

Modelling Eco-Efficiency For Vehicular Emissions From The Perspective Of Dhaka City: Development of a Tool for Sustainable Transport Planning

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Abstract

Development in the transport sector can achieve sustainability when efficiency in service and emissions reduction is ensured. The objective of this research was thus to generate scenarios of pollution and green house gas (GHG) levels at different states of the transport system in Dhaka City, Bangladesh, along with assessing its efficiency level. The innovative idea encompassed in this research is in developing a model based on the relationships developed with the system parameters, capable of dealing with a system provided with very detailed data of the parameters or with a limited data set, to assess transport eco-efficiency of a city with a similar urban structure. This eco-efficiency approach can create new opportunities for rapidly motorizing cities in developing countries (such as Dhaka City) for the purpose of appraising the performance of their transport system in attaining increased environmental efficiency through policy and/or strategic planning modifications to the road network and land use.

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1. Introduction

Eco-efficiency is a management philosophy that aims at minimizing ecological damage while maximizing efficiency of the development processes; eco-efficiency is achieved by providing affordable services that satisfy human needs and improve quality of life, while gradually reducing ecological footprints (Enterprise Ireland 2011; Geldermann and Treitz 2008; Hellweg et al. 2005; Huang 2000; Kortelainen 2006; WBCSD 2000). This concept thus can be incorporated into pollution control policy for the transportation sector, where both service quality and ecological impacts are important. In the transportation sector, sustainable transportation is a widely used concept for a better system securing both social and environmental sustainability. In order to achieve the broader scaled transport sustainability, 'eco-efficiency' can be an assessment tool for transport planning, when the quality of the transport system needs to be assessed at a shorter timescale taking into account its service quality and environmental impacts. Thus, a crucial line of inquiry of this research is to examine the questions of how eco-efficiency is related to transport system factors. The aim of this paper is to provide a mathematical modelling structure, that allows the application of computerised solutions in situations that range from a limited to an extensive availability of data, in order to assess the eco-efficiency of a given urban transport system of a city in a developing country, such as that of characterised by Dhaka City's urban road transport system.

Bangladesh, a third world country, with a huge population of about 166 million people (CIA World Factbook, 2014), is neither well planned nor managed to mitigate growing environmental concerns arising from its rapidly developing sectors of its economy. Dhaka City, in the central part of Bangladesh, is the urban centre for all of the country's business and activities. This centralized structure stimulates migration of new residents to the city each day seeking a better life; this makes it one of the most densely populated cities in the world. In addition, thousands of new vehicles are introduced into the city every month, most of which are private vehicles, leading to extreme traffic congestion on Dhaka's roads. In order to develop a model for mega cities of developing countries, Dhaka provides a variety of stressors that can be assessed justifying its selection as a suitable study area.

In order to assess the eco-efficiency of a given transport system, this paper outlined the relationships between efficiency and system characteristics based on the values obtained from surveying Dhaka City. These relationships were then expressed in the form of equations, which were

determined from regression analysis and were subsequently used to formulate a modelling structure that could then provide the algorithm for a computer-based model.

The approach taken in this research was to apply a detailed digitised emission inventory to support the generation of a number of emission scenarios. The innovative aspect of this research is that a meso-scale modelling approach was adopted for the inventory as opposed to a static approach which characterises most national emissions inventories (IPCC, 2006), where the factors that influence the emissions and the magnitude of variations were identified. Road links with specific detailed data were collected through a field survey in 2012. The research identified the relationships between emissions and efficiency indicators and the system attributes, through an accounting of their variances under different conditions, for the purpose of quantifying the extent of eco-efficiency achievable for the system modifications due to a policy, plan or strategy. Appropriate policies can reduce the number of private vehicles on the road; land use planning can produce options for better traffic movement, and optimization analysis can identify the best mass rapid transit for Dhaka City. But notwithstanding the fact that policies or land use planning strategies can be extensive and diverse, this research has not focused on identifying a suitable policy coupled with land use planning; instead, it has focused on assessing the crucial outcome of different strategies.

This eco-efficiency modelling approach can create new opportunities for rapidly motorizing cities in developing countries (such as Dhaka City) for the purpose of appraising the performance of their transport system, policy formulations, and/or strategic planning modifications. The aim of this paper is to provide scientific information to policy makers; the model can facilitate decision making by testing new policy and management approaches, with a view to achieving environmental and economic efficiency objectives.

2. Methodology

The model for relating eco-efficiency and source characteristics was developed through analysing the scenarios generated for different transport system attributes of Dhaka City. In order to develop these relationships, a survey was conducted in Dhaka City focusing on fleet characteristics and number, fuel characteristics of vehicles, average vehicle speed, traffic congestion, road network characteristics and traffic management. The

scenarios were correlated with the source characteristics, and relationships were developed through regression analysis.

The detailed field survey was conducted in Dhaka City from February 2012 to May 2012; data was also collected from the Dhaka Transport Coordination Board (DTCB) (DTCB 2012) for the transport system's characteristics. Vehicles were classified into different categories according to their technology, viz. Passenger cars (PC), Microbus (MB), SUVs, three wheelers (3W), Bus, Truck/covered van, Light-duty vehicles (LDVs) and motorcycles (MC). The fuel usage pattern for different vehicles was obtained from BRTA (BRTA 2013). The map of sampling sites and the surveyed roads for this analysis is provided in Fig. 1.

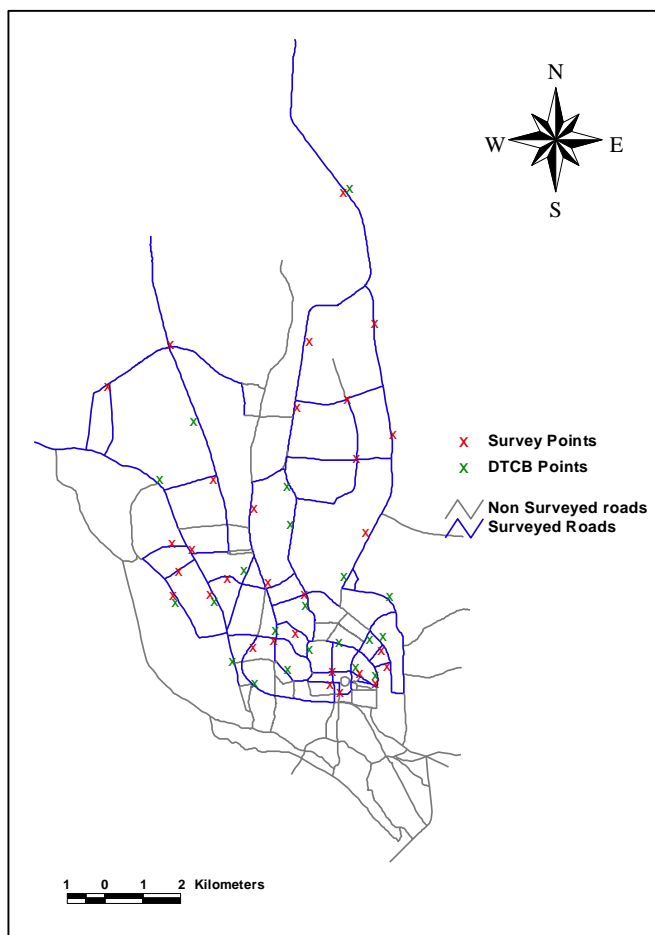


Fig. 1 Map of sampling sites in Dhaka City, indicating both survey points of this study and DTCB sampling sites

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

A field survey was conducted to measure second by second vehicular speeds on different roads and at different time periods of the day. The speed data was obtained with a portable GPS unit while travelling by car; since traveling a certain distance by other modes of transport required a similar period of time to that obtained by travelling by car, the GPS obtained speed data was used as a proxy for the speed profile of all vehicles using the surveyed sections of the road network. The GPS speed profile survey was conducted at 80 road segments of the city's main road network covering residential, commercial and mixed zones and all of the bus routes (Fig. 1). To simplify the analysis, the local road network was excluded from data collection as the main road network covers the major portion of vehicles' travel distance in the city and thus reasonably effectively demonstrates the transport system's characteristics.

A generalized model to assess the transport system's eco-efficiency was developed based on the relationships generated, which provided air pollution and socio-economic evaluation of a given system with the following inputs:

- Unit travel time / average vehicle speed
- Fleet characteristics and number
- Fuel characteristics
- Road network
- Unit travel cost

The model was aimed to assess quantitatively the transport system eco-efficiency by recognizing its pollution load, travel cost, and travel time; these three parameters were selected as it could quantify the environmental and economic values of the transport system in a simple way irrespective of the system characteristics.

Depending on the extent of input data, the model quantitatively generated an air pollution scenario following the basic emission inventory method suggested by IPCC (1996), EEA (2009) and elsewhere. Travel cost and travel time were assessed for the transport system depending on the

relationships developed for the transport system's attributes. The schematic diagram of the model's development methodology is shown in Fig. 2.

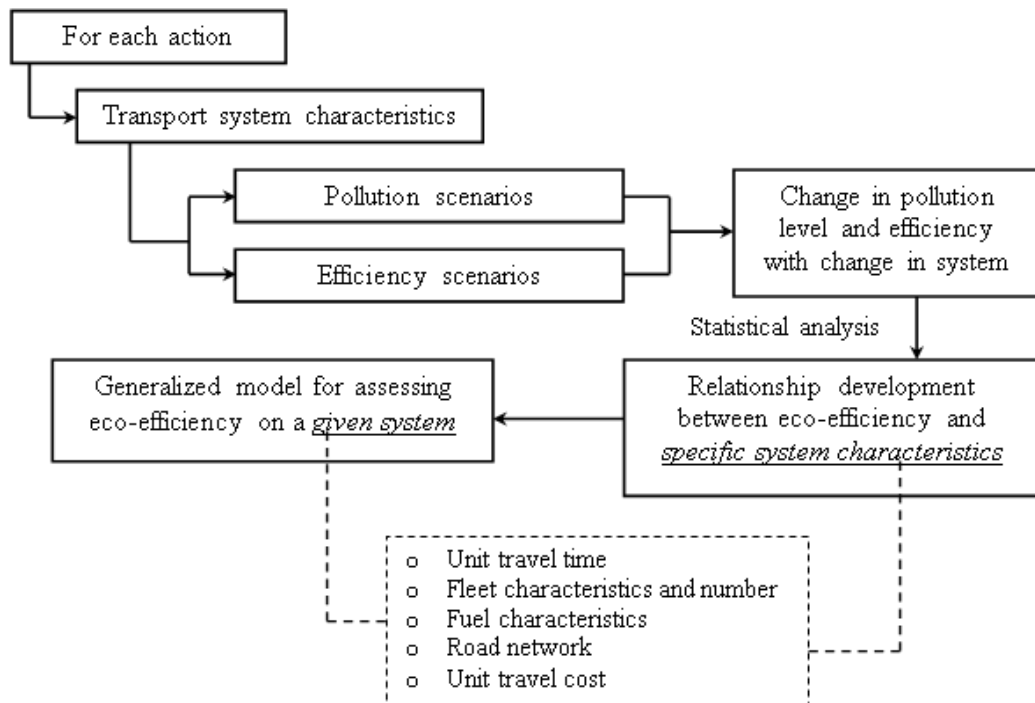


Fig. 2 Schematic diagram of the methodology to develop the generalized eco-efficiency assessment model

3. Relationship Between Efficiency and the Transport System's Characteristics

Although the relationships are based on Dhaka City's transport characteristics, the analysis of the field survey data was able to demonstrate over a wide spectrum of urban contexts, the combined effects of every change in efficiency with a change in transport characteristics. For example, data were obtained to provide second by second speed profiles of vehicles across the network through: surveying 52 road segments and 10 schools for traffic congestion; 22 bus stops and 50 bus routes for public transport efficiency; 65 road segments for traffic counts; and 80 road segments. However, the relationships shown in this research rely on the current state of energy efficiency of the vehicles; the relationships would be different for

changed energy efficiency of the vehicles due to its technological modification. The derivations (regression analysis) that provided the relationships of the responsible factors are provided in the Appendix.

3.1 Average speed versus emissions

The emissions from different vehicle categories have strong linear relationships with the average speed of vehicles (EEA 2009, Iqbal et al. 2014). The relationships of critically important emissions from vehicles were taken into consideration for the analysis in this research; CO (Carbon Monoxide) and NO_x (Nitrogen Oxides) are the most significant pollutants by volume, whilst particulates (i.e. PM10) and toxics (total emissions of Pb¹, NMVOC², PAHs³, POPs⁴, dioxins and furans) are critical concerns for public health issues, and CO₂ is the most concerning and potent of greenhouse gases from road transport that has a bearing on anthropogenic-induced climate change. The relationships shown here are specific for Dhaka City fuel characteristics and its resulting efficiencies (as the city-specific emission factors were used in the calculations), but whilst there might be minor differences, generally they would hold true for other cities with similar urban form and traffic characteristics.

Based on the regression analysis conducted, the series of equations to calculate the vehicle specific emissions in relation to average speed are as follows:

For CO emissions:

$$Em_{GMB,CO} = 182.3v^{-0.646} \quad (\text{eq. 1a})$$

$$Em_{GPC,CO} = 125.91v^{-0.606} \quad (\text{eq. 1b})$$

$$Em_{CBus,CO} = 120.42v^{-0.653} \quad (\text{eq. 1c})$$

$$Em_{MC,CO} = 76.553v^{-0.546} \quad (\text{eq. 1d})$$

$$Em_{DBus,CO} = 61.566v^{-0.653} \quad (\text{eq. 1e})$$

$$Em_{DTruck,CO} = 43.632v^{-0.548} \quad (\text{eq. 1f})$$

$$Em_{DLDV,CO} = 16.259v^{-0.473} \quad (\text{eq. 1g})$$

¹ Lead

² Non Methane Volatile Organic Carbon

³ Polycyclic Aromatic Hydrocarbon

⁴ Persistent Organic Pollutants

$$Em_{CPC,CO} = 6.3433v^{-0.353} \quad (\text{eq. 1h})$$

For NOx emissions:

$$Em_{GMB,NOx} = 10.938v^{-0.646} \quad (\text{eq. 2a})$$

$$Em_{GPC,NOx} = 7.5545v^{-0.606} \quad (\text{eq. 2b})$$

$$Em_{CBus,NOx} = 28.6v^{-0.653} \quad (\text{eq. 2c})$$

$$Em_{MC,NOx} = 4.5932v^{-0.546} \quad (\text{eq. 2d})$$

$$Em_{DBus,NOx} = 104.66v^{-0.653} \quad (\text{eq. 2e})$$

$$Em_{DTruck,NOx} = 74.175v^{-0.548} \quad (\text{eq. 2f})$$

$$Em_{DLDV,NOx} = 27.64v^{-0.473} \quad (\text{eq. 2g})$$

$$Em_{CPC,NOx} = 1.903v^{-0.353} \quad (\text{eq. 2h})$$

For PM10 emissions:

$$Em_{GMB,PM10} = 0.7292v^{-0.646} \quad (\text{eq. 3a})$$

$$Em_{GPC,PM10} = 0.5036v^{-0.606} \quad (\text{eq. 3b})$$

$$Em_{CBus,PM10} = 0.1505v^{-0.653} \quad (\text{eq. 3c})$$

$$Em_{MC,PM10} = 1.5311v^{-0.546} \quad (\text{eq. 3d})$$

$$Em_{DBus,PM10} = 9.8505v^{-0.653} \quad (\text{eq. 3e})$$

$$Em_{DTruck,PM10} = 6.9812v^{-0.548} \quad (\text{eq. 3f})$$

$$Em_{DLDV,PM10} = 2.6014v^{-0.473} \quad (\text{eq. 3g})$$

$$Em_{CPC,PM10} = 0.0381v^{-0.353} \quad (\text{eq. 3h})$$

For Toxics emissions:

$$Em_{GMB,toxics} = 29.175v^{-0.646} \quad (\text{eq. 4a})$$

$$Em_{GPC,toxics} = 20.15v^{-0.606} \quad (\text{eq. 4b})$$

$$Em_{CBus,toxics} = 10.035v^{-0.653} \quad (\text{eq. 4c})$$

$$Em_{MC,toxics} = 61.242v^{-0.546} \quad (\text{eq. 4d})$$

$$Em_{DBus,toxics} = 24.628v^{-0.653} \quad (\text{eq. 4e})$$

$$Em_{DTruck,toxics} = 17.455v^{-0.548} \quad (\text{eq. 4f})$$

$$Em_{DLDV,toxics} = 6.5114v^{-0.473} \quad (\text{eq. 4g})$$

$$Em_{CPC,toxics} = 2.5375v^{-0.353} \quad (\text{eq. 4h})$$

For CO₂ emissions:

$$Em_{GMB,CO_2} = 2747.9v^{-0.646} \quad (\text{eq. 5a})$$

$$Em_{GPC,CO_2} = 1423.4v^{-0.606} \quad (\text{eq. 5b})$$

$$Em_{CBus,CO_2} = 6899.2v^{-0.653} \quad (\text{eq. 5c})$$

$$Em_{MC,CO_2} = 692.34v^{-0.546} \quad (\text{eq. 5d})$$

$$Em_{DBus,CO_2} = 7877.6v^{-0.653} \quad (\text{eq. 5e})$$

$$Em_{DTruck,CO_2} = 2791.5v^{-0.548} \quad (\text{eq. 5f})$$

$$Em_{DLDV,CO_2} = 1386.9v^{-0.473} \quad (\text{eq. 5g})$$

$$Em_{CPC,CO_2} = 498.41v^{-0.353} \quad (\text{eq. 5h})$$

Where, v = vehicle average speed (km/h); Em = Emissions [GMB= gasoline driven MB/SUV (private vehicles with engine capacity >2.4L); GPC = gasoline driven private cars (engine capacity <1.5L); CBus = CNG driven Bus; MC = motorcycles; DBus = diesel driven Bus; DTruck = diesel driven truck; DLDV = diesel driven light duty commercial vehicles; CPC = CNG driven private vehicles (all engine capacities)]; all emissions units are in grams/km.

With the aim to generalize the speed versus emissions relationships even further, the following equations provide the emissions relationship with respect to all vehicles running on the road (here it represents the typical composition of the fleet of vehicles operating on Dhaka City's roads). The emissions shown in the following equations are per car equivalent (Ce)⁵. Although, the relationship shown is based on the vehicle fleet composition of Dhaka City roads obtained through the field survey, the relationship is factual for any vehicle composition operating on a road with similar emission factors. The generalized equation to portray the relationship is shown in eq. 6:

⁵ The Ce in this research is stated as the equivalent number of cars that can be substituted for the length of different categories of vehicles running on the road. For calculating Ce in this research, the conversion factors used for different vehicles (per vehicle) are: PC/MB/SUV/3W/LDV = 1 Ce; Bus = 2.5 Ce; Truck = 2 Ce; and MC = 0.4 Ce (assumed according to the typical vehicle size of Dhaka City as was found during the field survey).

$$Em_{Ce,NOx} = 11.052v^{-0.551} \quad (\text{eq. 6a})$$

$$Em_{Ce,CO} = 61.289v^{-0.584} \quad (\text{eq. 6b})$$

$$Em_{Ce,PM10} = 0.5314v^{-0.509} \quad (\text{eq. 6c})$$

$$Em_{Ce,Toxics} = 11.655v^{-0.455} \quad (\text{eq. 6d})$$

$$Em_{Ce,CO_2} = 1972.5v^{-0.539} \quad (\text{eq. 6e})$$

Where, Em_{ce} = Emissions per car equivalent (grams/h/km/Ce) [NOx, CO, PM10, toxics, CO₂]; v = vehicle average speed (km/h).

Based on the emissions and concentrations obtained through modelling different scenarios, it is evident that the emissions and the respective concentrations have strong linear relationships among them. Fig. 3 shows the CO emissions versus concentration relationships, as a demonstration of the relationship pattern for other emissions as well, based on the modelling done for Dhaka City's roads.

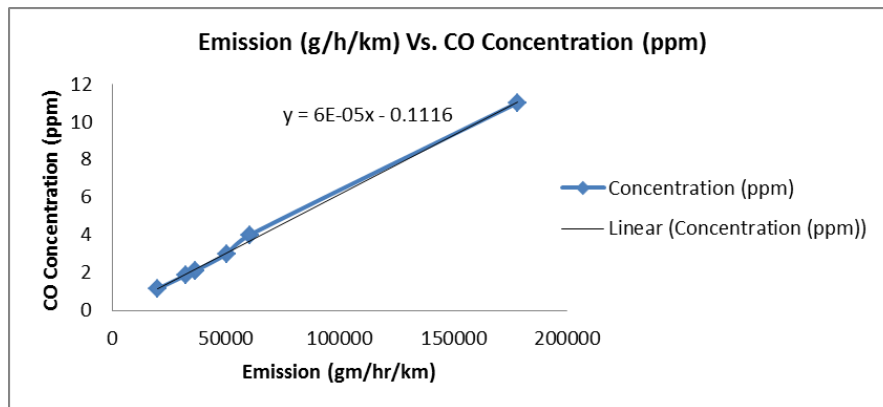


Fig. 3 Relationships between CO emissions from vehicles and their respective resulting concentrations in Dhaka City for the year 2012

The set of equations to describe the extent of proportional relationships of concentrations with emissions, as set out in Fig. 3 as an example, is described in eq. 7:

$$C_{CO} = 6E^{-05}Em_{CO} - 0.1116 \quad (\text{eq. 7a})$$

$$C_{NOx} = 3E^{-05}Em_{NOx} + 0.0008 \quad (\text{eq. 7b})$$

$$C_{PM10/Toxics} = 0.0958Em_{PM10/Toxics} - 0.0566 \quad (\text{eq. 7c})$$

Where, C = Concentration of emissions ($\mu\text{g}/\text{m}^3$) [CO, NO_x, PM10/toxics]; Em = Emissions (grams/hr/km) [CO, NO_x, PM10/toxics].

3.2 Average Speed Versus Travel Cost

To a large extent, the average travel cost of the city dwellers depends on the speed of the vehicles operating on roads; lower average speed increases the fuel consumption rate of vehicles, which increases the cost of travel especially while travelling in private vehicles. The relationship between average unit travel cost (of private vehicles) and the average speed of vehicles was calculated based on the speed profile of vehicles and the corresponding fuel efficiency of the private vehicles driven with different fuel types.

The analysis shows a linear relationship between the average speed of vehicles and the unit travel costs of travelling with private vehicles (CPC, GPC, and GMB); the cost increases drastically when the average speed drops below 10 km/h during peak time of the day. The reduced fuel efficiency of private vehicles during congestion results in the increased unit travel cost during the peak period of the day with very low average speed of vehicles.

Travelling in a gasoline powered MB/SUV was found to be the most expensive option among the three, and the extent of travel cost for this mode in relation to the average speed of a vehicle is presented in eq. 8. Travelling in a vehicle with a relatively lower capacity engine offers higher fuel efficiency that can lower the unit travel cost (eq. 9). Travelling in a CNG-powered PC (with any engine capacity) shows relatively lower variations in relation to changes in the average speeds of vehicles, however, the travel cost was found to decrease with increased average speed (eq. 10).

$$UTC_{GMB} = 204.54v^{-0.505} \quad (\text{eq. 8})$$

$$UTC_{GPC} = 111.26v^{-0.42} \quad (\text{eq. 9})$$

$$UTC_{CPC} = 28.795v^{-0.131} \quad (\text{eq. 10})$$

Where, UTC = Unit travel cost for travelling with GMB/GPC/CPC (Tk^6/km); v = average vehicle speed (km/h)

⁶ Tk = Taka (Bangladesh currency); 1 Tk = 0.014 USD (at the time of research conducted)

3.3 Vehicle Composition Versus Average Speed of Vehicles

As identified from the field survey, the composition of the vehicle fleet on the city's roads influences traffic congestion, and this in turn, affects the average speed of the vehicles as well. The relation between the average speed of vehicles and the vehicle fleet composition on Dhaka City's roads is shown graphically in Fig. 4.

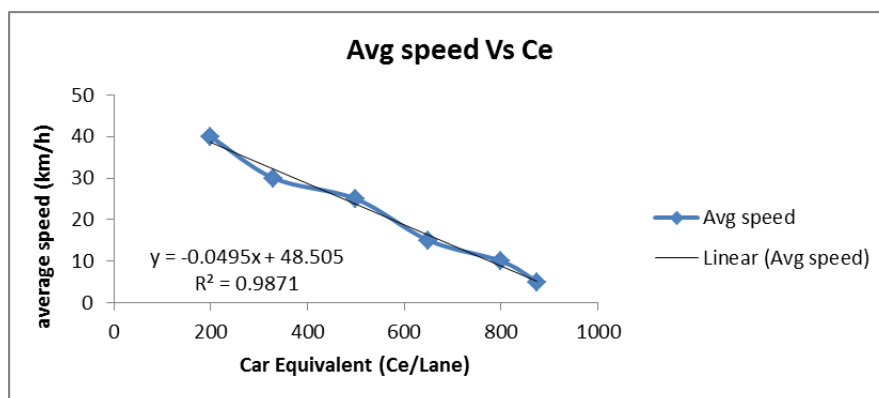


Fig. 4 Average speed of vehicles in relation to the vehicle volume on road denoted with car equivalent, Ce for Dhaka City of Bangladesh in 2012.

The vehicle composition was converted to Ce to bring all under a single unit, to provide greater clarity and simplicity in the analysis. Fig. 4 shows a very strong linear relationship between vehicle composition (Ce) and the average speed of vehicles, which is logical because of the change in road space usage for different vehicle compositions on the roads. The equation to show the relationship of average speed with Ce is as follows:

$$v = -0.0495Ce + 48.505 \quad (\text{eq. 11})$$

Where, v = vehicle average speed (km/h) [A negative 'v' indicates an overcapacity input of variables] - the average speed (v) was assumed to be 5 km/h higher than the calculated average speed in case of better traffic management, pedestrian road crossing management and disciplined driving but with the same traffic volume (the assumption is backed by the vehicle speed profile survey of Dhaka City which was conducted at different time periods on different days); Ce = Car equivalent of vehicles per lane running on road

A higher Ce was found for roads in the city when a higher number of private vehicles were operated on the roads. The analysis showed that the average vehicle speed in a road was found to increase by 50% when private

vehicles (PC) reduced by 25%, in a situation when the existing average speed of vehicles approximated 10 km/h; the relationship ranged from 200% to 70% for the speed increment and PC decrement respectively. In cases when the existing average speed of vehicles approximated 15 km/h, the relationship was found to be 67%, 100% and 167% of the increment respectively of the average speed and related to corresponding reductions of 25%, 50% and 70% in the volumes of private vehicles respectively. The equation for the % of speed increment in terms of % of PC reduction is illustrated as follows:

$$v_{(\%,10 \text{ km/h})} = 3.3607PC_{(-\%)} - 29.098 \quad (\text{eq. 12a})$$

$$v_{(\%,15 \text{ km/h})} = 1.7194PC_{(-\%)} - 16.769 \quad (\text{eq. 12b})$$

Where, $v_{(\%, 10 \text{ km/h})}$ = % of average speed increment when existing average speed is 10 km/h; $v_{(\%, 15 \text{ km/h})}$ = % of average speed increment when existing average speed is 15 km/h; $PC_{(-\%)}$ = % of PC reduction.

3.4 Number of Lanes on Road Versus Average Speed of Vehicles

The number of effective lanes (lanes that are usable for vehicle movement) increases the capacity of roads to enable the movement of a certain number of vehicles during a particular time period. Thus, the average speed of vehicles tends to increase if the number of effective lanes is increased in a road network keeping all the other factors as constant. The magnitude of effects of the number of effective lanes of a road network on the average speed of vehicles is shown with the equation below; the relationship shown here is based on the data obtained from field survey of Dhaka City for 2012 and through the arithmetic capacity calculation.

$$v = 15N_{EL} - 18.333 \quad (\text{eq. 13})$$

Where, v = Vehicle average speed (km/h); N_{EL} = Number of effective lanes on road.

4. Eco-Efficiency of a Given System: Modelling for Assessment

As revealed from the relationships above, the eco-efficiency of a system depends on many factors working together within the system. Thus, the eco-efficiency of a given system can be assessed based on the extent of data availability. When more detailed data is available of the system parameters, the assessment could be done with less reliance on the relationships of these

parameters. In a situation with a limited set of data, more assumptions would take place based on these interrelationships.

In order to develop a model for assessing the eco-efficiency of a given transport system, the eco-efficiency parameters adopted in this modelling approach are: (a) emissions concentration, (b) travel cost, and (c) travel time; as these parameters can be used to quantitatively assess both the economic and environmental values of a transport system. The development of generalized mathematical models in order to assess these parameters, based on the relationships revealed previously, is illustrated below.

4.1 Modelling emissions concentrations

Three different approaches for assessing the emissions concentrations are formulated in this section, which can serve as a basis for the assessment procedure that is tailored according to the extent of data availability.

Approach- 1:

The total emissions of the vehicle fleet are the product of speed dependent vehicle specific emissions that is obtained by considering every vehicle and fuel type. Thus:

$$\text{Emissions, } Em = \sum_{\text{fuel type } (j)}^{\text{vehicle type } (i)} (Em_{ij} \times n_{ij}) \quad (\text{eq. 14})$$

Where, Em = Total emissions from the vehicle fleet; Fuel type j = CNG, gasoline, diesel; Vehicle type i = PC, MB/SUV, 3W, Bus, Truck, LDV, MC; Em_{ij} = speed dependent vehicle specific emissions, for fuel type j and vehicle type i ; n_{ij} = number of vehicle of each category (with fuel type j and vehicle type i).

Note, if the average speed of the vehicles (v) is unknown, then this can be assumed from the 'average speed versus car equivalent' relationships (eq. 11); where the vehicle fleet is then modified by converting it into the car equivalent quantum of the vehicle fleet (as defined earlier in this chapter).

Total CO, NO_x, PM₁₀ and toxic emissions of the vehicle fleet can be obtained by rewriting eq.14 and incorporating eq. 1, 2, 3, 4 and 5 respectively within it.

Approach -2:

When the fuel usage pattern of the vehicles are unknown and assumed to have a similar fuel usage pattern of the vehicles as Dhaka City (with features like a typical mega city of a developing country), the emissions can be calculated from the typical emissions per car equivalent values. Thus:

$$\text{Emissions, } Em = Ce \times Em_{Ce} \quad (\text{eq. 15})$$

Where, Em = total emissions of the vehicle fleet (grams/hr/km); Ce = Car equivalent of the vehicle fleet; Em_{Ce} = Emissions per car equivalent (grams/hr/km/ Ce).

Now, for NO_x emissions, incorporating eq. 6a (relationship between average speed and NO_x emissions per car equivalent) into eq. 15 yields equation 16a:

$$\text{Emissions, } Em_{NO_x} = 11.052Ce \times v^{-0.551} \quad (\text{eq. 16a})$$

Where, v = average speed of vehicles

Likewise, for CO, PM10, toxics and CO_2 emissions:

$$\text{Emissions, } Em_{CO} = 61.289Ce \times v^{-0.584} \quad (\text{eq. 16b})$$

$$\text{Emissions, } Em_{PM10} = 0.5314Ce \times v^{-0.509} \quad (\text{eq. 16c})$$

$$\text{Emissions, } Em_{Toxics} = 11.655Ce \times v^{-0.455} \quad (\text{eq. 16d})$$

$$\text{Emissions, } Em_{CO_2} = 1972.5Ce \times v^{-0.539} \quad (\text{eq. 16e})$$

Approach -3:

When the average speed of the vehicles is also unknown along with the fuel usage pattern of the vehicles, the average speed can be assumed from 'average speed versus car equivalent' relationships (eq. 11) and the emissions can be calculated from eq. 16.

Thus, for NO_x emissions, incorporating eq. 11 into eq. 16a, the following relationships are derived:

$$\text{Emissions, } Em_{NO_x} = 11.052Ce (-0.0495Ce/lane + 48.505)^{-0.551} \quad (\text{eq. 17a})$$

Likewise, for CO, PM10, toxics and CO_2 emissions:

$$\text{Emissions, } Em_{CO} = 61.289Ce (-0.0495Ce/lane + 48.505)^{-0.584} \quad (\text{eq. 17b})$$

$$\text{Emissions, } Em_{PM10} = 0.5314Ce (-0.0495Ce/lane + 48.505)^{-0.509} \quad (\text{eq. 17c})$$

$$\text{Emissions, } Em_{Toxics} = 11.655Ce (-0.0495Ce/lane + 48.505)^{-0.455} \quad (\text{eq. 17d})$$

$$\text{Emissions, } Em_{CO_2} = 1972.5Ce (-0.0495Ce/lane + 48.505)^{-0.539} \quad (\text{eq. 17e})$$

4.2 Concentration model

The concentration due to the emissions from vehicles depends on many factors and thus the actual concentration assessment can be done through detailed modelling with all of the required data. However, in the situation with limited data availability and for a gross level assessment of emissions concentration, the relationships generated in this research can be used, assuming no influence from other factors (climatic condition, emission factors, road width, mixing height, etc.).

In such cases, the concentration of NO_x can be obtained by putting the Em_{NO_x} values in eq. 7b acquired through eq. 14, 16a or 17a subject to the adopted emissions modelling approach. Likewise, eq. 7a can calculate the CO concentration with the emission values obtained by applying equations 14, 16b or 17b to the data; whilst for the estimation of the concentration of PM₁₀ or toxics, equation 7c can be used.

4.3 Modelling travel cost

The total travel cost (Tk/km) for a vehicle fleet in a city consists of the costs associated with private vehicles and public passenger vehicles (bus, taxi, etc.). Thus the total travel cost (Tk/km) would be:

$$TTC = \sum_{travel\ mode\ (j)} TC_j \quad (eq. 18)$$

Where, TC_j = travel cost associated with travel mode j; j = mode of travel: private vehicles, bus, taxi, etc.

But, since the travel cost of buses are generally constant in a city, irrespective of travel characteristics (although it is recognized that fare structures do vary with different systems) and taxi fare structures are too diverse to be generalized to different systems (with fares generally being higher than the travel cost of private vehicles), changes in the travel cost of a system can be assessed for private vehicles. Hence lower private vehicles' travel cost is indicative of lower per capita travel expenses (i.e. higher economic efficiency).

The total travel cost for private vehicles of the vehicle fleet (Tk/km) are:

$$TC_{PC} = \sum_{PC\ type\ (i)} n_i \times UTC_i \quad (eq. 19)$$

Where, n_i = number of private vehicles of the type i ; i = private vehicle type: CNG PC (CPC), Gasoline MB/SUV (GMB), and Gasoline PC (GPC); UTC_i = unit travel cost of the private vehicles of type i (Tk/km).

The total travel cost for public transport can also be calculated using the same method, by substituting the number of private vehicles with the number of passengers. Now if the unit travel cost of each type of private vehicle is unknown for a given system, then the UTC_i can be assumed from the relationships provided by eq. 8, eq. 9 and eq. 10:

$$TC = [n_{GMB}(204.54v^{-0.505})] + [n_{GPC}(111.26v^{-0.42})] + [n_{CPC}(28.795v^{-0.131})]$$

(eq. 20)

Now, in the case of changes in the number of private vehicle in the vehicle fleet, the travel cost may change for private vehicles because of the changes in the average speed of the vehicles due to increased road capacity (C_e /lane would be decreased in such cases). The travel cost of private vehicles can be calculated for the changed scenario with eq. 19 by calculating the resultant average speed for the new C_e /lane for the new scenario (using eq. 11). Otherwise, based on the results of Dhaka City, the relationships between the percentage (%) value of the average speed increment with the percentage (%) value of the reduction in private vehicles (eq. 12(a) and (b)) can be used to calculate the resulting average speed for the new scenario incorporating the changed private vehicle composition.

4.4 Modelling structure and its application to Dhaka City

Based on the equations formulated earlier in this paper, the algorithm of modelling depending on the data availability is provided in the modelling structure schema (Fig. 5). The qualitative parameters like comfort and accessibility of transport are directly related to the ratio of commuters versus the total number of transport modes available to serve the travelling public. Thus, these qualitative parameters are not incorporated into the modelling structure, as a change in system parameters rarely affects those qualities and modelling the qualitative parameters would require a research of another dimension.

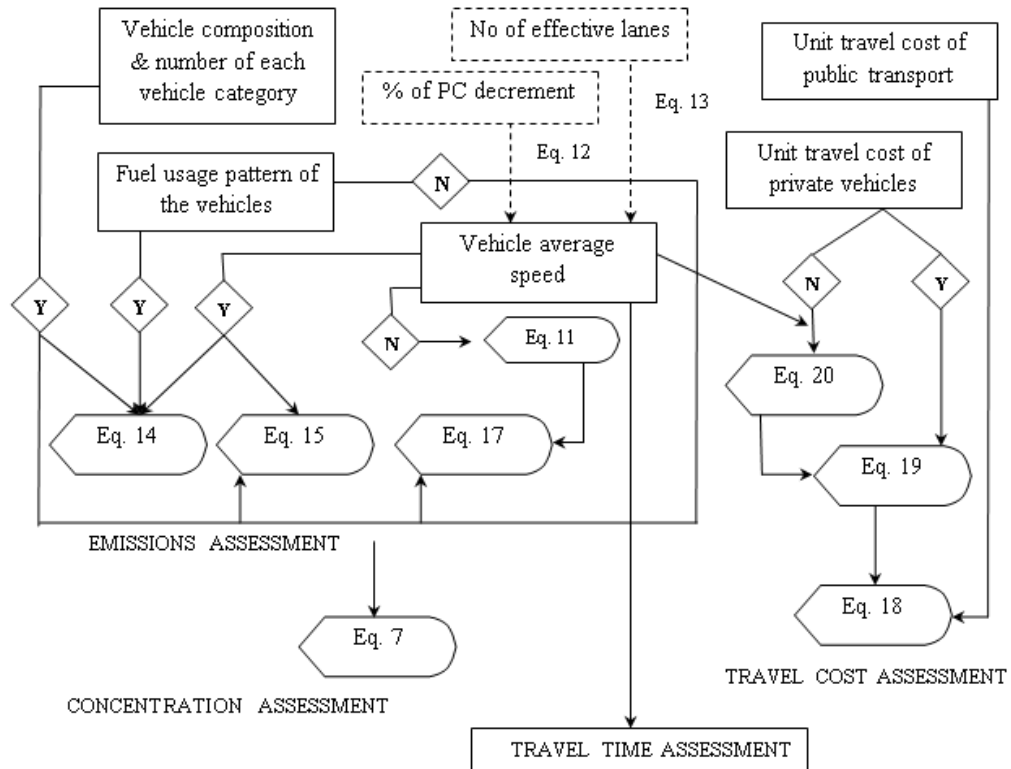


Fig. 5 Assessing the quantitative parameters of eco-efficiency of a given system: a modelling structure for Dhaka City

The modelling structure provided in Fig. 5 can be applied to any given urban transport system, when a city planner intends to model (and account for) the emissions of a city's roads against a planning or management strategy. Depending on the extent of availability of the required input data, the model is capable of providing an emissions reduction and efficiency improvement scenarios (in terms of travel cost and time) for the system through different approaches. The application of the model can be discussed further with a case study road of Dhaka City by assessing a specific road link in its original state and through different hypothetical scenarios generated against different strategic actions. Table 1 explains the scenarios analysed in detail and indicates how the different emission modelling approaches (as stated earlier) deal with different scenarios having different input data for the model. The model is required to have, at least, data on vehicle composition of the city roads to provide an account of emissions. Table 1 only shows the emissions modelling section of the eco-efficiency

assessment, although the model can also assess the economic efficiency using this modelling structure.

Table 1 Application of the modelling approaches, as an example, for assessing emissions of a case study road⁷ of Dhaka City for different hypothetical scenarios

Scenarios	Emission modelling approach	Emissions for the road link (tonnes/day)				
		CO ₂	NO _x	CO	PM10	Toxics
SCN-1	Approach-1	163	1.15	4.59	0.082	1.47
SCN-2	Approach-2	276	1.51	7.78	0.0793	1.96
SCN-3	Approach-3	317	1.74	9.08	0.0904	2.19
SCN-4	Approach-1	131	1.01	3.07	0.0688	0.88
SCN-5	Approach-2	93	4.99	2.46	0.0279	0.745
SCN-6	Approach-2 with ea. 13	90	0.48	2.36	0.027	0.72
SCN-7	Approach-1	52	0.44	1.04	0.0305	0.30

Note: **SCN-1**: Existing (of the study area road of Dhaka City) vehicle composition, existing fuel usage pattern of vehicles (known), and existing vehicle speed profile (known); **SCN-2**: Existing vehicle composition, fuel usage pattern of vehicles unknown, existing vehicle speed profile (known); **SCN-3**: Existing vehicle composition but unknown vehicle speed profile; **SCN-4**: SCN-1 but with Private vehicles reduced to 50% and Public buses increased to 110% hypothetically to demonstrate a what-if modal shift from private to public transport; **SCN-5**: SCN-4 but with fuel usage pattern of vehicles unknown and assuming average vehicle speed of 35 km/h in the peak period and 40 km/h in the off-peak period due to effective traffic management such as ensuring driving discipline and banning on-street parking; **SCN-6**: Existing vehicle composition, where the number of effective road lanes are hypothetically increased by 2 on each side of the road but with the resulting speed profiling unknown for this change in road width; **SCN-7**: SCN-1 but with private vehicles hypothetically reduced to 30% due to introducing Mass Rapid Transit and imposing parking restrictions on busy commercial areas and assuming an average vehicle speed of 40 km/h all day (as 40 km/h is the speed limit in Dhaka city).

⁷ At existing condition (field survey 2012), road (Pragati sarani) length=6.9 km; average traffic volume per day=59166 (Ce/day=66027) of which PC=55%; 80% of PCs using CNG as fuel; average speed of vehicles at peak time=10 km/h.

Table 1 shows an account of the resulting emissions, along with the treatment of modelling approaches, for different scenarios of the case study road. Thus, the model can show the magnitude of variations in emissions for the differences in the system's characteristics (as indicated within SCN-1 to SCN-7 in Table 1). For instance, for the case study road, if the number of private vehicles were reduced by 50% coupled with a 10% increase of public buses whilst other factors remain same, a 20% reduction in CO₂ emissions may take place; hence, a reduction of 43% from the current state can be achieved with average vehicle speed of 35 km/h. The scenarios shown here are examples only, which in real time situations would produce different outcomes based on the particular characteristics of a city's planning strategies. Whatever scenarios are adopted, the input parameters for the model allow the analysis of 'what-if' scenarios for the city's planning strategies with regard to eco-efficiency, so that a comparison can be done to examine the performance achievable for an adopted strategy. This approach also allows planners' to provide a rational justification to their proposed strategy (and fine tune it before it becomes enshrined in legislation).

In this paper, different modelling approaches yielded different values and hence a comparison was done to analyse the level of difference (% of difference) shown by different techniques in comparison with the meso-scale emissions inventory (Fig. 6); Iqbal et al. (2014) provided details of a meso-scale emission inventory for Dhaka City. The comparison was done to evaluate the emissions model's performance against a well-established emissions inventory technique.

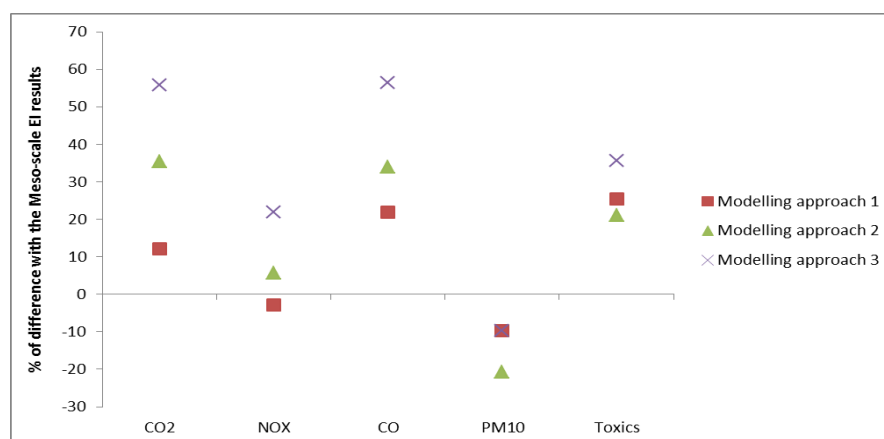


Fig. 6 Level of differences of the emissions modelling results (modelling approaches 1, 2, and 3) in comparison to the meso-scale emissions inventory conducted in Iqbal et al. (2014); the results are based on the data of 2012

Fig. 6 shows that the estimated emissions for various modelling approaches differed according to the level of assumptions that were applied for different calculation processes. For instance, the 'modelling approach 1' was generally estimated higher (within a 20% difference) than the meso-scale emissions modelling approach, which might be because of the development of generalized speed to emission factors relationships. The modelling approaches "2" and "3" yielded estimates that were higher than modelling approach "1", because of the larger number of assumptions. Although the modelling approaches' estimated emissions are higher than for that obtained with meso-scale emissions, it can be considered to have still reasonable validity due to its capacity to analyse the transport network, and because it is a conservative method of emissions estimation, especially when used to assess the efficiency of a planning strategy using very limited data sets.

5. Conclusion

The emissions from the transport sector is an issue for the modernized world because to date, the combustion of fossil fuels has been essential in supporting mobility, but it has come at a high cost to the environment, particularly concerning air quality and resource depletion. Scenario testing using this computer modelling technique can offer a range of solutions for dealing with these issues that would lead to improved economic performance and a more environmentally sound transport system for the city. This paper has discussed the formulation of a model that can be used to assess the economic and environmental efficiency and performance of a transport system with objective quantitative measures. Therefore, this model has the potential to become crucially important tool for city planners to apply before adopting a new strategy to ensure that appropriate transport network modifications and policy actions are chosen in order to get the desired level of efficiency, or vice versa.

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Appendices

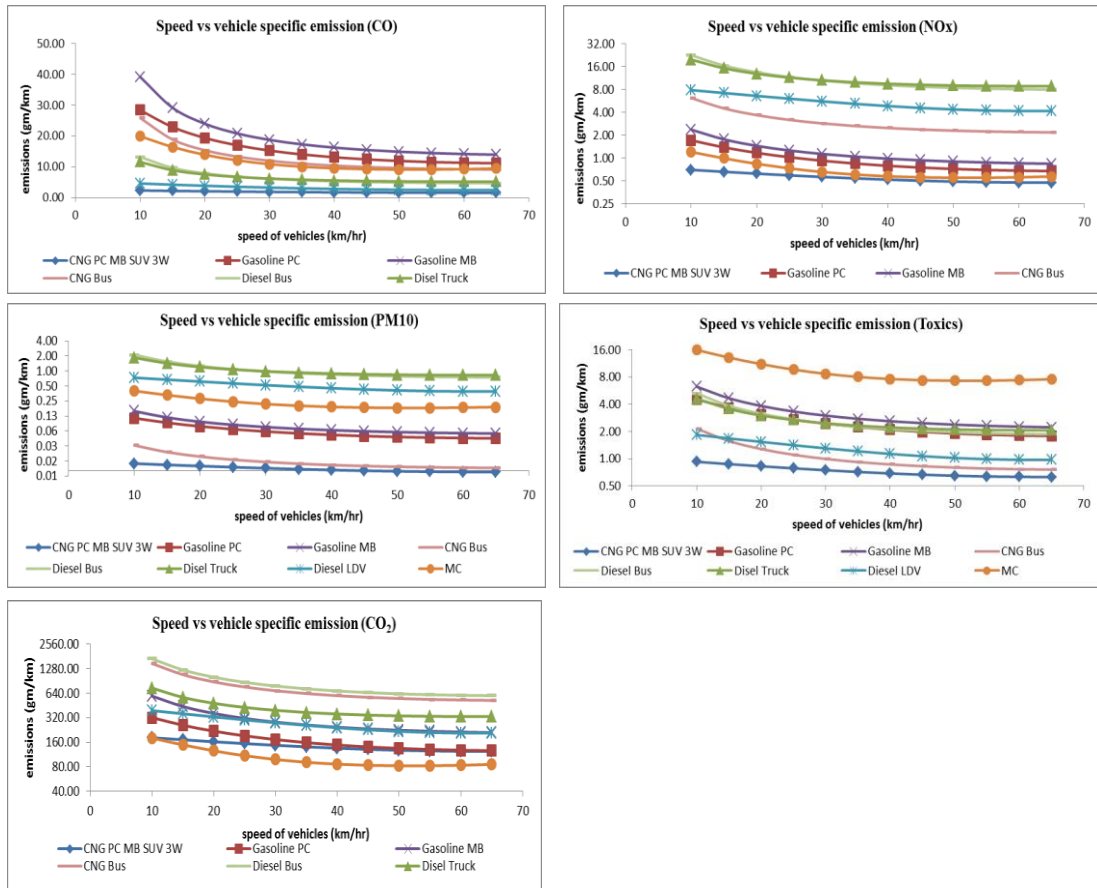


Fig. A1 Relationships between average speed of vehicles and emissions (CO, NO_x, PM₁₀, Toxics [total emissions of Pb, NMVOC, PAHs, POPs, dioxins and furans] and CO₂) from different vehicle categories of Dhaka City in 2012; calculated as per the methodology stated in EEA (2009) corrected according to Dhaka City characteristics.

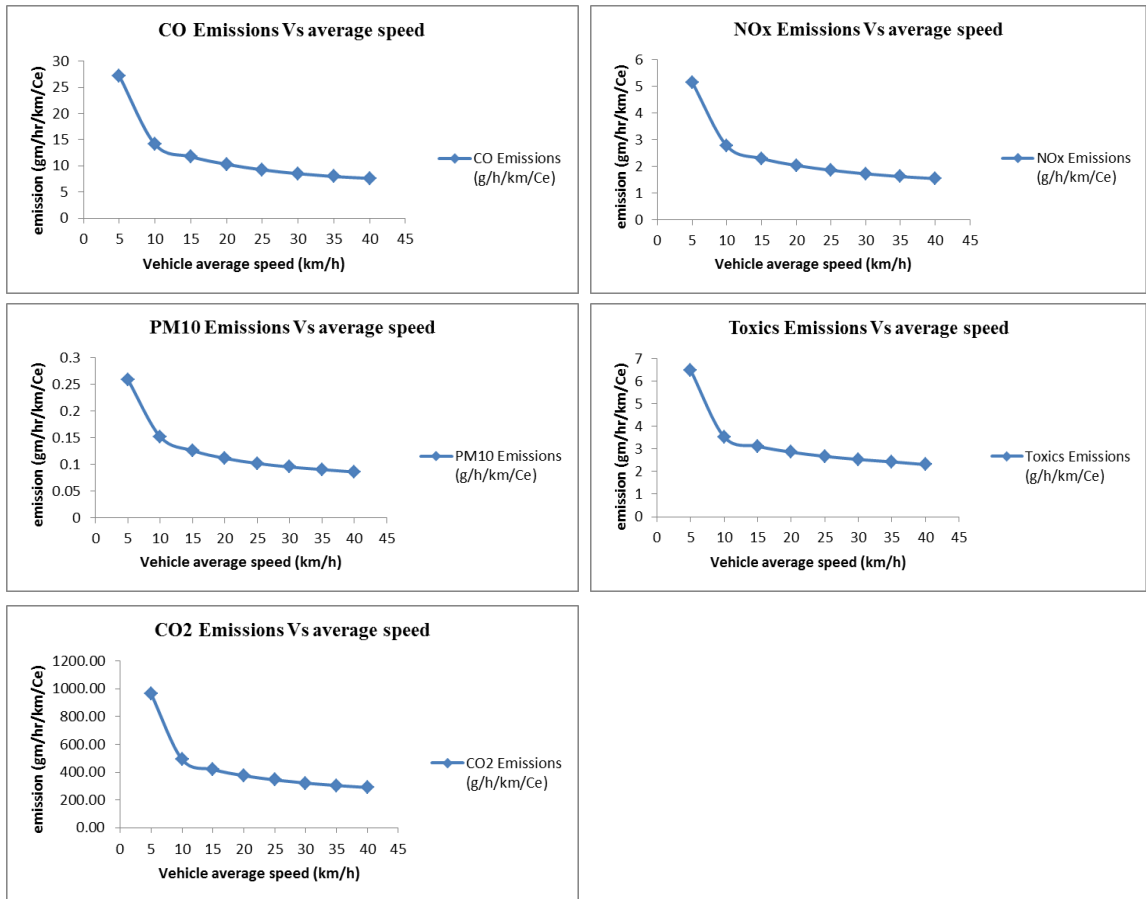


Fig. A2 Emissions (CO, NOx, PM10, Toxics and CO₂) from the vehicle fleet (combination of all vehicles) of Dhaka City in relation to the average speed of vehicles for the year 2012.

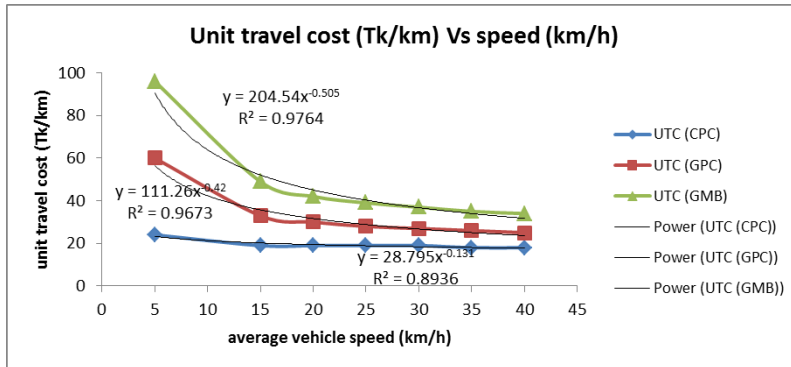


Fig. A3 Unit travel cost of different private vehicles (vehicles with different engine capacity and running with different types of fuels) in relation to the average speed of vehicles on road; note: UTC = Unit travel cost, CPC = CNG driven PC (private cars), GPC = Gasoline driven PC, and GMB = Gasoline driven PC with engine capacity >2.4 L.

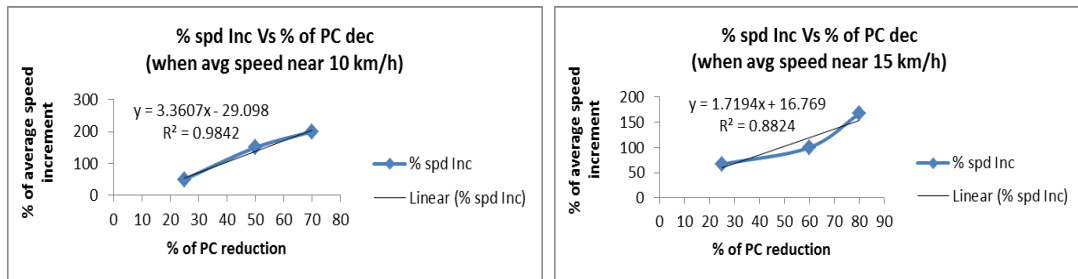


Fig. A4 Percentage of speed increment in relation to the percentage of private vehicle reduction in the city roads of Dhaka City, calculated based on the field survey in 2012.

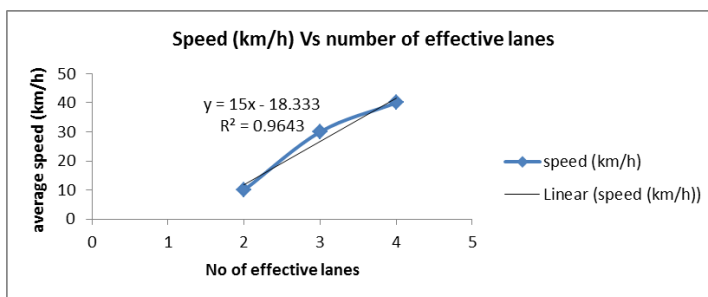


Fig. A5 Average speed of vehicles on road in relation to the number of effective lanes (i.e. lanes available for vehicle movement); relationship obtained based on field survey in Dhaka City in 2012).