INSTITUTE FOR SUSTAINABLE ENERGY, UNIVERSITY OF MALTA

SUSTAINABLE ENERGY 2014:
THE ISE ANNUAL CONFERENCE
Thursday 20th March 2014, Dolmen Hotel, Qawra, Malta

ISBN 978-99957-0-668-5

ENERGY-RELATED AIR POLLUTION IN MALTA: BLACK CARBON MEASUREMENTS BY USE OF A MOBILE AETHALOMETER

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ABSTRACT: Black Carbon (BC) is the component of fine particulate matter that is associated with energy use. It affects human health and is a significant contributor to climate change. Black Carbon (BC) concentrations in the atmosphere have been assessed by gathering 130 air samples in Malta, recording more than 230 hours of real-time data. A mobile micro-Aethalometer (microAeth AE51) was used for the measurements. Samples were taken under various conditions, from clean rural areas to the most polluted roads. Results showed that the highest levels of exposure to BC pollution are experienced in enclosed areas such as parking lots and inside motor vehicles while driving. The results also showed that the highest levels of BC concentration in the Maltese islands occur during the morning and the afternoon. These two periods coincide with the peaks in road traffic. All results indicated that the main source of BC in the Maltese islands comes from land transportation, and mostly from diesel engines.

Keywords: Black Carbon, micro-Aethalometer, Pollution

1 INTRODUCTION

Black carbon (BC) is emitted into the atmosphere in the form of particulate matter ($PM_{2.5}$) as a result of incomplete combustion of fossil fuels, biofuels and biomass. Fine particles can penetrate the lungs, in turn causing respiratory and cardiovascular effects. Black carbon, unlike particulate matter in general, may function as a universal carrier of a wide variety of toxic chemicals.

In terms of climate effects, black carbon interacts with clouds, absorbs light directly, and reduces the albedo of snow and ice when deposited.

2 MEASURING EQUIPMENT AND SAMPLING PROCEDURE

Black carbon concentrations can be measured as differentiated from total particulate matter concentrations based on the fact that BC absorbs infrared radiation. BC concentrations were measured by use of a micro-Aeth AE51 mobile micro-Aethalometer produced by Berkeley-based firm Magee Scientific. Samples were taken for one minute rates at an average sampling flow of 100 ml/min. Air samples are sucked into the device through an inlet on the front face of the unit where BC samples were collected on a filter strip consisting of a T60 Teflon coated borosilicate glass fiber medium. The instrument in turn targets the BC deposit on the filter strip with a light beam from a single LED source of 880nm-IR, and translates the light absorption of the spot into BC concentration in terms of nanogrammes per cubic metre (ng/m^3).

It was noticed that for long test durations, the BC deposits accumulated on the filter strips were producing more background noise, and spurious spikes were attained in the data. Direct communication with Aethlabs and from experience on the instrument suggested that each strip must be replaced before an attenuation of 50 is reached and the sense counts must not go below the 350,000 threshold. Most filter strips were getting replaced on an attenuation of 40. This drastically reduced the margin of error.

3 DATA PROCESSING

3.1 Raw Data and Smoothing

Raw data consisted of several readings, each representing the average of one-minute sampling. In some cases negative readings were obtained for several reasons. Instrumental noise in the system is proportional to the time base and flow rate. The longer the time base, and the higher the flow rate, the better the sensitivity of the instrument. The signal to noise ratio (SNR) would also increase, and the instrumental noise would get proportionally smaller. Noise resulted in negative readings due to a low SNR when low BC levels were being measured. Other negative readings were caused by mechanical shocks. Due to this observation the instrument was subsequently positioned onto a shock-absorbing cushion during mobile sampling.

The micro-Aeth AE51 software package, 'microAethCOM', was used for the smoothing of raw data. All raw data was smoothed by an 'Optimized Noise-reduction Algorithm' (ONA), which is software developed by the US Environmental Protection Agency (EPA) to correct for such negative readings produced by aethalometers [1]. Raw data was uploaded online on Aethlabs website, ran through the ONA, and a new Excel data file was generated for smoothed and noise-reduced data.

3.2 Data Correction Factor

The operating principle of the micro-Aethalometer is based on the measurement of the optical attenuation of a monochromatic light beam which is transmitted through a circular spot accumulated on a fibrous filter. The mass of the BC is calculated according to the following formula;

$$BC = \frac{ATN}{\sigma} = \frac{100 ln\left(\frac{I_o}{I}\right)}{\sigma} \quad (1)$$

where 'BC' defines the Black Carbon mass and is the reading shown by the instrument; 'ATN' is the light attenuation, a dimensionless value; 'I_o' and 'I' are the transmitted light intensities at the beginning of a sampling period and after material deposition on the filter is completed, respectively. The attenuation coefficient or 'σ' is a constant, assuming that the proportional relationship between ATN and BC remains the same at all BC values.

To be sure, various reports and journal papers in the last ten years have demonstrated that aethalometer readings underestimate the BC mass. This is ascribed to two effects. One is related to overloading of filter strips. As the filter is loaded with particles, the last deposited particles overlap and shadow those that were previously collected [2][3][4][5][6][7]. This effect causes a non-linearity in the BC-ATN relationship and is mostly susceptible when the filter strip is heavily loaded.

The second effect is that light which scatters on the BC deposits is not absorbed by the particles. The instrument will thus read the transmitted light intensity as too high compared to the actual BC mass, resulting in a reduction of the indicated mass concentration of BC. This effect is referred to as single scattering albedo (SSA), defined as the fraction of incident light that is scattered instead of absorbed [8].

These underestimations were adjusted to give a better approximation of what would be the appropriate reading by applying a correction algorithm that estimates the actual BC mass depending on the attenuation of the filter strip.

To compensate for the particle loading effect on the filter strip, the following equations were applied:

$$BC = \frac{BC_o}{SSA(0.88T_r + 0.12)} \quad (2)$$

where

$$T_r = \exp\left(-\frac{ATN}{100}\right) \quad (3)$$

where 'BC' and 'BC_o' are the corrected BC mass concentration and the original Aethalometer's reading, respectively; 'T_r' is the measured filter transmission which was calculated from the attenuation given for every reading from the Aethalometer's data and the constants '0.88' and '0.12' are the slope and intercept of the regression line from the instrument's normalized concentration curve issued by the Berkeley National Laboratory. This same laboratory also suggest an SSA of 0.6. This factor reduces the manufacturer's attenuation coefficient (880nm-IR) from 16.6 m^2/g to 10 m^2/g [9].

A linear correction algorithm needs to be applied to obtain an approximation of the actual BC mass concentration. For this study, the algorithm represented by Kirchstetter and Novakov was used [7]. The manufacturer's calibration for the attenuation coefficient of 16.6m^2/g was selected. This implies an SSA of '1'. Since aethalometer studies are the most common way to measure BC pollution from road traffic, and the described algorithm is widely accepted in the scientific community, equations (4) and (5) have been applied.

$$BC = \frac{BC_o}{(0.88T_r + 0.12)} \quad (4)$$

where

$$T_r = \exp\left(-\frac{ATN}{100}\right) \quad (5)$$

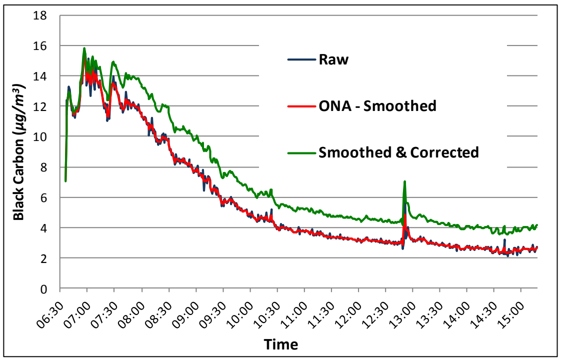

Figure 1: Raw data, Smoothed data and Corrected data

3.3 Other instrumentation

A handheld instrument, Lutron LM-8000, was used to record data relating to spot wind speed, relative humidity and temperature with a resolution of 0.1m/s, 0.1% and 0.1°C, respectively. Accuracies for the wind speed, RH and temperature are ±3%, ±4% and ±1%, respectively.

A handheld navigation device, Garmin Dakota 20, was used to log the GPS coordinates at measuring locations. It was also used to measure distances between measuring spots and main roads. Accuracy of this instrument is 5m.

An RMA-11 and an RMA-150 Dwyer flow meter were used for calibrating the air flow of the micro-Aeth AE51.

4 DATA ANALYSIS AND RESULTS

Black carbon spot measurements were taken by use of the micro-aethalometer and real-time measurements were downloaded, inspected and archived immediately following each sampling session. Data quality issues experimented due to the instrument limitations (such as negative and other spurious readings) have been addressed after the data was processed, smoothed and corrected. A very small number of inadequate data was selectively removed in the course of the analysis as it was associated with filter strip issues and high attenuation levels. All original raw data was archived.

Over 130 air samples were taken and more than 230 hours of real time data were gathered and analysed within this study.

4.1 Movement and vibration test for the micro-Aeth AE51

A test was performed to analyse the effect of movement and vibration applied on the micro-Aeth during measurement of black carbon. This was considered important to be able to assess the influence of movement on results from sampling onboard a driving vehicle. The instrument did indeed produce data spikes when movement and vibrations were performed. One reason these spikes happen is because some BC deposited onto the walls of the sampling chamber falls onto the filter strip during rapid movements and mechanical vibrations. This induces the instrument to measure a higher BC level than the actual sample.

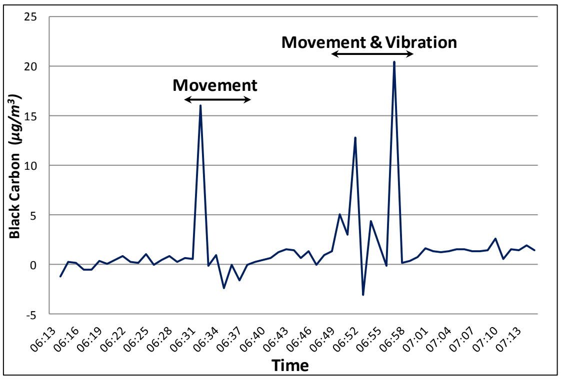

Figure 2: Raw data recorded during movement and vibration test

Following this insight, the instrument was moved gently during all sampling, and a shock-absorbing cushion was used during mobile sampling. To assess the effect of the latter, data was gathered while driving on bumpy roads with and without instrument cushioning. The shock absorption measure was found to reduce the recording of spurious spikes by 90%.

4.2 Air samples in Rural Areas

Measurements in rural areas typically indicated BC concentrations between 0.26µg/m^3 and 0.44µg/m^3 as illustrated in Table 1. One sample falling out of range was taken at Salib tal-Għolja in the limits of Siġġiewi. This measurement was performed over a period of more than 10 hours, and data showed higher concentration levels in the morning, and yet more evidently in the evening. Following a more elaborate analysis, and by comparing wind patterns with the periods of peak readings, it was concluded that BC was carried to the sampling point from a polluted area 7.5km away. BC levels in the Maltese rural areas have been found to be in the same range as found in other EU countries.

Table 1: BC concentration results from samples taken in rural areas

Location	BC µg/m³
Fanal ta' Ġordan at Żebbuġ, Gozo	0.27
Bassasa at Żurrieq, Malta	0.26
Salib tal-Għolja at Siġġiewi, Malta - No. 1	0.32
Salib tal-Għolja at Siġġiewi, Malta - No. 2	1.05
Il-Majjistral Park, Mellieħa	0.44

4.3 Exposure during working hours

One of the advantages of using a portable aethalometer is the possibility to measure the more relevant personal exposure rather than pollution at a fixed location. The tests presented in this section were performed to show by how much the levels of BC exposure will fluctuate in different environments during typical work days. Although many jobs in Malta involve mostly office work, others require frequent road travel as part of the daily routine.

Figure 3 shows typical BC levels sampled inside an office located in a heavily polluted area at Marsa. Although some fluctuations occur between one sample and another, the level of BC remained relatively constant and at an average of 5.67µg/m^3. Notably, this measured average office BC concentration is about 20 times higher than the average for the listed typical Maltese countryside values.

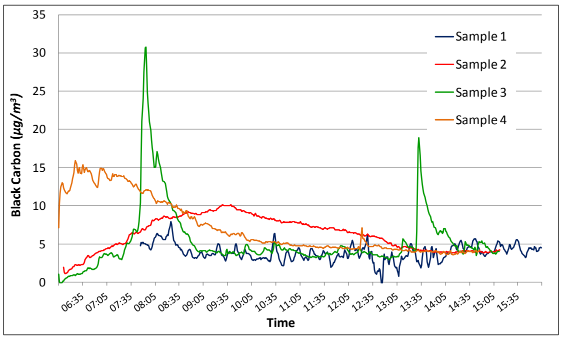

Figure 3: Typical days at an office inside a heavily polluted area

Many tests performed for a number of scenarios indicated that the highest levels of BC are met during road trips. Figure 4 illustrates a typical day at work for an employee whose office is located inside a polluted area, and whose work necessitates performing a number of trips to areas of lower outdoor pollution.

The graph shows BC levels under 5µg/m^3 at the office while an average of 50µg/m^3 is encountered during travelling, i.e. inside the car. This indicated a tenfold increase in the level of BC inhalation compared to staying at the office. While office indoor BC conditions will vary according to location and ventilation mechanisms (opening/closing of windows), and the same will be true for vehicles, the general conclusion can be maintained that exposure to BC will be far higher when travelling on Maltese roads than when staying inside buildings.

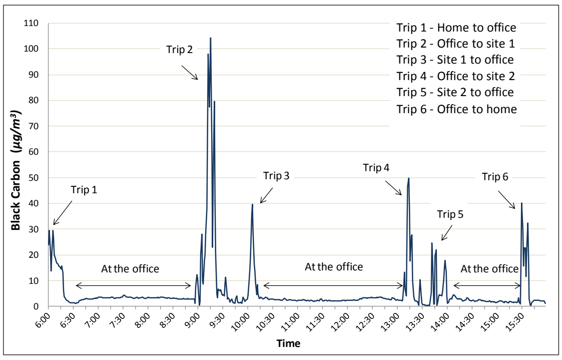

Figure 4: BC concentrations experienced during a work day as described in the main text.

4.4 Mobile rush hour sampling

This section presents results for BC concentrations inside and outside a car, measured from inside the vehicle while driving in rush hour traffic. Sampling took place during trips from Kirkop to Marsa at 06:00 and at 07:00, and during same-day return trips at 15:30 and 16:30. The trips at 06:00 and 15:30 served as reference for hours of minimum traffic compared to the trips an hour later. The route selected for these tests includes both urban and semi-urban areas as might be typical for many commuters. Wind speed is considered an essential factor and was recorded as part of the data set.

Table 2 shows the final results from 90 samples performed. A significant difference in BC concentrations has been found for samples from outside and inside the vehicle during the trip. This indicates that travelling with all ventilation closed reduces the level of BC exposure inside a vehicle by a large factor (43% for this particular case).

Values obtained from outside the vehicle during minimum hours of traffic are very similar to rush hour values. However, trips during hours of minimum traffic will be faster, and so inhalation of BC will be reduced.

Samples taken outside the vehicle were done by fixing the inlet pipe of the micro-Aethalometer at the driver's top corner window and projected for about 10cm horizontally outwards.

Table 2: BC concentrations obtained by sampling air inside and outside a vehicle while driving.

Black Carbon (μg/m³)					
	In-vehicle (Inside air)	On-road (outside air)			
Time	06:00	06:00	07:00	15:00	16:00
Min	4.2	10.8	3.1	4.5	4.8
Max	123.9	259.5	205.1	163.8	130.6
Av. Min	22.7	34.0	24.3	24.8	18.6
Av. Max	50.0	97.4	95.0	79.7	65.9
Average	**35.1**	**62.3**	**51.0**	**46.8**	**39.5**
Av. wind speed (m/s)	4.9	4.3	5.8	7.7	7.5

Values in the afternoon are somewhat higher than those in the morning due to lower wind speeds early in the day. Temperature and relative humidity do not seem to have a significant and detectable effect on BC measurements.

4.5 Stationary sampling during rush hours in Malta's most-trafficked roads

Stationary roadside measurements in three of Malta's most trafficked roads revealed BC concentrations between 11μg/m^3 and 15μg/m^3 during evening rush hours. These values are significantly lower than those resulting from outside air sampling onboard vehicles driving on roads of less traffic. This suggests that the concentration of BC declines significantly from the middle of the road to sites just slightly further away from the source of pollution, as the samples were taken 6m to 10m from the middle of the road. An additional test showed that a distance of just 100m away from the main road the BC concentration was reduced by a factor of more than three at Hompesch Road in Fgura.

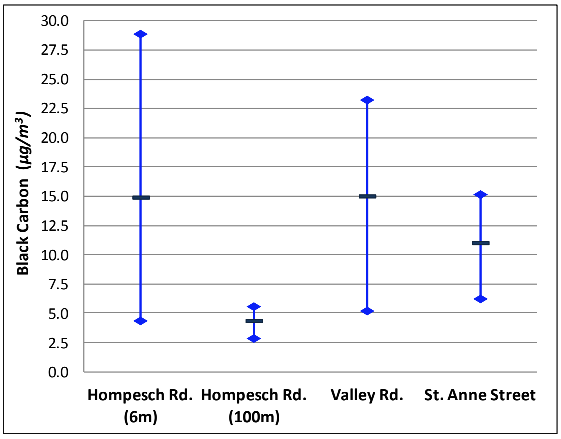

Figure 5: BC concentrations from stationary air sampling during rush hour in some of Malta's most trafficked roads.

4.6 BC samples taken inside underground car parks

Sampling inside a number of underground car parks showed a variety of BC readings. While some sites revealed low BC concentrations (<5μg/m^3), others had rather polluted air conditions (BC around 30μg/m^3). Enclosed spaces tend to accumulate higher levels of BC, and inadequate ventilation systems will prolong the time required to reduce pollution levels.

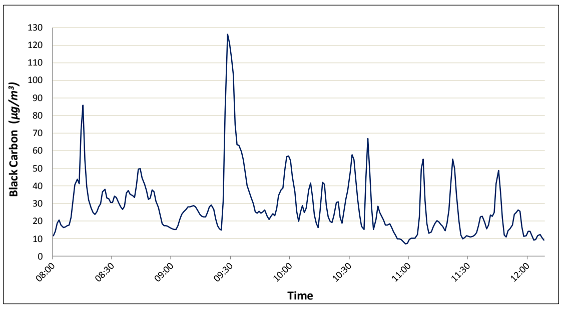

Figure 6: A BC profile sampled at the Mater Dei hospital's underground parking lot.

4.7 BC sampling inside the parking area of a ferry boat

Figure 7 shows a typical BC curve recorded inside the parking area of a ferry boat. The first peak occurs when vehicles access the area. The graph shows that the ferry's ventilation system lowers the BC levels to under 5μg/m^3 during the trip. Another peak occurs when passengers start their vehicles before leaving the ferry.

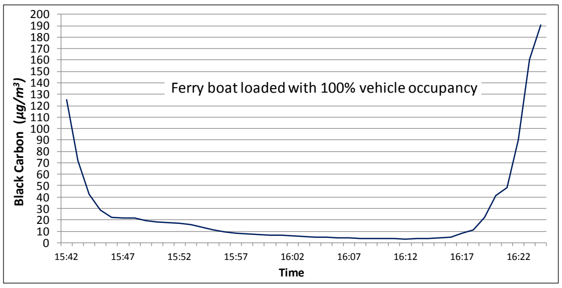

Figure 7: BC profile for a ferry boat 100% loaded with vehicles

Although the peaks occur for a limited time period, they are very high and thus alarming. In the longer run, frequent exposure to such high BC levels may be very dangerous even if each exposure is for a short period of time.

Table 3: BC concentration levels inside the parking area of a ferry boat.

	Black carbon (μg/m³)		
Vehicle occupancy	Min.	Max.	Av.
50%	1.87	48.71	10.84
100%	3.30	190.84	26.22

4.8 BC sampling in a sub-urban area

The tests described in this section were performed to study how BC concentration levels may differ between the inside and immediate outside of buildings. Results varied, as air inside enclosed buildings usually, but not always, contains lower BC values compared to outside air.

It was found that results depended on wind conditions. BC seems to accumulate only slowly in the air inside enclosed buildings via the natural ventilation system, while BC concentrations remain higher on the outside. However on the first windy day, the dispersion of outdoor BC particles is higher, leaving BC concentration levels inside the building relatively higher.

Table 4: Average indoor and outdoor BC concentration levels for a sub-urban building.

	Sample 1	Sample 2
Average indoor BC, µg/m³	1.42	2.18
Average outdoor BC, µg/m³	3.15	1.97

4.9 BC sampling near Delimara Power Station and Freeport Shipping Docks

BC values derived from a single sampling period 1km away from Delimara Power Station were very low (<1µg/m^3). Wind speed and direction were low enough as not to influence results. Some pronounced peaks were showing in the data set, but these were attributed to diesel vehicles passing by the sampling site.

Similarly, a single sampling session was performed in the vicinity of Malta's shipping terminal, but on a day of moderate wind speed with a direction that would decrease air pollution at the sampling site relative to the BC source of interest. The sampling resulted in an average BC value of 5.07µg/m^3 which is considered an indicative figure that might be higher on calmer days.

However, both results can in fact only serve as indications, while further sampling would be required for definitive conclusions to be drawn regarding these sites.

5 CONCLUSIONS

The following points can be concluded from the various results obtained within this study:

i. The places with the lowest BC concentrations are rural areas.
ii. The places with the highest BC concentrations are enclosed spaces like parking areas, as well as roads, especially as experienced while driving.
iii. The higher the wind speed, the higher is the dispersion factor.
iv. Low wind speeds will disperse emissions by a limited factor and may carry black carbon particles kilometres away even at low altitudes.
v. Outdoor BC can enter residential households via its natural ventilation system and its indoor concentration varies according to the location, the wind speed and the wind direction.
vi. Diesel engines are the main contributor of BC emissions in the Maltese islands.
vii. Highly trafficked roads in Malta contain substantial levels of BC content. A mere distance of 100m away from such roads can reduce the BC content by a factor greater than three.
viii. Those at greatest risk to experience health implications related to BC are people who spend long hours in the vicinity of, and travelling on, mobile BC sources. The high BC concentrations recorded imply that the risk of cardiovascular and respiratory diseases will increase by a large factor for these persons. Jobs such as parking attendants, taxi and bus drivers, truck drivers, delivery men, postmen, road cleaners, traffic policemen, wardens, etc., would involve high risks of health issues linked to BC.
ix. BC values in Maltese rural areas are within the same range as found in other developed countries.
x. BC values in certain urban areas are most likely higher than found in various other EU member countries.

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