Please cite this article as:
Rahman, M. H., Chin, H. C. and Haque, M. M. "Sustainability in road transport: an integrated life cycle analysis for estimating emissions", International Conference on Sustainable Built Environment (ICSBE) – The State of the Art, Kandy, Sri Lanka, 2010.

SUSTAINABILITY IN ROAD TRANSPORT: AN INTEGRATED LIFE CYCLE ANALYSIS FOR ESTIMATING EMISSIONS

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Abstract: Despite of a significant contribution of transport sector in the global economy and society, it is one of the largest sources of global energy consumption, green house gas emissions and environmental pollutions. A complete look onto the whole life cycle environmental inventory of this sector will be helpful to generate a holistic understanding of contributory factors causing emissions. Previous studies were mainly based on segmental views which mostly compare environmental impacts of different modes of transport, but very few consider impacts other than the operational phase. Ignoring the impacts of non-operational phases, e.g., manufacture, construction, maintenance, may not accurately reflect total contributions on emissions. Moreover an integrated study for all motorized modes of road transport is also needed to achieve a holistic estimation. The objective of this study is to develop a component based life cycle inventory model which considers impacts of both operational and non-operational phases of the whole life as well as different transport modes. In particular, the whole life cycle of road transport has been segmented into vehicle, infrastructure, fuel and operational components and inventories have been conducted on each component. The inventory model has been demonstrated using the road transport of Singapore. Results show that total life cycle green house gas emissions from the road transport sector of Singapore is 7.8 million tons per year, among which operational phase and non-operational phases contribute about 55% and about 45%, respectively. Total amount of criteria air pollutants are 46, 8.5, 33.6, 13.6 and 2.6 thousand tons per year for CO, SO_2, NO_x, VOC and PM_{10}, respectively. From the findings, it can be deduced that stringent government policies on emission control measures have a significant impact on reducing environmental pollutions. In combating global warming and environmental pollutions the promotion of public transport over private modes is an effective sustainable policy.

Keywords: Life Cycle Analysis, Environmental Pollution, Global Warming, Road Transport Emissions

1 Introduction

Global civil development is directly dependent on the performance of transport sector. Although mobility is the key parameter of economic, social as well as human development, its adverse impact on our ecological environment is also enormous. Road transport is one of the largest sources of energy consumption, green house gas emissions and environmental pollutions (Mayeres, 1996). To clearly understand and address the environmental impacts from this sector, it is important to quantify the impacts from the entire life cycle considering both operational and non-operational phases. An integrated approach is more appropriate in identifying significant contributors of emissions and thus will be helpful in designing guidelines and policies to combat negative environmental impacts from the road transport.

In the environmental inventory of transport sector, most of the studies focused on the operational phase of either passenger transport (e.g., Small, 1995, MacLean, 1998), public transport (e.g., Small, 1995) or freight transport (e.g., Stodolsky, 1998). Some studies have also been focused on individual components of non-operational phases. For example, Cohen et al. (2003) have conducted inventory on fuels used in transport and Lave (1977) has studied transport infrastructures. However, non-operational phases like manufacture, construction, and maintenance were not well addressed in estimating environmental impacts. Moreover, considerations on different modes of transport and different life-cycle phases in a same life cycle analysis were also not given a fuller attention. Therefore an integrated study considering different phases of life cycle as well as different modes of transport is needed to achieve a holistic understanding on the contributing factors of emissions.

The fast-emerging global environmental concerns lead the global leaders to employ alternative technologies and options in reducing environmental impacts from the road transport sector. Successful evaluations of the alternatives require a holistic look on the inventory of the whole life-cycle of transport system. The objective of this study is to develop a component based life cycle inventory model for estimating emissions from the road transport sector. To achieve this, the whole life cycle of road transport has been segmented into vehicle, infrastructure, fuel and operational components and inventories have been conducted on each of these components for different modes of transport. The model has been demonstrated for the road transport sector of Singapore. Note that Singapore is a densely populated (4.8 million) and city state island country with an area of about 707 sq. kilometers, and about 3,325 km of road.

2 Methodology

2.1 Approaches in Life Cycle Assessment

The whole life cycle of the road transport sector has been segmented into four phases: vehicle, infrastructure, fuel, and operation. The vehicle, fuel, and infrastructure phases are complex with many processes as well as many resource inputs and environmental outputs. Life-cycle assessment (LCA) is the most comprehensive tool for dealing with these complexities and for quantifying environmental effects of these phases. The basic framework (ISO 14040, 1997) of the life cycle assessment and its applications is shown in figure 1.

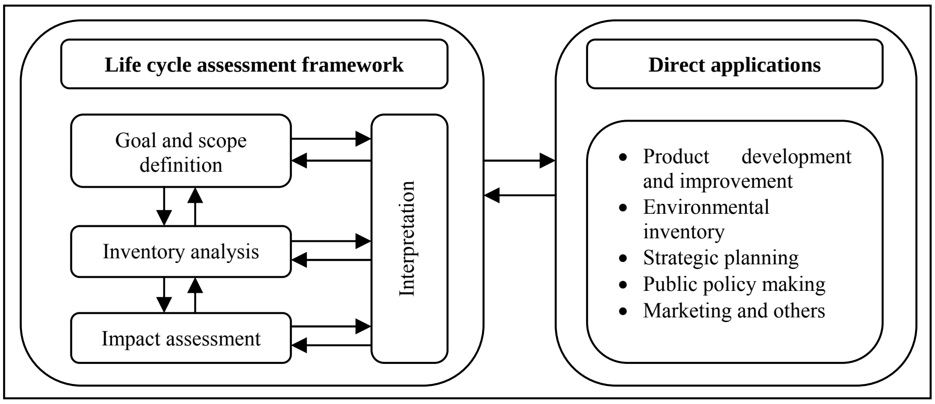


Figure 1 Framework and application of life cycle assessment

There are three approaches of LCA analysis: 1) process, 2) input-output, and 3) hybrid. The 'process' LCA approach identifies and quantifies resource inputs and environmental outputs at each life-cycle stage based on unit process modeling and mass balance calculations (Curran, 1996). Although 'process' LCA enables specific analyses more visual, it is usually time and cost intensive due to heavy data requirements, especially when primary, secondary, tertiary or higher level tiers of inputs are attempted to be included in the model. To overcome these limitations, an alternative LCA model has been emanated which is economic input-output based LCA (Leontief, 1936). The 'input-output' based LCA incorporates environmental impact data to economic flow databases. These databases are usually maintained by the statistical bodies of any nation or economy. This well-established econometric LCA model quantifies interdependencies among the different sectors by effectively mapping the economic interactions along the supply chain of any product or service in that particular economy. Emissions and associated impacts are then assigned to different sectors. In this study, the EIO-LCA software (EIO-LCA, 2008) has been used to calculate the environmental inventory of different products and processes. A hybrid LCA model combines the advantages of both process LCA and economic input-output LCA. In this study, the inventory from vehicle and fuel component is conducted using 'input-output' LCA approach whereas inventories from operation and infrastructure (except lighting) components have been computed following 'process' and 'hybrid' LCA approach, respectively. The inventory of the lighting sub-component in the infrastructure component is obtained by using 'process' approach. The estimation approaches will be briefly addressed in subsequent sections.

2.2 Proposed Model for Life Cycle Analysis of Road Transport

In order to assess the total environmental impact from road transport, the total transport life cycle has been divided into four phases: vehicle (which constitutes vehicle manufacture, tire production, vehicle maintenance and insurance), infrastructure (which includes construction and maintenance of road infrastructures, parking facilities, associated other infrastructure facilities and lighting operation), fuel (which includes fuel production) and operation (which includes the environmental inventory during the operational phase of vehicular travels). Due to uncertainties in the after-use dumping and recycling of vehicles, the end-use phase is not considered in this study. In addition, only operation phase of lighting has been considered due to insignificant contribution from non-operational phases of lighting facilities. The emission types considered in the inventory include both green house gases and criteria air pollutants. According to Land Transport Authority (LTA), vehicles are classified as motorcycles and scooters (MC), car and taxis, light goods vehicles (LGV) ($\leq$ 3.5 ton), heavy goods vehicles

(HGV) (> 3.5 ton) and buses (LTA, 2008). The scope of the analysis in terms of object boundaries of LCA in road transport has been presented in figure 2. The phases for the inventory are presented in the dashed border.

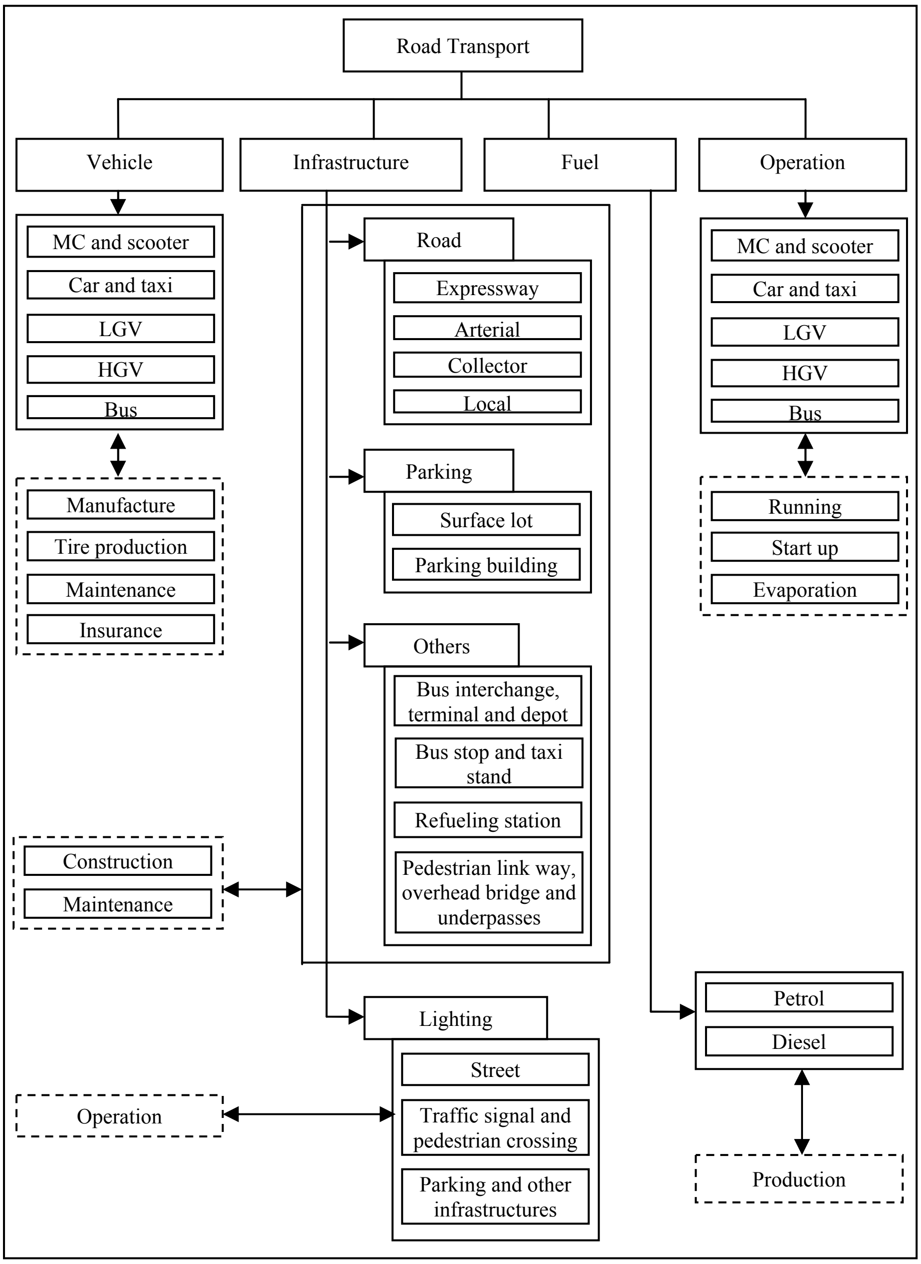


Figure 2 Component based LCA framework of road transport

2.3 Mathematical Equations for Estimating Emissions

To illustrate computation methodology of the total yearly inventory, let f_{ev} be the emission factor per VKT (vehicle kilometers travelled) of travel (summation of inventory from all life cycle components, obtained using methodologies described in section 2.4) for emission type *e* from vehicle type *v*. The total yearly amount of emission of emission type *e* from all vehicle types can be obtained from the following relationship:

$$\mathbf{X} = \mathbf{FT} \quad (1)$$

where **X** is the $(E \times 1)$ emission impact matrix, and E is the number of emission types given by

$$\mathbf{X} = \begin{bmatrix} \cdot \\ x_{Ye} \\ \cdot \end{bmatrix} \tag{2}$$

The elements x_{Ye} of **X** matrix represent the total yearly amount of emission type e generated from road transport. **F** is the *(E×V)* emission factor matrix; where *E* and *V* are the number of emission types and number of vehicle types, respectively. The elements of **F** matrix f_{ev} denote the per VKT emission factor in g/km of the emission type e from vehicle type v. **T** is the *(V×1)* VKT matrix, whose elements t_v denote the total annual VKT for vehicle type v. **F** and **T** are given by

$$\mathbf{F} = \begin{bmatrix} \cdot & \cdot & \cdot \\ \cdot & \frac{f_{ev}}{10^6} & \cdot \\ \cdot & \cdot & \cdot \end{bmatrix} \text{ and } \mathbf{T} = \begin{bmatrix} \cdot \\ t_v \\ \cdot \end{bmatrix} \tag{3a-b}$$

The matrix **T** is obtained from the following relationship:

$$\mathbf{T} = \mathbf{PK} \tag{4}$$

where **P** is a diagonal matrix with diagonals p_v representing the population of vehicle type v and **K** is the *(V×1)* average annual kilometers matrix with elements k_v representing the average annual kilometers travelled by vehicle category v.

2.4 Estimating Emission Factors for Life Cycle Components

The whole environmental inventory has been performed for data and economic year 2008. Emission factors have been obtained from the inventory of each life cycle component for all modes of road transport. Finally, these emission factors have been summed up to obtain the life cycle emission factor (f_{ev}). The subsequent sections discuss estimation of emission factors from vehicle, infrastructure, fuel, and operational components respectively.

2.4.1 Vehicle Component

For each category of vehicle the life cycle inventory has been performed by dividing it into four sub-components: manufacture, tire production, maintenance and insurance. Environmental inventory has been conducted for whole vehicle life. Afterwards based on life period of the vehicle the inventories have been normalized to per vehicle year. In order to reflect the vehicle usage policy of Singapore (VQS-CoE), the lifetime of each of motor cycle, car, LGV and HGV have been assumed to be 10 years and 12 years lifetime has been assumed for each bus. The vehicles used in Singapore are imported from different economies of the world. Therefore computation of the manufacturing inventory should be based on the economy where the vehicle was manufactured. The global market share for the motor vehicle production of different economies (OICA, 2009) shows that China shares the maximum of twenty three percent of global motor vehicle production followed by Japan, USA, Germany and other economies. Due to poor availability of the Japanese environmental data, the EIO-LCA database currently does not include Japanese economy. Therefore, China, USA and Germany have been considered in this study for the lifecycle environmental inventory of vehicle manufacture and weighted based on their respective global vehicle production share. In the EIO-LCA model, the accuracy of inventory from a particular economy increases with increase in number of sectors in input-output table. Therefore, the combined weight (based on global production share and number of sectors in EIO-LCA) of economies is used in computing inventory from vehicle manufacture. For each category of vehicle the economic cost of vehicle manufacture, tire production, maintenance and insurance based on economic year 2008 has been inputted into the EIO-LCA and the associated environmental inventories have been obtained. After obtaining the total life cycle (manufacture, tire production, maintenance and insurance) inventory of a particular vehicle type v, the emission factor, $f_{ev,vc}$ per VKT (from vehicle component) for emission type e and vehicle type v is computed as:

$$f_{ev,vc} = \frac{x_{ev,life}}{Life_v \times k_v} \quad (5)$$

where $x_{ev,life}$ = total amount of emission type e from whole life of a vehicle type v, $Life_v =$ life of vehicle type v in years.

2.4.2 Infrastructure Component

Road transport infrastructure component has been divided into three sub-components: (1) road construction and maintenance, (2) construction and maintenance of parking and other facilities and (3) lighting operation.

2.4.2.1 Road Construction and Maintenance

The roads in Singapore are classified as expressway, arterial, collector and local. The length and width of each type of roads are obtained from Land Transport Authority (LTA, 2008). The life of pavement has been assumed as 45 years with maintenance interval after initial construction (years) as 15-10-10 (AASHTO, 1993; Huang, 2004). The flexible pavement has two layers: sub base layers (compacted soil and aggregate) and wearing course layer (asphalt). In the inventory analysis, maintenance represents the replacement of wearing course. The thickness of layers is obtained from AASHTO specifications for roadway design. The life cycle assessment tool for flexible pavement PaLATE (PaLATE, 2004) has been used in this analysis in which total inventory is a function of length, width and thickness of wearing course and sub-base layers and materials. Inventory per year from road construction and maintenance is obtained from life cycle inventory for construction and maintenance of roads by dividing with their life period.

2.4.2.2 Construction and Maintenance of Parking and Other Facilities

An indirect approach has been undertaken to estimate the area of parking and other infrastructural facilities (other than roads) for the road transport. This approach divides parking and other infrastructural facilities (other than roads) into two sub-categories: (1) Sub-category 1: Construction of parking buildings, passenger facilities at bus interchanges, pedestrian overhead bridges and underpasses, and refueling stations; and (2) Sub-category 2: Construction of surface lots for parking, bus and truck terminals, bus interchanges, bus depots, bus stops, taxi stands and pedestrian covered link ways. Infrastructures of sub-category 1 are assumed as similar to typical concrete structure buildings and life cycle environmental inventory has been performed on account of total floor area of these concrete buildings. Infrastructures of sub-category 2 are assumed to be similar to road pavements and life cycle environmental inventory is performed on account of total area of these facilities. At first, net vehicle footprints of each vehicle type v have been computed from its net dimensions. An increase of 80% has been made on net vehicle footprint (based on AASHTO, 2004): 30% increase to get the parking footprint from the net vehicle footprint and another 50% increase to facilitate vehicle maneuvering for parking. Assuming that, every motorcycle and private car will consume double parking daily (a night-time origin parking and a day-time trip destination parking), their parking area have been doubled. A further 30% increase for each category of vehicles has been assumed since the available parking area or actual parking capacity is 30% more than the current usage. Assumed parking location by vehicle type is: Motorcycles (surface lots), cars and taxis (50% at multi-storied car parks and 50% at surface lots), goods vehicles (surface lots and truck terminals), buses (bus terminals, bus interchanges and bus depots). Total area of bus stops, taxi stands and pedestrian covered link ways and total area of passenger facilities at the bus interchanges, pedestrian overhead bridges and underpasses is obtained from LTA (LTA, 2008). Thus, total pavement equivalent area and total multi-storied car-park building floor equivalent area is estimated. Life of multi-storied car-park buildings has been assumed to be 50 years (Guggemos, 2005) and assumed reconstruction interval of surface lots or pavement equivalent areas is 15 years (Huang, 2004). LCA of the multi-storied car-park building equivalent areas are computed as the concrete structure based on floor area estimates (Guggemos, 2005) using 'hybrid' approach and LCA of pavement equivalent areas of surface lots are calculated by PaLATE using 'process' approach. Finally, the life cycle inventory of these parking areas is normalized to per year inventory by dividing by their respective life.

2.4.2.3 Lighting Operation (Street, Traffic, Parking and Others)

Road transport lighting has been classified into three classes: (1) street lighting, (2) traffic signals and pedestrian crossing lighting and (3) lighting for parking and other facilities. The street lighting pattern, spacing and bulb type, total number of traffic and pedestrian crossing lights and parking lighting data is obtained from LTA (LTA, 2008). Street and parking lights are assumed to operate 12 hours daily whereas traffic and pedestrian crossing lights operate for 24 hours. Based on bulb wattage used in each lighting type, total yearly electricity consumption has been computed for each lighting type and then summed up. The yearly inventory from lighting is computed by multiplying total yearly electricity consumed (KWh) by lighting by the amount of inventory per KWh of electricity production (Deru, 2007).

2.4.2.4 Summary on Infrastructure Component

Total yearly inventory from infrastructure component is obtained by summing up the yearly inventories from all of its sub-components (road, parking and other facilities, lighting). In order to estimate the infrastructure inventory by vehicle category, (1) the inventory from road construction and maintenance have been distributed to vehicle categories by their respective damage shares, which is the cumulative effect of damage factors (Huang, 2004), total numbers of vehicles and average annual VKT by vehicle type; and (2) the inventory from road lighting, parking and other infrastructure facilities have been distributed to vehicle categories by their respective cumulative effect of vehicle footprint area, total numbers of vehicles and average annual VKT. Finally, emission factor, $f_{ev,ic}$ per VKT (from infrastructure component) for emission type e and vehicle type v is computed as:

$$f_{ev,ic} = \frac{x_{ev,Y,ic}}{p_v \times k_v} \qquad (6)$$

where $x_{ev,Y,ic}$ = total amount of emission type e per year from infrastructure component for all vehicles of vehicle type v.

2.4.3 Fuel Component

The life cycle inventory from fuel component has been computed using input-output LCA. In Singapore, petrol is used as the primary fuel for motorcycles and cars and diesel is the primary fuel for LGV, HGV and buses. The production cost (EIA, 2010) of each fuel type is taken as input into the EIO-LCA model and corresponding environmental inventory has been obtained. Yearly inventory from fuel component by vehicle type v using fuel type f is calculated as:

$$x_{ev,Y,fc} = FE_{v,f} \times p_{v,f} \times k_{v,f} \times x_{e,f} \qquad (7)$$

where $x_{ev,Y,fc}$ = total amount of emission type e per year from fuel component for all vehicles of vehicle type v using fuel type f; $FE_{v,f}$ = fuel efficiency of vehicle type v using fuel type f (liter/km); $p_{v,f}$ = population of vehicle type v using fuel type f; $k_{v,f}$ = average annual kilometers travelled by each of vehicle type v using fuel type f; $x_{e,f}$ = amount of emission type e per liter of production of fuel type f and f = fuel type (petrol and diesel). Emission factor per VKT (from fuel component) for emission type e and vehicle type v is calculated as:

$$f_{ev,fc} = \frac{x_{ev,Y,fc}}{p_{v,f} \times k_{v,f}} = FE_{v,f} \times I_f \quad (8)$$

2.4.4 Operation Component

The regulations on vehicle emission control in Singapore are tabulated in table 1.

Table 1 Vehicle emission control regulations in Singapore

Emission control regulations	Effective from
Mandatory periodic inspection	na
Unleaded petrol and diesel	1 July, 1998
Sulfur content ≤ 0.05% or 500 ppm	1 March, 1999
Smoke emission test: Chassis dynamometer smoke test (CDST) instead of free acceleration smoke test	1 September, 2000
EURO II (1996) emission standard for all new vehicles	1 January, 2001
ULSD: Sulfur content ≤ 0.005% or 50 ppm	1 December, 2005
EURO IV (2005) emission standard for all new vehicles	3 September, 2006

Based on the emission standard followed in Singapore, the vehicle operational emission inventory model COPERT 4 (EEA, 2009) is considered as the most suitable and accurate model for Singapore context and therefore has been used in this study which estimates vehicle operational inventory based on vehicle emission standard, fuel standard, vehicle speed and weather data. The model inputs are: (1) weather data: minimum and maximum temperature: 77°F and 90°F respectively; specific humidity: 160 grains/lb (for average temperature of 85°F and an average relative humidity of 80%); (2) vehicle speed: average; (3) vehicle population by vehicle type, fuel type used, average annual VKT by vehicle type; (4) vehicle emission standard: EURO II; and (5) petrol and diesel standard: EURO II; fuel sulfur content: 50 ppm. Total yearly emission by vehicle and emission types is obtained as output. Emission factor $f_{ev,oc}$ per VKT (from operation component) for emission type e and vehicle type v is calculated as:

$$f_{ev,oc} = \frac{x_{ev,Y,oc}}{p_v \times k_v} \quad (9)$$

where $x_{ev,Y,oc}$ = total amount of emission type e per year from operation component of all vehicles of vehicle type v.

2.4.5 Inventory Summary

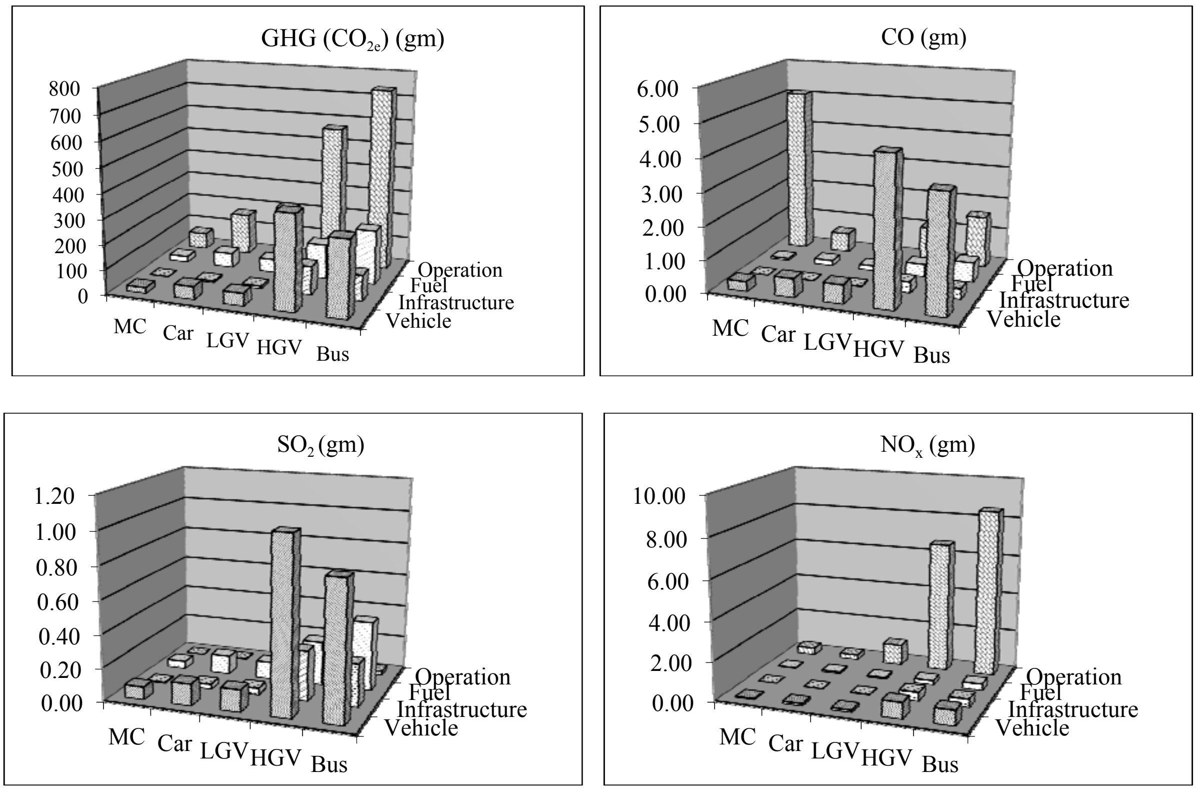
Total emission factor per VKT (from all life cycle phases) for emission type e and vehicle type v is calculated as:

(10)

where = emission factor per VKT for emission type e and vehicle type v from life cycle component c and c = life cycle components (i.e., vehicle, infrastructure, fuel and operation). Finally, the total yearly amount of emission for each emission type e from all vehicle types v is obtained from equation (1).

3 Results and Discussion

Figure 3 presents the emission factor per VKT of travel for different vehicle types. Here CO_{2e} (obtained from weighted global warming factor of CO_2, CH_4, O_3 and N_2O) is representative of all green house gases and CO, SO_2, NO_x, VOC and PM_{10} are criteria air pollutants. For a particular vehicle type v, the emission factor of emission type e is presented separately for different life cycle components, the sum of which determines the total life cycle emission factor per VKT (f_{ev}). For example, in year 2008, each kilometer of car travel was associated with 287 gm of CO_{2e} emission, of which 168 gm was from operational phase and 52, 8 and 59 gm were from vehicle, infrastructure and fuel components, respectively.



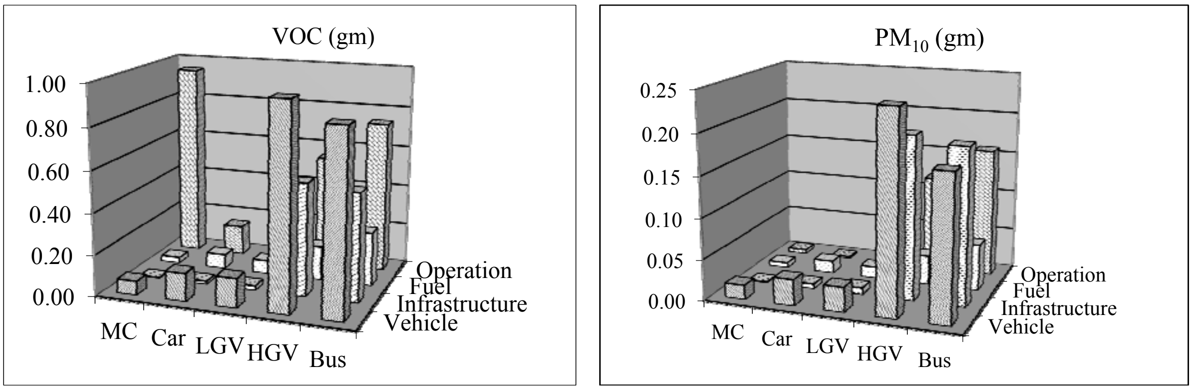


Figure 3 Pollutant emissions (by mode and LCA phase of road transport) per VKT

The vehicle component of the emission factor is determined by the amount of emission generating materials and processes involved in manufacture, maintenance etc. As noticed from figure 3, emissions from heavy vehicles are higher as more amounts of materials and processes are involved in their manufacture, tire production, maintenance and insurance. Green house gas (CO_{2e}) emission factors for vehicle component of MC, car, LGV, HGV and bus are 23, 52, 51, 379 and 305 gm, respectively. The emissions of air pollutants also exhibit variations in similar fashion.

The emissions associated with infrastructure component are primarily led by damages of different vehicles on road infrastructures. Hence it is not surprising that heavy vehicles lead higher emission factors (figure 3). The green house gas emission factors for this component are 2, 8, 10, 113 and 103 gm for MC, car, LGV, HGV and bus, respectively. PM_{10} emissions are higher for this component as more particulate matter in the form of dusts is associated with the construction and maintenance of roads and other infrastructure facilities.

For fuel component, the amount of emission is led by two factors: fuel type and vehicle fuel efficiency. In this component the emissions are generated in the processes and materials involved in the production of fuels. The CO_{2e} emission factors for this component for MC, car, LGV, HGV and bus are 24, 59, 54, 169 and 208 gm, respectively.

The emissions from the operational component is the most significant, as it is directly associated with the road environment. The principal factors affecting the emission from this component are vehicle fuel efficiency, fuel type and standard, vehicle emission standard, and emission control measures (e.g., inspection and maintenance, use of catalytic converters etc.). Green house gas emission factors for the operational phase are 65, 167, 215, 567 and 737 gm for MC, car, LGV, HGV and bus, respectively. The CO_{2e} emission factors are mainly determined by fuel type (carbon content of the fuel) and vehicle fuel efficiency. For example, hybrid cars and those fuelled by natural gas produce CO_{2e} up to 25% less than cars running on petrol. However, the usage of alternative fuels in all modes of transport is still at the initial phase. Recently, only 0.005% of buses are CNG-driven; about 1% of cars use alternative fuels (hybrid and bi-fuel CNG). However about 8% of taxis are now driven by bi-fuel CNG. Due to less hauling capacity, the usage of these alternative fuels in heavy goods vehicles is almost negligible. Singapore is looking forward to implement more energy efficient fuel and vehicle technologies in near future.

The use of catalytic converters significantly decreases the CO, NO_x and other hydrocarbon emissions. These emission factors were about 40% - 70% higher, when catalytic converters were not in place. Due to dimensional inconvenience, its usage on motorcycles is limited. This may lead in higher operational emission factors for CO, NO_x and VOC in case of motorcycles (figure 3). The improvement of vehicle emission standards has also significantly reduced the emissions from vehicles. For example, adoption of Euro II from Euro I standard has resulted in 70% and 40% reduction respective in CO and PM_{10} emissions and further stringent standard, i.e., Euro IV standard results in 50% and 60% reductions on those gases.

SO_2 emissions have drastically reduced due to stringent sulfur content regulations in both petrol and diesel fuels. For example, currently a bus using 50 ppm standard ULSD (ultra low sulfur diesel) emits only 0.02 gm SO_2 per km, while it was emitting approximately 10 times SO_2 when the fuel it used followed 500 ppm sulfur standard (before 2005).

Results imply that incorporation of continuous stringent emission control policies lead Singapore to reduce the emissions from the operational component significantly over last few years. The gradual implementation of stricter vehicle standards (see table 1) has reduced the operational emission factors.

The average car occupancy in Singapore is 1.7 while an average bus accommodates passengers in the range of 85 to 143 (Menon and Kuang, 2008), which is 50 to 85 times higher than that for an average car. An average bus emits only 4, 3, 4 and 5 times higher CO_{2e}, CO, SO_2 and VOC emissions, respectively, than that of an average car in the operational phase and these multipliers are 5, 4, 5 and 6, respectively when the whole life cycle emissions are considered (figure 3). However when emission per passenger km is considered, emission from buses are approximately 10 times lower than that of a private car. For a city state country like Singapore, good public transport is the most promising solution not only to combat the increasing problems of traffic congestion, but also contribute in lowering global green house gases and environmental pollution. Management policies are looking forward to a more sustainable transportation system mainly by further promoting public transport usage in Singapore (Haque et al., 2010).

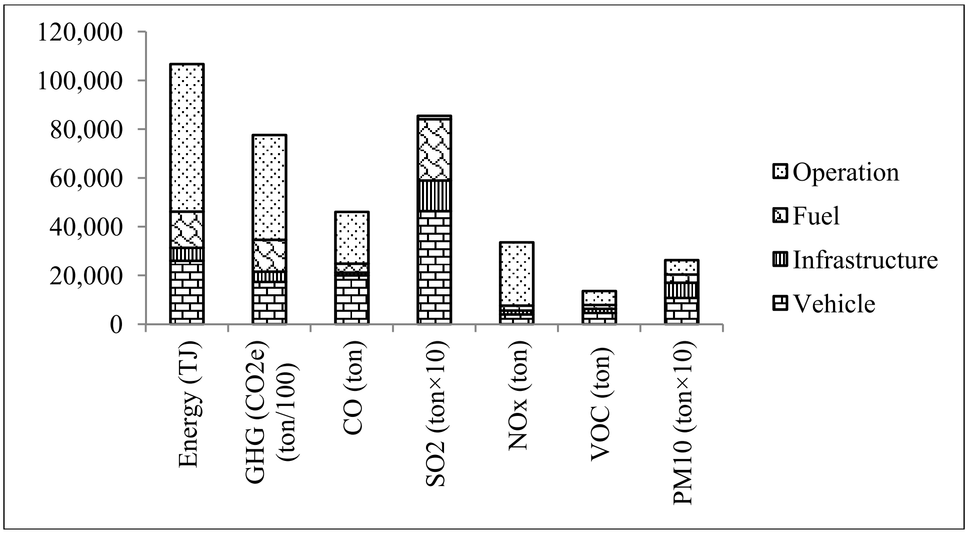


Figure 4 Energy consumption, GHG and pollutant emissions for year 2008

The total life cycle emissions from the road transport of Singapore in year 2008 are presented in figure 4. For year 2008, the total life cycle green house gas emissions from the road transport sector of Singapore is 7.8 million tons, among which operational phase and non-operational phases contribute about 55% and about 45%, respectively. Total amount of criteria air pollutants are 46, 8.5, 33.6, 13.6 and 2.6 thousand tons for CO, SO_2, NO_x, VOC and PM_{10}, respectively. In almost every emission type (except SO_2 and PM_{10}) the operational component is the dominating contributor in emissions. The drastic reduction in the operational SO_2 emission (figure 4) has been obtained by stringent sulfur content regulation in fuels. It is notable that, although the whole life cycle inventory for road transport of Singapore has been conducted in this study, all pollutants and gases are not emitted in Singapore. The operational inventory is fully emitted from the road environment, whereas part of emissions from other non-operational life-cycles components is not directly emitted from this road environment. For example, for the road construction and maintenance there are both on-site emissions and of-site emissions, which is associated with the production and processes associated with materials used in road construction and maintenance.

4 Conclusions

This study has been aimed to develop an integrated life cycle inventory of road transport which considers both operational and non-operational phases as well as takes into account different modes of transport. The model has been demonstrated for the road transport sector of Singapore. It has been found total life cycle green house gas emissions from the road transport sector of Singapore is 7.8 million tons per year. Importantly non-operational phases contribute a significant 45% of those emissions. While CO, NO_x, VOC criteria pollutants represent more pollution during operational phase, the corresponding proportions for SO_2 and PM_{10} are higher during non-operational phases. Stringent government policies and regulations on fuel and vehicle technologies and standards have been found to yield significant lower emissions from vehicles. The utilization and promotion of public transport modes is an effective policy in combating negative environmental impacts and will be helpful to achieve a sustainable transportation system.

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