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Development of Air Toxic Emission Factor and Inventory of On-road Mobile Sources

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ABSTRACT: Dynamic emission factors of air toxic compounds, emitted from vehicles in Bangkok, Thailand, are developed using the IVE model. The model takes into account the actual fleet and characteristics of vehicles in the study area. It is found that the calculated emission factors are greatly influenced by vehicle emission control policy. Approximately 2000 tons of benzene emission per year is reduced by the changing of fuel quality from Euro 2 to Euro 4 standards. As for mitigation measures, introduction of gasohol and natural gas as alternative fuels, as well as encouraging the utilization of public transportation systems, are analyzed. The outcomes reveal that a combined scenario using 100% gasohol plus decreasing vehicle kilometers traveled (VKT) by 20% is the most effective in reduction of benzene emission. In addition, 1,3-butadiene, acetaldehyde and formaldehyde emissions are greatly decreased by the combined scenario of using compressed natural gas (CNG) plus decreasing VKT by 20%.

KEYWORDS: air toxic, IVE, emission factor, mobile source, Bangkok

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Introduction

Thailand has experienced an exponential growth in number of vehicles due to fast economic development and increased income levels. Total numbers of motor vehicles increased from 16.09 million in 1996 to 28.48 million in 2010, with an annual average growth rate of 7%. Information from the Department of Land Transport, Ministry of Transport indicated that the cumulative number of vehicles registered in December 31, 2010 was 28,484,829. Among them, the most common vehicle type was motorcycle (17,156,712 or approximately 60%), followed by van or pick up (4,894,655, 17%) and passenger car (4,496,828, 16%). The number of cumulative registered vehicles in Bangkok was 6,444,631 or approximately 22.63% of the cumulative number of vehicles registered nationwide.[1]

Data on volatile organic compounds (VOCs) measured in Bangkok indicated that concentration of some air toxics, such as benzene and 1,3-butadiene, are higher than the Thai annual ambient air quality standard.[2,3] It is well known that the major emission source of air pollution in the Bangkok area is mobile sources. In this study, four air toxic compounds, namely benzene, 1,3-butadiene, acetaldehyde and formaldehyde, have been selected for analysis of their emission factor and emission inventory from mobile sources. These selected compounds are classified as group 1, which are carcinogenic to humans, except for acetaldehyde, which is group 2B, possibly carcinogenic to humans.[4] Other selection criteria were: these compounds are emitted from mobile sources, and they are of concern regarding their environmental risk in the urban Bangkok area.

Normally, assessments of amounts of air toxic emission from vehicles and the transport sector in Thailand are based on emission factors from abroad. Such information may not be suitable for application to the situation in Thailand. For some air toxics, there are virtually no data from studies based on the actual situation of the country, such as condition of vehicles, air pollution control laws, emission control technology, specification of fuel used, etc. In addition, the emission factors used are often fixed emission factors, which are not suitable to predict the amount of an air toxic in the exhaust from a vehicle because they do not take into account information that is subject to change at any time, such as deterioration of the engine, pollution control devices that have improved performance, changes in rates of fuel consumption etc.

To project vehicle emission inventories more accurately, this study developed dynamic emission factors, based on travel distance information, for air toxic compounds from vehicles using the IVE (International Vehicle Emission) model. These emission inventories, based on dynamic emission factors, are developed using a bottom up approach. Air toxic emission inventories for mobile sources in Bangkok from 2009 to 2024 are developed in this study.

Mitigation measures and control scenario analysis are evaluated in order to demonstrate appropriate measures for combating air toxic emission from the transportation sector in Bangkok. This study also evaluated the factor, influenced to emission factors and air toxic emission inventory from mobile sources in the study area.

Methodology

Type of vehicle. In this study, 2009 is selected as the base year. Data analysis is carried out for the period of 15 years (2009–2024). In order to forecast vehicle numbers in Bangkok, it is necessary to start from mobility prediction. The number of vehicles from 2009 to 2024 is forecasted using the average annual growth rate of each type of vehicle in 2000 to 2010. Fleet characteristics in each predicted year are set taking into account the proposed emission and fuel standards. Types of vehicles in this study are classified as 1) passenger car (PC); 2) van & pick up (VP); 3) taxi; 4) motorcycle (MC); 5) public motorcycle (PMC); 6) bus (fixed route bus); 7) public van (PV) and 8) truck.

The total number of vehicles from all types included in this study account for 97% of total registered vehicles in Bangkok. The scope of vehicle types in this study is, therefore, shown to be representative of vehicle types in the study area. The percentage of motorcycle, passenger car, van & pick up, truck, taxi and bus and public van are 40%, 37%, 16%, 2%, 1.5% and 0.5%, respectively.[1]

Calculation of emission factors. Calculation of emission factors in this study used the dynamic emission factor strategy, developed with the idea that vehicle emission control standards can reduce the emission factors of new vehicles. On the other hand, vehicle deterioration increases the emission factors of a specific vehicle model yearly.[5–9] Therefore, national vehicle emission control standards and vehicle deterioration are two of the most important factors that affect vehicle emission factors. These two factors are used to set parameters for data analysis in the study, using the IVE model. The IVE input data consist of a Location file and a Fleet file. Input data of the Location file include driving characteristics, fuel characteristics, and average velocity. The Fleet file is created from primary data collection using a questionnaire. Information on average distance traveled, odometer readings, vehicle models, fuel types and age of vehicle are collected in the survey and used as input data. Driving characteristics information is needed to estimate vehicle emissions, and must be considered for each kind of vehicle emission class. The parameters that affect the hot stabilized emissions from gasoline passenger cars in the IVE model are vehicle fleet technology distribution, vehicle specific power (VSP) and engine stress distribution, inspection and maintenance (I/M) scheme, fuel quality and meteorological condition (humidity and temperature). Cold-start and warm-start emissions are calculated separately in the IVE model. These data are computed to an average emission rate expressed in the unit of g/km for each type of vehicle in this study. In terms of determining the impact of driving pattern on vehicle emissions, the IVE model uses Vehicle Specific Power (VSP) as a key indicator of power, which is closely related to emissions production. In this study, the Bangkok driving cycle is converted to VSP. These data are obtained from the Pollution Control Department of Thailand.

Four air toxic compounds, namely benzene, 1,3-butadiene, acetaldehyde and formaldehyde, have been selected for this study. These compounds are a subset of mobile-source air toxics (MSATs), listed by the USEPA. They are compounds emitted by on-road vehicles and non-road equipment, and are known or suspected to cause cancer or other serious health effects and environmental effects. In 2001 list, the EPA named 21 compounds or compound classes as MSATs. In 2007, the EPA expanded this list. Mobile sources are the principal sources of exposure for only a few of these MSATs, because many are also emitted by non-mobile sources. For example, mobile sources are the most important contributors to 1,3-butadiene concentrations in ambient air in most locales. Because of 1,3-butadiene's short atmospheric lifetime, concentrations of 1,3-butadiene are highest near sources. As for acetaldehyde, mobile sources are a significant, but not the principal, source of exposure to this compound. Concentrations of acetaldehyde tend to be lowest outdoors; they are 2 to 10 times higher indoors and in vehicles. The EPA estimates that mobile sources are responsible for about 44% of estimated outdoor emissions of air toxics. Almost 50% of the estimated cancer risk and 74% of the estimated non-cancer risk from air toxics is estimated to come from mobile sources.[10]

In this study, Bangkok is selected as the study area and the year 2009 is selected as the base year. Analysis of predicted data for mitigation scenarios is carried out for the period of 15 years (2009–2024). A summary of input data for the IVE model used in this study is shown in Table 1.

BAU (Business as Usual) scenario assumes that vehicular growth will continue as expected, with all new vehicles based on current policies. In other words, it assumes there will be no considerable changes in transport or environmental policies.

Table 1. Summary of input data of IVE model.

<table>
<tr><th rowspan="2">TYPE OF VEHICLE</th><th rowspan="2">FUEL CHARACTERISTICS</th><th rowspan="2">DRIVING CHARACTERISTICS</th><th rowspan="2">AVERAGE VELOCITY</th><th colspan="4">FLEET</th></tr>
<tr><th>AIR/FUEL CONTROL</th><th>WEIGHT</th><th>EXHAUST</th><th>AGE</th></tr>
<tr><td>MC and PMC</td><td>Gasoline</td><td rowspan="6">Bangkok driving cycle</td><td rowspan="6">km/hr</td><td>4 cycle</td><td rowspan="6">light, medium, heavy</td><td>Catalyst</td><td rowspan="6">based on distance (km)</td></tr>
<tr><td>PC</td><td>Gasoline
Gasohol
CNG
LPG</td><td rowspan="5">carburetor, fuel injected</td><td rowspan="5">3 way/EGR, Euro 2, Euro 3</td></tr>
<tr><td>VP</td><td>Diesel
CNG</td></tr>
<tr><td>Taxi</td><td>Gasoline
CNG
LPG</td></tr>
<tr><td>Bus and PV</td><td>Diesel
CNG</td></tr>
<tr><td>Truck</td><td>Diesel
CNG</td></tr>
</table>

This is the reference case for comparison with other scenarios. In this study, percentages of fuel type of each type of vehicle under the BAU case are as shown in Table 2. Additionally, fuel type, fuel quality and engine technology of vehicles for calculation of average dynamic emission factors are shown in Table 3.

Results and Discussion

Dynamic air toxic emission factors for each type of vehicle are developed according to regulated limits and vehicle deterioration by age and VKT, while the scenarios of vehicles are also projected based on vehicle deterioration and alternative fuel from governmental policies in Thailand from 2009 to 2024. Air toxic emission inventories of benzene, 1,3 butadiene, acetaldehyde and formaldehyde are estimated according to vehicle fleet distribution, average travel distances per year, and developed emission factors. As for the base year, the value of the emission factors of benzene and 1,3 butadiene (unit of g/km) for public motorcycles is the highest compared with the other types of vehicles. For acetaldehyde and formaldehyde, types of vehicle with the highest emission factors are passenger car and taxi, respectively. However, the air toxic emission factors are altered in each year. It is found that emission factors of air toxic compounds, emitted from each type of vehicle, are greatly influenced by vehicle emission control policy and vehicle deterioration. Dynamic emission factors of air toxics from vehicles are shown in Figure 1.

Table 2. Percentage of fuel from vehicles in BAU case.

TYPE OF VEHICLE	FUEL TYPE (%)				
	GASOLINE	GASOHOL	CNG	LPG	DIESEL
Passenger car (PC)	18	52	2	12	16
Van & pick up (VP)	–	–	–	–	100
Taxi	2	–	50	48	–
Motorcycle (MC)	100	–	–	–	–
Public motorcycle (PMC)	100	–	–	–	–
Bus	–	–	40	–	60
Public van (PV)	–	–	40	–	60
Truck	–	–	4	–	96

Figure 1 illustrates the merit of utilizing the dynamic emission factors instead of the fixed values from the emission inventory data. In case of applying the fixed emission factors, the annual amount of air toxic emissions will only depend on the VKT values of each year. Therefore, an increasing trend of air toxic emissions is shown in this case. However, the dynamic emission factors can help to reveal better estimation of the amount of air toxic emissions, by taking into account the actual characteristics of inventory items. Hence, they can provide better results for further analysis.

Moreover, dynamic emission factors of air toxics from vehicles in this study are compared with other studies, as shown in Table 4. The variation of selection of samples, engine technologies, and fuel quality, as well as the calculation method used for the emission factor, are also presented for reference. Generally, emission factors obtained from this study are higher than other studies. These differences can be explained by the fact that emission factors in this study are computed as average emission factors, taking into consideration characteristics of the entire fleet of the study area. Characteristics considered include vehicle age, fuel type and technology. For example, an average emission factor of a passenger car is obtained by calculation of the actual weighted average of emission of gasoline (18%), gasohol (52%), CNG (2%), LPG (12%) and diesel (16%). On the other hand, the methodology used in other studies as presented in Table 4

Table 3. Fuel type, fuel quality and engine technology of vehicles input data.

<table>
<tr><th rowspan="2">TYPE OF VEHICLE WITH BAU CASE</th><th colspan="16">YEAR</th></tr>
<tr><th>2009</th><th>2010</th><th>2011</th><th>2012</th><th>2013</th><th>2014</th><th>2015</th><th>2016</th><th>2017</th><th>2018</th><th>2019</th><th>2020</th><th>2021</th><th>2022</th><th>2023</th><th>2024</th></tr>
<tr><td colspan="17">PC</td></tr>
<tr><td>Fuel type</td><td colspan="16">Gasoline + Gasohol + CNG + LPG + Diesel</td></tr>
<tr><td>Fuel quality</td><td colspan="3">Euro 2</td><td colspan="13">Euro 4</td></tr>
<tr><td>Engine technology</td><td colspan="11">Euro 2 + Euro 3</td><td colspan="5">Euro 3</td></tr>
<tr><td colspan="17">VP</td></tr>
<tr><td>Fuel type</td><td colspan="16">Diesel + CNG</td></tr>
<tr><td>Fuel quality</td><td colspan="3">Euro 3</td><td colspan="13">Euro 4</td></tr>
<tr><td>Engine technology</td><td colspan="7">Euro 2 + Euro 3</td><td colspan="9">Euro 3</td></tr>
<tr><td colspan="17">Taxi</td></tr>
<tr><td>Fuel type</td><td colspan="16">CNG + LPG + Gasoline</td></tr>
<tr><td>Fuel quality</td><td colspan="3">Euro 2</td><td colspan="13">Euro 4</td></tr>
<tr><td>Engine technology</td><td colspan="11">Euro 2 + Euro 3</td><td colspan="5">Euro 3</td></tr>
<tr><td colspan="17">MC</td></tr>
<tr><td>Fuel type</td><td colspan="16">Gasoline</td></tr>
<tr><td>Fuel quality</td><td colspan="3">Euro 2</td><td colspan="13">Euro 4</td></tr>
<tr><td>Engine technology</td><td colspan="9">Carburator + Direct injection</td><td colspan="7">Direct injection</td></tr>
<tr><td colspan="17">PMC</td></tr>
<tr><td>Fuel type</td><td colspan="16">Gasoline</td></tr>
<tr><td>Fuel quality</td><td colspan="3">Euro 2</td><td colspan="13">Euro 4</td></tr>
<tr><td>Engine technology</td><td colspan="9">Carburator + Direct injection</td><td colspan="7">Direct injection</td></tr>
<tr><td colspan="17">Bus</td></tr>
<tr><td>Fuel type</td><td colspan="16">Diesel + CNG</td></tr>
<tr><td>Fuel quality</td><td colspan="3">Euro 3</td><td colspan="13">Euro 4</td></tr>
<tr><td>Engine technology</td><td colspan="14">Euro 2 + Euro 3</td><td colspan="2">Euro 3</td></tr>
<tr><td colspan="17">PV</td></tr>
<tr><td>Fuel type</td><td>Diesel + CNG</td><td colspan="15">CNG</td></tr>
<tr><td>Fuel quality</td><td colspan="3">Euro 3</td><td colspan="13">Euro 4</td></tr>
<tr><td>Engine technology</td><td>Euro 2 + Euro 3</td><td colspan="15">Euro 3</td></tr>
<tr><td colspan="17">Truck</td></tr>
<tr><td>Fuel type</td><td colspan="16">Diesel + CNG</td></tr>
<tr><td>Fuel quality</td><td colspan="3">Euro 3</td><td colspan="13">Euro 4</td></tr>
<tr><td>Engine technology</td><td colspan="14">Euro 2 + Euro 3</td><td colspan="2">Euro 3</td></tr>
</table>

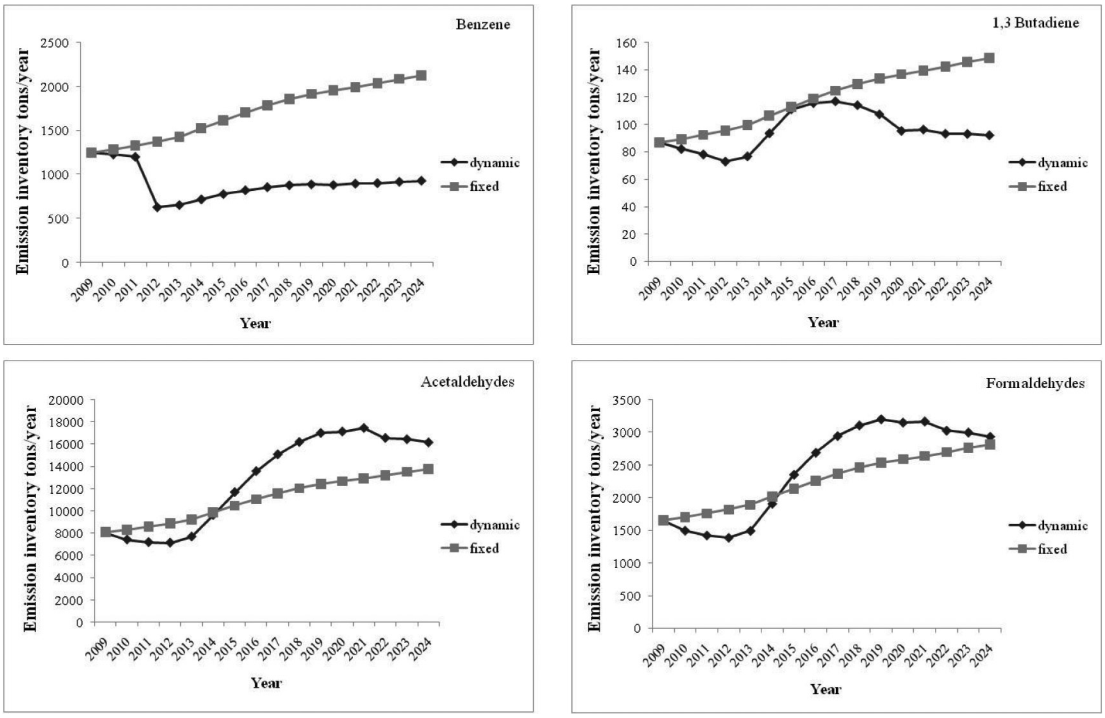

Figure 1. Comparison of emission inventory using fixed and dynamic emission factor.

elucidates result from direct measurement, which gives there presented emissions of individual or tested vehicles.

Air toxic emission inventory of vehicles in Bangkok from 2009 to 2024 is illustrated in Figures 2–5. Emission inventory of benzene is slightly decreased from 2009 to 2011, and significantly decreased from 2011 to 2012. Emission inventories of benzene from passenger cars and motorcycles are higher than from other vehicles from 2009 to 2011. Passenger cars are the dominant emission source of benzene compared with other types of vehicle from 2011 to 2024. Changing of fuel quality from Euro 2 standard to Euro 4 in 2012, results in a significant decrease in benzene emissions. Passenger cars and motorcycles are the major emission sources of 1,3 butadiene from 2009 to 2024. Acetaldehyde is mostly emitted from passenger cars. In addition, emission inventory of acetaldehyde from passenger cars is slightly decreased from 2009 to 2011, and increased from 2012 to 2024. This may be caused by a policy to introduce gasohol and phase out regular gasoline in the market from the year 2012. Annual emission amount of formaldehyde is mostly contributed by passenger cars, motorcycles and taxis. Emission inventory of formaldehyde is increased from 8288 tons/year in 2009 to 11,772 tons/year in 2024. This may also be as a result of the gasohol policy of the country.

Fleet turnover is also a significant parameter affecting emissions of air toxics in Bangkok. Starting in the year 2008, taxis driven in Bangkok have been modified to use CNG fuel instead of gasoline, through a subsidiary program of the Thai government. From 2012, all of the taxis were driven by CNG energy. Utilization of motorcycles with superior technology (direct injection) in place of the former inferior technology (carburetor) has also contributed to the reduction of air toxic emissions. Most of the motorcycle manufacturers in Thailand terminated their production of carbureted motorcycles in the year 2010. All new motorcycles from 2010 are driven by direct injection technology. The number of carbureted motorcycles in use in Bangkok will continue to decreasing until the year 2018, when it is expected that carbureted motorcycles will be less than 5% of the total number of motorcycles in Bangkok.

Although this study is focused on mobile-source air toxics, it should be noted that mobile sources are also major emission sources of conventional air pollutants and greenhouse gases. The IVE model has been used to estimate emission of these compounds, as in the study done by Hui et al (2007).[11] In their study, the IVE model was used with a dataset of remote sensing measurements on a large number of vehicles at five different sites in China, in 2004 and 2005. Average fuel-based emission factors derived from the remote sensing measurements were compared with corresponding emission factors derived from IVE calculations for urban conditions. For gasoline passenger cars operating under urban traffic conditions, this study has demonstrated a good agreement between the IVE model and on-road optical remote sensing measurements in the case of HC emissions, a reasonable agreement for CO, but a weaker agreement in the case of NO_x emissions. In the case of CO emissions, the modeled results were reasonably good, but systematically underestimated the emissions by almost 12%–50% for different

Table 4. Comparison of air toxic emission factor in other studies (unit: g/km).

PLACE	CONDITION	AIR TOXIC EMISSION FACTOR (g/km)				METHODOLOGY	REFERENCE
		BENZENE	1,3-BUTADIENE	ACETALDEHYDE	FORMALDEHYDE		
Switzerland	Passenger car					direct measurement	Norbert et al, 2000[13]
	EURO-0						
	FTP 75 phase I	0.0877 ± 0.0460	–	–	–		
	FTP 75 phase II	0.0465 ± 0.0148	–	–	–		
	FTP 75 phase III	0.0419 ± 0.0151	–	–	–		
	EURO-1						
	FTP 75 phase I	0.0287 ± 0.0171	–	–	–		
	FTP 75 phase II	0.0020 ± 0.0032	–	–	–		
	FTP 75 phase III	0.0056 ± 0.0056	–	–	–		
	EURO-2						
	FTP 75 phase I	0.0235 ± 0.0114	–	–	–		
	FTP 75 phase II	0.0022 ± 0.0037	–	–	–		
	FTP 75 phase III	0.0043 ± 0.0046	–	–	–		
	EURO-3						
	FTP 75 phase I	0.0126 ± 0.004	–	–	–		
	FTP 75 phase II	0.0005 ± 0.0006	–	–	–		
	FTP 75 phase III	0.0006 ± 0.0006	–	–	–		
Australian	Passenger car					direct measurement	Duffy et al, 1997[5]
	Pre-1986	0.1391	0.0418	–	–		
	Post-1986	0.0187	0.0036	–	–		
Switzerland	Passenger car					direct measurement	Norbert et al, 2000
	speed 15 km/h	0.0467	–	–	–		
	speed 25 km/h	0.0252	–	–	–		
	speed 35 km/h	0.0243	–	–	–		
USA	Light duty	–	–	0.0008	0.0026 ± 0.0011	direct measurement	Daniel et al, 2001[14]
	FRFG2b	0.0031	0.0004	0.0007	0.0013	fuel-cycle model	James et al, 2000[15]
China	Diesel vehicle	–	–	0.0114	0.0383	direct measurement	Ho et al, 2007[16]
	Non diesel vehicle	–	–	0.0007	0.0035		
Switzerland	Motorcycle (urban driving)	–	–	–	–	direct measurement	Saxer et al, 2006[17]
	non-catalyst	0.0770	–	–	–		
	3-way catalyst technology	0.0360	–	–	–		
Thailand	Passenger car gasoline (hot)	0.0041	0.0005	–	–	direct measurement	Kuson, 2009[18]
	Light duty diesel (hot)	0.0250	0.0700	–	–		
	Motorcycle gasoline (hot)	0.0330	0.0075	–	–		
This study	**Passenger car**	**0.0383**	**0.0270**	**0.2478**	**0.0506**	**Emission model**	
	Motorcycle	**0.1136**	**0.0143**	**0.0711**	**0.2842**		
	Bus (diesel)	**0.0029**	**0.0004**	**0.0036**	**0.0266**		

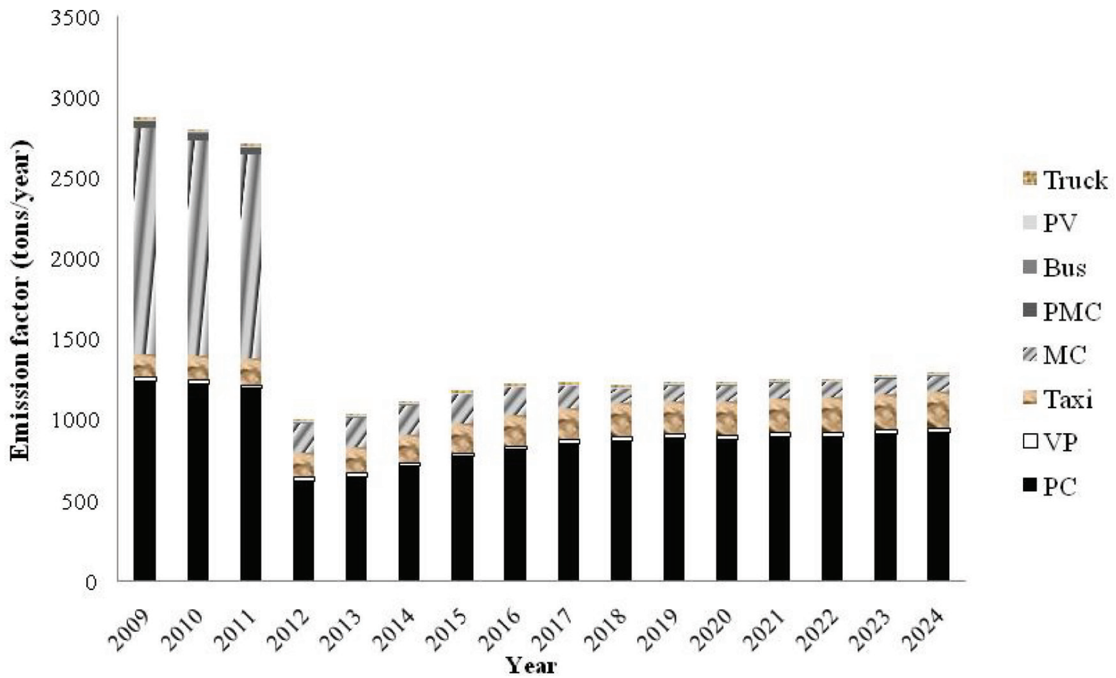

Figure 2. Emission inventory of benzene from 2009–2024 (BAU case).

technology classes. However, the model totally overestimated NO_x emissions. A similar study was carried out by Wang et al (2008).[12] This study presented a bottom–up approach, based on the IVE model to develop vehicle emission inventories for Shanghai. The results showed that the total emissions of CO, VOC, NO_x and PM from vehicles in Shanghai in 2004 were 57.06×10^4 tons, 7.75×10^4 tons, 9.20×10^4 tons and 0.26×10^4 tons, respectively. Heavy-duty vehicles such as trucks and buses contributed more than half of NO_x and PM. Motorcycles and mopeds provided 45.0% of VOC and 36.3% of PM. Light-duty vehicles were the main source of CO emissions.

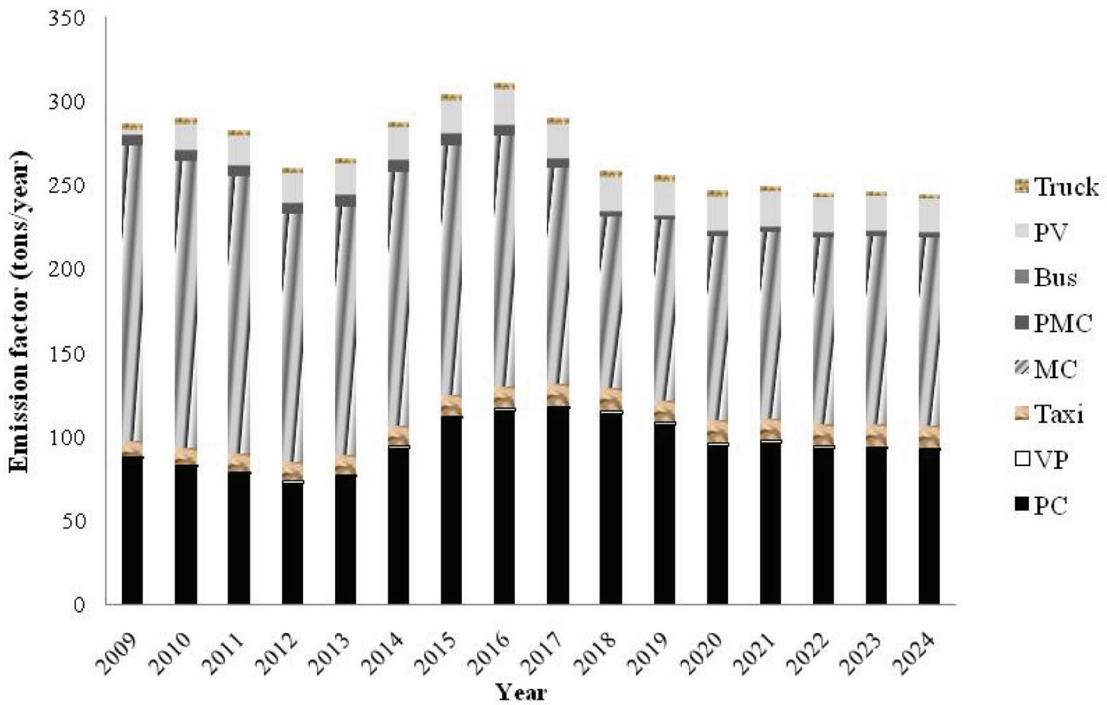

Figure 3. Emission inventory of 1,3-butadiene from 2009–2024 (BAU case).

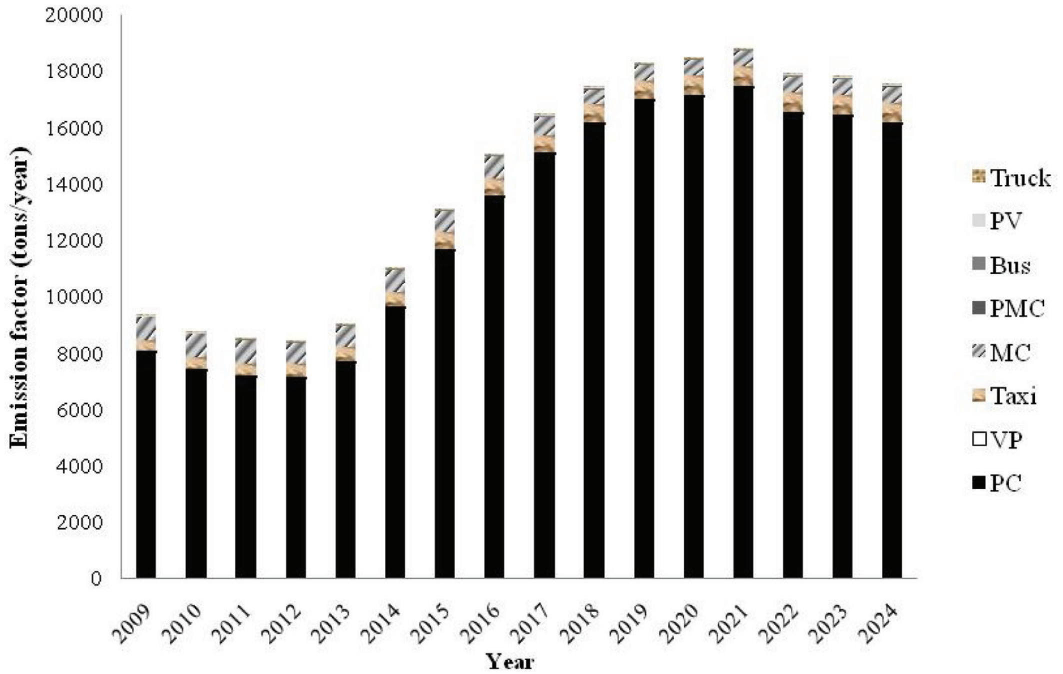

Figure 4. Emission inventory of acetaldehyde from 2009–2024 (BAU case).

Conclusion

The results of dynamic emission inventories indicate that factors influencing emission amounts of air toxics from vehicles in Bangkok are VKT, number of vehicles and emission factor. Therefore, mitigation to reduce air toxic emissions from the transportation sector can be achieved by reducing VKT, improving the public transport system, and increasing number of passenger cars fueled by CNG.

Thailand's policies to introduce gasohol and CNG as an alternative fuel and to encourage the use of public transport

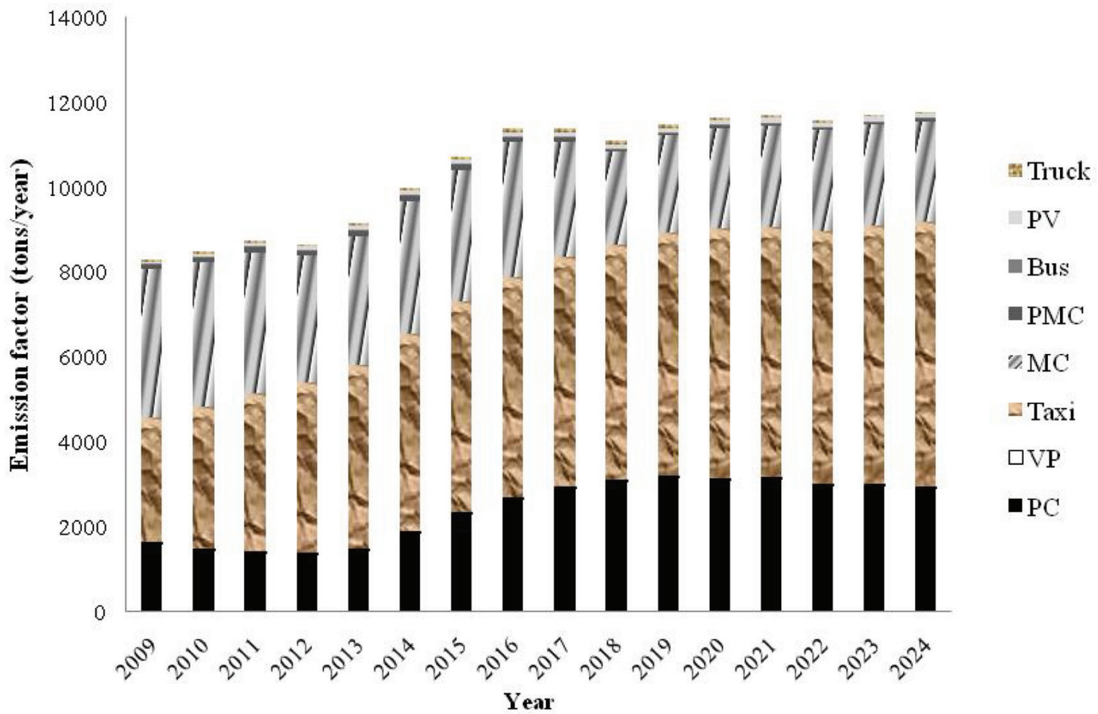

Figure 5. Emission inventory of formaldehyde from 2009–2024 (BAU case).

are evaluated to determine their influence on emission factors of air toxic compounds from mobile sources. These measures are analyzed as three groups (fuel-type scenarios, VKT scenarios, and combined scenarios). The analysis reveals that the combined scenario of using 100% gasohol plus decreasing VKT by 20% is the most effective scenario in reduction of benzene emission amount. In addition, 1,3-butadiene and acetaldehyde emissions are greatly decreased by the combined scenario of using 100% CNG plus decreasing VKT by 20%. As for formaldehyde, the emission amount is greatly reduced by a gasohol-based scenario. However, formaldehyde emission is increased under a CNG scenario. Normally, the highest ambient concentrations of formaldehyde were found at urban roadside sites. It appears that summer photochemical activity contributes more formaldehyde to ambient air than direct vehicle emissions do, as strong seasonal effects are observed. It is important to note that in Brazil, ambient formaldehyde concentrations have increased four fold over the past few years, following the expansion of the fleet of vehicles using compressed natural gas.[10] All scenarios' effects on air toxics emitted from vehicles are summarized in Table 5.

Introducing gasohol as a renewable alternative energy source is found to be an effective measure in reducing benzene and formaldehyde emissions. However, this policy might lead to an increase of acetaldehyde and 1,3-butadiene emissions as compared with regular gasoline fuel. Improvement of fuel quality from Euro 2 to Euro 4 standards, started in the year 2012, was found to be an effective measure in the reduction of benzene emissions from mobile sources in Bangkok, because benzene content in Euro 2 standard is 3.8% while its content in Euro 4 standard is 1%. Decreasing benzene ambient air concentrations, measured in the study area, confirmed the benefit of this policy in reducing air toxics. Benzene concentrations, measured in the traffic curbside stations in Bangkok, were significantly decreased in the year 2012, as illustrated in Figure 6.

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Author Contributions
Conceived and designed the experiments: ST and PO. Analysed the data: PO. Wrote the first draft of the manuscript: ST and PO. Agree with manuscript results and conclusions: ST and PO. Jointly developed the structure and arguments for the paper: ST and PO. Made critical revisions and approved final version: ST and PO. All authors reviewed and approved of the final manuscript.

DISCLOSURES AND ETHICS

As a requirement of publication the authors have provided signed confirmation of their compliance with ethical and legal obligations including but not limited to compliance with ICMJE authorship and competing interests guidelines, that the article is neither

Table 5. All scenarios of air toxics emitted from vehicles (2012–2024).

YEAR	SCENARIOS (%)																
	FUEL TYPE					VKT		COMBINED									
	GASOHOL 100%	CNG 25%	CNG 50%	CNG 75%	CNG 100%	DECREASE VKT 10%	DECREASE VKT 20%	GASOHOL 100% & DECREASE VKT 10%	CNG 25% & DECREASE VKT 10%	CNG 50% & DECREASE VKT 10%	CNG 75% & DECREASE VKT 10%	CNG 100% & DECREASE VKT 10%	GASOHOL 100% & DECREASE VKT 20%	CNG 25% & DECREASE VKT 20%	CNG 50% & DECREASE VKT 20%	CNG 75% & DECREASE VKT 20%	CNG 100% & DECREASE VKT 20%
Benzene	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
1,3-butadiene	×	√	√	√	√	√	√	×	√	√	√	√	×	√	√	√	√
Acetaldehyde	×	√	√	√	√	√	√	×	√	√	√	√	×	√	√	√	√
Formaldehyde	√	√	√	×	×	√	√	√	√	√	×	√	√	√	√	×	√

√ = decreasing of emission amount as compared with BAU.
× = increasing of emission amount as compared with BAU.

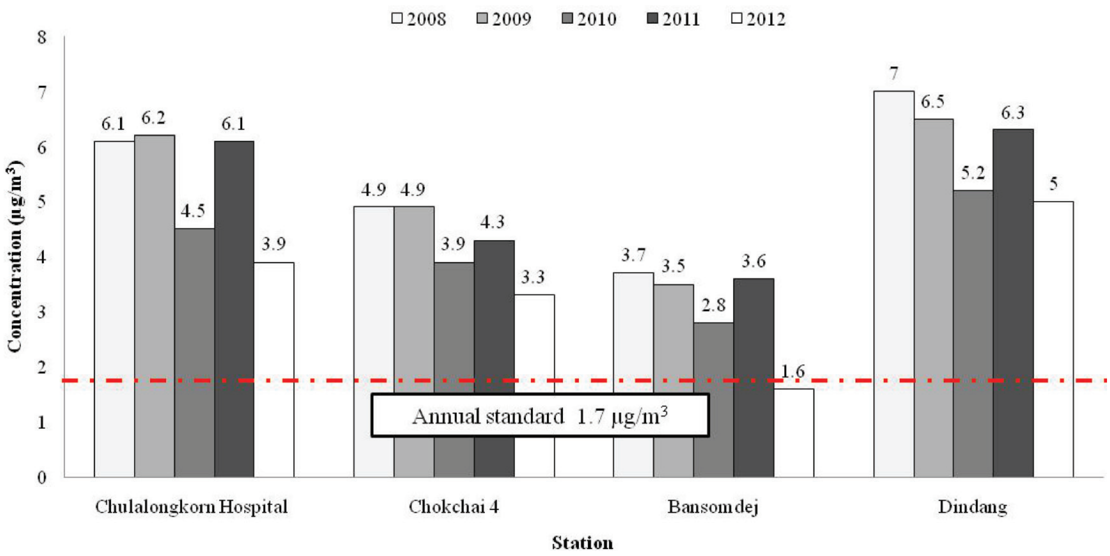

Figure 6. Annual concentration of benzene from 2008–2012 in Bangkok.

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