physical parameters are listed in TABLE I.

TABLE I
Table of Parameter

Parameter	Value	Range	Unit
v	Wind speed	0.50-3.20	km/hr
P	PM2.5 emission rate	35.44×10^3-215.55×10^3	μg/hr
Q	Air flow rate	5.72×10^9-29.80×10^9	m^3/hr
V	Box volumn	1,568,737,000	m^2
C_0	Initial PM2.5 concentration	20	μg/m^3

A. Scenario 1: Medium vehicle density with high wind speed

Assuming that the max-min wind speed are 1.10-3.20 km/hr, and the max-min PM2.5 emission rate from the vehicle density in Bangkok are 68.38×10^3-175.54×10^3 μg/hr in TABLE II. Both of them are represented by quadratic functions by using Eq. (8). The measured PM2.5 concentration is approximated by using Eqs. (1-4). The approximated wind speed, the PM2.5 emission rate, and the measured PM2.5 concentration are approximated by Eqs. (5-8) and Eq. (10), respectively. Their results are shown in TABLE V and Fig.2, as well.

TABLE II
TABLE WIND SPEED DATA AND PM2.5 EMISSION RATE OF SCENARIO 1

t (hr)	$v(t)$	$P(t)$
0	1.80	77633.41
1	1.70	78791.69
2	1.80	79846.11
3	1.90	80368.13
4	2.10	81553.41
5	2.20	82429.21
6	2.10	86356.81
7	2.30	90330.81
8	1.20	68367.22
9	1.10	72080.90
10	1.20	73511.95
11	1.20	74994.24
12	1.30	75147.24
13	1.40	76282.67
14	1.50	76670.38
15	1.60	77024.16
16	2.40	94136.56
17	2.50	102165.55
18	2.60	108061.46
19	2.60	113573.13
20	2.80	115659.82
21	3.10	117384.42
22	3.10	136861.84
23	3.20	175537.66

B. Scenario 2: Low vehicle density with medium wind speed

Assuming that the max-min wind speed are 0.50-3.10 km/hr, and the max-min PM2.5 emission rate from the vehicle density in Bangkok are 35.44×10^3-106.80×10^3 μg/hr in TABLE III. Both of them are represented by quadratic functions by using Eq. (8). The measured PM2.5 concentration is approximated by using Eqs. (1-4). The approximated wind speed, the PM2.5 emission rate, and the measured PM2.5 concentration are approximated by Eqs. (5-8) and Eq. (10), respectively. Their results are shown in TABLE VI and Fig.3, as well.

TABLE III
TABLE WIND SPEED DATA AND PM2.5 EMISSION RATE OF SCENARIO 2

t (hr)	$v(t)$	$P(t)$
0	0.70	35440.15
1	0.80	41591.88
2	0.90	41655.69
3	0.90	42353.09
4	1.10	64986.53
5	1.30	67662.24
6	1.30	68156.56
7	1.40	71953.67
8	1.50	42722.89
9	1.70	56269.54
10	1.90	59490.34
11	0.50	61295.76
12	0.80	72273.04
13	1.20	72462.40
14	1.20	72834.60
15	1.30	73559.10
16	1.40	74397.14
17	1.50	75281.16
18	2.70	76726.04
19	2.70	81539.58
20	2.70	81789.66
21	2.80	83819.77
22	3.00	103645.08
23	3.10	106803.10

C. Scenario 3: High vehicle density with low wind speed

Assuming that the max-min wind speed are 0.70-2.90 km/hr, and the max-min PM2.5 emission rate from the vehicle density in Bangkok are 71.53×10^3-215.55×10^3 μg/hr in TABLE IV. Both of them are represented by quadratic functions by using Eq. (8). The measured PM2.5 concentration is approximated by using Eqs. (1-4). The approximated wind speed, the PM2.5 emission rate, and the measured PM2.5 concentration are approximated by Eqs. (5-8) and Eq. (10), respectively. Their results are shown in TABLE VII and Fig.4, as well.

TABLE IV
TABLE WIND SPEED DATA AND PM2.5 EMISSION RATE OF SCENARIO 3

t (hr)	$v(t)$	$P(t)$
0	2.30	215553.14
1	2.10	209179.52
2	2.00	169167.50
3	2.20	165070.27
4	2.50	164565.56
5	2.30	154850.74
6	2.80	151934.63
7	2.90	150150.48
8	2.70	148459.11
9	2.80	146996.91
10	2.20	146245.72
11	2.20	145863.56
12	2.10	145218.99
13	2.30	137555.56
14	2.20	136557.90
15	2.40	131157.70
16	0.70	123708.89
17	0.80	120065.14
18	0.70	113564.82
19	0.80	86224.58
20	1.00	85478.24
21	1.10	84070.73
22	0.90	83941.96
23	0.80	71526.34

TABLE V
TABLE WIND SPEED AND POLLUTANT EMISSION REPRESENTATIVE FUNCTION SCENARIO 1

t (hr)	$\tilde{v}(t)$	$\tilde{P}(t)$	$\tilde{Q}(t)$	$\tilde{C}(t)$
0	2.33	96403.00	22101593591	20.000
1	2.49	90953.03	23647358525	21.791
2	2.64	86170.92	25020528847	22.855
3	2.77	82056.67	26221104556	23.329
4	2.87	78610.28	27249085654	23.353
5	2.96	75831.75	28104472139	23.055
6	3.04	73721.08	28787264011	22.550
7	3.09	72278.27	29297461272	21.936
8	3.13	71503.32	29635063920	21.295
9	3.14	71396.23	29800071956	20.691
10	3.14	71957.00	29792485380	20.174
11	3.12	73185.63	29612304191	19.783
12	3.09	75082.12	29259528390	19.547
13	3.03	77646.47	28734157977	19.491
14	2.96	80878.68	28036192951	19.633
15	2.86	84778.75	27165633314	19.991
16	2.75	89346.68	26122479064	20.582
17	2.63	94582.47	24906730201	21.427
18	2.48	100486.12	23518386727	22.547
19	2.32	107057.63	21957448640	23.971
20	2.13	114297.00	20223915941	25.734
21	1.93	122204.23	18317788630	27.881
22	1.71	130779.32	16239066706	30.468
23	1.48	140022.27	13987750170	33.566

TABLE VI
TABLE WIND SPEED AND POLLUTANT EMISSION REPRESENTATIVE FUNCTION SCENARIO 2

t (hr)	$\tilde{v}(t)$	$\tilde{P}(t)$	$\tilde{Q}(t)$	$\tilde{C}(t)$
0	1.12	42600.00	10591808926	20.000
1	1.06	44172.83	10097733140	20.686
2	1.02	45804.13	9715559356	21.467
3	1.00	47493.90	9445287573	22.327
4	0.98	49242.13	9286917791	23.253
5	0.97	51048.83	9240450011	24.231
6	0.98	52913.99	9305884232	25.244
7	1.00	54837.62	9483220454	26.277
8	1.03	56819.71	9772458678	27.310
9	1.07	58860.27	10173598903	28.325
10	1.13	60959.30	10686641130	29.302
11	1.19	63116.79	11311585358	30.220
12	1.27	65332.75	12048431587	31.059
13	1.36	67607.18	12897179818	31.797
14	1.46	69940.07	13857830050	32.415
15	1.57	72331.43	14930382283	32.895
16	1.70	74781.25	16114836518	33.223
17	1.84	77289.54	17411192754	33.385
18	1.98	79856.29	18819450992	33.375
19	2.14	82481.51	20339611231	33.189
20	2.32	85165.20	21971673471	32.829
21	2.50	87907.35	23715637712	32.303
22	2.70	90707.97	25571503955	31.622
23	2.90	93567.06	27539272200	30.804

TABLE VII
TABLE WIND SPEED AND POLLUTANT EMISSION REPRESENTATIVE FUNCTION SCENARIO 3

t (hr)	$\tilde{v}(t)$	$\tilde{P}(t)$	$\tilde{Q}(t)$	$\tilde{C}(t)$
0	2.17	196179.00	20573846776	20.000
1	2.25	191839.36	21325866158	26.756
2	2.31	187447.85	21950810386	32.291
3	2.37	183004.46	22448679460	36.734
4	2.41	178509.19	22819473379	40.227
5	2.43	173962.05	23063192145	42.909
6	2.44	169363.03	23179835757	44.918
7	2.44	164712.14	23169404214	46.378
8	2.43	160009.37	23031897518	47.403
9	2.40	155254.72	22767315667	48.093
10	2.36	150448.20	22375658662	48.536
11	2.30	145589.80	21856926503	48.806
12	2.24	140679.53	21211119190	48.966
13	2.16	135717.38	20438236723	49.071
14	2.06	130703.35	19538279102	49.167
15	1.95	125637.45	18511246327	49.292
16	1.83	120519.67	17357138398	49.482
17	1.70	115350.02	16075955314	49.769
18	1.55	110128.49	14667697077	50.184
19	1.38	104855.08	13132363685	50.757
20	1.21	99529.80	11469955140	51.521
21	1.02	94152.64	9680471440	52.512
22	0.82	88723.61	7763912586	53.773
23	0.60	83242.70	5720278578	55.354

V. DISCUSSION

Scenario 1: assuming that the lowest wind speed is 1.10 km/h, the highest wind speed is 3.20 km/h, and the PM2.5 emission around the lowest range is 68.38×10^3 μg/hr, and the highest range is 175.54×10^3 μg/hr. We can see that the measured PM2.5 concentration increases rapidly over 24 hours, as shown in Fig.2.

Scenario 2: assuming that the lowest wind speed is 0.50 km/h, the highest wind speed is 3.10 km/h, and the PM2.5 emission around the lowest range is 35.44×10^3 μg/hr, and the highest range is 106.80×10^3 μg/hr. We can see that the measured PM2.5 concentration did not increase much over 24 hours and tended to remain in control, as shown in Fig.3.

Scenario 3: assuming that the lowest wind speed is 0.70 km/h, the highest wind speed is 2.90 km/h, and the PM2.5 emission around the lowest range is 71.53×10^3 μg/hr, and the highest range is 215.55×10^3 μg/hr. We can see that the measured PM2.5 concentration increased rapidly over 24 hours, as shown in Fig.4.

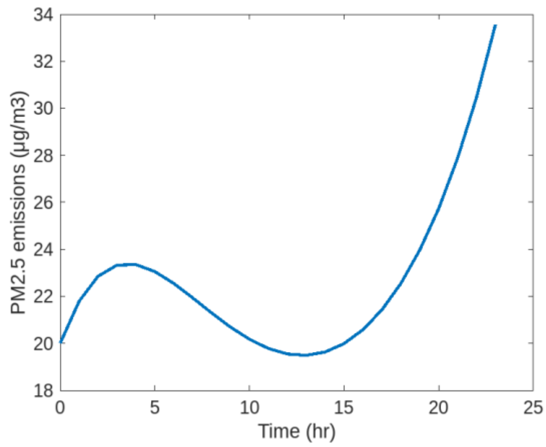

Fig. 2. Approximated PM2.5 in Bangkok over 24 hrs. of scenario 1.

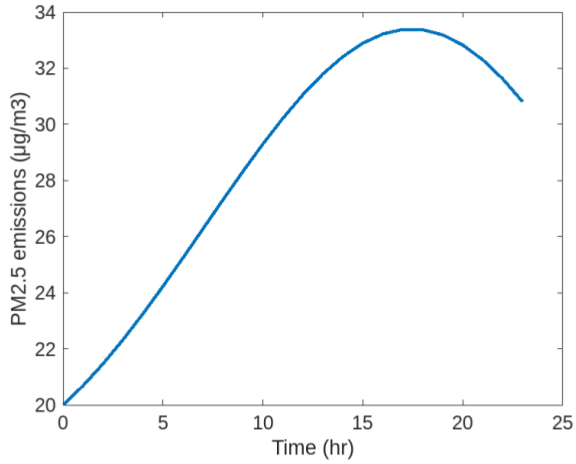

Fig. 3. Approximated PM2.5 in Bangkok over 24 hrs. of scenario 2.

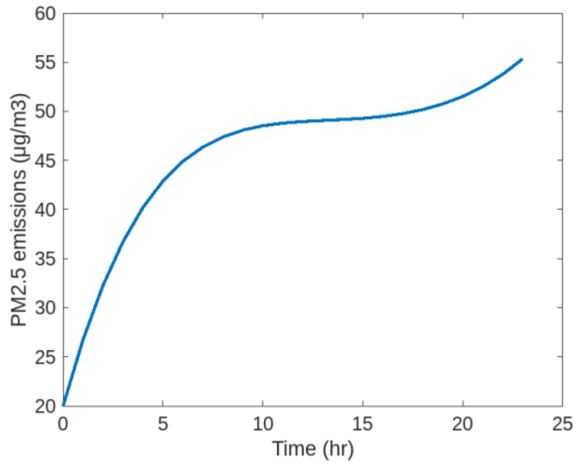

Fig. 4. Approximated PM2.5 in Bangkok over 24 hrs. of scenario 3.

VI. CONCLUSION

It is evident that the wind speed and daily vehicle density have an impact on the simulated PM2.5 concentration in Bangkok. The daily density of vehicles greatly influences PM2.5 emissions. Wind speed was measured in this experiment. The hourly vehicle density in Bangkok, which was represented by calculating functions for wind speed and PM2.5 emission rate, is what produces the computed PM2.5 emission rate. The simulation includes three 24-hour scenarios: low vehicle density with medium wind speed, high vehicle density with low wind speed, and medium vehicle density with high wind speed. All of the models indicated that the PM2.5 level would drop as wind speed increased and vehicle density decreased. The daily vehicle density and wind speed are two factors that affect the PM2.5 level. Focusing, especially on wind speed, will not always lead to PM2.5 reductions. However, daily vehicle density also has a significant role in PM2.5 management. Air pollution, particularly PM2.5, is a severe health concern impacting respiratory health, with high levels in Bangkok. A study used a zero-dimensional model to simulate PM2.5 concentrations based on daily vehicle density. Wind speed and vehicle density affect PM2.5 concentrations, with three scenarios showing that higher wind speed and lower vehicle density decrease PM2.5 levels. While wind speed plays a role in reducing PM2.5, vehicle density also significantly influences emissions. Managing PM2.5 requires addressing both daily vehicle density and wind speed, as focusing only on wind speed may not always lead to reductions.

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