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Energy and environmental benefits and policy implications for private passenger vehicles in an emerging metropolis of Southeast Asia – A case study of Metro Manila

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HIGHLIGHTS

- The new tax schedule of gas slightly reduces emissions but raises the tax revenue.
- The new tax schedule of vehicle reduces vehicle fleet but not emissions.
- The Euro 6 cars and Euro 4 buses and PUJs significantly improve public health.
- The improved accessibility reduces energy demand but not pollutant emissions.
- All the low carbon scenarios should be integrated to achieve sustainable mobility.

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ABSTRACT

An increase in private vehicle fleet and usage exacerbates the overuse of petroleum products, air quality degradation, and public health risks, among other drawbacks. This study investigated the energy and environmental benefits for private passenger vehicles under various scenarios in Metro Manila, the Philippines. The findings are informative to design policy implications for energy and environmental benefits. The study applied the Gaussian copula-based multinomial logit (MNL)-linear regression to develop the household vehicle ownership and energy consumption model using the disaggregated data of 1,795 households collected in 2017. The simulated vehicle fleet and energy consumption were then adopted to extrapolate energy demand, emissions, and public health risks for a 2010–2050 horizon using the bottom-up approach. Under the baseline scenario, the energy demand and carbon dioxide (CO\textsubscript{2}) emissions will reach 5.45 million tonnes of oil equivalent (Mtoe) and 16.93 million tonnes (Mt) in 2050, respectively. The amounts of hydrocarbon (HC), carbon monoxide (CO), sulfur dioxide (SO\textsubscript{2}), nitrogen oxides (NO\textsubscript{x}), particulate matter 10 (PM\textsubscript{10}) and particulate matter 2.5 (PM\textsubscript{2.5}) emissions, and economic loss of health risks will be 6,214 tonnes (t), 62,136 t, 536 t, 10,550 t, 1,348 t, 996 t, and 237 Million USD, respectively, under the baseline scenario in 2050. Improvement of accessibility significantly reduces energy demand and CO\textsubscript{2} emissions. Introduction of Euro 6 cars and Euro 4 buses and Public Utility Jeepneys noticeably improves public health. The new tax schedules on gas and vehicle maximize the tax revenue. The integration of all the mentioned alternatives can achieve sustainable mobility and urbanization.

1. Introduction

The global energy-related CO\textsubscript{2} emissions have become fairly steady in 2014, despite a roughly 3% growth rate of the global economy [1]. According to the 21st Conference of the Parties of the United Nations Framework Convention on Climate Change (UNFCCC) meets in Paris in December 2015, further effort, however, is required to limit global warming to an average of no > 2 °C, relative to the pre-industrial levels [1]. The energy-related CO\textsubscript{2} emissions are highly correlated with pollutant emissions [2]. Southeast Asia is an emerging region with the world’s 7th largest economy valued at 7.4 trillion USD in 2016, and strong economic growth has raised a 70% increase in energy demand in...
2016 relative to 2000 [3]. The region accounted for 5% of the global energy demand in 2016 with an annual growth rate of 3.4% on average since 2000, and this growth rate is outpacing the global growth rate of 2.0% per annum on average [4,3]. The total energy demand in the region was 640 million tonnes of oil equivalent (Mtoe) in 2016 [3]. The Philippines, an archipelagic country located in the southeastern part of Asia, accounted for 5.17% of the region’s total energy demand in 2016 [5]. This country has experienced an average economic growth of 6.6 percent per annum during the last three years [6]. The Philippines’ ratio of greenhouse gas (GHG) to gross domestic product (GDP), however, is higher than the world average [7], and the GHG productions are expected to increase further if left unchecked. The country’s total energy consumption increased from 30.5 Mtoe in 2015 to 33.1 Mtoe in 2016 with an average annual growth rate of 8.4% [5]. In 2016, the biomass and biofuel accounted for 7.7 Mtoe, while the total electricity consumption reached 6.4 Mtoe [5]. The archipelago has outstanding geographical conditions for energy production from renewable sources, viz., wind, solar, and geothermal. In December 2008, the government enacted the Renewable Energy Act of 2008 to increase renewable energy use in the country’s energy mix with the role to effectively reduce harmful emissions and achieve economic development [8,9]. However, the proportion of renewable energy for electricity demand decreases from 44% in 1999 to 32% in 2012 [8]. The country’s total petroleum-based energy demand reached 16.3 Mtoe in 2016 (or 49.24% of the country’s total energy demand) [5], and the petroleum products accounted for a 99.92% share of the transport sector’s total energy demand in 2015 [10]. The transport sector may be argued to be one of the integral parts of the environmental sustainability of the national econosphere accounting for 30.4% of the country’s CO₂ emissions from fuel combustion in 2012 [11] and 36.5% of the total energy demand in the Philippines [12]. The road transport sector typically accounted for roughly 80% of the transport sector’s total energy demand and 70% of the country’s petroleum-based fuel consumption [12]. In short, the road transport sector of the Philippines is mainly dependent on petroleum fuels. We are wondering whether there is a glimmer of hope to reduce petroleum product consumption for the road transport sector in the Philippines.

The unceasing GDP growth over the years has shot up the private vehicle sales and usage in Metro Manila, the national capital region (NCR) of the Philippines. The metropolis leads all the regions in the vehicle fleet with a total of 1.698 million units registered in 2016 and an average annual uptake of 204,404 new passenger vehicles from 2015 to 2016 [13]. The vehicle stock in Metro Manila is 38.61% of the country’s vehicle stock [13]. The private vehicles accounted for 31.7% of person trips and 71.3% of vehicle trips in Metro Manila in 2012, and the private vehicles in terms of vehicle trips increased by 3.3% per annum from 1996 to 2012 [14]. About 50% of the roads in Metro Manila operate already at volume/capacity (V/C) ratios above 0.80 [14]. The growing private vehicle dependency in the metropolis over the years has rapidly reduced the effectiveness of the Unified Vehicular Volume Reduction Program (UVVRP), commonly known number coding or color-coding scheme [15,16]. The projected up-trend in vehicle ownership is speculated to saturate the roads further.

Excessive use of private vehicles exacerbates traffic congestion, requires higher imported oil demand, and elevates flue gas productions. Traffic congestion negatively affects the household economy and degrades the quality of life, and higher energy demand and GHG emissions are consistent with energy insecurity and unsustainable development. The vehicular flue gas productions including carbon monoxide (CO), hydrocarbon (HC), sulfur dioxides (SO₂), nitrogen oxides (NOₓ), and particulate matter (PM) can degrade public health and provokes mortality and hospital admission via respiratory and cardiovascular risks, asthma attack, and acute and chronic bronchitis [2]. Previous studies have looked at various pathways to address the issues by cutting back the energy demand and flue gas productions from the passenger transport sector in Metro Manila. The proposed solutions include the improvement of fuel quality and the implementation of the Euro 4 emission standard [17], the expansion of metropolitan railway network and the development of public transport service [18,19,20,21], and the reduction of private vehicle kilometers traveled (VKT) [22,23,24]. All the mentioned studies indicate the importance of management of private car ownership, penetration of greener cars, demotivation of private vehicle usage, and encouragement of public transport usage. However, prioritization of policies to promote those things needs to be able to account for the market and citizens’ behavior, vehicle and gas tax policies, and land-use patterns, not only based on the macroeconometric approach or historical trend. The latter might not be reliable with regard to policy changes, technological progress, and social development.

Regidor and Javier [25] and Asian Development Bank (ADB) [26] emphasized the contribution of managing private vehicle ownership, usage, and energy intensity to combat GHG emissions. Mijares et al. [27] speculated that the improvement of mass public transport service may be inefficient if car ownership cost is not increased. Recently, the government launched the Tax Reform for Acceleration and Inclusion (TRAIN) law or RA No. 10963 to increase gas and vehicle prices [28], and the impact thereof on private vehicle fleet, energy demand, mobile emissions, and public health has remained largely unexplored. Regarding the transportation perspective, the prerequisite of designing effective, proactive transport policies toward sustainable urbanism and mobility, along with social development, is to understand the potential determinants of household vehicle ownership and usage well [29].

The gas and vehicle taxes, urban form attributes, and socioeconomic characteristics in Metro Manila can be considered as peculiarities different from other countries. For instance, the dominant public transport mode in Metro Manila is Public Utility Jeepney (PUJ), and its features are similar to a mini-bus. The majority of PUJs are not air-conditioned. For other peculiarities, the socioeconomic characteristics and tax policies on gas and vehicle are different from one country to another, even in Southeast Asia. Hence, the specific objectives of the study are threefold: a) to develop the joint model of household vehicle ownership and usage decision in Metro Manila, and b) to apply the developed model to project the vehicle stock, new vehicle sales, energy demand, CO₂ and pollutant emissions, public health outcomes, and tax revenues as well as the net value under different scenario designs; and c) to discuss and propose policy implications based on the model estimation and application results. The study used the disaggregated data of 1,795 households to develop the joint household vehicle ownership and energy consumption using the Gaussian copula-based discrete–continuous choice model. The main reason for using the disaggregated data is that the disaggregated model does not provide an unbiased estimate of an average probability or an average response [30]. Compared to more developed countries, disaggregated data availability and support to gather first-hand data are limited in emerging economies.

For the practical term, a sound understanding of the potential determinants of household vehicle ownership and usage is the primary informative precursor to pioneer consistent, pro-active policies to discourage private vehicle dependency. The developed model was also applied for scenario analysis of energy demand, flue gas emissions, public health risks, and net value during 2010–2050. The contributions of the study are twofold. Firstly, the empirical findings of the study are exhaustive, innovative, and peculiar, which is highly expected to aid transport and energy policymakers to craft the strategic interventions to enhance traffic flow, reduce energy demand, mitigate mobile emission inventories, and improve the public health of citizens in a metropolis of a developing country with a minimum reduction in tax revenues on gas and vehicle. Secondly, the study expands the scope of the existing low-carbon scenario analysis that has never taken account of the improvement of accessibility in residential areas and tax policy. In short, this is the first case study of public health risk assessment and tax revenues on gas and vehicle under the low-carbon scenario analysis for the road transport sector in Metro Manila, the Philippines. The policy
implications of this research are highly expected to be informative for metropolises located in some other ASEAN countries, viz., Thailand, Indonesia, Malaysia, and Vietnam.

The remainder of this paper is structured as follows. Section 2 briefly reviews the existing literature of bottom-up approaches, low-carbon scenarios, and discrete-continuous choice models. Section 3 is the methodology comprising the conceptual framework of the study, the disaggregated data, the joint model of household vehicle ownership and energy consumption, the scenario designs, and the bottom-up approach. Section 4 presents the model estimation results and discuss the low-carbon scenario analysis. Section 5 shows some policy implications. Section 6 describes the role of the energy mix and the generalization of the developed model outcomes for some ASEAN countries. Section 7 discusses the uncertainty analysis of the study and bang for buck analysis. The last section concludes the findings, outlines the limitations of the study, and suggests directions for future research.

2. Literature review

2.1. Bottom-up approach

Two main model categories are widely carried out for projection of the road transport’s energy demand and mobile emission inventories – top-down and bottom-up approaches. The top-down approach is a simple method based on the statistical data of transport fuel sales, and this approach cannot apply the counter-measure scenarios to extrapolate the road transport energy demand and emissions for low-carbon policy analysis. The other approach, the bottom-up, is more detailed and used to support either national or local level policies regarding various strategic approaches. It can approximately quantify long-term energy demand and emissions based on vehicle fleet, vehicle size, fuel type, fuel economy, and vehicle travel activity. The bottom-up approaches applied in the existing literature of low-carbon scenario analysis for the road transport sector are listed in Table 1. For the bottom-up, the Long-Range Energy Alternatives Planning (LEAP) model, developed by Stockholm Environment Institute in 1997, has been extensively applied to investigate the potential options to cut back the road transport energy demand and vehicular emissions thanks to its simplicity and ease in application and interpretation. The LEAP model has been applied by Liu et al. [2] for China’s transport sector, Prasad and Raturi [31] for Fiji’s road transport sector, Hao et al. [32] for China’s passenger transport, Peng et al. [33] for urban passenger transport in Tianjin, Ahanchina and Biona [17] for the land transport sector in Metro Manila, Shabbir and Ahmad [34] for the urban transport sector in Rawalpindi and Islamabad. The LEAP approach can link the energy demand and emissions with historical trend and macro-economic characteristics and capture the effects of vehicle technological progress and fuel feature on energy demand and emissions. However, the LEAP model is violated when there exist changes in public transport services and land use, household income, and taxes on gas and vehicle. Similar to the LEAP approach, IEA/SMP is the framework of the Sustainable Mobility Project (SMP) implemented by the World Business Council for Sustainable Development and International Energy Agency. Deendarlianto et al. [35] applied the IEA/SMP approach to investigate the potential pathways toward the reduction of energy and fossil-based oil consumption.

Another tool is VISION, released by the Argonne National Laboratory’s Transportation Systems Assessment Group. The VISION tool was applied by Kay et al. [36] to forecast the GHG emissions of the US road transportation sector. Another modeling approach is ASIF (total activity, modal structure, modal energy, and carbon content of fuels), proposed by Schipper et al. [37]. The ASIF was recently applied by Li et al. [38] to quantify the impact of local public transport characteristics and land-use changes on the future energy consumption and CO₂ emissions of the passenger transport sector in China. The other bottom-up approach is AIM/Enduse, which was applied by Selvakumaran and Limmeechokchai [39] to forecast the energy demand, CO₂ emissions, and co-benefits of the transport sector based on various low-carbon measures. However, it is an arduous task to use the VISION, ASIF, and AIM/Enduse models to extrapolate the atmospheric pollutants, unlike the LEAP approach.

There is a need to explore whether there is a synergistic approach that can be applied to overcome the limitations of the previous bottom-up approaches and consider new low-carbon scenarios.

2.2. Low-carbon scenario analysis

The existing literature of low-carbon scenario analysis for the road transport sector is summarized in the second column of Table 1. The typical low-carbon options proposed are the promotion of greener vehicle usage, the reduction of private VKT, the promotion of non-motorized and public transport mode share, switching road public transport modes from diesel to compressed natural gas (CNG), switching motorcycles from two-stroke to four-stroke, the promotion of low-carbon fuel usage, and the improvement of the public transport system, etc.

Evident from the previous studies, the vehicle fleet is projected using a macroeconomic approach and based on the historical trends. The LEAP and IEA/SMP models are not applicable to control the vehicle fleet and usage influenced by changes in tax policy on gas and vehicle and changes in land use and travel behavior of commuters. The number of vehicles owned by households is mainly influenced by household income, vehicle cost, land use patterns [29,40,41], while the vehicle usage (VKT) is mainly influenced by gas price and built environment characteristics [29,41,42,43]. Furthermore, it is not simple to use the VISION, ASIF, and AIM/Enduse models to extrapolate the atmospheric pollutants, and the previous studies using the mentioned bottom-up models have never taken into account the atmospheric pollutants as the output variables.

Based on the existing literature, a long-term analysis of energy demand and pollutant emissions from the road passenger transport sector has never considered the taxes on gas and vehicle and the improvement of accessibility from residential areas to key destinations (e.g., school, hospital, market, and recreation center). This might be due to the limitations of the aggregated models (i.e., LEAP, IEA/SMP, VISION, ASIF, and AIM/Enduse). The novelty of our research is the consideration of these mentioned low-carbon scenarios by applying the simulated results ascertained from the microeconomic theory because the macroeconomic approach is closely linked to the historical trend and cannot capture the impact of policy changes of gas and vehicle prices and land-use changes on vehicle fleets, new vehicle sales, and vehicle usage.

2.3. Discrete-continuous model

The first thing to consider the taxes on gas and vehicle and the improvement of accessibility as the low-carbon scenarios for a long term analysis is to apply the microeconomic theory to develop a disaggregated model (i.e., the analysis of the individual level of data) of household vehicle ownership and usage taking into account the mentioned variables (i.e., gas price, vehicle cost, accessibility). The microeconomic theory provides some merits over the aggregated model such as looking at the actions of individual/household decisionmaking units, estimation of parameters with more precision, and less covariation among factors [44]. Next, we apply the disaggregated model to capture the marginal effects of a tax levy on gas and vehicle and land use changes on vehicle ownership and usage. Finally, the simulated vehicle fleet and usage can be applied for a long-term analysis of energy demand and emissions based on the bottom-up approach under different scenario designs. There are many disaggregated models of discrete-continuous choice decision, such as the multiple discrete-continuous extreme value (MDCEV) proposed by Bhat [45], the Bayesian
multivariate ordered probit and Tobit (BMOPT) model proposed by Fang [46], the copula-based binary logit-linear regression model proposed by Bhat and Eluru [47], and the multinomial probit-multinomial logit-linear regression model proposed by Liu et al. [43]. The MDCEV is not possible to simulate the vehicle usage for a given change of variables of interest because of the assumption of fixed vehicle usage for each household [43,46], while the BMOPT consists of a concern that the ordered mechanism may not perform as well as the unordered mechanism based on the Random Utility Maximization principle in modeling car ownership because the ordered mechanism is based on the hypothesis that an unidimensional continuous latent variable ownership propensity index determines household vehicle ownership levels [48,43]. The multinomial probit-multinomial logit-linear regression model cannot estimate the alternative specific parameters of vehicle usage for different vehicle ownership categories because of the limited computational capacity, which cannot be applied to simulate the vehicle usage by vehicle ownership category. Furthermore, the linear regression of this discrete-continuous model is adopted to deal with the overall car usage per household even though households have no car. This concept might not affect much the results of studies in the US because the percentage of no-car households is very small in the US, 7.28% in 2009 [43], but this concept does not make sense in developing countries because the proportion of no-car households is very high therein. A copula-based binary logit-linear regression model is a kind of unordered mechanism of the disaggregated model, and it can estimate the alternative specific parameters for vehicle usage and simulate the vehicle usage by vehicle ownership category. Based on the concept of Bhat [45], Spissu et al. developed the copula-based multinomial logit (MNL)-linear regression model for multiple-choice categories to simulate the impact of gas price on the usage of each vehicle type in the US [49].

Consequently, the originality of this study is to propose an idea to develop the joint model of household vehicle ownership and energy consumption at the disaggregated level by applying the copula-based MNL-linear regression for a developing metropolis. The developed model is then applied to calculate the marginal effects of variables of interest on vehicle fleet and energy consumption. Finally, the simulated vehicle fleet and energy consumption are used to project the output variables (i.e., vehicle fleet, vehicle sales, scrapped vehicle numbers, private VKT, energy demand, emissions, public health risks, and net

### Table 1

Table 1: Bottom-up approaches and low-carbon measures of the existing literature.

| Model, Period, Case Study | Mitigation Scenario Analysis | Output Variable | References |
|---------------------------|-----------------------------|-----------------|------------|
| LEAP, 2010 – 2050, China  | Improvement of energy efficiency | Energy demand | [2] |
|                           | Travel mode optimization | Emissions | |
| LEAP, 2016 – 2040, Fiji   | Penetration of electric cars and taxis | Energy demand | [31] |
|                           | Penetration of hybrid cars, taxis, and buses | GHG emissions | |
|                           | Increasing non-motorized mode share | | |
|                           | Improvement of vehicle fuel economy | | |
|                           | Adoption of the number coding scheme | | |
|                           | Increasing the proportion of biofuel usage | | |
| LEAP, 2010 – 2040, Tianjin| Policy initiatives of the road passenger transport of Tianjin; The 12th five-year plan policy (PP) | Energy demand | [33] |
|                           | Comprehensive policy (CP) | Emissions | |
|                           | The hybrid policy of PP and CP | | |
| LEAP, 2010 – 2040, Metro Manila | Switching the buses from diesel to CNG | Fuel demand | [17] |
|                           | Improvement of fuel quality | Emissions | |
|                           | Regulation of Euro 4 emission standard | | |
|                           | Modernization of old Jeepsneys (mini-bus) | | |
| LEAP, 2000 – 2030, Rawalpindi & Islamabad | Switching the motorcyclists/tricycles form two-stroke to four-stroke | Fuel demand | [34] |
|                           | Promotion of bus usage in place of private vehicle usage | Emissions | |
| IEA/SMP, 2015 – 2030, Indonesia | Improvement of vehicle fuel economy via the introduction of new vehicles, retirement of old vehicles, and the introduction of biodiesel up to 20% | Energy consumption | [35] |
|                           | Increase biofuel usage up to 30% | Oil consumption | |
| VISION, 2000 – 2040, the US | Introduction of CNG public transport vehicles and trucks | CO₂ emissions | [36] |
|                           | Reduction of the distance from employment centers and residential areas to transit-oriented cores | | |
|                           | Improvement of transit service | | |
|                           | An increase in VKT tax | | |
| ASIF, 2010 – 2050, China  | Optimistic and pessimistic economic growth | Energy | [38] |
|                           | Promotion of alternative fuel usage and small-sized car ownership | CO₂ emissions | |
|                           | Land usage pattern and public transport characteristics | | |
|                           | Increasing car and taxi loading factor | | |
| AIM/Enduse, 2010 – 2050, Thailand | Low-carbon society measure (i.e., low, medium, high) | Energy | [39] |
|                           | Emission taxes | Emissions | |
|                           | Penetration of biofuel usage | Co-benefit | |
| Bottom-up, 2014 – 2030, Beijing-Tianjin-Hebei | Regulation of vehicular emission standard | Energy | [93] |
|                           | Limitation of vehicle registration | Emissions | |
|                           | Improvement of the public transit system | | |
|                           | Penetration of electric vehicles | | |
| Bottom-up, 2000 – 2050, China | Technology penetration | GHG emissions | [32] |
|                           | Improvement of vehicle fuel economy | | |
|                           | Promotion of alternative fuels | | |
| Bottom-up, 2000 – 2050, China | Promotion of fuels with low GHG emission intensity | Fuel | [94] |
|                           | Limitation of vehicle registration | GHG emissions | |
|                           | Reduction of VKT | | |
|                           | Fuel consumption rate strengthening | | |
|                           | Vehicle downsizing | | |
|                           | Penetration of electric vehicles | | |
value) for private passenger vehicles under various low-carbon scenarios (i.e., taxes on gas and vehicle, accessibility improvement, and modernization of road-based public transport modes) based on the bottom-up approach. These scenarios have been less considered for low-carbon scenario analysis of the road transport sector, mostly in developing countries, and this synergistic method can overcome the limited capacity of the previous bottom-up approaches.

3. Methodology

In the following sub-sections, we discuss the conceptual framework of the study, the disaggregated data, the model formulation of household vehicle ownership and energy consumption, the scenario designs, the bottom-up approach for estimation of energy consumption and emissions, and the health impact assessment.

3.1. Conceptual framework

The conceptual framework of the study is illustrated in Fig. 1. The contents of the conceptual framework are highlighted in five different constituents, viz., the calibration and input data, the discrete-continuous choice framework, the developed models, the competing scenarios, and the output variables. The calibration data of household vehicle ownership and usage are used to develop an integrated model of household vehicle ownership and energy consumption in terms of socioeconomic characteristics, urban form patterns, and gas and vehicle prices, using the copula-based MNL-linear regression model. Next, the developed model is used to calculate the marginal effects of vehicle fleet and energy consumption for a given change of variables of interest (i.e., accessibility, gas price, vehicle cost, household income). The simulated vehicle fleet and energy consumption, along with the calibration data of population and household, surviving vehicles by purchase years, and the input data of fuel economy and emission factors, are used to extrapolate the energy demand and mobile emissions under various low-carbon scenarios formulated. The surviving vehicles by purchase years are calculated using the vehicle survival rate model and the data of the total vehicle fleet and new vehicle sales. The projected emissions are used to assess the public health risks using the data of concentration–response coefficients and mortality and morbidity incidence rates.

3.2. Data sample

The sample data of 1,795 households were gathered from various residential areas in Metro Manila. The metropolis consists of sixteen cities and one municipality, and the number of samples collected from each city is based on the household distribution by city. Fig. 2 illustrates the map of Metro Manila, of which the numbers are the TAZs’ numbers. The paper-based household travel survey was conducted from April through May 2017, using a simple random sampling technique. The
Table 2
Descriptive statistics of the explanatory variables.

| Variable                                                  | Mean   | SD      | Min   | Max   |
|-----------------------------------------------------------|--------|---------|-------|-------|
| Household size (continuous variable)                      | 3.3548 | 1.2606  | 1     | 11    |
| No. of working adults (continuous variable)               | 1.8172 | 0.8340  | 0     | 6     |
| No. of overseas Filipino workers (OFWs) (continuous variable) | 0.1153 | 0.3711  | 0     | 3     |
| No. of pre-schoolers (continuous variable)                | 0.2133 | 0.4993  | 0     | 3     |
| No. of K-12 school children (continuous variable)         | 0.6144 | 0.9292  | 0     | 5     |
| No. of college children (continuous variable)             | 0.2022 | 0.4938  | 0     | 3     |
| No. of elderly people (continuous variable)               | 0.2005 | 0.5320  | 0     | 2     |
| Age of household head (1 = aged 40 years and higher, 0 = otherwise) | 0.6785 | 0.4671  | 0     | 1     |
| Educational level of household head (1 = bachelor degree or higher, 0 = otherwise) | 0.5754 | 0.4944  | 0     | 1     |
| Homeownership (1 = owning a home, 0 = otherwise)          | 0.6122 | 0.4873  | 0     | 1     |
| Household income (PHP/month)                              | 65,933 | 59,175  | 2,500 | 300,000 |
| Urban form attributes                                     |        |         |       |       |
| Multi-criteria accessibility a                           | 8.9239 | 2.3922  | 1.1256| 13.1294 |
| Railway station (distance from home to the shortest station in km) | 1.1685 | 1.7209  | 0.0251| 14.2947 |
| Road public transport line density b (10 km/km²)          | 2.7013 | 2.9850  | 0     | 15.4221 |
| Road density b (10 km/km²)                               | 0.9270 | 0.3928  | 0.0419| 2.8200  |
| Population density at the TAZ level c (10⁴ persons/km²)  | 4.2076 | 1.7159  | 0.1524| 14.78481 |
| CBD (distance from home to the shortest central business district in km) | 4.6965 | 2.6514  | 0.2366| 19.1000 |
| Vehicle cost and gas expenditure                         |        |         |       |       |
| Gas expenditure (PHP/month-vehicle)                      | 4,409  | 1,321   | 716   | 12,857 |
| Vehicle cost (PHP/vehicle)                               | 786,488| 349,643 | 200,000| 3,615,000 |

1 USD = 50 PHP.

a Based on [50].
b Based on [59].
c Based on [65].
Table 3
Distribution of household vehicle numbers by household income stratum.

| Household Income (PHP/month) | Household vehicle numbers |
|-----------------------------|--------------------------|
|                            | No Vehicle | One Vehicle | Two Vehicles | Total   |
| 0-49,999                    | 39.94%     | 2.90%       | 0.00%        | 42.84%  |
| 50,000-100,000              | 13.09%     | 25.85%      | 1.11%        | 40.06%  |
| > 100,000                   | 3.34%      | 9.92%       | 3.84%        | 17.10%  |
| Total                       | 56.38%     | 38.66%      | 4.96%        | 100.00% |

Table 4
Distribution of energy consumption by household vehicle ownership category.

| Energy consumption (MJ/month) | Household vehicle ownership |
|------------------------------|-----------------------------|
|                              | One Vehicle | Two Vehicles | Total   |
| 0-2,000                      | 17.44%      | 2.25%        |         |
| 2,000-4,000                  | 59.22%      | 24.72%       |         |
| 4,000-6,000                  | 12.68%      | 35.96%       |         |
| 6,000-8,000                  | 6.48%       | 22.47%       |         |
| 8,000-10,000                 | 3.46%       | 5.62%        |         |
| 12,000-14,000                | 0.43%       | 6.74%        |         |
| 14,000-16,000                | 0.29%       | 2.25%        |         |
| Total                        | 100.00%     | 100.00%      |         |

status of each randomly selected household had not been known beforehand. This technique is the ease of assembling the sample, and every household gets an equal probability of being selected. Furthermore, Metro Manila has no baseline data on household vehicle ownership distribution. Based on the Cochran formula, the sample size of 1,795 observations provides a confidence level of 99% with a margin of error of 3.04% if the standard deviation is assumed to be 0.5 (a typical value). Table 2 presents the descriptive statistics of the independent variables. For the multi-criteria accessibility, it is the accessibility from a residential area to multiple key facilities (i.e., schools, hospitals and medical centers, markets, and recreation centers), and the accessibility data at the TAZ level are based on the study of Rith et al. [50]. The distribution of vehicle numbers by household income stratum is presented in Table 3, and the distribution of energy consumption by household vehicle number is tabulated in Table 4.

3.3. Model formulation

The household vehicle and usage model formulation is visualized in Fig. 3. A number of vehicles owned by households are classified into no vehicle, one vehicle, and two vehicle categories. Households owning more than two vehicles (i.e., three and four vehicles) are deliberately excluded from the model formulation because of very few sample numbers that disturbs the model estimation. The term of the vehicle in our study refers to private cars, viz., hatchback, sedan, SUV, MPV, minivan, and pickup. The cars used as taxis and for hire are not considered. Motorcycles are excluded from the model development because they are not the dominant energy-consumed transport mode and the data sample size cannot handle more categories. The energy consumption was used as the measure of vehicle usage. The zero-vehicle households do not have vehicles, and therefore do not consume energy. The discrete and continuous choices in the same bundle are assumed to be inter-dependent, but each bundle is supposed to be independent of the other bundles (i.e., Bundle 0 is independent of Bundles 1 and 2, Bundle 1 is independent of Bundles 0 and 2, and Bundle 2 is independent of Bundles 0 and 1). The number of vehicles owned by a household is the discrete choice, while the consumed energy is the continuous choice. Based on previous studies, household vehicle ownership and usage are correlated, and the dependency parameters are significant [40,42,43,49,51]. The MNL model was applied to develop the model of household vehicle numbers. The energy consumption is assumed to be lognormally distributed, or the logarithm of the energy consumption is normally distributed because the energy consumption is higher than zero. Afterward, the Gaussian copula is applied to couple the discrete and continuous choices as a single bundle by capturing the statistical correlation between unobserved variables affecting vehicle type choice and utilization. The mathematical framework is presented in detail in [49,52]. The main reason for using the Gaussian copula-based MNL-linear regression is that the unordered mechanism in modeling household car ownership performs better than that of the ordered mechanism [48], and the copula-based discrete–continuous model can simulate vehicle usage in response to changes in policy [43,49]. R programming language was written to estimate the parameters of the joint model using the maximum likelihood estimation approach via applying the Newton Raphson type optimization routine. A core i7 laptop with a 4 GB random access memory (RAM) was used to estimate the model.

3.4. Scenario designs

The developed model of household vehicle ownership and energy consumption is applied to simulate the vehicle fleet and energy consumption for a 1% change in variables of interest (i.e., accessibility, gas price, vehicle cost, household income). These simulated results can be used as the references to project the private VKTs, vehicle stocks, vehicle sales, scrapped vehicle numbers, energy demands, flue gas emissions (i.e., CO₂, HC, CO, NOX, SO₂, PM₁₀, and PM₂.₅), public health risks, and net values under different scenario designs. For the low-carbon scenario study, the selected study period ranges from 2010 to 2050, with 2017 used as the reference year. Below are the information and assumptions for the scenario designs:

- According to the Republic Act No. 8749, known as the Philippines Clean Air Act of 1999, the new vehicle fleet introduced after January 2003 was equivalent to the Euro 1 emission standard [53]. The implementation of the Euro 2 emission standard began in January 2006 [54]. The Euro 2 emission standard ended in December 2015, and then the Euro 4 emission standard is implemented from January 2016 to 2030. The penetration of passenger car technology for our study is based on a series of emission standards enacted by the Philippines government.
- The annual household income growth in Metro Manila is assumed to be 3.23%.
- The changes in yearly retail gas prices are assumed to be the same as changes in the world crude oil prices, and crude oil forecasting is based on the World Bank [56] and Statista [57] and the gas tax schedules (see Table 5). An increase in crude oil prices from 2030 to

Fig. 3. The model formulation of household vehicle ownership and energy consumption.
Table 5
New tax schedule on gas in the Philippines.

| Fuel Price                     | Old tax rate | New tax rate |
|-------------------------------|--------------|--------------|
| Unleaded gasoline (PHP/liter) | 4.35         | 7.00         |
| Diesel fuel oil (PHP/liter)   | 0.00         | 2.50         |

Source: [28].

Table 6
New tax schedule on the passenger cars in the Philippines [28]

| Tax Type             | Year               | Selling Price (PHP) | Tax Rate                                           |
|----------------------|--------------------|---------------------|---------------------------------------------------|
| Old tax              | Before January 2018 | 600,000 – 1,100,000  | 12,000 PHP + 20% of value in excess of 600,000 PHP |
| New tax              | From January 2018  | 600,000 – 1,000,000,000 – 4,000,000 | +10% of selling price + 20% of selling price |

50 PHP = 1 USD.

2050 is assumed to be the same as that from 2020 to 2030. The forecasting of world crude oil is the nominal value. The percentage changes in retail gas prices relative to the year 2017 in Metro Manila for both the old and new tax schedules are plotted in Fig. 4.

- The estimated purchase prices of passenger cars are based on the consumer price index (CPI) in Metro Manila. The CPI from 2002 to 2016 was obtained from the Philippine Statistics Authority [58], and the CPI function is developed as

\[ \text{CPI}_{\text{Vehicle price}} = (4.79 \times \text{year}) - 9483.9 \]

with \( R^2 = 0.99 \). The future vehicle prices are calculated as a function of the CPI in Metro Manila and based on the vehicle tax schedules (see Table 6). The vehicle prices are estimated using equation (1). The vehicle prices in terms of year relative to the year 2017 for both the old and new tax schedules are shown in Fig. 5.

\[ \text{Vehicle price}_{\text{new}} = \frac{\text{CPI}_{\text{Vehicle price}}}{\text{CPI}_{\text{2017}}} \times \text{Vehicle price}_{\text{2017}} \]

(1)

- We assume that the reduction in private vehicle usage (km) influenced by gas price and vehicle cost increases and improvement of accessibility is assumed to be replaced by the road public transport modes (i.e., PUJ and Bus) because the percentage share of person kilometers traveled (PKT) of urban rail transit mode accounts for 5.91% only (see Table 7). Additionally, the data of emission factors of the urban rail transit mode are not available in Metro Manila. On that account, we assume that the reduction in passenger kilometers traveled (PKT) of private vehicles is replaced by that of the PUJs for 76.29% and the buses for 23.71%. The load factors of the private car, PUJ, and bus are 1.7 persons [14], 14.98 persons [59], and 35.3 persons [14], respectively.

- The percentage shares of gasoline and diesel private cars from 2010 to 2013 are 64.77% and 35.23%, respectively [13], and these shares are assumed to be constant for all the study years.

The seven scenarios are designed to study the energy and environmental benefits of passenger cars, and the detailed description of each scenario is shown below:

3.4.1. Baseline scenario
The assumptions for the baseline scenario are given below:

- All the new passenger cars registered from 2016 through 2050 are assumed to comply with the Euro 4 emission standard.
- We assume that the projected retail gas prices are based on the old tax schedule (see Fig. 4). The peak gas prices are observed in 2011 and 2012, and then it sharply drops off to the minimum point in 2016. Afterward, it increases again by 29% in 2018, and finally, it gradually increases.
- The estimated vehicle prices are based on the old vehicle tax schedule. The projected percentage changes in vehicle prices are illustrated in Fig. 5.
- For the baseline scenario, the fuel economies and emission factors of the PUJ and bus are shown in Table 8, and the emission factors of passenger cars are tabulated in Table 9.

3.4.2. Fuel price scenario
This scenario assumes that the changes in gas prices in terms of year are based on the new gas tax schedule. The government has implemented the TRAIN law or RA No. 10963 to increase the gas prices from January 2018 [28], and the new tax rates on gas are tabulated in Table 5. We assumed that the tax rate on gas from 2021 to 2050 is the same as that of the year 2020. Therefore, the projected percentage changes in retail gas prices based on the new gas tax relative to the year 2017 in Metro Manila is apparent from Fig. 4.
The vehicle price no-
tax on the new vehicle tax and the CPI. Accordingly, the estimated per-
same as that of 2020. The predicted vehicle prices are calculated based
of RA No. 10963 to increase vehicle price since 01 January 2018[28],
\[29\]– 2050, and the vehicle cost is based on the new vehicle tax schedule and

3.4.3. Vehicle cost scenario

The government has restructured and implemented the TRAIN law
of RA No. 10963 to increase vehicle price since 01 January 2018[28],
and the new vehicle tax schedule is listed in Table 6. For this scenario,
we assumed that the vehicle price is based on the new vehicle tax
standard-based emission factors of the passenger cars.

Table 9

| Emission Standard | Uncontrolled | Euro 1 | Euro 2 | Euro 4 | Euro 6 |
|-------------------|--------------|--------|--------|--------|--------|
| **Gasoline Passenger Car** | | | | | |
| HC (g/km) | 6.00 | 0.43 | 3.5 | 0.10 | 0.10 |
| CO (g/km) | 23.50 | 2.72 | 2.20 | 1.00 | 1.00 |
| NOx (g/km) | 2.76 | 0.50 | 0.34 | 0.08 | 0.06 |
| SO2 (g/km) | 0.0076 | 0.0766 | 0.0766 | 0.0077 | 0.0015 |
| PM10 (g/km) | 0.05 | 0.05 | 0.05 | 0.014 | 0.005 |
| PM2.5 (g/km) | 0.0021 | 0.0025 | 0.0025 | 0.0013 | 0.0023 |
| **Diesel Passenger Car** | | | | | |
| HC (g/km) | 0.70 | 0.31 | 0.4 | 0.05 | 0.09 |
| CO (g/km) | 6.54 | 2.72 | 1.00 | 0.50 | 0.50 |
| NOx (g/km) | 4.28 | 0.66 | 0.66 | 0.25 | 0.08 |
| SO2 (g/km) | 0.0615 | 0.0615 | 0.0615 | 0.0061 | 0.0015 |
| PM10 (g/km) | 0.07 | 0.14 | 0.08 | 0.025 | 0.005 |
| PM2.5 (g/km) | 0.1983 | 0.1589 | 0.0701 | 0.0351 | 0.0015 |

Table 8

| Emission Factor | PUJ | Bus |
|-----------------|-----|-----|
| Fuel economy (km/liter) | 5.630 | 3.570 |
| CO2 (g/km) | 459.850 | 1,016 |
| HC (g/km) | 0.883 | 3.700 |
| CO (g/km) | 2.818 | 12.400 |
| NOx (g/km) | 1.552 | 12.500 |
| SO2 (g/km) | 0.002 | 0.374 |
| PM10 (g/km) | 0.461 | 0.900 |
| PM2.5 (g/km) | 0.198 | 0.591 |

Note: Bus and PUJ run on diesel.

a [61].
b [92].
c [96].
d [97].

3.4.6. Integration scenario

An integration scenario is considered as a combination of scenarios
2 through 5. This scenario can inform us how the energy demand,
emissions, and public health risks are affected when the reduced PKT of
private cars is replaced by that of the current road-based public trans-
port modes. In Metro Manila, the dominant public transit mode is PUJ
[41]. The engines of PUJs are mostly the imported second-hand Japa-
nese engines (i.e., Isuzu C190 and C240 and Mitsubishi 4DR5 engines
manufactured in the ‘80 s and Isuzu 4BC2, 4bA1 and 4BE1 engines for
the newer versions) [61]. These engines are based on the naturally
aspirated indirect injection technology which significantly causes
higher emissions [61].

3.4.7. Comprehensive scenario

The Department of Transportation of the Philippine government
issues the Department Order No. 2017–011 in 2017 to launch the Public
Utility Vehicle Modernization Program (PUVMP) [62], and the primary
objective of the program is to phase in new modernized PUJs [63]. A
piilot implementation with a total of 35 units equipped with the Euro 4
emissions-compliant engine is being carried out [64].

In this scenario, we suppose that the government will implement the
Euro 4 emission standard policy for the PUJ and Bus from 2020 through
2050. It means that the reduced PKT of passenger cars in scenario 6 (the
Integration scenario) is replaced by the PKT of the Euro 4 emission
compliant PUJs and buses from 2020 through 2050. The fuel economies
and emission factors of the Euro 4 emission compliant PUJ and bus are
tabulated in Table 12. Under this scenario, energy demand, emissions,
and public health risks will be reduced to a greater degree than those
under the other above scenarios.

3.5. Calculation of vehicle stock, scrapped vehicle numbers, vehicle sales,
and total VKT

The vehicle stock equation is expressed below:

\[ \text{Vehiclestock}_{y} = \sum_{t=0}^{2} (t \times \% \text{ of Bundle}_{t}) \]

where the indices y and t are the projected year and household
bundle type (see Fig. 3), respectively. HH is the total household num-
bers projected, and % of Bundle is the percentage share of household

2 1 USD = 50 PHP
Table 11
Emission factors of the Euro 6 cars.

| Emission Standard                   | Euro 6 |
|-------------------------------------|--------|
| Gasoline Passenger Car              |        |
| HC (g/km)                           | 0.10^a |
| CO (g/km)                           | 1.00^b |
| NOx (g/km)                          | 0.06^b |
| SO₂ (g/km)                          | 0.0015^a |
| PM₁₀ (g/km)                         | 0.005^a |
| PM₂.₅ (g/km)                        | 0.0023^a |
| Diesel Passenger Car                |        |
| HC (g/km)                           | 0.09^b |
| CO (g/km)                           | 0.50^a |
| NOx (g/km)                          | 0.08^b |
| SO₂ (g/km)                          | 0.0012^a |
| PM₁₀ (g/km)                         | 0.005^a |
| PM₂.₅ (g/km)                        | 0.0015^a |

^a [96].
^b [97].
^c Calculated by the authors.
^d [60].

Table 12
Fuel economies and emission factors of the Euro 4 PUJ and bus.

| Factor                          | Euro 4 PUJ | Euro 4 Bus |
|---------------------------------|------------|------------|
| Fuel economy (km/liter)         | 10.050^a   | 3.422^b   |
| CO₂ (g/km)                      | 257.542^a  | 469.000^a |
| HC (g/km)                       | 0.017^c    | 0.09^d    |
| CO (g/km)                       | 0.072^a    | 0.613^b   |
| NOx (g/km)                      | 0.673^c    | 2.341^b   |
| SO₂ (g/km)                      | 0.001^c    | 0.003^a   |
| PM₁₀ (g/km)                     | 0.051^c    | 0.032^a   |
| PM₂.₅ (g/km)                    | 0.031^c    | 0.032^c   |

^a [61].
^b [60].
^c [99].
^d [100].
^e calculated by the authors.

3.6. Calculation of energy consumption and emissions

The total energy demand is calculated based on the average energy demand per household by vehicle ownership category, as expressed in equation (6):

\[
\text{Energy}_j = \frac{\text{HH} \sum_{i=1}^{M} (\% \text{ of Bundle}_{ij} \times \text{Per household energy}_{ij})}{\text{HH}}
\]

where \( \text{Per household Energy}_j \) refers to an average energy demand per household of bundle, \( i \), in year, \( y \).

The amount of CO₂ emissions is calculated using the energy consumption multiplied by the emission factor, as presented in equation (7), while the tailpipe pollutant concentrations are projected using the approach of distance-based pollution emission shown as equation (8):

\[
\text{CO}_2 \text{ Emissions}_j = \text{Energy}_j \times E\text{F}_{\text{CO}_2}
\]

\[
\text{AP}_j = \sum_f \sum_r \text{Vehicle}_{r,f} \times \text{VKT}_{r,f} \times EF_{j,f}
\]

where \( \text{CO}_2 \text{ Emissions}_j \) is the amount of total \( \text{CO}_2 \) emissions, and \( E\text{F}_{\text{CO}_2} \) is the \( \text{CO}_2 \) emission factor that is equal to 74.10 tons/TJ [67]. The indices \( j \) and \( f \) area pollutant type (i.e., HC, CO, NOx, SO₂, PM₁₀, or PM₂.₅) and a vehicle fuel type (i.e, gasoline or diesel), respectively. \( \text{AP}_j \) is the amount of air pollutant emissions, \( j \), emitted in year, \( y \). \( EF \) is the emission factor of pollutant type, \( j \), and \( \text{Vehicle}_{r,f} \) is a number of new vehicles with fuel type, \( f \), registered in year, \( r \), and still survive in year, \( y \).

3.7. Health impact assessment

3.7.1. Monetary value of health risks

The Intake Fraction (IF) method was applied in our study to assess the health risks caused by atmospheric pollutant concentrations emitting from the private passenger vehicles. The IF is a ratio of the mass of pollutant inhaled by the exposed population to the mass of pollutant emitted by a given source, and this metric is typically used to characterize an emission-to-intake relationship and evaluate health risks [68]. The IF equation is apparent as follows:

\[
\text{IF} = \frac{\text{DOSE}_j}{\text{AP}_j} \Rightarrow \text{DOSE}_j = \text{IF} \times \text{AP}_j
\]

where IF is the intake fraction, \( \text{DOSE}_j \) is the amount of pollutant inhaled by a person.

The atmospheric pollutant concentrations provoke many health risk types, but we consider only six primary types, i.e., premature mortality, respiratory hospital admission, cardiovascular hospital admission, asthma attack, acute bronchitis, and chronic bronchitis [2].

\[
\text{HE}_{h,j} = \sum \text{DOSE}_{h,j} \times \text{DR}_{h,j}
\]

where the index \( h \) is the health risk type, \( \text{HE}_{h,j} \) is the number of cases of health outcome, \( h \), exposed to pollutant, \( j \), and \( \text{DR}_{h,j} \) is the dose-response coefficient of health risk type, \( h \), caused by pollutant type, \( j \). The \( \text{DR}_{h,j} \) is calculated using the equation below [69]:

\[
\text{DR}_{h,j} = \frac{\text{CR}_{h,j} \times f_{h,j} \times 10^{12}}{365 \times \text{BR}}
\]

where \( \text{CR}_{h,j} \) is the concentration-response coefficient, \( f_{h,j} \) is the baseline of mortality or morbidity incidence rate of health outcome, \( h \), ravaged by pollutant, \( j \), and \( \text{BR} \) is the breathing rate with a critical value of 20 m³/day [2]. Substituting equations (9) and (11) into equation (10), the health impact, \( h \), caused by pollutant, \( j \), is written as equation (12). The health impact can be converted into monetary value using equation (13):
where $MV_h$ is the monetary value of health outcome, $h$, due to pollutant, $j$, and $UV_h$ is the unit economic cost of health outcome, $h$ (USD/case).

### 3.7.2. Data sources of health risks

According to the previous studies of health impact assessment regarding air pollution [2, 68, 69, 70, 71], SO$_2$, NO$_x$, PM$_{10}$, and PM$_{2.5}$ are typically selected to evaluate public health outcomes because these pollutants are the dominant causes of health risks. The intake fraction (IF) is influenced by several factors, such as the exposed population size and its spatial density, the distance between the sources and the receptor areas, the exposure pathways, the environmental conditions of pollution dispersion, the pollutant persistence, the urban morphology, and its spatial density, the distance between the sources and the receptor areas, the exposure pathways, the environmental conditions of pollution dispersion, the pollutant persistence, the urban morphology, and the chemical and physical transformation [68, 72]. The IF can be adjusted under the variation of population density from one country to another [2, 70], and the original IF of [68] was adopted for our study. The intake fraction estimates of all the pollutants are listed in Table 13. Table 14 presents the concentration-response coefficients and baseline of mortality or morbidity incidence rates. The concentration-response coefficients and baseline of mortality or morbidity incidence rates of one country can be used for other countries [2].

The monetary value of health risk per case can be adjusted from one country to another based on the per-capita GDP [73]. Table 15 shows the monetary values of health risks per case in the Philippines. The unit costs of total mortality and respiratory hospital admission are adopted from the study in Indonesia [74], the unit monetary value of cardiovascular hospital admission and chronic bronchitis are primarily adopted from China [2], and the cost of acute bronchitis per case is adopted from the study in the Philippines [75].

### 4. Results and discussion

#### 4.1. Joint model of household vehicle ownership and energy consumption

There are many explanatory variables considered in the development of the joint model of household vehicle ownership and energy consumption. Pearson’s product-moment correlation approach was initially applied to select the potential determinants and control the multicollinearity problem. The estimation results of the streamlined initial model are tabulated in Table 16. The insignificant coefficients above the 0.10 level (p-value > 0.10) were deliberately removed using the backward elimination approach. At the convergence of model estimation, the log-likelihood and Akaike Information Criterion (AIC) values were $-1196.068$ and $2450.137$, respectively (see the two last rows of Table 16). The intercept coefficients of the discrete choice component have no interpretable meaning, and they are included to capture the average unobserved effect [30]. The intercept coefficient for the continuous choice implies that the estimated average energy consumption of vehicle-owning households was equal to $\exp(8.585) = 5,351$ MJ/month.

| Year  | SO$_2$     | NO$_x$    | PM$_{10}$ | PM$_{2.5}$ |
|-------|------------|-----------|-----------|------------|
| 2010  | $1.58 \times 10^{-6}$ | $1.46 \times 10^{-6}$ | $2.25 \times 10^{-4}$ | $2.37 \times 10^{-4}$ |
| 2015  | $1.72 \times 10^{-4}$ | $1.59 \times 10^{-4}$ | $2.45 \times 10^{-4}$ | $2.59 \times 10^{-4}$ |
| 2020  | $1.90 \times 10^{-4}$ | $1.76 \times 10^{-4}$ | $2.71 \times 10^{-4}$ | $2.86 \times 10^{-4}$ |
| 2025  | $2.12 \times 10^{-4}$ | $1.96 \times 10^{-4}$ | $3.02 \times 10^{-4}$ | $3.19 \times 10^{-4}$ |
| 2030  | $2.39 \times 10^{-4}$ | $2.20 \times 10^{-4}$ | $3.40 \times 10^{-4}$ | $3.58 \times 10^{-4}$ |
| 2035  | $2.70 \times 10^{-4}$ | $2.49 \times 10^{-4}$ | $3.84 \times 10^{-4}$ | $4.05 \times 10^{-4}$ |
| 2040  | $3.06 \times 10^{-4}$ | $2.83 \times 10^{-4}$ | $4.36 \times 10^{-4}$ | $4.59 \times 10^{-4}$ |
| 2045  | $3.45 \times 10^{-4}$ | $3.19 \times 10^{-4}$ | $4.92 \times 10^{-4}$ | $5.18 \times 10^{-4}$ |
| 2050  | $3.88 \times 10^{-4}$ | $3.58 \times 10^{-4}$ | $5.52 \times 10^{-4}$ | $5.82 \times 10^{-4}$ |

Adopted from [68].

### 4.2. Elasticity of vehicle stock and energy consumption

The developed model was applied to calculate the elasticity of the vehicle stock and energy consumption for given changes in 1%...
household income, 1% gas price, 1% vehicle cost, and 1% improvement of accessibility, as shown in Table 17. A 1% vehicle cost increase and 1% accessibility improvement would reduce the private vehicle stock by 0.22% and 0.52%, respectively, while a 1% household income growth would raise the private vehicle stock by 0.22%. Evident from the last column of the table, the energy consumption would be increased by 17.608 MJ/month-vehicle with an increase in 1% household income, but the energy consumption would decrease by 7.110 MJ/month-vehicle with a 1% gas price increase, 10.695 MJ/month with a 1% vehicle cost increase, and 38.470 MJ/month with a 1% accessibility improvement. These elasticity results are used to project the vehicle stock, scrapped vehicle numbers, new vehicle sales, total VKT of private cars, energy consumption, emissions, public health risks, tax revenues, and net value under the formulated scenarios.

4.3. Low-carbon scenario analysis

4.3.1. Vehicle stock, scrapped vehicle numbers, vehicle sales, and total VKT

The projected vehicle stocks are illustrated in Fig. 7. Under the baseline scenario, the private vehicle stock will exponentially increase from 1.38 million units in 2010 to 3.78 million units in 2050, with a growth rate of 4.35% per annum on average. Under the vehicle price, Table 15

| Year | Total mortality | Respiratory HA | Cardiovascular HA | Asthma attack | Acute bronchitis | Chronic bronchitis |
|------|----------------|---------------|-------------------|--------------|-----------------|-------------------|
| 2010 | 19,415         | 3             | 319               | 165          | 136             | 11,275            |
| 2015 | 22,323         | 3             | 366               | 190          | 157             | 12,964            |
| 2020 | 25,480         | 3             | 418               | 216          | 179             | 14,798            |
| 2025 | 28,638         | 4             | 470               | 243          | 201             | 16,631            |
| 2030 | 31,795         | 4             | 522               | 270          | 223             | 18,465            |
| 2035 | 34,952         | 5             | 573               | 297          | 245             | 20,298            |
| 2040 | 38,110         | 5             | 625               | 324          | 267             | 22,132            |
| 2045 | 41,267         | 5             | 677               | 350          | 289             | 23,965            |
| 2050 | 44,424         | 6             | 729               | 377          | 311             | 25,799            |

HA: Hospital admission.
* Adopted from [74].
* Adopted from [2].
* Adopted from [75].

The zero-vehicle choice was used as the reference category for the discrete choice component.

Significance level codes: ‘***’ 0.001; ‘**’ 0.01; ‘*’ 0.05; ‘’ 0.1.

Fig. 6. The estimated and actual private vehicle stocks.

Table 17

| 1% increase | Vehicle stock (% change) | Energy consumption (MJ/month-vehicle) |
|-------------|--------------------------|---------------------------------------|
| Household income | 0.22                  | 17.608                                |
| Gas price     | –                      | –7.110                                |
| Vehicle cost  | –0.22                  | –10.695                               |
| Accessibility | –0.52                  | –38.470                               |

Table 16

| Variables                                   | Discrete choice | Continuous choice |
|---------------------------------------------|-----------------|-------------------|
|                                             | One vehicle     | Two vehicles      |                   |
| Intercept                                   | 5.2551 (0.571)**| 4.3552 (0.982)**  | 8.585 (0.094)***  |
| Household characteristics                   |                 |                   |                   |
| No. of working adults                       | –               | –                 | –                 |
| No. of preschoolers                         | –0.3127 (0.179) | 1.3698 (0.603)*   | 0.1087 (0.037)**  |
| No. of K-12 school children                 | –               | 0.0487 (0.02)*    |                   |
| No. of college children                     | –               | 0.2907 (0.172)    | 0.0911 (0.031)**  |
| Age of household head                       | –               | 0.7634 (0.339)*   |                   |
| Educational level of household head         | 1.4412 (0.189)**| 1.7418 (0.406)**  |                   |
| Home ownership                              | 0.8441 (0.172)**| 0.9967 (0.333)**  |                   |
| Urban form attributes                        |                 |                   |                   |
| Multi-criteria accessibility                | –0.6211 (0.046)**| –0.6636 (0.071)** | –0.0356 (0.008)***|
| Road density                                | 1.9809 (0.27)**  | 2.2953 (0.366)**  |                   |
| CBD                                         | –0.2842 (0.032)**| –0.3451 (0.054)** | –0.0177 (0.006)** |
| 10xgas expenditure/monthly income           | –0.456 (0.053)** | –0.456 (0.053)**  |                   |
| Vehicle cost/annual income                  | –1.4187 (0.128)**| –4.3816 (0.439)** |                   |
| Dependency parameters                       | –0.2574 (0.101)* | –0.873 (0.032)**  |                   |
| Scale parameters of energy consumption      | 0.4657 (0.013)** | 0.5485 (0.032)**  |                   |
| Maximum likelihood estimation               |                 |                   |                   |
| Newton-Raphson maximization: 14 iterations  |                 |                   |                   |
| Log-likelihood at the convergence: – 1196.068|                 |                   |                   |
| Akaike Information Criterion (AIC): 2450.137|                 |                   |                   |

-200 400 600 800 1,000 1,200 1,400 1,600 1,800 2,000 2012 2013 2014 2015 2016 Thousand units

Fig. 6. The estimated and actual private vehicle stocks.
accessibility, and comprehensive scenarios, the private vehicle stock will be cut back to 3.48, 2.22, and 1.90 million units in 2050, respectively. As compared to these three respective countermeasure scenarios with the baseline scenario, the private vehicle stock will decrease by 7.93%, 41.27%, and 49.74%. The fuel price scenario-based vehicle stock is the same as that of the baseline scenario. The Euro 6 scenario-based vehicle stock is marginally lower than that of the vehicle price scenario because the Euro 6 emission compliant vehicle’s price is slightly higher than that of the Euro 4 vehicle (see Fig. 5), while the vehicle stocks of the integration and comprehensive scenarios are comparable. It is worthwhile to note for the vehicle price, integration, and comprehensive scenarios that the vehicle stock growth rate slightly drop off in 2018 and 2023 because of an increase in vehicle tax rate and average vehicle price (see Fig. 5). The evidence from the figure suggests that the development of accessibility from home to the crucial destinations by 2.5% per annum on average is the most efficient option to reduce the vehicle stock as compared to an increase in gas price and vehicle cost as well as the implementation of Euro 6 emission standard.

The scrapped vehicle projections are apparent in Fig. 8. The scrapped vehicle numbers increase from 0.08 million units in 2010 to 0.24, 0.17, 0.15 million units in 2050 under the vehicle cost, accessibility, and comprehensive scenarios, respectively.

The projected new vehicle sales under the different designed scenarios are illustrated in Fig. 9. The new vehicle sales will exponentially increase from 0.11 million units in 2010 to 0.21 million units in 2017, but they sharply go down to 0.14 million units in 2018. This decline shall translate to a drop in new vehicle sales by 33.33% in 2018 relative to 2017 because the government declared the implementation of the TRAIN law or RA No. 10963 to increase tax rate (i.e., new vehicle tax schedule) before the arrival of January 2018. Therefore, the citizen with higher income probably decides to purchase new vehicles before 2018 even though they prefer to buy in 2018 or afterwards. The projected vehicle sales are 0.34 million units in 2050 for the baseline scenario, and this figure will decrease to 0.31, 0.18, and 0.15 million units under the vehicle cost, accessibility, and integration scenarios, respectively. The new vehicle sales are found to fall off in the years 2018 and 2023 for some scenarios, which implies that the new vehicle sales are significantly influenced by vehicle cost, accessibility, regulation of Euro 6 emission standard, and their integration.

The total VKT curves under the different scenarios are plotted in Fig. 10. The total VKT marginally drops off from the year 2010 to 2011 and slightly increases to the year 2014, and then noticeably goes up in the year 2016. This wide fluctuation was mainly caused by the erratic gas price, evident from Fig. 4. In the case of no strategic intervention from the government, the total VKT is 14.55 billion km in 2010 and will increases approximately 5 times to 71.53 billion km in 2050 with an average annual growth rate of 9.8%. In 2050, the total VKT will decline to 69.91, 64.41, 63.96, 15.52, 12.46, and 12.46 billion km under the fuel price, vehicle cost, Euro 6, accessibility, integration, comprehensive scenarios, respectively. It highlights that the new gas and vehicle tax schedules and Euro 6 emission standard alternatives play a minor role to mitigate the total VKT of private vehicles. The improvement of accessibility by per-annum 2.5% on average is found to have the greatest negative impact on the VKT because the accessibility has a statistically significant effect on both the private vehicle ownership and usage, as can be seen from row 13 of Table 16. It is worthy to note that the total VKT will gradually decrease from 21.27 billion km in 2017 to 15.52 billion km in 2050 under the accessibility scenario.
The improvement of accessibility of residential areas to Mtoe under the accessibility, integration, and comprehensive scenarios, saving. The energy demand in 2050 will decline to 2.14, 1.70, and 1.51 relative to the baseline, is found to have a trivial impact on energy scenario. The intervention of new tax schedules on fuel price and vehicle 2010 and will increase to 5.45 Mtoe in 2050 under the baseline sce- 4.3.2. Energy consumption and emissions

Fig. 11 shows the projection of energy consumption under the different scenarios designed for the 2010–2050 horizon. The trend of energy consumption from 2010 to 2017 is the same as that of the VKT (as illustrated in Fig. 10). The estimated energy demand is 1.11 Mtoe in 2010 and will increase to 5.45 Mtoe in 2050 under the baseline scenario. The intervention of new tax schedules on fuel price and vehicle cost and the implementation of Euro 6 emission compliant vehicles, relative to the baseline, is found to have a trivial impact on energy saving. The energy demand in 2050 will decline to 2.14, 1.70, and 1.51 Mtoe under the accessibility, integration, and comprehensive scenarios, respectively. The improvement of accessibility of residential areas to crucial facilities by 2.5% per annum on average is the most efficient way to minimize energy demand for the private vehicle dependency, while the modernization of the road-based public transport modes (i.e., PUJs and Buses) has a marginal impact on the energy saving, as compared the comprehensive scenario to the accessibility scenario. It is not surprising to see that the total VKT of private cars gradually decreases for the comprehensive scenario (see Fig. 10), while the comprehensive scenario-based energy demand becomes fairly steady during 2020–2050 because the reduction of VKT of private cars is replaced by road-based public transport mode usage that requires somewhat more energy demand.

The extrapolated CO2 emissions through the different emission mitigation options from 2010 through 2050 are illustrated in Fig. 12. The CO2 emissions are perfectly correlated with energy demand. The same finding in China was also reported that the trend of CO2 emissions is similar to that of energy demand [2]. The CO2 emissions are projected to increase from 3.44 Mt in 2010 to 16.93 Mt in 2050 under the baseline scenario at an average annual growth rate of 9.8%. The new tax schedule, implementation of the Euro 6 vehicle standard, and modernization of the road-based public transport modes are found to have a minor impact on the CO2 emission mitigation. Like the option for energy saving, accessibility development is still the dominant choice to lessen CO2 emissions. The highlight suggests that the CO2 emissions slightly dropped under the comprehensive scenario as compared to those of the accessibility scenario.

The projected HC emissions based on the different scenarios are illustrated in Fig. 13. The amount of HC emissions considerably dropped off from the year 2010 to 2014 because the government implemented the introduction of Euro 2 vehicles in place of Euro 1 vehicles from 2006, and it is also consistent with a period of mass scrappage bulk of the uncontrolled emission vehicles and Euro 1 emission compliant vehicles. The HC emissions then slightly rose from 2014 to 2016 because of a sudden decline in gas prices in 2016. Under the baseline scenario, the amount of HC emissions will exponentially decrease from 2017 to 2025 and stagnate from 2025 to 2030 even if there is an increase in the private vehicle stock. This trend could be explained that the new vehicles introduced from 2016 comply with the Euro 4 emission standard, while the uncontrolled, Euro 1, and Euro 2 vehicles will be phasing out. However, the amount of HC emissions will linearly increase from 3,400 t in 2030 to 6,214 t in 2050 in light of a further increase in vehicle stock. It is worthwhile to note that only the modernization of PUJs and public buses can considerably mitigate the HC emissions. Ahanchian and Biona [17] also empirically corroborate that phasing out old PUJs considerably reduces HC emissions.

Fig. 14 illustrates the extrapolated CO emissions under the different scenarios from 2010 through 2050. The trend of CO emissions is the same as that of HC emissions, and it was also reported in [17]. However, the impact of accessibility development on mitigation of CO emissions is greater than that of HC emissions. Under the baseline scenario, the amount of CO emissions is 97,520 t in 2010 and will
decline roughly 3 times to the minimum point of 32,620 t in 2028. However, the CO emissions will decidedly increase to 62,140 t in 2050. The CO emissions in 2050 will be cut back by 51% under the accessibility scenario and 81% under the comprehensive scenario relative to the baseline scenarios. A similar study also illustrates that the modernization of the PUJs is the CO emission mitigation potential [17].

Fig. 15 shows the projected SO2 emissions under the different formulated scenarios. The amount of SO2 emissions will decline from 352 t in 2017 to the minimum point of 230 t in 2024 and then increase up to 536 t in 2050 under the baseline scenario. Gas price and vehicle cost have a marginal effect on SO2 emission mitigation. Compared to the baseline scenario, the amount of SO2 emissions in 2050 will decrease by 79.5%, 59.0%, and 80.4% under the Euro 6, accessibility, and comprehensive scenarios, respectively. The implementation of the Euro 6 emission standard for the private passenger cars from 2025 and the Euro 4 emission standard for the PUJs and Bus from 2020 and the improvement of accessibility are the SO2 emission mitigation potentials.

The projected NOX emissions under the different scenarios are plotted in Fig. 16. It is surprising to note that the projected NOX emissions are found higher for the gas price, vehicle cost, accessibility, and integration scenarios as compared to the baseline scenario. These increases could be likely that the emission factors of NOX per passenger kilometer traveled (PKT) of the road public transport modes are higher than that of the private vehicles. Only the implementation of Euro 6 vehicle and comprehensive scenarios is consistent with NOX emission mitigation, and the impact of these two mentioned scenarios on the NOX emissions are comparable, specifically from 2033 until 2050. The emissions will be 10,550 t in 2050 under the baseline scenario, and this figure will be reduced by 37.25% and 36.78% under the Euro 6 and comprehensive scenarios, respectively. These empirical findings suggest that the modernization of the road-based public transport modes and the penetration of Euro 6 emission compliant cars in Metro Manila’s market are the efficient pathways to suppress the NOX emissions. Similar findings were found by Ahanchian and Biona [17].

Fig. 17 and Fig. 18 illustrate the PM10 and PM2.5 emissions estimated under the different scenarios, respectively. Evident from the year 2010 to 2017, the amounts of PM10 and PM2.5 emissions significantly covary with private VKT and vehicle emission standards. Under the baseline scenario, the amount of PM10 emissions will decrease from 1,182 t in 2017 to the minimum of 777 t in 2031 while the amount of PM2.5 emissions will decline from 641 t in 2017 to the minimum of 509 t in 2028 mainly as a result of the market penetration of Euro 6 emission compliant cars from 2016 and phasing out the Euro 1 and uncontrolled emission cars. However, the amounts of PM10 and PM2.5 emissions will increase to 1,348 t and 996 t in 2050, respectively on account of increasing vehicle stock. A drop in private vehicle usage through the implementation of new tax schedules on gas and vehicle, the improvement of accessibility, and the integration of them cannot lessen the amounts of PM10 and PM2.5 emissions if the reduced VKT of private cars is replaced by the old PUJs and buses that are not modernized. The potential of PM10 and PM2.5 emission mitigation is to penetrate the private vehicles compliant with the Euro 6 emission standard and the PUJs and buses compliant with the Euro 4 emission standard.

4.3.3. Public health impact assessment

The pollutant emissions damage public health, and the estimation of air pollutant emissions is used to evaluate the health risks in our study. As mentioned earlier, only six health outcomes (i.e., total mortality, respiratory hospital admission, cardiovascular hospital admission,
asthma attack, acute bronchitis, and chronic bronchitis) caused by four pollutants (i.e., SO$_2$, NO$_X$, PM$_{10}$, and PM$_{2.5}$) are considered. The health impact assessment in monetary value under the different scenarios by pollutant type is illustrated in Fig. 19. The health impact is mainly caused by the NO$_X$ emissions for all the scenarios and all the study years, followed by the PM$_{10}$, PM$_{2.5}$, and SO$_2$ emissions. Unlike the finding in China, PM$_{10}$ is mainly attributed to health outcomes [2]. Evident from the figure, the reduction of private vehicle usage through increasing tax rates on gas and vehicle, improvement of accessibility to key destinations, and integration of them cannot improve the public health in Metro Manila if the road-based public transport modes (i.e., PUJs and buses) are not modernized to comply with the Euro 4 emission standard (see the comprehensive scenario). The other pathway to provide a considerable reduction in public health risks is the implementation of the Euro 6 emission standard for private passenger vehicles from 2025. Under the baseline scenario, the public health impact will exponentially increase from 113 million USD in 2010 to 491 million USD in 2050 with an average annual growth rate of 8.23%. In 2050, the cost of public health risks will be reduced by 46.0% under the Euro 6 scenario and 51.7% under the comprehensive scenario compared with the baseline scenario.

Fig. 20 illustrates the public health impact assessment by disease type under the different scenarios in five-year intervals. Based on the evaluation of economic loss, the total mortality accounts for the most massive loss ravaged by air pollutant emissions, followed by acute bronchitis, asthma attack, chronic bronchitis, and the rest of cardiovascular and respiratory hospital admission.

### 4.3.4. Monetary values of energy demand and CO$_2$ emission

Fig. 21 illustrates the monetary value of energy consumption under the different scenarios. The cost is calculated using the estimated energy consumption multiplied by crude oil price estimated by the World Bank [56] and Statista [57]. The energy consumption cost will marginally drop from 587 million USD in 2010 to 520 million USD in 2015 mainly in light of lower fuel prices in 2015 relative to those in 2010 (see Fig. 4). Under the baseline scenario, the energy consumption cost will increase to 2,986 million USD in 2050 at a growth rate of 13.55% per annum on average from 2015 to 2050. The implementation of new taxes on gas price and vehicle cost and the introduction of Euro 6 vehicles have a marginal impact on the reduction in the cost of energy

![Fig. 19. Health impact assessment by pollutant type under the different scenarios.](image)

![Fig. 20. Health impact assessment by health risk type under the different scenarios.](image)
consumption for all the study years. Compared to the baseline scenario in 2050, the energy consumption cost will decrease by 60.7%, 68.9%, and 72.4% under the accessibility development, integration, and comprehensive scenarios, respectively. Correspondingly, the improvement of accessibility and modernization of the PUJs and public buses are the potential options to mitigate energy consumption cost.

The social costs of CO₂ emissions under the designed scenarios are apparent in Fig. 22. The social cost of CO₂ emissions is the monetary value of total damages ravaged by the emitting CO₂ emissions, and the cost is calculated by multiplying the amount of CO₂ emissions with the social cost of CO₂ emissions per tonne. The social cost of CO₂ emissions in the Philippines ranges from 1 to 10 USD/t [82]. In our study, we assumed the social cost of CO₂ emissions to be 5 USD/t in 2010, and this cost is varied in terms of years influenced by the CPI in the Philippines. The total cost of CO₂ emissions is 15 million USD in 2010 and will increase 11.2 times to 168 million USD at an average annual growth rate of 25.5% under the baseline scenario. Like the energy consumption cost, the new tax schedules on gas and vehicle implemented by the government, along with the market penetration of private passenger vehicles complying with the Euro 6 emission standard, have a little effect on the reduction in CO₂ emission cost. Compared to the baseline scenario in 2050, the CO₂ emissions in monetary value will decline by 66.0%, 67.2%, and 74.4% under the accessibility, integration, and comprehensive scenarios, respectively. Under the last three mentioned scenarios, the cost will gradually increase from 2010 to 2050.

4.3.5. Tax revenue

The tax revenues on gas under the different scenarios are illustrated in Fig. 23. Under the baseline scenario, the gas tax revenue is 71 million USD in 2010 and will increase approximately 5 times to 340 million USD in 2050, with an average annual growth rate of 9.75%. The implementation of the new gas tax schedule from January 2018 will raise the gas tax revenue by 2.9 times compared to the baseline scenario after 2020, and this implementation is the most efficient way to gain the highest tax revenue on gas. The lowest tax revenue on gas is observed for the accessibility scenario because the improvement of accessibility significantly discourages vehicle ownership and usage, which in turn does not increase the gas tax revenue. The gas tax revenue will be 112 million USD under the baseline scenario in 2020, and this figure will reach 274 million USD under the comprehensive scenario in the same year and become fairly steady afterwards. Fig. 24 illustrates the vehicle tax revenues under the different scenarios. Under the baseline scenario, the vehicle tax revenue is 48 million USD in 2010 and will abruptly rise 26.7 times to 1,281 million USD in 2050, with an average annual growth rate of 64.2%. The vehicle tax revenue will skyrocket to 2,217 and 2,232 million USD in 2050 under the vehicle cost and Euro 6 vehicle scenarios, respectively. Compared to the baseline scenario in 2050, the vehicle tax revenue will dramatically plunge by 48.1% and 17.8% under the accessibility and comprehensive scenarios, respectively. The tax revenue is found much higher for the new vehicle tax than the new gas tax (see Fig. 23 and Fig. 24).

4.3.6. Net value analysis

The net value analysis is applied to compare the net cost of each scenario in monetary value for choosing the best option, and the net value analysis adds up the total costs for each scenario. The negative costs considered are the public health risks in monetary value, the damage cost of CO₂ emissions, the cost of energy consumption, while the tax revenues on gas and vehicle are the positive values. Fig. 25 illustrates the net value analysis of the different scenarios during 2010–2050. The net value is − 9 million USD in 2010 and increases to 970 million USD in 2050 under the baseline scenario. The gas tax, integration, and comprehensive scenarios are the highest net values in 2020, but the net value of the Euro 6 scenario will become higher than that of the gas tax in 2025. From 2030 to 2050, the implementation of
5. Policy implications and bang for buck analysis

The Philippine government is constructing more roads and skyways to enhance traffic flow, and this solution is a major constituent of the “Build! Build! Build!” program that is the comprehensive infrastructure development program launched by President Duterte’s administration in April 2017 [83]. However, building more roads and skyways encourages vehicle usage that triggers higher energy demand and GHG productions. Based on our empirical findings, the improvement of accessibility to key facilities significantly discourages private passenger car dependency. This strategic alternative can reduce private vehicle-related trip activities replaced by non-motorized modes (i.e., walking and cycling) and public transport modes. Traffic flow is highly expected to be faster once the improved accessibility is taken in place. However, the amounts of air pollutant emissions are not lessened if the road-based public transport modes (i.e., PUJs and buses) cannot cut back the air pollutant emissions. The implementation of the new tax schedules on gas and vehicle directly boosts the government tax revenue, and these increasing tax rates can also be an indirect tax increase levied on vehicular emissions causing climate change and citizens’ public health risks. Our empirical findings, by contrast, show that the public health risks are marginally higher for the new tax schedule scenarios of gas and vehicle as compared to the baseline scenario for the projected years. This can be due to that the dominant transit mode is PUJ in Metro Manila. Most of the PUJs are equipped with the imported second-hand Japanese engines manufactured in the 1980s, and these old engines cause higher pollutant emissions [61]. The vehicle and gas tax increases are associated with higher vehicle ownership costs (i.e., vehicle purchase and operating costs) and raise the tax revenues obtained from higher-income households. If the tax revenue is used for a subsidy of phasing in Euro 4 buses and PUJs, the pollutant emissions are considerably reduced and thereby improving public health and well-being. These are benefits for citizens and communities.

The penetration of new passenger cars compliant to the Euro 6 emission standard in Metro Manila’s market can be applicable from 2025, and this option has the potential to minimize the pollutant emissions, improve public health, and increase the tax revenue. Furthermore, the highest net value is highlighted for this proposed alternative, see Fig. 25. The government should prioritize this low-carbon alternative. However, this option can marginally reduce vehicle stock, energy consumption, and CO2 emissions. This implies that this option cannot significantly improve traffic flow and reduce travel fare.

The reduction of private vehicle usage without modernization of the road-based public transport modes (i.e., PUJs and buses) cannot cut back the air pollutant emissions. Another option is the modernization of the PUJs and buses by phasing in Euro 4 emission compliant PUJs and buses from 2020. This strategic option can improve urban air quality and decrease public health risks, which benefits the sustainable development of communities. The benefit of this option can be quantified in financial cost by combining the environmental and energy benefits as well as household economy (i.e., job opportunities of local part production) and minus the initial investment cost of phasing in Euro 4 buses and PUJs.

To be specific, the combination of all the mentioned approaches should take place to reduce private vehicle stock and usage, energy demand, GHG and air pollutant emissions, and public health risks. Furthermore, the comprehensive approach can increase the government tax revenues on gas and vehicle. Those approaches are the implementation of road public transport modes compliant to the Euro 4 emission standard from 2020, the introduction of Euro 6 emission compliant passenger cars from 2025, the improvement of residential areas’ accessibility to key facilities by 2.5% per annum on average, and the implementation of the new tax schedules on gas and vehicle from 2018. The empirical findings of this research provide some insights into the reduction of petroleum-based energy dependency and mobile emissions and the improvement of public health by raising the government tax revenue. On a final note, policy advisers and managers may simultaneously focus on improving residential areas’ accessibility, modernizing road-based public transport modes, phasing in Euro 6 cars, and slightly increasing tax rates on gas and vehicle.
6. Generalization of the developed model for some ASEAN metropolises

The deployment of renewable energy is still embryonic in the Philippines, and the contribution of petroleum products in the sustained growth of the road transport sector cannot be ignored. The possibility of penetration of private electric vehicles (EVs) in Metro Manila might take a long time, and it is impossible to reduce petroleum-based energy demand and CO₂ and pollutant emissions and improve public health only if the electricity demand for private EVs is still produced from fossil fuels. The government has yet to enact any law to penetrate private EVs to reduce CO₂ and pollutant emissions. The electricity demand accounted for a 19.3% share of the country’s total energy demand in 2016, and only 0.1% of the country’s total electricity demand was used in the transport sector (i.e., E-trikes and rail transit modes) [5]. The percentage share of renewable energy for electricity demand decreased from 44% in 1999 to 32% in 2012 [8] and will further decline to 15% by 2030 based on the baseline scenario due to increasing energy demand and higher fossil fuel investments [84]. About 11 million Filipinos lived without access to electricity in 2016, and the government is trying to extend the electricity to all the households by 2022 [3]. Biofuels (i.e., ethanol and biodiesel) accounted for 3.5% of the transport sector’s total energy demand in 2016 [5], and the Biofuels Roadmap 2017–2040 showed an introduction of ethanol with E10 and biodiesel with B2 from 2017 to 2019 [85]. The promotion of the use of biofuels in the Philippines is very difficult to achieve due to the limited raw materials [86].

The Philippines is mainly dependent on petroleum products for the road transport sector, similar to Indonesia, Thailand, Vietnam, and Malaysia. The shares of biofuels are insignificant as compared to the shares of petroleum products of the transport sector’s total energy demand for these ASEAN countries [86]. The promotion of biofuel production and exploitation for the transport sector is embryonic in Thailand, Indonesia, the Philippines, Malaysia, and Vietnam. Thailand launches the Alternative Energy Development Plan (AEDP) 2015–2036 to promote E20/E85 and B10/B20 in 2036, Indonesia enacts the Regulation No. 20/2014 to reach E20 and B30 by 2030, the Philippines issues the National Biofuels Program to introduce E20 and B20 until 2025, Malaysia implements the 11th Malaysian Plan (2016–2020) to introduce Energy Efficient Vehicle (EEV) and promote B15 and compressed natural gas (CNG) in the transport sector, and Vietnam develops the Biofuel Roadmap to introduce E10 in 2017 and B5 in 2015 [86]. Therefore, the contribution of fossil fuels to the transport sector is still playing an important role at present and during the short and medium term in these five ASEAN countries. The study of 20 countries also reported that China and South Africa significantly depend on non-renewable energy, and these countries focus on improving energy efficiency rather than deploying renewable energy sources [87]. According to the similar energy-mix characteristics for the transport sector among the five ASEAN countries, the low-carbon policy implications of our research are highly expected to be applied for metropolises located in Thailand, Indonesia, Malaysia, and Vietnam.

7. Uncertainty analysis

The term of uncertainty is complex and needs a semantic discussion on its meaning, and many modelers and decision-makers introduce different categories of uncertainties [88]. For the transport section, Nocera et al. simplify the concept of uncertainty by classifying it into three categories, viz., technical aspect, economic valuation, and decisional processes [88]. Additionally, each category is further divided into ontological and epistemological elements [88]. Ontological uncertainty means that people with different cultural, religious, scientific, or political backgrounds are expected to have different ideas and thoughts about the anthropogenic impact on climate change, and the epistemological uncertainty refers to a more knowledge-based approach [88]. This concept of uncertainties is applied to analyze the overall uncertainty of our research results as follows.

7.1. Technical uncertainties

The epistemological uncertainty type consists of four main aspects, viz., current levels of emissions, atmospheric emission concentrations, the adoption of a unique unit of measure for all GHGs, and the choice of the most suitable programs and algorithms [88]. The assessment of public health risks ravaged by pollutants can be significantly influenced by the exposed population size and its spatial density, the scale of the study area, the distance between the sources and the receptor areas, the exposure pathways, the environmental conditions of pollution dispersion, the pollutant persistence, urban morphology, and the chemical and physical transformation, and the methods applied [2,68,72]. The Intake Fraction (IF) method is applied to evaluate the public health damaged by atmospheric pollutant concentrations thanks to the absence of site-specific information bypassing air dispersion modeling. The IF is a ratio of the mass of pollutant inhaled by the exposed population to the mass of pollutant emitted by a given source. Another traditional approach is the Impact Path Approach (IPA) that is applied to compute the specific-site benefits of health using the data on meteorological conditions, pollutant concentrations, and population distribution [69]. The cases of public health risks will change regarding a method applied. Researchers proposed both statistical and stochastic solutions to address the uncertainties of energy demand and make sure the results obtained are more robust [89]. However, it is not easy to give a response on how to deal with the uncertainties of CO₂ emissions [88].

For the ontological element, the future infrastructure layout, population changes, household income, and technological progress are dynamic, thereby instigating a major inaccuracy of the long-term prediction of private car-related travel demand and road vehicle fleets, energy demand, and emissions over time. The future infrastructure layout (e.g., road density, intersection designs, flyovers, toll roads, on-ramps, off-ramps, and the traffic light system) affects traffic flow, travel demand, energy consumption, and flue gas emissions. It is impossible to take into account the future infrastructure layout in our model to project energy demand and emissions. Population changes are influenced by national employment policy and the global economy. For instance, the population growth in Metro Manila might be slowed down if the number of job opportunities increases in towns and rural areas or if the global and national economies turn upside down. A lesson from the past in Metro Manila, the population growth rate from 2005 to 2010 was noticeably slower than those from 2010 to 2015 and from 2000 to 2005 [13], probably thanks to the worldwide economic crisis 2008. Similarly, the household income growth is not constant in reality, at a varying rate due to the ripple effect. Global lessons at present and from the past, some people lose their jobs and some portion of the income caused by the Covid-19 and the 2002–2004 SARS pandemic outbreaks. For technological progress, our modeling tool is not able to effectively deal with some types of radical technological developments. For instance, the rapid development of the e-hailing digital platform may promote sharing economy behavior, and therefore, some car owners will be seduced to join carpooling and carsharing rather than the public transport modes and driving alone. This will increase the private car occupancy rate. Similarly, history showed that there was a sharp decline in international maritime passenger transport caused by the emergence of mass-market aviation in the 1950s [90]. Technological improvement of engine, tires, transmissions, air-conditioning, catalytic converter, and materials can also instigate uncontrolled uncertainties of the projected results. The diffusion of electric and fuel cell cars and low-carbon fuel cars (e.g., biofuels, natural gas, and liquefied petroleum gas) might be possible in a medium-to-long term in the Philippines, and the rates and time of penetration of these technologies are unpredictable. Also, technological progress and infrastructure layout
might affect the average lifespan of private cars, which influences the vehicle fleets and new vehicle sales. It is found an increase in the average lifespan of passenger cars in the US [91]. The policy of vehicle scrappage might be implemented in Metro Manila in the future and can also affect vehicle lifespan, on-road vehicle stock, and new vehicle sales. Population and economic changes and technological progress are exogenous changes, while policy changes are endogenous changes [90]. The future transport demand is at high levels of uncertainty, and there is an urgent need for accurate modeling of future travel demand and capacity [90].

7.2. Economic uncertainties

The CO2 and pollutant emissions are converted to the monetary value by multiplying the social cost of carbon and the unit cost of health risk, respectively. The social cost of carbon is a measure of the economic cost associated with climate damage resulting from the emission of one tonne of CO2 into the atmosphere for over 100 years [82,88]. The economic valuation of CO2 emissions will change if we use the avoidance cost (or mitigation cost) in place of the social cost of carbon. These two aspects are ontological uncertainties, and however, the avoidance cost is not clear and inevitably entails a significant risk of overestimating [88].

Political visions of policymakers, geographical scale, spatial dimension, temperature variation, temporal issues are the epistemological uncertainties of the evaluation of CO2 emissions in monetary value [88]. Similarly, the inaccuracy of the assessment of public health risks ravaged by pollutants can be provoked by the exposed population size and its spatial density, the scale of the study area, the environmental conditions of pollution dispersion, and urban morphology, among other factors. Tax schedules on gas and vehicle might be changed in medium and long terms, which might affect the private vehicle dependency. Correspondingly, the monetary values of energy demand, CO2 emissions, public health risks, and tax revenues will vary. Similarly, the predicted global crude oil price is erratic with a large confidence bound, which triggers the uncertainties of tax revenue on gas, economic valuation of energy demand and CO2 emissions, and monetary values of health risks.

7.3. Decisional uncertainties

All the aspects of decisional uncertainties belong to the ontological element because the uncertainty is inherent to human nature based on different beliefs, values, preferences, choices, and political actions [88]. The projected population and household income are associated with future travel demand, and the higher level of spatial disaggregation of population and economic activities can minimize uncertainties of the projected travel demand [90]. The projected population used for our study is obtained from the small area population estimations for Metro Manila [65], and therefore, there are acceptable standard errors of parameter estimates to project the population. The household income change is an average annual change between 2009 and 2015 in Metro Manila published in the Philippines Statistics Yearbook 2017 [13], and the household income growth rate is assumed to be constant for the projected years. The average vehicle lifespan is assumed to be constant in our research, but the average lifespan is varied due to social development, human behavior transition, vehicle scrappage program, etc. The gas price estimates are obtained from the World Bank and Statista [56,57], and the direction is in a smooth trend even though the gas price widely fluctuates in reality. The retail gas prices are mainly dependent on national and global recession and ripple effects, and these outbreaks cannot be known beforehand how the economy is going to crash. The vehicle prices are adopted from the CPI in Metro Manila [58]. Another major cause of uncertainty of our research is using the existing transport systems, and it cannot implicitly predict the revolutionary changes in transport provision. For all the projected years of our research, the percentage shares of gasoline and diesel private cars are assumed to be 64.77% and 35.23%, respectively, but these percentages will vary over time. To minimize this uncertainty, it is necessary to estimate the fuel mix of the road vehicle fleet based on economic and technological factors (e.g., prices of greener fuels and purchase prices of alternative fuel vehicles), but it increases complexity to the model and is not easy to forecast [90]. Furthermore, the reduced VKT of private vehicle usage is assumed to be replaced by the PUJs for 76.29% and the buses for 23.71% for all the projected years, see Table 7. Additionally, the occupancy rates of the private car, PUJ, and bus are assumed to be 1.7 persons, 14.98 persons, and 35.3 persons, respectively. These assumed values, however, are not constant and vary over time thanks to travel behavior transition, technological development, household and national economic growth rates, urban planning and transport policy changes, etc. Regarding CO2 and pollutant emissions, emission factors are the main causes of uncertainty. To reduce the uncertainty, we use the local data of emission factors available for some pollutants of some emission standards [61,92]. Because there is no research on health benefits in Metro Manila, the intake fraction estimates are adopted from Warsaw, Poland under the variations of population density, and the concentration-response coefficients and baseline of mortality or morbidity incidence rates refer to some studies in China and some EU countries. The unit health costs of many diseases are adopted from China and Indonesia based on per-capita GDP. The geographical scales used to assess public health risks also affect the results [88]. In our study, we just consider the population in Metro Manila, but the pollutants also damage the public health of people living around the metropolis that is not considered in the study boundary. Furthermore, the assessment of health risks does not include the secondary pollutants of acid rain and ozone. However, the extent of uncertainty remains to be explored.

8. Conclusions, limitations, and recommendations

8.1. Conclusions

The study investigated the energy and environmental benefits and proposed policy implications for private passenger vehicles in Metro Manila. First, the study developed the joint model of household vehicle ownership and energy consumption using the disaggregated data of 1,795 households gathered in 2017. Then, the simulated results of the developed model were applied for the projection of vehicle stocks, scrapped vehicle numbers, vehicle sales, private VKT, energy demand, emissions, public health risks, tax revenues, and net values under various scenarios for a 2010–2050 horizon, with 2017 used as the reference year. The following conclusions of the study are shown below:

- Under the baseline scenario, the vehicle stock, energy demand, CO2 emissions, and the total economic loss of public health risks will increase from 1.38 million units, 1.11 Mtoe, 3.44 Mt, and 113 million USD in 2010 to 3.78 million units, 5.45 Mtoe, 16.93 Mt, and 491 million USD in 2050, respectively.
- In 2020, the gas tax revenue is 112 million USD under the baseline scenario, and the new tax schedule on gas raises the tax revenue by 2.45 times as compared to the baseline. The vehicle tax revenue will increase from 48 million USD in 2010 to 1,281 million USD in 2050 under the baseline scenario. In 2050, the vehicle tax revenue will be boosted by 1.73 times under the new vehicle tax schedule relative to the baseline. Correspondingly, the new tax schedules on gas and vehicle can raise the great amount of tax revenue. However, it does not noticeably affect the increasing trends of vehicle stock, energy demand, emissions, and public health risks, as compared to the baseline scenario.
- The introduction of Euro 6 emission compliant passenger cars from the year 2025 based on the new tax schedule on vehicle will extremely mitigate the pollutant emissions, improve the public health,
and raise the tax revenues and net value. In 2050, the economic loss of public health risks will be 491 million USD in 2050 under the baseline scenario, and it will decline by 46.0% under the Euro 6 scenario as compared to the baseline.

- The improvement of accessibility from residential areas to key facilities is an effective alternative to discourage private car dependency, thereby sharply reducing the vehicle stock, vehicle sales, energy demand, and CO₂ emissions. However, the pollutant emissions and public health risks are not significantly reduced in Metro Manila since the dominant road public transport modes are PUJs that are mostly equipped with old and dilapidated engines. The reduction of private vehicle usage without modernization of the road public transport modes cannot improve public health but can combat the GHG emissions.

- Modernization of the road public transport modes by phasing in the Euro 4 emission compliant PUJs and buses considerably decreases the pollutant emissions, thereby significantly improving the public health. The increasing tax revenue from the implementation of the increased tax rate levies on gas and vehicle should be used as a subsidy for phasing in Euro 4 buses and PUJs to improve the public health, which is a possible advantage brought to the metropolis.

- The best way to achieve sustainable urban mobility, the government should combine these strategic approaches, i.e., (1) the continuity of the implementation of the new tax schedules on gas and vehicle, (2) the penetration of new cars compliant to the Euro 6 emission standard from 2025, (3) the improvement of accessibility from residential areas to key facilities to enrich mixed land use, and (4) the penetration of buses and PUJs compliant to the Euro 4 emission standard from 2020.

8.2. Limitations and recommendations

Even though this research is comprehensive and novel, various vehicle types (e.g., van, minivan, SUV, UV, sedan, and hatchback) and different fuel types (e.g., gasoline and diesel) are not classified into more different categories because of the limited data sample size that cannot handle a large number of alternatives and factors. A sound understanding of vehicle category and fuel type choice is the prerequisite for the penetration of lower-carbon and fuel-efficient vehicles. Further effort is required to develop the vehicle ownership and usage model by including vehicle type classifications and fuel types using other discrete-continuous choice models (e.g., MDCEV, BMOPT, and integrated MNP-MNL-linear regression). An optimization model for increasing tax rates imposed on gas and vehicle should be developed to compute the tax revenue as a subsidy to reach the targeted number of Euro 4 buses and PUJs phased in. Additionally, the potential extension of these findings to other developing countries located in the southeastern part of Asia (e.g., Thailand, Indonesia, Cambodia, Myanmar, and Laos) or the region (e.g., ASEAN) should be added and compared with the empirical findings of this case study. Furthermore, some simulated results of household vehicle fleet and energy consumption are expected to be informative for future studies of cost-benefit analysis of low-carbon alternatives for the road transport sector of some metropolises in the ASEAN region.

CRediT authorship contribution statement

**Monorom Rith:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Writing - original draft. **Alexis M. Fillone:** Conceptualization, Funding acquisition, Methodology, Resources, Supervision, Validation, Visualization, Writing - review & editing. **Jose Bienvenido Manuel M. Biona:** Conceptualization, Funding acquisition, Investigation, Methodology, Resources, Project administration, Validation, Visualization, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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