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Urban transportation energy and carbon dioxide emission reduction strategies ☆

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HIGHLIGHTS

- We established a 30-year-simplified system dynamics model.
- We simulated the effects of various urban transportation management policies.
- Our proposed approach develops appropriate models in other cities.

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ABSTRACT

Sustainability is an urban development priority. Thus, energy and carbon dioxide emission reduction is becoming more significant in the sustainability of urban transportation systems. However, urban transportation systems are complex and involve social, economic, and environmental aspects. We present solutions for a sustainable urban transportation system by establishing a simplified system dynamics model with a timeframe of 30 years (from 1995 to 2025) to simulate the effects of urban transportation management policies and to explore their potential in reducing vehicular fuel consumption and mitigating CO_2 emissions. Kaohsiung City was selected as a case study because it is the second largest metropolis in Taiwan and is an important industrial center. Three policies are examined in the study including fuel tax, motorcycle parking management, and free bus service. Simulation results indicate that both the fuel tax and motorcycle parking management policies are suggested as potentially the most effective methods for restraining the growth of the number of private vehicles, the amount of fuel consumption, and CO_2 emissions. We also conducted a synthetic policy consisting of all policies which outperforms the three individual policies. The conclusions of this study can assist urban transport planners in designing appropriate urban transport management strategies and can assist transport operation agencies in creating operational strategies to reduce their energy consumption and CO_2 emissions. The proposed approach should be generalized in other cities to develop an appropriate model to understand the various effects of policies on energy and CO_2 emissions.

1. Introduction

Sustainable development has become a worldwide priority. Sustainable development is viewed as the development that meets the current needs without compromising the ability of future generations to meet their own needs [1]. The transportation sector is important as it relates to sustainability because this sector supports the economy and most social activities and has substantial environmental impact [2]. Thus, a well-established urban transportation system should not only harmonize economic growth with land-use planning and promote the use of public transit systems but also conserve resources and be environmentally friendly [3–5].

According to Key World Energy Statistics [6], the aggregate energy demand of the global transport system increased from 23% in 1973 to 28% in 2012. The World Energy Outlook [7] reported that the transportation sector will account for 30% of the growth in petroleum consumption between 2004 and 2030. This finding indicates that the increasing use of motor vehicles will accelerate

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resource exhaustion and global warming, despite its promotion of road transportation mobility.

In Taiwan, the road transportation system not only facilitates the mobility of people and goods over space and time but also is essential for the industrial and economic development of Taiwan's trade-oriented economy. According to Taiwan's Statistical Abstract of Transportation and Communications [8], the number of registered vehicles in Taiwan rose from 4.7 million in 1980 to 21.3 million in September 2014. This rise was a consequence of the increase in individual disposable income, the opening of the first national north–south expressway in 1978, and the subsequent improvement of the highway infrastructure: a second national north–south expressway, a west coast highway, and an east–west highway, among others. Along with the rapid growth of the number of motor vehicles, energy consumption in the road transportation sector reached the equivalent of 13,272 kl of oil in 2013, which was 3.37 times higher than that in 1980, and accounted for 95.75% of aggregate transport fuel demand. The amount of CO_2 emitted in the road transportation system increased at an annual rate of 4.38% per annum, from 8.2 million tons in 1980 to an estimated 33.7 million tons in 2013.

Under the pressure of global warming and significant great fluctuations in fuel prices, we face issues related to humanity-oriented transportation, energy conservation, and CO_2 mitigation, which have already become important topics in transportation planning and management. The Ministry of Transportation and Communications (MOTC) in Taiwan had invested NT$ 15 billion from 2010 to 2012 to reduce the number of private vehicles driven and the amount of fuel consumption and CO_2 emissions through the use of public transportation promotion programs.

Many academic works focused on CO_2 emission and energy consumption in the urban system context [9–18]. However, interactions between various transportation subsystems are not considered. Moreover, a systematic approach covering more aspects of the urban air pollution problem is still lacking to examine the effects of various transport policies.

An urban transportation system is complex and involves a variety of social, economic, and environmental issues. Interpreting the inherent mechanisms of the system and capturing the dynamic behavior of the components with analytical methods, such as decomposition analysis, grey theory, least-squares regression, and geometric average method, are not easy because the database is limited and because these subsystems are interlinked and dependent on each other. System dynamics (SD) provide a simulation platform to analyze a large-scale and complex socioeconomic system with multiple variables that change over time. With the aid of an SD model, we selected Kaohsiung as a case study to explore the effects of variations in demographics, fuel prices, and economic growth rate, among other factors, on the number of vehicles, fuel consumption, and energy-related CO_2 emissions. In addition, we developed three scenarios based on the possible policies that could be adopted by the city government to simulate their potential both for reducing the vehicular fuel consumption and for mitigating CO_2 emissions in Kaohsiung.

2. Literature review

SD, which is based on systems theory, is a method for analyzing complex management problems with cause–effect relationships among different systems. *Industrial Dynamics* [19] was the first book to illustrate the influence of organizational structure, policies, and action delays on industrial activity. An urban dynamics model was then constructed to show the effects of the interactions among business, housing, and people on the growth pattern of a city. Finally, a large and complex socioeconomic simulation system, i.e., World Dynamics, was developed [20]. The world socioeconomic system might collapse if actions are not taken to slow population growth and the continuous and unrestrained exploitation of natural resources.

In recent years, the SD model has been widely used to analyze agricultural systems [21,22], environmental management and planning [23,24], industrial sectors [25–31], strategy planning and decision making [32–34], transportation systems [35–39,15,40], urban planning [41–45], waste management [46–50], and water resources and lake eutrophication [51–54]. The transport mode for distributing goods in Germany was explored with the aid of an SD model [35].

In addition, policy interventions such as infrastructure investments, and carbon tax were simulated to examine their effects on energy savings, CO_2 reduction, public expenditure, and economic development. An SD model was used to evaluate the influence of the traditional supply chain and the vendor-managed inventory system on the performance of a firm's supply chain [36]; to examine the effects of policy scenarios on traffic volume, modal share, energy conservation, and CO_2 mitigation [37]; and to investigate how incorporated systems, such as population, economy, transportation demand, transportation supply, and the vehicular emission of nitrous oxides, affect the dynamic development of urban transportation systems under five policy interventions on vehicle ownership [38]. An SD model was developed to explore the interrelationships among population, economy, housing, transport, and urban land in Hong Kong; the long-term constraints of and potentials for urban development yielded by the study were offered as policy suggestions for city planning [39]. Previous relevant studies rarely considered interactions among various transportation subsystems simultaneously with CO_2 emission and energy consumption.

Although certain developed countries, such as the United States, the United Kingdom, and members of the European Union, have focused on improving fuel efficiency using advanced technologies [55,56], few studies have developed a practical SD approach for urban planners to further assess the effect of urban transportation policies on energy consumption and CO_2 emission. This study examines three main urban transportation policies in our proposed model: fuel tax, motorcycle parking management, and free bus service. Prior studies mainly investigate the effect of a particular policy, such as fuel tax in Europe and the US [57]; parking management policies in China [58]; and free bus policy in Japan, Belgium, and England [59–61]. A limited number of studies analyze the effect of these policies on energy consumption and CO_2 emission reduction simultaneously and compare the respective policy with the synthetic policy to compare the policy effectiveness. Our study aims to fill this research gap by developing a systematic and simplified analytical tool that can help urban planners to evaluate the influence of various transportation policies on energy consumption and CO_2 emission reduction.

3. Methodology

Briefly, an SD model describes the information, structural boundaries, strategies, and action delay inside the system structure through a feedback process. A quantitative simulation is performed to study the dynamic behavior of the interaction of interrelated components inside the system structure. The SD model analyzes a complex system with multiple variables that change over time and determines how the system is affected by the implementation of specific policies [62]. In addition, Kummerow [63] revealed that the SD model not only relatively easily incorporates qualitative mental and written information as well as quantitative data but also can be used when the database is insufficient to support statistical forecasting analysis. Thus, the SD model is an appropriate approach to display the inherent behavior and influences inside the system structure despite multidirectional dynamic interactions and the fact that life is infinitely more complicated and difficult than we can effectively simulate [21,27,37,38,53,39].

Although an SD model is an appropriate approach to simulate a complex and multidirectional dynamic system by constructing mathematic functions, it is a subjective and time-consuming operation. The causal relationships of the SD model are based on the subjective judgment of the operator, reference suggestions, data availability, and information acquisition. Thus, the simulation result will change if the operator adopts different stock and flow variables. In addition, error analysis based on historical statistical data should be evaluated to ensure that the forecasted results are accurate and efficient and that the causal relationships used are reasonable.

An SD model contains two parts. The first part is a causal–loop diagram that describes an idea, both conceptually and as a set of simplified cause–effect relationships between the different systems developed during model construction. The second part is a stock–flow diagram that represents the quantitative relationships among variables. A more detailed description follows.

3.1. Causal–loop diagram

The relationships of real urban transportation systems are not likely to be simple, but the SD model offers an opportunity to show how interrelated variables in a system affect one another by arrows. A plus or minus sign indicates the direction of the variations between two variables: the "+" sign indicates that a change in one variable causes another variable to change in the same direction, and the "−" sign indicates that one variable causes another to change in the opposite direction. Fig. 1 shows the causal–loop of the SD model for an urban transportation system (more explanation is described in Section 5).

3.2. Stock–flow diagram

A stock–flow diagram has four components: stock, flow, auxiliary variables, and arrows (Appendix A). The stock variables are represented by labeled rectangles, e.g., "individual disposable income" and "urban population." Each stock variable accumulates all the values that flow into and out of it (indicated by the thick heavy arrows pointing from and to the stock variables, such as "increases in individual disposable income") and reflects the condition within a system at a specific point in time. Stock variables can be changed only through flows. Thus, the value of the stock variable is controlled by the pipes (the thick heavy arrows with a valve in the center and a cloud symbol at the end) pointing into or out of the stock variable. A flow variable refers to the rate of changes over a certain interval of time. An auxiliary variable is an intermediate variable used to show the informational transformation process, the environmental parameter values, or the systematic test functions or values. The causal relationship between variables is depicted by the curved blue arrows.

4. Background of Kaohsiung City

The city of Kaohsiung in southwestern Taiwan comprises an area of 15,360 ha (59.3 square miles or 153.6 square kilometers). Kaohsiung City is the second largest metropolis in Taiwan and offers air, land, rail, and sea transportation. Air and sea transport traffic determines the industrial structure share and the scope of city development. The Kaohsiung Harbor is an important transport point for the Taiwan Straits and the Bashi Channel. The Kaohsiung International Airport has 12 airlines flying worldwide through 40 air routes. Kaohsiung is not only important for the import and export businesses in Taiwan but also Taiwan's industrial center because of the predominance of the international harbor and airport. Heavy industries, such as steel-making, refining, shipbuilding, and those involved in the manufacture of petrochemicals and cement, as well as two export-processing zones in Kaohsiung and neighboring NanTse have significantly accelerated the diversity of local industrial activities and turned Kaohsiung into the most important industrial and commercial center in southern Taiwan. The population of Kaohsiung rose from 1.39 million in 1990 to 1.56 million in 2013. With the urbanization and internationalization of Kaohsiung, individual disposable income has also increased: in 2013, it was 29.6% higher than in 2003, with an average annual growth rate of 2.63%.

The number of motor vehicles in the city grew at an annual rate of 1.55% over the past 10 years, reaching 1.57 million in 2013. Among the 1.57 million vehicles, 25.70% and 70.91% represent the number of private cars and the number of motorcycles, respectively. The percentages of light trucks, heavy trucks, and city buses were 2.66%, 0.71%, and 0.03%, respectively. Vehicle ownership rates for private cars and motorcycles were 259 and 715 vehicles for every 1000 people.

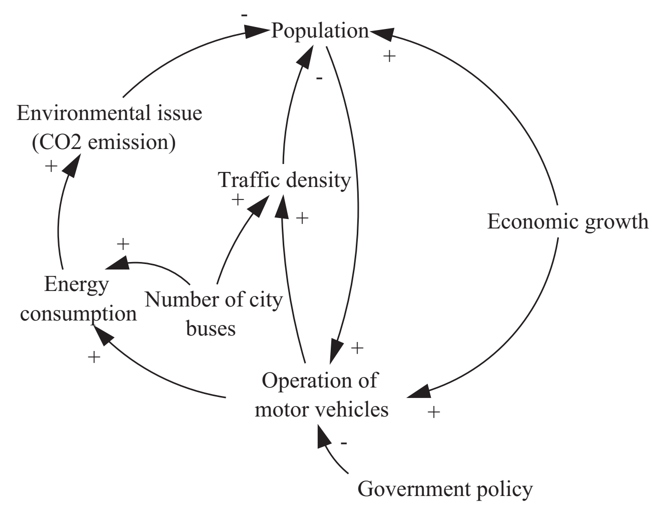

Fig. 1. Causal–loop of system dynamics model for urban transportation system.

5. Model description

In this study, the SD model includes seven subsystems: urban population, individual disposable income, private cars, motorcycles, light trucks, heavy trucks, and city buses (Appendix A). The size of the human population is the foundation of a city's development, and issues such as the growth rate in the number of motor vehicles, vehicular energy consumption, and CO_2 emissions are derivatives of the interaction between human population and economic activities. Based on this assumption, the subsystem of the transportation mode and the related variables [i.e., vehicle kilometers of travel (VKT), vehicular fuel efficiency, transfer ratio among modes, emission coefficient, and other factors] were added to the model after the dynamic behavior of urban population and individual disposable income had been determined. Furthermore, using commercial simulation software (Vensim 5; Ventana Systems, Inc., Harvard, MA), the causal relationships between the various components within the system were simulated from 1995 to 2025.

Vensim is herein used to develop, analyze, and package high-quality dynamic feedback models. Models are constructed graphically or in a text editor. Features include dynamic functions, subscripting (arrays), Monte Carlo sensitivity analysis, optimization, data handling, application interfaces, and more options. Vensim is an interactive software environment that allows the development, exploration, analysis, and optimization of simulation models [64].

Fig. 1 shows the causal–loop of the SD model for the urban transportation system. Economic growth increases the number of motor vehicles and attracts more migrants from other cities. The amount of energy requirement and CO_2 emission will rise as the number of motor vehicles increases. However, the increase in the amount of CO_2 will reduce the growth rate of the urban population. Simultaneously, the number of motor vehicles will decrease with the reduction of urban population. Economic development affects population, wherein economic growth leads to an increased number of vehicles [15]. Therefore, we assume that economic growth positively affects the number of motor vehicles and population growth.

Moreover, fuel use can positively influence CO_2 emission [15]. We thus assume that energy consumption can positively affect environmental issues (CO_2 emission). The number of private vehicles and buses positively affects traffic congestion and energy consumption [17]. We assume that the number of city buses and the number of motor vehicles both positively affect traffic density and energy consumption. In addition, the tax policy on fuel can reduce the fuel consumption of motor vehicles, leading to reduced CO_2 emissions [65].

Traffic density is also a significant and robust predictor of habitant survival, more so than ambient air quality [66]. We assume the association between traffic density and CO_2 emission as well as the existence of the negative effect of traffic density on population growth. In Fig. 1, the *p* values of each variable are less than 0.05, which indicates statistical significance.

In Kaohsiung, one out of two residents own motorcycles, whereas one out of three residents own cars. These residents are accustomed to the convenience, independence, and flexibility that are provided by private vehicles. Energy consumption and CO_2 emission issues are mainly derived from private vehicles. Therefore, we mainly focused on the influence of private vehicles in our case. Less than 1% of the population uses the taxi service because of the higher charge compared with other forms of transportation [67]. Moreover, the Uber platform service is not currently allowed to be officially operated by the authority, and this service is thus less popular in Kaohsiung. Road motor vehicles account for the relative large CO_2 emission and energy consumption (95.75%) compared with the metro system that, having its own electrification system, supplies electric power for movement without a local fuel supply [68]. Therefore, the other possible variables, including vehicle technology, emission legislation, and automobile park age, are not currently emergent in this stage for Kaohsiung and can be further examined in future studies.

Contributions of our study include the use of a systematic approach to examine energy and CO_2 emission reduction by implementing various transport policies in the urban transportation context. Adopting this proposed approach is useful in other cities, and their specific features should be considered to develop an appropriate model to understand the various effects of policies. We considered two equations to explain the effects of individual disposable income and an economically active population on the number of motorcycles in the main text.

Linear least-squares regression analysis was performed to reflect the effects of individual disposable income and an economically active population on the variation of private cars and motorcycles. The equations of the simple linear regression are expressed as follows:

$$\begin{aligned}\text{Number of motorcycles} = & -1{,}698{,}892.93 + 1.88 \\ & \times \text{size of economically active population} \\ & + 1.35 \times \text{individual disposable income}, \\ & R^2 = 0.98,\end{aligned}$$

$$\begin{aligned}\text{Number of private cars} = & -305{,}641 + 0.43 \\ & \times \text{size of economically active population} \\ & + 0.52 \times \text{individual disposable income}, \\ & R^2 = 0.92.\end{aligned}$$

MOTC surveyed fuel price increases on mode choice in 2008 because the price of crude oil increased rapidly since the beginning of 2007. Therefore, the effect of fuel prices on the variations in the number of private vehicles was simulated according to the growth rate of fuel price and the survey data provided by the authoritative report. For example, the equation of the decrease in private cars operating by the increase in fuel price can be measured as follows.

The SD model is an approach to understand the behavior of complex systems over time. SD can estimate fuel price while considering the time effect. Therefore, we used DELAY1I to consider this time effect. This delay function can be used in the equation as with normal SD modeling. This function is frequently used in SD for modeling postponed effects. We adopted the delay function to model the effect of fuel price on the relationship between the decrease in private car use and the increase in fuel price. The postponed effects of fuel price are considered in our model by using the delay function.

The decrease in private car use is associated with the increased fuel price that can be estimated by the following formula:

$$\begin{aligned}\text{Decrease in private car use} = & \text{ private cars} \times (33.8\%/13.45\% \\ & * (\text{Fuel price} - \text{DELAY1I} \\ & (\text{Fuel price}, 1, 1))/\text{DELAY1I} \\ & (\text{Fuel price}, 1, 1)),\end{aligned}$$

where 33.8% is the probability that the number of private cars that will decrease when fuel prices increase by 13.45%

5.1. Urban population subsystem

The size of the human population not only reflects the scale of urban development but also drives the transport demand. The size of the urban population was selected as a stock variable, and natural changes in the population and changes caused by social migration were selected as flow variables because the size of the human population is affected by both natural changes in the population and changes caused by social migration. The formulation of the natural changes in the population is expressed as the product of the human population and the natural population ratio per year, where the natural population ratio is adopted from the Statistical Yearbook of Kaohsiung City [69]. In addition, individual disposable income, traffic density, and aggregate CO_2 emissions were considered in this study to control the variations in social migration.

5.2. Individual disposable income subsystem

Economic performance is an important index for evaluating the competitiveness of a city. If individual disposable income grows, then the number of migrants and the number of motor vehicles increase; otherwise, these values decrease. Therefore, individual disposable income was chosen as a stock variable dependent on the growth ratio of the GDP [70]. Furthermore, the prediction of the Global Insight database [71] on the future GDP growth ratio of Taiwan was reduced by 0.5% to avoid an overestimate.

5.3. Private car subsystem

Several studies have indicated that the number of motor vehicles, as well as the number of new vehicles purchased, is closely associated with economic growth and population [72–76]. We analyzed this subsystem to evaluate the effect of the changes in the level of the individual disposable income and in the size of the economically active population on the variation of the number of private cars. According to the 2008 survey of MOTC, the number of private cars driven decreased by 33.8% after fuel prices increased by 13.45%. Thus, the effect of fuel prices on the variations of automobile use was also considered because of the rise in the price of crude oil, which has almost doubled since the beginning of 2007.

The auxiliary variable energy consumption by private cars was calculated by multiplying the number of private cars, VKT, and the inverse of the average vehicular fuel efficiency (km/l), where the value of VKT and fuel efficiency were obtained from the Taiwan Emissions Database System (TEDS) 8.1. Estimations of energy-related CO_2 emissions were determined by the product of vehicular energy consumption and its emissions coefficient, published by the Intergovernmental Panel on Climate Change (IPCC).

The reason for the omission of electric vehicles in the model is that the electric vehicle technology in Taiwan is currently in the early stages. Moreover, the central and city government did not provide strong incentives, including direct subsidies, fiscal reduction, and regulatory policy, to increase the use of electric vehicles. In terms of user perspectives, short driving range and slow speed of electric vehicles lead to the less popularity of electric vehicles in Taiwan. Even when considering improvements in the fuel economy of vehicles, we observe that the dense traffic in Kaohsiung requires the car to stop and go frequently. Thus, fuel economy improvements of vehicles are not significant in the local context. Therefore, the policy imposing fuel tax seems to remain useful in Kaohsiung.

The Kaohsiung Mass Rapid Transit (KMRT) system opened for service in 2008. The system not only provided a new lifestyle for citizens but also reduced the number of private vehicles used for commuting to work. To reflect the influence of the KMRT on vehicular fuel consumption, the transit system was also incorporated into this subsystem. Specifically, the decrease in the number of commuters who switched from using private cars to using the KMRT was estimated by combining the average number of passengers carried by the KMRT, the average number of kilometers per passenger trip, the average number of occupants per automobile, and the transfer ratio. Thus, the effect on vehicular energy consumption was calculated by multiplying the decrease in private car use and the average vehicular fuel efficiency of private cars.

5.4. Motorcycle subsystem

Motorcycles accounted for 70.91% of the 1.57 million registered vehicles in Kaohsiung in 2013; motorcycles provide greater mobility and are less expensive than other types of motor vehicles. In this study, the increase in the number of motorcycles was primarily driven by individual disposable income and the size of the economically active population [76–79]. As mentioned previously, fluctuations in fuel prices affect the number of private vehicles driven and the distances that they are driven. Hence, the effect of fuel prices on mode choice and mode transfer was further incorporated into the model through the operation of flow variables: mode transfer from private cars and the decrease in motorcycle use by fuel price increase (Appendix A). In addition, the formulation of vehicular fuel consumption and associated CO_2 emissions derived from the number of motorcycles was the same as that from the number of private cars, but the average occupancy rate (the number of passengers per motorcycle) and the transfer ratio between the KMRT and motorcycles were different.

5.5. Heavy truck subsystem

As the world's thirteenth (2013) largest international port and the largest industrial center in Taiwan, the city of Kaohsiung is important both for freight transportation and for industrial and commercial activities. Many cargos and freight need to be transported to the northern metropolitan areas because Kaohsiung is located in the south of Taiwan and is a harbor city. After exiting the harbor, some heavy trucks need to pass the city area to the highway system. This phenomenon is reason for the consideration of heavy-duty trucks in our model.

The dynamic behavior of this subsystem is analyzed through the operation of a stock variable: the number of heavy trucks; a flow variable: the increase in the number of heavy trucks; and two auxiliary variables: the effect of GDP on heavy truck function and the growth ratio of GDP. The growth of freight transport demand is primarily a consequence of the growth of economic activity [80–83,5]. Hence, the growth of GDP was selected as the motivational factor in this study to reflect the variation in the number of heavy trucks. The auxiliary variable effect of GDP on the heavy truck function was constructed based on the concept of a table function, which is a graphical tool that captures the causal and non-linear relationship between two variables.

5.6. Light truck subsystem

Business activities and commercial services, such as food markets, street vendors, bazaars, superstores, cargo carriers, and other such entities, are closely linked with the number of light trucks. Thus, GDP growth rate was selected as an auxiliary variable to reflect the effect of economic development. In this subsystem, the number of light trucks was defined as a stock variable, and the change in the number of light trucks was defined as a flow variable inspired by the growth of the GDP by constructing a table function. The formula used to calculate the aggregate energy demand of light trucks was the same as the one used for heavy trucks.

5.7. City bus subsystem

Despite the 7.2% modal share of the city buses, they were incorporated into the model to reflect a complete picture of the transportation system in Kaohsiung City. In this subsystem, the number of city buses was selected as a stock variable, and its value is influenced by the flow variable the annual change in the number of city buses. The historical value of auxiliary variables and the government-set target determined the number of city buses through the feedback loops. To improve the quality of the city bus service, the city bus operation agencies added 156 buses since 2008 by adjusting the frequency and routes of city buses, releasing 30 government-run routes to private enterprises, enhancing real-time bus information, and upgrading the service quality.

6. Discussion of analytical results

6.1. Reference model

To detect the effectiveness of the proposed model, the simulation results were validated by comparing the estimated values with their historical trends [21,27,37,38,53,39]. The examined

Table 1
The validation of simulation results: Part 1.

Year	Urban population			Individual disposable income (NT$)			Motorcycles			Passenger cars		
	Actual value	Simulated result	Residual values (%)	Actual value	Simulated result	Residual values (%)	Actual value	Simulated result	Residual values (%)	Actual value	Simulated result	Residual values (%)
1995	1,426,035	1,426,040	0.00	255,929	255,929	0.00	588,426	588,426	0.00	278,590	278,590	0.00
1996	1,433,621	1,439,090	−0.38	270,275	271,752	−0.55	647,941	602,708	6.98	295,025	283,145	4.03
1997	1,436,142	1,454,323	−1.27	288,305	288,448	−0.05	700,518	650,466	7.14	300,179	297,020	1.05
1998	1,462,302	1,468,826	−0.45	301,590	301,942	−0.12	745,528	714,053	4.22	318,174	314,084	1.29
1999	1,475,505	1,476,554	−0.07	309,552	310,164	−0.20	741,687	766,563	−3.35	301,730	326,845	−8.32
2000	1,490,560	1,481,403	0.61	313,799	316,929	−1.00	785,663	801,501	−2.02	320,593	335,125	−4.53
2001	1,494,457	1,484,853	0.64	326,691	324,545	0.66	808,038	826,071	−2.23	329,066	341,263	−3.71
2002	1,509,510	1,488,443	1.40	302,490	334,275	−10.51	826,460	851,880	−3.08	331,513	348,676	−5.18
2003	1,509,350	1,491,157	1.21	307,249	336,802	−9.62	841,240	868,862	−3.28	341,477	352,785	−3.31
2004	1,512,677	1,491,496	1.40	330,895	343,697	−3.87	871,683	886,189	−1.66	354,929	357,886	−0.83
2005	1,510,649	1,492,884	1.18	344,032	348,949	−1.43	902,912	908,534	−0.62	370,617	365,087	1.49
2006	1,514,706	1,494,872	1.31	352,882	355,995	−0.88	928,208	924,031	0.45	375,430	369,368	1.61
2007	1,520,555	1,494,660	1.70	355,196	355,052	0.04	938,148	936,991	0.12	372,559	368,956	0.97
2008	1,525,642	1,497,939	1.82	362,358	358,638	1.03	983,869	955,808	2.85	368,840	372,420	−0.97
2009	1,527,914	1,499,831	1.84	369,521	362,009	2.03	1,010,944	970,003	4.05	367,265	375,674	−2.29
2010	1,530,182	1,498,637	2.06	376,683	365,191	3.05	1,038,019	987,035	4.91	370,895	378,744	−2.12
2011	1,551,565	1,496,759	3.53	383,845	368,205	4.07	1,065,094	1,000,426	6.07	392,579	381,651	2.78
2012	1,558,515	1,497,475	3.92	391,007	371,070	5.10	1,092,169	1,023,412	6.30	399,082	384,411	3.68
2013	1,565,465	1,495,217	4.49	398,170	373,801	6.12	1,119,244	1,052,700	5.95	405,585	387,041	4.57

Table 2
The validation of simulation results: Part 2.

Year	Light trucks			Heavy trucks			City buses		
	Actual value	Simulated result	Residual values (%)	Actual value	Simulated result	Residual values (%)	Actual value	Simulated result	Residual values (%)
1995	31,027	31,027	0.00	12,124	12,124	0.00	470	470	0.00
1996	32,078	32,228	−0.47	11,980	12,223	−2.03	465	470	−1.08
1997	30,734	33,338	−8.47	11,826	12,275	−3.80	480	470	2.08
1998	32,385	32,880	−1.53	12,054	12,315	−2.17	495	473	4.44
1999	28,825	32,680	−13.37	11,928	12,298	−3.10	473	475	−0.42
2000	31,354	32,806	−4.63	12,560	12,624	−0.51	472	475	−0.64
2001	32,614	34,103	−4.57	12,567	12,846	−2.22	454	473	−4.19
2002	32,304	35,504	−9.91	12,439	12,958	−4.17	432	468	−8.33
2003	33,623	36,833	−9.55	12,665	13,080	−3.28	427	461	−7.96
2004	35,210	37,262	−5.83	12,950	13,153	−1.57	438	455	−3.88
2005	37,114	36,684	1.16	13,119	13,176	−0.43	450	453	−0.67
2006	38,434	38,094	0.88	13,137	13,291	−1.17	435	451	−3.68
2007	38,645	38,689	−0.11	12,622	13,197	−4.56	424	440	−3.87
2008	38,779	39,224	−1.15	12,430	13,062	−5.09	422	432	−2.46
2009	39,808	39,664	0.36	11,840	12,836	−8.41	418	423	−1.30
2010	39,773	39,990	−0.54	12,132	12,505	−3.08	413	414	−0.16
2011	40,565	40,183	0.94	11,627	12,058	−3.70	408	403	1.23
2012	41,273	40,225	2.54	11,392	11,481	−0.78	404	391	3.11
2013	41,982	40,097	4.49	11,248	10,762	4.32	399	379	5.00

variables included urban population, individual disposable income, motorcycles, private cars, light trucks, and heavy trucks (Tables 1 and 2). The model developed in this study appears to be reasonable because the relative errors were all less than 10% [38].

The behavior analyzed using the reference model was simulated from 1995 to 2025 based on existing socioeconomic conditions and policies. The decline in the natural population of Taiwan for the past 19 years has lowered the growth rate of the urban population. A decreasing natural population is both the current and the future trend in most developed countries. Our simulation predicted that in 2025, the population of Kaohsiung would gradually decline to 1.44 million, 54,128 fewer than today's population (Table 3). Global Insight projected that the annual economic growth rate of Taiwan in 2015 would be 0.07% higher than it is in 2014. However, in the next 11 years, the growth rate of the GDP of Taiwan is expected to be lower than those during the past two decades. Given this slowdown in economic activity, individual disposable income will grow at only a moderate rate. For example, our simulation predicts that the annual growth rate of individual disposable income from 2014 to 2025 will be 1.95%, which is lower than previous rates. Our simulation also predicts that this income will reach NT$ 539,977 in 2025 (1 US dollar = 30 NT$).

The simulation indicated that the number of motorcycles will increase by 68,659 vehicles between 2014 and 2025, which is a growth rate of 0.57% per year. This growth in the number of motorcycles and private cars is attributed to the size of the economically active population, the level of individual disposable income, and the variation of fuel prices. Similarly, the simulation estimated that the number of private cars in 2025 will be 26,570, a decrease of 9.23% over 11 years. Economic weaknesses will also cause a slow growth rate (1.57%) in the number of heavy trucks until 2025, when 17,427 of such vehicles will show an increase of 18.65% compared with the number in 2014. The effect of a lower GDP growth rate on the number of light trucks will be limited because they are used for daily commodity exchanges and business transactions.

Table 3
Number of motor vehicles, energy consumption, CO_2 consumption and toxic emission simulation results.

Year	Urban population	individual disposable income (NT$)	Motorcycles	Passenger cars	Light trucks	Heavy trucks	City buses	Number of motor vehicles	Energy consumption (kl)	CO_2 emissions (metric tons)	CO emissions (kg)	NMHC emissions (kg)	NOx emissions (kg)
1995	1,426,040	255,929	588,426	278,590	31,027	12,124	470	910,637	783,504	1,929,615	7,463,659	1,730,760	9,872,934
1996	1,439,090	271,752	602,708	283,145	32,228	12,223	470	930,774	796,358	1,960,680	7,586,106	1,759,155	10,034,907
1997	1,454,323	288,448	650,466	297,020	33,338	12,275	470	993,569	822,604	2,021,100	7,836,126	1,817,132	10,365,633
1998	1,468,826	301,942	714,053	314,084	32,880	12,315	473	1,073,804	849,958	2,082,440	8,096,700	1,877,557	10,710,321
1999	1,476,554	310,164	766,563	326,845	32,680	12,298	475	1,138,861	870,432	2,127,943	8,291,735	1,922,784	10,968,314
2000	1,481,403	316,929	801,501	335,125	32,806	12,624	475	1,182,530	893,136	2,182,740	8,508,014	1,972,937	11,254,407
2001	1,484,853	324,545	826,071	341,263	34,103	12,846	473	1,214,756	912,636	2,230,213	8,693,771	2,016,013	11,500,126
2002	1,488,443	334,275	851,880	348,676	35,504	12,958	468	1,249,487	931,062	2,274,058	8,869,297	2,056,716	11,732,312
2003	1,491,157	336,802	868,862	352,785	36,833	13,080	461	1,272,021	944,712	2,307,236	8,999,327	2,086,869	11,904,316
2004	1,491,496	343,697	886,189	357,886	37,262	13,153	455	1,294,946	955,686	2,333,034	9,103,865	2,111,110	12,042,599
2005	1,492,884	348,949	908,534	365,087	36,684	13,176	453	1,323,934	965,521	2,354,782	9,197,553	2,132,836	12,166,530
2006	1,494,872	355,995	924,031	369,368	38,094	13,291	451	1,345,235	979,254	2,388,182	9,328,374	2,163,172	12,339,580
2007	1,494,660	365,325	936,991	373,080	37,336	13,247	448	1,361,103	981,810	2,392,671	9,352,722	2,168,818	12,371,788
2008	1,497,939	375,832	955,808	299,812	37,715	13,362	454	1,307,151	911,822	2,237,642	8,686,016	2,014,215	11,489,869
2009	1,499,831	383,174	970,003	253,487	39,279	13,571	478	1,276,817	874,211	2,157,461	8,327,734	1,931,132	11,015,933
2010	1,498,637	390,530	987,035	251,380	40,909	13,786	497	1,293,606	882,545	2,180,301	8,407,124	1,949,542	11,120,950
2011	1,496,759	401,348	1,000,426	255,590	42,866	14,004	589	1,313,474	901,266	2,227,274	8,585,460	1,990,897	11,356,853
2012	1,497,475	417,694	1,023,412	265,753	45,193	14,206	664	1,349,228	927,998	2,292,236	8,840,109	2,049,948	11,693,703
2013	1,495,217	429,345	1,052,700	278,301	47,359	14,430	725	1,393,514	958,027	2,364,577	9,126,165	2,116,282	12,072,098
2014	1,490,785	436,733	1,071,850	287,740	49,364	14,688	775	1,424,417	983,485	2,426,841	9,368,678	2,172,518	12,392,894
2015	1,486,456	443,939	1,080,210	291,416	51,418	14,947	815	1,438,806	1,001,368	2,472,136	9,539,032	2,212,022	12,618,238
2016	1,482,549	451,569	1,085,378	290,232	53,556	15,204	848	1,445,218	1,013,831	2,505,286	9,657,754	2,239,553	12,775,284
2017	1,478,468	459,564	1,090,760	287,917	55,782	15,460	875	1,450,794	1,025,301	2,536,237	9,767,017	2,264,890	12,919,818
2018	1,474,231	468,138	1,096,617	285,350	58,098	15,711	897	1,456,672	1,036,622	2,566,839	9,874,861	2,289,898	13,062,474
2019	1,469,675	477,090	1,102,938	282,933	60,509	15,960	915	1,463,256	1,048,354	2,598,407	9,986,620	2,315,814	13,210,309
2020	1,464,834	486,449	1,109,075	279,804	63,019	16,209	929	1,469,036	1,059,522	2,628,764	10,093,007	2,340,484	13,351,037
2021	1,459,864	496,318	1,114,968	275,626	65,632	16,454	941	1,473,621	1,069,581	2,656,673	10,188,829	2,362,704	13,477,790
2022	1,454,659	506,672	1,121,173	271,440	68,351	16,697	951	1,478,611	1,079,883	2,685,176	10,286,965	2,385,462	13,607,606
2023	1,449,102	517,429	1,127,576	267,457	71,182	16,939	959	1,484,112	1,090,697	2,714,912	10,389,980	2,409,350	13,743,873
2024	1,443,130	528,571	1,133,950	263,711	74,129	17,182	965	1,489,936	1,102,056	2,745,966	10,498,185	2,434,442	13,887,008
2025	1,436,657	539,977	1,140,509	261,170	77,198	17,427	970	1,497,274	1,115,078	2,780,882	10,622,233	2,463,207	14,051,098

Table 4
Number of motor vehicles, energy consumption and CO_2 consumption simulation results for different policies.

Year	Fuel tax			Motorcycle parking management			Free bus service			Synthetic policy		
	Number of motor vehicles (vehicles)	Energy consumption (kl)	CO_2 emission (metric tons)	Number of motor vehicles (vehicles)	Energy consumption (kl)	CO_2 emission (metric tons)	Number of motor vehicles (vehicles)	Energy consumption (kl)	CO_2 emission (metric tons)	Number of motor vehicles (vehicles)	Energy consumption (kl)	CO_2 emission (metric tons)
1995	910,637	783,504	1,929,615	910,637	783,504	1,929,615	910,637	783,504	1,929,615	910,637	783,504	1,929,615
1996	930,774	796,358	1,960,680	930,774	796,358	1,960,680	930,774	796,358	1,960,680	930,774	796,358	1,960,680
1997	993,569	822,604	2,021,100	993,569	822,604	2,021,100	993,569	822,604	2,021,100	993,569	822,604	2,021,100
1998	1,073,804	849,958	2,082,440	1,073,804	849,958	2,082,440	1,073,804	849,958	2,082,440	1,073,804	849,958	2,082,440
1999	1,138,861	870,432	2,127,943	1,138,861	870,432	2,127,943	1,138,861	870,432	2,127,943	1,138,861	870,432	2,127,944
2000	1,182,530	893,136	2,182,740	1,182,530	893,136	2,182,740	1,182,530	893,136	2,182,740	1,182,530	893,136	2,182,740
2001	1,214,756	912,636	2,230,213	1,214,756	912,636	2,230,213	1,214,756	912,636	2,230,213	1,214,756	912,636	2,230,213
2002	1,249,487	931,062	2,274,058	1,249,487	931,062	2,274,058	1,249,487	931,062	2,274,058	1,249,487	931,062	2,274,058
2003	1,272,021	944,712	2,307,236	1,272,021	944,712	2,307,236	1,272,021	944,712	2,307,236	1,272,021	944,712	2,307,236
2004	1,294,946	955,686	2,333,034	1,294,946	955,686	2,333,034	1,294,946	955,686	2,333,034	1,294,946	955,686	2,333,034
2005	1,323,934	965,521	2,354,782	1,323,934	965,521	2,354,782	1,323,934	965,521	2,354,782	1,323,934	965,521	2,354,783
2006	1,345,235	979,254	2,388,182	1,345,235	979,254	2,388,182	1,345,235	979,254	2,388,182	1,345,235	979,255	2,388,182
2007	1,361,103	981,810	2,392,671	1,361,103	981,810	2,392,671	1,361,103	981,810	2,392,671	1,361,103	981,810	2,392,671
2008	1,307,151	911,822	2,237,642	1,307,198	908,169	2,229,460	1,307,151	911,822	2,237,642	1,307,198	908,169	2,229,460
2009	1,273,963	871,833	2,152,134	1,000,320	827,970	2,053,882	1,276,817	874,211	2,157,461	990,890	825,560	2,048,484
2010	1,278,535	870,385	2,153,061	1,012,833	831,280	2,065,466	1,291,347	881,976	2,179,024	988,829	818,030	2,035,787
2011	1,278,280	872,891	2,163,715	1,029,352	849,178	2,110,597	1,309,079	900,168	2,224,815	983,435	818,672	2,042,264
2012	1,292,457	882,159	2,189,555	1,058,705	874,663	2,172,765	1,342,702	926,368	2,288,585	989,499	825,708	2,063,106
2013	1,314,751	894,514	2,222,308	1,094,662	903,172	2,241,701	1,384,777	955,838	2,359,673	1,002,048	835,694	2,090,550
2014	1,323,407	902,449	2,245,319	1,120,106	927,497	2,301,427	1,413,388	980,709	2,420,623	1,004,156	841,725	2,109,298
2015	1,316,466	904,569	2,255,307	1,132,030	944,587	2,344,947	1,425,483	998,009	2,464,611	994,049	842,380	2,116,003
2016	1,302,815	904,093	2,259,473	1,136,815	956,284	2,376,381	1,429,655	1,009,917	2,496,518	978,618	840,620	2,117,293
2017	1,288,996	904,419	2,265,461	1,140,739	966,970	2,405,577	1,433,017	1,020,847	2,526,262	963,397	839,776	2,120,661
2018	1,276,396	906,079	2,274,421	1,144,851	977,489	2,434,380	1,436,694	1,031,640	2,555,679	949,530	840,351	2,127,191
2019	1,265,460	909,342	2,287,019	1,149,546	988,403	2,464,117	1,441,081	1,042,850	2,586,078	937,342	842,590	2,137,495
2020	1,261,354	917,045	2,309,616	1,153,471	998,741	2,492,614	1,444,689	1,053,512	2,615,302	931,011	849,195	2,157,633
2021	1,265,853	929,702	2,343,343	1,156,253	1,007,691	2,518,038	1,447,130	1,063,085	2,642,122	931,832	860,328	2,187,945
2022	1,273,165	944,146	2,381,126	1,159,373	1,016,876	2,544,041	1,449,970	1,072,906	2,669,549	935,116	873,237	2,222,291
2023	1,281,495	959,419	2,420,850	1,162,956	1,026,571	2,571,270	1,453,349	1,083,255	2,698,243	939,358	886,991	2,258,610
2024	1,290,273	975,233	2,461,882	1,166,870	1,036,817	2,599,830	1,457,076	1,094,163	2,728,285	944,013	901,282	2,296,233
2025	1,300,117	992,053	2,505,306	1,172,267	1,048,746	2,632,300	1,462,290	1,106,724	2,762,169	949,570	916,558	2,336,198

Table 5
Toxic emission simulation results for different policies.

Year	Fuel tax			Motorcycle parking management			Free bus service			Synthetic policy		
	CO emission (kg)	NMHC emission (kg)	NOx emission (kg)	CO emission (kg)	NMHC emission (kg)	NOx emission (kg)	CO emission (kg)	NMHC emission (kg)	NOx emission (kg)	CO emission (kg)	NMHC emission (kg)	NOx emission (kg)
1995	7,463,659	1,730,760	9,872,934	7,463,659	1,730,760	9,872,934	7,463,659	1,730,760	9,872,934	7,463,659	1,730,760	9,872,934
1996	7,586,106	1,759,155	10,034,907	7,586,106	1,759,155	10,034,907	7,586,106	1,759,155	10,034,907	7,586,106	1,759,155	10,034,907
1997	7,836,126	1,817,132	10,365,633	7,836,126	1,817,132	10,365,633	7,836,126	1,817,132	10,365,633	7,836,126	1,817,132	10,365,633
1998	8,096,700	1,877,557	10,710,321	8,096,700	1,877,557	10,710,321	8,096,700	1,877,557	10,710,321	8,096,700	1,877,557	10,710,321
1999	8,291,735	1,922,784	10,968,314	8,291,735	1,922,784	10,968,314	8,291,735	1,922,784	10,968,314	8,291,735	1,922,784	10,968,314
2000	8,508,014	1,972,937	11,254,407	8,508,014	1,972,937	11,254,407	8,508,014	1,972,937	11,254,407	8,508,014	1,972,937	11,254,407
2001	8,693,771	2,016,013	11,500,126	8,693,771	2,016,013	11,500,126	8,693,771	2,016,013	11,500,126	8,693,771	2,016,013	11,500,126
2002	8,869,297	2,056,716	11,732,312	8,869,297	2,056,716	11,732,312	8,869,297	2,056,716	11,732,312	8,869,297	2,056,716	11,732,312
2003	8,999,327	2,086,869	11,904,316	8,999,327	2,086,869	11,904,316	8,999,327	2,086,869	11,904,316	8,999,327	2,086,869	11,904,316
2004	9,103,865	2,111,110	12,042,599	9,103,865	2,111,110	12,042,599	9,103,865	2,111,110	12,042,599	9,103,865	2,111,110	12,042,599
2005	9,197,553	2,132,836	12,166,530	9,197,553	2,132,836	12,166,530	9,197,553	2,132,836	12,166,530	9,197,553	2,132,836	12,166,530
2006	9,328,374	2,163,172	12,339,580	9,328,374	2,163,172	12,339,580	9,328,374	2,163,172	12,339,580	9,328,383	2,163,174	12,339,592
2007	9,352,722	2,168,818	12,371,788	9,352,722	2,168,818	12,371,788	9,352,722	2,168,818	12,371,788	9,352,722	2,168,818	12,371,788
2008	8,686,016	2,014,215	11,489,869	8,651,218	2,006,145	11,443,838	8,686,016	2,014,215	11,489,869	8,651,218	2,006,145	11,443,838
2009	8,305,081	1,925,879	10,985,968	7,887,242	1,828,986	10,433,250	8,327,734	1,931,132	11,015,933	7,864,285	1,823,662	10,402,882
2010	8,291,288	1,922,680	10,967,721	7,918,773	1,836,298	10,474,959	8,401,703	1,948,285	11,113,780	7,792,554	1,807,028	10,307,996
2011	8,315,160	1,928,216	10,999,299	8,089,270	1,875,834	10,700,492	8,575,000	1,988,471	11,343,017	7,798,669	1,808,446	10,316,086
2012	8,403,447	1,948,689	11,116,086	8,332,040	1,932,131	11,021,628	8,824,582	2,046,347	11,673,163	7,865,694	1,823,989	10,404,747
2013	8,521,140	1,975,981	11,271,771	8,603,616	1,995,107	11,380,870	9,105,313	2,111,446	12,044,515	7,960,821	1,846,048	10,530,580
2014	8,596,729	1,993,510	11,371,760	8,835,336	2,048,841	11,687,390	9,342,234	2,166,386	12,357,914	8,018,272	1,859,371	10,606,577
2015	8,616,924	1,998,193	11,398,474	8,998,136	2,086,593	11,902,741	9,507,034	2,204,602	12,575,911	8,024,512	1,860,817	10,614,830
2016	8,612,390	1,997,141	11,392,476	9,109,561	2,112,431	12,050,135	9,620,469	2,230,907	12,725,964	8,007,746	1,856,930	10,592,653
2017	8,615,495	1,997,862	11,396,584	9,211,356	2,136,037	12,184,789	9,724,589	2,255,051	12,863,693	7,999,706	1,855,065	10,582,017
2018	8,631,309	2,001,529	11,417,501	9,311,560	2,159,273	12,317,339	9,827,403	2,278,893	12,999,696	8,005,184	1,856,335	10,589,263
2019	8,662,392	2,008,736	11,458,619	9,415,527	2,183,382	12,454,866	9,934,189	2,303,656	13,140,953	8,026,512	1,861,281	10,617,477
2020	8,735,771	2,025,752	11,555,684	9,514,007	2,206,219	12,585,135	10,035,755	2,327,208	13,275,305	8,089,432	1,875,872	10,700,706
2021	8,856,341	2,053,712	11,715,175	9,599,264	2,225,989	12,697,914	10,126,948	2,348,355	13,395,934	8,195,485	1,900,465	10,840,993
2022	8,993,935	2,085,619	11,897,184	9,686,761	2,246,279	12,813,654	10,220,503	2,370,049	13,519,689	8,318,456	1,928,981	11,003,659
2023	9,139,425	2,119,357	12,089,639	9,779,115	2,267,695	12,935,821	10,319,087	2,392,910	13,650,096	8,449,476	1,959,363	11,176,974
2024	9,290,070	2,154,290	12,288,911	9,876,719	2,290,329	13,064,931	10,422,997	2,417,006	13,787,548	8,585,612	1,990,932	11,357,054
2025	9,450,297	2,191,445	12,500,860	9,990,354	2,316,680	13,215,248	10,542,653	2,444,753	13,945,829	8,731,132	2,024,677	11,549,547

The simulation showed that the number of light trucks will have grown an average of 4.15% per year and will have reached 77,198 vehicles in 2025. After 2014, the aggregate energy consumed by motor vehicles will increase by 1.15% until 2025. The aggregate increase in CO_2 emissions will be nearly 354,041 metric tons between 2014 and 2025, which is 14.59% higher than the emission level in 2014.

Most of our simulated results have an estimation error lower than 5% except for rare cases. Therefore, the prediction capability of our model is acceptable [38]. The reason for the main percentage errors concentrated between 1999 and 2003 may be the Severe Acute Respiratory Syndrome (SARS) outbreak in Taiwan between 2002 and 2003. SARS caused widespread social disruption and economic losses, and its economic effect has been considerable in Taiwan. Moreover, after Taiwan's first experience of party alternation in 2000, the government system experienced instability in the early stages that led to the negative effect on economic propensity and motor-vehicle growth. These major unusual events caused the disturbance in our model predictions during this period.

We failed to fully understand the real effect of CO_2 emission and energy use reduction under various transportation policies because the data were limited. To demonstrate the accuracy of our proposed model, a comparison is performed between real data from 2013 to 2014 and the estimated number of motor vehicles in the reference model during the same period, after a free bus policy was implemented in 2013. The deviation between simulated data and real data is within 5%, which is reasonable [38]. The reason for the reduced population in 2007 can be that the increasing labor costs have encouraged numerous manufacturers to leave Kaohsiung, which has reduced the number of residents in the city.

6.2. Policy analysis

Among all strategies for sustainable transport policy, the implementation of programs including those that encourage the use of the public transportation system using benefits, such as subsidies, free transfers, or transfer discounts, and deterrents (e.g., restraining the use of private vehicles by parking management and levying taxes on fuel oil), is mostly discussed and encouraged in Taiwan. Furthermore, the Taiwanese government is considering an additional NT$ 2.5 per liter tax on fuel prices to reflect social justice and the user-pays principle and to restrain the use of private vehicles. Thus, based on the various assumptions and the past trends of the variables in the reference model, the policies including fuel tax, motorcycle parking management, free bus service, and synthetic policy are discussed in this study to explore their energy-saving and CO_2-emission-reducing potential (see Tables 4 and 5).

We analyzed three scenarios considering including low, medium, and high oil price in our revised paper (see Tables 6–9). We used the average oil price to represent the medium price; high oil price can be estimated by the average oil price plus one standard deviation of oil price. Lastly, low oil price can be estimated by the average oil price minus one standard deviation of oil price.

This study examines the appropriate urban transportation policies that mitigate a global warming effect mainly from CO_2 emission. Nitrous oxides (NOx), hydrocarbons (HC), CO, and soot emissions affect the health of urban populations. However, due to data limitation, we assume that the relationship between CO_2 emission and NOx, HC, CO, and soot emissions is of proportional equivalence. The estimated NOx, HC, CO, and soot emissions are included in. The detailed study regarding the precise toxicity of the emissions in the model can be further examined in future

Table 6
Fuel Tax policy's effect under low/medium/high oil price scenarios.

Year	Fuel tax														
	Energy consumption (kl)			CO_2 emission (metric tons)			CO emission (kg)			NMHC emission (kg)			NOx emission (kg)		
	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
1995	787,083	783,504	763,269	1,938,430	1,929,615	1,879,780	7,497,756	7,463,659	7,270,901	1,738,667	1,730,760	1,686,061	9,918,037	9,872,934	9,617,954
1996	799,996	796,358	775,791	1,969,637	1,960,680	1,910,043	7,620,762	7,586,106	7,390,186	1,767,191	1,759,155	1,713,723	10,080,750	10,034,907	9,775,744
1997	826,362	822,604	801,359	2,030,333	2,021,100	1,968,903	7,871,924	7,836,126	7,633,748	1,825,434	1,817,132	1,770,203	10,412,987	10,365,633	10,097,928
1998	853,841	849,958	828,007	2,091,953	2,082,440	2,028,659	8,133,689	8,096,700	7,887,593	1,886,135	1,877,557	1,829,067	10,759,249	10,710,321	10,433,714
1999	874,408	870,432	847,952	2,137,664	2,127,943	2,072,986	8,329,615	8,291,735	8,077,591	1,931,568	1,922,784	1,873,126	11,018,421	10,968,314	10,685,044
2000	897,216	893,136	870,070	2,192,712	2,182,740	2,126,368	8,546,881	8,508,014	8,288,284	1,981,951	1,972,937	1,921,984	11,305,821	11,254,407	10,963,748
2001	916,805	912,636	889,066	2,240,401	2,230,213	2,172,615	8,733,487	8,693,771	8,469,244	2,025,223	2,016,013	1,963,947	11,552,663	11,500,126	11,203,122
2002	935,315	931,062	907,016	2,284,447	2,274,058	2,215,328	8,909,815	8,869,297	8,640,236	2,066,112	2,056,716	2,003,599	11,785,910	11,732,312	11,429,311
2003	949,028	944,712	920,314	2,317,776	2,307,236	2,247,649	9,040,439	8,999,327	8,766,908	2,096,402	2,086,869	2,032,973	11,958,699	11,904,316	11,596,873
2004	960,052	955,686	931,004	2,343,692	2,333,034	2,272,781	9,145,455	9,103,865	8,868,747	2,120,755	2,111,110	2,056,588	12,097,614	12,042,599	11,731,585
2005	969,932	965,521	940,585	2,365,539	2,354,782	2,293,967	9,239,571	9,197,553	8,960,015	2,142,579	2,132,836	2,077,753	12,222,111	12,166,530	11,852,315
2006	983,728	979,254	953,964	2,399,092	2,388,182	2,326,504	9,370,989	9,328,374	9,087,457	2,173,054	2,163,172	2,107,306	12,395,951	12,339,580	12,020,895
2007	986,295	981,810	956,454	2,403,602	2,392,671	2,330,877	9,395,449	9,352,722	9,111,177	2,178,726	2,168,818	2,112,806	12,428,307	12,371,788	12,052,272
2008	915,988	911,822	888,273	2,247,864	2,237,642	2,179,852	8,725,697	8,686,016	8,461,690	2,023,416	2,014,215	1,962,195	11,542,359	11,489,869	11,193,129
2009	875,816	871,833	849,317	2,161,966	2,152,134	2,096,553	8,343,022	8,305,081	8,090,593	1,934,677	1,925,879	1,876,141	11,036,156	10,985,968	10,702,242
2010	874,361	870,385	847,906	2,162,897	2,153,061	2,097,456	8,329,165	8,291,288	8,077,155	1,931,464	1,922,680	1,873,025	11,017,826	10,967,721	10,684,467
2011	876,879	872,891	850,348	2,173,600	2,163,715	2,107,834	8,353,146	8,315,160	8,100,411	1,937,025	1,928,216	1,878,418	11,049,548	10,999,299	10,715,229
2012	886,189	882,159	859,376	2,199,558	2,189,555	2,133,007	8,441,837	8,403,447	8,186,418	1,957,592	1,948,689	1,898,362	11,166,868	11,116,086	10,828,999
2013	898,600	894,514	871,412	2,232,460	2,222,308	2,164,914	8,560,068	8,521,140	8,301,072	1,985,008	1,975,981	1,924,949	11,323,264	11,271,771	10,980,664
2014	906,572	902,449	879,142	2,255,576	2,245,319	2,187,331	8,636,002	8,596,729	8,374,708	2,002,617	1,993,510	1,942,025	11,423,710	11,371,760	11,078,071
2015	908,701	904,569	881,207	2,265,610	2,255,307	2,197,061	8,656,290	8,616,924	8,394,382	2,007,321	1,998,193	1,946,587	11,450,546	11,398,474	11,104,095
2016	908,223	904,093	880,744	2,269,795	2,259,473	2,201,119	8,651,734	8,612,390	8,389,965	2,006,265	1,997,141	1,945,563	11,444,521	11,392,476	11,098,252
2017	908,551	904,419	881,061	2,275,810	2,265,461	2,206,953	8,654,854	8,615,495	8,392,990	2,006,989	1,997,862	1,946,264	11,448,648	11,396,584	11,102,253
2018	910,218	906,079	882,678	2,284,811	2,274,421	2,215,681	8,670,739	8,631,309	8,408,395	2,010,672	2,001,529	1,949,837	11,469,661	11,417,501	11,122,631
2019	913,496	909,342	885,857	2,297,467	2,287,019	2,227,954	8,701,965	8,662,392	8,438,675	2,017,913	2,008,736	1,956,858	11,510,966	11,458,619	11,162,686
2020	921,234	917,045	893,361	2,320,167	2,309,616	2,249,967	8,775,679	8,735,771	8,510,159	2,035,007	2,025,752	1,973,435	11,608,475	11,555,684	11,257,245
2021	933,949	929,702	905,691	2,354,048	2,343,343	2,282,823	8,896,800	8,856,341	8,627,616	2,063,094	2,053,712	2,000,672	11,768,694	11,715,175	11,412,617
2022	948,459	944,146	919,762	2,392,004	2,381,126	2,319,631	9,035,022	8,993,935	8,761,656	2,095,146	2,085,619	2,031,755	11,951,534	11,897,184	11,589,925
2023	963,802	959,419	934,641	2,431,909	2,420,850	2,358,329	9,181,178	9,139,425	8,903,389	2,129,039	2,119,357	2,064,622	12,144,869	12,089,639	11,777,409
2024	979,688	975,233	950,046	2,473,129	2,461,882	2,398,301	9,332,510	9,290,070	9,050,142	2,164,131	2,154,290	2,098,653	12,345,051	12,288,911	11,971,535
2025	996,585	992,053	966,432	2,516,751	2,505,306	2,440,603	9,493,469	9,450,297	9,206,232	2,201,456	2,191,445	2,134,848	12,557,968	12,500,860	12,178,010

Table 7
Motorcycle parking management policy's effect under low/medium/high oil price scenarios.

Year	Motorcycle parking management														
	Energy consumption (kl)			CO_2 emission (metric tons)			CO emission (kg)			NMHC emission (kg)			NOx emission (kg)		
	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
1995	787,083	783,504	763,269	1,938,430	1,929,615	1,879,780	7,497,756	7,463,659	7,270,901	1,738,667	1,730,760	1,686,061	9,918,037	9,872,934	9,617,954
1996	799,996	796,358	775,791	1,969,637	1,960,680	1,910,043	7,620,762	7,586,106	7,390,186	1,767,191	1,759,155	1,713,723	10,080,750	10,034,907	9,775,744
1997	826,362	822,604	801,359	2,030,333	2,021,100	1,968,903	7,871,924	7,836,126	7,633,748	1,825,434	1,817,132	1,770,203	10,412,987	10,365,633	10,097,928
1998	853,841	849,958	828,007	2,091,953	2,082,440	2,028,659	8,133,689	8,096,700	7,887,593	1,886,135	1,877,557	1,829,067	10,759,249	10,710,321	10,433,714
1999	874,408	870,432	847,952	2,137,664	2,127,943	2,072,986	8,329,615	8,291,735	8,077,591	1,931,568	1,922,784	1,873,126	11,018,421	10,968,314	10,685,044
2000	897,216	893,136	870,070	2,192,712	2,182,740	2,126,368	8,546,881	8,508,014	8,288,284	1,981,951	1,972,937	1,921,984	11,305,821	11,254,407	10,963,748
2001	916,805	912,636	889,066	2,240,401	2,230,213	2,172,615	8,733,487	8,693,771	8,469,244	2,025,223	2,016,013	1,963,947	11,552,663	11,500,126	11,203,122
2002	935,315	931,062	907,016	2,284,447	2,274,058	2,215,328	8,909,815	8,869,297	8,640,236	2,066,112	2,056,716	2,003,599	11,785,910	11,732,312	11,429,311
2003	949,028	944,712	920,314	2,317,776	2,307,236	2,247,649	9,040,439	8,999,327	8,766,908	2,096,402	2,086,869	2,032,973	11,958,699	11,904,316	11,596,873
2004	960,052	955,686	931,004	2,343,692	2,333,034	2,272,781	9,145,455	9,103,865	8,868,747	2,120,755	2,111,110	2,056,588	12,097,614	12,042,599	11,731,585
2005	969,932	965,521	940,585	2,365,539	2,354,782	2,293,967	9,239,571	9,197,553	8,960,015	2,142,579	2,132,836	2,077,753	12,222,111	12,166,530	11,852,315
2006	983,728	979,254	953,964	2,399,092	2,388,182	2,326,504	9,370,989	9,328,374	9,087,457	2,173,054	2,163,172	2,107,306	12,395,951	12,339,580	12,020,895
2007	986,295	981,810	956,454	2,403,602	2,392,671	2,330,877	9,395,449	9,352,722	9,111,177	2,178,726	2,168,818	2,112,806	12,428,307	12,371,788	12,052,272
2008	912,318	908,169	884,714	2,239,645	2,229,460	2,171,882	8,690,740	8,651,218	8,427,790	2,015,310	2,006,145	1,954,334	11,496,117	11,443,838	11,148,287
2009	831,752	827,970	806,587	2,063,265	2,053,882	2,000,838	7,923,274	7,887,242	7,683,545	1,837,341	1,828,986	1,781,750	10,480,913	10,433,250	10,163,799
2010	835,078	831,280	809,811	2,074,902	2,065,466	2,012,123	7,954,949	7,918,773	7,714,262	1,844,686	1,836,298	1,788,873	10,522,813	10,474,959	10,204,431
2011	853,057	849,178	827,247	2,120,239	2,110,597	2,056,088	8,126,224	8,089,270	7,880,355	1,884,404	1,875,834	1,827,389	10,749,376	10,700,492	10,424,139
2012	878,659	874,663	852,074	2,182,691	2,172,765	2,116,651	8,370,104	8,332,040	8,116,855	1,940,957	1,932,131	1,882,231	11,071,979	11,021,628	10,736,982
2013	907,298	903,172	879,847	2,251,942	2,241,701	2,183,806	8,642,921	8,603,616	8,381,418	2,004,221	1,995,107	1,943,581	11,432,862	11,380,870	11,086,946
2014	931,734	927,497	903,543	2,311,941	2,301,427	2,241,990	8,875,699	8,835,336	8,607,153	2,058,201	2,048,841	1,995,927	11,740,782	11,687,390	11,385,549
2015	948,902	944,587	920,192	2,355,660	2,344,947	2,284,386	9,039,242	8,998,136	8,765,748	2,096,125	2,086,593	2,032,704	11,957,117	11,902,741	11,595,338
2016	960,653	956,284	931,587	2,387,237	2,376,381	2,315,008	9,151,177	9,109,561	8,874,296	2,122,082	2,112,431	2,057,875	12,105,184	12,050,135	11,738,926
2017	971,387	966,970	941,997	2,416,567	2,405,577	2,343,450	9,253,437	9,211,356	8,973,462	2,145,795	2,136,037	2,080,871	12,240,453	12,184,789	11,870,102
2018	981,955	977,489	952,244	2,445,501	2,434,380	2,371,509	9,354,099	9,311,560	9,071,078	2,169,138	2,159,273	2,103,507	12,373,609	12,317,339	11,999,229
2019	992,918	988,403	962,876	2,475,374	2,464,117	2,400,478	9,458,541	9,415,527	9,172,360	2,193,357	2,183,382	2,126,994	12,511,765	12,454,866	12,133,204
2020	1,003,304	998,741	972,947	2,504,001	2,492,614	2,428,239	9,557,470	9,514,007	9,268,296	2,216,298	2,206,219	2,149,241	12,642,629	12,585,135	12,260,109
2021	1,012,294	1,007,691	981,666	2,529,541	2,518,038	2,453,007	9,643,117	9,599,264	9,351,352	2,236,159	2,225,989	2,168,501	12,755,923	12,697,914	12,369,976
2022	1,021,521	1,016,876	990,614	2,555,663	2,544,041	2,478,338	9,731,013	9,686,761	9,436,589	2,256,541	2,246,279	2,188,266	12,872,192	12,813,654	12,482,727
2023	1,031,261	1,026,571	1,000,059	2,583,016	2,571,270	2,504,864	9,823,790	9,779,115	9,526,558	2,278,055	2,267,695	2,209,129	12,994,917	12,935,821	12,601,738
2024	1,041,554	1,036,817	1,010,040	2,611,707	2,599,830	2,532,686	9,921,839	9,876,719	9,621,641	2,300,792	2,290,329	2,231,178	13,124,616	13,064,931	12,727,514
2025	1,053,537	1,048,746	1,021,661	2,644,325	2,632,300	2,564,318	10,035,994	9,990,354	9,732,342	2,327,263	2,316,680	2,256,849	13,275,620	13,215,248	12,873,949

Table 8
Free bus service policy's effect under low/medium/high oil price scenarios.

Year	Free bus service														
	Energy consumption (kl)			CO_2 emission (metric tons)			CO emission (kg)			NMHC emission (kg)			NOx emission (kg)		
	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
1995	787,083	783,504	763,269	1,938,430	1,929,615	1,879,780	7,497,756	7,463,659	7,270,901	1,738,667	1,730,760	1,686,061	9,918,037	9,872,934	9,617,954
1996	799,996	796,358	775,791	1,969,637	1,960,680	1,910,043	7,620,762	7,586,106	7,390,186	1,767,191	1,759,155	1,713,723	10,080,750	10,034,907	9,775,744
1997	826,362	822,604	801,359	2,030,333	2,021,100	1,968,903	7,871,924	7,836,126	7,633,748	1,825,434	1,817,132	1,770,203	10,412,987	10,365,633	10,097,928
1998	853,841	849,958	828,007	2,091,953	2,082,440	2,028,659	8,133,689	8,096,700	7,887,593	1,886,135	1,877,557	1,829,067	10,759,249	10,710,321	10,433,714
1999	874,408	870,432	847,952	2,137,664	2,127,943	2,072,986	8,329,615	8,291,735	8,077,591	1,931,568	1,922,784	1,873,126	11,018,421	10,968,314	10,685,044
2000	897,216	893,136	870,070	2,192,712	2,182,740	2,126,368	8,546,881	8,508,014	8,288,284	1,981,951	1,972,937	1,921,984	11,305,821	11,254,407	10,963,748
2001	916,805	912,636	889,066	2,240,401	2,230,213	2,172,615	8,733,487	8,693,771	8,469,244	2,025,223	2,016,013	1,963,947	11,552,663	11,500,126	11,203,122
2002	935,315	931,062	907,016	2,284,447	2,274,058	2,215,328	8,909,815	8,869,297	8,640,236	2,066,112	2,056,716	2,003,599	11,785,910	11,732,312	11,429,311
2003	949,028	944,712	920,314	2,317,776	2,307,236	2,247,649	9,040,439	8,999,327	8,766,908	2,096,402	2,086,869	2,032,973	11,958,699	11,904,316	11,596,873
2004	960,052	955,686	931,004	2,343,692	2,333,034	2,272,781	9,145,455	9,103,865	8,868,747	2,120,755	2,111,110	2,056,588	12,097,614	12,042,599	11,731,585
2005	969,932	965,521	940,585	2,365,539	2,354,782	2,293,967	9,239,571	9,197,553	8,960,015	2,142,579	2,132,836	2,077,753	12,222,111	12,166,530	11,852,315
2006	983,728	979,254	953,964	2,399,092	2,388,182	2,326,504	9,370,989	9,328,374	9,087,457	2,173,054	2,163,172	2,107,306	12,395,951	12,339,580	12,020,895
2007	986,295	981,810	956,454	2,403,602	2,392,671	2,330,877	9,395,449	9,352,722	9,111,177	2,178,726	2,168,818	2,112,806	12,428,307	12,371,788	12,052,272
2008	915,988	911,822	888,273	2,247,864	2,237,642	2,179,852	8,725,697	8,686,016	8,461,690	2,023,416	2,014,215	1,962,195	11,542,359	11,489,869	11,193,129
2009	878,205	874,211	851,633	2,167,317	2,157,461	2,101,742	8,365,778	8,327,734	8,112,660	1,939,954	1,931,132	1,881,258	11,066,258	11,015,933	10,731,433
2010	886,005	881,976	859,198	2,188,979	2,179,024	2,122,748	8,440,085	8,401,703	8,184,719	1,957,185	1,948,285	1,897,968	11,164,551	11,113,780	10,826,753
2011	904,280	900,168	876,920	2,234,979	2,224,815	2,167,356	8,614,174	8,575,000	8,353,541	1,997,555	1,988,471	1,937,116	11,394,836	11,343,017	11,050,070
2012	930,600	926,368	902,443	2,299,040	2,288,585	2,229,480	8,864,895	8,824,582	8,596,676	2,055,695	2,046,347	1,993,498	11,726,490	11,673,163	11,371,690
2013	960,205	955,838	931,152	2,370,453	2,359,673	2,298,732	9,146,909	9,105,313	8,870,157	2,121,092	2,111,446	2,056,916	12,099,538	12,044,515	11,733,451
2014	985,189	980,709	955,381	2,431,681	2,420,623	2,358,108	9,384,913	9,342,234	9,100,960	2,176,283	2,166,386	2,110,437	12,414,370	12,357,914	12,038,756
2015	1,002,568	998,009	972,234	2,475,870	2,464,611	2,400,959	9,550,465	9,507,034	9,261,503	2,214,673	2,204,602	2,147,665	12,633,363	12,575,911	12,251,124
2016	1,014,531	1,009,917	983,835	2,507,923	2,496,518	2,432,042	9,664,419	9,620,469	9,372,009	2,241,098	2,230,907	2,173,291	12,784,101	12,725,964	12,397,301
2017	1,025,511	1,020,847	994,482	2,537,803	2,526,262	2,461,018	9,769,014	9,724,589	9,473,439	2,265,353	2,255,051	2,196,812	12,922,459	12,863,693	12,531,473
2018	1,036,353	1,031,640	1,004,997	2,567,354	2,555,679	2,489,676	9,872,298	9,827,403	9,573,598	2,289,304	2,278,893	2,220,038	13,059,083	12,999,696	12,663,963
2019	1,047,614	1,042,850	1,015,917	2,597,892	2,586,078	2,519,289	9,979,572	9,934,189	9,677,627	2,314,180	2,303,656	2,244,161	13,200,985	13,140,953	12,801,572
2020	1,058,325	1,053,512	1,026,304	2,627,250	2,615,302	2,547,759	10,081,602	10,035,755	9,776,570	2,337,840	2,327,208	2,267,105	13,335,951	13,275,305	12,932,454
2021	1,067,942	1,063,085	1,035,630	2,654,192	2,642,122	2,573,886	10,173,211	10,126,948	9,865,407	2,359,083	2,348,355	2,287,706	13,457,132	13,395,934	13,049,968
2022	1,077,807	1,072,906	1,045,197	2,681,744	2,669,549	2,600,605	10,267,194	10,220,503	9,956,546	2,380,877	2,370,049	2,308,840	13,581,451	13,519,689	13,170,526
2023	1,088,204	1,083,255	1,055,279	2,710,570	2,698,243	2,628,558	10,366,228	10,319,087	10,052,584	2,403,842	2,392,910	2,331,111	13,712,455	13,650,096	13,297,566
2024	1,099,162	1,094,163	1,065,905	2,740,749	2,728,285	2,657,824	10,470,613	10,422,997	10,153,810	2,428,048	2,417,006	2,354,584	13,850,534	13,787,548	13,431,468
2025	1,111,780	1,106,724	1,078,142	2,774,788	2,762,169	2,690,833	10,590,815	10,542,653	10,270,376	2,455,922	2,444,753	2,381,615	14,009,539	13,945,829	13,585,661

Table 9
Synthetic policy's effect under low/medium/high oil price scenarios.

Year	Synthetic policy														
	Energy consumption (kl)			CO_2 emission (metric tons)			CO emission (kg)			NMHC emission (kg)			NOx emission (kg)		
	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
1995	787,083	783,504	763,269	1,938,430	1,929,615	1,879,780	7,497,756	7,463,659	7,270,901	1,738,667	1,730,760	1,686,061	9,918,037	9,872,934	9,617,954
1996	799,996	796,358	775,791	1,969,637	1,960,680	1,910,043	7,620,762	7,586,106	7,390,186	1,767,191	1,759,155	1,713,723	10,080,750	10,034,907	9,775,744
1997	826,362	822,604	801,359	2,030,333	2,021,100	1,968,903	7,871,924	7,836,126	7,633,748	1,825,434	1,817,132	1,770,203	10,412,987	10,365,633	10,097,928
1998	853,841	849,958	828,007	2,091,953	2,082,440	2,028,659	8,133,689	8,096,700	7,887,593	1,886,135	1,877,557	1,829,067	10,759,249	10,710,321	10,433,714
1999	874,408	870,432	847,952	2,137,665	2,127,944	2,072,987	8,329,615	8,291,735	8,077,591	1,931,568	1,922,784	1,873,126	11,018,421	10,968,314	10,685,044
2000	897,216	893,136	870,070	2,192,712	2,182,740	2,126,368	8,546,881	8,508,014	8,288,284	1,981,951	1,972,937	1,921,984	11,305,821	11,254,407	10,963,748
2001	916,805	912,636	889,066	2,240,401	2,230,213	2,172,615	8,733,487	8,693,771	8,469,244	2,025,223	2,016,013	1,963,947	11,552,663	11,500,126	11,203,122
2002	935,315	931,062	907,016	2,284,447	2,274,058	2,215,328	8,909,815	8,869,297	8,640,236	2,066,112	2,056,716	2,003,599	11,785,910	11,732,312	11,429,311
2003	949,028	944,712	920,314	2,317,776	2,307,236	2,247,649	9,040,439	8,999,327	8,766,908	2,096,402	2,086,869	2,032,973	11,958,699	11,904,316	11,596,873
2004	960,052	955,686	931,004	2,343,692	2,333,034	2,272,781	9,145,455	9,103,865	8,868,747	2,120,755	2,111,110	2,056,588	12,097,614	12,042,599	11,731,585
2005	969,932	965,521	940,585	2,365,541	2,354,783	2,293,968	9,239,571	9,197,553	8,960,015	2,142,579	2,132,836	2,077,753	12,222,111	12,166,530	11,852,315
2006	983,729	979,255	953,965	2,399,092	2,388,182	2,326,504	9,370,999	9,328,383	9,087,467	2,173,056	2,163,174	2,107,308	12,395,964	12,339,592	12,020,908
2007	986,295	981,810	956,454	2,403,602	2,392,671	2,330,877	9,395,449	9,352,722	9,111,177	2,178,726	2,168,818	2,112,806	12,428,307	12,371,788	12,052,272
2008	912,318	908,169	884,714	2,239,645	2,229,460	2,171,882	8,690,740	8,651,218	8,427,790	2,015,310	2,006,145	1,954,334	11,496,117	11,443,838	11,148,287
2009	829,331	825,560	804,239	2,057,842	2,048,484	1,995,579	7,900,211	7,864,285	7,661,180	1,831,993	1,823,662	1,776,564	10,450,406	10,402,882	10,134,215
2010	821,767	818,030	796,903	2,045,087	2,035,787	1,983,210	7,828,153	7,792,554	7,591,302	1,815,283	1,807,028	1,760,360	10,355,087	10,307,996	10,041,780
2011	822,412	818,672	797,529	2,051,594	2,042,264	1,989,520	7,834,297	7,798,669	7,597,260	1,816,708	1,808,446	1,761,741	10,363,213	10,316,086	10,049,661
2012	829,480	825,708	804,383	2,072,531	2,063,106	2,009,824	7,901,628	7,865,694	7,662,553	1,832,322	1,823,989	1,776,882	10,452,279	10,404,747	10,136,032
2013	839,512	835,694	814,111	2,100,100	2,090,550	2,036,559	7,997,189	7,960,821	7,755,223	1,854,481	1,846,048	1,798,372	10,578,688	10,530,580	10,258,615
2014	845,570	841,725	819,986	2,118,934	2,109,298	2,054,823	8,054,903	8,018,272	7,811,191	1,867,865	1,859,371	1,811,350	10,655,031	10,606,577	10,332,649
2015	846,228	842,380	820,625	2,125,670	2,116,003	2,061,355	8,061,171	8,024,512	7,817,269	1,869,318	1,860,817	1,812,760	10,663,323	10,614,830	10,340,690
2016	844,460	840,620	818,910	2,126,966	2,117,293	2,062,611	8,044,328	8,007,746	7,800,937	1,865,413	1,856,930	1,808,972	10,641,044	10,592,653	10,319,085
2017	843,612	839,776	818,088	2,130,349	2,120,661	2,065,892	8,036,252	7,999,706	7,793,104	1,863,540	1,855,065	1,807,156	10,630,360	10,582,017	10,308,724
2018	844,190	840,351	818,648	2,136,909	2,127,191	2,072,254	8,041,754	8,005,184	7,798,440	1,864,816	1,856,335	1,808,393	10,637,639	10,589,263	10,315,783
2019	846,439	842,590	820,829	2,147,260	2,137,495	2,082,292	8,063,180	8,026,512	7,819,218	1,869,784	1,861,281	1,813,212	10,665,981	10,617,477	10,343,268
2020	853,074	849,195	827,264	2,167,490	2,157,633	2,101,910	8,126,387	8,089,432	7,880,512	1,884,441	1,875,872	1,827,425	10,749,591	10,700,706	10,424,348
2021	864,258	860,328	838,109	2,197,940	2,187,945	2,131,439	8,232,924	8,195,485	7,983,826	1,909,147	1,900,465	1,851,383	10,890,519	10,840,993	10,561,012
2022	877,226	873,237	850,685	2,232,443	2,222,291	2,164,898	8,356,457	8,318,456	8,103,622	1,937,793	1,928,981	1,879,162	11,053,928	11,003,659	10,719,477
2023	891,043	886,991	864,083	2,268,928	2,258,610	2,200,279	8,488,077	8,449,476	8,231,258	1,968,314	1,959,363	1,908,760	11,228,034	11,176,974	10,888,315
2024	905,399	901,282	878,005	2,306,723	2,296,233	2,236,930	8,624,835	8,585,612	8,363,879	2,000,027	1,990,932	1,939,514	11,408,938	11,357,054	11,063,745
2025	920,745	916,558	892,887	2,346,871	2,336,198	2,275,863	8,771,018	8,731,132	8,505,640	2,033,926	2,024,677	1,972,387	11,602,310	11,549,547	11,251,267

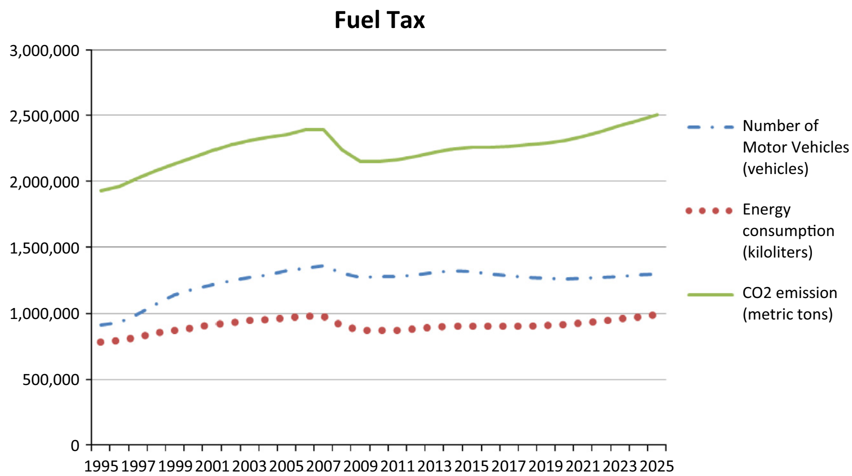

Fig. 2. Fuel tax policy simulation.

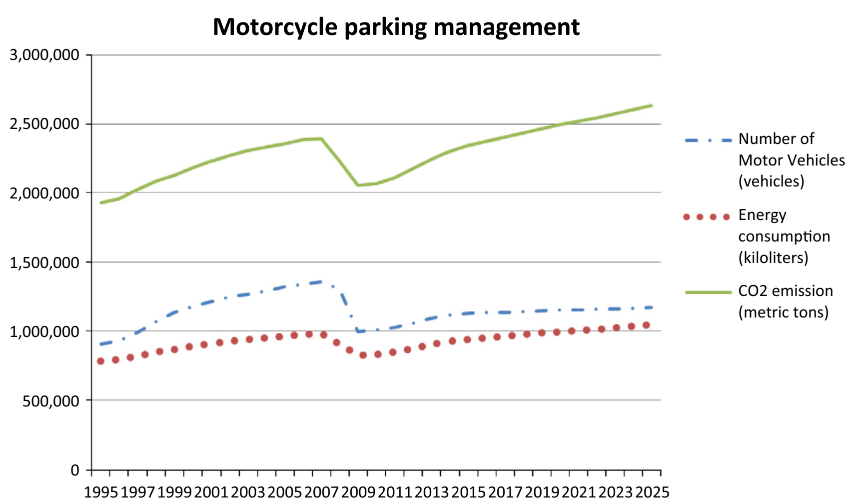

Fig. 3. Motorcycles parking management policy simulation.

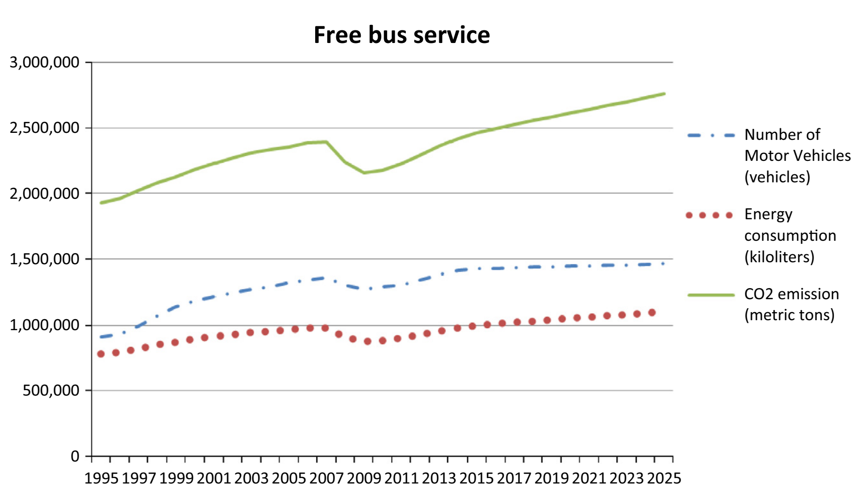

Fig. 4. Free bus service policy simulation.

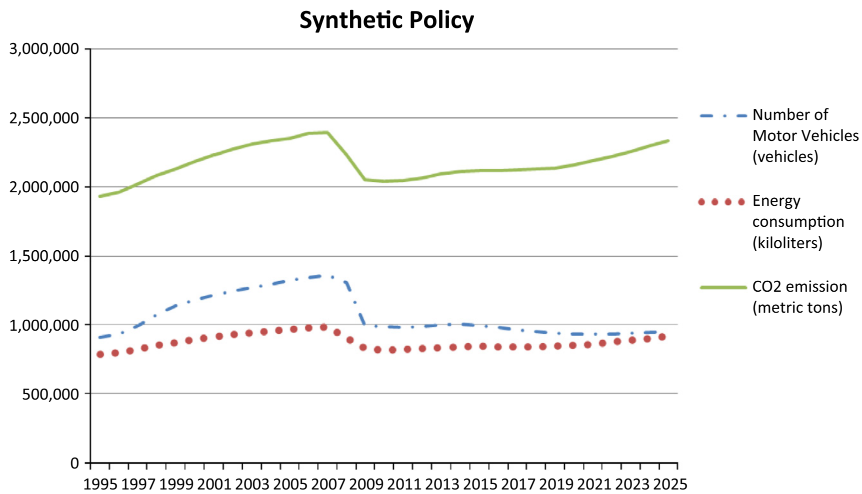

Fig. 5. Synthetic policy simulation.

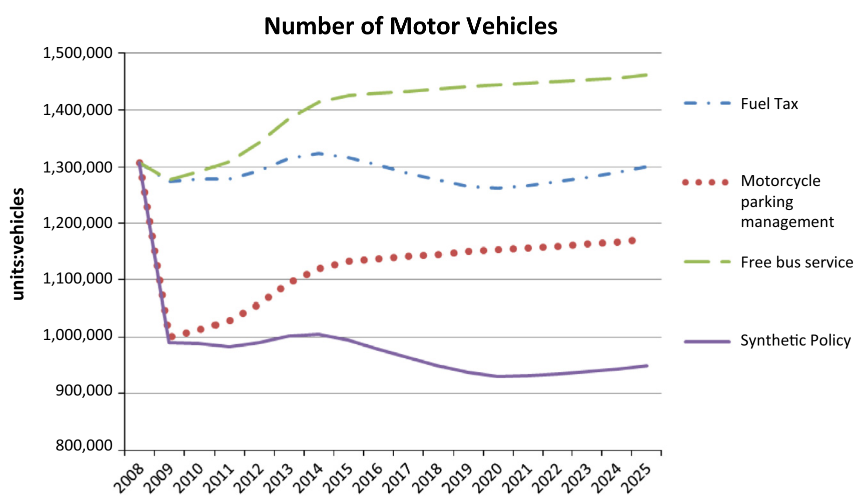

Fig. 6. Motor vehicles simulation of policies.

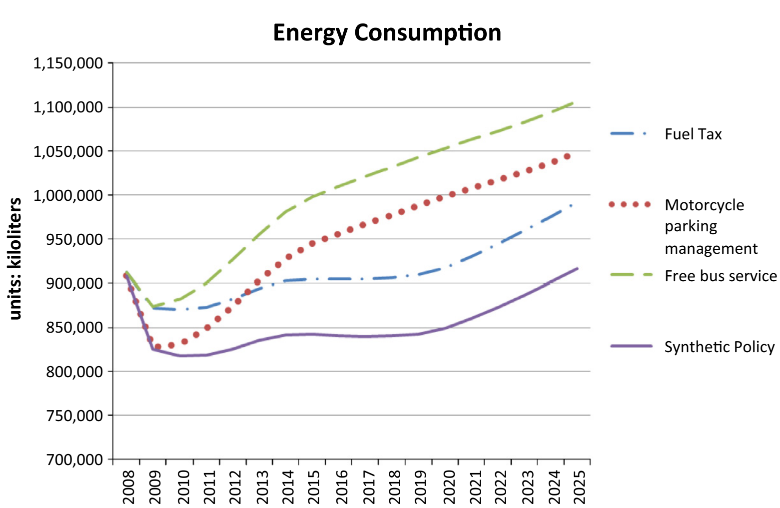

Fig. 7. Energy consumption simulation of policies.

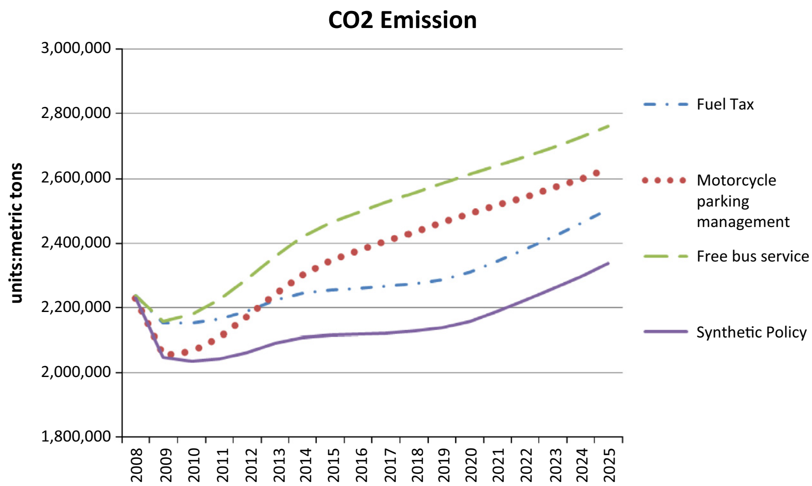

Fig. 8. CO_2 emission simulation of policies.

studies. Basing on Taiwan Emission Database System [83], we can derive the following formula. We used this relationship to estimate the emissions of CO, non-methane HC (NMHC), and NOx.

– 1 kl of gasoline consumption emits 2240 kg of CO_2.
– 1 kl of gasoline consumption emits 9.526 kg of CO.
– 1 kl of gasoline consumption emits 2.209 kg of NMHC.
– 1 kl of gasoline consumption emits 12.601 kg of NOx.

6.2.1. Policy 1: Fuel tax

We simulated the scenario of a fuel tax because the increase in oil price not only influences the transportation mode choice but also reduces the amount of vehicular energy consumption. Therefore, oil price is a relatively direct and efficient incentive for inducing consumers to reduce private vehicle use, which lowers fuel consumption and CO_2 emissions. Currently, a fixed fuel tax is levied per year according to the engine capacity of vehicles in Taiwan. An additional NT$ 1 per liter of fuel tax will also be considered in the next 10 years.

In our simulation, once the tax was included in the prices of gasoline and oil and levied according to the amount of fuel used, the numbers of motorcycles and automobiles used in Kaohsiung were both predicted to decrease. Overall, the number of vehicles in 2025 is estimated to be 1.3 million (Fig. 2), which is 13.2% lower than the base. This reduction in the number of motor vehicles caused by the increase in fuel prices will lead to changes in the modal shares of the means of transport. Under this policy, the projected growth of vehicular energy consumption varies from 991,822 kl to 992,053 kl from 2008 to 2025. During the same period, motor-vehicle CO_2 emissions are expected to increase by 267,664 metric tons. Compared with the reference model, the energy requirements and CO_2 emissions in 2025 are predicted to be 11.0% and 9.9% lower, respectively.

6.2.2. Policy 2: Motorcycle parking management

The increase in the price of crude oil will not only reduce fuel consumption but will also force a transformation in traffic modes. As seen in the reference model, the number of motorcycles in Kaohsiung increased because of the prior rise in fuel prices.

Since 2008, the Kaohsiung City government has planned a system of six regional transit centers, which are areas composed of two major and four subsidiary transit stations that link the KMRT and the shuttle bus terminals in Kaohsiung into a 30-min access metropolitan circle. Under these measures, the number of passengers carried by mass transit increased by about 60 million. In 2005, the Taipei City government introduced a successful parking management program that prohibits motorcycles from being parked on sidewalks and in building arcades, requires payment for roadside motorcycle parking, and offers a parking-information inquiry system. The ownership of motorcycles in Kaohsiung City is 71.5%, the highest in Taiwan. From the success of this policy, Kaohsiung introduced a similar system to other popular centers such as night markets, train stations, and department stores since April 2012 to reduce motorcycle use.

In this study, the rate of shifting from motorcycles to the KMRT, city buses, and bicycles was based on a survey made by the Taipei parking management office, because the motorcycle parking management system in Kaohsiung is still under implementation (Fig. 3). The number of motor vehicles driven in Kaohsiung will sharply decrease when the city introduces and enforces its parking management policy. Our simulation estimated that the number of motor vehicles will decline to 1.17 million at the end of 2025, which is 21.7% fewer than in the reference model. Concurrently, fuel consumption and CO_2 emissions will be 6.0% and 5.3% lower than in the base model.

6.2.3. Policy 3: Free bus service

In this scenario, the simulation assumed a 40% increase in bus ridership if both free bus service and discounted tickets for KMRT transfers from the subway to the bus were extensively implemented to the other weekdays. The simulation outcome indicates that the number of vehicles in Kaohsiung City will decrease by 2.3% (Fig. 4). In 2025, the number of motor vehicles will reach 1.46 million, whereas the vehicular fuel requirement will decrease by only 0.8%. By 2025, the need for vehicular fuel will increase by 194,902 kl. The change in energy consumption will also imply the estimated increase of CO_2 emissions to be 2.76 million metric tons in 2025, which is 0.52 million more than in 2008.

6.2.4. Policy 4: Synthetic policy

To evaluate the maximum potential for vehicular fuel and CO_2 reduction, the interventions act together as a package of measure, which is also considered in this study. According to the simulation, the results indicate that the number of vehicles in Kaohsiung City will decrease to 0.95 million vehicles in 2025, which is 36.6% lower than the base model (Fig. 5). In terms of the variation in vehicular fuel requirement, the variable will increase slightly from 908,169 kl to 916,558 kl from 2008 to 2025. Compared with the value at the end of 2025, the value is 17.8% lower than that in the reference model. The growth patterns of CO_2 emission and energy demand are similar because the variation of CO_2 levels is directly related to energy consumption. Thus, the contribution of aggregate CO_2 emission will be 2.34 million metric tons until 2025, which is lower by 0.44 million metric tons than the emission amount in the base model. From the observations of the forecasted patterns, the aggregate CO_2 emission needs to be reduced by about 0.15 million metric tons compared with the emission level in 2000. This result implies the difficulties and urgency of CO_2 mitigation in Kaohsiung City, despite the synthetic policy being considered in the SD model.

Furthermore, we simulated the scenario of a fuel tax because the increase in oil prices not only influences the mode choice but also reduces the amount of vehicular energy consumption. Therefore, oil price is a relatively direct and efficient incentive for inducing consumers to reduce private vehicle use, which lowers fuel consumption and CO_2 emissions.

Despite the limited effect of the separate policies of motorcycle parking management and free bus service on reducing vehicular fuel consumption, the government was able to reduce the number of private vehicles in use and promote the use of the public-transit system. Thus, we suggest that all three policies can be implemented simultaneously to restrain the growth of the number of private vehicles, motor-vehicle fuel consumption, and CO_2 emissions in Kaohsiung.

With regard the effect of various policies, the number of motor vehicles, CO_2 emission, and emergency consumption significantly decreased between 2007 and 2009, and the reason can probably be the global financial crisis during this period because this negative influence caused the slowdown of economic development (see Figs. 6–8).

7. Conclusions

The SD model is not only able to analyze a system with many interrelated variables but is also able to describe its dynamic trends based on a limited information set. By using a simplified SD model, which we constructed to analyze issues of urban population, disposable income, number of motor vehicles, vehicular energy consumption, and CO_2 emissions, we conclude that the fuel tax policy is the most effective method to reduce vehicular fuel consumption and CO_2 emissions. This policy is even more effective than the motorcycle parking management and free bus service policies.

According to the investigation of the MOTC of Taiwan, the fluctuations in fuel prices affect the number of private vehicles driven and the distances they are driven. For instance, the use of private cars and motorcycles decreased by 33.8% and 10.2%, but the rate of transfer from driving private cars to driving motorcycles was 28.36% when the average price of gasoline increased by 13.45%. The simulation of a fuel tax also suggests that the increase in fuel prices will lead to changes in the modal shares of the means of transport. The number of motor vehicles in Kaohsiung will decline by 13.2% in 2025, with a 0.5% decrease in the actual number of registered motor vehicles in the city between 2008 and 2025. The fuel tax will also cause a considerable reduction in the growth rates of vehicular fuel use and CO_2 emissions. The motorcycle parking management policy will also cause a 21.7% decrease in the number of motor vehicles by 2025, as well as 6.0% and 5.3% reductions in fuel demand and CO_2 emissions, respectively. An extensively implemented free bus service will reduce the number of motor vehicles and the fuel requirement by only 2.3% and 0.8%, respectively. Furthermore, the maximum potential of vehicular fuel consumption and CO_2 reduction is suggested in the scenario of all the interventions acting together as a package of measure. In 2025, the aggregate vehicular energy requirement and CO_2 emission will reach 916,558 kl and 2.34 million metric tons, respectively, which suggests a 17.8% and a 16.0% decrease in energy requirement and CO_2 emission compared with the reference model.

Simulation results indicate that both the fuel tax and motorcycle parking management policies are suggested as potentially the most effective methods for restraining the growth of the number of private vehicles, the amount of fuel consumption, and CO_2 emissions. We conducted a synthetic policy consisting of all policies which outperforms the three individual policies.

Compared with other countries, Taiwan is densely populated (its average population density is 646 persons/sq. km. of 2014) and has limited energy resources. In terms of energy consumption, the Taiwanese economy is sensitive to oil price variations because the country lacks conventional energy resources and is highly dependent on energy imports (nearly 99% of total energy consumption). Similar to the case of South Korea, road transportation in Taiwan accounts for more than 80% of CO_2 emission of the transport sector [84]. Taiwan is not yet a member of the United Nations Framework Convention on Climate Change. The country's CO_2 emission increased significantly over the past two decades, making Taiwan the 23rd largest CO_2 emitter in the world [6]. Taiwan's transportation sector accounted for 15% of the country's CO_2 emission in 2012. Taiwan, which is newly transformed from a developing country to a developed country [85], pursues economic development even with limited energy resources. Therefore, finding a compromise between economic development and energy consumption as well as CO_2 emission is a critical issue for Taiwan. Many transferable lessons can be learned from Taiwan's experience and can be a useful reference for countries with analogous characteristics such as economic development pattern, high population density, and high energy dependence.

With respect to generalizability of the proposed model, this study proposes policies to restrain the use of private vehicles, for example, by increasing fuel tax and launching a strict motorcycle parking management strategy. This study also examines the policy of providing free bus service from the perspective of increasing public transportation service supply and enhancing service quality to decrease urban transportation energy consumption and CO_2 emission. In this study, we present the example of Kaohsiung, a city that is highly dependent on using private vehicles (i.e., every two residents have one motorcycle, and every three residents have one private car). The lessons from Kaohsiung are applicable to other cities with similar population density, urban environment, and economic development pattern, especially Asian cities, such as Bangkok, Kuala Lumpur, and Ho Chi Minh, which are characterized by high popularity of motorcycles and limited public transportation services.

The proposed SD model examines the factors, including the influence of GDP evolution, population growth, and individual disposable income, on urban transportation energy consumption and CO_2 emission of various urban transportation systems simultaneously. The model also considers the interactions among these factors over time to assess the effectiveness of various urban transportation policies. Cities can modify our proposed approach according to their specific urban environment, economic development pattern, and public transportation service level to derive an appropriate model to understand the influence of urban transportation policies on energy consumption and CO_2 emission.

The SD model can also be applied to other programs such as urban planning, low emission vehicles, speed limits, high occupancy vehicle control lanes, strengthening energy conservation standards for new vehicles, and other aspects of transportation are certainly considerable. They provide a helpful reference for city

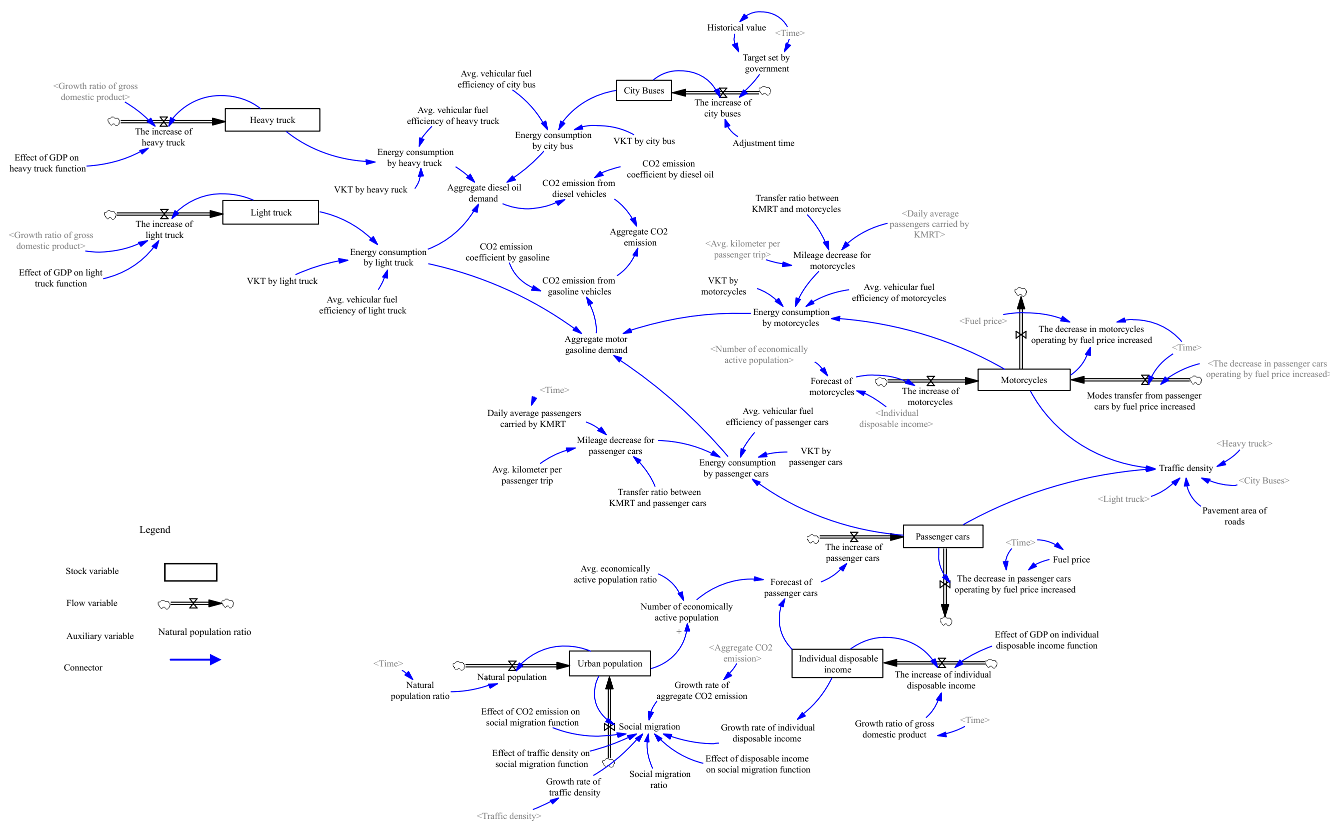

Fig. A1. Stock–flow diagram of urban transportation system in Kaohsiung City.

governments in urban development planning and setting policies associated with transport-related energy policies.

7.1. Research limitation and future research

The cost of implementing a free bus policy needs a certain amount to subsidize the ticket price of passengers. In 2013, the central government provided 1.67 million US dollars to Kaohsiung to implement a free bus policy for two months. The motorcycle parking management and fuel tax policies need the extra administration and resources to pay the costs. Compared with the latter policies, implementing a free bus policy seems to be a more costly policy. Among the three proposed policies, the fuel tax policy seems to be the most cost effective. The information with respect the cost of implementing different policy measures is useful for the urban planner and the decision maker. However, due to the data limitation, the precise cost–benefit analysis of various scenarios can be implemented in the future studies.

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Appendix A

See Fig. A1.

Appendix B. Variable explanation of urban transportation system in Kaohsiung city

Variable	Classification	Notation/Data source
Urban population system		
Urban population	Stock	The Statistical Yearbook of Kaohsiung City 2013 [69]
Natural population	Flow	–
Natural population ratio	Auxiliary	The Statistical Yearbook of Kaohsiung City 2013 [69]
Social migration	Flow	–
Social migration ratio	Auxiliary	The Statistical Yearbook of Kaohsiung City 2013 [69]
Effect of disposable income on social migration function	Auxiliary	Constructed by table function
Growth rate of individual disposable income	Auxiliary	–
Effect of CO_2 emission on social migration function	Auxiliary	Constructed by table function
Growth rate of aggregate CO_2 emission	Auxiliary	–

Appendix B (*continued*)

Variable	Classification	Notation/Data source
Effect of traffic density on social migration function	Auxiliary	Constructed by table function
Growth rate of traffic density	Auxiliary	–
Avg. economically active population	Auxiliary	The Statistical Yearbook of Kaohsiung City 2013 [69]
Number of economically active population	Auxiliary	–
Individual disposable income subsystem		
Individual disposable income	Stock	The Statistical Yearbook of Kaohsiung City 2013 [69]
The increase of individual disposable income	Flow	–
Growth ratio of gross domestic product	Auxiliary	1. Statistical Yearbook of the Interior [70] 2. Database of Global Insight
Effect of GDP on individual disposable income function	Auxiliary	Constructed by table function
Passenger cars subsystem		
Passenger cars	Stock	Statistical Yearbook of Transportation 2013
The increase of passenger cars	Flow	–
The decrease in passenger cars operating by fuel price increased	Flow	The survey of fuel price increased on mode choice [86]
Fuel price	Auxiliary	1. Adjustments of Fuel Prices in Transportation Sector [87] 2. Annual Energy Outlook 2013 [88]
Forecast of passenger cars	Auxiliary	Linear least squares regression analysis
Energy consumption by passenger cars	Auxiliary	–
VKT by passenger cars	Auxiliary	Taiwan Emission Database System (TEDS8.1) [83]
Avg. vehicular fuel efficiency of passenger cars	Auxiliary	Taiwan Emission Database System (TEDS8.1) [83]
Mileage decrease for passenger cars	Auxiliary	–
Daily average passengers carried by KMRT	Auxiliary	Mass Rapid Transit Bureau, Kaohsiung City
Avg. kilometer per passenger trip	Auxiliary	Mass Rapid Transit Bureau, Kaohsiung City
Transfer ratio between KMRT and passenger cars	Auxiliary	Research on Kaohsiung urban housing trip and trip characteristic analysis [90]
Motorcycles subsystem		
Motorcycles	Stock	Statistical report of Transportation and Communications [89]
The increase of motorcycles	Flow	–
The decrease in motorcycles operating by fuel price increased	Flow	The survey of fuel price increased on mode choice [86]
Modes transfer from passenger cars by fuel price increased	Flow	The survey of fuel price increased on mode choice [86]
Forecast of motorcycles	Auxiliary	Linear least squares regression analysis
Energy consumption by motorcycles	Auxiliary	–
VKT by motorcycles	Auxiliary	Taiwan Emission Database System (TEDS8.1) [83]
Avg. vehicular fuel efficiency of motorcycles	Auxiliary	Taiwan Emission Database System (TEDS8.1) [83]
Mileage decrease for motorcycles	Auxiliary	–
Transfer ratio between KMRT and motorcycles	Auxiliary	Research on Kaohsiung urban housing trip and trip characteristic analysis [90]
Aggregate motor gasoline demand	Auxiliary	–
CO_2 emission from gasoline vehicles	Auxiliary	–
CO_2 emission coefficient by gasoline	Auxiliary	Intergovernmental Panel on Climate Change (IPCC)
Heavy truck subsystem		
Heavy truck	Stock	Statistical report of Transportation and Communications [89]
The increase of heavy truck	Flow	–
Effect of GDP on heavy truck function	Auxiliary	Constructed by table function
Energy consumption by heavy truck	Auxiliary	–
VKT by heavy truck	Auxiliary	Taiwan Emission Database System (TEDS8.1) [83]
Avg. vehicular fuel efficiency of heavy truck	Auxiliary	Taiwan Emission Database System (TEDS8.1) [83]

(*continued on next page*)

Appendix B (*continued*)

Variable	Classification	Notation/Data source
Light truck subsystem		
Light truck	Stock	Statistical report of Transportation and Communications [89]
The increase of light truck	Flow	–
Effect of GDP on light truck function	Auxiliary	Constructed by table function
Energy consumption by light truck	Auxiliary	–
VKT by light truck	Auxiliary	Taiwan Emission Database System (TEDS8.1) [83]
Avg. vehicular fuel efficiency of light truck	Auxiliary	Taiwan Emission Database System (TEDS8.1) [83]
City Buses subsystem		
City Buses	Stock	Statistical report of Transportation and Communications [89]
The increase of city buses	Flow	–
Target set by government	Auxiliary	Transportation Bureau, Kaohsiung City
Historical value	Auxiliary	Statistical report of Transportation and Communications [89]
Adjustment time	Auxiliary	–
Energy consumption by city bus	Auxiliary	–
VKT by city bus	Auxiliary	Taiwan Emission Database System (TEDS8.1) [83]
Avg. vehicular fuel efficiency of city bus	Auxiliary	Taiwan Emission Database System (TEDS8.1) [83]
Aggregate diesel oil demand	Auxiliary	–
CO_2 emission from diesel vehicles	Auxiliary	–
CO_2 emission coefficient by diesel oil	Auxiliary	Intergovernmental Panel on Climate Change (IPCC)
Aggregate CO_2 emission	Auxiliary	–
Traffic density	Auxiliary	–
Pavement area of roads	Auxiliary	The Statistical Yearbook of Kaohsiung City 2013 [69]

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