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$PM_{2.5}$ Footprint: a Tool for Enhancing Sustainable Passenger Transport

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Abstract

Fine particulate matter ($PM_{2.5}$) is one of major causes of premature deaths globally. $PM_{2.5}$ has also become a serious health issue in Thailand. In Bangkok, vehicle exhaust is the most important $PM_{2.5}$ source. This research aimed to assess and compare health impacts and costs of $PM_{2.5}$ emissions from different passenger transport modes including road transport, water transport, and rail transport (elevated electric train or sky train) in Bangkok; to identify important factors causing the impacts; and to provide recommendations on enhancing environmentally sustainable passenger transport. Six passenger transport systems including road transport (private passenger cars, private passenger pickups, public buses, and private motorcycles), public water transport, and sky train were considered. Primary and secondary $PM_{2.5}$ emissions from fuel combustion were estimated by using emission factors from European Monitoring and Evaluation Programme/European Environment Agency and research work in Thailand. The emissions from fuel production were obtained from ecoinvent database. The $PM_{2.5}$ footprint or the health impact caused by primary and secondary $PM_{2.5}$ in the unit of Disability-Adjusted Life Years (DALY) per passenger-kilometer (pkm) was quantified by using impact characterization factors based on a life cycle impact assessment approach. The elevated electric train/sky trains were the passenger transport system with the lowest health impacts and costs followed by public water transport, public buses, private motorcycles, and private passenger cars and pickups. Although exhaust emissions caused health impacts locally, the study addressed the importance of cleaner fuel/energy production in order to enhance environmental sustainability of passenger transport systems in Thailand. The age of vehicle technologies (directly linked with vehicle emission standards) and fuel types significantly affected the emissions, health impacts and costs. Future policies on $PM_{2.5}$ footprint reduction should promote public transport systems (sky trains, public ferries, and buses), stricter vehicle emission limits as well as the use of cleaner fuels.

Keywords: *$PM_{2.5}$ footprint; fine particulate matter; human health impacts; life cycle impact assessment; environmentally sustainable transport*

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1. Introduction

Nowadays, the major environmental problem in Thailand is $PM_{2.5}$ emissions that exceed the standards for $PM_{2.5}$ emissions. According to Attavanich (2019), the cost of self-defensive equipment per family in Bangkok is around 6,124.89 baths annually, which overall is approximately 16,857 baths per year. Then they are willing to pay more than 6,402 baths per family annually (18,946.87 million baths per year) to reduce 1 microgram of $PM_{2.5}$ (Attavanich, 2020). The research of the World Health Organization (WHO) revealed that $PM_{2.5}$ emissions cause negative effects on health. One of the effects resulting from $PM_{2.5}$ is the loss of income. The study revealed that three main human sources of emissions are automobile diesel, biomass incineration, and secondary $PM_{2.5,}$ which is the byproduct of the reaction between vehicle exhaust and ammonia from agricultural fertilizers (Panyametheekul and Pansawat, 2018). According to the Pollution Control Department, the average $PM_{2.5}$ level per 24 hours in 2011-2018 is between 22-133 $\mu g/cm^3$ (72 $\mu g/cm^3$ on average), which exceeds the standard of 50 $\mu g/cm^3$. As well as the annual average, although the mean is around 24 $\mu g/cm^3$, some of them exceed the standard of 25 $\mu g/cm^3$ (in between the range of 9-41 $\mu g/cm^3$) (PCD, 2018). Thus, this research aimed to assess and compare the health impacts and costs of $PM_{2.5}$ emissions from different passenger transport modes, including road transport, water transport, and rail transport (elevated electric train or sky train) in Bangkok; to identify important factors causing the impacts; and to provide recommendations for enhancing environmentally sustainable passenger transport.

2. Material and methods

The scope of the study is limited to both health impacts and health costs from traffic related $PM_{2.5}$ formations from the passenger transport system in Bangkok. The study is divided into 2 sections; tank-to-wheel (emissions come from combustion of fuel in Bangkok) and well-to-tank (emissions originate from upstream fuel and electricity production that took place outside of Thailand). Six passenger transport systems, including road transport (private passenger cars, private passenger pickups, public buses, and private motorcycles), public water transport (Cross river ferries (100-300 hp), Chao Phraya boats (300-750 hp), Saen Saep boats (300-750 hp)), and sky train were considered. The information used for calculating the road transport sector were engine types, fuel types (Gasoline, Diesel (B7), Biodiesel (B20), Liquefied Petroleum Gas (LPG), and Compressed Natural Gas (CNG)), and technology ages. The road transport sector emissions were conducted according to the EMEP/EEA (2019) (Kouridis et al., 2019) manual as shown in equation 1, with the specific data for quantification of road transport emissions shown in **Table 1**. According to the study, total emissions resulting from diverse scenarios will be estimated based on the Tier 2 Methodology of the joint EMEP/EEA (2019) (Kouridis et al., 2019). The equation used in this research are:

$$\textbf{Emission} = \textbf{Activity Data} \times \textbf{Emission Factor}_{i,j,k} \qquad \textbf{(1)}$$

Where;
Activity Data = distance driven per vehicle in category j and technology k (in unit km)
Emission Factor = technology specific emission factor of pollutant i for vehicle j and technology k (in unit of g/pkm)

The secondary $PM_{2.5}$ precursors considered in this study are NO_x, NH_3, and SO_2. Meanwhile, NO_x and NH_3 have been calculated using equation 1, the same as the primary $PM_{2.5}$ based on the Tier II Methodology of EMEP/EEA (2019) (Kouridis et al., 2019). Besides, the calculation of SO_2 emissions in various paths is shown below:

$$\textbf{SO}_2 \textbf{ emissions} = 2 \times \textbf{Fuel Usage} \times \textbf{Fuel Sulfur Content} \qquad \textbf{(2)}$$

The emissions inventory from upstream production of fuel and electricity were considered in this calculation: petrol (low sulfur), diesel, liquefied petroleum gas (LPG), compressed natural gas (CNG), and electricity. Their emission factors were obtained from ecoinvent database version 3.4 calculated in SimaPro version 9.1.1.7 as shown in **Tables 2 and 3** (Moreno et al., 2017). The research provided the assumption that the energy sources is generated from outside Thailand. Next, the sky train transport sector emissions were calculated according to the EMEP/EEA (2019) (Kouridis et al., 2019) as shown in equation 1. Specific data for quantification of sky train emissions is shown in **Table 3.** The research provided the assumption that the electricity for the sky train is generated from outside Thailand. The water transport sector calculated emissions according to the guidelines from the final report of the Development of Emissions Inventory for Inland Water Transport in Bangkok, Thailand (Winijkul et al., 2021). As shown in equation 3. The specific data for quantification of water transport systems is shown in **Table 4**

$$\textbf{Water Transport Emissions} = \textbf{Cruising Emissions} + \textbf{Idling Emissions} \quad (3)$$

The $PM_{2.5}$ impact on health based on Fantke et al., (2016) clarified that particulate matter formation originates from the emission of primary pollutants or primary $PM_{2.5}$, or secondary $PM_{2.5}$ precursors including NO_x, NH_3, and SO_2, which are related via intake fraction and effects. Thus, the total damages to human health are in the form of Disability-adjusted life years (DALY), which is an indicator of disease burden for comparing the severity of both mild and severe diseases (Fantke et al., 2016). The characterization factor (CF) value for tank-to-wheel emissions is gathered from Prapaspongsa et al., (2021), which is provincial-specific as shown in **Table 5**. Meanwhile, the characterization factor value for well-to tank emissions is gathered from the report of Global Guidance 2016 (Fantke et al., 2016) as shown in **Table 5**. Then, this study combined the health impacts of $PM_{2.5}$, NO_x, NH_3, and SO_2 to obtain a total health impact (Fantke et al., 2016). The equation can be written as follows:

$$\mathbf{IS = CF \times m} \quad (4)$$

Where;

CF = Characterization Factor ($DALY/kg_{emitted}$)

m = the emission mass per functional unit ($kg_{emitted}/pkm$)

The relationship between Quality-Adjusted Life Years (QALYs) and Disability-Adjusted Life Years (DALYs) is indicated in the Economic Assessment by Weidema (2009). Since QALYs are used for assessing health interventions in the long term with the well-being condition. It is in contrast with DALY. Therefore, the equation that is generally used is 1 DALY = -1 QALY, which allows many studies to estimate one value from the other (Weidema, 2009). This study uses the study by Kaenchan & Gheewala (2017), which estimated the value of 1 DALY for the Thailand context, which is equivalent to -512,000 Thai Baht. This study updated the parameters required for the values of 1 DALY for the Thailand context, which is equivalent to – 581,130 Thai Baht in 2021. The equation can be written as follows:

$$\textbf{Future Value of DALY}_{2011}\textbf{ in 2021} = \textbf{Value of DALY}_{2011}\times(1+r)^{2021-2011} \quad (5)$$

Where, r = The average inflation rate of Thailand from 2011 to 2021 was 1.27% (Neill, 2021).

Table 1 Specific data for quantification of road transport emissions (Kouridis et al., 2019)

Type of vehicle	Age (year)	Technology	Fuel	Primary $PM_{2.5}$ Emission Factor (g $PM_{2.5}$ /pkm)	NO_x Emission Factor (g NO_x /pkm)	NH_3 Emission Factor (g NH_3 /pkm)	Typical Fuel Consumption (kg/km)	Sulfur Emissions standard (ppm)
Passenger Car	1< to 5	Euro 4	Gasoline	9.57E-07	5.30E-05	2.97E-05	0.07	50
			B7	2.47E-05	4.55E-04	7.85E-07	0.06	50
			B20	3.64E-06	6.72E-05	1.16E-07	0.06	50
			LPG	9.57E-07	4.87E-05	2.94E-05	0.06	140
			CNG	9.57E-07	4.87E-05	2.94E-05	0.06	50
Passenger Car	6 to 10	Euro 3 + 4	Gasoline	9.57E-07	7.18E-05	2.97E-05	0.07	50
			B7	2.83E-05	5.46E-04	7.85E-07	0.06	50
			B20	0.00E+00	0.00E+00	0.00E+00	0.06	50
			LPG	9.57E-07	6.64E-05	2.94E-05	0.06	140
		Euro 4	CNG	9.57E-07	4.87E-05	2.94E-05	0.06	50
Passenger Car	11 to 15	Euro 2+3	Gasoline	1.15E-06	1.12E-04	4.19E-05	0.07	50
			B7	3.32E-05	5.98E-04	7.85E-07	0.06	50
			B20	0.00E+00	0.00E+00	0.00E+00	0.06	50
			LPG	1.15E-06	9.39E-05	4.10E-05	0.06	140
		Euro 4	CNG	9.57E-07	4.87E-05	2.94E-05	0.06	50
Passenger Car	16 to 20	Euro 1 + 2	Gasoline	1.91E-06	3.02E-04	8.65E-05	0.07	50
			B7	5.23E-05	5.54E-04	7.85E-07	0.06	50
			B20	0.00E+00	0.00E+00	0.00E+00	0.06	50
			LPG	1.91E-06	2.38E-04	8.31E-05	0.06	140
		Euro 4	CNG	9.57E-07	4.87E-05	2.94E-05	0.06	50
Passenger Car	>20	Euro 1	Gasoline	1.91E-06	4.22E-04	8.02E-05	0.07	50
			B7	6.61E-05	5.42E-04	7.85E-07	0.06	50
			B20	0.00E+00	0.00E+00	0.00E+00	0.06	50
			LPG	1.91E-06	3.60E-04	7.65E-05	0.06	140
		Euro 4	CNG	9.57E-07	4.87E-05	2.94E-05	0.06	50
Passenger Pick ups	1< to 5	EURO 4	Gasoline	9.17E-07	5.33E-05	2.52E-05	0.10	50
			B7	3.08E-05	6.25E-04	9.03E-07	0.08	50
			B20	4.54E-06	9.23E-05	1.33E-07	0.08	50
			LPG	9.17E-07	4.67E-05	2.82E-05	0.06	140
			CNG	9.17E-07	4.67E-05	2.82E-05	0.06	50
Passenger Pick ups	6 to 10	Euro 3 + 4	Gasoline	9.17E-07	8.58E-05	2.52E-05	0.10	50
			B7	4.77E-05	7.15E-04	9.03E-07	0.08	50
			B20	0.00E+00	0.00E+00	0.00E+00	0.08	50
			LPG	9.17E-07	6.37E-05	2.82E-05	0.06	140
		Euro 4	CNG	9.17E-07	4.67E-05	2.82E-05	0.06	50
Passenger Pick ups	11 to 15	Euro 2+3	Gasoline	1.12E-06	1.24E-04	3.53E-05	0.10	50
			B7	6.47E-05	8.04E-04	9.03E-07	0.08	50
			B20	0.00E+00	0.00E+00	0.00E+00	0.08	50
			LPG	1.10E-06	9.00E-05	3.93E-05	0.06	140
		Euro 4	CNG	9.17E-07	4.67E-05	2.82E-05	0.06	50
Passenger Pick ups	16 to 20	Euro 1 + 2	Gasoline	1.92E-06	3.03E-04	7.08E-05	0.10	50
			B7	8.80E-05	9.18E-04	9.03E-07	0.08	50
			B20	0.00E+00	0.00E+00	0.00E+00	0.08	50
			LPG	1.83E-06	2.28E-04	7.97E-05	0.06	140
		Euro 4	CNG	9.17E-07	4.67E-05	2.82E-05	0.06	50
Passenger Pick ups	>20	Euro 1	Gasoline	1.92E-06	4.69E-04	6.32E-05	0.10	50
			B7	8.80E-05	9.18E-04	9.03E-07	0.08	50
			B20	0.00E+00	0.00E+00	0.00E+00	0.08	50
			LPG	1.83E-06	3.45E-04	7.33E-05	0.06	140
		Euro 4	CNG	9.17E-07	4.67E-05	2.82E-05	0.06	50

Table 1 Specific data for quantification of road transport emissions (Kouridis et al., 2019) (Continue)

Type of vehicle	Age (year)	Technology	Fuel	Primary $PM_{2.5}$ Emission Factor (g $PM_{2.5}$ /pkm)	NO_x Emission Factor (g NO_x /pkm)	NH_3 Emission Factor (g NH_3 /pkm)	Typical Fuel Consumption (kg/km)	Sulfur Emissions standard (ppm)
Public Buses	1< to 5	Euro 3	Gasoline	0.00E+00	2.63E-04	7.57E-08	0.24	50
			B7	7.45E-06	3.37E-04	1.04E-07	0.24	50
			B20	1.10E-06	4.98E-05	6.64E-05	0.24	50
			LPG	3.98E-07	3.98E-04	0.00E+00	0.50	140
			CNG	3.98E-07	3.98E-04	0.00E+00	0.50	50
Public Buses	6 to 10	Euro 3	Gasoline	0.00E+00	2.63E-04	7.57E-08	0.24	50
			B7	7.45E-06	3.37E-04	1.04E-07	0.24	50
			B20	0.00E+00	0.00E+00	0.00E+00	0.24	50
			LPG	3.98E-07	3.98E-04	0.00E+00	0.50	140
			CNG	3.98E-07	3.98E-04	0.00E+00	0.50	50
Public Buses	11 to 15	Euro 2+1	Gasoline	0.00E+00	2.63E-04	7.57E-08	0.24	50
			B7	9.78E-06	3.81E-04	1.04E-07	0.24	50
			B20	0.00E+00	0.00E+00	0.00E+00	0.24	50
			LPG	4.78E-07	6.10E-04	0.00E+00	0.50	140
			CNG	4.78E-07	6.10E-04	0.00E+00	0.50	50
Public Buses	16 to 20	Euro 1	Gasoline	0.00E+00	2.63E-04	7.57E-08	0.24	50
			B7	1.72E-05	3.63E-04	1.04E-07	0.24	50
			B20	0.00E+00	0.00E+00	0.00E+00	0.24	50
			LPG	7.97E-07	6.57E-04	0.00E+00	0.24	50
			CNG	7.97E-07	6.57E-04	0.00E+00	0.50	140
Public Buses	>20	Euro 1	Gasoline	0.00E+00	2.63E-04	7.57E-08	0.50	50
			B7	1.72E-05	3.63E-04	1.04E-07	0.24	50
			B20	0.00E+00	0.00E+00	0.00E+00	0.24	50
			LPG	7.97E-07	6.57E-04	0.00E+00	0.24	50
			CNG	7.97E-07	6.57E-04	0.00E+00	0.5	140
Motorcycle	1< to 5	Euro 3	Gasoline	3.18E-06	1.76E-04	1.73E-06	0.04	50
Motorcycle	6 to 10	Euro 3	Gasoline	3.18E-06	1.76E-04	1.73E-06	0.04	50
Motorcycle	11 to 15	Euro 2	Gasoline	1.10E-05	2.30E-04	1.73E-06	0.04	50
Motorcycle	16 to 20	Euro 1	Gasoline	3.55E-05	2.15E-04	1.73E-06	0.04	50
Motorcycle	>20	Euro 1	Gasoline	3.55E-05	2.15E-04	1.73E-06	0.04	50

Table 2 Emission Factor for fuel production (Moreno et al., 2017)

Fuel Types	Emission Factor (kg pollutant / kg fuel)			
	$PM_{2.5}$	NO_x	NH_3	SO_2
Gasoline	3.91E-04	2.34E-03	1.58E-05	5.38E-03
Diesel	2.57E-04	1.76E-03	1.00E-05	3.99E-03
LPG	2.97E-04	1.92E-03	1.13E-05	4.51E-03
CNG	4.58E-05	3.88E-04	1.20E-06	9.49E-04

Table 3 Specific data for quantification of sky train transport emissions

Specific data			References
Emission Factor (kg/kwh)	Primary $PM_{2.5}$	1.36E-04	Moreno et al., (2017)
	NO_x	8.67E-04	
	NH_3	5.60E-06	
	SO_2	1.22E-03	
Electricity per 1 passenger-kilometre (kWh/pkm)	0.053		BTS GROUP (2021)

Table 4 Specific data for quantification of inland water transport emissions (Winijkul et al., 2021)

Type of boat	**Load Factor, LF (Unitless)**	**Average Power (hp/passenger)**	**Cruising Emission Factor adj, g/pkm**				**Ave**	**Ave**	**Idling Factor**			
			Primary $PM_{2.5}$	**NO_x**	**NH_3**	**SO_2**			**Primary $PM_{2.5}$**	**NO_x**	**NH_3**	**SO_2**
Cross river ferries (100-300 hp)	0.31	5	1.23E-02	2.15E-01	2.50E-05	4.00E-04	6.80	0.092	0.25	1.07	1	7
Chao Phraya boats (300-750 hp)	0.31	13.125	1.23E-02	2.15E-01	2.50E-05	4.00E-04	13.20	0.45	0.25	1.07	1	7
Saen Saep boats (300-750 hp)	0.14	7.5	7.00E-03	1.23E-01	1.43E-05	2.29E-04	20.80	0.14	0.25	1.07	1	7

Table 5 Characterization factors for fine particulate matter formation in Bangkok, Thailand, and the world

Spatial Scope	**Characterization Factors (DALY/ kg emitted)**				**References**
	$PM_{2.5}$	**NO_x**	**NH_3**	**SO_2**	
Bangkok	6.92E-03	1.69E-05	1.43E-04	8.35E-05	Prapaspongsa et al., (2021)
Thailand	2.10E-03	2.04E-05	1.73E-04	1.01E-04	Prapaspongsa et al., (2021)
Global Average	4.90E-03	3.10E-05	2.60E-04	1.50E-04	Fantke et al., (2016)

3. Results and Discussion

A comparison of the health impacts and costs of each transport mode demonstrated by the energy production and use phase can be seen in **Figure 1.** The horizontal axis shows different modes of transport that have been developed from the past to present, passenger cars, passenger pickups, public buses, private motorcycles, water transport and sky train. The vertical axis shows the amount of total health impacts in DALY/pkm and total health costs in baht/pkm. When the production and use phases of transport are compared, the health impacts and costs are greater for old passenger pickup technology than for new technology, followed by old motorcycle technology and old passenger car technology, respectively. The passenger pickups have significantly higher impacts because of their high share of diesel use than others. In contrast, this research discovered that the health impacts and costs associated with elevated electric train/sky train, water transport, public buses, new motorcycle technology, and new passenger car technology have the lowest health impacts and costs.

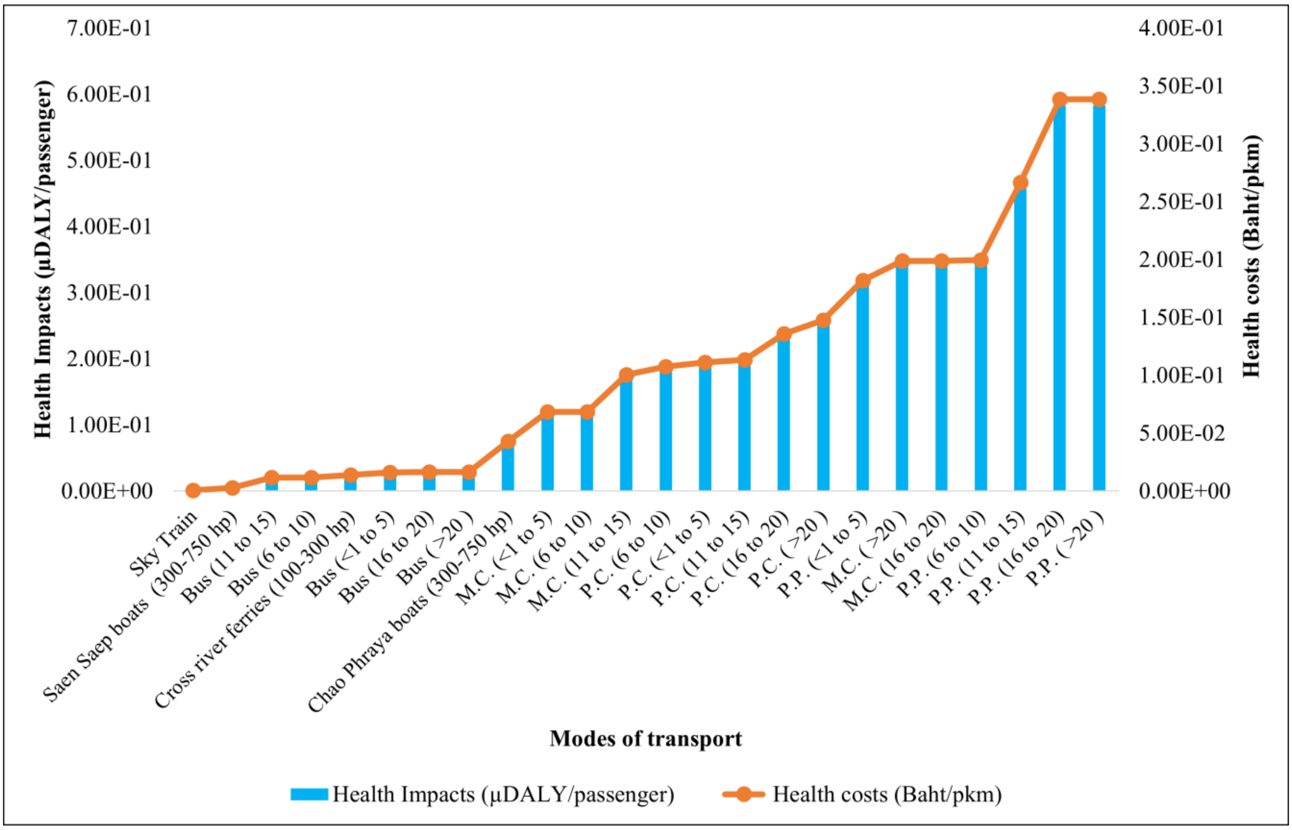

Figure 1 Comparative total health impacts and costs demonstrated in different modes of transport in Bangkok

Next, **Figure 2** shows the share of health impacts, where each stacked column shows 100% of health impacts from the merger of energy production and vehicle use. The horizontal axis shows different modes of transport that have been developed from the past to present – passenger cars, passenger pickups, public buses, private motorcycles, water transport, and sky train. The vertical axis shows the share of health impacts categorized by use and production phases. The fuel production and use phase of **passenger cars** are considered. The result shows that gasoline production has the highest effect on health impact, with contributions of 9.98E-02 to 1.14E-01µDALY/pkm equal to 5.80E-02 to 6.63E-02 baht/pkm (45-61% of total impact), followed by diesel use with the contributions of 4.38E-02 to 9.64E-02 µDALY/pkm equal to 2.54E-02 to 5.60E-02 baht/pkm (24-38% of total impact), and diesel production with the contributions of 1.79E-02 to 2.67E-02 µDALY/pkm equal to 1.04E-02 to 1.55E-02 baht/pkm (7-14% of total impact) as shown in **Figure 2**. The fuel production and use phase of **passenger pickups** are considered. The result shows that diesel use has the highest effect on health impact, with contributions of 2.03E-01 to 4.65E-01 µDALY/pkm equal to 1.18E-01 to 2.70E-01 baht/pkm (65-80% of total impact), followed by diesel production with the contributions of 7.92E-02 to 9.62E-02 µDALY/pkm equal to 4.60E-02 to 5.59E-02 baht/pkm (14-31% of total impact), and gasoline production with the contributions of 1.07E-02 to 2.95E-02 µDALY/pkm equal to 6.23E-03 to 1.71E-02 baht/pkm (3-8% of total impact) as shown in **Figure 2**. The fuel production and use phase of **public buses** are considered. The highest health impact was caused by diesel use with contributions of 7.59E-03 to 2.14E-02 µDALY/pkm equal to 4.41E-03 to 1.25E-02 baht/pkm (37-77% of total impact) followed by CNG use with the contributions of 5.72E-03 to 1.41E-02 µDALY/pkm equal to 3.32E-03 to 8.20E-03 baht/pkm (20-57% of total impact). The fuel production and use phase of **private motorcycles** are considered. The result shows that gasoline production has the highest effect on health impact, with contributions of 9.25E-02 µDALY/pkm equal to 5.38E-02 baht/pkm (27-78% of total impact), followed by gasoline use with the contributions of 2.55E-02 to 2.50E-01 µDALY/pkm equal to 1.48E-02 to 1.45E-01 baht/pkm (22-73% of total impact) as shown in **Figure 2**. The fuel production and use phase of **water transport** are also considered. The highest health impact was caused by diesel use with contributions of 4.67E-03 to 7.36E-02 µDALY/pkm equal to 2.72E-03 to 4.28E-02 baht/pkm (96-99% of total impact) followed by diesel production with the contributions of 1.75E-04 to 5.36E-04 µDALY/pkm equal to 1.02E-04 to 3.11E-04 baht/pkm (1-4% of total impact) as shown in **Figure 2**. In contrast, the assessment of the health impacts of the **sky train** revealed that health effects mostly come from the production of electrical energy of 1.11E-03 µDALY/pkm equal to 6.47E-04 baht/pkm (100% of total impact) as shown in **Figure 2.** The findings indicated that both the usage and manufacturing phases had a substantial influence on emissions, health effects, and costs. As a result, control over energy production processes should be emphasized in concert with new vehicle technology.

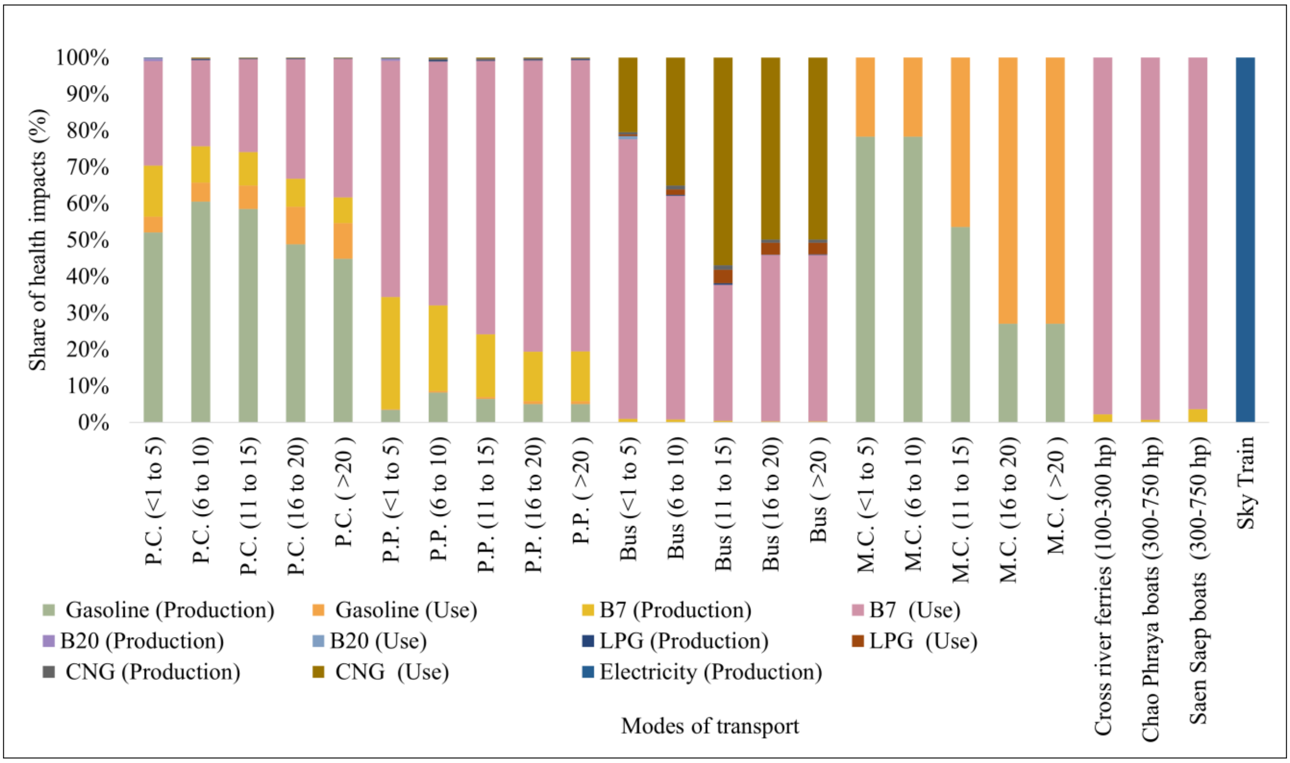

Figure 2 Share of total health impacts demonstrated in different modes of transport in Bangkok

Additional information and sensitivity analyses will be provided in the next subsection, where the scope emphasis will be modified to include just vehicle usage phases to determine how the results consequently changed. This would allow future research to focus on finding better input data to make the results more accurate.

4. Sensitivity analysis

A comparison of the health impacts and costs of each transport mode demonstrated by use phase can be seen in **Figure 3.** The Horizontal axis shows the different modes of transport, which are passenger cars, passenger pickups, buses, motorcycles in each technology age, including water transport and sky train. The vertical axis shows the amount of total health impacts in DALY/pkm and total health costs in baht/pkm. This research discovered that the health impacts and costs associated with sky train, water transport, public buses, new motorcycle technology, and new passenger car technology have the lowest health impacts and costs as shown in **Figure 3**. In the use phase, the sky train has significantly less impact due to sky trains emitting no pollutants at the tailpipe**.**

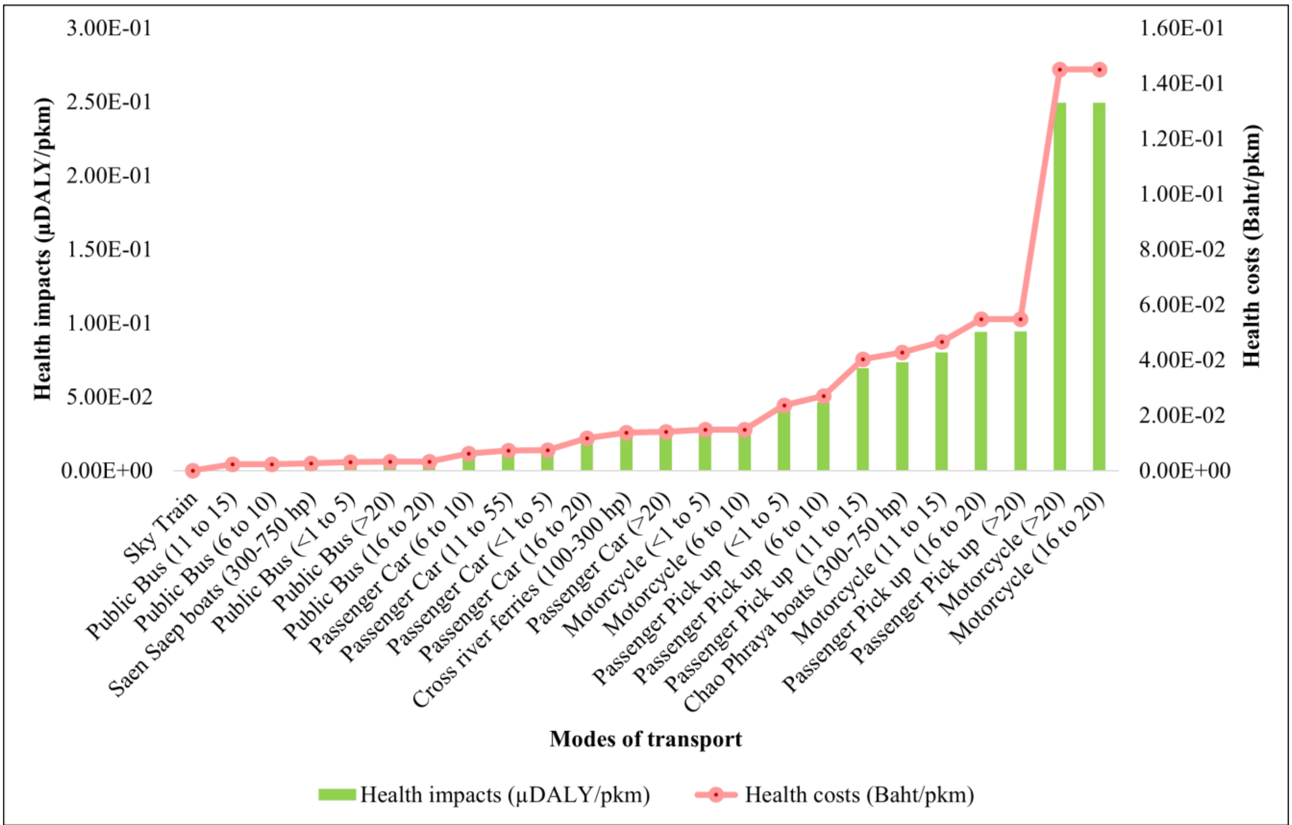

Figure 3 Sensitivity analysis-comparative total health impacts and costs demonstrated in different modes of transport in Bangkok

In the context of research sensitivity analysis focusing only on the reduction of health effects and costs associated with car usage in Bangkok, sky train use should be promoted. The sky train should be promoted as the mode of passenger transport with the least negative health effects and costs, followed by public water transport, buses, new private motorcycle technology, and new passenger vehicle technology.

5. Conclusions

This study showed that the elevated electric train/sky train was the passenger transport system with the lowest health impacts and costs followed by public water transport, public buses, private motorcycles, and private passenger cars, while the private passenger pickups yielded the highest health impacts and costs. Total health impacts and total health costs from traffic related $PM_{2.5}$ would be on an upward trend if the cumulative old technologies have still increased. Older technologies with less stringent emission standards will cause more emissions leading to higher health impacts and costs. Total health impacts and total health costs of passenger transport were analyzed by using both fuel combustion and fuel production. The result indicates that 29%- 48% of road transport (P.C.) impacts, 65%- 81% of road transport (P.P.) impacts, 98% - 99% of road transport (Public bus) impacts, 22% - 73% of road transport (M.C.) impacts, and 96-99% of water transport impacts were from fuel combustion. On the other hand, 100% of sky train impacts were from electricity production. Furthermore, the study of fuel types showed that in fuel combustion, the majority of road transport impacts was derived from diesel. While in the phase of fuel production, most of the impacts were from gasoline production. According to the results, technology ages (directly relating to emission standards) and fuel types had a major effect on pollution, health impacts, and costs. Future policies on $PM_{2.5}$ footprint reduction should promote public transport systems (elevated electric train/sky trains, public ferries, and buses). Future strategies aimed at reducing the $PM_{2.5}$ footprint should place an emphasis on technological age restrictions or stricter vehicle emission limits. Key activities aiming at reducing the $PM_{2.5}$ impact should encourage the use of low-emission fuels (i.e., gasoline, liquefied petroleum gas, compressed natural gas). Although exhaust emissions caused health impacts locally, the study addressed the importance of cleaner fuel/energy production to enhance the environmental sustainability of passenger transport systems in Thailand. Especially, increasing energy generation from cleaner and more sustainable sources (low-emission renewable energy sources) would have a significant increase of the environmental sustainability of sky trains.

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