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SYSTEM DYNAMICS MODEL OF CO_2 EMISSIONS FROM URBAN TRANSPORTATION IN CHIANG MAI CITY

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ABSTRACT: The transportation sector has significant economic, social, and environmental impacts on cities. It represents the key contributor to energy consumption and CO_2 emissions which cause global warming and climate change. The energy consumption and CO_2 emissions data at city level are important for policy makers to develop sustainable urban transportation. In Thailand, most earlier studies have emphasized at country level. In addition, urban transportation system is a complex system with multiple variables and feedback behaviors. Therefore, the objective of this study is to develop a model for estimate and analyze energy consumption and CO_2 emissions from urban transportation systems using the system dynamics approach. To demonstrate the application of the model, Chiang Mai city has been taken as a practical case. The proposed model comprised of five subsystems including population, economy, transport supply, vehicle, and energy consumption and CO_2 emissions. The validation of a proposed model revealed that this model was reliable to estimate CO_2 emissions and analyze the reduction policy for the city level. The proposed model can be used as a key decision support system (DSS) for urban transportation planning for the sustainability of the city.

Keywords: System Dynamics, CO_2 Emissions, Urban Transportation, Environmental Sustainability

1. INTRODUCTION

The issue of energy demand and CO_2 emissions, which are linked to global warming and climate change, has become an area of intense research because of the recent rapid growth of population and economic [1]. Transportation represents the key contributor to energy consumption and CO_2 emissions [2].

The transportation sector accounts for about a quarter of global energy consumption and energy-related CO_2 emissions [3]. According to the IEA's report in 2019, almost 27% of the world's total final consumption of energy is from the transportation sector [4].

The transportation sector in Thailand is the second largest sector which produces carbon dioxide next to the power generation sector. It contributes approximately 26% of energy-related CO_2 emissions. In addition, almost of CO_2 emissions from the transportation sector is from road transportation, approximately 97% of total CO_2 emissions from transportation.

In Thailand, most of the available data on energy consumption and CO_2 emissions are reported by the government sector. These estimated CO_2 emissions data are calculated using the top-down method. The top-down method is considered not reliable in analyzing the impact of different energy demand and vehicle emissions reduction policies from road transport at the regional level [5]. Even though there were some earlier studies used the bottom-up method, all of them were a country level.

Chiang Mai city is the economic, investment and transport center of northern Thailand. In the last decade, Chiang Mai city is growing very fast and increasingly faces problems common to large cities; for example, unplanned and sprawling development, air and water pollution, waste management and traffic congestion [6]. The uncontrollable land developments and urban sprawl affect the transportation network of the city. The public transportation system (bus and red car taxi) unable to support the needs of the people; therefore, 90 percent of the Chiang Mai population uses private vehicles as the first mode of transportation [7]. For this reason, Chiang Mai city experiences more traffic congestion, energy consumption, and CO_2 emissions, which affects the sustainability of the city. Consequently, this city needs to focus on sustainable urban transportation in order to develop the city to meet sustainable growth.

In addition, the urban transportation system is a complex system with multiple variables and feedback behaviors.

Therefore, the purpose of this study is to develop the urban transportation model for estimate and analyze energy consumption and CO_2 emissions from road transport at the city level by using a system dynamics approach, which can be used to assess the appropriate reduction policy. Chiang Mai city has been taken as a practical case to demonstrate the application of the model.

2. METHODS

2.1 Overview of the Study Area: Chiang Mai City

Chiang Mai city is a principal province of the northern region of Thailand. It is 700 km north of Bangkok with an area of 20,107.057 square kilometers. In 2016, the population was 1,735,762 people and the gross province product (GPP) per capita of the year 2016 was 133,229.18 baht.

The urban passenger transport in Chiang Mai city (under motor vehicle Act.) share by private vehicles, including private cars, passenger vans, pick-up trucks, and motorcycles, around 99.7%, while less than 0.3% are made by public transport, including, motor tricycle taxi (TukTuk), urban taxi, red car taxi, and bus (as shown in Fig.1). As of 31 December 2018, the number of an accumulated registered private car (not more than 7 passengers) in Chiang Mai is 338,882 units, the second rank in Thailand after Bangkok. While the motorcycle is 823,176 units, the third rank in Thailand after Bangkok and Chonburi [8].

Urban passenger transportation in Chiang Mai involves a variety of vehicle types and fuel types (under motor vehicle Act.) consequently the CO_2 emissions model of Chiang Mai city can be demonstrated as in Fig.2. The transport mode can be divided into two categories; private transport and public transport. The private transport modes include car, van, pick-up truck, and motorcycle. The public transport modes include motor tricycle taxi (TukTuk), urban taxi, red car taxi, and bus. The types of fuel include gasoline (benzene), diesel, LPG, CNG, and electricity.

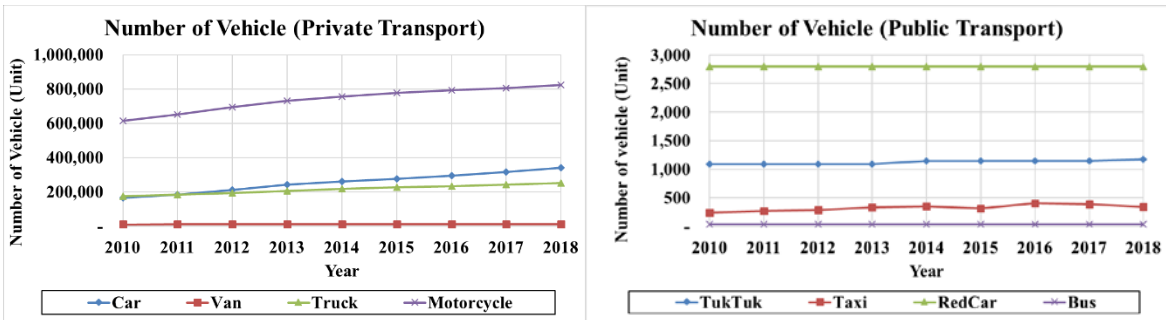

Fig.1 Number of vehicles by vehicle mode type of Chiang Mai city in 2010 – 2018

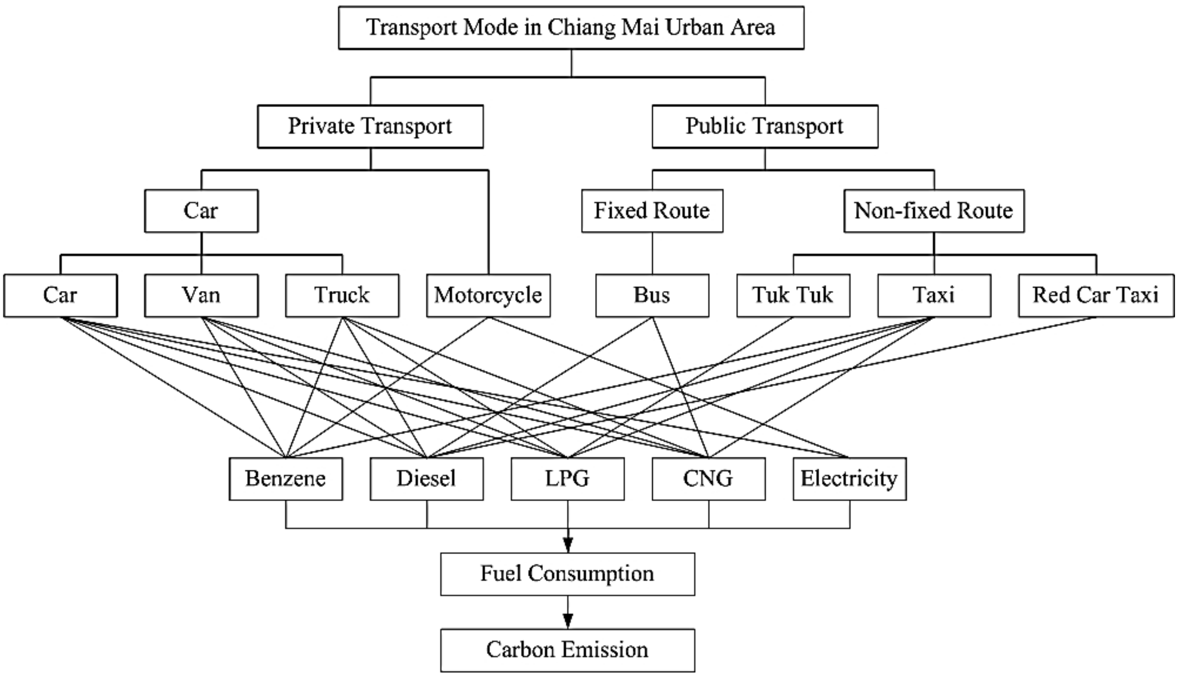

Fig.2 Transport mode CO_2 emissions model of Chiang Mai city

2.2 System Dynamics Modeling

System dynamics (SD) was developed in 1956 by J. W. Forrester at the M.I.T. [9, 10]. It is a proven effective method for modeling and analyzing the behavior of the complex dynamic feedback systems over time [10-12]. It has been used as a holistic modeling and dynamic simulation approach in many areas [13].

The methods of SD utilize feedback loops, variables, and equations [14, 15]. The feedback loops are represented by the causal relationship diagram. The variables include stock, flow, and auxiliary variables. The stock (or level) variable is the state of an element of the system which accumulates a flow over a continuous time period. The flow (or rate) variable is the increase or decrease amount of value of the stock during a time period. The auxiliary variables are the rates that identify the flow variable. All of these variables are linked by different equations in the form of integral, differential, or other types [13,14]. This SD method is supported by computer simulation software, such as Vensim, Stella, iThink, and PowerSim. The software Vensim and Stella are widely adopted by SD models for simulation applications, which provide a user-friendly interface [16]. The SD model proposed in this study was simulated on Vensim PLE software.

The SD model comprises of two parts, the first is a causal loop diagram (CLD) which describes cause-effect relationships between the different systems developed during model construction, the second is a stock-flow diagram which represents the quantitative relationships among variables [17].

To develop the model for estimate and analyze the energy consumption and CO_2 emissions from road transport at the city level, the CLD of Chiang Mai's urban transport system was constructed, as shown in Fig.3.

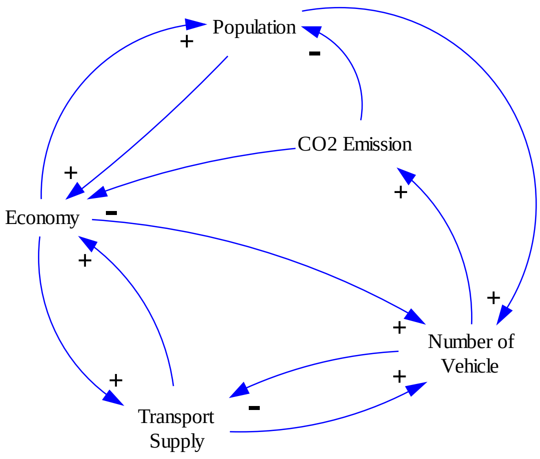

Fig.3 Causal loop diagram for the urban transport system of Chiang Mai city

The stock and flow diagram of the urban transport system for estimate energy consumption and CO_2 emissions of Chiang Mai city was comprised of five subsystems, including population, economy, transport supply, vehicle, and energy consumption and CO_2 emissions subsystems.

2.2.1 Population subsystem

The population is an important factor that affects urban passenger transport. The total population was chosen as the stock variable while birth rate, death rate, in-migration rate, and out-migration rate as auxiliary variables, the in-migration is influenced by GPP per capita, as shown in Fig.4.

2.2.2 Economy subsystem

The economy of Chiang Mai city is reflected by the Gross Province Product (GPP). The GPP was considered as the stock variable with the GPP growth rate as an auxiliary variable, as shown in Fig.4.

2.2.3 Transport supply subsystem

The transport supply is reflected by the total lane kilometers which considered as the stock variable. The road transport infrastructure investment was an auxiliary variable that directly affecting the total lane kilometers. The GPP, traffic congestion, and VKT were also influencing to transport supply, as shown in Fig.4.

2.2.4 Vehicles subsystem

A number of vehicles of all vehicle types were considered as the stock variables. The increasing rates of each vehicle were the auxiliary variables along with GPP per capita. The stock and flow diagram of the vehicle subsystem as shown in Fig.5.

2.2.5 Energy consumption and CO_2 emissions subsystem

The annual average vehicle kilometers traveled (VKT) as the important variable plays a crucial role in the estimation of vehicle emissions [18, 19].

In this study, energy consumption (EC), CO_2 emissions (CE), and total CO_2 emissions (TCE) from urban transportation in Chiang Mai city are calculated based on vehicle population (N), vehicle kilometers traveled (VKT), energy efficiency of vehicle (EE), and emission factor (EF) for each vehicle type and each energy type using Eq.(1), Eq.(2), and Eq. (3), respectively [3].

$$EC_{i,j} = N_i \cdot VKT_i \cdot EE_{i,j} \tag{1}$$

$$CE_i = \sum_j^n EC_{i,j} \cdot EF_j \tag{2}$$

$$TCE = \sum_i^m CE_i \tag{3}$$

Where i and j represent the types of vehicle and type of fuel, respectively.

The stock and flow diagram of the energy consumption and CO_2 emissions of a personal car, as for example, and the total CO_2 emissions were shown in Fig.6.

Table 1 and Table 2 give the values of variables or initial values of variables and emission factors, respectively. The information used in the proposed model was obtained from the government agencies, such as the National Statistical Office of Thailand, the Department of Highways, and the Department of Land Transport.

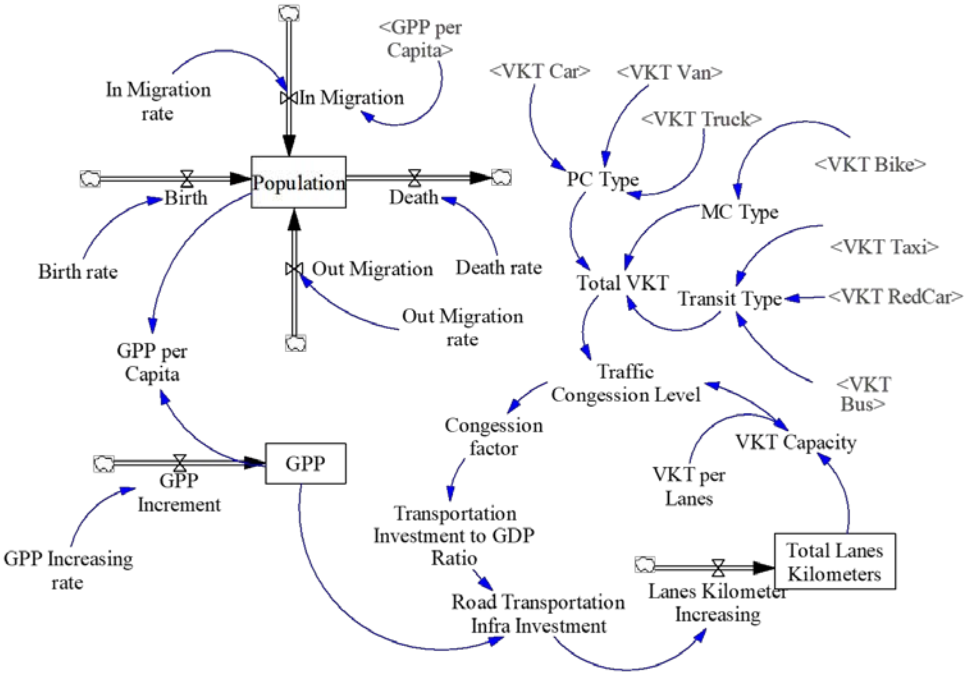

Fig.4 Stock and flow diagram of the population, economy, and transport supply subsystems

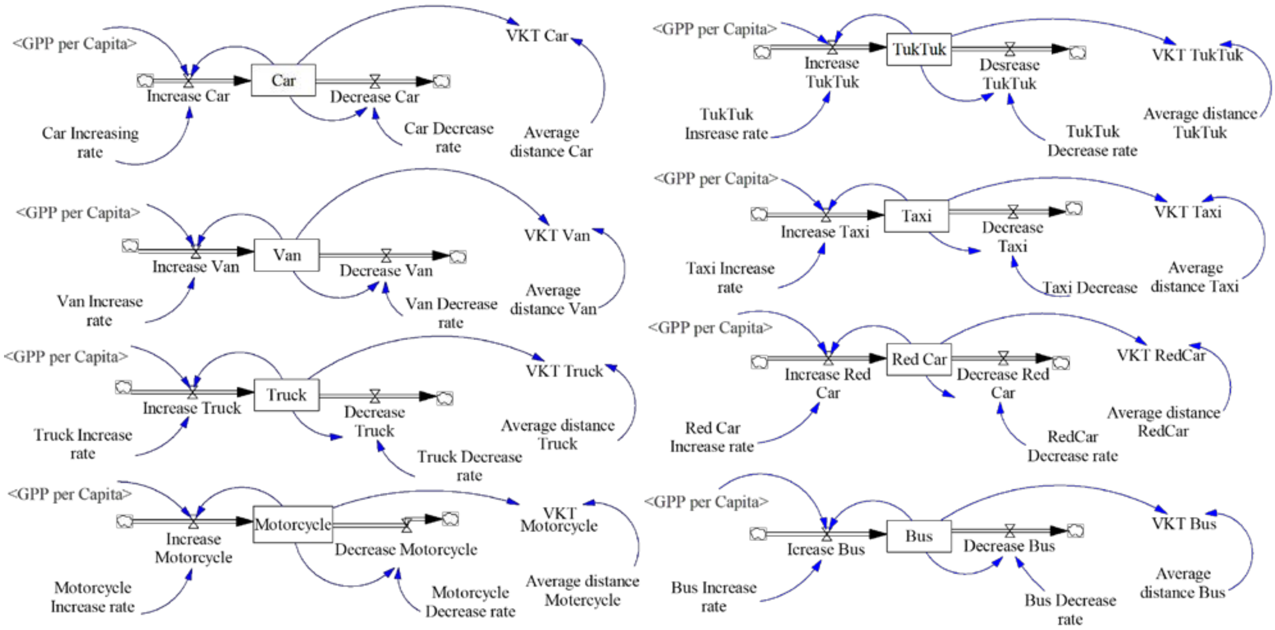

Fig.5 Stock and flow diagram of the vehicle subsystem

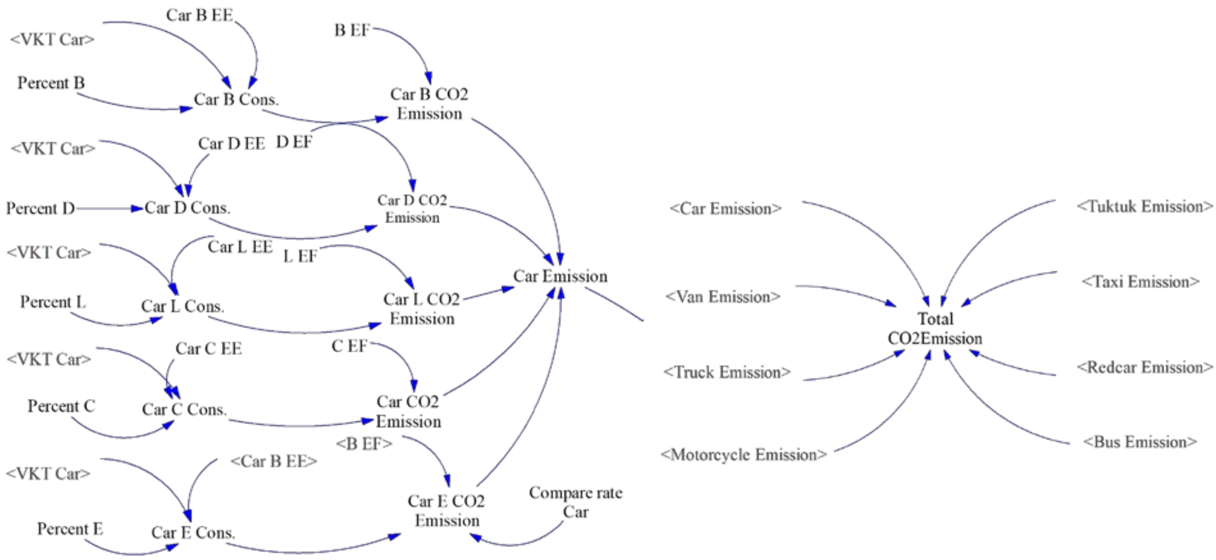

Fig.6 Stock and flow diagram of the energy consumption and CO_2 emissions subsystem

Table 1 Values of variables or initial values

Variables	Values	Units
Population	1,640,479	Person
Birth rate	0.011	-
Death rate	0.008	-
In-migration rate	0.056	-
Out- migration rate	0.054	-
GPP per capita	103,971	Baht
GPP growth rate	0.026	-

Table 2 Emission factor

Energy Type	Values ($kgCO_2$/unit)	Data Source
Benzene	2.181564	[20]
Diesel	2.698722	[20]
CNG	2.126190	[20]
LPG	1.493382	[20]
Electricity	0.581300	[20]

3. RESULTS AND DISCUSSION

3.1 Model Validation

Model validation is the process of establishing confidence in the sadness and usefulness of the model, it constitutes an important step in system dynamics methodology [13, 21, 22]. Confidence in system dynamics models can be increased by a wide variety of tests; including, tests of model structure, model behavior, and a model's policy implication [22]. In this study, after obtained all the variables and parameters, the units of measure for all variables and parameters and the dimensional consistency of all equations were verified. The simulation results were validated by comparing the simulated data with the historical data. Table 3 demonstrates the validation results of examined variables, included population, GPP per capita, and the number of passenger cars. According to the results, the error term of the population was less than 1% while GPP per capita and the number of cars were less than 10%. The proposed model appears to be reasonable because the relative errors were less than 10% [10, 14, 17].

Table 3 Comparison of model output with reported values

Year	Model Output	Reported Data	Error (%)
Population (people)			
2010	1,640,479	1,640,479	-
2011	1,646,144	1,653,503	0.45
2012	1,655,642	1,666,725	0.67
2013	1,666,888	1,680,150	0.80
2014	1,678,284	1,693,783	0.92
2015	1,728,242	1,707,629	1.19
2016	1,735,762	1,721,693	0.81
2017	1,746,840	1,735,980	0.62
		Average error =	0.78
GPP per Capita (Baht)			
2010	103,970.93	103,971.00	-
2011	112,855.64	106,785.05	5.38
2012	122,565.97	109,675.27	10.52
2013	120,599.40	112,643.71	6.60
2014	123,597.62	115,692.49	6.40
2015	127,880.60	118,823.79	7.08
2016	133,229.18	122,039.84	8.40
		Average error =	7.39

Table 3 (Continued)

Year	Model Output	Reported Data	Error (%)
Number of Passenger Car (Unit)			
2010	166,013	166,013	-
2011	183,178	180,121	1.67
2012	210,893	195,446	7.32
2013	240,781	212,095	11.91
2014	260,258	230,183	11.56
2015	277,209	249,837	9.87
2016	295,232	271,195	8.14
2017	315,535	294,406	6.70
2018	338,882	319,635	5.68
		Average error =	7.86

3.2 Policy Scenarios

After model validation, in this study, four policy scenarios were established to evaluate the CO_2 emissions reduction policy. The first scenario (business as usual, BAU) was not implement any CO_2 emissions reduction policies, it was set in accordance with the current development situation. The second scenario was to reduce half of the growth rate of the motorcycle by electric motorcycle. The third scenario was to reduce half of the growth rate of the personal car by eco-car. The fourth scenario was the second scenario combined with the third scenario. In Chiang Mai city, the private vehicle is the first mode of transportation; therefore, the public transport policy was not included in the policy scenarios.

The results of four different policy scenarios were shown in Fig.7. The comparison of all scenarios was shown in Fig.8. Briefly comparing the results of four scenarios, the fourth scenario yields the best policy to reduce CO_2 emissions.

4. CONCLUSION

In this paper, the model for estimate and analyze energy consumption and CO_2 emissions from urban transportation was developed using a system dynamics approach. Chiang Mai city was used as a practical case to demonstrate the application of the model. The relative errors were less than 10%. The appropriate reduction policy which proposed in this study was to reduce half of the growth rate of the motorcycle by electric motorcycle and to reduce half of the growth rate of the personal car by eco-car. This policy revealed a 32.04% reduction of CO_2 emissions different from BAU in 2040.

The proposed model appears to be reasonable and quite reliable to estimate and analyze the reduction policy for the city level. Therefore, it can be used as a key decision support system (DSS) for urban transportation planning to develop the sustainability of the city. Different policy options can be considered as future work.

5. ACKNOWLEDGMENTS

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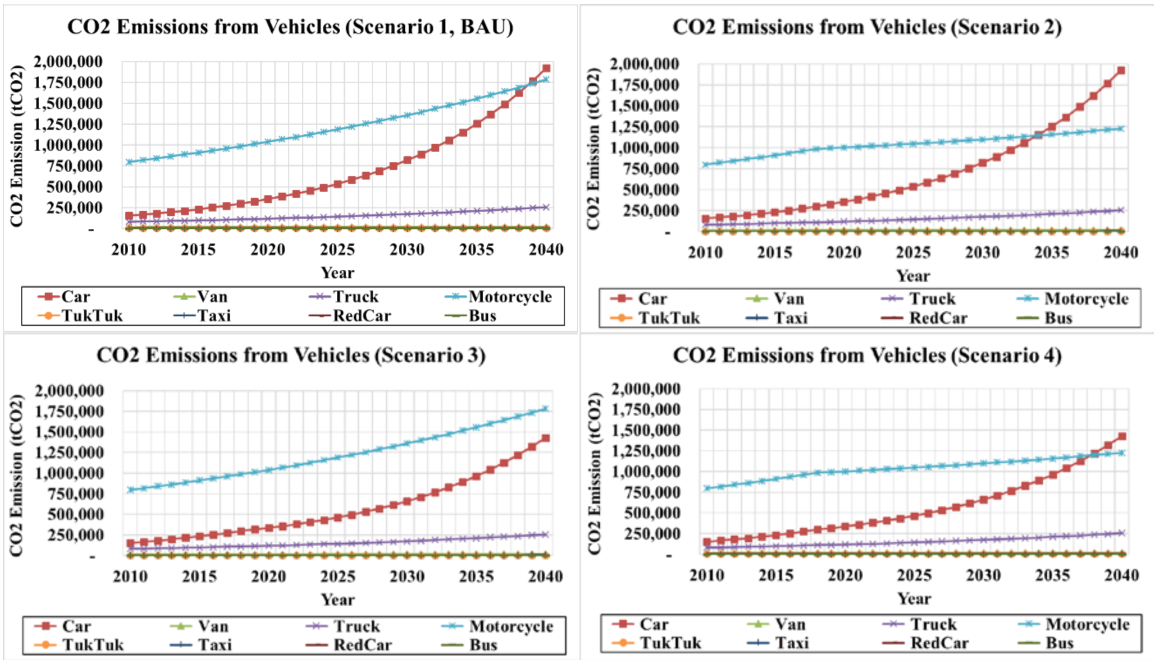

Fig. 7 The CO_2 emissions from vehicles of different scenarios

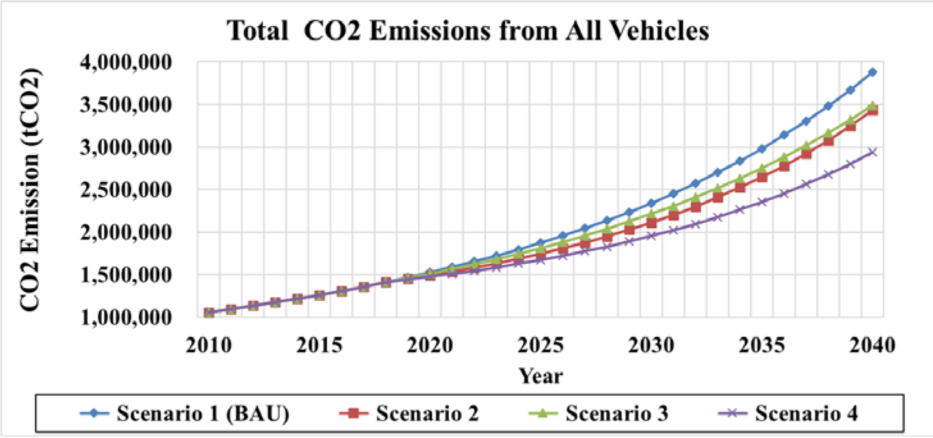

Fig. 8 The total CO_2 emissions from all vehicles of each scenario

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