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Assessment of Air Quality Using Personal Exposure Sensors during the 2023 Dhofar Monsoons Period

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Abstract **-** Dhofar, the largest governorate by area in the Sultanate of Oman, is the only area in the Arabian Peninsula that experiences the influence of the southwest monsoon originating from the southern tropical Indian Ocean. Dhofar experienced its highest peak in tourism during the monsoon of 2023, with an 18.4% increase compared to the same period in 2022. Increased tourists' arrivals, active transportation, elevated patronage of restaurants and shops, high engagement of tour operators, expanded participation in recreational activities, staging of cultural and festival events in tourist destinations; collectively impact on the air quality. The aim of this study is to investigate personal exposure to indoor and outdoor air pollutants during the Dhofar monsoon season through real-time air quality monitors equipped with GPS-Enabled weather tracker. Selected air pollutants include PM10, PM2.5, PM1, CO_2, CO, VOC, NO_2 and O_3. The various microenvironments were characterized by differing pollutant levels. PM10 levels were highest at festivals (489 µg/m³), while PM2.5 and PM1 were most prevalent in homes (207 µg/m³ and 64.4 µg/m³, respectively). The TAD identified incense burning at festivals and in homes as a significant source of high PM levels. Diesel bikes for children entertainments, tourist vehicles, and diesel generators for outdoor restaurant electricity were major contributors to PM emissions at festivals and on streets. Restaurants had the highest concentration of VOCs (58.7 ppm), while the highest NO2 levels were found in the valleys (10.0 ppm). CO2 concentration was high in restaurants and cars (both at 1.5 x 10^3 ppm), while CO levels were elevated only in restaurants (3.8 ppm). Except for ozone, which was either undetected or present at low levels, the PE of tourists is concluded to be well above the background concentrations of other pollutants during the measurement campaign. With respect to the relative contributions of specific microenvironments to tourists' time-weighted, integrated exposure to PM2.5, hills were the most significant contributors, followed by markets, valleys, and beaches.

Keywords**:** Air quality, Tourism, personal exposure, Monsoon.

1. Introduction

Salalah is the main city in Dhofar, the largest governorate by area in the Sultanate of Oman. Dhofar is bordered by the Arabian Sea to the south and shares boundaries with Al Wusta governorate to the north, Al Sharqiyah governorate to the northeast, and the Republic of Yemen to the west. According to the most recent data from National Centre for Statistics and Information (NCSI), Dhofar has a population of just under 500,000 people, with approximately 50% of them being expatriates. This represents roughly 10% of the entire country's population, which is 5,169,000 as of 2023 [1]. During the summer months, typically from June to September, Salalah experiences a unique phenomenon known as "Khareef season" (monsoon season) that delivers cold, foggy weather to the city. This is the only area in the Arabian Peninsula that experiences the influence of the southwest monsoon originating from the southern tropical Indian Ocean [2]. Such temperate weather and occasional rainfall results in a lush, green scenery and a pleasant climate making Salalah a popular tourist destination for both local and international visitors. Salalah city was selected as top tourists' destination in the Arab world for the year 2022 [3]. However, air travel and road transportation within popular tourist destinations contribute to pollution, particularly air pollution [4]. The link between tourism and air quality has been extensively explored in academic literature [5]. The estimated number of visitors to Salalah during Khareef 2023 reached nearly 1 million visitors, marking an increase of about 18.4% compared to visitors number in 2022 [6].

Pollutants such as particulate matter (PM), carbon dioxide (CO_2), carbon monoxide (CO), volatile organic compounds (VOC), nitrogen oxides (NOx), and ground-level ozone (O_3) are common contributors to the degradation of air quality in particular in urban area [7]. Some air pollutants such as NOx, O_3 and PM are common pollutants in outdoor and indoor environment, yet some of them may have been originated from outdoor sources [8]. Research has indicated also that outdoor air quality tends to be cleaner than indoor air quality [9, 10]. Outdoor air pollution is a significant factor that cannot be overlooked in studies related to indoor air quality [11]. Several factors affect indoor air quality, including the type of indoor pollution sources, ventilation conditions, and indoor activities [8].

In Oman one prevalent indoor pollution source is burning of incense [12] and it is famously found in Dhofar [13]. Burning incense has been an integral aspect of the daily customs of local communities for centuries, with its origins tracing back to the period before the rise of Islam in Arabia [14]. Traditionally, personal exposure (PE) to environmental factors has often been indirectly quantified relying on estimating overall exposure of populations through annual averaging of networks data obtained from stationary monitoring stations [15]. The PE of air pollutant across spatial and temporal dimensions is a nontrivial endeavour, owing to the multifaceted interactions that govern the determinants between environmental and human systems [15]. Airborne pollutants are ubiquitous and encompass a diverse array of substances that interact, react, and form a wide range of pollutant mixtures [16]. The complicated dynamics of environmental, meteorological, and microclimatic factors, which are characterized by fluctuation in magnitude and variability over time, can significantly add to the complexity of exposure measurements. Furthermore, the mobility of individuals between spatial and temporal domains, which is behavioural patterns dependent, contributes further to the intricacy [17]. To quantify PE, it is essential to account for pollutant concentrations at each point in time a person is present throughout the day [18]. The advent of affordable, highly portable air quality monitors presents an opportunity to apply new technology in various applications beyond the conventional of regulatory or non-regulatory monitoring. Various portable personal monitors for air pollutants concentrations, have been developed and employed in research endeavours [16, 19]. The employment of time-activity diary (TAD) to capture detailed data on an individual's daily activities and how they allocate their time throughout the day offers supplementary information about people's daily routines, travel patterns, transportation and activity choices [20].

The aim of this study is to investigate PE to indoor and outdoor air pollutants during the Dhofar monsoon season through real-time air quality monitors equipped with GPS-Enabled weather tracker. To the best of our knowledge, this study is of its first kind in Oman. Portable air pollution technology that creates accurate human air pollution exposure have not been deployed in a research work in Oman yet evidence from global indices increasingly indicate air quality in Oman might be unhealthy [21]. Selected air pollutants include PM_{10}, $PM_{2.5}$, CO_2, CO, VOC, NO_2 and O_3.

2. Methodology

2.1. STUDY AREA

The study was undertaken in the largest by area governorate in the Sultanate of Oman, Dhofar (17.0322° N, 54.1425° E), for 15 consecutive days during August 10th to 24th, 2023. Dhofar witness a highest peak tourism ever in monsoon 2023 which stands at about 1 million visitors, an increase of 18.4% compared with the same period last year, 2022, where it stood at 760,000 visitors (NCSI, 2023b). The dominance of seasonal visitors is notably concentrated in the month of August, constituting 55% of the total, followed by July at 39%, September at 4% and June at a mere 2%. As a result, August emerges as the pinnacle in terms of both population density and the rates of overall tourist activities. Consequently, the selected time frame for the study was August. According to the NCSI (2023), tourists visited Dhofar primarily arrived either by car (75.1%), or by air (24.9%), landed at Salalah Airport, which serves as the primary international entry point for the region. Once they reach Dhofar, tourists commonly opt for road transportation to move around the area. The road infrastructure in Dhofar is well maintained, making it relatively convenient for tourists to explore various attractions at their own pace. Hence, movement within cities and to various points of interest between the major attractions is performed mainly by personal owned or rented cars. The attractions are situated at distances ranging from 20 to 50 Km from the main city of Salalah. These activities include experiencing natural waterfalls, engaging in games, enjoying laser and drone shows, participating in outdoor and indoor festivals, exploring restaurants, shopping markets, and walking beaches.

2.2. SAMPLING LOCATIONS AND MICROENVIRONMENTS

The sampling locations included area in the main city of Salalah, popular nature trail destinations (Ain and hills of Darbat, Khor, Sahalanoot, Arazat, Jarziz, Itin, Humran and Ishat) and Beaches (Al Maghseel and Raysut). The sampling microenvironments were classified into indoor microenvironments (home, car, festivals, shopping malls and shopping markets and restaurants) and outdoor microenvironments (hills, valleys, beaches, shopping markets, streets, and restaurants). Personal monitoring of each of the six pollutants was undertaken every minute for a total of 84-96 hours. Due to the high influx of tourists, many tourism destinations feature a vast road network, with significant locations experiencing substantial traffic congestion.

2.3. EXPOSURE ASSESSMENT

The 12 h monitoring of six urban air pollutants (PM, CO_2, CO, VOC, NO_2, and O_3) was conducted between August 10th to 24th using Aeroqual Ranger™. The Aeroqual Ranger™ is a real-time active sampling, and friendly alternative to conventional monitors. Concentrations of pollutants were recorded at 1 min interval at a flow rate of 1 L/min. The operating range of the instrument is 0-30.0 mgm-3 for PM1, PM2.5, PMresp, PM10, and TSP (accuracy ≤±8% with a resolution of 0.1 µgm-3 and a response time of 1 s) , 0 -2000 ppm for CO2 (accuracy ≤±10 ppm with a resolution of 1 ppm and a response time of 120 s), 0-25 ppm for CO (accuracy ≤±0.5 ppm for operating range of 0-5 ppm and ≤±10 ppm for operating range of 5-25 ppm with a resolution of 0.01 ppm and a response time of 60 s), is 0-30 ppm for VOC (accuracy ≤±0.02 ppm with a resolution of 0.01 ppm and a response time of 30 s), and 0-0.15 ppm for O3 (accuracy ≤±0.002 ppm with a resolution of 0.001 ppm and a response time of 60 s). The Skywatch® BL 500 is an instant portable weather monitoring station that records measurements and GPS coordinates automatically. With its tracking mode and automated recording of data and GPS positions, along with the ability to capture microenvironment photos and display readings on a map, it reduces the workload for participants while enhancing the accuracy of collected data. All sensors measure, log, display data and instantly synchronize with cloud over Wi-Fi, ensuring secure real time backup. To allow for continuous online data transmission, subjects were provided with portable mobile router (D-LINK, DWR-932, 4G LTE, weight 86 g). For walking, the Ranger and Skywatch units were carried on the back in a custom-made back bag. However, for in-car journeys, the back bag unit were placed on the front passenger seat, while for indoor measurements, they were placed close to the participants using stand sets. The same vehicle, a 2021 RAM Laramie, was utilized for all monitoring campaigns, and the car's ventilation conditions remained unchanged. Throughout the monitoring period, the car's windows remained closed. There were no alterations in the car's mechanical condition during the 15-day monitoring period. Sampling was carried out for continuous 12 h per day between 08:00 and 23:00 (exact times based on scheduled journey and activities).

2.4. QUALITY CONTROL

To assess the quality of in situ measurements by Ranger monitors and to evaluate the quantitative uncertainties in the PE measurements, experiments were conducted continuously for 12 hours under the same experimental conditions and microenvironments. Intercomparison of data produced by three Ranger monitors were employed, each equipped with a set of six swappable sensors. The primary objective of the experiment was to assess whether the three sensor sets exhibited any significant differences in their operational performance. Temperature and relative humidity were carefully monitored to ensure optimal operational parameters for the monitors, maintaining the temperature within the range of -10 ºC to 40 ºC and humidity within the range of 0% to 95% RH.

To validate the performance of the Ranger monitors, calibration against stationary monitoring equipment was performed. Samplers were placed alongside a stationary monitoring station for a continuous of 12 hours. Ambient air quality data were collected from a stationary monitoring unit located within Dhofar Governance and belonged to the Omani Environment Authority (EA). This fixed-site monitoring unit was situated within a schoolyard approximately 200 meters from the main Sultan Qaboos Street. The data collected in this study and monitored by the EA consist exclusively of measurements for PM2.5, PM10, NO_2, O_3, and CO. Other pollutants were not included in the monitoring conducted by the EA, hence they are not included in the calibration study. Data were analysed using R studio [22].

3. RESULTS

3.1. Quality control

Table 1 shows ANOVA statistical summary of the sensors used in the study. The results of the ANOVA analysis revealed no statistically significant differences in the performance of the sensors (P values ranges from 0.11-0.73). This suggests that, under the tested experimental conditions, the observed variations in measurements across the sensors were likely due to random chance rather than inherent differences in their operational performance. The absence of statistical significance differences indicates a degree of homogeneity among the sensors, reinforcing the notion that, within the specified operational parameters, they produce comparable results.

Table 1 ANOVA statistically summary of the sensors used in the study.

SENSOR	F VALUE	Pr(>F)
PMrsp	0.89	0.41
PM10	0.40	0.67
TSP	0.36	0.70
PM1	1.11	0.33
PM2.5	0.94	0.39
VOC	0.97	0.38
NO2	0.45	0.64
O3	1.85	0.16
CO	2.21	0.11
CO2	0.31	0.73

Table 2 shows Welch two sample t-test of the sensors used in the study and EA fixed-site monitoring station. The results indicate no statistical difference between the two means (P values ranges from 0.18-0.80) and T-value were calculated at a range of -1.40-0.48. This demonstrate acceptable agreement between the readings obtained from the Ranger units and those from the EA fixed-site monitoring station.

Table 2 Welch two sample t-test of the sensors used in the study and EA fixed-site monitoring station.

SENSOR	T-VALUE	P-VALUE
PM2.5	0.48	0.64
PM10	0.26	0.80
NO2	-1.40	0.18
O3	-1.19	0.24
CO	-1.18	0.24

3.2. Exposure Assessment

During the study period of August 10th to 24th, average measured temperatures range from 20.8°C to 32.5°C and RH 39.9-95.0 with an average precipitation level of 389.3 mm of rainfall. It was also generally a less sunny time of the year with an average of 133.7 W/m^2 of solar radiation in Salalah during the entire measurement period. The dataset of pollutants collected from various microenvironments consists of over 5000 entries for each pollutant. The results show that exposure to air pollution exhibit large variability across studied microenvironments throughout the measurement campaign, including intense peaks of short duration for most pollutants. Mean concentrations and standard deviations for each pollutant in each microenvironment are provided in a supplementary material.

The mean concentrations of PM10 were higher at festivals (489 µgm^{-3}), on streets (346 µgm^{-3}), at beaches (315 µgm^{-3}), followed by levels at home (263 µgm^{-3}). However, for PM2.5, high concentrations were observed at home (207 µgm^{-3}), followed by festivals (107 µgm^{-3}) and streets (77.4 µgm^{-3}). Ultrafine particles (PM1) exhibited higher concentrations at home (64.4 µgm^{-3}), followed by the shopping market (28.4 µgm^{-3}) and then the restaurant (24.3 µgm^{-3}). Given the presence of well characterized PM emission sources such as burning incense in festivals and homes, kids' diesel bikes in festivals, vehicles in streets and diesel engine for electricity supply in most outdoor restaurants in such microenvironments, the higher concentrations recorded are not unexpected. Burning incense to release fragrance which is accompany by a thick smoke is one common indoor pollutants in the Gulf region [12]. Background concentrations of PM10 and PM2.5 was determined at 35.2 µgm^{-3} and 13.7 µgm^{-3}, respectively, reflecting source of pollution exposure is human activity. A 12-hr exposure profile and associated time-activity pattern data, Figure 1, emphasizes on this. Average concentration of PM2.5 during the burning event is 835.7 µgm^{-3} (exceeding the guidelines by 2287.7%). Maximum fine PM2.5 and ultrafine PM1 particles detected at home are exceeding the established guidelines by 1280% and 540%, respectively. Such practice contributes immensely to indoor air pollution as the thick smoke produced by burning incense contain various compounds PM, CO, NOx, HCHO and SO_2 [23].

Of the measured microenvironment for VOC, restaurants were shown to have the highest concentration (58.7 ppm), followed by car (26.4 ppm) and home (16.5 ppm). The use of liquefied petroleum gas (LPG), charcoal, and wood as cooking fuels for grilling or frying products can emerge as a significant contributor to the emission of pollutants within commercial restaurant settings. Numerous investigations have indicated that concentrations of volatile organic compounds (VOCs) within the cabins of vehicles are like, or in some cases exceed, those found in buildings. The elevated levels of VOCs in vehicles can be ascribed to a combination of factors, including the infiltration of VOCs from the external environment, engine fuel combustion, emissions from interior materials, emissions originating from human activities, and various other contributing sources [24]. However, NO_2 was detected at high concentration in the valley (10.0 ppm) and the restaurant (7.4 ppm). Background concentration of NO_2 at the time of the measurement campaign is 3.5×10^{-3} ppm. Ozone was not detected above the standard level of WHO. While CO_2 was detected at high concentrations in the restaurant and the car (both at 1.5×10^{3} ppm), CO was found to be at elevated level only in the restaurant (3.8 ppm). Background concentration of CO was measured at 3.1×10^{-4} ppm, indicating exposure to emissions from nearby sources such as barbecuing.

The figure below provides an example of exposure information of a participant in a particular day. The figure indicates exposure to PM2.5 depends on the pollutant levels and the person's activities during time spent in a microenvironment. The record shows some intervals of higher and lower exposure of PM2.5 than the guidelines [25]. Average exposure to PM2.5 over the 12-hour measurement period exceeds the indoor guidelines by 65% and the outdoor guidelines by 286.7%. The figure clearly indicates that this is due to the practice of burning incense at home.

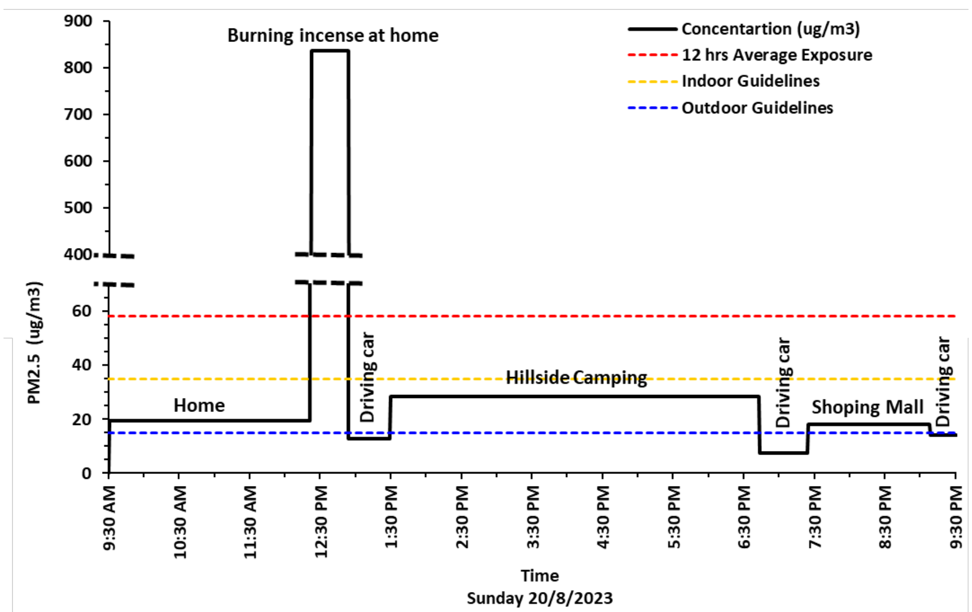

Figure 1 A 12-hr exposure profile and associated time-activity pattern.

The contribution of different microenvironments to overall exposure during the tourism period in Khareef Salalah was determined by the time spent in each environment over the full tourism period. The percentage contribution from a microenvironment to personal exposure was then estimated by calculating time-weighted integrated exposure using the formula:

$$E_i = \sum_{j}^{J} C_j t_{ij} \qquad [26]$$

where Ei represents the time-weighted integrated exposure for individual i over the specified period; Cj is the pollutant concentration in microenvironment j; tij is the total time individual i spends in microenvironment j; and J is the total number of microenvironments that individual i passes through during the specified period.

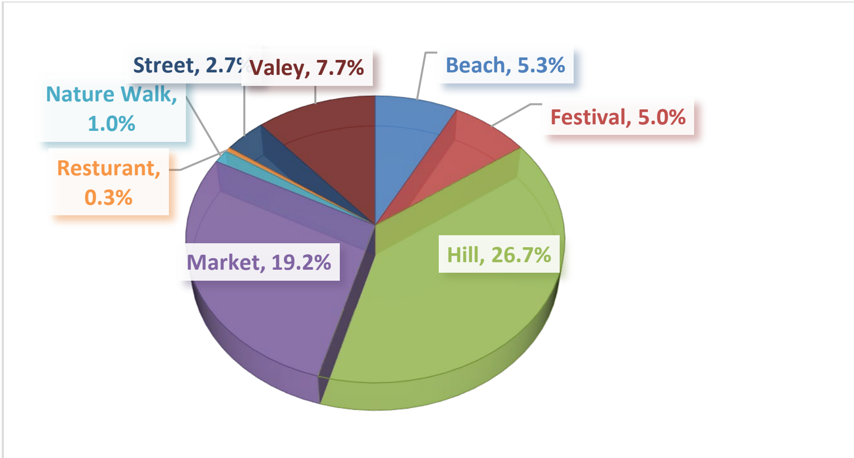

Figure 2 Relative contributions from specific microenvironments to a tourist's time-weighted, integrated exposure to PM2.5

The figure shows that hills contribute the most to tourists' exposure, followed by markets, valleys, and beaches. The high levels of exposure in hilly areas might be due to mist sources and common tourist activities like driving and barbecuing, especially during the monsoon period, which currently lacks government restrictions. Further investigation is needed to study the chemical composition of the PM in these areas. The map below illustrates PM2.5 levels across various outdoor microenvironments in Salalah during Khareef Salalah, highlighting the distinct PM2.5 levels associated with different locations frequented by tourists.

Figure 3 PM2.5 levels across various outdoor microenvironments in Khareef Salalah 2023, associated with different locations frequented by tourists.

4. Conclusion

Dhofar experienced its highest peak in tourism during the monsoon of 2023, with an 18.4% increase compared to the same period in 2022. The various microenvironments were characterized by differing pollutant levels. PM10 levels were highest at festivals (489 µg/m³), while PM2.5 and PM1 were most prevalent in homes (207 µg/m³ and 64.4 µg/m³, respectively). The TAD identified incense burning at festivals and in homes as a significant source of high PM levels. Diesel bikes for children entertainments, tourist vehicles, and diesel generators for outdoor restaurant electricity were major contributors to PM emissions at festivals and on streets. Restaurants had the highest concentration of VOCs (58.7 ppm), while the highest NO2 levels were found in the valleys (10.0 ppm). CO2 concentration was high in restaurants and and cars (both at 1.5 x 10^3 ppm), while CO levels were elevated only in restaurants (3.8 ppm). Except for ozone, which was either undetected or present at low levels, the PE of tourists is concluded to be well above the background concentrations of other pollutants during the measurement campaign. With respect to the relative contributions of specific microenvironments to tourists' time-weighted, integrated exposure to PM2.5, hills were the most significant contributors, followed by markets, valleys, and beaches.

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6. References

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Appendix-1 Supplementary Material for pollutants data collected at different microenvironment during Salalah Monso

Microenv	**PM10 (μgm^{-3})**		**PM1 (μgm^{-3})**		**PM2.5 (μgm^{-3})**		**VOC (ppm)**		**NO2 (ppm)**		**O3 (ppm)**		**CO (ppm)**		**CO2 (ppm)**	
	M ean	SD	Mea n	D	M ean	S D	M ean	SD	M ean	SD	M ean	S D	ean	S D	M ean	SD
Beach	3	89	13.4		68	9	0	0.0	0	0.	0	0		0	45	58.5
	15.0	.0		.4	.3	.1	.0		.0	02	.01	.01	.2	.4	1.0	
Car	5	15	4.8		13	1	2	11	5	23	0	0		2	14	463.0
	3.9	6.0		.2	.3	4.4	6.4	4.0	.7	.90	.00	.00	.2	.4	54.0	
Festival	4	23	23.3		10	2	0	0.1	0	0.	0	0		3	51	136.0
	89.0	6.0		.5	7.0	0.3	.1		.1	04	.00	.00	.0	.3	5.0	
Hill	7	31	7.5		32	1	1	57.	2	9.	0	0		1	42	25.8
	4.5	.8		.1	.4	0.3	.8	4	.1	67	.01	.01	.4	.1	9.0	
Home	2	35	64.4		20	3	1	43.	5	15	0	0		2	77	277.0
	63.0	6.0		1.8	7.0	15.0	6.5	6	.3	.60	.00	.00	.3	.2	7.0	
Shoping Mall	4	27	11.0		18	7	0	0.0	0	0.	0	0		1	57	149.0
	3.7	.4		.6	.1	.0	.0		.0	04	.00	.00	.9	.5	4.0	
Shoping	1	21	28.4		73	1	0	0.1	0	0.	0	0		2	64	268.0
Market	69.0	7.0		9.6	.7	23.0	.1		.0	03	.00	.00	.3	.0	5.0	
Nature Walk	1	15	9.2		43	5	0	0.4	0	0.	0	0		1	68	500.0
	21.0	.3		.7	.8	.1	.1		.1	03	.00	.00	.7	.1	7.0	
Resturant	1	66	24.3		41	2	8	14	7	13	0	0		3	15	390.0
	04.0	.1		1.9	.8	5.3	5.7	7.0	.4	.50	.00	.00	.8	.3	02.0	
Street	3	33	18.7		77	4	0	0.0	0	0.	0	0		3	87	586.0
	46.0	1.0		0.3	.4	8.4	.1		.1	04	.00	.00	.5	.4	9.0	
Valey	7	27	7.0		31	1	0	2.0	1	23	0	0		0	42	40.7
	4.8	.8		.2	.1	0.9	.6		0.0	.30	.01	.01	.2	.8	6.0	

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