Journal of Economics and Sustainable Development
ISSN 2222-1700 (Paper) ISSN 2222-2855 (Online)
Vol.5, No.18, 2014

On-Road Vehicular Emission Inventory in View of Its Distribution Over Dhaka City, Bangladesh: A Bottom-Up Modelling Approach to Support Sustainability Assessment

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Abstract
The study aims to account emissions from the vehicular sources of Dhaka city, more specifically, for the major roads of the city. Transport sector being one of the highest contributors of air emissions in the city makes it important to investigate the factors that catalyse the on-road emissions and acts as constraints in attaining environmental sustainability. Due to several reasons, on road congestion level is very high in the city that reduces the fuel efficiency of the vehicles. The research tends to reflect the fact while accounting the emissions with a meso scale bottom-up modelling approach, where the road by road vehicle characteristics are considered. The study estimated emissions of criteria pollutants, greenhouse gases and toxic substances by adopting a bottom-up technique to cover the major roads of the city in the current state of operation, where the actual moving pattern of the vehicles on different city roads were considered. Detailed survey was conducted in the Dhaka city roads in the year 2012 to collect diurnal traffic volume, speed profiles and vehicle composition. In general, the results suggested that the roads with higher traffic volume coupled with traffic congestion contributed at a higher rate to the emission load. The increasing trend of private vehicles along with uncontrolled traffic movement keeps the city under the threat of the harmful level of emission if proper management strategy is not adopted. As considering the detailed system-data can offer greater proximity to identify the key areas of concern, the methodological approach of this research can be adopted by others as well concerned with the on-road vehicular emissions, and can work towards attaining sustainability by reducing emissions and increasing fuel efficiency.
Keywords: Emission inventory; bottom-up modelling; vehicle speed profile; Dhaka city, Bangladesh

1. Introduction

Dhaka, being the centre for all the business and opportunities, hosts the migrated population from other places of the country; every day about 1418 persons are added to the city population contributing to about 6% growth of the city's population each year (BBS 2012). In parallel, thousands of new vehicles, mostly private vehicles, are introduced into the city roads to meet public demand for movement (BRTA 2013; STP 2004). As a consequence, a huge amount of air pollutants especially Nitrogen oxides (NOx), Carbon monoxide (CO), Particulate matter (PM), Green House Gases (GHGs) and toxic substances are emitted from this sector (US EPA 2007; EEA 2009). Moreover, the indiscipline in vehicle movement and traffic management issues in the city act as a catalyst for creating congestion and retarded vehicle speed (GOB 2001; Rahman 2008; Sultana 2010), which increases the travel time of vehicles to reach a destination. The extra travel time burns extra fuel and thus, this study aims to conduct an emission inventory of the city considering the road specific vehicle characteristics, speed profile and traffic volume through a bottom up modelling approach.

Unlike the macro level approach where the gross transport data of the city is considered, the meso scale bottom-up modelling approach described in this paper considered the typical characteristics (travel characteristics and behaviour in different time period of the day) of every major roads of the city to account the emission load. There has been much research conducted focusing on transport emissions of Dhaka city (ADB 2006; Afrin et al. 2012; Iqbal and Kim Oanh 2011; MoEF 2002; Wadud and Khan 2011), which mainly adopted the macro level emission inventory (MLEI) approach. However, the city's travel behaviour remained unattended within the MLEI, which is incorporated in this study. The standard emission factors of different categories of vehicles were scaled for the city following the fuel consumption rate of vehicles at different time period of the day in different roads. The study emission inventory with the factor-influence relationship thus allows assessing the co-benefits of transport system management strategies by accounting increased efficiency and reduced emission load and can act as a tool for detailed sustainability assessment of the transport sector.

2. Methods for Conducting Emission Inventory of On-road Transport in the Current Situation of Bangladesh

The emission (all the major constituents that form a vehicular emission profile including criteria pollutants, greenhouse gases and toxic substances; CO_2, NOx, CO, SO_2, PM10, NMVOC, Pb, NH_3, N_2O, CH_4, PAHs, POPs, total dioxin and total furans) inventory for the on-road mobile sources was developed using the standard vehicular emission calculation methodology as was adopted by European Environment Agency (EEA) for The European Monitoring and Evaluation Programme (EMEP) (EEA 2009) and also stated in the IPCC (1996) and elsewhere.

Emissions, E (gm/day) = $\sum_{fueltype(j)}^{vehicletype(i)} AADT \times FP_{ij} \times EF_{ijk} \times RL \times SF$ ---------------------- (eq. 1)

Where,

Vehicle Type i = All vehicle types being considered; viz. Passenger cars (PC), Microbus (MB), SUVs, three wheelers (3W), Bus, truck/covered van, light duty vehicles (LDVs) and motorcycles (MC) according to their technology.

Fuel type j = All fuel types being considered (Petrol, Diesel, LPG)

AADT = Average Annual Daily Traffic

FPij = Fleet Proportion; Proportion of vehicle type i and fuel type j

EFijk = Base emissions factor for vehicle type i, fuel type j& emission type k (gm/km)

SF = Scale Factor to be applied to adjust emission factor for the study area

RL = Length of road being considered (km)

The bottom-up calculation approach necessitated comprehensive data on the transport system features of Dhaka city. Thus, data on traffic volume, speed profile of the vehicles in different time periods of the day, vehicle specific fuel types, and air conditioner usage patterns were collected, which are critical factors in vehicular emissions.

2.1 Data collection

In order to obtain the road wise diurnal traffic volume and vehicles' speed profile of the city roads, an extensive field survey was conducted in the Dhaka city of Bangladesh during February 2012 to May 2012. Data was also collected from Dhaka Transport Coordination Board (DTCB 2011) for the traffic count of some roads and the fuel usage pattern for different vehicles. The field survey didn't extend to the entire city roads but covered the major roads of the city and all of the bus routes. Therefore, this inventory accounts the emission of the major road network of the city; not for the whole Dhaka city. However, since the larger portion of travel occurs on these roads, they are representative of average daily vehicles' travel distances. The traffic count sampling sites and the surveyed road links for profiling vehicle speed is provided with a map in Figure 1.

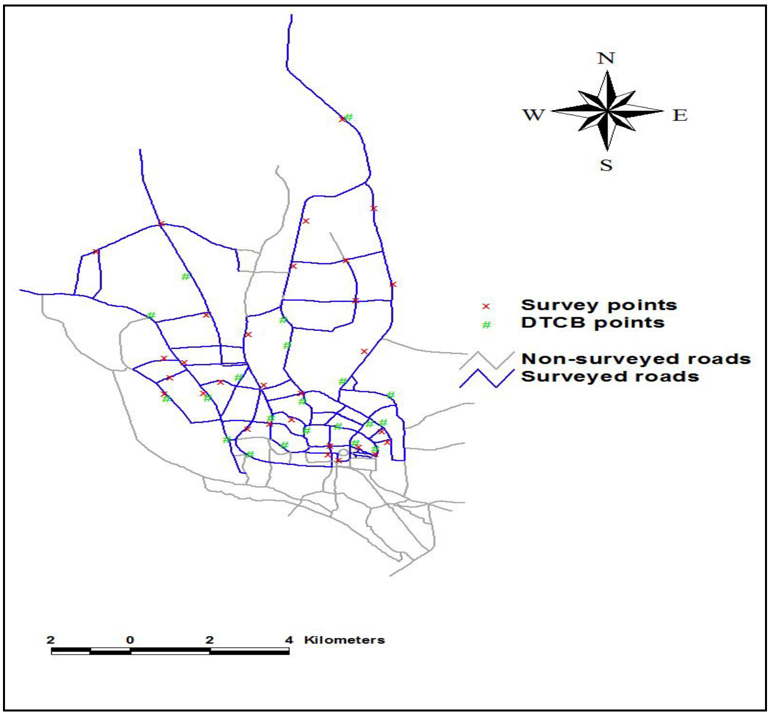


Figure 1. Sampling locations; Major road networks of Dhaka city indicating the sampling sites for diurnal traffic volume (indicating both survey points of this study and DTCB sampling sites) and surveyed roads for speed profiling

Traffic count

- A mid-block traffic count survey was conducted at 30 sampling points in the city, which covered 45 major roads of residential, commercial and mixed zones. During the survey, traffic data was collected for 17 hours (from 6 am to 11 pm) at each sampling point, accumulated in every hour; all the survey was conducted in the normal working weekdays.
- Mid-block traffic count data of 20 other city points were obtained from the Dhaka Transport Coordination Board (DTCB 2011).

A/C usage pattern survey

- Diverse 30 samples (each sample over a 15 minute period) were taken to represent different time of day and roads of the city to identify the air conditioner (AC) usage pattern of private vehicles, as these vehicles were having AC facilities in the city.
- A survey to identify the AC usage of the vehicles was carried out through monitoring the windows of the vehicles. The closed window of vehicles was considered indicative of the vehicles using AC, as the survey was conducted in the summer when ambient temperatures and humidity are very high.

Speed profile of vehicles

As the speed of vehicles is an important influencing factor of vehicular emissions (EEA 2009),

- A GPS speed profile (second by second) survey was conducted for all of the major roads of the city while travelling by car; this covered residential areas, commercial areas and mixed zones and all of the bus routes of the city. Since, with the normally high levels of congestion, travelling a certain distance by car or other modes of transport required a similar time frame, the obtained speed data was assumed to be the speed profile of all vehicles of the road segment.
- The speed profiling survey covered 80 road links representative of peak and off-peak times of the day (Figure 1 shows the map of surveyed roads).
    - The road links were pre-assessed to classify the peak and off-peak phases in view of the traffic volume and travel times at different spells of the day (for instances, *High congested:* 0900-1100; 1300-1430; 1700-1900; *Medium congested:* 0800-0900; 1100-1300; 1430-1700; 1900-2100; *Low congested:* 0600-0800; 2100-0600).
    - The second by second speed profiling survey of each road link was conducted at those pre-identified peak and off-peak periods, instead of collecting every hour data of each road.

2.2 Emission factor

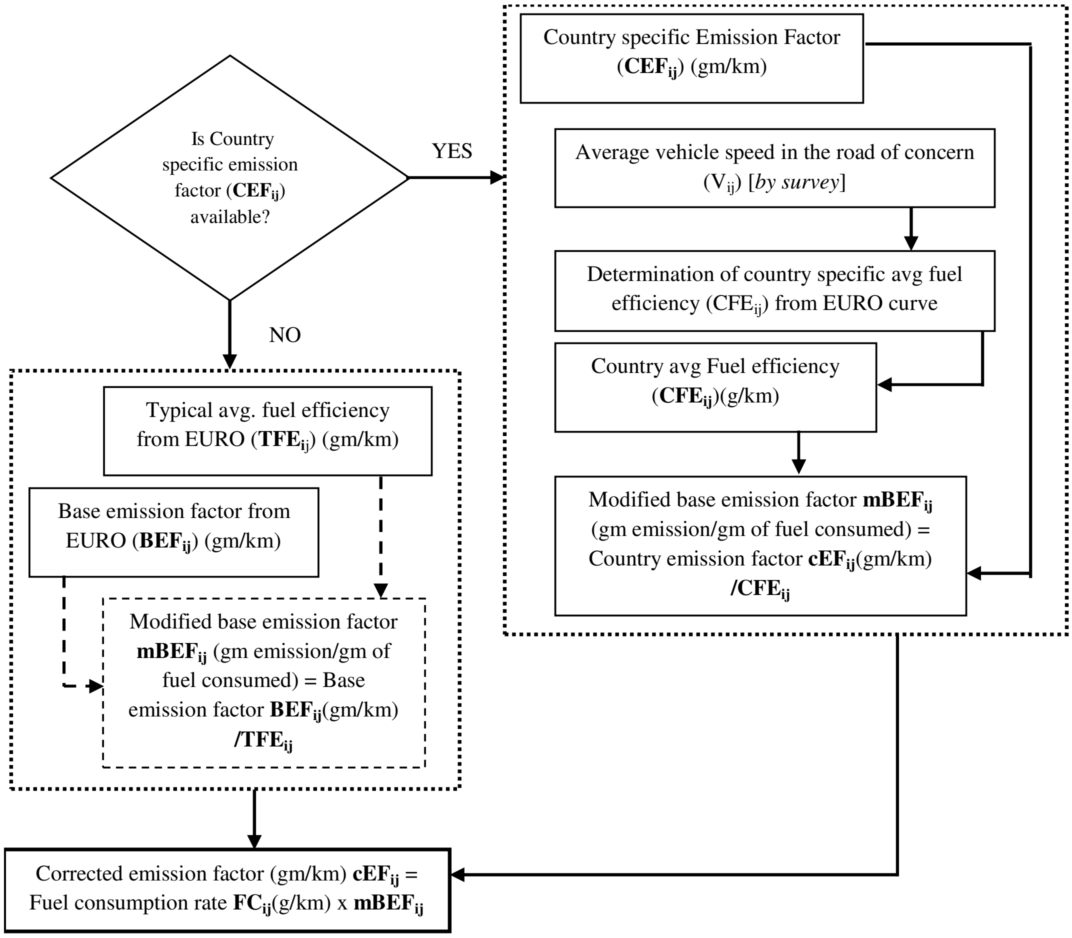
The base emission factor is the typical rate of vehicle specific emissions (in grams/km; for different types of vehicles using different fuels). The base emission factor for this study was obtained from European Environment Agency (EEA) (EEA 2009), which is also used in different studies and modelling techniques (IVE 2010; Mobile 2003). Bangladesh had its own base emission factors for some pollutants (SOE 2005), which were considered first in those pollutants' emission calculation. The base emission factors were corrected according to the scale factors (fuel consumption corrections mainly denoted with FC_{ij} in Figure 2) and thus provided the corrected emission factors for the study area. The methodological structure to obtain the study area specific scaled emission factors is provided in Figure 2.

Therefore,

Corrected Emission Factor (gm/km) = Base emission factor (gm/gm) x Scale factor (SF)

Where,

Scale factor (SF) = Corrected fuel consumption (g/km) depending on driving behaviour



Note: i = vehicle technology type; j = fuel type

Figure 2. Methodological structure adopted in the study to calculate study area specific scaled emission factor

<u>Scale Factor (SF) calculation (fuel consumption corrections)</u>

Vehicle speed/fuel consumption correction factor calculation: The European Environment Agency (EEA 2009) provided generalized relationships of 'speed' versus 'fuel consumption rate' of different vehicle categories (engine technologies and fuel types used by vehicles); hence, the equations were used in this study of Dhaka city as well (the relations are provided in Figure 3).

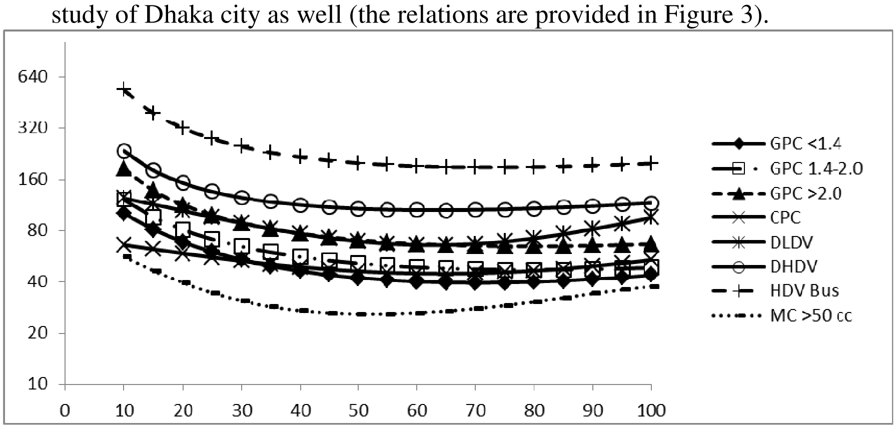


Figure 3. Relationships for calculating vehicle speed dependent fuel consumption rate generated based on the equation provided by EEA (2009); note: GPC = Gasoline PC (with the engine capacity in cc), CPC = CNG PC; DLDV = Diesel light duty vehicles, DHDV = Diesel heavy duty vehicles, MC = motorcycles

Air conditioner usage/Fuel consumption correction factor calculation: AC usage in vehicles increases the load on the engines (VSPac) because of increased power required to driving an additional accessory belt to run the air conditioner compressor, above that needed to drive the vehicles. So, The VSPac is proportional to fuel consumption while other conditions (vehicle speed, technology, fuel) remain the same (IVE 2010; mobile 2003). The generalised changed fuel efficiency under AC usage condition was calculated using the equation provided in International Vehicle Emission model (IVE 2010) and used in this study for AC usage adjustments to emission factors.

2.3 Emission inventory

The emission inventory was conducted using 'Road by Road Detailed Emission Inventory (RRDEI)' approach, considering:

i. Daily traffic count data of the road;
ii. Second by second vehicle speed profiling for different time periods of the day (km/hr); and
iii. Length of the road (km).

As vehicle's speed influences its emissions significantly, this study inventory was developed to use the typical variations of the vehicles' speed on major roads of the city through accounting second by second speed profiling for different time period of the day, which enabled to develop the strata of the roads according to the vehicle speed. The congestion stopping time, while travelling the road segment, was also identified at the same time. Types of vehicles running on those roads were identified through the mid-block traffic count survey. The emissions of each strata of a particular road segment was then calculated using the modified emission factor corrected according to speed and AC usage of vehicles considering each type of vehicle running on the road. The summation of emissions from all the strata thus provided the total emission. The accumulation of different time period specific emissions thus provided the total day emissions for the road segment. The methodological structure to conduct the emission inventory is provided in Figure 4.

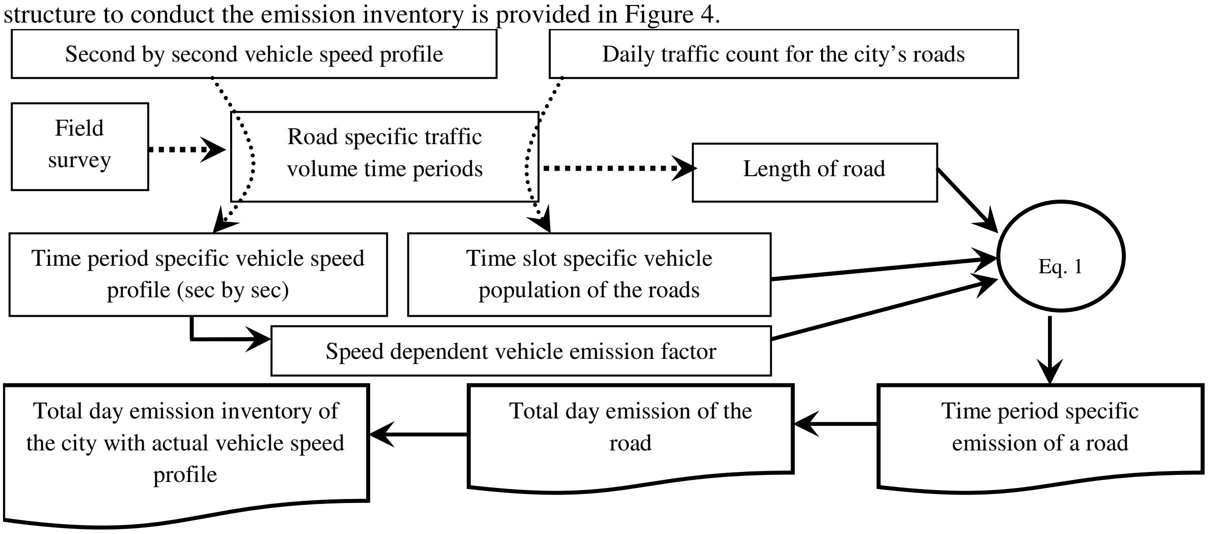


Figure 4. Methodological structure for conducting Road by Road Detailed Emission Inventory (RRDEI)

3. Results and Discussions

The average speed of the vehicles exhibits the total time frame of travelling a specified road length, which doesn't evidently show the vehicle speed when running and also the span of time the vehicles remains stagnant in the congestions. The rate of fuel consumption or emissions could be different for vehicles (although should be in a similar range) if only the average vehicle speed is considered rather than considering its actual moving speed and standing time. This study experimented with the approach to consider the typical movement patterns of the vehicles, and as a glimpse, Figure 5 shows a graphical representation of a sample road (kakoli-Moahakhali road segment) demonstrating a vehicle's speed profile (second by second vehicle speed) while travelling in peak time.

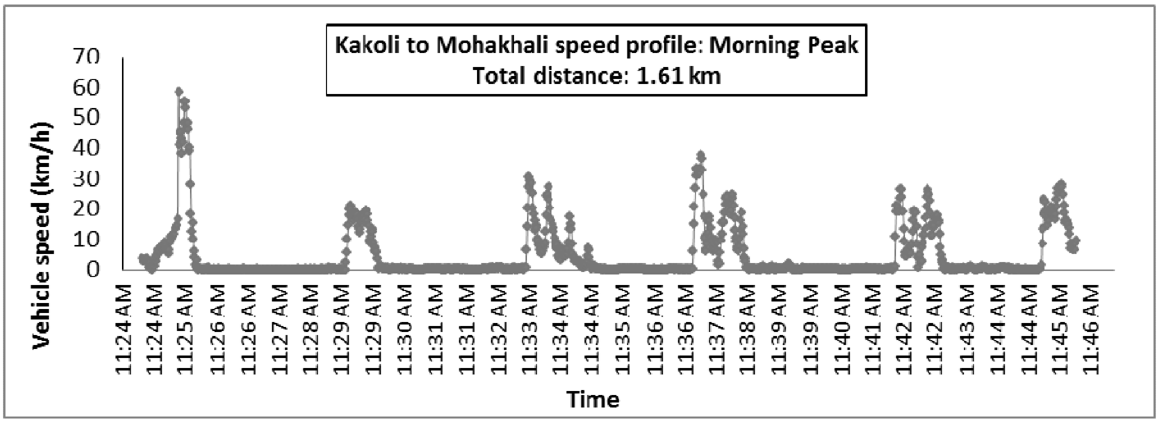
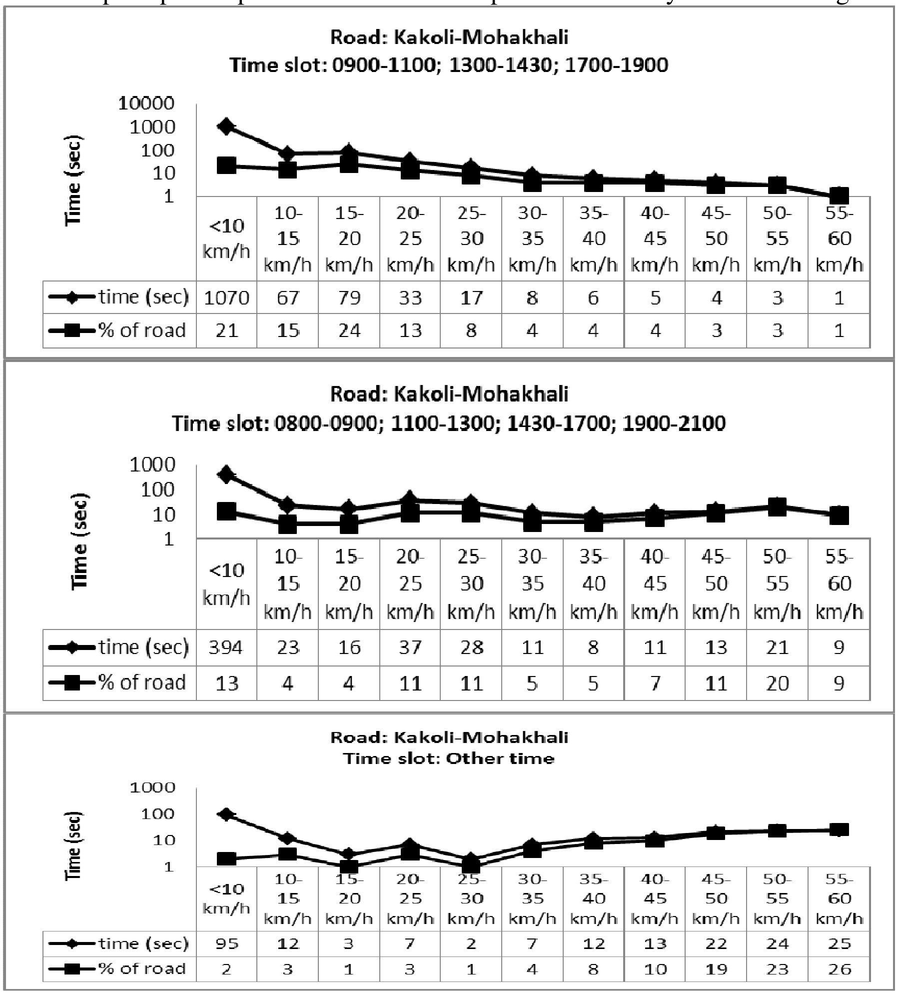


Figure 5. Peak time second by second speed profile of vehicles in Dhaka city (sample data of a road); data collected through GPS survey in 2012 (January to May)

As revealed with the speed profiling survey (Figure 5), the vehicle remained stagnant at the congestion points for around 73% of its total time to travel the sample road of 1.6 km. In the most cases, the vehicle moving speed was below 30 km/h, predominantly between 10 km/h to 20 km/h speed, due to high traffic volume and congestion. Analysing the speed profiling of vehicles for different roads, three general categories of the speed profile were found dominant in a day for the Dhaka City roads, which demonstrates the behaviour of traffic movement on the roads in a day for Dhaka city. The speed profile pattern indicates to the level of extra fuel usage during a trip in the city, which is required to be considered when conducting an emission inventory, as was done in this study. Vehicle speed profile pattern of the same sample road for a day is shown in Figure 6.



	<10 km/h	10-15 km/h	15-20 km/h	20-25 km/h	25-30 km/h	30-35 km/h	35-40 km/h	40-45 km/h	45-50 km/h	50-55 km/h	55-60 km/h
time (sec)	1070	67	79	33	17	8	6	5	4	3	1
% of road	21	15	24	13	8	4	4	4	3	3	1

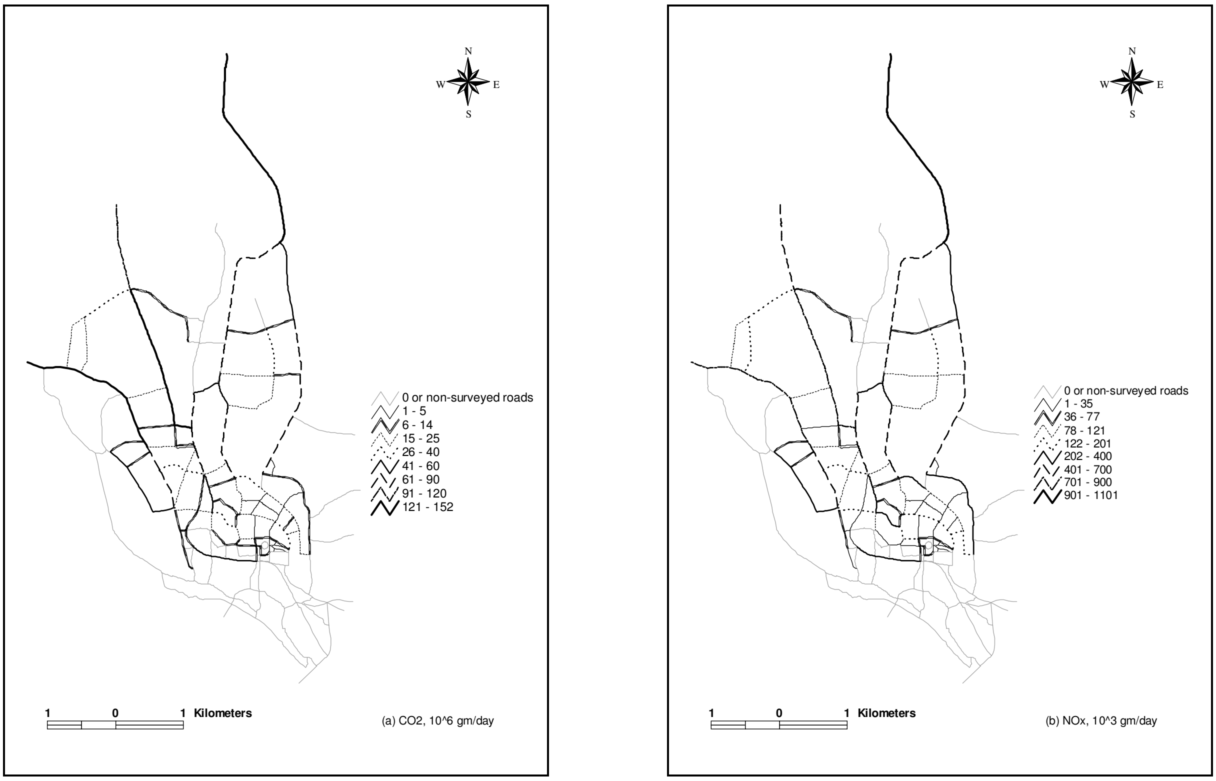
	<10 km/h	10-15 km/h	15-20 km/h	20-25 km/h	25-30 km/h	30-35 km/h	35-40 km/h	40-45 km/h	45-50 km/h	50-55 km/h	55-60 km/h
time (sec)	394	23	16	37	28	11	8	11	13	21	9
% of road	13	4	4	11	11	5	5	7	11	20	9

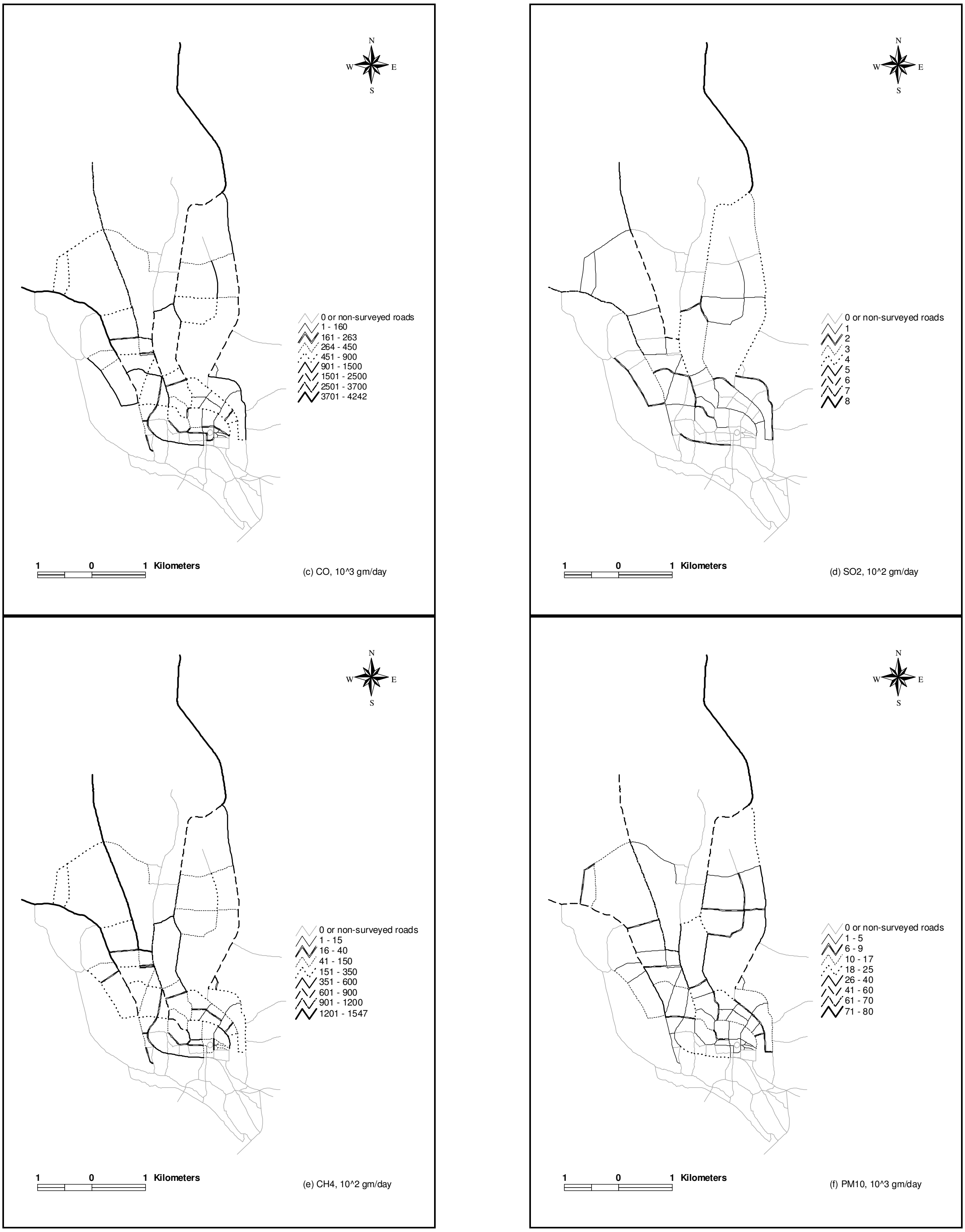
	<10 km/h	10-15 km/h	15-20 km/h	20-25 km/h	25-30 km/h	30-35 km/h	35-40 km/h	40-45 km/h	45-50 km/h	50-55 km/h	55-60 km/h
time (sec)	95	12	3	7	2	7	12	13	22	24	25
% of road	2	3	1	3	1	4	8	10	19	23	26

Figure 6. Vehicle speed profile pattern of the day in a sample road (Kakoli-Mohakhali) of Dhaka city; data collected through GPS survey in 2012 (January-May)

As stated earlier, the fuel efficiency of vehicles reduces in parallel with its AC usage. In Dhaka city, as per the survey, around 80% of the vehicles (private vehicles that have the AC facility) use AC in the summer while, in the winter, the usage rate drops to nearly negligible rate to be considered for increased fuel consumption calculation. Other than the private vehicles, the limited number of buses that has AC facility was also considered while calculating the emissions.

Like the sample road of Figure 5 and Figure 6, the speed profiling was done for all the major roads of the city in order to develop the strata of the roads according to the vehicle speed. Figure 7 portrays the road-wise estimated emissions from the vehicular sources, considering the actual diurnal speed profile patterns and traffic volume. The typical AC usage pattern of the vehicles was also incorporated to calculate the emission, thus the results representing the summer emissions of the roads.




N
W
E
S
0 or non-surveyed roads
1 - 160
161 - 263
264 - 450
451 - 900
901 - 1500
1501 - 2500
2501 - 3700
3701 - 4242
1 0 1 Kilometers
(c) CO, 10^3 gm/day
0 or non-surveyed roads
1
2
3
4
5
6
7
8
1 0 1 Kilometers
(d) SO2, 10^2 gm/day
0 or non-surveyed roads
1 - 15
16 - 40
41 - 150
151 - 350
351 - 600
601 - 900
901 - 1200
1201 - 1547
1 0 1 Kilometers
(e) CH4, 10^2 gm/day
0 or non-surveyed roads
1 - 5
6 - 9
10 - 17
18 - 25
26 - 40
41 - 60
61 - 70
71 - 80
1 0 1 Kilometers
(f) PM10, 10^3 gm/day

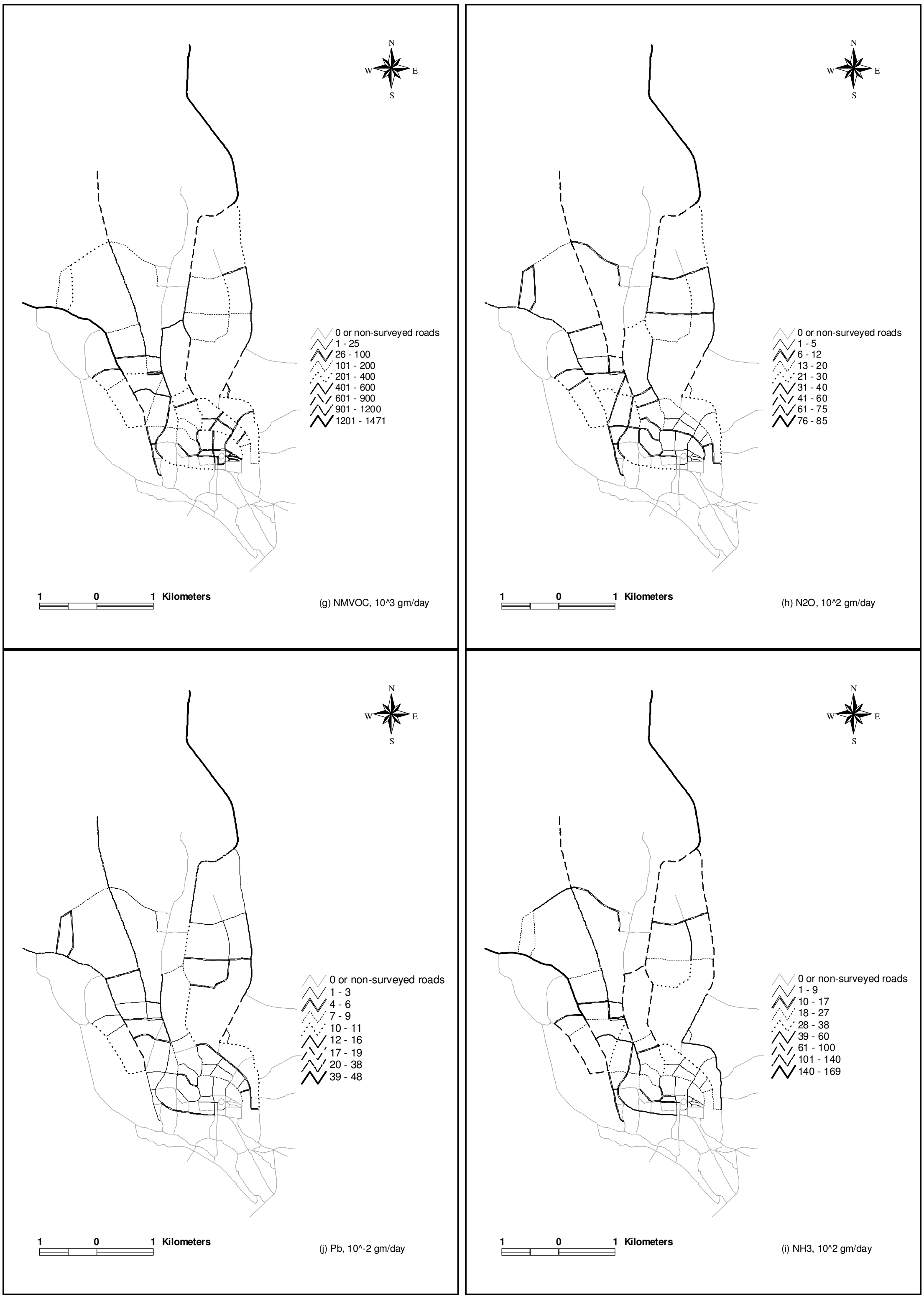


Figure 7. Road specific emission level (gm/day) of Dhaka city in 2012; the roads in the map are classified according to the emission range, actual emissions of the road are not provided

Critically reviewing Figure 7 reveals that, in general the roads featuring congestion, high traffic volume, and a higher number of diesel buses and trucks are the high emission generating roads. The roads occupied with private vehicles and three wheelers throughout the day, and where buses are very limited, are at the medium emission generating roads group. Taking into account the emissions generated at different roads of the city, the total emissions of the survey roads (the main road network of the city where majority of the vehicles operate) is provided in Figure 8, which shows the presence of noticeable level of greenhouse gases (CO_2, CH_4 and N_2O), criteria pollutants (CO, PM, NOx and SO_2), and other toxic and hazardous pollutants (NMVOC, Pb, NH_3, PAHs and POPs); PM10 is denoted with PM in this study. CO_2 is presumably the dominant emission because of the combustion; however, other significant emissions include CO, NMVOC, NOx, CH_4 and PM, followed by NH_3, N_2O and SO_2 and toxics such as POPs and PAHs. The emissions of other toxic pollutants (dioxin and furans) are found in trace amounts, which sometimes may have significant health effects even at very low concentrations.

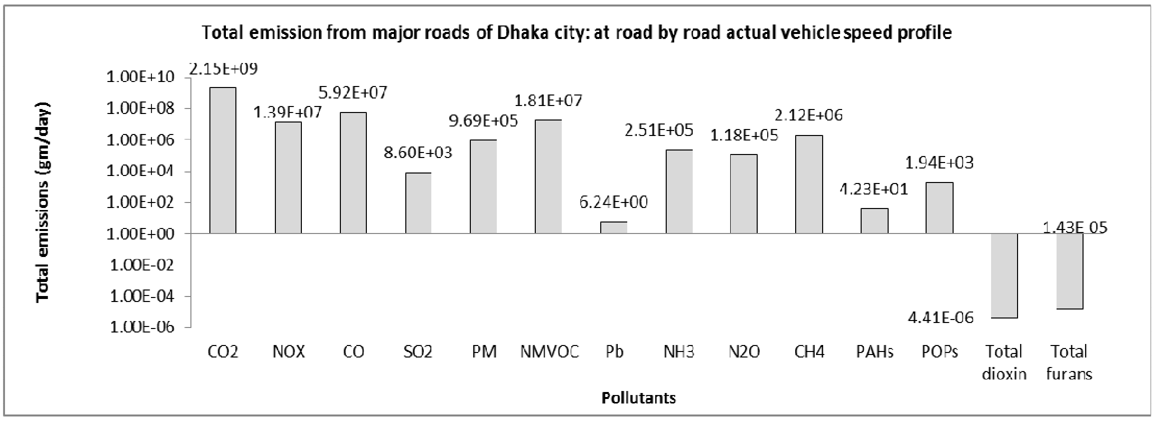


Figure 8. On-road vehicular emissions from the major road networks of Dhaka city in 2012 considering actual speed profile of vehicles

4. Conclusion

The study reveals the fact that the emission inventory can act as a diagnostic tool in decision making through detecting the level of emission from sources. A bottom-up emission inventory can act further as it considers the typical nature of the system in details while estimating, and thus can support in assessing sustainability of the road transport system.

The study identified the effect of traffic congestion on the emissions load as it considered the actual speed profile of the vehicles; the stagnant time period of vehicles was found responsible for increasing the amount of emission in large extent. Reducing the congestion thus can help increase the average speed of vehicles and alongside can change the emission scenarios significantly as there is a strong linear relationship between speed and emission level of the pollutants. The traffic management strategy to reduce the congestion thus can improve the efficiency of the system by reducing travel time, as well as can act to reduce emissions and increase fuel efficiency. The sustainability of Dhaka city road transport system can be achieved by adopting appropriate management strategies and by assessing the eco-efficiency of the adopted strategies with the meso scale modelling. Further studies can concentrate on the factors that affect the vehicles' speed on the road, and a cause-effect analysis can be done to assess different transport system characteristics on its emission efficiency; the relationship can justify the significance of different management strategies on the level of emission. Within the limitations of accurate available data, the adopted modelling approach in this study can provide a structure to estimate emissions from vehicular sources with greater proximity to be able to use for decision making.

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