Sustainable consumption, production and infrastructure construction for operating and planning intercity passenger transport systems

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ABSTRACT

Two bi-level programming models—an operational model and a planning model—for the intercity passenger transport systems under sustainability contexts are proposed in this study. In the upper-level models, the government (regulator) aims to provide the transport infrastructures and to regulate the fares (tolls) to achieve some sustainability objectives, indexed by energy consumption, air pollution, traffic safety, and travel time. In the lower-level models, the transport carriers aim to determine the service frequencies to maximize their profits; whereas the users aim to choose available transport modes to maximize their utilities. The rationales for the proposed models are based on the behavioral conjectures in game theory. A case of 400-km intercity passenger transport (e.g., Taipei–Kaohsiung in the western corridor of Taiwan) is exemplified with sensitivity analysis. The results indicate that rail transport is the priority mode toward overall sustainability for intercity passenger transport. Based on the results, some policy implications are addressed.

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1. Introduction

Sustainable transport, an expression of sustainable development in transport sector, has been defined in different ways (Satoh and Lan, 2007). Whatever the definitions are, most researchers may agree that sustainable transport is highly affected by such factors as spatial and land-use planning, government policy, economic forces, technology, and social and behavioral trends (e.g., Masser et al., 1993; Nijkamp et al., 1998; Nijkamp, 1999). Substantial planning, policies and initiatives associated with these sustainable transport factors have also been formulated and exercised. To make the current transport systems more sustainable, OECD (1996) clearly pointed out some specific changes, including significant reduction in car ownership and use, and shifts to more efficient vehicles; reduced long-distance passenger and freight travel, particularly air travel, and increased non-motorized short-distance travel; electric powered high-speed rail; energy-efficient less-polluting shipping; more accessible land-development patterns; increased use of telecommunications to substitute for physical travel; and more efficient production to reduce long-distance freight transport.

A number of works have attempted to address the scope, directions and indicators of sustainable transport. Nijkamp (1994) and Black (1996) proposed the directions, research needs and perspectives of sustainable transport. Transportation Research Board (1997) and Richardson (1999) focused on the issues of sustainable passenger transport, while Gordon (1995), Browne (1997), and Richardson (2001) addressed the issues of sustainable freight transport. Moreover, attentions have also been given to planning and operational levels of sustainable transport development. Friedl and Steininger (2002) analyzed the long-term impacts of sustainable transport to Austria. Loo (2002) employed stated preference methods to plan for sustainable urban transportation. Wilhelm and Posch (2003) evaluated the impacts of mobility management projects in thirteen European countries. Shiftan et al. (2003) employed scenario-building tool for planning a sustainable transport system. Richardson (2005) presented analytical frameworks to illustrate the interaction of factors influencing the indicators of transport sustainability. Lee et al. (2008) proposed a sustainability evaluation system to support infrastructure investment decisions by applying the "System of Sustainable Development Indicators for Taiwan." More recently, Köhler et al. (2009) employed the transition theory as a framework to assess possible pathways by which a transition to a sustainable mobility society might happen. Their results, based on the UK data, showed that hydrogen Fuel Cell Vehicles (FCVs) come to dominate, but only in the long run (after 2030), while biofuels and ICE (Internal

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Combustion Engine)–electric hybrids are the main alternatives to the regime in the next 10–30 years, because they are already developed and they fit better into current infrastructures. The model shows that technological transitions are most likely and that life-style change transitions require sustained pressure from the environment on society and behavioral change from users.

Very few studies have employed analytical modeling approaches which satisfactorily elucidate the interactions among different parties under sustainable transport contexts. Because the transport systems include at least three parties—users, carriers, and regulators, modeling for sustainable transport consumption, production, and infrastructure construction can be a very complex issue. The complexity not only derives from the pluralism of infrastructures and vehicles, but also sources from the intertwining behaviors of users, carriers and regulators. Generally, the users (customers) will select the optimal transport services provided by the existent carriers (operators). The government (regulator) provides transport infrastructures to meet the demands for both customers and carriers and to impose fare (toll) regulations to alter users' and carriers' behaviors to achieve some sustainability objectives. Without an in-depth analysis, the insights for sustainable transport and the interactions among different parties can hardly be understood. As such, this paper aims to develop two bi-level programming models—an operational model and a planning model—to determine the optimal decisions for intercity passenger transport systems under sustainability contexts. The operational model is applicable to a well-developed corridor wherein various types of transport infrastructures have been completed. In contrast, the planning model is applicable to a corridor wherein transport infrastructures are still under development. The proposed models can serve as effective and supportive policy tools for determining the appropriate construction time horizons of transport infrastructures as well as the proper rates of regulated fares (tolls) to achieve overall sustainability objectives.

The remaining parts are organized as follows. Section 2 develops the operational and planning models. Section 3 proposes the genetic-based algorithms to solve the models. A case of 400-km intercity corridor is exemplified with sensitivity analysis conducted in Section 4. Finally, the concluding remarks and suggestions for future studies are addressed in Section 5.

2. Model formulation

In this section, two bi-level programming models—an operational model and a planning model—for intercity passenger transport systems under sustainability contexts are respectively presented. To facilitate the model formulation, some postulations are stated below.

2.1. Postulations

Consider an intercity corridor linking two metropolitan areas. Three public transport modes (air, rail, bus) and one private mode (car) are considered in the planning horizons with the corresponding infrastructures being constructed. For simplicity, each public transport mode is assumed to be operated by only one carrier under a regulated fare (toll). The air, rail, bus, and car will compete with each other under Nash equilibrium (i.e., no one acts like a leader). The travel times of air and rail are assumed constant regardless of the number of passengers embarked; however, the travel times of bus and car on the freeway are increased with traffic volumes.

In the operational model, this paper postulates that three transport infrastructures including railway, airports, and freeway have been completed. Thus, users have four different modes to

choose from—air, rail, bus, and car. The operational model is then formulated to determine the optimal fares (tolls) for each mode. However, in the planning model, this paper postulates that only a freeway is constructed (hence only bus and car are available) between these two cities at the very beginning (base year). The planning model is then to determine the optimal construction time horizons for airports, railway, and perhaps the second freeway as well as the optimal fares (tolls) in the base year.

Typical sustainable transport indexes may include energy consumption (e.g., Satoh and Lan, 2007; Yedla and Shrestha, 2003), air pollution (e.g., Satoh and Lan, 2007; Yedla and Shrestha, 2003; Loo and Chow, 2006); traffic safety (e.g., Loo and Chow, 2006), and operation cost (e.g., Yedla and Shrestha, 2003). Accordingly, this paper assumes that the government aims to provide the transport infrastructures and to regulate the fares (tolls) to achieve overall sustainability objectives indexed by energy consumption, air pollution, safety, and travel time. The carriers aim to determine the service frequencies, with the fares regulated by the government, to maximize their profits. The users aim to choose available transport modes to maximize their utilities. The rationales for the proposed bi-level programming models are based on some behavioral conjectures in game theory. Stackelberg equilibrium is postulated between the government (who acts like a leader) and the public transport carriers (who are all followers). Nash equilibrium is postulated between different public transport carriers (no one acts like a leader) who will compete with each other in quantity (service frequencies). However, Stackelberg equilibrium is postulated between the transport carriers (who act like leaders) and passengers (who are the followers). A Logit model that maximizes the utilities with consideration of waiting time, travel time and out-of-pocket cost (fare) is formulated to explicate the users' mode choice behaviors.

The proposed operational model is most applicable to a well-developed corridor wherein various types of transport infrastructures, including freeway, railway, airports have been completed and there is no need to further introduce any other transport infrastructures. Therefore, the major responsibility for the government is to regulate the fares (tolls) to guide the carriers' service frequencies as well as to direct the users' mode choices toward sustainability. In contrast, the proposed planning model is most applicable to a corridor wherein most of the transport infrastructures are still under development. In this study, only a freeway is completed in the base year; the government aims to determine the optimal construction time horizons for the other transport infrastructures including airports, railway, and perhaps the second freeway as well as to determine the optimal fares (tolls) in the base year. In other words, the adoption of either operational model or planning model depends upon the infrastructure development status in the study corridor.

2.2. The operational model

The operational model can be formulated as follows:
[Upper level]

$$\underset{x_i}{\text{Min}}\, SC \tag{1}$$

[Lower level i]

$$\underset{y_i}{\text{Max}}\, \pi_i = x_i \times D \times \text{Pr}_i - y_i \times c_i \quad \text{for } i = 1, 2, 3 \tag{2}$$

s.t.

$$CA_i \times y_i \geq D \times \text{Pr}_i \quad \text{for } i = 1, 2, 3 \tag{3}$$

$$y_i \leq F_i, \quad \text{for } i = 1,2,3 \tag{4}$$

$$\text{Pr}_i = \frac{e^{a_1 t_i + \frac{a_2}{2y_i} + a_3 x_i}}{\sum_{i=1}^{3} e^{a_1 t_i + \frac{a_2}{2y_i} + a_3 x_i} + e^{a_1 t_4 + a_3 x_4}} \quad \text{for } i = 1,2,3 \tag{5}$$

$$\text{Pr}_4 = \frac{e^{a_1 t_4 + a_3 x_4}}{\sum_{i=1}^{3} e^{a_1 t_i + \frac{a_2}{2y_i} + a_3 x_i} + e^{a_1 t_4 + a_3 x_4}} \quad \text{for car} \tag{6}$$

$$x_i \geq 0, \quad \text{for all } i \tag{7}$$

$$y_{it} \in \text{integer}^+ \quad \text{for } i = 1,2,3 \tag{8}$$

where x_i is the regulated fare (toll) rate of transport carrier i ($/trip) for rail ($i = 1$), air ($i = 2$), bus ($i = 3$), and for car, respectively. y_i is the frequency of transport carrier i (number of scheduled trains, scheduled flights and scheduled buses per day). x_i and y_i are decision variables at upper level and lower level, respectively. SC is the sustainable cost (total cost of four sustainability indexes); that is, $SC = AP + AC + EC + TC$ where AP, AC, EC, and TC respectively represent the total costs of air pollution, energy consumption, accident and travel time, which are further expressed as follows:

$$AP = \sum_{i=1}^{3} (b_{i1} \times y_i \times l) + b_{41} \times \frac{D \times \text{Pr}_4}{f} \times l \tag{9}$$

$$AC = \sum_{i=1}^{3} (b_{i2} \times y_i \times l) + b_{42} \times \frac{D \times \text{Pr}_4}{f} \times l \tag{10}$$

$$EC = \sum_{i=1}^{3} (b_{i3} \times y_i \times l) + b_{43} \times \frac{D \times \text{Pr}_4}{f} \times l \tag{11}$$

$$TC = \sum_{i=1}^{3} \left[b_{i4} \times D \times \text{Pr}_i \times \left(\frac{1}{2y_i} + t_i \right) \right] + b_{44} \times D \times \text{Pr}_4 \times t_4 \tag{12}$$

where b_{ij} is the unit cost of sustainability index j ($j = 1$ stands for air pollution, 2 for accident, 3 for energy consumption, 4 for travel time, respectively) of transport mode i ($/veh-km or $/day). l is the length of the corridor (km). D is the daily travel demand (trips), which is for simplicity assumed uniform distribution over the daily operation period (say, from 6:00 am to 24:00 pm). f is average loading factor of passenger car (persons/veh). Pr_i is the market share of transport mode i (%). t_1 and t_2 are the travel times of rail and air, which are assumed constant independent of traffic volumes. The travel times of bus and car on the freeway are assumed following the well-known BPR travel time function:

$$t_3 = t_4 = t_0 \left[1 + \alpha \left(\frac{\frac{D \times \text{Pr}_4}{18f} + w \frac{y_3}{18}}{C} \right)^{\beta} \right] \tag{13}$$

where t_0 is the travel time under free-flow conditions in the freeway. α, β are the parameters of BPR function. C is the capacity of freeway (pcu/h). w is passenger-car equivalent (pce) of a bus. Eqs. (9)–(11) assume that the air pollution, energy consumption and accident rate are linearly proportional to the traffic exposure – total veh-km of corresponding transport mode ($=y_i \times l$ respectively for rail, air and bus; and $=((D \times \text{Pr}_4)/(f)) \times l$ for car). For simplicity, the average waiting time of rail, air and bus are assumed one-half of its headway, i.e., $=(1/2y_i)$. Of course, one can replace the "one-half"

with a smaller figure (e.g., 0.1 or 0.2 of the headway) for the pre-planned users who know in advance the transport schedules. Eq. (2) is the profit (π_i) of transport carrier i ($) for air and bus. c_i is the average cost per frequency of transport carrier i for rail, air, and bus. Eq. (3) states that the seat supplied by transport carrier i must exceed its patronage for rail, air, and bus. CA_i is the seat capacity of transport mode i (persons per train, per flight, or per bus). F_i is the frequency of transport mode i (trains, flights, or buses per day). Eqs. (5) and (6) represent the Logit-choice based market share of transport mode i (%). a_1, a_2, a_3 are three negative parameters corresponding to travel time, waiting time and fare, respectively.

2.3. The planning model

Similar to the framework of operational model, the planning model is also formulated as bi-level with one leader (government) and multi-followers (transport carriers). The upper level is to simultaneously determine the optimal construction years for different infrastructures over the planning horizon as well as the optimal fare (toll) rates discounted to the base year, according to an annual discount rate. The lower level is formulated as same as that of the operational model. Hence, the bi-level planning model is expressed as follows:
[Upper level]

$$\underset{x_{it}, z_{it}}{\text{Min}} \, SC + CC + MC \tag{14}$$

[Lower level i at year t]

$$\underset{y_{it}}{\text{Max}} \, \pi_{it} = x_{it} \times D \times \text{Pr}_{it} - y_{it} \times c_i \quad \text{for } i = 1,2,3 \text{ and all } t \tag{15}$$

s.t.

$$x_{it+1} = x_{it}(1+r) \quad \text{for all } i, t \tag{16}$$

$$\sum_{i=1}^{3} z_{it} \leq 1 \quad \text{for all } t \tag{17}$$

$$CA_{it} \times y_{it} \geq D_t \times \text{Pr}_{it} \quad \text{for } i = 1,2,3 \text{ and all } t \tag{18}$$

$$y_{it} \leq F_{it}, \quad \text{for } i = 1,2,3 \tag{19}$$

$$\text{Pr}_{it} = \frac{e^{a_1 t_{it} + \frac{a_2}{2y_{it}} + a_3 x_{it}}}{\sum_{i=1}^{3} e^{a_1 t_{it} + \frac{a_2}{2y_{ti}} + a_3 x_{it}} + e^{a_1 t_{4t} + a_3 x_{4t}}} \quad \text{for } i = 1,2,3 \text{ and all } t \tag{20}$$

$$\text{Pr}_{4t} = \frac{e^{a_1 t_{4t} + a_3 x_{4t}}}{\sum_{i=1}^{3} e^{a_1 t_{it} + \frac{a_2}{2y_{it}} + a_3 x_{it}} + e^{a_1 t_{4t} + a_3 x_{4t}}} \quad \text{for all } t \tag{21}$$

$$x_{it} \geq 0, \quad \text{for all } i \text{ and } t \tag{22}$$

$$y_{it} \in \text{integer}^+ \quad \text{for } i = 1,2,3 \text{ and } t \tag{23}$$

$$z_{it} \in \{1, 0\} \quad \text{for } i = 1,2,3 \text{ and } t \tag{24}$$

where SC is the sustainable cost, which is similar to Eqs. (9)–(12) with the replacement of y_i, D, Pr_i by y_{it}, D_t and Pr_{it}, respectively. However, since the operational model is a daily-base model, the total sustainable cost over the planning period can be calculated as:

$$SC = \sum_{t=1}^{T} \frac{356}{(1+r)^{t-1}} (AP + AC + EC + TC) \tag{25}$$

T is total number of years of the planning period. r is discounted rate.

CC is the total construction cost of transportation systems discounted to the base year. It can be expressed as follows:

$$CC = \sum_{i=1}^{3} \sum_{t=1}^{T} z_{it} \sum_{j=1}^{m_i} \frac{cc_i}{m_i(1+r)^{t+j-1}} \qquad (26)$$

z_{it} is the decision variable, taking binary values only. $z_{it} = 1$ indicates that the government decides to construct transport infrastructure i at the year t for $i = 1$ (railway), 2 (airport), and 3 (second freeway). If not to construct, $z_{it} = 0$. cc_i is the construction cost of transport infrastructure i. m_i is the number of construction years for transport infrastructure i.

MC stands for maintenance cost, which can be expressed as follows:

$$MC = \sum_{i=1}^{3} \sum_{t=1}^{T} z_{it} \sum_{j=1}^{T-t-m_i} \frac{mc_i}{(1+r)^{t+m_i+j}} \qquad (27)$$

mc_i is the annual maintenance cost of transport infrastructure i.

Eq. (16) is the fare (toll) rates adjusted by the discounted rate each year, thus the upper level only has to determine the fares (tolls) at the beginning base year (i.e., $t = 1$). Eq. (17) assumes that the government can only construct at most one type of infrastructure in each year due to the limited budget (capital, labor, equipment, etc.) constraint. Eq. (18) is the seat capacity constraint. Eq. (19) is the frequency constraint, where F_{it} depends upon how many transport infrastructures coming into operation. It can be expressed as:

$$F_{it} = F_{i0} + F_i \sum_{j=1}^{t} z_{i,j+m_i} \qquad (28)$$

where F_{i0} is the frequency in the base year, depending upon how many transport infrastructure i available in the base year. If there is no transport infrastructure i in the base year, then $F_{i0} = 0$. Eqs. (20) and (21) are the Logit-based market share constraints.

3. Solution algorithm

Both of the proposed operational and planning models are complex bi-level programming models. To solve these models, this paper develops a genetic-based algorithm, detailed as follows.

3.1. Encoding method for the operational model

In the operational model, the upper level is to determine the optimal fare (toll) of the corresponding transport mode. The upper bound of each fare (toll) is set equal to NT$9999 (NT$32.00 equivalent to US $1.00), four genes are used to represent one fare (toll). It makes a total of 16 genes in a chromosome. A chromosome as depicted in Fig. 1 with a sequence genes of 1572203409542103, for example, represents that the fare (toll) rates of rail, air, bus and car are NT$1572, 2034, 954, and 2103, respectively.
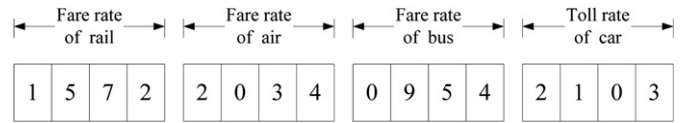

Fig. 1. An illustration of encoding for the operational model.

Once the fares (tolls) are determined at the upper level, the optimal operating frequencies at the lower level can be determined by a total enumeration method. However, to greatly enhance the computational efficiency, this paper first fixes the frequency of rail and finds the optimal frequencies of air and bus iteratively with the enumeration method. Then, the rail frequency is gradually altered and the corresponding optimal frequencies of air and bus are solved with the enumeration method again. As such, the optimal frequencies of three modes can be determined.

3.2. Encoding method for the planning model

In the planning model, the upper level is to determine the optimal construction horizon years of various transport infrastructures associated with their fares (tolls). A 30-year planning period in this exemplified case is considered. Using one gene to represent the construction decision of the corresponding year, it makes a total of 30 genes to represent the overall construction horizons. Each gene takes values from 0 to 9, where 0 represents the decision not to construct any transport infrastructure, 1 through 3 represent the decision to construct the railway system, 4 through 6 represent the decision to construct the air transport system, and 7 through 9 represent the decision to construct the second freeway system. To simultaneously determine the optimal fare (toll) rates in the base year, extra 16 genes are added. For instance, a chromosome depicted in Fig. 2 with a sequence genes of 030060090000001 0000000000000001572203409542103 represents that four transport infrastructures will be respectively constructed at the second (railway), fifth (air), eighth (freeway) and fifteenth (railway) years, with fare (toll) rates equal to NT$1572, 2034, 954, and 2103 for rail, air, bus and car at the beginning year, respectively. It suggests that at the end of the planning period, two railways, one air and two freeways will be provided in this corridor.

3.3. Genetic operators

Because the genes in the proposed models are not encoded binary, it is not proper to adopt the operations of simple genetic algorithms proposed by Goldberg (1989). Instead, max-min-arithmetical crossover proposed by Herrera et al. (1995) and non-uniform mutation proposed by Michalewicz (1992) are adopted. A brief description of both methods is given below.

3.3.1. Max-min-arithmetical crossover

If $G_w^t = \{g_{w1}^t, \dots g_{wk}^t, \dots g_{wK}^t\}$ and $G_y^t = \{g_{v1}^t, \dots g_{vk}^t, \dots g_{vK}^t\}$ are two chromosomes chosen to be crossed, generate the following four offsprings:
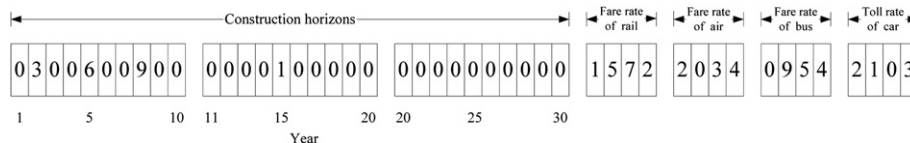

Fig. 2. An illustration of encoding for the planning model.

Table 1
The settings of parameters for different transport modes.

Parameters	Notation	Rail	Air	Bus	Car
Air pollution cost (NT$/veh-km)	b_{i1}	80.11	236.12	353.77	283.99
Energy consumption cost (NT$/veh-km)	b_{i2}	83.71	334.86	209.29	167.43
Accident cost (NT$/veh-km)	b_{i3}	10.03	60.52	10.51	0.13
Travel time cost (NT$/h)	b_{i4}	76.20	76.20	76.20	94.2
Operating cost (NT$/veh-km)	c_i	100.00	500.00	30.00	–
Seat capacity/load factor (seats)	CA_i	624	150	21	2.03
Daily frequency (trains/flights/buses)	F_i	78	60	1000	–

Note: NT$32.00 equivalent to US$1.00. Source: Institute of Transportation (2002).

$$G_1^{t+1} = aG_w^t + (1-a)G_v^t \tag{29}$$

$$G_2^{t+1} = aG_v^t + (1-a)G_w^t \tag{30}$$

$$G_3^{t+1} \text{ with } g_{3k}^{t+1} = \min\{g_{wk}^t, g_{vk}^t\} \tag{31}$$

$$G_4^{t+1} \text{ with } g_{4k}^{t+1} = \max\{g_{wk}^t, g_{vk}^t\} \tag{32}$$

where a is a parameter either a constant or a variable taking a value depending on the age of population, t is the number of generations.

3.3.2. Non-uniform mutation

Let $G^t = \{g_1^t, \ldots g_k^t, \ldots, g_K^t\}$ be a chromosome and the gene g_{wk} be selected for mutation (the domain of g_k^t is $[g_k^l, g_k^u]$).

$$g_k^{t+1} = \begin{cases} g_k^t + \Delta\left(t, g_k^u - g_k^t\right) & \text{if } b = 0 \\ g_k^t - \Delta\left(t, g_k^u - g_k^t\right) & \text{if } b = 1 \end{cases} \tag{33}$$

where b is a random number taking a binary value of 0 or 1. The function $\Delta(t,y)$ returns a value in the range [0,y] such that the probability of $\Delta(t,y)$ is close to 0 as t increases:

$$\Delta(t,z) = z\left(1 - r^{(1-t/T)^h}\right) \tag{34}$$

where r is a random number in the interval [0,1], T is the maximum number of generations and h is a given constant. As known from Eq. (34), the value returned by $\Delta(t,y)$ will gradually decrease as the evolution goes by. It borrows the concept from simulated annealing.

4. An exemplified case

4.1. Data and parameters

A case of 400-km corridor linking two metropolitan areas (e.g., Taipei and Kaohsiung in western Taiwan) is tested in this study. The related parameters of four transport modes and three transport

Table 2
The settings of parameters for different transport infrastructures.

Cost items	Notation	Railway	Airport	Freeway
Construction cost (billion NT$)	cc_i	370	200	250
Maintenance cost (million NT$/year)	mc_i	73.00	91.25	36.50
Construction period (years)	m_i	5	5	5

Note: NT$32.00 equivalent to US$1.00. Source: Institute of Transportation (2002).

infrastructures are set in Tables 1 and 2, respectively (Institute of Transportation, 2002). The travel times of rail and air from Taipei to Kaohsiung are 5 h and 1 h, respectively. The travel time of bus and car is calculated according to the BPR function with free-flow speed = 100 km h^{-1} and $\alpha = 0.15$, $\beta = 4.0$. The capacity of the freeway (C) is 4000 pcu h^{-1} (i.e., a two-lane freeway was constructed at the base year). Discounted rate (r) is 10%. The planning period (T) is 30 years. The daily travel demand is 50,000 trips for the operational model and 150,000 trips for the planning model; both have an annual growth rate of 5%. Three parameters of Logit model is set as: $a_1 = -0.0012$ (for travel time), $a_2 = -0.01$ (for waiting time), and $a_3 = -0.0005$ (for fare/toll). Due to the limited line capacity, assume that the railway is operated with a daily frequency of 40 trains for the long-distance intercity passengers; the remaining line capacity is reserved for short-distance commuting trains.

The parameters of genetic algorithms are set as: crossover rate = 0.9, mutation rate = 0.01, population = 100 chromosomes, mature rate = 80%.

4.2. Results

4.2.1. The operational model

The upper-level objective value of the operational model is NT$268 million per day. The results are presented in Table 3. To achieve sustainability, the optimal fares (tolls) for rail, air, bus and car are NT$945, 2460, 2493 and 7060, respectively. Namely, the optimal toll for private car should be set triple of the bus or air fare, which should be more than double of the rail fare. It suggests that passenger car is by no means a sustainable transport mode for the 400-km intercity transport and thus should be strictly regulated by imposing an extremely high toll. To simplify the total enumeration, here the long-distance rail frequency is set as 40 trains per day, taking into account the line capacity to operate the commuting trains as well. The optimal frequencies for air and bus are 78 flights and 577 buses per day, respectively. At optimality, the rail should take nearly one-half of the total travel demands (49.92%), followed by the air and the bus, each of which should take approximately one-fourth of the total travel demands. The passenger car should take only 2.45% of the total travel demands.

The majority of car users may not accept such an extremely high toll (NT$7060) in practice, thus a ceiling toll of NT$ 3000 (NT$300 per passing a toll station; there are 10 toll stations in this 400-km corridor) is reset for the car users in the operational model. It is found that the objective value at the upper level now changes from

Table 3
The results of operational model.

Conditions	Items	Rail	Air	Bus	Car
No limitation of toll imposed on car	Fare (toll) (NT$)	945	2460	2493	7060
	Daily frequency (trains/flights/buses)	40	78	577	–
	Market share (%)	49.92	23.40	23.23	2.45
A ceiling toll of NT$3000 imposed on car	Fare (Toll) (NT$)	794	1508	794	3000
	Daily frequency (trains/flights/buses)	40	77	785	–
	Market share (%)	33.00	23.09	32.97	10.94
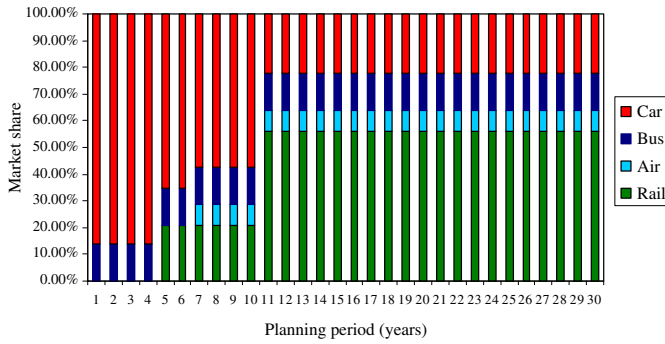
Fig. 3. Market shares of transport modes over the 30-year planning horizons.
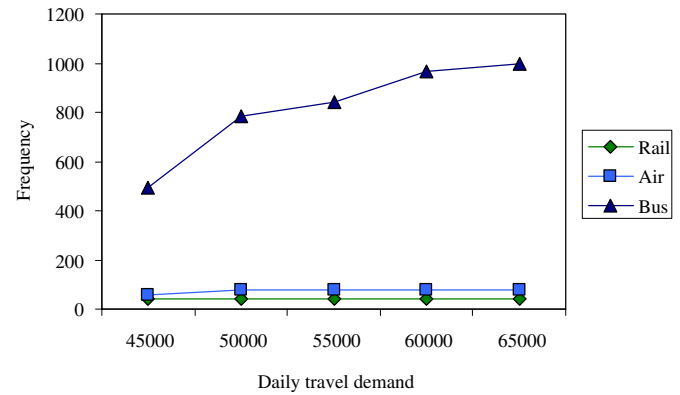
NT$268 million per day to NT$693 million per day. The results with this ceiling toll are also presented in Table 3. Notice that the market share of passenger cars increases from 2.45% to 10.94%; while the patronage of bus is also largely increased from 23.23% to 32.97%. Rail has lost its market share from 49.92% to 33%. This paper further lowers the ceiling toll for cars and the results indicate that it will remarkably deteriorate the objective value due to an increasing market share of passenger cars. Hence, it is imperative important to regulate the car usage for such a long-distance intercity travel in order to achieve overall sustainability objectives.

4.2.2. The planning model

The planning model simultaneously determines the optimal construction horizons for different infrastructures with their associated fares (tolls). With only a freeway system existent at the beginning base year, the optimal chromosome evolves as 1040002000000000000000000000000767161208273000, indicating that two railways should be constructed at the first and 7th years, respectively; an air transport system should be constructed at the 3rd year and no second freeway should be constructed over the 30-year planning horizons. To achieve overall sustainability, the provisions of transport infrastructures between these two metropolitan cities are varied with market shares presented in Fig. 3. Under sustainability contexts, during the first four years there is only a freeway in the corridor and the market shares are 14.00% (bus) and 86.00% (car), respectively. During the 5th to 6th years, one railway is introduced and the market shares become 20.80% (rail), 14.00% (bus) and 65.20% (car). During the 8th to 10th years, the air transport system is introduced and the market shares become 20.80% (rail), 7.80% (air), 14.00% (bus) and 57.40% (car), respectively. During the 11th to 30th years, there are two railways, one air transport system, and one freeway with the corresponding market

Fig. 5. Frequencies of transport modes under various travel demands.

shares 56.18% (rail), 7.80% (air), 14.00% (bus) and 22.02% (car), respectively.

4.3. Sensitivity analysis

To look into the effects of some key parameters on the optimal decisions, sensitivities for daily travel demand and long-distance rail frequency are further tested.

4.3.1. Travel demand

The daily travel demand has been set as 50,000 trips in the operational model as abovementioned. The daily travel demands are varied from 45,000 to 65,000 trips with a ceiling toll NT$3000 for cars and a daily frequency of 40 trains for rail. The corresponding optimal fares (tolls), frequencies, and market shares are displayed in Figs. 4–6. Notice that the tolls for car and fares for rail under various travel demands remain binding at NT$3000 and NT$794, respectively; while the fares for air and bus increase with the daily travel demands. The bus frequency is remarkably increased with the travel demand, while air frequency is increased with the daily travel demands up to 50,000 and then decreased as the demands further grow. Rail takes the largest market share under various scenarios of travel demands. The market share for car reaches 25% as the daily travel demands are lowered to 45,000, but it declines to approximately 12% as the travel demands grow. The distributions of market shares for air and bus are similar: both decrease at a daily travel demand of 45,000 but remain unchanged or slightly decreased as the daily demands exceed 50,000.

The daily travel demand has been set as 150,000 trips in the aforementioned planning model. The daily travel demands are
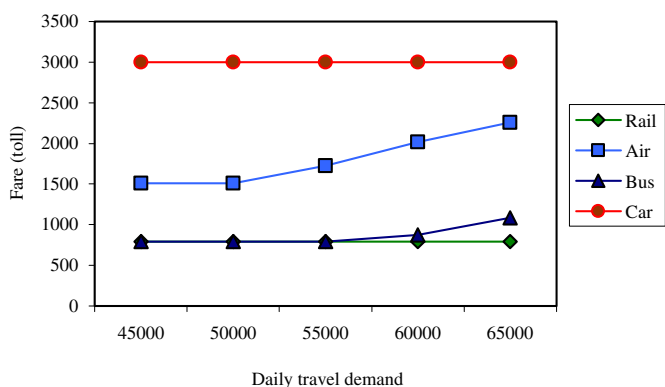

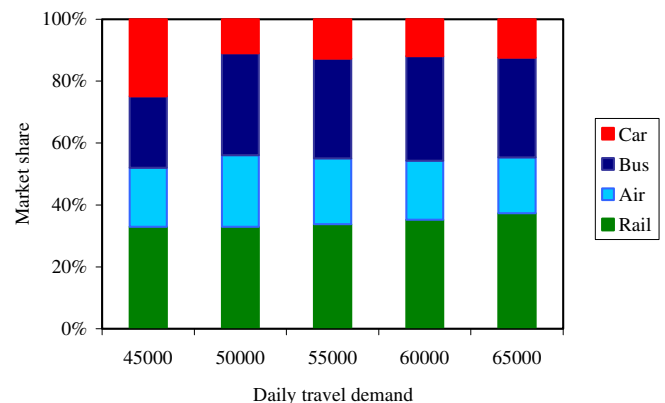**Fig. 4.** Fares (tolls) of transport modes under various travel demands.

Fig. 6. Market shares of transport modes under various travel demands.

varied from 100,000 to 350,000 trips, and the optimal construction horizons for different infrastructures are reported in Table 4. As expected, the necessity of infrastructure construction becomes keener as travel demands grow. Railway turns out to be the priority choice for expanding the transport system, followed by airport. No second freeway is deemed necessary over the entire 30-year planning horizons even though the daily travel demand has increased to 350,000 trips. It is interesting to notice that all of the newly-introduced infrastructures must be completed within the first ten years.

4.3.2. Rail frequency

In the above analysis, the rail frequency is set as 40 trains per day. To further analyze the sensitivity of rail frequency, various frequencies ranging from 10 to 60 trains per day are examined and the results are displayed in Figs. 7 and 8. Note that the rail fare sharply declines from NT$3000 to NT$794 and remain unchanged after daily frequency reaching 30 trains. The passenger-car tolls increase from NT$2600 to NT$3000 as rail frequency increases from 10 to 20 trains per day and remains unchanged afterward. In contrast, the air fares slightly decrease as rail frequency increases and remain unchanged after it reaches 30 trains per day. The bus fares are not affected by rail frequency. However, both air and bus frequencies decrease with the increase of rail frequency from 10 to 30 trains per day, and afterward, they remain unchanged.

4.4. Discussions

Based on the above results, several policy and managerial implications can be identified. Firstly, due to the unsustainable characteristics of private cars, the results of operational and planning models suggest a rather harsh control over this mode by either raising its toll to a drastic level or not constructing an additional freeway in the first place. Note that the toll in this paper only acts as a metaphor of the usage cost of private car. Similar results can be anticipated by significantly raising other types of usage costs including gas price, parking fee, etc. Of course, tactics such as raising the car registration fee, license-plate tax or purchasing tax might also be effective in lowering the ownership of private cars.

Secondly, rail transportation is obviously the priority choice toward sustainability among four transport modes in this exemplified case. It is necessary to provide sufficient rail transportation to serve the majority of intercity passenger demands. This philosophy has been supported by more and more high-speed rail transport systems being introduced between the mega cities in different countries nowadays. Namely, to become more sustainable for intercity passenger transport, it is essential for a country to construct railway systems, especially the high-speed rails.

Thirdly, to avoid attracting too many private car trips, freeway construction is not a favorable solution for the intercity people mobility. However, it can also hamper the intercity bus transport. This can be overcome by introducing high-occupancy-vehicle (HOV) lanes operated in certain time slots on the existent freeways.
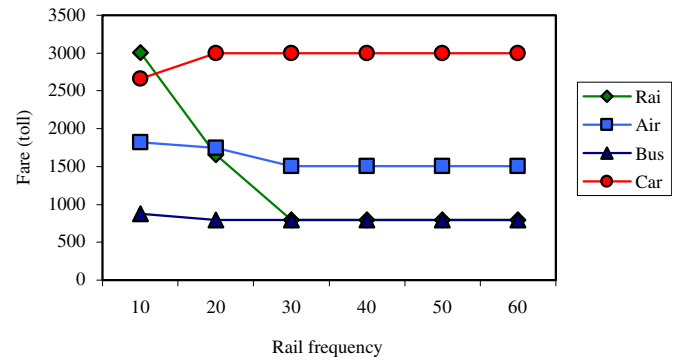

Fig. 7. Fares (tolls) of transport modes under various rail frequencies.

Similar HOV operations have been found in many countries during commuting hours (e.g., USA) and during festivals (e.g., Taiwan).

Fourthly, provision of more frequent much cheaper public transport services can also play a key role on inviting more passengers from the private-vehicle users. The government can consider regulating the public transport by subsidizing the carriers in a way to operate higher frequencies with lower fares. And these would break or even reverse the direction of public—private transport vicious circle.

Over the past few decades, Taiwan government has aimed to accelerate economic growth by giving priority to build highway infrastructures for convenient mobility of people and freight rather than to develop public transport systems. As such, a vicious circle of public—private transport systems was gradually formed. The economic growth provided an initial momentum to increase car ownership and usage. More car ownership and usage reduced the demand for public transport, to which the carriers responded by either raising the fares or curtailing the frequencies or both. Thus, the use of cars became more attractive than before and induced more people to purchase cars, further the vicious circle. As a consequence, after several cycles, car drivers are experiencing more congestion, buses are running less frequently because of the roadway congestion, and almost everyone is worse off than before.

The vicious circle has caused serious impacts to the environmental, economic and societal systems. The impacts to the environment mainly contain air pollution and noise from road vehicles, destruction of open land space and natural habitats. The impacts to the economy mainly include ever-greater consumption of fossil fuel resource, considerable time loss due to traffic congestion, huge financial burden on maintaining and operating the highway infrastructures and transport service industries. The impacts to the society cover inequitable accessibility and mobility to the transport disadvantaged (e.g., the poor, the handicapped) and to the inhabitants in less developed areas, serious mortality and morbidity due to traffic accidents and high emission concentrations of motor vehicle usage. In other word, the private-oriented transport had in effect led Taiwan toward unsustainable development.

Table 4
Optimal infrastructure construction horizons under various travel demands.

| Daily travel demand	Optimal chromosome	Beginning construction year of		
		Railway	Airport	Freeway
100,000	1400000000 0000000000 0000000000	1	2	None
150,000	1400020000 0000000000 0000000000	1, 7	3	None
200,000	1112400000 0000000000 0000000000	1, 2, 3, 4	5	None
250,000	1325100000 0000000000 0000000000	1, 2, 3, 5	4	None
300,000	1411101000 0000000000 0000000000	1, 3, 4, 5, 7	2	None
350,000	1114101000 0000000000 0000000000	1, 2, 3, 5, 7	4	None
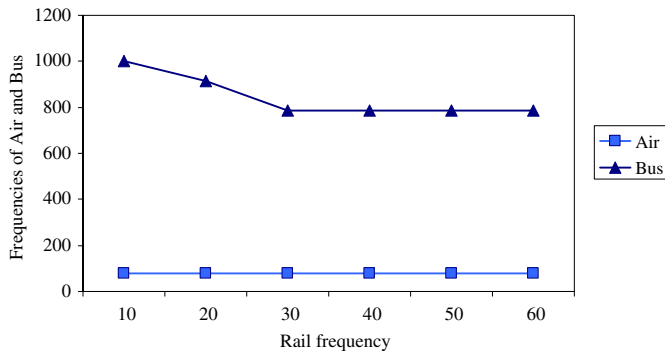
Fig. 8. Frequencies of air and bus under various rail frequencies.

In response to the mandates of *the Agenda 21*, Taiwan government has formulated policies and action plans to make transport more in line with sustainable development. In its first *Transportation Policy White Book* (Ministry of Transportation and Communications, 1995) the government proclaimed the pursuit of sustainable development by factoring the environmental, economic and societal considerations into the transport policy decision-makings. Development of public transport with top priority was the most prominent policy attempting to break (or even reverse) the direction of public–private transport vicious circle. Strategies such as providing bus exclusive lanes in urban congested areas and direct subsidy and tax/fee/toll exemption to the bus carriers have been implemented to ameliorate the public transport service quality and operating efficiency and to relieve the pressure of fare increase. Meanwhile, imposing higher charges on private cars ownership (e.g., license-plate tax) and usage (e.g., parking fee) have also been implemented to internalize the private-vehicle external costs. Such "carrot and stick" policy planning and operational philosophy was clearly documented in *the 1995 Transportation Policy White Book* (Lan et al., 2006).

Furthermore, in response to *the Kyoto Protocol and the Copenhagen Accord*, Taiwan government should take effective steps in developing more sustainable transport systems. For instance, in maintaining the environmental sustainability, the government should enhance the efficiency of transport energy usage and lower the air pollutions, noise, and greenhouse gas emissions by introducing low- or zero-pollution and high-energy efficiency transport modes. In upholding the economic sustainability, the government should promote the economic development and enhance the efficiency of infrastructure construction and transport service operations by stimulating more private participation in transport infrastructures, more liberalization in transport service industries, and expediting the integration of inter-modal transport systems. In keeping the social sustainability, the government should ameliorate public transport service quantity and quality and consider the social equity by providing safe, healthy, and comfortable environment to meet the basic needs of transport for all people, including the poor, the aged, the handicapped, the rural areas and the offshore islands.

5. Concluding remarks

In many countries, transportation is one of the large sectors in consuming energy and emitting pollutants. To guide users' and carriers' choices toward cleaner transport modes through appropriate infrastructure construction, service frequency provision and fares (tolls) regulation is definitely an effective and essential strategy to achieve overall sustainability. However, modeling for sustainable transport consumption, production, and infrastructure construction is a very complex issue. The complexity not only derives from the pluralism of infrastructures and vehicles, but also sources from the intertwining behaviors of users, carriers and regulators. Generally, the users choose the optimal transport services provided by the transport carriers (operators). The carriers determine the most profitable service frequency depending on whether the corresponding infrastructure being completed and how many users being attracted. The government (regulator) constructs transport infrastructures and imposes fare/toll regulations to alter users' and carriers' behaviors toward a sustainable consumption and production.

Based on this, this paper develops two bi-level programming models—an operational model and a planning model—to achieve overall sustainable transport objectives for the intercity passenger transport. The core logics are based on various perspectives viewed by the government, the transport carriers and the users, which are hardly incorporated into a single model. The objectives for the government are to achieve overall sustainable transportation indexes in terms of energy consumption, air pollution, safety, and travel time. The objectives for the carriers are to maximize their profits in determining the service frequencies provided that their fares are regulated by the government. The objectives for the users are to choose available transport modes to maximize their utilities. Following the game theory, this study makes several conjectures: Stackelberg equilibrium exists between the government (leader) and the carriers (followers); Nash equilibrium exists among the carriers when they compete service frequencies with each other; Stackelberg equilibrium also exists between carriers (leaders) and users (followers).

The results show that if a ceiling (lower) toll level is imposed on the passenger cars, the objective value will be remarkably deteriorated due to the increasing market share of car usage. The policy implication is to harshly regulate the car usage for sustainability purposes. The sensitivity analysis has found that as the daily travel demands increase, the necessity of newly-added transport infrastructures becomes keener. Railway system turns out to be the first priority alternative, followed by the air transport system, and an additional freeway is not deemed necessary over the 30-year planning horizon in this 400-km exemplified city pairs. It is also interesting to note that all the new transport infrastructures must be constructed within the first ten years.

Several directions for future studies can be identified. Firstly, this paper employs an iterative enumeration method to solve the lower-level model problem. A more effective solution algorithm for the single-leader-multi-followers problem deserves further exploration. Secondly, the proposed models postulate that Nash equilibrium exists among transport carriers; in practice, one of the carriers might act as a leader who possesses higher market power over others, implying that Stackelberg equilibrium might exist instead of Nash equilibrium, which deserves further exploration as well. Thirdly, some parameters of the proposed models are set according to relevant studies or prevailing situations in Taiwan, more proper values of these parameters are worthy of in-depth investigation or when applying in other countries. Fourthly, other options of transportation systems, such as high-speed rail, can be easily introduced into the proposed model, once the related parameters of sustainability indexes are specified. Fifthly, the objective function of the proposed model is formed by summing-up various sustainability index values. A more general approach is to obtain the relative weights or to formulate the problems with multi-objective functions. In addition, other sustainability indexes taking into account of future generations can also be explored.

Last but not least, it is worth noting that the results obtained in this study are based upon the current vehicle technologies with emission and energy consumption indicated by the parameter

settings in Table 1. With the rapid evolution of low- to zero-emission vehicle technologies, such as biofuel, electricity, and hydrogen fuel cell (e.g., see McNicol et al., 2001; Piel, 2001; van Mierlo et al., 2006; van den Hoed, 2007; Schwoon, 2008), the results of optimal fares (tolls) and optimal construction schedules for different transport infrastructures might be changed. These can be easily solved by simply varying the parameter settings in Table 1 for the corresponding transport modes.

Acknowledgements

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