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Assessment on Health and Ecosystem Impacts and Costs of Ozone Formation from Passenger Transport in Bangkok Metropolitan Region

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Abstract

Using life cycle assessment framework, this research aimed to estimate and compare the emission inventories, health and ecosystem impacts, and costs of ozone formation from passenger road, rail, and water transport in the Bangkok Metropolitan Region (BMR) in 2022 and in 2027. The study considered passenger cars, public buses, and motorcycles in the road transport; electric trains and rail cars in the public rail transport; and cross river ferries, Chao Phraya boats and Saen Saep canal boats in the public water transport. The ReCiPe 2016 method and Thai Spatially Differentiated Life Cycle Impact Assessment (ThaiSD) method were applied in the impact assessment taking into account health and ecosystem impacts from two ozone precursors - NO_x and NMVOCs. Thai-specific factors were applied for assessing impacts from exhaust emissions in Thailand, while global average factors were applied for assessing impacts from the energy production. In 2022, total NO_x emissions, NMVOCs emissions, health impacts, ecosystem impacts and costs from the passenger transport in BMR were 5.05E+04 tonnes, 2.61E+04 tonnes, 1.21E+03 DALY, 4.95E+00 species·yr and 1.94E+03 million Baht, respectively. In 2027, total NO_x emissions, NMVOCs emissions, health impacts, ecosystem impacts and costs from the passenger transport in BMR will be 5.37E+04 tonnes, 2.91E+04 tonnes, 1.40E+03 DALY, 5.42E+00 species·yr and 2.32E+03 million Baht, respectively. The scenario analysis on the modal shifts from the business-as-usual situations of BMR in 2022 and 2027 to the public transport systems (buses, electric trains and water transport) was performed. Although the modal shifts to the public buses increased NOx emission, they could reduce NMVOCs emissions, health impacts, ecosystem impacts and costs. The modal shifts to the electric trains helped reduce NO_x emissions, NMVOCs emissions, health impacts, ecosystem impacts and costs. The modal shifts to the water transport resulted in increasing the emissions, impacts and costs. This study suggests the promotion of public buses and electric trains and addresses the need to improve public water transport with low emission technologies in the future.

Keywords : Ozone formation; health impact; ecosystem impacts; public transport; modal shift; life cycle assessment

Introduction

The effects of ozone on ecosystem includes the loss of species diversity, the alterations in the habitat quality of plants and animals, and the alterations in the water and nutrient cycles [1]. Since the industrial revolution, ozone has caused the reduction in the tree photosynthesis (11%) and the tree productivity (7%) [2]. In addition, ozone has adverse health effects. In 2019, the long-term ozone exposure caused an estimated 365,000 deaths; globally 1 out of every 9 deaths were from Chronic Obstructive Pulmonary Disease (COPD) [3]. Ozone has been linked to COPD for children, particularly those under the age of 5. It increases their vulnerability to lower respiratory tract infections, which accounted for 28% and 17% of air pollution-related mortality in Thailand in 2019 [3]. According to the 2019 report on air pollution and noise issues in Thailand, the ozone concentrations of Bangkok Metropolitan Region (BMR) exceeded the 1-hour ambient air quality standard from 2009 to 2019 [4]. The photochemical reaction between volatile organic compounds (VOCs) and nitrogen oxides (NO_x) produces ozone [5]. Additionally, 77% of NMVOCs emissions and 78% of NO_x emissions in BMR are attributed to road transport [6]. The Ministry of Transport (MOT) is now attempting to improve public transport, particularly in BMR, by reducing traffic congestion and minimizing transport-related pollution by modal shifting from private automobiles to public transit and modifying the modes of transport [7].

Life cycle assessment (LCA) is a tool for determining which of the compared alternative products has the lowest environmental impacts [8], as information for policymakers to determine the project priorities and budget allocations. In this investigation, LCA framework has been used as a health impact and ecosystem impact assessment tool. There are many studies related to the health impact and cost of $PM_{2.5}$ emissions from road, rail, and water transport in BMR [9-10]. However, data related to the health and ecosystem impacts and the cost of ozone formation is lacking. In this study, we develop and analyze the emission inventory of ozone formation from road, rail, and water transport. We also estimate and compare the health impacts, ecosystem impacts and costs of ozone formation originating from road, rail, and water transport to saturate the air pollution content in Thailand. The effectiveness of public transport management of BMR in mitigating the impacts and costs of ozone formation on human health and ecosystems as the result of modal shift in transportation were also assessed.

Methodology

Goal and scope definition

The scope of this study is to assess the health and ecosystem impacts and costs of ozone formation originating from road, rail, and water transport in BMR including 6 provinces - Bangkok, Samut Prakan, Nonthaburi, Pathum Thani, Nakhon Pathom and Samut Sakhon [11]. The air emissions in this study can be divided into two parts: emissions from the vehicle use phase and emissions from the energy production phase. Two functional units have been defined in this study: 1 passenger-kilometer (1 pkm) - the unit of measurement representing the transport of one passenger by a defined mode of transport over the distance of 1 km; and annual passenger transport services in BMR in 2022 and 2027.

This study includes road, rail, and water transport: passenger cars≤7 seats, passenger cars >7 seats, buses, motorcycles, electric trains (including BTS Skytrain which is an elevated electric train system and MRT (Mass Rapid Transit) which has both underground and elevated electric trains), rail cars (SRT; State Railway of Thailand), cross river ferries, Chao Phraya boats and Saen Saep canal boats. Engine types, technology ages and fuel types were used for road transport calculation. The fuel varieties included gasoline, B7 biodiesel, B20 biodiesel, liquefied petroleum gas (LPG), and Compressed Natural Gas (CNG). The emission inventory for vehicle transport is based on Tier 2 methodology of EMEP/EEA 2019 [12]. The framework used in this study is shown in **Figure 1** and the specific data used in this study are shown in **Table A-1 and A-2**.

Ozone precursors inventory phase

The road transport emissions were calculated in this study as:

Emission (kg/pkm) = Emission factor (kg/vkm) x 1/Occupancy rate (passenger/vehicle) (1)

The ozone precursors considered in this study are NO_x and NMVOCs. The NO_x, NMVOCs emissions were calculated using equation (1). For rail transport (rail car and electric trains), the emissions calculations were based on the EMEP/EEA 2019 [10]. Specific data for rail transport emissions are shown in **Tables A-3 and Tables A-4**. The rail car emission equation used in this study is:

Emission (kg/pkm) = Emission factor (kg/tonnes) x Fuel consumption (tonnes/pkm) (2)

The electric trains emission equation used in this study is:

Emission (kg/pkm) = Emission factor (kg/kWh) x Electricity consumption (kWh/pkm) (3)

Water transport emissions were calculated based on [13] as shown in equations (4-6) and the specific data on the water transport are shown in **Table A-5**.

Water transport emissions = Cruising emission + Idling emission (4)

Cruising emission (kg/pkm) = Travelling time trip (hr/trip) x Load factor (unitless) x Avg. power (hp/p) x Cruising factor (kg/hp-hr) x 1/Avg. distance (km/trip) (5)

Idling emission (kg/pkm) = Idling factor x Cruising emission (kg/pkm) (6)

The emissions were calculated for the health and ecosystem impact assessment for the functional units of all passengers in BMR in 2022 and 2027 as shown in equation 7.

Emission (kg/year) = Number of pkm (pkm/year) x Emission (kg/pkm) (7)

Ozone formation impact assessment phase

The methods applied for assessing health and ecosystem impacts from ozone formation in this study are the ReCiPe 2016 method [14, 15] and Thai Spatially Differentiated Life Cycle Impact Assessment (ThaiSD) method [16] considering two ozone precursors - NO_x and NMVOCs. Ozone could be inhaled by humans or absorbed by plants. Ingestion of ozone causes an increase in mortality, and the resulting harm to human health is measured in Disability-Adjusted Life Years (DALY). It could also cause the disappearance of plant species. Terminal damage to terrestrial ecosystems were evaluated and reported in the unit species·yr [14-16]. The emission factors for the emissions from the energy production were collected from the ecoinvent Database version 8.3.0 [17]. The characterization factors were obtained from the ReCiPe 2016 method [14] and the Thai SD Method version 1.0 report [16] as shown in **Table A-6**.

This study combined the health impacts of NO_x and NMVOCs to determine the total health impacts. Likewise, the ecosystem impacts of NO_x and NMVOCs were combined to determine the total ecosystem impacts. In this investigation, the equation used for health and ecosystem impact assessment is:

IS = CF x m (8)

where CF = Characterization Factor (DALY/$kg_{emitted}$, species·yr/$kg_{emitted}$)
m = the emission mass per functional unit (in unit $kg_{emitted}$/pkm, $kg_{emitted}$/year)

In this study, the equation used for the economic assessment of the health impacts is as follows:

Cost of health impact = Health impact x MCF_{Health} (9)

MCF is a monetary conversion factor for the valuation of damage to health quality and ecosystem quality in Thailand, based on the budget constraint method [18]:

Future Value of $DALY_{2011}$ in 2022 = Value of $DALY_{2011}$ x $(1+r)^{2022-2011}$ (10)

where r = the average inflation rate of Thailand from 2021 to 2022

In this study the equations used for assessing the costs of the ecosystem impacts are as follows:

Cost of ecosystem impact =
Ecosystem impact x $MCF_{Ecosystem}$ (11)

Future Value of $BAHY_{2011}$ in 2022 =
Value of $BAHY_{2011}$ x $(1+r)^{2022-2011}$ (12)

$MCF_{Ecosystem}$ $(Baht/(PDFm^2.yr))$ =
($MCF_{Ecosystem}$ (Baht/BAHY))/10000 (13)

where $MCF_{Ecosystem}$ = Monetary conversion factors for the damage to ecosystem quality
BAHY = Biodiversity-adjusted hectare year

Interpretation phase

The interpretation phase includes the comparison of ozone precursor emissions, ozone-related health and ecosystem impacts and costs from the applications of different modes of transport and different transport scenarios. This phase also covers discussion, recommendations, and conclusions based on the obtained results.

There are eight scenarios in this study as shown in **Table 1**.

The data used for the public transport scenarios in this study are from the three-year operational plan (2020-2022) of Department of Land Transport. In addition, the Pollution Control Department (PCD) and the Office of Transport and Traffic Policy and Planning (OTP) operational plan for 2023-2027 includes the scenarios for 2027. This study considered 7,751 electric buses based on the white paper, "$PM_{2.5}$ and health impact reduction options for road transport in Bangkok Metropolitan Region" [19].

Results and Discussion

The health impacts and costs of ozone formation from various modes of transport in the BMR region (in the functional unit of pkm)

The horizontal axis of **Figure 2** depicts the modes of transport in BMR in 2022. The vertical axis represents the total health impacts in µDALY/pkm and the total health costs in Baht/pkm.

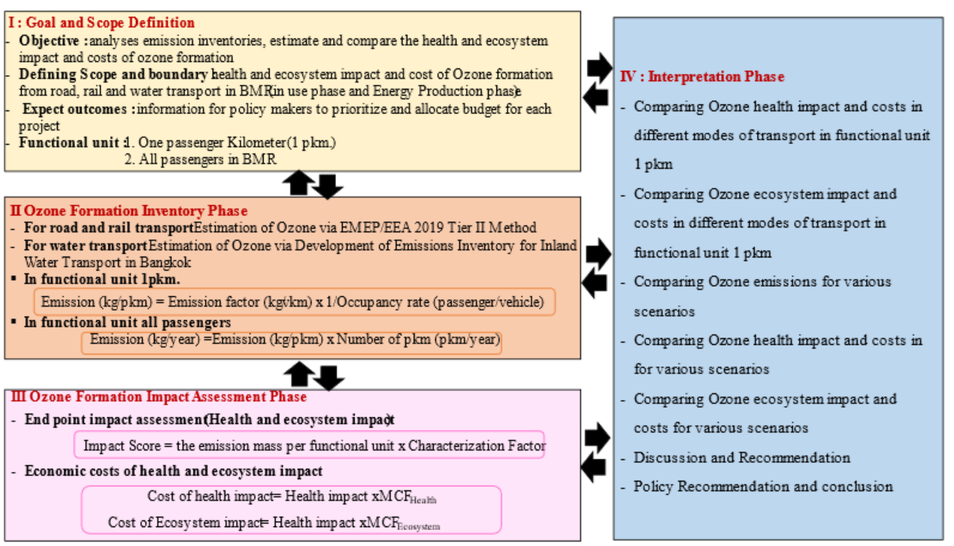

Figure 1 Research Framework of this study

Table 1 Scenarios analyzed in this study

Scenarios	
S1 2022 (BAU)	All modes of passenger road, rail and water transport in BMR in 2022
S2 2022	30% of all modes of transport shift to public buses in 2022
S3 2022	30% of all modes of transport shift to public water transport in 2022
S4 2022	30% of all modes of transport shift to electric trains in 2022
S1 2027	All modes of passenger road, rail and water transport in BMR in 2027
S2 2027	30% of all modes of transport shift to public buses in 2027
S3 2027	30% of all modes of transport shift to public water transport in 2027
S4 2027	30% of all modes of transport shift to electric trains in 2027

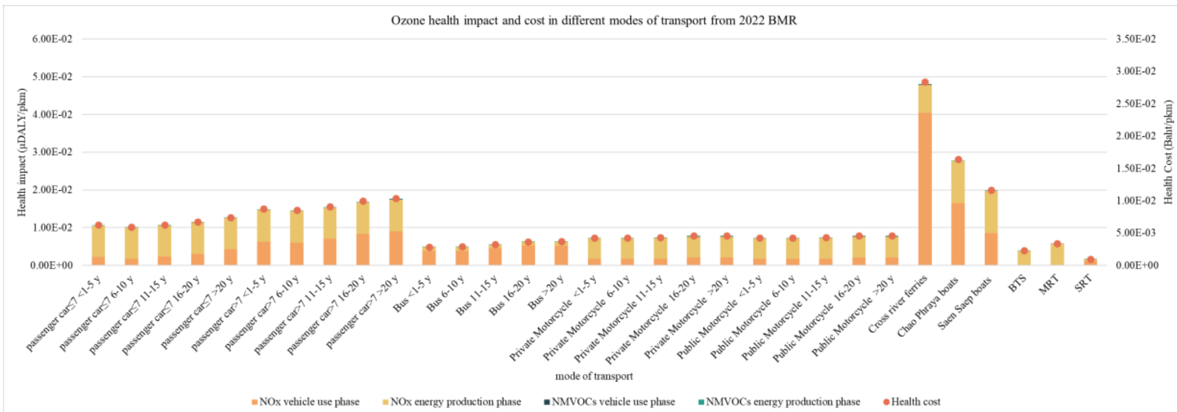

Figure 2 Total health impacts and costs from different modes of transport in BMR in 2022

In BMR, passenger cars ≤ 7 seats are mostly gasoline, followed by diesel, CNG, and LPG. The health impacts and costs ranged from 1.00E-02 to 1.25E-02 µDALY/pkm, and 5.96E-03 to 7.44E-03 Baht/pkm. Passenger cars with seven or more seats mostly used diesel fuel, followed by CNG, gasoline, and LPG. The health impacts and costs ranged from 1.44E-02 to 1.75E-02 µDALY/pkm and 8.53E-03 to 1.04E-02 Baht/pkm. The bus used CNG as the primary fuel, followed by diesel, LPG, and gasoline. The health impacts and costs ranged from 4.83E-03 to 6.28E-03 µDALY/pkm and 2.86E-03 to 3.72E-03 Baht/pkm. The health impacts and costs of private and public motorcycles, ranged from 7.21E-03 to 7.74E-03 µDALY/pkm and 4.28E-03 to 4.59E-03 Baht/pkm. The health impacts and costs of cross river vessels, Chao Phraya boats, and Saen Saep boats ranged from 1.97E-02 to 4.79E-02 µDALY/pkm and 1.17E-02 to 2.84E-02 Baht/pkm. The health impacts and costs of electric trains ranged from 3.84E-03 to 5.65E-03 µDALY/pkm, and 2.28E-03 to 3.35E-03 Baht/pkm. The rail car (SRT) results in negative impacts on health (1.59E-03 µDALY/pkm) and cost (9.43E-04 Baht/pkm).

The results indicate that NO_x had the greatest impacts on all modes of transport (greater than 90 percent). Thermal NO_x (Zeldovich Mechanism) is a chemical reaction between oxygen and nitrogen that forms combustion at high temperatures. The Fenimore Mechanism (Immediate NO_x) is a chemical reaction between a hydrocarbon compound and nitrogen in the air, influenced by several variables including fuel-air ratio, temperature, and pressure [20-22]. Thermal and immediate NO_x significantly emits during the vehicle use phase from the old water transport engines technology (pre-EURO) and old engine model years. The engine model years of cross river ferries, Chao Phraya boats and Saen Saep canal boats are all older than 20 years [13].

Consequently, the river crossing ferries had the greatest emissions, health impacts, and costs. In contrast, the rail cars (SRT) had the lowest health impact and expenditures due to their low fuel consumption and high occupancy rate. The passenger cars ≤7 seats, passenger cars >7 seats, buses, and motorcycles resulted in higher health impacts and costs due to their older age and inferior technology. LPG had the highest health impacts during the energy production phase, whereas CNG had the lowest health impacts. LPG and CNG engines were modified from gasoline engines and required a pressure-reducing device for complete combustion. In addition, LPG and CNG combustion temperatures were lower than gasoline and diesel [23-26]. As a result of advancements in road transport's engine technology, the health impacts and costs of road transport per pkm in 2027 were lower than in 2022. The health impacts and costs were ranked similarly.

The ecosystem impacts and costs of ozone formation from various modes of transport in the BMR region (in the functional unit of pkm)

The horizontal axis of **Figure 3** depicts the modes of passenger transport in BMR in 2022. The vertical axis displays the total ecosystem impacts in species·yr/pkm and the total ecosystem costs in Baht/pkm.

The ecosystem impacts of passenger car ≤7 seats ranged from 3.16E-11 to 5.37E-11 species·yr/pkm, and the costs ranged from 7.81E-03 to 1.33E-02 Baht/pkm. The ecosystem impacts of passenger car > 7 seats ranged from 6.39E-11 to 8.81E-11 species·yr/pkm, and the costs ranged from 1.58E-02 to 2.18E-02 Baht/pkm. The ecosystem impacts of bus ranged from 3.17E-11 to 4.20E-11 species·yr /pkm, and the costs ranged from 7.83E-03 to 1.04E-02 Baht/pkm. The ecosystem impacts and costs of private motorcycles and public motorcycles ranged from 3.08E-11 to 7.14E-11 species·yr/pkm, and 7.61E-03 to 1.76E-02 Baht/pkm. The motorcycles (more than 16 years) had highest NMVOCs emissions during the use phase. The motorcycles have two-stroke engines using the pre-mixing of oil and fuel and have a higher fuel consumption [25, 27, 28]. The ecosystem impacts and costs of Cross river ferries, Chao Phraya boats and Saen Saep boats ranged from 8.97E-11 to 3.26E-10 species·yr/pkm, and 2.22E-02 to 8.06E-02 Baht/pkm. The ecosystem impacts and costs of electric trains ranged from 7.43E-12 to 1.09E-11 species·yr/pkm, and 1.84E-03 to 2.70E-03 Baht/pkm. The ecosystem impacts and costs of rail car (SRT) were 1.00E-11 species·yr/pkm and 2.48E-03 Baht/pkm.

More than 90% of the impacts of NO_x on ecosystem was attributed to all modes of transport, as indicated by the results. Older water transport engine technology (pre-EURO) and older engine model year in the cross-river transport systems resulted in the highest ecosystem impacts and costs. The elevated electric trains (BTS) have no emissions from vehicle use phase, the lowest electricity consumption, and a high occupancy rate resulting in the lowest costs and impacts on the ecosystem. Passenger cars ≤ 7 seats, passenger cars > 7 seats, buses, and motorcycles had high ecological impacts and costs due to their advanced age and limited emission control technology. The vehicle use phase and energy production phase of NO_x, and NMVOCs energy production phase had higher ecosystem impacts than NMVOCs vehicle use phase by 5, 9, and 3 times, respectively. The vehicle use phase and energy production phase of NO_x, and NMVOCs energy production phase had a greater impact on human health by 187, 1,306, and 3 times, respectively. Consequently, the ranking of ecosystem impacts was different from that of health impacts. As a result of advancements in road transport engine technology, the ecosystem impacts and costs of road transport per pkm in 2027 were less than in 2022. The ecosystem impacts and costs were ranked similarly.

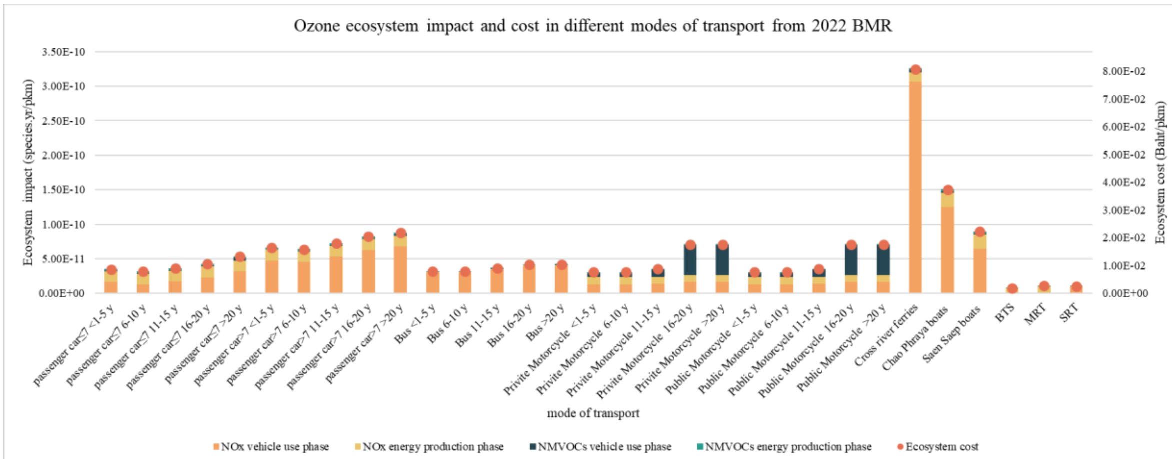

Figure 3 Total ecosystem impacts and costs in different modes of transport in BMR in 2022

Total BMR emissions in 2022 and 2027 (in the functional unit of annual passenger transport services)

The horizontal axis in **Figure 4** displays the eight study scenarios. The vertical axis displays the total NO_x and NMVOC emissions in tonnes/year for all modes of transport in the functional unit of transport in 2022 and 2027 in BMR.

Under the S1 2022 (BAU) scenario, NO_x emissions were summed as 5.05E+04 tonnes per year. The annual emissions of NMVOCs were equal to 2.61E+04 tonnes. In 2022, the cumulative NO_x emissions for scenarios 2, 3, and 4 were 5.19E+04, 9.06E+04, and 3.92E+04 tonnes per year, respectively. In 2022, scenarios 2, 3, and 4, NMVOCs emissions were 2.31E+04, 2.61E+04, and 1.96E+04 tonnes per year, respectively. In the scenario 1 2027, total NO_x emissions were 5.37E+04 tonnes per year. The annual emissions of NMVOCs equals to 2.91E+04 tonnes. In 2027, the total NO_x emissions for scenarios 2, 3, and 4 were 5.07E+04, 1.05E+05, and 4.23E+04 tonnes per year, respectively. The emissions of NMVOCs in 2027 for scenarios 2, 3, and 4 were 2.56E+04, 2.97E+04, and 2.23E+04 tonnes per year, respectively.

Passenger cars ≤7 seats, passenger cars > 7 seats and buses had the highest effects on the total NO_x emissions. Similarly, private motorcycle, passenger car ≤ 7 seats and passenger car > 7 seats had the highest influence on total NMVOCs emissions. In scenario 2 2022, NO_x emission was 3% higher than scenario 1 2022, while NMVOCs emission was 11% lower. The shifts in modes of transport to electric buses with no vehicle use phase emission in 2027 resulted in the reduction in the NO_x emissions (6% lower than NO_x emissions from scenario 1 2027). In scenario 3 for 2022, NO_x emissions were 79% higher than scenario 1 2022 because all modes of transport were shifted to water transport by 30% (which had the maximum NO_x emission per pkm in 2022). Similarly, the NO_x emissions in scenario 3 for 2027 were 96% higher than scenario 1 for 2027, and the NO_x emissions for road transport were lower in 2027 than in 2022. In scenario 4 for 2022, the NO_x and NMVOCs emissions were 22% and 25%lower than scenario 1 for 2022, respectively. This is because all modes of transport shifted to electric trains, which had no vehicle use phase emissions. Scenario 4 2022 had a greater percentage reduction than Scenario S 2027, due to the increase of transport in 2027. The best alternative with the lowest NO_x and NMVOC emissions in this assessment is Scenario 4 2022.

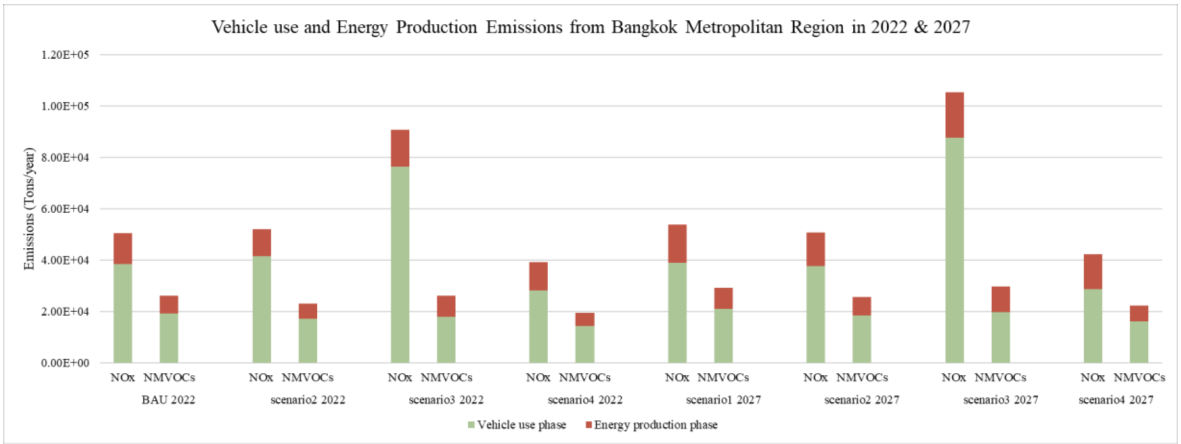

Figure 4 Total emissions in different 2022 and 2027 BMR scenarios

Total BMR ozone health impact and cost in 2022 and 2027 (in the functional unit of annual passenger transport services)

The horizontal axis of **Figure 5** depicts the eight scenarios examined in this study. The vertical axis displays the total health impacts in DALYs per year and the total health costs in Baht per year.

The total health impacts and costs under the BAU 2022 scenario was 1.21E+03 DALY/year and 7.17E+02 million baht/year. The total health impacts and costs for scenarios 2, 3, and 4 for 2022 were 1.14E+03, 1.75E+03, and 1.04E+03 DALY/year; and 6.73E+02, 1.04E+03, and 6.18E+02 million Baht/year (6.02%lower, 44.76%higher, and 13.70%lower than the BAU, respectively). The NO_x energy production phase had the greatest contribution on the total health impacts and costs of scenario 1 in 2027, which was 1.40E+03 DALY/year and 8.89E+02 million Baht/year. Scenarios 2, 3, and 4 2027 had total health impacts of 1.28E+03, 2.10E+03, and 1.23E+03 DALY/year, which were equivalent to the costs of 8.11E+02, 1.33E+03, and 7.78E+02 million Baht/year (8.78% less, 49.66% higher, and 12.52% less than scenario S1 2027).

The results indicate that the NO_x energy production phase had the greatest effect on the total health impacts (56.73 - 76.84% of the total health impacts). Scenario 2 for 2022 had the reduced health impacts from the NO_x energy production phase, NMVOCs vehicle use phase, and NMVOCs production phase by 12%, 12%, and 10% respectively, compared to scenario 1 for 2022. Scenario 2 for 2027 has the potential to lower the health impacts and costs than scenario 2 for 2022, due to the modal shift of transport to electric buses, which have no emission during the vehicle use phase. Scenario 3 for 2022 had the highest total health impacts from NO_x vehicle use phase and production phase, which were 98% and 20% higher, respectively, than the Scenario 1 for 2022. The health impacts and costs of Scenario 3 for 2027 were greater than those of Scenario 3 for 2022 as the result of the transition from road transport engines with more advanced technology in 2022 to water transport engines with older technology in 2027. Scenario 4 for 2022 had the lowest health impacts and costs because of the shift in all modes of transport to electric trains, which had nil vehicle use phase and low energy production phase emissions and health impacts per pkm. Scenario 4 for 2022 had a greater percentage reduction than Scenario 4 for 2027, due to the increase in transport in 2027 (similar to emissions).

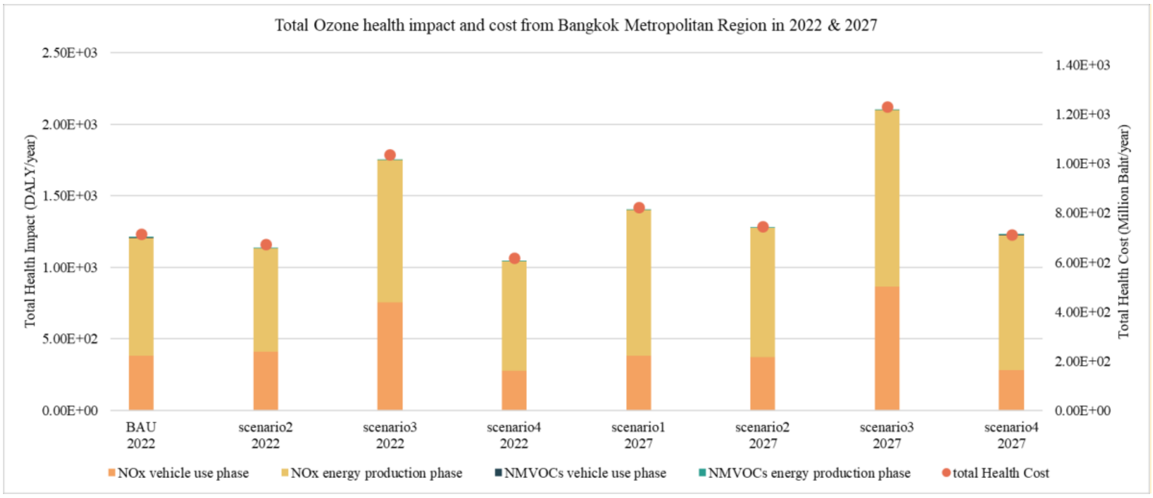

Figure 5 Total health impact and cost in different 2022 and 2027 BMR scenarios

Total ozone ecosystem impacts and costs in 2022 and 2027 (in the functional unit of annual passenger transport services)

The horizontal axis of **Figure 6** depicts the eight scenarios examined in this investigation. The vertical axis represents the entire ecosystem impact of a species·yr/year and total ecosystem cost expenditures in Baht/year.

The total ecosystem impacts and costs under the BAU 2022 scenario is 4.95E+00 species per year, or 1.22E+03 million Baht per year. The total ecosystem impacts for Scenarios 2, 3 and 4 2022 were 4.92E+00, 8.12E+00 and 3.93E+00 species·yr/year, respectively. This is equivalent to 1.21E+03, 2.01E+03 and 9.70E+02 million Baht/year, respectively (0.58% less, 64.07% higher and 20.61% less than the BAU 2022). The total ecosystem impact and cost of Scenario 1 for 2027 was 5.42E+00 species·yr per year, or 1.43E+03 million Baht per year. Scenario 2, 3 and 4 for 2027 had total ecosystem impacts and costs equal to 5.03E+00, 9.50E+00 and 4.34E+00 species·yr/year, or 1.33E+03, 2.51E+03 and 1.15E+03 million Baht/year, respectively (7.20% less, 75.30% higher and 19.83% less than Scenario 1 for 2027).

These results indicate that the NO_x vehicle use phase had the greatest influence on the total ecosystem impacts (49.19% to 70.37%). The NO_x energy production phase, the NMVOCs vehicle use phase, and the NMVOCs production phase had lower impact on the ecosystem in Scenario 2 2022 compared to Scenario 1 for 2022. Due to the modal transition of transport to electric buses, which have zero vehicle use phase emissions corresponding to Scenario 2's annual health impacts and emissions, Scenario 2 for 2027 could have a lesser impact on the ecosystem compared to Scenario 2 for 2022. The cumulative ecosystem impacts of Scenario 3 for 2022 from NO_x vehicle use phase and production phase were greater by 98% and 20% than Scenario 1 for 2022. Scenario 3 for 2027 had the highest ecosystem impacts and costs as the consequence of shifting all modes of transport from road transport engines with newer technology to water transport engines with older technology. As a result of shifting all modes of transport to electric trains, which has zero vehicle use phase emissions, low energy production phase emissions and ecosystem impacts per pkm, Scenario 4 for 2022 had the lowest ecosystem impacts and costs. Due to the increase in transportation in in 2027, the emissions and health impacts for Scenario 4 for 2027 was greater than Scenario 4 for 2022.

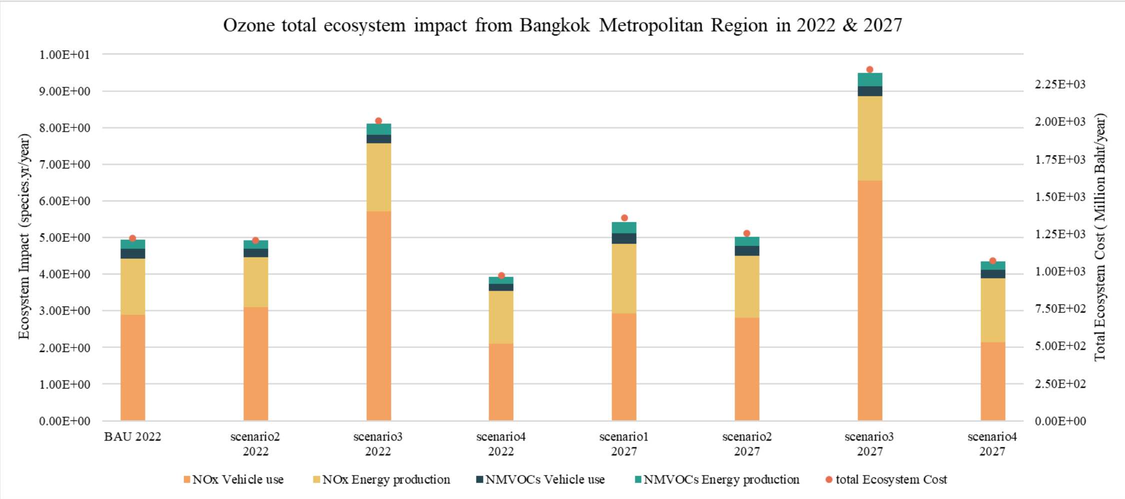

Figure 6 Total ecosystem impacts and costs in different 2022 and 2027 BMR scenarios

Conclusions

In BMR, the health impacts, ecosystem impacts and costs of ozone formation for various modes of transport were determined. BAU of transport in BMR has the greatest effect on the health and ecosystem impacts and costs compared to passenger cars ≤7 seats, passenger cars >7 seats, buses, and private motorcycles. 30% of all modes of transport in BMR were converted to buses in 2022. As a result, the NO_x emissions were 3% higher, while the NMVOC emissions, health impacts, and ecosystem impacts were 11%, 6.02%, and 0.5% lower than BAU transport in BMR, respectively. In addition, shifting all modes of transport to electric buses could reduce the NO_x and NMVOC emissions, health impacts, and ecosystem costs in 2027. 30% of transport in BMR shifted to water transport in 2022, which has the highest vehicle use phase emission per pkm and the highest health and ecosystem impacts per pkm. As a result, the NO_x emissions, health, and ecosystem impacts were 97%, 44%, and 64% higher than BAU transport in BMR. All modes of transport shifted to electric trains, which has zero vehicle use phase emissions and low energy production phase emissions and ecosystem impacts per pkm. As a result, the NO_x and NMVOCs emissions were 22% and 25% less than BAU transport in BMR, and health and ecosystem impacts were 13% and 20% less than BAU transport in BMR. Shifting all modes of transport to the electric trains resulted in the lowest emissions, heath, ecosystem impacts and costs. It is therefore essential that Thai government increases the main public transport system; electric trains should be covering the BMR area in the same way as feeder development, such as the use of EURO 4 and above for boats and buses or the use of electricity as fuel. In addition, the technology of private cars should be developed, such as the use of EURO 4 and above, including the use of electricity as fuel. This result corresponds to the 20-year transport system development strategies for Thailand [7], 5-year action plan (2023-2027) of the PCD [29] and MOT Transport Action Plan for 2022 [30]. This will help in developing environmentally friendly and safe modes of transport with focus on rail and electric buses and create connections between stations to facilitate travel. Moreover, this result is consistent with the Annual PCD Action Plan for 2022 [31]. BMR should concentrate on transport pollution solutions. For conducting more comprehensive scenario analysis in the further studies, electric cars (passenger cars≤7 seats, passenger cars>7 seats) should be considered, because there were 41,784 new registered electric cars in 2023 compared to the number of new registered cars between January and June in 2022 [32].

Appendix A. Supplementary data

Supplementary data to this article can be found online at
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References

[1] Global Challenge Network on Tropospheric Ozone. 2020. Ecosystem effects of ozone. www.ozone-net.org.

[2] Wittig, V. E., Ainsworth, E. A. and Long, S. P. 2007. To what extent do current and projected increases in surface ozone affect photosynthesis and stomatal conductance of trees? A meta-analytic review of the last 3 decades of experiments. Plant, Cell & Environment. 30(9): 1150-1162.

[3] Health Effects Institute. 2020. State of Global Air 2020. Special Report. Boston. MA: Health Effects Institute.

[4] Pollution Control Department. 2021. The state of air and noise pollution in Thailand 2021.

[5] United State Environmental Protection Agency. 2022. Sources of Hydrocarbon and NOx Emissions in New England. Available at https://www3.epa.gov/region1/airquality/piechart.html.

[6] Winijkul, E. and Punpukdee, P. 2022. Final Project Report "Improving Calculation in the Emission Inventory Management Platform".

[7] Ministry of Transport. 2019. The 20-year strategy for the development of Thailand's transportation system (2018-2037).

[8] Hauschild, M. and Huijbregts, M. 2015. Introducing Life Cycle Impact Assessment. In: Hauschild, M., Huijbregts, M. (eds) Life Cycle Impact Assessment. LCA Compendium – The Complete World of Life Cycle Assessment. Springer, Dordrecht.

[9] Chavanaves, S., Fantke, P., Limpaseni, W., Attavanich, W., Panyametheekul, S., Gheewala, S. and Prapaspongsa, T. 2021. Health impacts and costs of fine particulate matter formation from road transport in Bangkok Metropolitan Region. Atmospheric Pollution Research. 12(10): 101191.

[10] Sakpheng, P., Chavanaves, S., Mankhong, C., Saengdao, S., Limpaseni, W., Panyametheekul, S., Winijkul, E., Fantke, P., Gheewala, S. H. and Prapaspongsa, T. 2021. $PM_{2.5}$ Footprint: a Tool for Enhancing Sustainable Passenger Transport. 8th International Conference on Green and Sustainable Innovation, Krabi, Thailand.

[11] Office of Transport and Traffic Policy and Planning. 2018. Travel demand survey (final report).

[12] European Environment Agency. 2019. EMEP/EEA air pollutant emission inventory guidebook 2019: technical guidance to prepare national emission inventories.

[13] Winijkul, E. 2020. Development of Emissions Inventory for Inland Water Transport in Bangkok, Thailand (Final Report).

[14] Huijbregts, M., Steinmann, Z., Elshout, P., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A. and Zelm, R. 2016. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. The International Journal of Life Cycle Assessment. 22: 138-147.

[15] Huijbregts, M., Zelm, R. v., Steinmann, Z., Stam, G., Elshout, P., Vieira, M., Zijp, M. and Hollander, A. 2020. ReCiPe2016 country factors v1.1 20171221. Available at https://www.rivm.nl/documenten/recipe2016country-factorsv1120171221.

[16] Prapaspongsa, T., Gheewala, S. H., Mankong, P., Rotthong, M., Sakpheng, P., Chavanaves, S., Balasuriya, T., Deuja, A. and Oo, P. Z. 2021. ThaiSD v1.0: Thai

Spatially Differentiated Life Cycle Impact Assessment Method version 1.0 – Background Report.

[17] Moreno Ruiz E., FitzGerald D., Symeonidis A., Ioannidou D., Müller J., Valsasina L., Vadenbo C., Minas N., Sonderegger T., and Dellenbach D. 2021. Documentation of changes implemented in the ecoinvent database v3.8.

[18] Kaenchan, P. and Gheewala, S. H. 2017. Budget constraint and the valuation of environmental impacts in Thailand. The International Journal of Life Cycle Assessment. 22(11): 1678-1691.

[19] Prapaspongsa, T., Jumsai Na Ayudhya, M., Sukuman, T. and Chavanaves, S. 2022. White Paper "$PM_{2.5}$ and Health Impact Reduction Options for Road Transport in Bangkok Metropolitan Region". Mahidol University.

[20] Charernporn, P. 2014. NO_x Emissions mitigation in a fluidized bed combustor firing biomass fuel. Silpakorn University.

[21] Pollution Control Department. 2003. Adjustment and maintenance of large diesel engines to reduce pollution and save energy.

[22] Semakula, M. and Inambao, F. 2018. The Formation, Effects and Control of Oxides of Nitrogen in Diesel Engines. International Journal of Applied Engineering Research. 13: 3200-3209.

[23] Century Fuel Products. 2023. Fuel characteristics. Available at https://centuryfuelproducts.com/media/schematics/Fuel_Characteristics. pdf.

[24] Suranaree University of Technology. 2016. Combustion Science. Available at http://eng.sut.ac.th/ae/ae2016/src/file/SubjectDocument/file/%E0%B8%9A%E0%B8%97%E0%B8%97%E0%B8%B5%E0%B9%88%202_1_1492766706.pdf.

[25] Kulprasut, P. 2008. Gasoline engine theory. Chulalongkorn University Press.

[26] Kulprasut, P. 2010. Diesel engine theory. Chulalongkorn University Press.

[27] Berryman Products. 2023. What's The Difference Between 2-Stroke & 4-Stroke Engines? Available at https://www.berrymanproducts.com/two-stroke-vs-four-stroke-engines/.

[28] Edgar School District. 2023. Two-Cycle and Four-Cycle Engines. Available at https://www.edgar.k12.wi.us/faculty/mreinders/Chapter%205%20%202%20and%204%20cycle%20engines.pdf.

[29] Pollution Control Department. 2022a. 5-year action plan (2023-2027) of the Pollution Control Department. Available at https://www.pcd.go.th/wp-content/plugins/wonderplugin-pdf-embed/pdfjs/web/images/texture.png.

[30] Office of Transport and Traffic Policy and Planning. 2022. Transport action plan in 2022 of Ministry of Transport. Available at https://www.otp.go.th/post/view/6124.

[31] Pollution Control Department. 2022b. Annual Pollution Control Department action plan in 2022. Available at https://www.pcd.go.th/wp-content/plugins/wonderplugin-pdf-embed/pdfjs/web/images/texture.png.

[32] Department of Land Transport. 2023. Number of new registered cars classified by fuel type. Available at https://web.dlt.go.th/statistics/.