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Bangladesh Air Pollution Studies (BAPS): Task - 4 (Cost-effectiveness Assessment for Dust Control Measures, Dhaka)
Final Report

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Executive Summary

Government of Bangladesh (GOB) initiated Clean Air and Sustainable Environment (CASE) project with the assistance from International Development Association (IDA)/World Bank (WB). For one of the components (S-13), Norwegian Institute for Air Research (NILU) was selected by GOB/WB.

Among the sub-components, all related to air quality in Bangladesh, two sub-components - Cost-effectiveness Assessment for Dust Control Measures, Dhaka (Task - 4) and Industrial Emission Estimate (Task- 5) were sub-contracted by NILU to a group in the Chemical Engineering Department, Bangladesh University of Engineering & Technology (BUET), Dhaka (ChE BUET Team). The core group for Task 5 consists of Mr. Md. Mominur Rahman, Assistant Professor, Dr.DilAfroza Begum, Professor and Dr.Nooruddin Ahmed, Retd. Professor/UGC Professor in the ChE Department. The group for Task 4 consists of Dr. Kazi Bayzid Kabir, Assistant Professor, Mr. Md. Mominur Rahman, Assistant Professor, Dr. Dil Afroza Begum, Professor and Dr. Nooruddin Ahmed, Retd. Professor/UGC Professor in the ChE Department. Other teachers and technicians were also involved in the field work/ measurements/analysis work. The team had access to necessary state of the art equipment and technical know-how for this type of work.

The current report for Task-4 describes the field work undertaken at 30 different locations in and around Dhaka city; 6 locations on highways, 10 locations on arterials and 14 locations on commercial/residential areas. The work involved dust collections/ sieve analysis/ moisture analysis, on-road traffic survey and ambient PM_{10} measurements by Anderson HV PM_{10} Sampler. US EPA-approved methods were followed for all measurements, which were described in the Inception Report and accepted by CASE/WB. It may be mentioned here that this is the first time road dust measurements were carried out in the country.

As is known, the most severe exceedances of air quality standards in Bangladesh are due to particulates in the air, $PM_{2.5}$ and PM_{10}. The annual average PM_{10} concentrations varies from area to area in Dhaka. Typical annual average of fine particles measured in the city centre was 64 µg/m^3 (Begum et. al 2014). Other studies have reported annual average concentrations of PM_{10} at about 144 µg/m^3. Model estimated PM_{10} concentrations were from the Task 2 report of the BAPS programme reported at about 300 µg/m^3. About 17 % of the fine particles was estimated to originate from the transport sector (from vehicles and road dust) while about 60 % of PM_{10} was due to emissions from brick kilns in Dhaka.

The silt loading for arterial, commercial-residential and highways are 5.58, 2.46 and 3.46 g/m^2, respectively. The overall silt loading is 3.69 g/m^2. The PM_{10} emission factor for dry weather was calculated to be 11.74 g/VKT. However, the emission factor reduced to 10.89 g/VKT when 105 rainy days per annum was considered.

PM_{10} control efficiency of dry and wet sweeping of the streets were conducted in three road types; arterial, commercial-residential and highways. The control efficiency of dry sweeping varied from 31-74 % for different road types. For wet sweeping, the efficiency varied from 69-86%.

The annual costs of dry and wet sweeping using hand brooms were BDT 10.37 crore (USD 1.30 m) and BDT 18.69 crore (USD 2.34 m) per square km, respectively. The cost effectiveness of PM_{10} emission reduction were BDT 1,65,700/metric ton (USD 2071/metric ton) and BDT 2,42,500/metric ton (USD 3031/metric ton) for dry and wet sweeping with hand brooms, respectively.

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List of Abbreviations

BUET	Bangladesh University of Engineering &Technology
CASE	Clean Air and Sustainable Environment
ChE	Chemical Engineering
DCC	Dhaka City Corporations
GOB	Government of Bangladesh
IDA	International Development Association
JICA	Japan International Cooperation Agency
NILU	Norwegian Institute for Air Research
PM	Particulate Matter
UGC	University Grant Commission
US EPA	United States Environmental Protection Agency
WB	World Bank

1. Introduction

The Clean Air and Sustainable Environment (CASE) project is being implemented in Bangladesh with support from IDA/world Bank. Task-4 of S-13 (BAPS) part of the CASE Project involves control of road dust. The most severe exceedance of air quality standards in Bangladesh is due to PM_{10} and $PM_{2.5}$ concentrations. The annual average particulate concentration in Dhaka city strongly varies from the dry winter season to the wet rainy season. The annual average PM_{10} concentrations varies from area to area in Dhaka. Typical annual average of fine particles measured in the city centre was 64 $\mu g/m^3$ (Begum et. al 2014). Other studies have reported annual average concentrations of PM_{10} at about 144 $\mu g/m^3$. Model estimated PM_{10} concentrations was reported at about 300 $\mu g/m^3$ (Randall et.al 2014). About 17 % of the fine particles was estimated to originate from the transport sector (from vehicles and road dust) while about 60 % of PM_{10}, was due to emissions from brick kilns in Dhaka (Begum et. al 2014). Also soil dust and biomass burning contribute to the PM concentrations in Dhaka. This means even if all non-dust PM_{10} sources were controlled with 100% efficiency, Dhaka would still exceed the 50 $\mu g/m^3$ annual air quality standard. The CASE project intends to conduct a cost-benefit analysis on dust control measures for Dhaka city during the dry months when PM_{10} level are the highest, rainfall is limited and general air quality is very poor due to the absence of the washing out effect of the precipitation.

2. Work Plan for Task-4

Field measurement survey program was conducted in Dhaka to measure paved road dust silt loading using US EPA AP-42 Method 13.2.1; Appendices C-1 and C-2. Locations for the measurements include highways, arterials and commercial-residential segments. Traffic counting survey was also conducted at the same segments. The detailed plans for the field investigations was presented in an Inception report (Ahmed et. al 2012). Dust samples were analysed in the laboratory following ASTM C-136 standard protocol. Silt is defined as the material that passes a 200 mesh screen using the ASTM C-136 analysis method. During dust collection with vacuum cleaner, dust loading within one meter of the roadside curb was avoided, as suggested in US EPA AP-42.Sieve analysis (ASTM C-136), and moisture analysis of the dust collected were performed as per US EPA AP-42. 8-hours average PM_{10} data were collected at each of the road segments through ambient air sampling with Anderson HV PM_{10} sampler (Anderson Instruments INC., USA; model 1200) which is US EPA approved (Federal reference method no: REPS-1287-063). This consists of a size selective inlet for PM_{10} cut off, an impactor, a filter holder, a flow control system and a pump.

Initially, 30 locations for dust collection, traffic survey and ambient PM_{10} measurements were planned (Highway-6; arterials-10; commercial-residential-14). Based on the work plan, ChE-BUET team completed sampling at all these 30 locations between April and May 2014. The locations and corresponding sampling dates are shown in Table 1. The sampling locations in Google map are shown in Figure 1. The photographs taken during sampling, ambient PM_{10} measurements, and traffic survey are attached as Appendix A.

Table 1:Locations and sampling dates

Location Code	Location	Sampling Date
Arterial:		
A1	Shamoly Ring Road	23/04/2014
A2	Darussalam Road	6/05/2014
A3	Mazar road	7/05/2014
A4	Atishdipankar Road	20/04/2014
A5	ProgotiSharani	7/04/2014
A6	Demra	9/05/2014
A7	Dhaka-Narayangonj Road	10/05/2014
A8	Ashulia EPZ Road	13/05/2014
A9	Tongi to Kaliganj Road	6/04/2014
A10	Hatkhola Road	19/04/2014
Commercial-residential:		
CR1	Palashi	12/04/2014
CR2	Secretariat Road	13/04/2014
CR3	Dhanmondi Road 16 (Old 27)	15/05/2014
CR4	Mirpur Road (New Market)	10/04/2014
CR5	Shatmasjid Road (Dhanmondi-2)	11/04/2014
CR6	Begum RokeyaSarani (Mirpur-10)	12/05/2014
CR7	Kazi Nazrul Islam Avenue (TelejogajogBhaban)	16/04/2014
CR8	Kazi Nazrul Islam Avenue (Karwan Bazar)	17/04/2014
CR9	Tejgoan-Gulshan Link Road	24/04/2014
CR10	Gulshan Avenue	18/05/2014
CR11	Toyenbee Road	15/04/2014
CR12	Madani Avenue	19/05/2014
CR13	RabindraSarani	5/04/2014
CR14	Kazi Nazrul Islam Avenue (Dhaka Cantonment)	17/05/2014
Highways:		
H1	Dhaka-Aricha (Savar)	21/04/2014
H2	Dhaka-Jamuna Bridge Highway (Mouchak)	26/04/2014
H3	Dhaka-Mymensingh Highway (Tongi Board Bazar)	22/04/2014
H4	Dhaka-Sylhet Highway (Rupgonj)	20/05/2014

H5	Dhaka-Chittagong Highway (Kanchpur)	21/05/2014
H6	Dhaka-Khulna Highway (Keranigonj)	16/05/2014

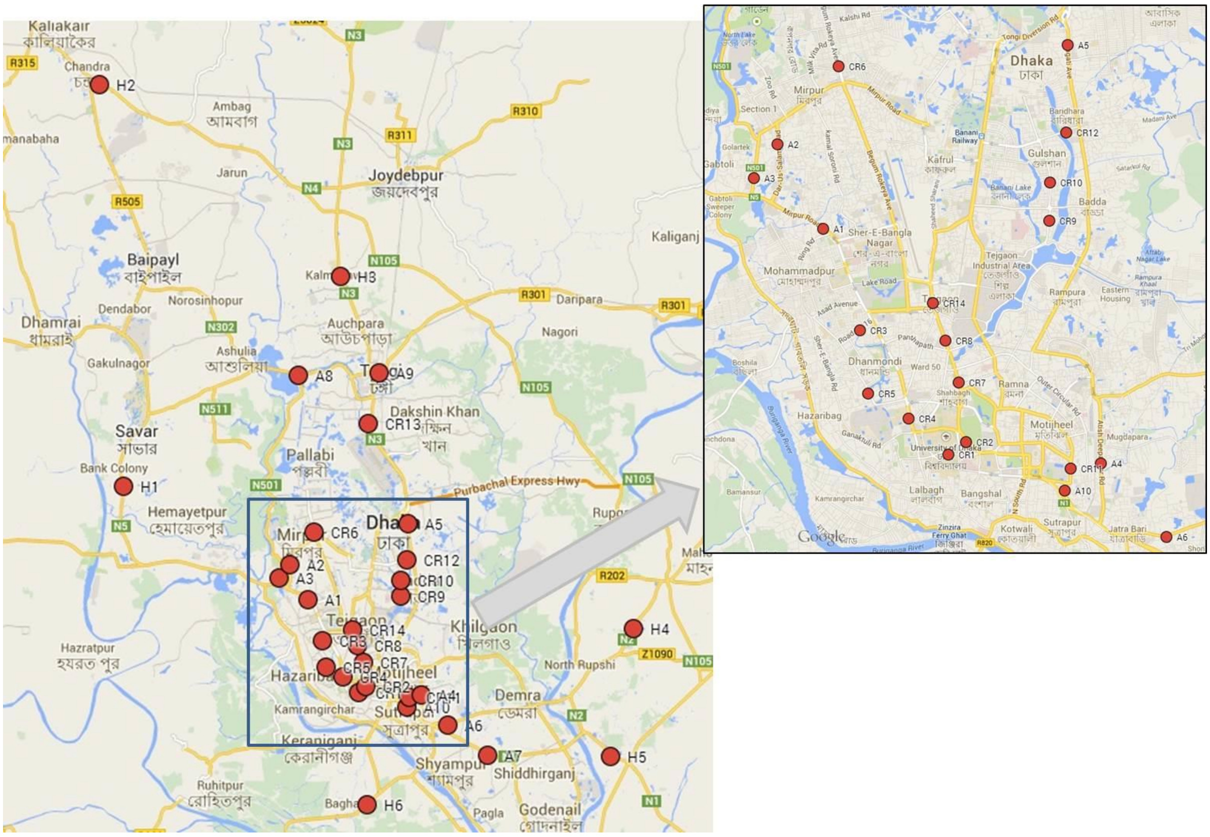

Figure 1: Sampling locations (A1-A10: arterial; CR1-CR14: Commercial residential road; H1-H6: Highways)

3. Results

3.1 Traffic Survey Results

Traffic survey was carried out at 30 locations (10 arterial, 14 commercial-residential and 6 highways). Effective survey time was 50 minutes followed by a 10 minute break per hour. The survey was carried out round the clock. Variations in traffic flows and vehicle mix from day to day was taken into account in the design. The survey results were converted to hourly averages. The 24 hours average value is shown in Table 2. Survey was carried out on the same date as the silt sampling and the PM_{10} measurements.

Table 2: Daily average traffic data at 30 locations

	Car/Jeep/ Microbus/ Taxicab	CNG driven 3-wheeler	Motor Cycle	Tempo /Human Hauler	Large Bus	Small Bus	Large Truck	Small Truck	Total
A1	19033	9056	5305	2971	11492	10136	5480	3925	67398
A2	13674	3868	2388	2886	7900	9472	4526	1581	46295
A3	9082	5316	3625	4778	8623	6082	5706	4989	48201
A4	7480	4407	2967	1761	7356	5790	4090	2548	36399
A5	12477	6792	4174	0	5056	5838	3294	3259	40890
A6	6688	4910	3154	9457	7219	5899	5496	3884	46707
A7	9392	4964	3242	2900	14000	6393	11326	7569	59786
A8	14712	3964	3147	1636	11760	7219	11587	10300	64325
A9	4552	2340	2086	3801	1902	877	3382	2466	21406
A10	14259	5083	4262	354	3223	5203	1881	1359	35624
CR1	4700	1863	1658	94	192	69	80	156	8812
CR2	9816	5715	4929	0	171	123	96	291	21141
CR3	15004	6482	4490	3088	596	777	601	796	31834
CR4	14643	3828	4743	4353	2541	5124	567	1188	36987
CR5	10000	3612	3067	2775	2296	1263	412	552	23977
CR6	12733	5300	4594	0	3537	6391	2535	2982	38072
CR7	32937	17522	11371	0	11468	12415	5576	7881	99170
CR8	26810	13742	8412	0	10222	10255	3058	3898	76397
CR9	26742	5355	4332	0	205	199	368	536	37737
CR10	33284	6788	5768	0	331	849	264	672	47956
CR11	15662	6931	4341	0	5481	6895	1981	1796	43087
CR12	20522	4101	2442	850	284	223	288	308	29018
CR13	19778	11000	7638	0	9394	10238	7045	7048	72141
CR14	30307	13231	10155	0	10335	11320	4561	4065	83974
H1	8067	4173	2566	1599	13375	8761	8737	5540	52818

H2	6856	3925	3206	4233	9464	7382	11349	4032	50447
H3	7233	2362	1482	676	8980	6480	5362	4663	37238
H4	9662	4182	2046	4581	12532	10792	9240	8343	61378
H5	8691	8354	3964	9538	15976	8481	14149	6686	75839
H6	5137	8000	1905	2108	8486	3820	4731	2650	36837
	429933	187166	127459	64439	204397	174766	137768	105963	1431891

A: Arterial; CR: Commercial-residential; H: Highway

3.2 Paved Road Silt Survey

Collection of road surface silt loadings at 30 locations on arterial, commercial-residential and highways were carried out in April and May, 2014. Sampling was done only during dry days. Dry weather was required 2 days prior to (and during) sampling. Sampling and analytical protocols were taken from USEPA AP-42, Section 13.2.1, Appendix C-1 and C-2. Silt is defined as the material that passes a 200-mesh screen using the ASTM C-136 analysis method. Dust loading near the roadside curb and the divider was avoided, as per US EPA AP-42 sampling protocol. The road dust sampling was done using a vacuum cleaner installed with high performance particulate air (HEPA) filter. Test results, including the surface area, silt loading and the ambient PM_{10} concentration, for 30 locations of three different types of roadways are shown in Table 3.

Table 3: Silt loading and ambient PM_{10} concentration at 30 locations

Location code	Sampling area (m^2)	Road surface silt loading (g/m^2)	Number of Vehicles (Daily average)	Ambient PM_{10} ($\mu g/Nm^3$)
A1	14.41	11.53	67398	381
A2	21.38	1.68	46295	139
A3	34.86	1.98	48201	147
A4	30.67	0.94	36399	235
A5	13.94	6.69	40890	415
A6	13.94	4.11	46707	229
A7	20.91	1.73	59786	236
A8	9.30	7.32	64325	188
A9	5.58	16.75	21406	326
A10	13.01	6.21	35624	304
CR1	55.77	2.08	8812	125
CR2	27.89	2.38	21141	184
CR3	27.89	5.74	31834	159
CR4	27.89	6.14	36987	287
CR5	27.89	6.43	23977	281
CR6	27.89	1.32	38072	149
CR7	44.62	0.44	99170	204

CR8	62.74	0.16	76397	275
CR9	41.83	1.55	37737	337
CR10	43.69	2.72	47956	247
CR11	23.24	3.09	43087	261
CR12	27.89	2.83	29018	133
CR13	11.15	5.01	72141	231
CR14	46.48	1.10	83974	140
H1	13.01	3.49	52818	357
H2	18.59	6.52	50447	165
H3	11.15	10.80	37238	523
H4	55.77	1.26	61378	126
H5	83.66	0.82	75839	67
H6	83.66	0.87	36837	205

Sampling areas were varied from one road segment to the other. For visually cleaner roads larger surface area for dust collection was selected to ensure at least 200 g of dust sample was collected (as per USEPA AP-42 sample specification for paved roads). Three samples were taken from each road segment. The distance between the consecutive sampling locations was chosen according to Figure C.1-3 (Appendix B of the current report) of Appendix C.1, USEPA AP-42. All the road segments sampled in this study were less than 1.5 mile. Therefore, method for road length less than 1.5 mile (shown in Figure C.1-3) was applied for selection of sampling sites.

The ambient PM_{10} concentrations could not be directly linked with silt loading as the ambiance of the sampling locations varies a great deal from one to another. The observed daily average number of vehicles also varied over a wide range. Roadside PM_{10} does not include only the re-suspended road dust of this size range, but also include PM_{10} from vehicle emission. PM emission from vehicle also depends on its age and speed. Contributions from other off-road activities such as construction work, operation of small scale generators in houses and commercial places during power cut etc., also influence the ambient PM_{10} concentration. Therefore the net contribution of silt loading to the ambient PM_{10} concentration could not be established.

3.3 Weighted Average Gross Vehicle Weight

Gross weight of the various types of vehicles were collected as per the types and models of the vehicles observed on the road during the survey. The weighted average of the vehicle weight was determined from the fraction and gross weight of each type of vehicle. The weighted average was calculated to be 5.57 metric tonnes, as shown in Table 4.

Table 4: Calculation of average vehicle weight

Types	Daily average no.	Fraction	Average Gross weight (Metric Tonnes)	Fraction x Gross weight (Metric Tonnes)
Car/Jeep/Microbus/ Taxicab	429933	0.30	1.72	0.52
CNG	187166	0.13	0.368	0.05
Motor Cycle	127459	0.09	0.195	0.02
Tempo /Human Hauler	64439	0.05	1.4	0.06
Large Bus	204397	0.14	16.2	2.31
Small Bus	174766	0.12	5	0.61
Large Truck	137768	0.10	16	1.54
Small Truck	105963	0.07	6.25	0.46
	Daily Total =1431891		Weighted average vehicle weight = 5.57 M. tonnes	

Table 5: Weighted silt loading for road types (Appendix C shows further breakdown of the calculation)

Road types	Silt loading (g/m^2)	Weighted Individual(g/m^2)	Overall weighted (g/m^2)
A1	11.53	5.58	3.69
A2	1.68		
A3	1.98		
A4	0.94		
A5	6.69		
A6	4.11		
A7	1.73		
A8	7.32		
A9	16.75		
A10	6.21		
CR1	2.08	2.46	
CR2	2.38		
CR3	5.74		
CR4	6.14		
CR5	6.43		
CR6	1.32		
CR7	0.44		
CR8	0.16		
CR9	1.55		
CR10	2.72		
CR11	3.09		
CR12	2.83		
CR13	5.01		
CR14	1.10		
H1	3.49	3.46	

H2	6.52		
H3	10.80		
H4	1.26		
H5	0.82		
H6	0.87		

3.4 PM_{10} Emission factor from road dust in Dhaka

Weighted silt loading was calculated for each type of road. Silt loading for the arterial type was 5.58 g/m^2 and greater than both commercial-residential roads and highways. Highway slit loading was 3.46 g/m^2. Among these three types of roads, commercial-residential road segments had least slit loading, 2.46 g/m^2. However, the overall weighted silt loading was found to be 3.69 g/m^2, which includes contribution from all 30 locations and hence used for the calculation of the PM_{10} emission factor, from road dust, for Dhaka.

For emission factor calculation, a particle size multiplier for PM_{10} of 0.62 g/VKT was used as per USEPA AP-42. The emission factor, without considering precipitation, was calculated to be 11.74 g/VKT. According to the Bangladesh Meteorological Department, yearly number of normal rainy days in Dhaka is 105. Considering this the emission factor is 10.89 g/VKT.

4. Preventive and mitigative measures

4.1 Trackout control

There are many construction sites in and around Dhaka city. At the same time there are many unpaved access roads near the city. Therefore, trackout is responsible for heavy silt loading on the roads of Dhaka city. Trackout can be defined as (City of Tempe, 2008):

- dirt, mud or other debris tracked onto a paved public road by a vehicle leaving a construction site,
- dirt and mud adhering to the exterior or undercarriage of a vehicle leaving a construction site that falls onto a paved public roadway,
- traces of dirt or other bulk material that spill onto a paved public road from an improperly loaded haul vehicle leaving a construction site, and
- dirt and mud leaving an unpaved access road going onto a paved public roadway.

Minimizing trackout is a preventive measure to reduce silt loading on the paved roads. Trackout can be controlled:

- by restricting vehicle use to properly designated exit points from the construction sites.

- by installing trackout pads at designated exit points. Trackout pads usually consist of gravel, rock, or crushed rock one inch or more in diameter.
- by using trackout plates (Figure 2). Trackout plates are usually steel base plate with ribs and effective in removal of dirt and debris that is typically carried out on vehicle wheels
- by paving the surface. The paved surface must extend from the point of intersection with a paved public roadway at least 100 feet back onto the site and have a width of at least twenty feet.
- For hauling operations
    - preventing spills from holes and openings
    - covering the load with a suitable closure

Figure 2: Trackout plate

Measures to control or minimize trackout are non-existent in and around Dhaka city. Therefore, it was not possible to measure the effectiveness of trackout control on silt loading and particulate emission from road dust. However, other studies in developed countries showed that implementing trackout control measures can reduce 40-80% PM_{10} emission (Countess Environment, 2006). For Dhaka city, the reduction can be assumed to be on the upper side, because of the heavy contribution of trackout in silt loading.

4.2 Dry and wet sweeping

Regular street sweeping on paved roads removes sand and dirt on roads, reducing the amount of particulate matter released into the air. Both city corporations in Dhaka (North and South) have dedicated street sweepers. Though these sweepers carry out dry sweeping every morning, they only engage themselves on removing rags, leaves, papers, etc. from the roads.

Lack of proper monitoring of the sweeping activities has led to ineffective cleaning of the roads in Dhaka City.

The ChE BUET team have performed PM_{10} control efficiency by effective hand sweeping (dry and wet) of the streets. There were three road types: highway (H6, Dhaka-Khulna Highway (Keranigonj)), arterial (A2, Darussalam Road) and commercial-residential (CR1, Palashi), where the removal efficiency of dry sweeping and wet sweeping with hand broom applied. The cost effectiveness of the control techniques (dry and wet sweeping with hand broom) was also determined for CR1.

The studied road segments were less than 1.5 mile in length. Hence, the US EPA AP-42 sampling protocol was followed accordingly (Appendix B, Figure 10) for selecting sampling locations. For each of the locations, initial road dust was sampled using high performance vacuum cleaner from the slits marked as 1, in Figure 3. Slits marked as 2 were swept dry with hand broom effectively towards road shoulders. After dry sweeping, residual dust on the road surface of the slits (Slit-2) was sampled using another high performance vacuum cleaner. Silts marked as 3 were watered with a hand shower and swept wet with hand broom effectively towards the rod shoulders. After wet sweeping, the slits were restricted for vehicle entry and kept undisturbed for drying. After drying, residual dust on the slit area was sampled with third high performance vacuum cleaner.

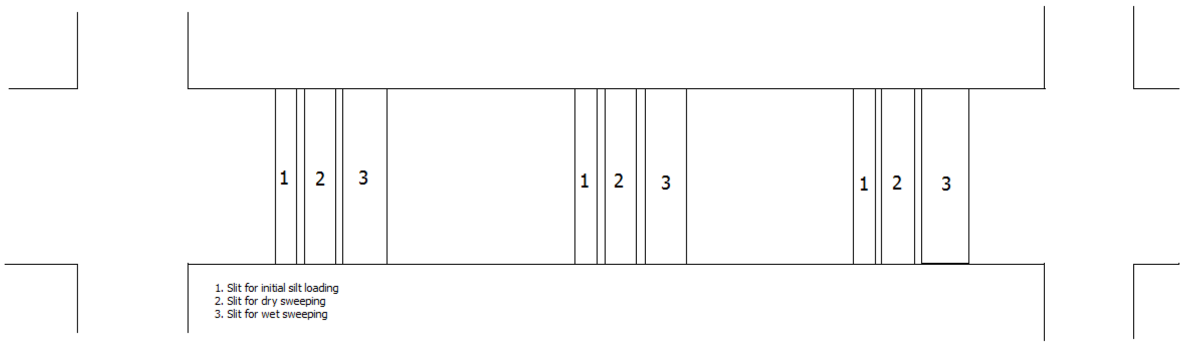

Figure 3: Slit pattern applied for measuring initial silt loading and removal efficiency of dry and wet sweeping technique

For PM_{10} removal efficiency of dry and wet sweeping technique, the aforementioned steps were repeated 3 times for each of the road type at an interval of seven days. The first sampling date was on May 01, 2015, second one was on May 08, 2015 and the final one was on May 15, 2015. PM_{10} control efficiencies of the applied techniques are shown in Table 6. Sample calculation for PM_{10} control efficiency is shown in Appendix D.

Table 6: PM_{10} control efficiencies of mitigative measures

Road	PM_{10} control efficiency (%)	
	Dry sweeping	Wet sweeping
A2	74±6	86±3
CR1	69±8	85±4
H6	31±9	69±11

The PM_{10} control efficiency for A2 and CR1 was found to be higher than the literature value (4-26%) (Countess Environment, 2006) for dry sweeping. These reported values were obtained from Western Regional Air Partnership (WRAP) region of USA. The dust loadings in the streets of Dhaka are much heavier. The higher removal efficiency is due to the fact that silt can be easily swept out with the larger dust particles during dry sweeping. Better removal efficiency by wet sweeping, compared to the dry sweeping, can be attributed to the agglomeration of dust particles in presence of moisture.

4.3 Cost estimation and effectiveness

For cost effectiveness assessment of the applied techniques, commercial-residential road type was selected (CR1, Palashi). The road section had a length of 625 m and a width of 15 m. Initial silt loading of both sides of the road section was determined as per US EPA AP-42. One side of this road section was swept dry effectively with hand broom towards the road shoulder and the collected dust was put into the black polyethylene bag which was further collected by the Dhaka City Corporation for disposal. Another side of the road section was watered by a hired water tanker (from Roads and Highways Department) and swept wet by hand broom towards the road shoulder. The accumulated wet dust was then collected and filled in black polyethylene bag which was further collected by the Dhaka City Corporation for disposal. D-0 is the Figure 4 marks the location of sampling for initial silt loading on the day of cleaning prior to applying the control techniques. Further silt loading measurements were performed on the same road segment after 2, 3, 4 and 5 days of applying control measures and shown as D-2, D-3, D-4 and D-5 in the Figure 4, respectively. These measurements were performed to determine the time required to reach a silt loading equal or more than the initial silt loading, measured on D-0 locations. It was found that the silt loading value reached to its initial value after 3.5 and 5 days for the dry and wet sweeping, respectively. Therefore, the recommended sweeping frequency for either techniques should be twice a week.

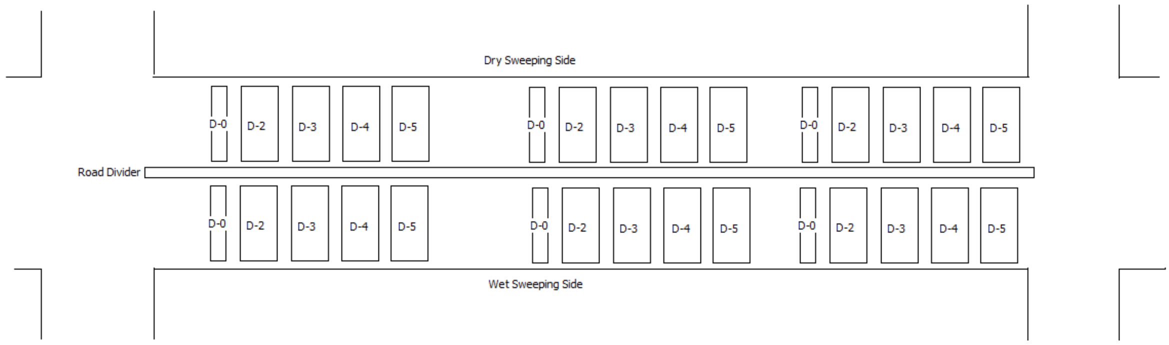

Figure 4: Slit pattern applied for measuring initial silt loading and time required to reach initial silt loading for dry and wet sweeping technique

For cost effectiveness calculations, both uncontrolled and controlled PM_{10} emissions were calculated using the predictive emission factor equation from US EPA AP-42 and VKT per day for the experimental road section. For dry sweeping the estimated cost is 10.37 crore/year/square km (USD 1.30m). The cost is BDT 18.69 crore/year/square km (USD 2.34m) for wet sweeping. The cost effectiveness for PM_{10} emissions for dry sweeping is BDT 1,65,700/metric ton (USD 2071/metric ton). For wet sweeping, it is BDT 2,42,500/metric ton (USD 3031/metric ton). The cost effectiveness calculations include cost of labor and equipment, capital and operational costs of trucks for water spraying and disposal of collected dust to the landfilling site. The breakdown of the calculations is shown in Appendix E.

5. Conclusion

Silt loading measurements were carried out at 30 locations in Dhaka. The paved dust sampling areas were determined visually to conform to the minimum sample requirement of USEAP AP-42. Simultaneously, traffic survey and ambient PM_{10} measurements were also carried out at each sampling location. Out of these 30 locations, 10, 14 and 6 were arterial, commercial-residential and highways, respectively.

Road silt loading varied from a low of 0.16 g/m^2 (CR9) to a high of 16.75 (A9). The type of the roads was not the only determining factor for silt loading, as a great deal of variation was observed within each sub-class (e.g. arterial, commercial-residential, highways). The ambience and anthropogenic activities in the surrounding area affected the silt loading to a considerable extent. Hence, the measured ambient PM_{10} concentrations did not follow trend similar to the silt loading. Also, the fractional contribution of silt loading to the ambient PM_{10} could not be determined.

The individual weighted silt loading for arterial, commercial-residential and highways were calculated to be 5.58, 2.46 and 3.46 g/m^2, respectively. The overall silt loading for Dhaka was 3.69 g/m^2.

All the measurements were done in dry conditions. Assuming this condition, the emission factor for Dhaka is 11.74 g/VKT. On the other hand, considering 105 days of rain per year, as per Bangladesh Meteorological Department, the corrected emission factor is 10.89 g/VKT.

PM_{10} control efficiency of dry and wet sweeping of the streets were conducted in three road types, arterial, commercial-residential and highways. The control efficiency of dry sweeping varied from 31-74 % for different road types. For wet sweeping, the efficiency varied from 69-86%.

The annual costs of dry and wet sweeping using hand brooms were BDT 10.37 crore (USD 1.30 m) and BDT 18.69 crore (USD 2.34 m) per square km, respectively. The cost effectiveness of PM_{10} emission reduction were BDT 1,65,700/metric ton (USD 2071/metric ton) and BDT 2,42,500/metric ton (USD 3031/metric ton) for dry and wet sweeping with hand brooms, respectively.

Dhaka City Corporations (North and South) already have staffs for conducting road sweeping. However, lack of monitoring and negligence on the sweeper's part made the road cleaning job ineffective. If properly monitored and supervised, both City Corporations can undertake the road cleaning work effectively.

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Appendix A: Photographs - road dust collection, ambient PM_{10} measurement, and traffic survey

Figure 5: Road surface silt loading survey

Figure 6: Marking on the road surface for road dust collection

Figure 7: Collecting road dust with high efficiency vacuum cleaner

Figure 8: Traffic survey and ambient PM_{10} sampling

Figure 9: Traffic survey and ambient PM_{10} sampling

Appendix B: Sampling Locations for Paved Roads (as per US EPA AP-42)

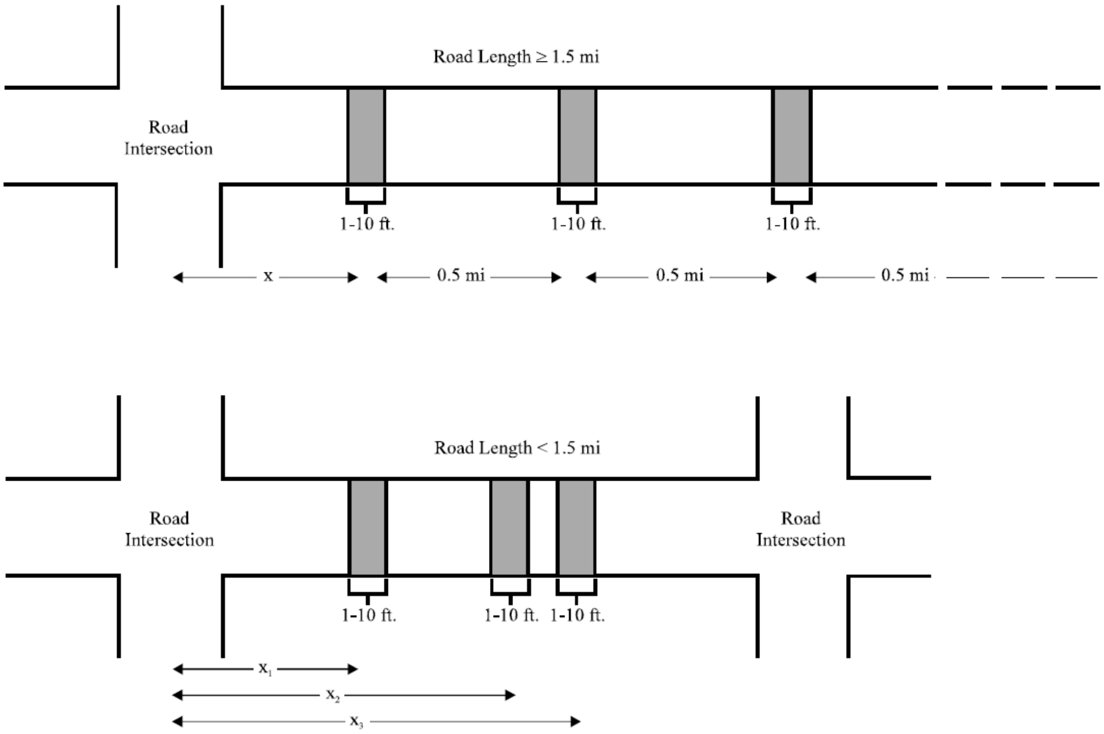

Figure 10: Sampling location for paved roads

Appendix C: Sample Calculation for Weighted silt loading

	Sampling Locations	Sampling area (m^2)	Slit loading (sL) (g/m^2)	Average Daily Traffic										Fraction*sL (g/m^2)	Weighted sL for different Road segments	Weighted sL
				Car/Jeep/ Microbus/ Taxicab	CNG	Motor Cycle	Tempo/ Human Hauler	Large Bus	Small Bus	Large Truck	Small Truck	Total	Fraction			
A1	Shamoly Ring Road (Intersection)	14.41	11.53	19033	9056	5305	2971	11492	10136	5480	3925	67398	0.05	0.543		
A2	Darussalam Road	21.38	1.68	13674	3868	2388	2886	7900	9472	4526	1581	46295	0.03	0.054		
A3	Mazar road	34.86	1.98	9082	5316	3625	4778	8623	6082	5706	4989	48201	0.03	0.066		
A4	Atishdipankar Road	30.67	0.94	7480	4407	2967	1761	7356	5790	4090	2548	36399	0.03	0.024		
A5	ProgotiSharani	13.94	6.69	12477	6792	4174	0	5056	5838	3294	3259	40890	0.03	0.191		
A6	Demra	13.94	4.11	6688	4910	3154	9457	7219	5899	5496	3884	46707	0.03	0.134	5.58	
A7	Dhaka Narayangonj Road	20.91	1.73	9392	4964	3242	2900	14000	6393	11326	7569	59786	0.04	0.072		
A8	Ashulia EPZ Road	9.30	7.32	14712	3964	3147	1636	11760	7219	11587	10300	64325	0.04	0.329		
A9	Kali Gonj (Tongi Road)	5.58	16.75	4552	2340	2086	3801	1902	877	3382	2466	21406	0.01	0.250		
A10	Hatkhola Road	13.01	6.21	14259	5083	4262	354	3223	5203	1881	1359	35624	0.02	0.155		
CR1	Palashi	55.77	2.08	4700	1863	1658	94	192	69	80	156	8812	0.01	0.013		
CR2	Atomic Energy Centre (DU)	27.89	2.38	9816	5715	4929	0	171	123	96	291	21141	0.01	0.035		
CR3	Dhanmondi 27	27.89	5.74	15004	6482	4490	3088	596	777	601	796	31834	0.02	0.127		
CR4	New Market	27.89	6.14	14643	3828	4743	4353	2541	5124	567	1188	36987	0.03	0.159		
CR5	Dhanmondi-2(Shatmasjid Road)	27.89	6.43	10000	3612	3067	2775	2296	1263	412	552	23977	0.02	0.108		
CR6	Mirpur-10	27.89	1.32	12733	5300	4594	0	3537	6391	2535	2982	38072	0.03	0.035		
CR7	Hotel Sheraton Intersection	44.62	0.44	32937	17522	11371	0	11468	12415	5576	7881	99170	0.07	0.030	2.46	
CR8	Hotel Sonargoan Intersection	62.74	0.16	26810	13742	8412	0	10222	10255	3058	3898	76397	0.05	0.009		
CR9	Gulshan-1	41.83	1.55	26742	5355	4332	0	205	199	368	536	37737	0.03	0.041		
CR10	Gulshan-2	43.69	2.72	33284	6788	5768	0	331	849	264	672	47956	0.03	0.091		
CR11	Motijheel (Bangladesh Bank)	23.24	3.09	15662	6931	4341	0	5481	6895	1981	1796	43087	0.03	0.093		
CR12	Baridhara (Canada	27.89	2.83	20522	4101	2442	850	284	223	288	308	29018	0.02	0.057		3.69

	Embassy)														
CR13	Uttara (RabindraSarani Intersection)	11.15	5.01	19778	11000	7638	0	9394	10238	7045	7048	72141	0.05	0.252	
CR14	Farmgate (Air Port Road) Cantonment	46.48	1.10	30307	13231	10155	0	10335	11320	4561	4065	83974	0.06	0.065	
H1	Dhaka-Aricha (Savar)	13.01	3.49	8067	4173	2566	1599	13375	8761	8737	5540	52818	0.04	0.129	
H2	Dhaka Jamuna Bridge Highway (Mouchak)	18.59	6.52	6856	3925	3206	4233	9464	7382	11349	4032	50447	0.04	0.230	
H3	Tongi (Board Bazar)	11.15	10.80	7233	2362	1482	676	8980	6480	5362	4663	37238	0.03	0.281	
H4	Dhaka Sylhet Highway (Rupgonj)	55.77	1.26	9662	4182	2046	4581	12532	10792	9240	8343	61378	0.04	0.054	3.46
H5	Dhaka Comilla CTG Highway After Kanchpur	83.66	0.82	8691	8354	3964	9538	15976	8481	14149	6686	75839	0.05	0.043	
H6	Dhaka Khulna Highway (Keranigonj)	83.66	0.87	5137	8000	1905	2108	8486	3820	4731	2650	36837	0.03	0.022	

Weighted average car weight (From Table 4), W = 5.57 mt

PM_{10} multiplier (From US EPA AP-42), k = 0.62 g/VKT

Road surface silt loading (From Table 5), sL=3.69 g/m^2

Emission Factor, $E = k(sL)^{0.91}(W)^{1.02}$= 11.74 g/VKT

Emission Factor considering precipitation on daily basis, $E_{ext} = [k(sL)^{0.91}(W)^{1.02}](1 - P/4N)$= 10.89 g/VKT
where, N=365 for a year and P= number of wet days with = 105 (according to Bangladesh Meteorological Department)

Rainfall data on hourly basis is currently not available from BMD. They provide meteorological data on 3 hourly basis.

Appendix D: Sample Calculation for PM_{10} control efficiency

Sampling location: CR1, Palashi

Calculated silt loading, sL = 1.31 (uncontrolled)
0.35 (dry sweeping)
0.15 (wet sweeping)

PM_{10} multiplier (From US EPA AP-42), k = 0.62 g/VKT

Uncontrolled Emission Factor considering precipitation on daily basis, $E_{ext} = [k(sL)^{0.91}(W)^{1.02}](1 - P/4N)$= 4.23 g/VKT

Emission factor after dry sweeping, $E_{ext,dry} = [k(sL)^{0.91}(W)^{1.02}](1 - P/4N)$= 1.27 g/VKT

Emission factor after wet sweeping, $E_{ext,wet} = [k(sL)^{0.91}(W)^{1.02}](1 - P/4N)$= 0.58 g/VKT

where, N=365 for a year and P= number of wet days with = 105 (according to Bangladesh Meteorological Department)

Uncontrolled/controlled PM_{10} emission = emission factor × VKT/day × 365

Control efficiency = 1- controlled emission / uncontrolled emission = 1- controlled emission factor/uncontrolled emission factor

Control efficiency for dry sweeping = 1- 1.27/4.23= 70%

Control efficiency for wet sweeping = 1- 0.58/4.23 = 86%

Appendix E: Cost estimation and effectiveness

Road segment: CR1, Palashi
Road length: 625 m
Road width: 7.62 m
Road area = 625 × 7.62 = 4762.5 m^2 = 4.76×10^{-3} sq. km

6 sweepers could effectively clean this road segment in 3 hours totalling to 18 man-hours
Assuming BDT 100/man-hour and 2 cycles per week, the annual labor cost = 18 × 100 × 104 cycles/year = BDT 1,87,200

6 PE bags/cycle are required to collect the dust. Each bag costs BDT 25. Total annual cost = 6 × 25 × 104 = BDT 15,600

6 brooms (to be replaced every month), each costs BDT 120. Total annual cost = 6 ×120 × 12 = BDT 8,640

1 shovel (to be replaced every six months), costing BDT 600. Total annual cost = 600 × 2 = BDT 1,200

1 cart (to be replaced annually), costing BDT 3000. Annual maintenance cost for the cart is BDT 500. Total annual cost = BDT 3,500

1 truck for garbage collection and disposal:

Capital cost	BDT 15,00,000
Lifetime	20 years
Salvage value	BDT 1,50,000
Annual maintenance cost	BDT 40,000

Each truck is assumed to have a capacity of 3 metric ton and will be able to serve two such sites for garbage collection and disposal
To serve each site estimated diesel cost/cycle BDT 1,000. Total annual cost = 1000 × 104 = BDT 1,04,000
Salary of the driver and the assistant BDT 30,000/month. Total annual cost = 30,000 ×12/3 = BDT 1,20,000 (assuming the same driver will serve 6×2 locations every week, including twice for this site)

Total annual cost of operation of the garbage truck for the sampling site = 0.5 × [(Capital cost-salvage value)/lifetime + annual maintenance cost] + diesel cost + salary = BDT 2,77,750

Total annual cost for dry sweeping the site = BDT 4,93,800

Total annual cost for dry sweeping per square km = 4,93,500/4.76×10^{-3}=BDT 10,37,03,937

For wet sweeping, cost of water and the truckused to water spraying should be added to the cost of dry sweeping.

For this site, 6000 litres of water is required to wet the road segment. The cost of water is BDT 600/cycle. Total annual cost = 600 × 104 = BDT 62,400

For the water truck

Capital cost	BDT 40,00,000
Lifetime	20 years
Salvage value	BDT 4,00,000
Annual maintenance cost	BDT 1,00,000

Each truck is assumed to have a capacity of 10 metric ton. Therefore to normalize the cost for the site a ratio of 6000/10000 will be used.

To serve each site estimated diesel cost/cycle BDT 1,000. Total annual cost = 1000 × 104 = BDT 1,04,000

Salary of the driver and the assistant BDT 30,000/month. Total annual cost = 30,000 × 6000/ 10,000 ×12/3.5 = BDT 61,714 (assuming the same driver will serve other locations during the week, including twice for this site)

Total annual cost of operation of the garbage truck for the sampling site = 6000/10000 × [(Capital cost-salvage value)/lifetime + annual maintenance cost] + diesel cost + salary + water cost = BDT3,96,114

Adding this cost to the dry sweeping cost, total cost of wet sweeping for the site = BDT 8,90,000

Total annual cost for wet sweeping per square km = 8,90,000/4.76×10^{-3} =BDT 18,68,77,540

The vehicle count for the location CR1 was 8812/day (Appendix C). The measurements were conducted on the half width of the road. Therefore, vehicles travelling through the section of the road was 4406/day (8812/2). Therefore, calculated VKT for the section = 4406 × 0.625 = 2753.75 VKT/day.

Uncontrolled PM_{10} emission = uncontrolled emission factor × VKT/day × 365/1×10^6 = 4.25 metric ton

Controlled PM_{10} emission (dry sweeping) = Controlled emission factor (dry sweeping) × VKT/day × 365/1×10^6 = 1.27 metric ton

Cost effectiveness (dry sweeping) = annual cost/(uncontrolled emission – controlled emission) = 4,93,800/(4.25-1.27) = BDT 1,65,700/metric ton (USD 2071/metric ton)

Controlled PM_{10} emission (wet sweeping) = Controlled emission factor (wet sweeping) × VKT/day × 365/1×10^6 = 0.59 metric ton

Cost effectiveness (wet sweeping) = annual cost/(uncontrolled emission – controlled emission) = 8,90,000/(4.25-0.58) = BDT 2,42,500/metric ton (USD 3031/metric ton)

Appendix F: Photographs – PM_{10} control efficiency and cost effectiveness measurements

Figure 11. Dry sweeping, wet sweeping, dust collection activity on Dhaka Khulna Highway (Keranigonj) for PM10 control efficiency determination

Figure 12. Dry sweeping, wet sweeping, dust collection activity on Road segment: CR1, Palashi for PM10 control efficiency determination

Figure 13. Dry sweeping, wet sweeping, dust collection activity on Road segment: A2, Darussalam for PM10 control efficiency determination

Figure 14. Dry sweeping, wet sweeping, dust collection activity on Road segment: CR1, Palashi for cost effectiveness assessment

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ABSTRACT
Field work was undertaken at 30 different locations in and around Dhaka city; 6 locations on highways, 10 locations on arterials and 14 locations on commercial/residential areas. The work involved dust collections/ sieve analysis/ moisture analysis; on-road traffic survey and ambient PM_{10} measurements.
PM_{10} control efficiency of dry and wet sweeping of the streets were conducted in three road types, arterial, commercial-residential and highways. The control efficiency of dry sweeping varied from 31-74 % for different road types. For wet sweeping, the efficiency varied from 69-86%. The cost effectiveness of PM_{10} emission reduction was estimated for dry and wet sweeping.

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