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EFFECT OF SPEED ON EMISSIONS OF AIR POLLUTANTS IN URBAN ENVIRONMENT: CASE STUDY OF TRUCK EMISSIONS

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ABSTRACT: Dynamic emission factors and emission inventories of CO, VOC, $VOC_{evap.}$, NO_x, SO_x and PM of truck in Bangkok, Thailand were developed using IVE (International vehicle emission) model for the year 2012 to 2024. The year 2012 was chosen as base year since fuel quality had been improved from Euro II to Euro IV standard from that year. Speed of truck driven in study area was chosen as variable parameter for sensitivity analysis of its influence to the emissions of air pollutants because there are no further plans in upgrading or improvement of fuel quality during this period. Truck's Bangkok driving cycle was used as input data in the IVE model. Average speeds used in the model simulation were varied from existing condition (15 km/hr) to the maximum of 80 km/hr. It was found that an average speed of 40 km/hr was the optimal speed in reducing of air pollutants emitted from truck. At this speed, reduction of emission factors of air pollutants as compared with current average velocity of 15 km/hr were about 46%, 54%, 16%, 51%, 53% and 27% for CO, VOC, $VOC_{evap.}$, NO_x, SO_x and PM, respectively. Therefore, efforts in increasing average speed of at least to about 40 km/hr can be used as a measure to achieve the sustainable transport particularly in the green logistic businesses.

Keywords: Emission factors, Emission inventory, Conventional air pollutants, Speed, IVE model

1. INTRODUCTION

Demanding of energy in the transport sector is increased since Thailand started to transform its economy to an industrialized country. The transport sector has been the largest energy consuming sector since 1995 [1]. In Thailand, manufacturing and mining sector and transport sector are about 70 percent of total energy use. Almost all energy used by the transport sector comes from petroleum products which represent 72 percent of the total consumption of petroleum products and 76 percent of transport energy are consumed in the road sector. Truck transport is a dominant of Thailand's freight of the logistics industry that was carrying over 95 percent of ton/km of freight [2]. In addition, consumption of the fuel in the transport sector is also produced an extremely large amount of pollutants emissions. Almost all of the carbon monoxide (CO), 75% of the hydrocarbon (HC) and volatile organic compound (VOC), and 65% of the nitrogen oxide (NO_x) are emitted from vehicles [3]. Pollutant emissions from vehicles are determined by the vehicle's engine type and the fuel it uses that are the two most common engines including spark-ignition (gasoline engines) and diesel engines [4]. Emission control technologies and the age of emission control equipments are one of the factors that effected of pollutants emissions [5].

Moreover, emissions from vehicles are also affected by the driving patterns depend on traffic conditions. Therefore, driving cycles have been developed to represent behavior and characteristics of driving patterns to support estimation of mobile source emissions in many studies.

There are two major alternatives to develop driving cycle. Firstly, it can be computed from various driving modes of constant acceleration, deceleration and speed such as the New European Driving Cycle (NEDC) and the Urban Driving Cycle (ECE-15). Secondly, it can be derived from actual driving data and is referred as real world cycle. The real world cycles are more dynamic, reflecting the more rapid acceleration and deceleration patterns experienced during on road conditions [3].

Defining the speed limits based on the concept of optimal speed of road transport systems has a significant part in the speed management of vehicles [6], [7]. In the logistic business, trucks are important vehicle type used for transporting of goods. There are high variability with regard to trucks characteristics, types and possible uses [8]. Trucks potentially emit air pollutants such as carbon monoxide (CO), nitrogen oxide (NO_x), particulate matter (PM) and volatile organic compound (VOC). These emissions generally relate to speed of the truck. Generally, emissions of air pollutants from mobile sources are higher at lower average speeds, less sensitive for mid-range speeds, and higher as speeds increased depend on the type of pollutants [7]. Results from a study of the US.EPA showed that VOC and CO emissions rates normally drop as speed increases. In addition, NO_x emissions rates turn up at higher speeds. However, the emissions rates at all speeds have been falling over time as newer and more controlled vehicles enter the fleet [9].

This paper proposes the optimal speed in reducing of air pollutants emitted from trucks in Bangkok, Thailand. The dynamic emission factors and emission inventories of conventional air pollutants namely CO, VOC, $VOC_{evap.}$, NO_x, SO_x and PM of trucks were developed using the IVE model for the year 2012 to 2024. The year 2012 was selected as base year in this study since it was the start year which fuel quality in Thailand had been improved from Euro II to Euro IV standard. Bangkok driving cycle developed for truck was used to represent driving pattern and characteristics in this analysis. Average speeds used in the model simulation were varied from 15, 20, 30, 40, 50, 60, 70 and 80 km/hr.

2. METHODOLOGY

In this study, average speed of truck driven in Bangkok was chosen as variable parameter for sensitivity analysis of its influence to the emissions of air pollutants. We assumed that there are no further plans in upgrading or improvement of fuel quality which may affect to truck's emissions. Estimations of emissions were carried out from the year 2012 to 2024 (12 years). Numbers of trucks in the inventory period were forecasted using data of average annual growth rate of truck in Bangkok. This value of 4 % increasing from previous year was derived from average of statistical data from the year 2000 to 2010. Moreover, fleet characteristics of each predicted year were used taking into accounts the existing regulated emission controls and fuel standards in that year. A truck in this study is defined by weight of more than 12 tons and was named as heavy duty diesel truck. An average speed of 15 km/hr was used as BAU (Business as Usual) case. This study assumed that vehicular growth will be estimated, with all new vehicles based on current policies. The BAU case also assumed there will be no considerable changes in environmental or transport policies [10].

The IVE input data consist of a Location file and a Fleet file. Input data of the Location file include truck's Bangkok driving cycle, soak time, number of start-up, fuel characteristics, and average velocity. The Bangkok driving cycle of truck used in this study was as shown in Fig. 1. This driving cycle was converted to vehicle specific power (VSP) bin prior be used in IVE model. The Fleet files in each year were created from secondary data collection. An information on average kilometer traveled, vehicle models, fuel types and age of trucks were collected as the secondary data and were used as input data in Location file. Parameters which affect to the hot stabilized emissions of trucks are trucks technology distribution, VSP and engine stress distribution, inspection and maintenance (I/M) scheme, fuel quality, altitude and meteorological condition (humidity and temperature). These parameters were placed in the model by using actual characteristic of truck and study area. Warm-start and cold-start emissions were separately calculated in the IVE model. These data were computed to obtain an average emission rate expressed in the unit of g/km of trucks.

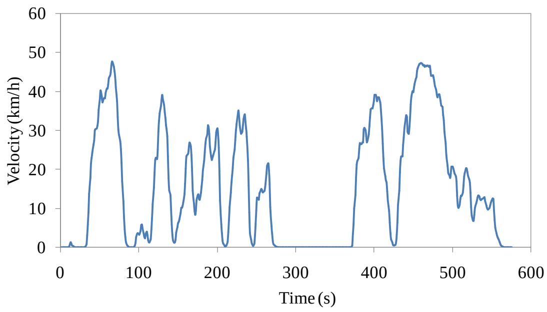


Fig. 1 Truck's Bangkok driving cycle, Thailand.

In BAU scenario, there were about 4% and 96% of trucks in Bangkok driven by CNG (Compress Natural Gas) and diesel (Euro IV standard) fuels, respectively. Fleet technologies of trucks and their index number code used in IVE model in this study were listed in Table 1. The IVE model has a total of 1372 established technologies, and 45 non-defined technologies [11]. All technologies are set as index; each index has an engine/vehicle description including type of vehicle, fuel type, weight, air/fuel control system, exhaust control system, evaporation control system and vehicle age; depends on vehicle kilometer travel.

The conceptual diagram of emission calculation in this study was as presented in Fig. 2.

Characteristics of fuel type, fuel quality and technology of engine used as input data in the inventory year were presented in Table 2. The fuel quality used in this calculation is complied with the Euro IV standard. We assumed that all of the Euro II engine will be replaced by Euro III engine's standard in the year 2023. Compress natural gas (CNG) engine was equipped with the three-way catalyst and Exhaust Gas Recirculation system in throughout the inventory year.

Table 1 Fleet technology of trucks

Index	Meaning
996 997 998	Heavy duty fuel injected natural gas vehicle with 3 way catalyst and Exhaust Gas Recirculation (EGR). Vehicles >33,001 lbs Gross Vehicle Weight Rating (GVWR) and typically >60,000 lbs.
1132 1133	Heavy duty fuel injected diesel vehicle certified to Euro II standards. Vehicles >33,001 lbs GVWR and typically >60,000 lbs.
1140 1141 1142	Heavy duty fuel injected diesel vehicle certified to Euro III standards. Vehicles >33,001 lbs GVWR and typically >60,000 lbs.

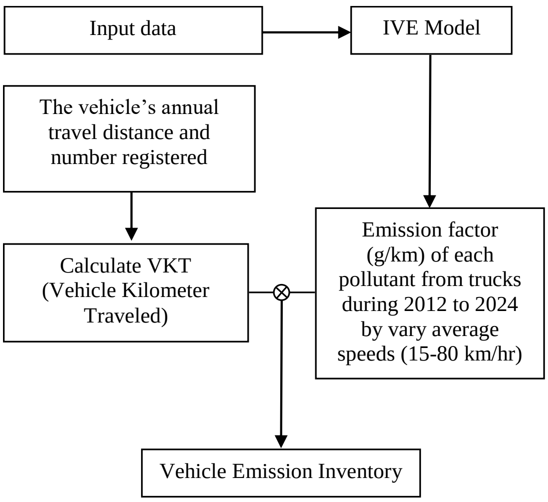


Fig. 2 Calculation process.

3. RESULTS AND DISCUSSIONS

3.1 Number of trucks, speed limited and vehicle kilometer traveled

Criterion used in this study, which the truck age doesn't exceed more than 15 years was assumed in this inventory. Average annual growth rate of truck of 4% is used to estimate total number of truck in each inventory year. Results are as shown in Fig. 3. Number of trucks is slightly decreased from 2013 to 2024. Speeds of truck are varied from its existing value (15 km/hr) to the maximum of 80 km/hr.

Table 2 Fuel type, fuel quality and technology of engine of trucks

Condition/Year	2012-2022	2023-2024
Fuel type		
• Diesel	← 96% →	
• CNG	← 4% →	
Fuel quality		
• Diesel	← Euro IV →	
Technology of engine		
• Diesel	← Euro II & III →	← Euro III →
• CNG	← 3Wy/EGR* →	

*3 way catalyst and Exhaust Gas Recirculation

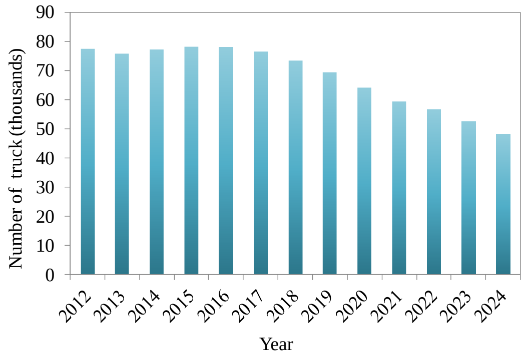


Fig. 3 Number of trucks from 2012 to 2024.

VKT (Vehicle Kilometer Traveled) was calculated by multiplying the annual travel distance (km/year/truck) and number of registered trucks. The annual travel distance of truck was reported as 66,777 km/year/truck. Calculated VKT is shown in Fig.4. The results showed decreasing tendency of VKT which was resulted from termination of old trucks. In this study, the age of in-use trucks was assumed not over 15 years. This termination rate was higher than the replacement rate of new truck. Therefore, VKT was slightly decreased as compare with the base year (2012).

3.2 Truck dynamic emission factors

In this study, dynamic emission factors were calculated since they can help to reveal better estimation of the amount of air toxic emissions, by taking into account the actual characteristics of inventory items [10]. The obtained values were more robust as compared with those obtained from the fixed emission factor, which only depend on the VKT of each year.

The dynamic emission factors of air pollutants of truck calculated from the BAU scenario (average speed of 15 km/hr) was shown in Fig. 5. It was found that NOx was the dominant pollutant having the highest emission factor from truck as compared with other pollutants followed by CO, PM, VOC, $VOC_{evap.}$ and SO_x, respectively. Emission factors of these pollutants in the base year (2012) were 17.32, 5.19, 2.82, 1.01, 0.08 and 0.01 g/km for NO_x, CO, PM, VOC, $VOC_{evap.}$ and SO_x, respectively.

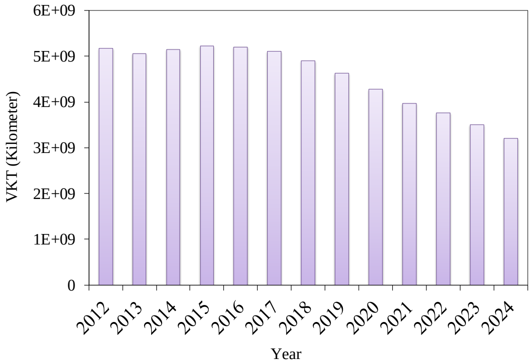


Fig. 4 Vehicle kilometer travel from 2012 to 2024.

Average speeds used in the model simulation were varied from its existing condition/BAU (15 km/hr) to the maximum of 80 km/hr. Temporal variations of dynamic emission factors of each pollutant at each average speed were shown in Fig. 6. Generally, it was found that the lower average speed of the trucks is the higher of emission factor of air pollutant, they emitted. In order to evaluate the difference of emission factor obtained from calculation using each average speed with the BAU scenario, percentage of reduction of emission factors of each air pollutants as compared with current average velocity of 15 km/hr in BAU case were shown in Fig. 7-8.

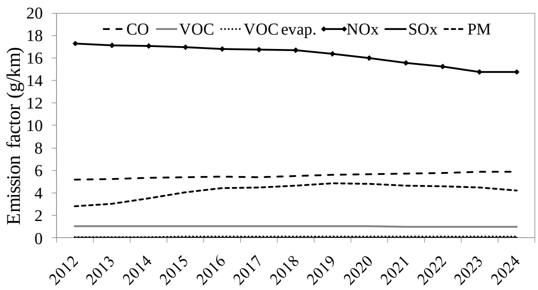
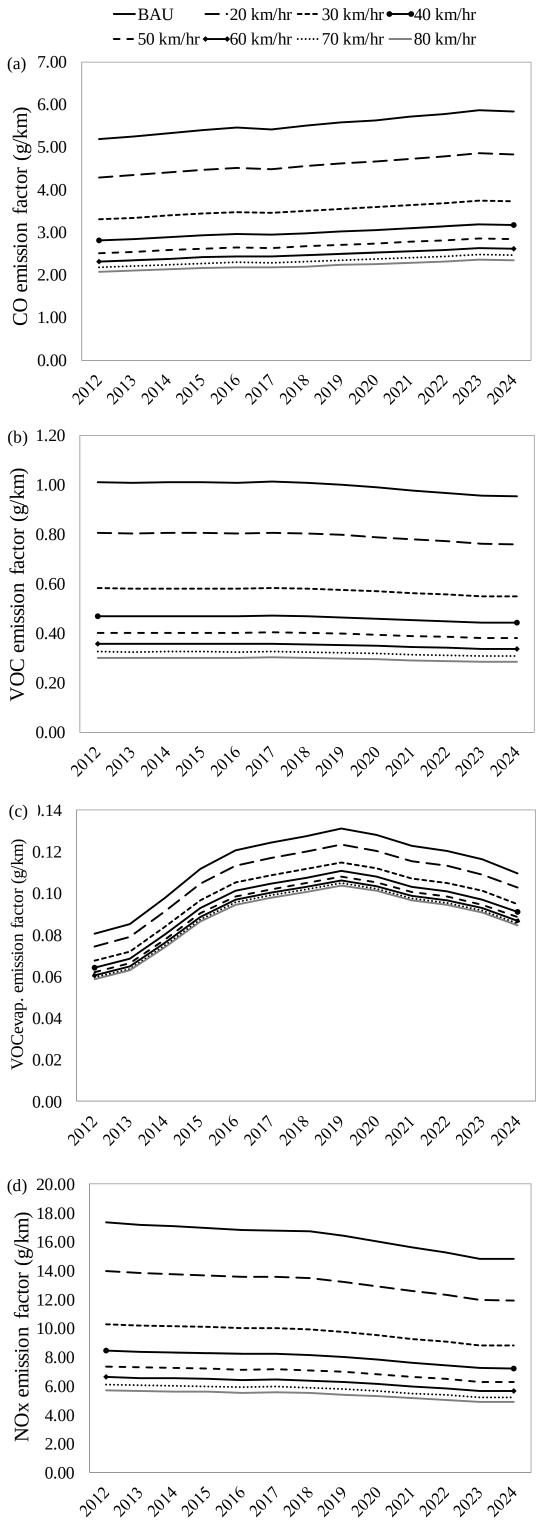


Fig. 5 Dynamic emission factor for BAU case.

Emission factors dramatically decreased when the average speed increased from BAU (15 km/hr) to 40 km/hr (Fig.6). More than 50% reduction of VOC, NO_x and SO_x were reached at this average velocity (Fig.7).

Fig. 8 clearly illustrated that emission factors of NO_x was the most sensitive to changing of average speed of truck. Almost 60% of NO_x emission factor was decreased from its BAU scenario when average speed of 40 km/hr was applied in the calculation. At higher speed (50-80 km/hr), emission factors were still slightly decreased. CO and VOC emissions were significantly affected by the alteration of average speed.



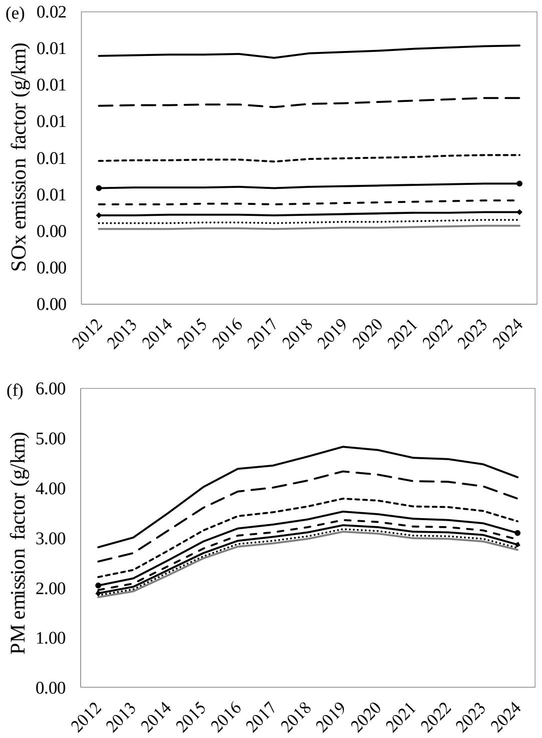
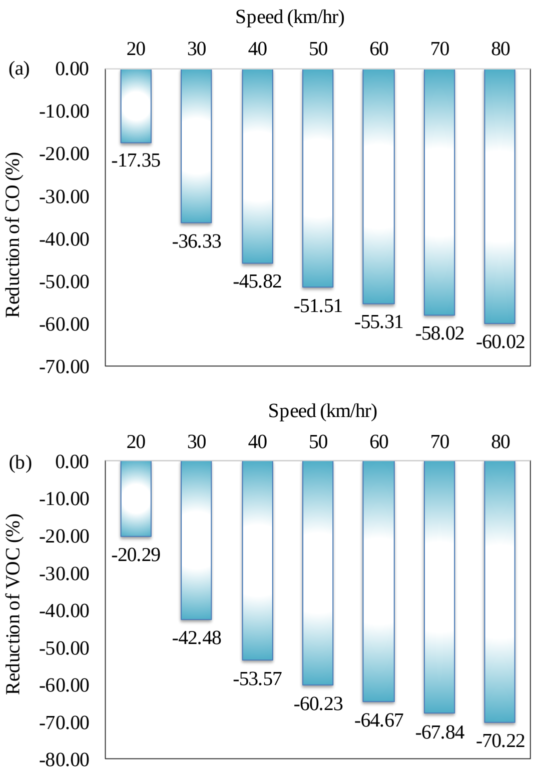


Fig. 6 Effect of speed to emission factors

Maximum reduction rate of SO_x emission was about 25% from its BAU scenario when average speed of truck was increased to about 80 km/hr. These could be explained by the fact that mostly of sulfur dioxide emissions were emitted as result of conversion from sulfur contained in fuel. Unlike with SO_x emissions, oxides of nitrogen were mostly emitted as results of combustion activities (thermal NO_x).



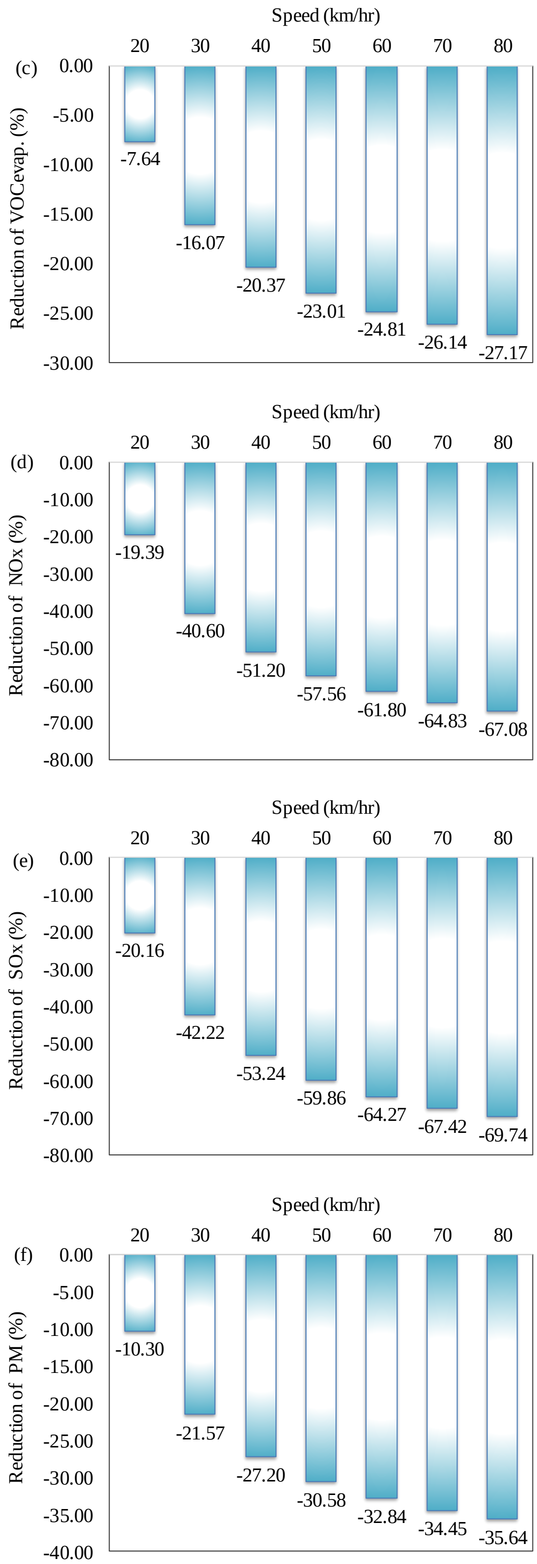


Fig. 7 Effect of increasing speed to reduction of trucks emission factors

US.EPA reported the average in use emissions from diesel heavy-duty truck by using MOBILE 6 emission model [12]. Emission rates of NO_x and

CO at the average speed of 64 km/hr (40 miles/hour) were reported as about 13.78 and 3.70 g/km, respectively. These values were higher than emission rates obtained from calculation at the same speed using IVE model in this study. These differences can be explained by difference of driving cycle, fleet characteristics and fuel quality in each area.

The optimal speed in this study was determined based on decreasing rate of emission factor. This speed was also used as reference value to maintain speed limits at higher than or on average equal to the optimal speed [6].

In this study, an average speed of 40 km/hr was selected as the optimal speed in reducing of air pollutants emitted from truck. This selected value was based on two major criteria.

The first criteria were obtained from results of this study which indicated that an average speed of 40 km/hr could yield significantly decreased of air pollutants emitted from truck, though emission factors were still slightly decreased at higher speed than this level.

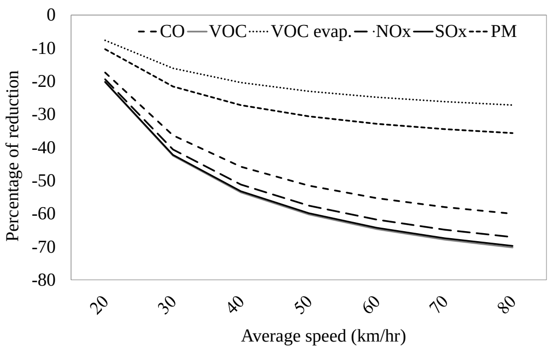


Fig. 8 Percentage of reduction of trucks emission factors comparing with BAU case are affected by average speed.

The second factor of selection of optimal speed was speed limit of truck of not more than 60 km/hr regulated in Thailand. Therefore, with the current policy, trucks are not allowed to drive faster than this level. However, by considering existing speed of 15 km/hr, and characteristics of Bangkok which is a mega-city, we proposed that in practical, the optimal average speed of truck in Bangkok can be raised up to level of 40 km/hr and no driving over than 60 km/hr.

3.3 Truck dynamic emission inventories

Other objective of this study is to assess and elaborate total amount of emission in order to identify factor influenced to emission inventory of air pollutants. Dynamic emission inventories indicate that factors influencing emission amounts of air pollutants from trucks in Bangkok are Vehicle Kilometer Travel (VKT), number of vehicles and emission factor [10].

The VKT of trucks in Bangkok were estimated base on the VKT studied in urban area by [13]. Emission inventories of CO, VOC, $VOC_{evap.}$, NO_x, SO_x and PM were calculated for the year 2012 to 2024. Results were as shown in Fig. 9.

Emission inventory of VOC, NO_x were slightly increased from 2012 to 2015, and were significantly decreased from 2015 to 2024. CO, SO_x and PM were slightly increased from 2012 to 2016, and were significantly decreased from 2016 to 2024. Moreover, $VOC_{evap.}$ was slightly increased from 2012 to 2017, and was significantly decreased from 2017 to 2024. These trends were relevant to number of truck driven and their fleet technologies in each year. Results clearly indicated that NO_x was the major pollutant emitted from truck. Comparison of emission inventory from proposed optimal speed (average speed of 40 km/hr), calculated results showed that emission amount of CO, VOC, $VOC_{evap.}$, NO_x, SO_x and PM were about 46%, 54%, 17%, 51%, 53% and 27% decreased from BAU scenario (average speed of 15 km/hr), respectively.

4. CONCLUSION

Emission factors of air pollutants from truck driven in Bangkok, Thailand were developed using the IVE model. It was found that NO_x was the major type of pollutant emitted from truck. Speed of truck in Bangkok driving cycle was used as variable parameter for testing its influenced to values of emission factor. Results indicated that the higher of average speed, the lower of emission factors of air pollutants emitted from truck. Temporal analysis during the year 2012 to 2024 clearly indicated that dynamic emission factors of air pollutants had decreasing tendency. Emission factor of NO_x was successfully decreased as a result of higher speed of truck which could be explained by better control of thermal NO_x from increasing of combustion efficiency. Average speed of 40 km/hr was proposed as optimal speed for truck in this study.

Two major criteria were used to support this selection. Firstly, at this proposed speed, there were dramatically decreased of emission factors of air pollutants as compared with current fleet characteristics of truck in Bangkok (average speed of 15 km/hr). At higher speed than this level (>40 km/hr), emission factors were still slightly decreased. Secondly, speed limit of truck in Thailand is regulated as not higher than 60 km/hr. By considering that Bangkok is a mega-city, this regulated speed limit may not appropriate to use, practically. Other supporting of this proposed was the maximum speed of truck from the survey of truck driving cycle in Bangkok was 48 km/hr.

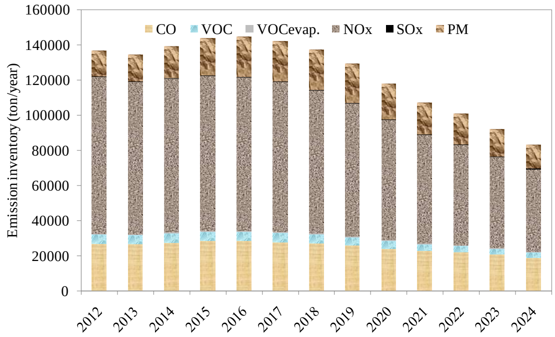


Fig. 9 Trucks emission inventory from 2012-2024 as BAU case.

Therefore, average speed of 40 km/hr was selected as optimal speed of truck in this urban area. Emission inventory of air pollutants emitted from truck were also calculated using derived emission factors obtain from this study. Results indicated that amount of air pollutants emitted from trucks had decreasing tendency. These reductions were resulted by decreasing of emission factors which mostly due to termination of old truck as well as replacing by the new one with higher technology. By increasing average speed from its current level (15 km/hr) to the proposed optimal average speed of 40 km/hr, emission amount of air pollutants was decreased. Particularly, NO_x emissions were decreased more than 50% from their BAU scenario. However there are many factors that affect to emission factors including engine technology, vehicle age, level of maintenance, fuel quality and emission standard in each area. These factors should be considered when estimating emission rate from mobile sources.

The proposed optimal speed at 40 km/hr can be reached by improvement of highway system as well as designated specific time period to allow commuting of truck during the on-road off peak period (from 22.00 – 05.00) when traveling in urban and sub-urban areas should be strictly implemented.

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