ME 794

Statistical Design of Experiments

Course Project on

<u>Statistical Study of Variation of PM –10 particulate matter</u>

Submitted by

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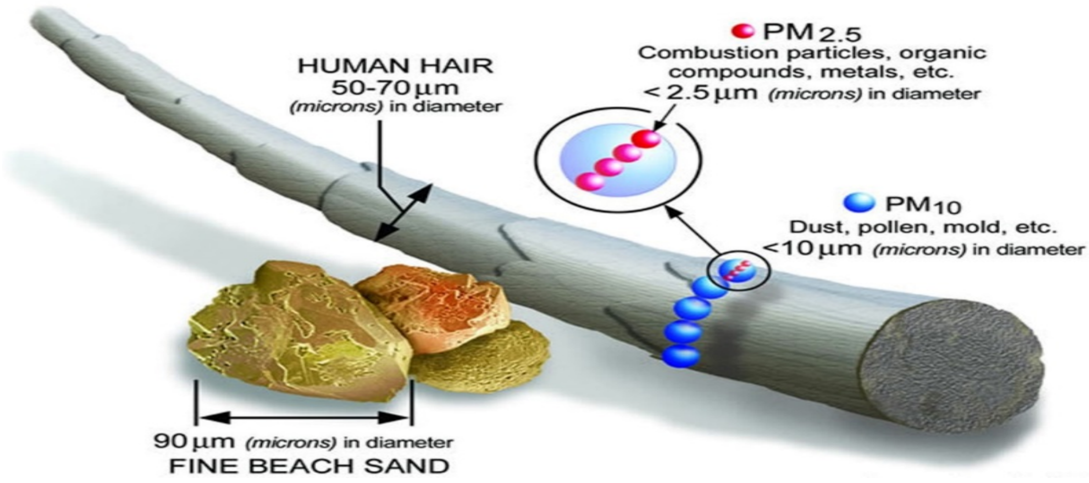
Introduction

One of the significant pollutants we discuss daily falls under the 10µm range and are commonly called suspended particulate matter; the respirable particles suspended in the air.

PM-10 can be produced by various sources, including natural sources such as dust and wildfires, as well as human activities such as transportation, industrial processes, and burning fossil fuels.



Exposure to PM-10 can have a range of adverse health effects, particularly on the respiratory and cardiovascular systems. PM-10 can penetrate deep into the lungs and cause inflammation, exacerbate asthma symptoms, and increase the risk of respiratory infections. Long-term exposure to PM-10 has also been linked to increased risk of lung cancer and cardiovascular disease.

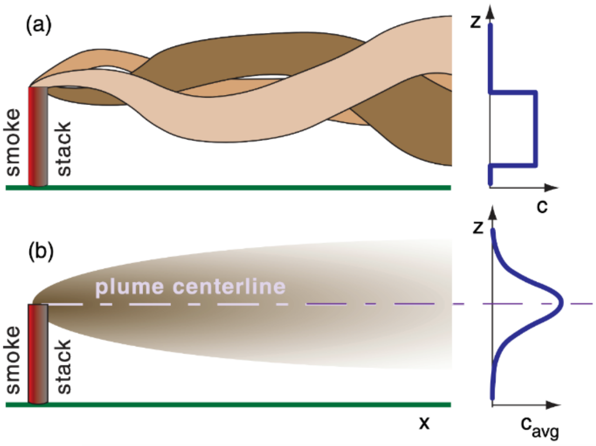
Studying PM-10 particulate matter is crucial because it is a widespread environmental health risk affecting millions worldwide. Air pollution is a complex and multifaceted problem that requires careful scientific investigation to understand its sources, health effects, and potential solutions.

By studying PM-10 particulate matter, we can contribute to a better understanding of the health effects of air pollution and make informed public health policies which are aimed at reducing exposure to this pollutant.

Literature Review

The Gaussian plume model was used for predicting the dispersion of air pollutants, including PM-10 particulate matter, in the atmosphere. The model assumes that the concentration of a pollutant at any point downwind of a source can be described by a Gaussian (or normal) distribution, with the highest concentrations occurring close to the source and decreasing with distance.

The Gaussian plume model considers a range of factors that can affect the dispersion of pollutants, including wind speed and direction, atmospheric stability, and the height and location of the source. The model was used to estimate the concentration of PM-10 at different distances and in different directions from a point source, such as a factory or a highway.



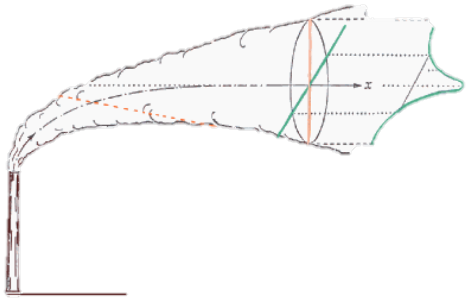
The Gaussian plume model can help to explain some of the variation in PM-10 concentrations observed in various locations and under different weather conditions. For example, when wind speeds are low and atmospheric stability is high, PM-10 can become trapped close to the source and accumulate in nearby areas, resulting in higher concentrations than would be predicted by the Gaussian plume model. On the other hand, when wind speeds are high and atmospheric stability is low, PM-10 can be rapidly dispersed and diluted, resulting in lower concentrations than would be predicted by the Gaussian plume model.

By considering the factors that influence the dispersion of PM-10, the Gaussian plume model can help predict how PM-10 concentrations will vary in distinct locations and under different conditions.

Objective and Hypothesis

Study the month-wise variation of the amount of Particulate matter over MET stations in different cities in India. Furthermore, try correlating the variation with natural factors like the monthly average Windspeed, Precipitation and Temperature.

Based on our literature review, we hypothesise the variations to be prominent with the precipitation, wind speed and temperature.



Precipitation and wind speed should reduce the pollutants, while the temperature should increase the pollutants.

Approach

1. Methodology

To understand the effects of these factors more closely we initially studied their variation w.r.t these factors by creating 2^3 factorial design model where each result to variation was obtained by setting factors to appropriate levels created.

To understand the statistical significance of main and interaction effect of these factors in all combination, two factor ANOVA model were used.

After finding their average main and interaction effects, to get some sense of uncertainty in all these effects obtained for each factor, their confidence interval was calculated by estimating their variances associated with each of these average effects and interactions.

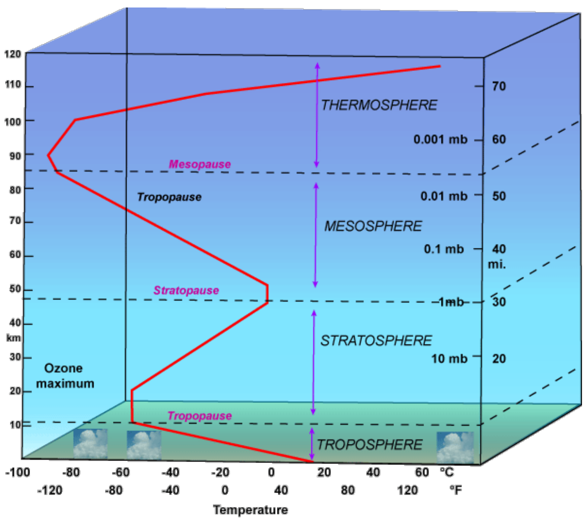
Finally, to put all these together in one place, the target feature, or the concentration dependence of PM-10 particles linear relationship with all these isolated or in combination factors were set up using regression model and then optimizing it by reducing the difference between model's predictive result with actual observed result.

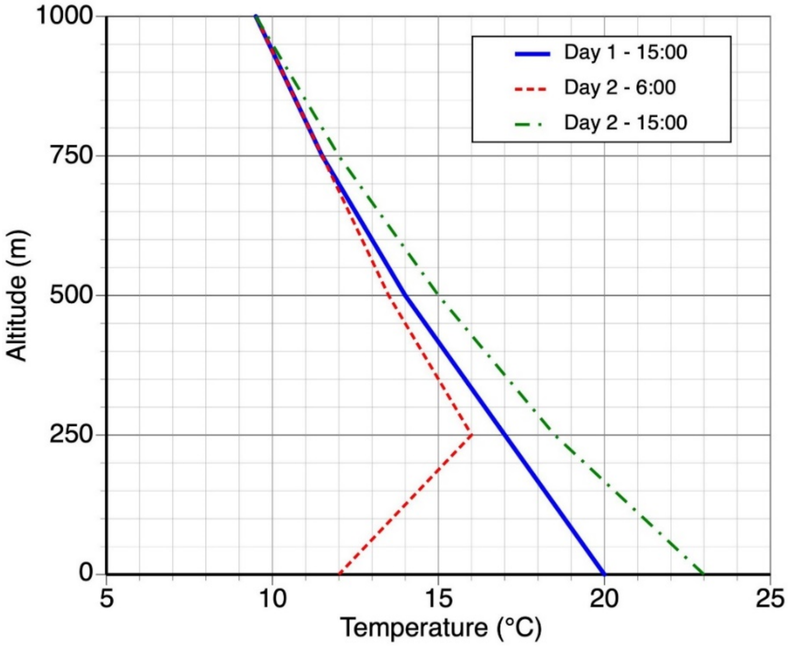
2. Factors

i. Temperature

Temperature is a crucial factor because it affects the buoyancy and stability of the atmosphere, which in turn influences the vertical and horizontal dispersion of pollutants.

In particular, the temperature gradient (or lapse rate) in the atmosphere determines the degree of atmospheric stability, which can have a significant impact on the dispersion of pollutants.



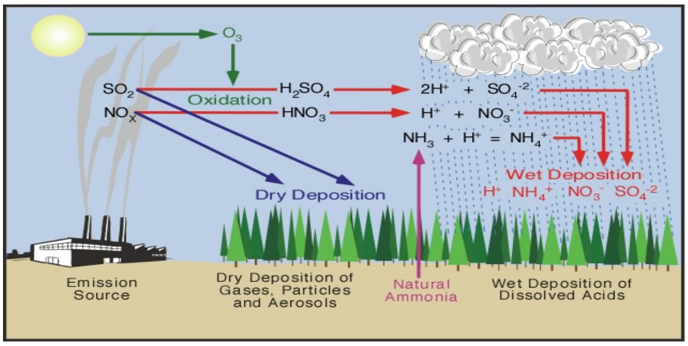


In an unstable atmosphere (where the temperature decreases rapidly with height), warm air near the surface rises rapidly, carrying pollutants with it and causing them to disperse more widely.

Conversely, in a stable atmosphere (where the temperature increases with height), pollutants tend to be trapped close to the surface and can accumulate in certain areas, resulting in higher concentrations.

ii. Precipitation

Precipitation is a crucial factor to consider because it can significantly affect the dispersion and deposition of air pollutants, including PM-10 particulate matter.



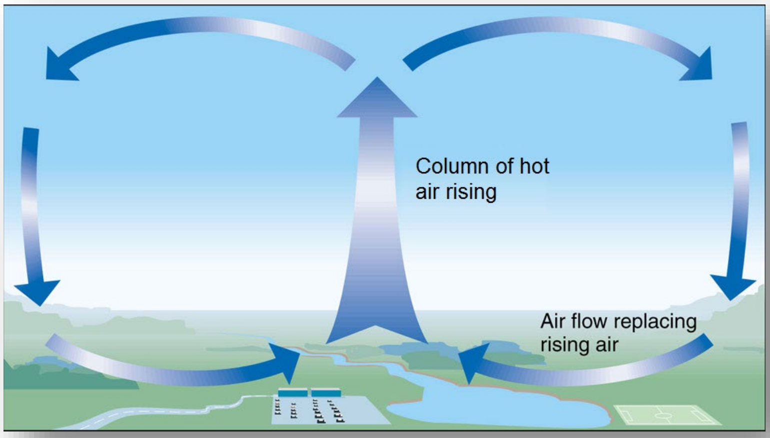
Precipitation can remove pollutants from the atmosphere by wet deposition (rainout) or dry deposition (settling of particles on surfaces), resulting in lower concentrations of pollutants downwind of a source. In the Gaussian plume model, precipitation is typically accounted for by using a modified dispersion coefficient that considers the effects of rainfall on the dispersion of pollutants.

This modified dispersion coefficient accounts for the increased turbulence and vertical mixing that can occur during rainfall, enhancing the dispersion and dilution of pollutants.

Overall, including precipitation as a factor can improve the accuracy of pollutant concentrations and deposition predictions, particularly in areas with high rainfall or frequent precipitation events.

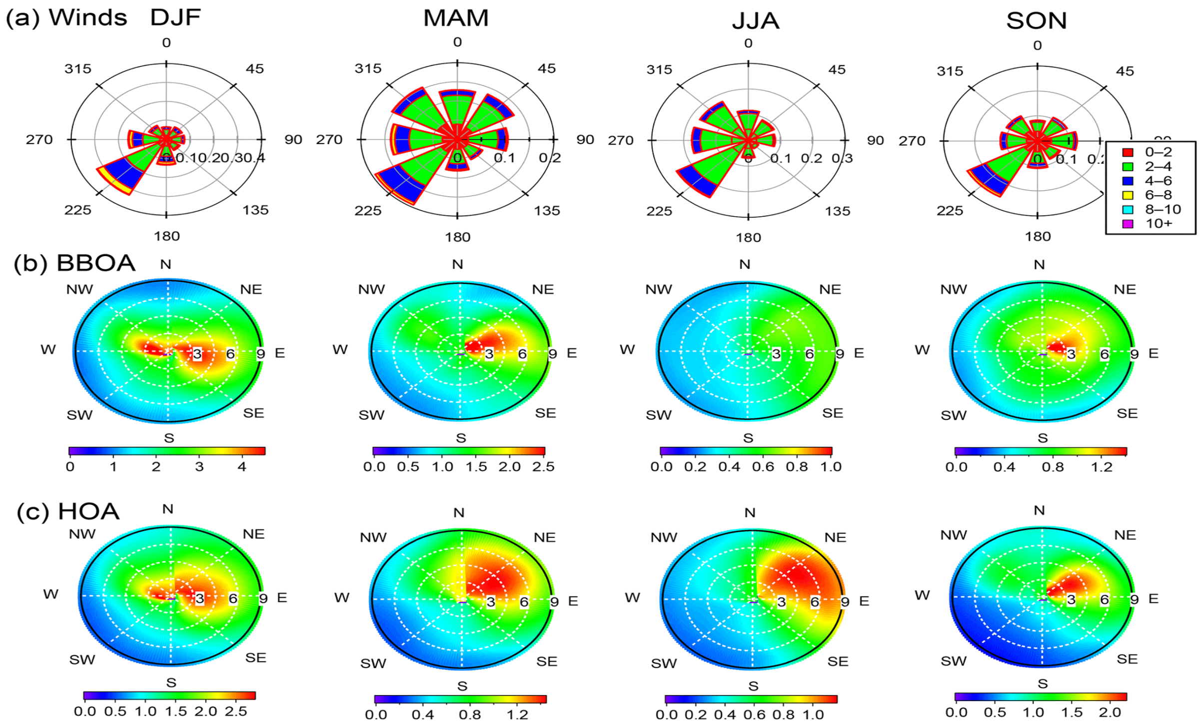
iii. Windspeeds

Wind speed is also a necessary factor as it determines the speed at which pollutants, including PM-10 particulate matter, are dispersed in the atmosphere.



The faster the wind speed, the more rapidly the pollutants are carried away from the source and the more widely dispersed they become.

In contrast, when wind speeds are low, pollutants can become trapped close to the source and accumulate in nearby areas, leading to higher concentrations than would be predicted by the Gaussian plume model.



By incorporating wind speed into model, we can more accurately predict the concentrations of PM-10 particulate matter at different distances and in different directions from a source.

iv. Station Elevation

As air rises or sinks due to changes in temperature, pressure, or other factors, it can carry pollutants with it and change their concentration at different heights.

In the model, the station elevation is used to estimate the height of the pollutant release above the ground.

This information is then used to calculate the vertical dispersion of the pollutant plume, considering atmospheric stability and other factors that can affect the mixing of air masses at different heights.

By incorporating the station elevation into the Gaussian plume model, it is possible to predict the spatial distribution of pollutants more accurately at different heights above the ground.

3. Data Used

In our case, both the factors and target variables vary a lot, when studied on a daily basis. Therefore we considered the variation along months. Furthermore to reduce random errors we took long annual averages of monthly variations for each factors and variables.

i. Temperature and AQI (PM –10 concentration result):

Data for these factors were taken for 10 different cities across India at similar elevation or terrain areas (to block station elevation factor and other noise factors).

These cities included Chennai, Hyderabad, Kota, Ludhiana, Mysuru (Mysore), Nagpur, Puducherry, Pune, Udaipur, Visakhapatnam.

This data was taken for the last 5 years (2018 – 2023) over each month for each city mentioned above.

ii. Precipitation

Monthly average precipitation rate for each above-mentioned city for temperature and AQI factor were collected of over recent 20 years duration.

iii. Windspeed

The monthly average precipitation rate for each mentioned city in above factors were taken of over last 40 years duration.

4. Blocking External Noises

To avoid uncontrolled known factors to hamper our analysis, we mostly rely on blocking that factor. These blocking factors need to be identified earlier so that necessary methods can be used to block it.

In our analysis, we blocked the factor of station elevation i.e., terrain from M.S.L since tracking elevation of each city and feeding it in factorial design model is tedious and can incur more error chance in our analysis.

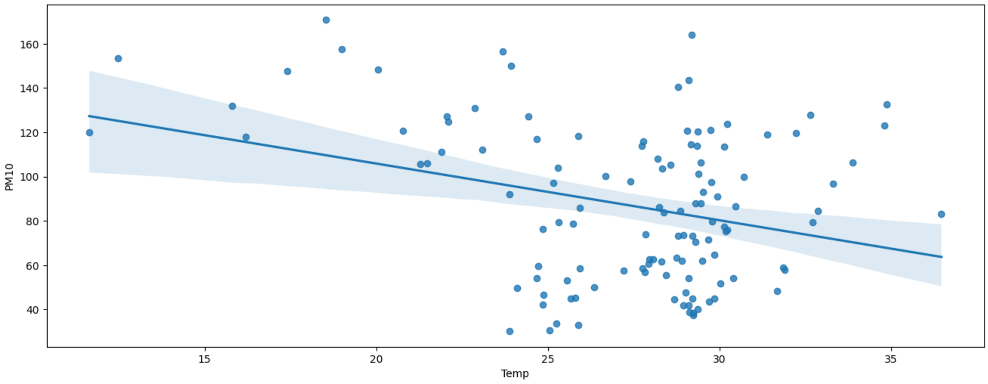
The second factor blocked was the height of station building or the height of nearby hills, high –rise structure, monuments etc. which could block pollution cloud and increase its concentration in that locality.

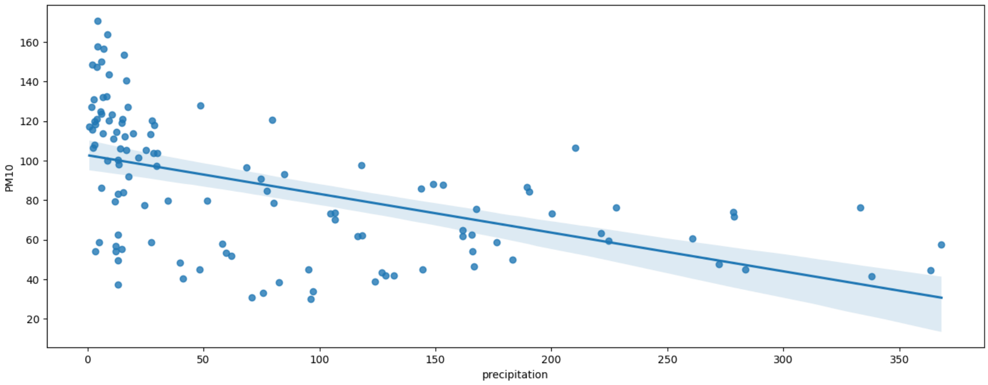
Inclusion of these factors cannot be easily tracked and accommodated in our model for which they need to block from selecting it as one of the factors used.

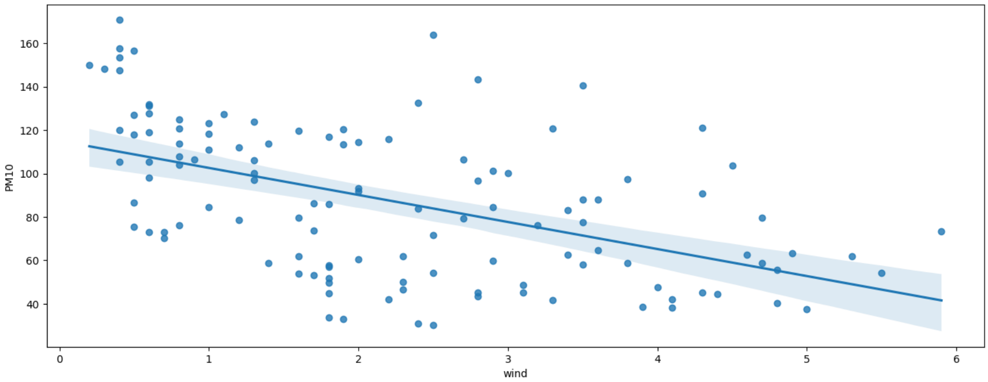
Model Used

An exploratory data analysis of the influence of distinct factors indicates;

- A negative influence of precipitation
- A negative influence of Wind speeds
- A negative influence of Temperature







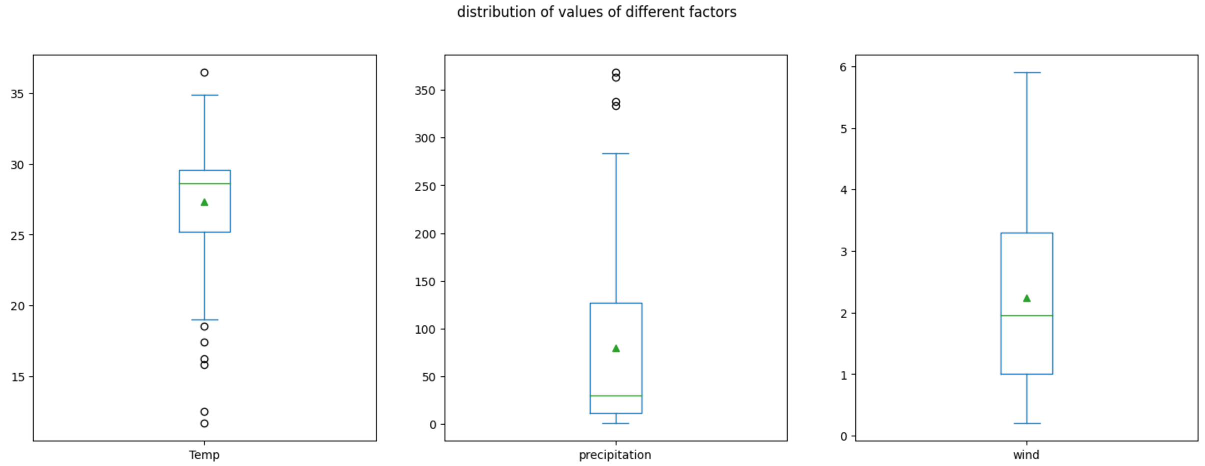
As mentioned, we shall use the 3-factor 2-level factorial design to study the effects of distinct factors on the target variable.

But one problem we face here is that the values of *factors are not binary*. Since the data was procured rather than experimented with in a controlled environment, we have more than two levels of data.

(i) Data Coding

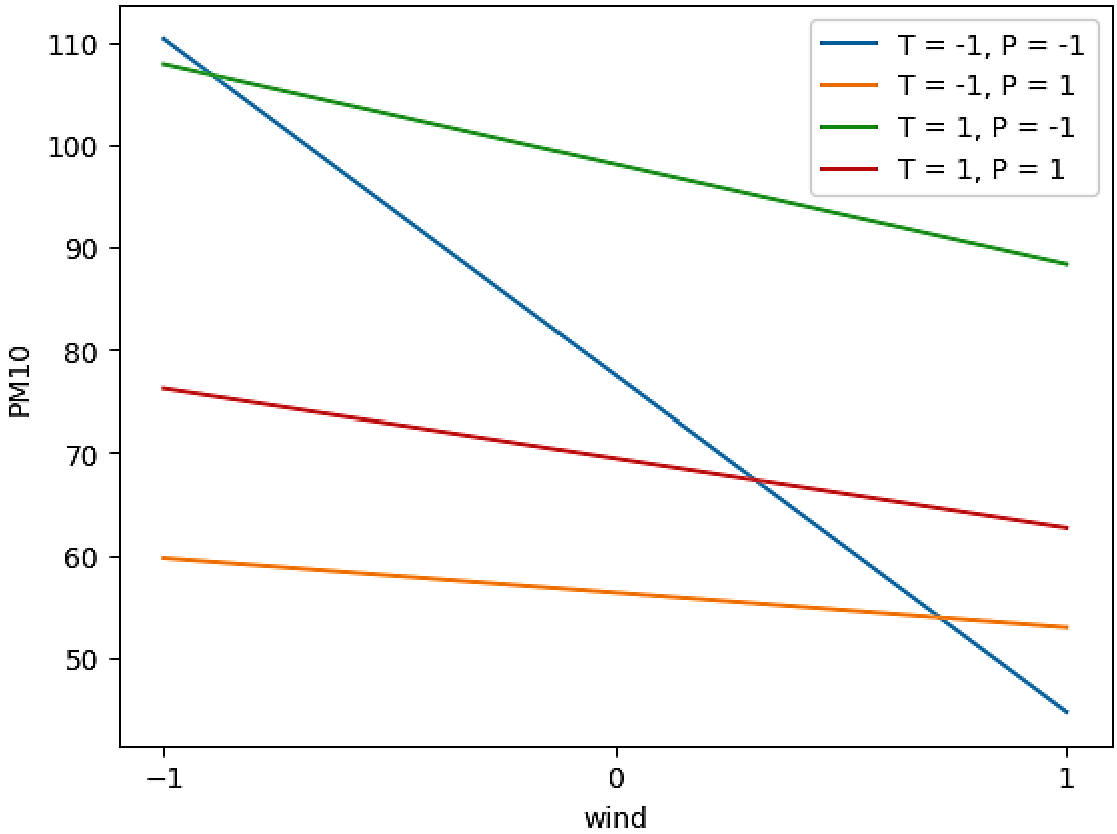
To solve this problem, we use the method of **range coding** to cast the data into binary levels.

The idea is to segregate the distinct levels of a factor by one of the central tendencies and label the values falling into the respective ranges as high (+1) or low (-1).



For our analysis, we considered the **mean** to divide the levels of factors—namely, 28 for temperature, 80 for precipitation, and 2.3 for wind speed. The values falling higher than that of the mean are labelled as +1, while that falling below the mean are labelled as -1. *The final table, both before and after range coding, can be found in the appendix*. The shortened Table can be found in the following line;

Temp	Precipitation	Wind speed	Average
1	1	-1	76.189821
1	-1	1	88.328767
1	-1	-1	107.849541
-1	1	1	52.949944
-1	1	-1	59.702406
-1	-1	1	44.682849
-1	-1	-1	110.32828
1	1	1	62.668464



Graphical Visualisation of effects

Based on the graph one can say that the interaction effects do have significant effects over the target variable.

Therefore we finally, end up in our effects model as;

$$PM10 = T + P + W + TP + PW + TW + PTW + \varepsilon$$

Results

a) Calculation Matrix:

Sr no	Temp	Precipitation	wind	Temp and Precipitation	Precipitation and wind	Temp and wind	Temp and wind and precipitation	Average Aqi
1	-1	1	1	-1	1	-1	-1	52.94994
2	-1	1	-1	-1	-1	1	1	59.70241
3	-1	-1	1	1	-1	-1	1	44.68285
4	-1	-1	-1	1	1	1	-1	110.3283
5	1	1	1	1	1	1	1	62.66846
6	1	1	-1	1	-1	-1	-1	76.18982
7	1	-1	1	-1	-1	1	-1	88.32877
8	1	-1	-1	-1	1	-1	1	107.8495
Effects	16.84328	-24.9197005	-26.360006	-3.740311	16.2231	9.838941	-13.223388	

So, from the Calculation matrix, we can see that the effect of Temperature is *positive* (contrary to what we got in the initial exploratory analysis). At the same time, precipitation and wind speed are negative (same as EDA).

b) Anova Analysis:

Source	*DOF*	*Sum of Squares*	*Mean Squares*	*F values*	*P Values*
Temp	1	2391.390128	2391.390128	3.066573	0.0827
Precipitation	1	38530.968553	38530.968553	49.409765	0
Wind	1	9487.224676	9487.224676	12.165839	0.0007
*Temp*Precipitation*	1	1381.476971	1381.476971	1.771522	0.1859
*Temp*Wind*	1	357.961798	357.961798	0.459028	0.4995
*Precipitation*Wind*	1	1886.243416	1886.243416	2.418804	0.1227
*Temp*Precipitation*Wind*	1	2596.786036	2596.786036	3.32996	0.0707
Residual	112	87340.395873	779.824963	-	-

statistical significance of 95%; So, p value < 0.05 is significant

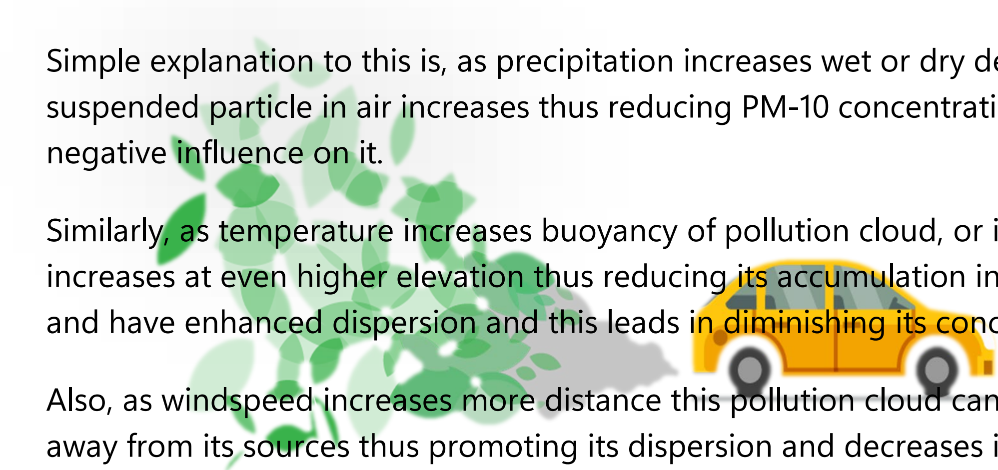
c) Regression:

$$PM10 = 8.4215T - 12.46\boldsymbol{P} - 13.18W - 1.87\boldsymbol{TP} + 8.1115\boldsymbol{PW} + 4.9195\boldsymbol{WT} - 6.6115\boldsymbol{PTW}$$

Clearly temperature does not affect the amount of particulate matter by statistical significance. While wind and precipitation do affect the particulate matter. Moreover, the effect of Precipitation and Wind is negative.

Discussion and Limitations

1.) Why negative model of Precipitation, temperature, and wind – speed was used?



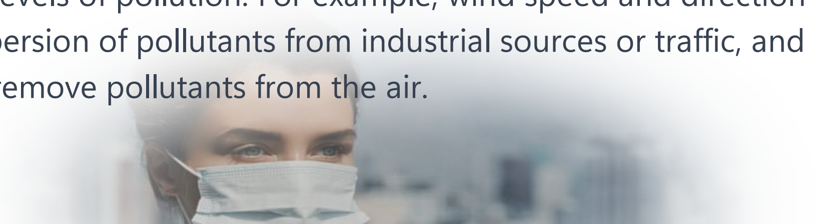
Simple explanation to this is, as precipitation increases wet or dry deposition of suspended particle in air increases thus reducing PM-10 concentration and have negative influence on it.

Similarly, as temperature increases buoyancy of pollution cloud, or its stability increases at even higher elevation thus reducing its accumulation in particular areas and have enhanced dispersion and this leads in diminishing its concentration.

Also, as windspeed increases more distance this pollution cloud can travel farther away from its sources thus promoting its dispersion and decreases its concentration in expected nearby areas.

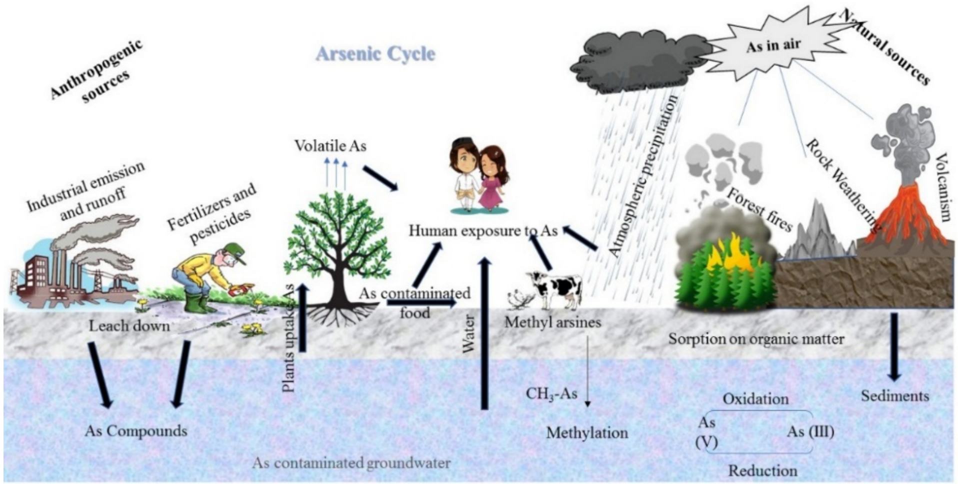
2.) How can this analysis be beneficial?

- **Provides a comprehensive understanding of the factors that contribute to air pollution:** By examining the relationship between PM-10 particles and temperature, precipitation, and wind speed, we can identify the factors that contribute to the levels of pollution. For example, wind speed and direction can affect the dispersion of pollutants from industrial sources or traffic, and precipitation can remove pollutants from the air.



- **Helps identify the most effective interventions for improving air quality:** By understanding the factors that contribute to pollution, policymakers can develop targeted interventions that are more likely to be effective in reducing pollution levels. For example, if the project finds that PM-10 particles are more likely to be present on days with low wind speed policies could be developed to reduce emissions from industrial sources on those days.

- **Provides insights into the sources of PM-10 particles:** By examining the relationship between PM-10 particles and temperature, precipitation, and wind speed, a project can provide insights into the sources of PM-10 particles. For example, if PM-10 particles are found to be more prevalent on days with low wind speed, it could suggest that emissions from local sources such as traffic or industrial activity are the primary source. On the other hand, if PM-10 levels are found to increase during dust storms, it could indicate that natural sources such as desert dust are a significant contributor. These insights can help policymakers develop more targeted interventions to reduce pollution levels, as they can focus on addressing the specific sources of PM-10 particles.



- **Helps identify trends in pollution levels over time.**
- **Can be used to evaluate the effectiveness of interventions aimed at improving air quality.**

3.) Limitations faced during analysis

One limitation is that it may be difficult to control for other factors that contribute to air pollution. For example, the analysis may not consider the impact of human activities such as industrial production or transportation, or the presence of natural sources of pollutants such as wildfires or dust storms. Without considering these factors, the analysis may provide an incomplete picture of the sources of pollution in a given area.

Another limitation is that the analysis may not be generalizable to other areas or regions. The relationship between PM-10 particles and temperature, precipitation, and wind speed may differ depending on a particular region's geography, climate, and other factors. Thus, the project results may only apply to a variety of geography.

Another critical factor we missed out on is the spatial location of the measuring station concerning the nearby terrains, thereby, the corresponding wind directions.

Figure-a demonstrates a scenario where the measuring station would miss report the figures because of the high hill

One more possibility, demonstrated in figure-b, lies where there is a hill after the station, because of which the pollutants get accumulate near the hill, and the amount reported by the measuring station is higher than the actual

Figure a

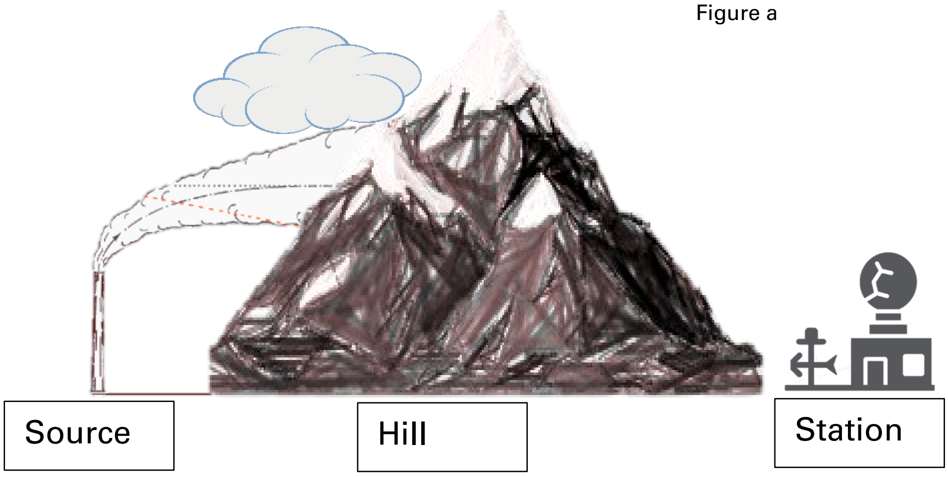
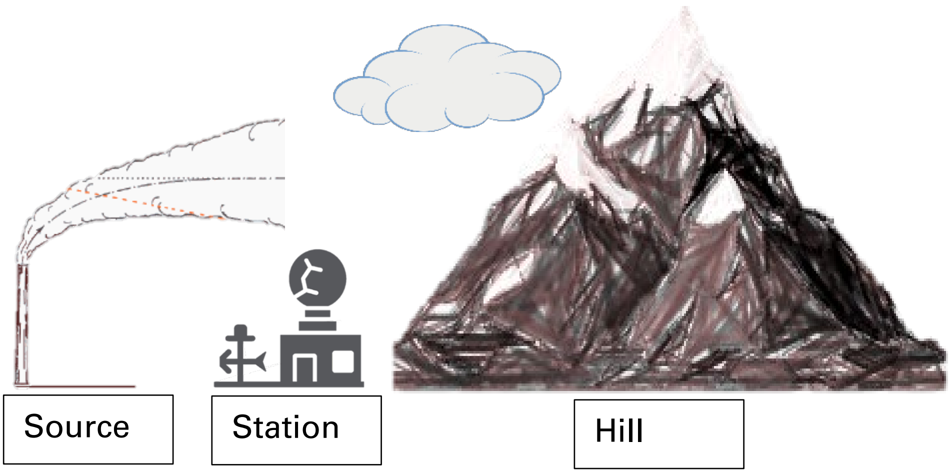


Figure b



Conclusion

So finally we conclude the study over monthly variation of Particulate matter and our attempt to correlate them with different natural factors. Contrary to what we had initially hypothesised, the Temperature doesn't affect the amount of particulate matter present over an area, while Precipitation and wind do affect negatively the amount of particulate matter over some area.

The interaction effects appeared significant in our initial analysis of factorial design, while the ANOVA model concluded that their effects aren't statistically significant.

Furthermore, the effects concluded from factorial design for temperature contradicted the effect analysed from initial Exploratory data analysis. The EDA showed temperature to be affecting negatively while the Factorial Design effect was positive.

We also went over further scope of the project and possible limitations.

Considering the effects of natural factors, this study can be further extended to some larger model which can be used to predict the amount of particulate matter over some place.

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Appendix

Final Non-Coded Table:

	PM10	TEMP	PRECIPITATION	WIND
0	97.221	25.16	29.8	1.3
1	100.294	26.674	13.1	1.3
2	86.086	28.243	5.9	1.7
3	54.281	30.413	12	2.5
4	48.482	31.678	39.9	3.1
5	58.064	31.893	58	3.5
6	45.038	29.863	95.3	2.8
7	43.47	29.707	126.8	2.8
8	62.032	28.916	118.5	2.3
9	73.861	27.851	278.4	1.7
10	57.714	27.206	368.2	1.8
11	86.045	25.931	143.9	1.8
12	113.719	29.351	6.6	1.4
13	120.245	29.379	9.1	1.9
14	114.499	29.162	12.6	2
15	101.35	29.402	22	2.9
16	103.647	28.34	30	4.5
17	73.525	28.941	106.6	5.9
18	54.166	29.098	165.9	5.5
19	61.886	29.501	161.6	5.3
20	64.816	29.858	161.8	3.6
21	93.141	29.522	84.8	2
22	113.389	30.139	27	1.9
23	123.733	30.221	6	1.3
24	131.937	15.807	6.5	0.6
25	120.855	20.775	3.9	0.8
26	118.417	25.896	3.2	1
27	119.677	32.234	2.9	1.6
28	132.662	34.883	8.4	2.4
29	96.665	33.307	68.5	2.8
30	71.651	29.678	278.8	2.5
31	60.636	27.927	260.9	2
32	61.717	28.308	116.6	1.6

33	113.932	27.731	19.5	0.8
34	156.551	23.691	7.1	0.5
35	147.485	17.42	4.1	0.4
36	120.079	11.645	27.7	0.4
37	117.947	16.192	28.8	0.5
38	105.512	21.294	25.3	0.6
39	97.962	27.406	13.4	0.6
40	119.118	31.399	14.8	0.6
41	127.844	32.65	48.7	0.6
42	86.472	30.477	189.4	0.5
43	75.404	30.193	167.5	0.5
44	73.092	28.794	104.8	0.6
45	127.096	24.426	17.5	0.5
46	170.75	18.527	4.2	0.4
47	153.467	12.468	15.6	0.4
48	54.043	24.686	3.4	1.6
49	58.655	25.941	5.1	1.4
50	56.858	27.826	12.1	1.8
51	51.839	30.033	62	1.8
52	42.101	24.851	128.5	2.2
53	30.749	25.046	70.8	2.4
54	30.229	23.877	96.4	2.5
55	33.061	25.898	75.8	1.9
56	33.837	25.242	97.2	1.8
57	44.838	25.663	144.4	1.8
58	53.267	25.569	59.9	1.7
59	49.559	24.114	13.3	1.8
60	105.983	21.48	14	1.3
61	91.901	23.889	17.7	2
62	83.803	28.381	15.5	2.4
63	79.288	32.724	11.7	2.7
64	83.184	36.469	13.2	3.4
65	58.883	31.852	176.5	3.8
66	41.688	28.956	338.2	3.3
67	45.12	25.791	283.8	3.1
68	49.954	26.345	183.2	2.3
69	79.561	25.315	51.7	1.6
70	112.131	23.09	16.1	1.2
71	110.975	21.903	11.1	1
72	62.508	28.073	13.2	4.6
73	58.617	27.77	27.6	4.7
74	55.447	28.454	14.8	4.8

75	37.471	29.231	13	5
76	40.232	29.36	41.3	4.8
77	45.006	29.216	48.4	4.3
78	38.288	29.226	82.4	4.1
79	38.709	29.13	124.1	3.9
80	42.001	29.113	132.1	4.1
81	47.682	29.009	272.1	4
82	44.62	28.688	363.4	4.4
83	63.219	28.755	221.4	4.9
84	127.273	22.05	1.8	1.1
85	117.07	24.671	0.8	1.8
86	115.744	27.78	2	2.2
87	100.034	30.721	8.7	3
88	77.44	30.14	24.5	3.5
89	62.741	27.967	165.8	3.4
90	76.286	24.847	333.2	3.2
91	59.659	24.726	224.5	2.9
92	46.661	24.879	166.6	2.3
93	78.587	25.726	80.4	1.2
94	103.86	25.29	28.4	0.8
95	124.854	22.092	5.8	0.8
96	157.682	18.989	4.2	0.4
97	131.045	22.873	2.8	0.6
98	107.974	28.193	3.1	0.8
99	106.522	33.893	2.5	0.9
100	123.137	34.8	10.4	1
101	84.54	32.861	77.2	1
102	76.148	30.218	227.8	0.8
103	73.184	29.223	200.2	0.7
104	70.36	29.304	106.6	0.7
105	105.421	28.575	16.6	0.4
106	150.086	23.919	6.1	0.2
107	148.377	20.06	2	0.3
108	163.927	29.193	8.6	2.5
109	140.537	28.792	16.8	3.5
110	121.03	29.751	15.2	4.3
111	79.643	29.779	34.5	4.7
112	90.885	29.931	74.6	4.3
113	97.564	29.763	118.1	3.8
114	88.055	29.297	149.1	3.6
115	87.875	29.455	153.2	3.5
116	84.468	28.864	190.3	2.9

117	106.403	29.463	210.3	2.7
118	120.806	29.065	79.7	3.3
119	143.498	29.114	9.2	2.8

Final coded Table:

INDEX	PM10	TEMP	PRECIPITATION	WIND
0	97.221	-1	-1	-1
1	100.294	-1	-1	-1
2	86.086	1	-1	-1
3	54.281	1	-1	1
4	48.482	1	-1	1
5	58.064	1	-1	1
6	45.038	1	1	1
7	43.47	1	1	1
8	62.032	1	1	1
9	73.861	-1	1	-1
10	57.714	-1	1	-1
11	86.045	-1	1	-1
12	113.719	1	-1	-1
13	120.245	1	-1	-1
14	114.499	1	-1	-1
15	101.35	1	-1	1
16	103.647	1	-1	1
17	73.525	1	1	1
18	54.166	1	1	1
19	61.886	1	1	1
20	64.816	1	1	1
21	93.141	1	1	-1
22	113.389	1	-1	-1
23	123.733	1	-1	-1
24	131.937	-1	-1	-1
25	120.855	-1	-1	-1
26	118.417	-1	-1	-1
27	119.677	1	-1	-1
28	132.662	1	-1	1
29	96.665	1	-1	1
30	71.651	1	1	1
31	60.636	-1	1	-1
32	61.717	1	1	-1
33	113.932	-1	-1	-1
34	156.551	-1	-1	-1
35	147.485	-1	-1	-1

36	120.079	-1	-1	-1
37	117.947	-1	-1	-1
38	105.512	-1	-1	-1
39	97.962	-1	-1	-1
40	119.118	1	-1	-1
41	127.844	1	-1	-1
42	86.472	1	1	-1
43	75.404	1	1	-1
44	73.092	1	1	-1
45	127.096	-1	-1	-1
46	170.75	-1	-1	-1
47	153.467	-1	-1	-1
48	54.043	-1	-1	-1
49	58.655	-1	-1	-1
50	56.858	-1	-1	-1
51	51.839	1	-1	-1
52	42.101	-1	1	-1
53	30.749	-1	-1	1
54	30.229	-1	1	1
55	33.061	-1	-1	-1
56	33.837	-1	1	-1
57	44.838	-1	1	-1
58	53.267	-1	-1	-1
59	49.559	-1	-1	-1
60	105.983	-1	-1	-1
61	91.901	-1	-1	-1
62	83.803	1	-1	1
63	79.288	1	-1	1
64	83.184	1	-1	1
65	58.883	1	1	1
66	41.688	1	1	1
67	45.12	-1	1	1
68	49.954	-1	1	1
69	79.561	-1	-1	-1
70	112.131	-1	-1	-1
71	110.975	-1	-1	-1
72	62.508	1	-1	1
73	58.617	-1	-1	1
74	55.447	1	-1	1
75	37.471	1	-1	1
76	40.232	1	-1	1
77	45.006	1	-1	1

78	38.288	1	1	1
79	38.709	1	1	1
80	42.001	1	1	1
81	47.682	1	1	1
82	44.62	1	1	1
83	63.219	1	1	1
84	127.273	-1	-1	-1
85	117.07	-1	-1	-1
86	115.744	-1	-1	-1
87	100.034	1	-1	1
88	77.44	1	-1	1
89	62.741	-1	1	1
90	76.286	-1	1	1
91	59.659	-1	1	1
92	46.661	-1	1	1
93	78.587	-1	1	-1
94	103.86	-1	-1	-1
95	124.854	-1	-1	-1
96	157.682	-1	-1	-1
97	131.045	-1	-1	-1
98	107.974	1	-1	-1
99	106.522	1	-1	-1
100	123.137	1	-1	-1
101	84.54	1	-1	-1
102	76.148	1	1	-1
103	73.184	1	1	-1
104	70.36	1	1	-1
105	105.421	1	-1	-1
106	150.086	-1	-1	-1
107	148.377	-1	-1	-1
108	163.927	1	-1	1
109	140.537	1	-1	1
110	121.03	1	-1	1
111	79.643	1	-1	1
112	90.885	1	-1	1
113	97.564	1	1	1
114	88.055	1	1	1
115	87.875	1	1	1
116	84.468	1	1	1
117	106.403	1	1	1
118	120.806	1	-1	1
119	143.498	1	-1	1