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# Optimization of Urban Bus Routes based on Principles of Sustainable Transportation

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**Abstract:** Optimizing the location of urban bus routes is a major challenge owing to the enormous range of possible alternatives, as well as the numerous associated requirements and limitations. Additionally, considerable information must be involved in models. For instance, detailed spatial data on population locations and trip demands is crucial for examining bus accessibility. This study employs fuzzy programming, and use four indicators representing sustainable transportation, such as accessibility, operator profit, user cost and reduction of external cost, to optimize urban bus route allocation. The proposed model is applied to Taoyuan County, the most rapidly growing city in Taiwan, and managerial implication are identified to help decision-makers align bus routes based on sustainability criteria, and consideration is also given to extending the model to more comprehensive evaluation functions.

***Key Words:*** *bus route optimization, sustainable transportation, fuzzy programming*

## 1. INTRODUCTION

The provision of sufficient urban transportation is a key issue for most metropolitan areas worldwide. Urban transportation in large cities typically consists of a mix of public transit, including guided mass rapid transit (MRT) systems, buses and taxis, and private vehicles, including automobiles, motorcycles and bicycles. Asian cities have experienced fundamental socio-economic changes resulting from increased population and use of private vehicles. Quality of life is being negatively impacted by increases in accidents, travel time and natural resource consumption, along with congestion, as well as environmental impacts such as air pollution, noise and vibration. It is critical to determine an efficient and effective approach to improve mobility, accessibility and environmental quality, by re-constructing urban public transportation (Alterkawi, 2006).

Moreover, a consensus exists that improving public transport helps to solve metropolitan congestion. Although previous studies concluded that investment in rail offers the best solution to public transit problems (Kain, 1988; Hensher and Waters, 1994), it is difficult to establish comprehensive MRT systems in most cities due to the huge monetary investment and the limited accessibility of such systems (Kain, 1988). Besides, many cities utilize bus-based systems as legitimate alternatives to rail systems (Wright and Hook, 2006) because of the lower associated risks, including more limited potential for cost overruns, and greater flexibility in responding to forecast demand (Hensher, 2007). Bus-based systems thus make an important contribution to in urban public transportation (Bentley, 1998).

Additionally, stable and visible bus-based systems will attract the passengers in medium-density corridors if they are properly designed (Hensher, 2007). However, optimizing urban bus routes is a complex and challenging task owing to the need to consider numerous socio-economic factors. It is necessary to obtain an enormous quantity of diverse temporal-spatial information to assess the value of alternatives and solutions (Jha et al., 2007), and that information can differ considerably in format and quality.

Accordingly, a prototype model is constructed to analyze urban bus route allocation based on sustainable transportation criteria. Taoyuan, the most rapidly growing city in Taiwan, is selected as the focus of an empirical study for discussing the managerial implications of the model. Taoyuan suffers from a poor public transportation system, with residents relying primarily on private vehicles owing to a poorly organized bus system. The model for optimizing the allocation of urban bus routes can help planners decide when, how and where to invest in public transportation services. The definition and criteria of sustainable transportation are illustrated in the next section, after which the research approach is described in detail. The route allocation model is then constructed in section 4, followed by empirical study and discussion. Finally, section 6 describes conclusions and future research directions.

## 2. SUSTAINABLE TRANSPORTATION

Although the common definition of sustainability is unavailable (Pope et al., 2004; Loo and Chow, 2006; Jeon et al., 2006), sustainable development is generally conceived as balancing environmental, social and economic qualities (Kasemir et al., 2003; Steg and Gifford, 2005; Ness et al., 2007). Moreover, the World Commission of Environment and Development (1987) defined sustainability as “meeting the needs of the present without compromising the ability of future generations to meet their own needs”. Shafer et al. (2000) identified sustainability as the ability to achieve a good quality of life both in the present and in the future. Therefore, the emerging consensus is that a sustainable transport system should efficiently, equitably and safely fulfill basic user transportation needs, stimulates economic development, and not damage environment (Pope et al., 2004; Jeon et al., 2006).

To overcome the issues associated with sustainable transportation indicators being considered differently due to distinct temporal-spatial scale with diverse socio-economic characteristics, many researchers have suggested various criteria related to sustainable transportation, including mobility, economic health, reliability, safety, accessibility, affordability, externality and excessive utilization of natural resources (Feitelson, 2002; Black et al., 2002; Yedla and Shrestha, 2003; Feng and Hsieh, 2009). In fact, different transport stakeholders, such as users, operators, residents and regulators, have diverse needs in relation to transportation services (Koontz, 2003; Sohail et al., 2006).

Accordingly, four quantitative indicators, which refer to stakeholder needs, based on the sustainable transportation criteria in three sustainability dimensions, namely social equity, economic efficiency and environmental conservation, are considered in this study. These indicators, including accessibility, operator profit, user cost and the reduction of external cost, are briefly described below.

Accessibility is utilized to evaluate the potential of interactions between urban spatial patterns from the perspectives of users, residents and regulators. Levine and Garb (2002) measured accessibility by the ease of interactions between network nodes. Accessibility thus can be used to evaluate the equitable distribution of transport services. Moreover, operator profit is used to monitor whether an operation is moving towards financial sustainability, i.e. its economic health. Besides, user cost comprises monetary cost and time value, representing affordability and mobility, respectively. Furthermore, external cost, calculated by the reductions in air pollution, noise energy consumption and accidents caused by private vehicle use, consists of stakeholder needs in safety, externality and natural resource over-utilization. The reliability is excluded from this study due to the unavailability of data.

## 3. RESEARCH APPROACH

This study aims to construct a prototype model to analyze the allocation of urban bus routes. The previous literature exploring network design for public transportation has identified some objective functions and constraints. In fact, the goal of urban bus route allocation is to minimize total costs and maximize the consumer surplus, whereas the constraints comprise service capacity and user trip demand (Ceder and Wilson, 1986; Martins and Vaz Pato, 1998). However, meeting the multiple objectives of sustainable transportation implies making trade-offs in considering the benefits and costs to different stakeholders. Lee and Moore (1973) argued that single objective models have neglected conflicting targets influencing decision processes related to transportation issues. The problems of public transit network design can be solved by analytical models (van Nes and Bovy, 2000; Aldaihani et al., 2004), simulation analysis (Alterkawi, 2006) and heuristic algorithms (Gao et al., 2004; Jha et al., 2007).

During recent decades, fuzzy programming, which is a good method for identifying compromised solutions for optimization problem, has been applied to solve multi-objective linear, as well as nonlinear, programming problems (Bit et al., 1992; Lee and Li, 1993; Chang, 2007). Fuzzy programming combines fuzzy set theory and multi-criteria decision-making problems. The objective functions are represented via a fuzzy set, and the decision rule is used to select the solution with the highest membership of the decision sets. Zimmermann (1978) developed a fuzzy linear program, identical to the max-min program, and applied the fuzzy set theory concept with suitable membership functions. Solutions obtained by fuzzy programming are always efficient and optimize the comprised solution.

Moreover, fuzzy programming has been used in many fields. Li and Lee (1990) proposed a two-phase approach to get non-dominated solution and adapt it to de Novo programming with fuzzy parameters. Bhattacharya et al. (1992) utilized fuzzy programming to solve a multi-objective facility location problem. The genetic algorithm approach has been proved to be able to solve fuzzy programming with fuzzy nonlinear function goals and nonlinear constraints (Sasaki et al. 1995). Furthermore, some studies concluded that using fuzzy programming for large problems, a compromise solution can easily be found, and is applicable to all types of multi-objective transportation problem (Bit et al., 1993; Islam and Roy, 2006).

All the achievements of past studies increase the practicability of fuzzy programming.

Accordingly, fuzzy programming is utilized in this allocation model. In the compromise programming, the weights indicate the importance of the relative deviation of the objectives from the ideal, but in the fuzzy programming they express the importance of the deviations from the anti-ideal (Martinson, 1993). Following the procedures of the fuzzy programming algorithm, the ideal solution set $I^* = \{W_s^*\}$ and the anti-ideal solution set $I^\# = \{W_s^\#\}$ should first be determined for the basic model, where $W_s^*$ denotes the independently optimal performance for each indicator $s$ while $W_s^\#$ represents the worst performance for each indicator $s$ due to the optimization of the objective indicators non-$s$. For example, the model considers four indicators, e.g. $s = 1, 2, 3, 4$. $W_1^*$ shows the optimal solution when indicator *1* is identified as the objective function. Conversely, $W_1^\#$ illustrates the worst value among the performance for indicator *1* in the optimization for indicators *2*, *3* and *4*.

Furthermore, both the ideal and anti-ideal solution set are employed as a reference point to define the membership function, $DS_s(W_s)$, indicating the satisfaction degree of each objective $W_s$. The membership functions are represented as Eqn.1 for maximization problems, in which $W_s^*$ denoting the independently optimal performance, i.e. the maximum target value, whereas $W_s^\#$ referring to the worst performance, i.e. the minimum threshold value, for each indicator $s$ are utilized as the upper and lower boundary, respectively, to identify the domain.

$$DS_s(W_s) = \begin{cases} 1, & W_s > W_s^* \\ \dfrac{(W_s^* - W_s)}{(W_s^* - W_s^\#)}, & W_s^* > W_s > W_s^\# \\ 0, & W_s^\# > W_s \end{cases} \tag{1}$$

According to Eqn.1, the satisfaction degree of each objective $W_s$ is determined via normalization if any objective for each indicator was in the domain. Additionally, the satisfaction degree of each objective $W_s$ would be assumed as constants to prevent an irrational value if the performance occurs out of the domain. In fact, objectives performing better than target values are defined as 1, while objectives performing worse than threshold values are defined as 0. Moreover, a compromise-grade $\lambda$, referring to overall satisfaction of the optimization model, is expressed as Eqn.2.

$$\lambda = \underset{s}{Min}\ \{DS_s(W_s)\} \tag{2}$$

Through maximizing $\lambda$, the multi-objective problem can be transformed into the following problem and the compromised solutions, including the values of decision variables $x_i$, compromise-grade $\lambda$ and compromised objectives $W_s$ with each degree of satisfaction $DS_s$, are thus obtained.

$$
\begin{aligned}
Max \quad & \lambda \\
s.t. \quad & \lambda \le \frac{(W_s^{\#} - W_s)}{(W_s^{\#} - W_s^{*})} \\
& \sum A_i x_i \le B \\
& x_i \in \{0,1\}, \quad \forall i \\
& 0 \le \lambda \le 1
\end{aligned}
$$

## 4. ROUTE ALLOCATION MODEL

As mentioned above, the poor allocation of public transit in Taoyuan results in residents relying on private vehicles. However, the bus service network connected by bus stops covers the entire Taoyuan urban area. The location of bus stops, stop spacing and related linkages thus are not key issues, the low bus ridership arising mainly from inadequate allocation of bus routes. Bus service routes are employed instead of individual linkages between bus stops in this study. Besides, this study assumes that the set of bus routes, such as existing routes, proposed route adjustments and planned routes, is given. This study also assumes that operational times and headways do not differ between peak and non-peak hours, or between weekday and holiday. Accordingly, objectives and constraints are formulated as follows.

The first objective is to maximize bus accessibility (as shown in Eqn.3) to enhance the equity of bus service provision to residents. Feng and Hsieh (2007) suggested that bus accessibility represents the ratio of the resident population in a specific service area to the total urban population. Bus service area is defined as the area easily accessible on foot, i.e. the area within 500 meters of a station.

$$Max \quad \sum_i (a_i - a_i^o) x_i \tag{3}$$

In Eqn. 3, $x_i$, the decision variable, which denotes whether route $i$ has service, $a_i$ refers to the resident population of service area of route $i$, and $a_i^o$ represents the overlapped population served by routes other than route $i$ in the same service area. Moreover, this model achieves economic efficiency via the second and the third objectives (shown as Eqns.4 and 5) maximizing operator profit and minimizing user costs, respectively, where $F_i$ denotes the fare regulated by local government, $C_i^o$ represents the operating cost per passenger in route $i$, $k_i$ describes the average number of trips per person for residents traveling via bus on route $i$, $TT_i$ denotes the travel time for a bus operating on route $i$ and $VOT$ refers to the average value of time for bus users. Due to the unavailability of individual data in the mesoscopic analysis, average level of each variable, including cost, fare and travel time, is employed in this study. Therefore, the average travel time for users in Eqn.5 consists of in-vehicle travel time calculated by the half of the operational length divided by the average travel speed as well as the out-of-vehicle travel time expressed by the average waiting time represented by the half bus headway.

$$Max \quad \sum_i (F_i - C_i^o) a_i k_i x_i \tag{4}$$

$$Min \quad \sum_i \left[ F_i + \frac{1}{2} TT_i \times VOT \right] a_i k_i x_i \tag{5}$$

The user cost in Eqn.5 is composed by monetary cost, in-vehicle time and waiting time. Although the fare would be nullified if Eqn.4 integrates Eqn.5, it is meaningful from the perspective of different stakeholder. The fourth objective, representing the reduction of external cost caused by the shift from private vehicles to bus service is indicated in Eqn.6, where $R_i^P$, $R_i^N$, $R_i^A$ and $R_i^C$ denote the reductions in air pollution, noise pollution, accidents and congestion, respectively.

$$Max \quad \sum_i (R_i^P + R_i^N + R_i^A + R_i^C) a_i k_i x_i \tag{6}$$

Moreover, this study considers four constraints. Bus routes are divided into four categories including existed routes without adjustment alternatives (routes set $p$), existed routes with adjustment alternatives (routes set $q$), suggested routes of adjustment alternatives (routes set $r$) and planned brand-new routes (routes set $s$). Therefore, $i \in \{p, q, r, s\}$. The first constraint, shown as Eqn.7, shows that the existing routes with adjustment alternatives and the suggested adjustment routes can-not be employed simultaneously because of high collinearity and the reduplicated function.

$$x_{i \in q} + x_{i \in r} \le 1, \quad \forall\, i \tag{7}$$

$$x_i \in \{0, 1\} \quad \forall\, i \tag{8}$$

$$\sum_i \frac{(a_i - a_i^o) x_i}{P} \ge G, \quad \forall\, i \tag{9}$$

$$\sum_i (F_i - C_i^o) a_i k_i x_i \ge 0, \quad \forall\, i \tag{10}$$

Furthermore, Eqn.8 indicates that route $i$ should be allocated ($x_i = 1$) or not ($x_i = 0$). The third constraint, shown as Eqn.9, presents the threshold value for accessibility based on stakeholder needs, where $P$ denotes total resident population in Taoyuan and $G$ represents the basic service level of bus accessibility. Finally, the last constraint, indicated as Eqn.10, confirms the existence of a non-negative operator profit. All the constraints should be substituted into the algorithm of fuzzy programming. The value of parameters in this empirical study is calculated based on the statistical data of domestic research in Taiwan are illustrated in the Appendix.

## 5. EMPIRICAL STUDY

Taoyuan County, a bi-core development urban area, is selected to test the applicability of the proposed model. The problem is to optimize the alignment of bus routes serving county, including residential, commercial and industrial properties. Key input parameters, listed in the Appendix, are used for the model according to the procedures of fuzzy programming. Consequently, the ideal and anti-ideal solution set, examined by Table 1 based on constraints and each single objective, are listed in Table 2.

Table 1 Solutions to the route allocation model under a single objective

| Single Objective | $W_1$ | $W_2$ | $W_3$ | $W_4$ |
|---|---|---|---|---|
| Eqn.3 (*Max* accessibility) | 753,042 | 7,427 | 2,035,393 | 904,232 |
| Eqn.4 (*Max* operator profit) | 596,080 | 72,045 | 1,548,995 | 628,720 |
| Eqn.5 (*Min* user cost) | 595,704 | 2,861 | 1,215,220 | 504,634 |
| Eqn.6 (*Max* reduction of external cost) | 752,042 | 10,319 | 2,068,267 | 920,432 |

Notably, the objective of Eqn.5 in Table1 is to minimize the user cost ($W_3$), a reverse indicator, the value of ideal solution is thus smaller than the value of anti-ideal solution. Moreover, the calculation of membership function through normalization prevents a negative satisfaction degree.

Table 2 Ideal and anti-ideal solution set

| Item | $W_1$ | $W_2$ | $W_3$ | $W_4$ |
|---|---|---|---|---|
| Ideal solution set | 753,042 | 72,045 | 1,215,220 | 920,432 |
| Anti-ideal solution set | 595,704 | 2,861 | 2,068,267 | 504,634 |
| $W_s^* - W_s^\#$ | 157,338 | 69,184 | $\underline{-853,047}$ | 415,798 |

Using the ideal and anti-ideal solution set, the multi-objectives problem can be transformed into a single objective problem maximizing $\lambda$, as shown below, where the total population of Taoyuan is 1,190,419 and to meet basic accessibility demand it is suggested that half of the resident population should be served by buses, i.e. $G = 0.5$.

$$
\begin{aligned}
&Max \quad \lambda \\
&s.t. \quad \lambda \le (753{,}042 - W_1)/157{,}338 \\
&\qquad \lambda \le (72{,}045 - W_2)/69{,}184 \\
&\qquad \lambda \le (W_3 - 2{,}068{,}267)/(\underline{-853{,}047}) \\
&\qquad \lambda \le (920{,}432 - W_4)/415{,}798 \\
&\qquad x_{q01} + x_{r01} \le 1 \\
&\qquad x_{q02} + x_{r02} \le 1 \\
&\qquad x_i \in \{0, 1\}, \quad \forall\, i = 1, 2, 3, \cdots, 45 \\
&\qquad \sum \frac{a_i x_i}{1{,}190{,}419} \ge 0.5, \quad \forall\, i = 1, 2, 3, \cdots, 45 \\
&\qquad \sum_i (F_i - C_i^o) a_i k_i x_i \ge 0, \quad \forall\, i = 1, 2, 3, \cdots, 45 \\
&\qquad 0 \le \lambda \le 1
\end{aligned}
$$

By maximizing compromise-grade $\lambda = 0.45$, the compromised objective values standing for accessibility ($W_1$), operator profit ($W_2$), user cost ($W_3$) and reduction of external cost ($W_4$) are 667086, 34875, 1655926 and 709665, respectively. The optimized alignment shown in Table 3 indicates that 23 of 28 existing routes should maintain bus service whereas it is suggested that routes P02, P03, P13, P17 and P20 should be suspended. Besides, route Q01 is retained on the existed route while route Q02 is replaced by the adjustment alternative route R02. Investment is recommended in all of the planned new routes except route S12. In fact, the results of empirical study reveals that bus routes less than 5 km in length should be excluded from the network, for example, routes P03, P13, R01 and S12, because private vehicles, particularly motorcycles, are utilized to displace the extremely short bus routes without frequently services. Further routes having a served population of less than 7000 should be eliminated due to the worst performance of accessibility, including routes P13, P17 and P20.

Table 3 Optimal bus route allocation via fuzzy programming

| ID | Decision (1: Yes, 0: No) | $a_i$ (person) | $a_i - a_i^o$ (person) | $L_i$ (km) | Operation Time (hr) | $h_i$ (min) | $F_i$ (NTD/trip) | $C_i^o$ (NTD) | External Cost (NTD) |
|---|---|---|---|---|---|---|---|---|---|
| P01 | 1 | 103,115 | 34,371 | 12.38 | 17.0 | 12.00 | 27 | *44,530* | 58,938 |
| P02 | **0** | 113,881 | 37,960 | 12.71 | 18.0 | 6.25 | 27 | *92,940* | 63,011 |
| P03 | **0** | 22,772 | 7,591 | 4.90 | 16.0 | 20.00 | 18 | 11,172 | 14,786 |
| P04 | 1 | 11,152 | 8,152 | 6.20 | 17.0 | 11.25 | 18 | 23,788 | 31,484 |
| P05 | 1 | 75,438 | 27,719 | 10.32 | 16.5 | 12.50 | 18 | 34,588 | 45,778 |
| P06 | 1 | 37,947 | 16,974 | 8.00 | 17.0 | 15.00 | 18 | 23,020 | 30,469 |
| P07 | 1 | ***9,360*** | ***6,788*** | 3.50 | ***2.5*** | 50.00 | 18 | 444 | 588 |
| P08 | 1 | 27,461 | 14,889 | 11.70 | 17.0 | 14.25 | 18 | 35,439 | 46,906 |
| P09 | 1 | 39,129 | 16,564 | 6.76 | 17.0 | 15.00 | 18 | 19,452 | 25,746 |
| P10 | 1 | 35,434 | 15,717 | 10.31 | 17.0 | 20.00 | 18 | 22,251 | 29,450 |
| P11 | 1 | 28,883 | 12,926 | 8.20 | 12.5 | 84.00 | 18 | 3,098 | 4,101 |
| P12 | 1 | 80,117 | 45,044 | 15.10 | 12.5 | 84.00 | 18 | 5,705 | 7,551 |
| P13 | **0** | 18,094 | 5,522 | 3.43 | 13.0 | 87.00 | 18 | 1,301 | 1,722 |
| P14 | 1 | 40,883 | 19,441 | 7.10 | 17.0 | 20.00 | 18 | 15,323 | 20,281 |
| P15 | 1 | 25,900 | 10,633 | 9.39 | 13.0 | 98.00 | 18 | 3,163 | 4,186 |
| P16 | 1 | 46,408 | 15,469 | 13.21 | 13.5 | 116.00 | 18 | 3,903 | 5,166 |
| P17 | **0** | 26,960 | 4,732 | 11.80 | 13.0 | 35.00 | 18 | 11,128 | 14,729 |
| P18 | 1 | 30,891 | 10,297 | 15.38 | 13.0 | 60.00 | 18 | 8,461 | 11,198 |
| P19 | 1 | 22,837 | 9,612 | 5.70 | 17.0 | 15.00 | 18 | 16,402 | 21,709 |
| P20 | **0** | 26,683 | 4,639 | 8.80 | 16.5 | 25.00 | 18 | 14,747 | 19,518 |
| P21 | 1 | 23,048 | 8,524 | 7.90 | 6.0 | 120.00 | 27 | 1,003 | 1,327 |
| P22 | 1 | 31,182 | 15,225 | 8.50 | 13.0 | 78.00 | 18 | 3,597 | 4,761 |
| P23 | 1 | 28,099 | 15,527 | 5.66 | 15.0 | 60.00 | 18 | 3,593 | 4,755 |
| P24 | 1 | 33,490 | 15,745 | 5.30 | 16.5 | 18.00 | 18 | 12,335 | 16,327 |
| P25 | 1 | 26,645 | 9,142 | 7.47 | 13.5 | 54.00 | 18 | 4,742 | 6,276 |
| P26 | 1 | 33,564 | 20,600 | 6.70 | 16.0 | 35.00 | 18 | 7,777 | 10,293 |
| P27 | 1 | 45,213 | 15,354 | 8.00 | 15.5 | 35.00 | 18 | 8,995 | 11,906 |
| P28 | 1 | 50,768 | 14,654 | 6.43 | 15.5 | 77.50 | 18 | 3,265 | 4,322 |
| Q01 | 1 | 15,971 | 7,324 | 6.38 | 17.0 | 20.00 | 18 | 13,769 | *18,224* |
| Q02 | **0** | *45,036* | *14,223* | 7.66 | 13.0 | 86.67 | 18 | 2,917 | 3,861 |
| R01 | **0** | 23,645 | 8,324 | 4.03 | 13.0 | 87.00 | 18 | 1,529 | *2,024* |
| R02 | 1 | *48,804* | *20,221* | 8.27 | 13.0 | 86.67 | 18 | 3,150 | 4,169 |
| S01 | 1 | 37,834 | 17,208 | 5.17 | 14.5 | 97.00 | 18 | 1,962 | 2,597 |
| S02 | 1 | 25,432 | 12,716 | 7.81 | 11.0 | 94.00 | 18 | 2,321 | 3,071 |
| S03 | 1 | 37,576 | 18,788 | 6.70 | 10.0 | 300.00 | 18 | 567 | 751 |
| S04 | 1 | 22,533 | 9,267 | 5.49 | 13.0 | 195.00 | 18 | 929 | 1,230 |
| S05 | 1 | 33,572 | 14,768 | 13.87 | 16.0 | 20.00 | 18 | 28,173 | 37,288 |
| S06 | 1 | 27,008 | 13,504 | 8.96 | 15.0 | 60.00 | 18 | 5,687 | 7,528 |
| S07 | 1 | 34,947 | 15,474 | 15.93 | 11.0 | 95.00 | 27 | 4,683 | 6,199 |
| S08 | 1 | 35,393 | 11,798 | 5.46 | 17.0 | 20.00 | 18 | 11,784 | 15,596 |
| S09 | 1 | 66,179 | 22,059 | 10.99 | 17.0 | 20.00 | 18 | 23,718 | 31,392 |
| S10 | 1 | 33,753 | 16,897 | 9.64 | 17.0 | 20.00 | 18 | 20,796 | 27,525 |
| S11 | 1 | 27,547 | 13,785 | 7.30 | 17.0 | 20.00 | 18 | 15,757 | 20,855 |
| S12 | **0** | 10,596 | 8,596 | 4.32 | 17.0 | 20.00 | 18 | 9,321 | 12,337 |
| S13 | 1 | 45,121 | 40,121 | 21.21 | 17.0 | 20.00 | 27 | 45,775 | 60,585 |

Moreover, termination of service is proposed for route P02 since it can be substituted by route P01 with a better performance on operational costs. The ratio between the served and resident population of route R02 (*20221/48804=0.41*) is significantly higher than for route Q02 (*0.32*). The benefit is accompanied by further reductions in external cost based on the comparison between route Q01 and R01. Conversely, it is recommended that service be maintained on route P07, with a short distance (3.5 km) and a small served population (6,788), because it is a subsidized service to a remote area. In fact, route P07 has the highest ration between served population and resident population without substitute, and operates only during peak hours.

There are several input parameters whose effects on the optimal route alignment should be determined via sensitivity analysis. First, difference in bus ridership, the most important factor impacting on bus network design, are chosen to examine the influence on allocation selection. For this purpose, the change percentage of bus ridership, ranging from -20% to 20%, is discussed. Unfortunately, no compromise solution existed when bus ridership reduced by more than 10%. This result indicates that an urban transportation system becomes unsustainable if most users utilize private vehicles rather than buses for their trips. According to Fig. 1, bus ridership does not significantly impact bus accessibility but make operator profit a steep increase. Additionally, reduction of external and user costs, calculated by the aggregate cost for all bus users rather than individual cost, are slightly and positively proportional to bus ridership. Notably, these analytical results suggest that increases in user cost could be compensated for by savings in environmental cost, and urban transportation systems can benefit from the incremental bus ridership.

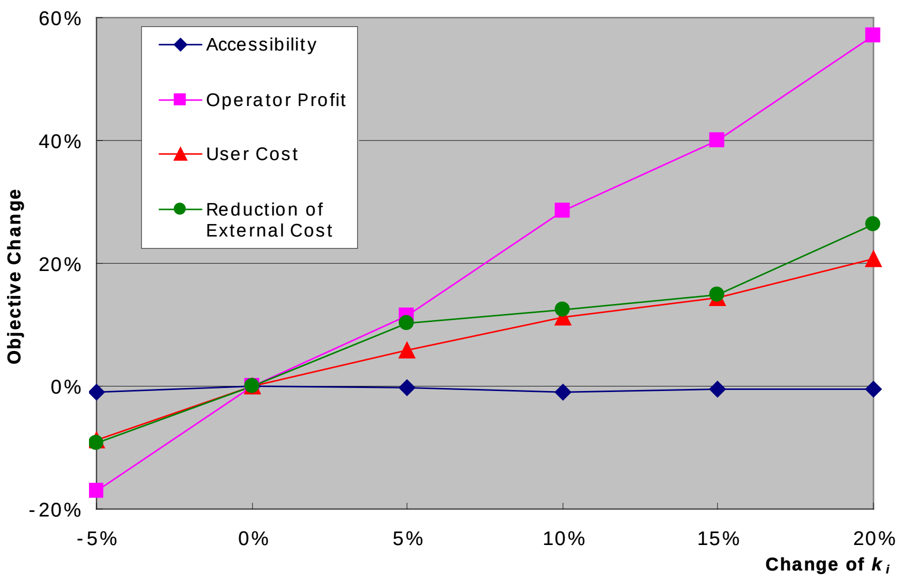


Figure 1 Sensitivity analysis for the bus ridership

Moreover, Fig. 2 reveals the results of sensitivity analysis for bus headway. While bus accessibility does not essentially influenced by bus headway, increasing bus frequency simultaneously reduces user costs and operator profits. The benefits of little headway derive from mitigating external costs and transferring social welfare from a smaller producer surplus (operator profit) to a larger consumer surplus (reduction of user cost), thus promoting a sustainable urban transportation system. The increase of external costs and the diversion of social surplus from consumers to operators resulted from longer bus headway make urban transportation system less equitable. All results of sensitivity analysis are reasonable in practical situations.

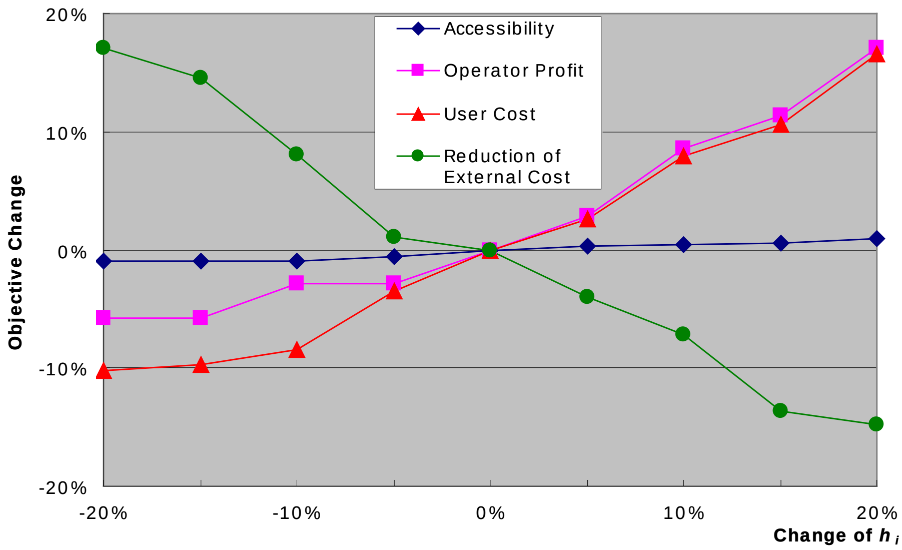


Figure 2 Sensitivity analysis for the bus headway

## 6. CONCLUSION

This study introduces a prototype model to help decision-makers comprehensively understand transportation system behavior and investigate the influence of bus route allocation policies on sustainable urban transportation. Four objectives, including accessibility, operator profit, user cost and the reduction of external cost, referring to criteria of sustainable transportation are formulated and incorporated into a fuzzy programming model. An empirical study using real data from Taoyuan County in Taiwan demonstrates the capabilities of the model. The evidence reveals that inefficient bus route allocation significantly impacts urban transportation system sustainability.

Sensitivity analysis indicates that neither bus ridership nor bus headway significantly impact bus accessibility. Moreover, the increase in the frequency of bus service is helpful to incremental and more equitably distributed social welfare and policies, and thus helps promote bus ridership and urban transportation system sustainability. This study contributes to systems research on urban transportation by establishing a simply constructed model for evaluating bus route alignment policies to improve system performance. Furthermore, the capability of the developed model can be improved through more detailed and comprehensive analysis; for example, the decomposing decision variable from routes to links and the interactions between critical factors including bus headway and ridership.

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# APPENDIX: PARAMETERS OF EMPIRICAL STUDY

| ID | $a_i$ (person) | $a_i - a_i^o$ (person) | $L_i$ (km) | Operation Time (hr) | $h_i$ (min) | $F_i$ (NTD /trip)* | $k_i$ (trips /person) | $C_i^o$ (NTD) | User Cost (NTD /trip) | External Cost (NTD) |
|---|---|---|---|---|---|---|---|---|---|---|
| P01 | 103,115 | 34,371 | 12.38 | 17.0 | 12.00 | 27 | 0.0165 | 44,530 | 66 | 58,938 |
| P02 | 113,881 | 37,960 | 12.71 | 18.0 | 6.25 | 27 | 0.0303 | 92,940 | 63 | 63,011 |
| P03 | 22,772 | 7,591 | 4.90 | 16.0 | 20.00 | 18 | 0.0422 | 11,172 | 45 | 14,786 |
| P04 | 11,152 | 8,152 | 6.20 | 17.0 | 11.25 | 18 | 0.1626 | 23,788 | 41 | 31,484 |
| P05 | 75,438 | 27,719 | 10.32 | 16.5 | 12.50 | 18 | 0.0210 | 34,588 | 52 | 45,778 |
| P06 | 37,947 | 16,974 | 8.00 | 17.0 | 15.00 | 18 | 0.0358 | 23,020 | 48 | 30,469 |
| P07 | 9,360 | 6,788 | 3.50 | 2.5 | 50.00 | 18 | 0.0031 | 444 | 59 | 588 |
| P08 | 27,461 | 14,889 | 11.70 | 17.0 | 14.25 | 18 | 0.0521 | 35,439 | 57 | 46,906 |
| P09 | 39,129 | 16,564 | 6.76 | 17.0 | 15.00 | 18 | 0.0348 | 19,452 | 45 | 25,746 |
| P10 | 35,434 | 15,717 | 10.31 | 17.0 | 20.00 | 18 | 0.0288 | 22,251 | 57 | 29,450 |
| P11 | 28,883 | 12,926 | 8.20 | 12.5 | 84.00 | 18 | 0.0062 | 3,098 | 92 | 4,101 |
| P12 | 80,117 | 45,044 | 15.10 | 12.5 | 84.00 | 18 | 0.0022 | 5,705 | 110 | 7,551 |
| P13 | 18,094 | 5,522 | 3.43 | 13.0 | 87.00 | 18 | 0.0099 | 1,301 | 82 | 1,722 |
| P14 | 40,883 | 19,441 | 7.10 | 17.0 | 20.00 | 18 | 0.0249 | 15,323 | 49 | 20,281 |
| P15 | 25,900 | 10,633 | 9.39 | 13.0 | 98.00 | 18 | 0.0061 | 3,163 | 104 | 4,186 |
| P16 | 46,408 | 15,469 | 13.21 | 13.5 | 116.00 | 18 | 0.0030 | 3,903 | 125 | 5,166 |
| P17 | 26,960 | 4,732 | 11.80 | 13.0 | 35.00 | 18 | 0.0165 | 11,128 | 70 | 14,729 |
| P18 | 30,891 | 10,297 | 15.38 | 13.0 | 60.00 | 18 | 0.0084 | 8,461 | 95 | 11,198 |
| P19 | 22,837 | 9,612 | 5.70 | 17.0 | 15.00 | 18 | 0.0596 | 16,402 | 42 | 21,709 |
| P20 | 26,683 | 4,639 | 8.80 | 16.5 | 25.00 | 18 | 0.0297 | 14,747 | 56 | 19,518 |
| P21 | 23,048 | 8,524 | 7.90 | 6.0 | 120.00 | 27 | 0.0026 | 1,003 | 123 | 1,327 |
| P22 | 31,182 | 15,225 | 8.50 | 13.0 | 78.00 | 18 | 0.0064 | 3,597 | 89 | 4,761 |
| P23 | 28,099 | 15,527 | 5.66 | 15.0 | 60.00 | 18 | 0.0107 | 3,593 | 70 | 4,755 |
| P24 | 33,490 | 15,745 | 5.30 | 16.5 | 18.00 | 18 | 0.0328 | 12,335 | 43 | 16,327 |
| P25 | 26,645 | 9,142 | 7.47 | 13.5 | 54.00 | 18 | 0.0113 | 4,742 | 71 | 6,276 |
| P26 | 33,564 | 20,600 | 6.70 | 16.0 | 35.00 | 18 | 0.0163 | 7,777 | 57 | 10,293 |
| P27 | 45,213 | 15,354 | 8.00 | 15.5 | 35.00 | 18 | 0.0118 | 8,995 | 61 | 11,906 |
| P28 | 50,768 | 14,654 | 6.43 | 15.5 | 77.50 | 18 | 0.0047 | 3,265 | 84 | 4,322 |
| Q01 | 15,971 | 7,324 | 6.38 | 17.0 | 20.00 | 18 | 0.0639 | 13,769 | 47 | 18,224 |
| Q02 | 45,036 | 14,223 | 7.66 | 13.0 | 86.67 | 18 | 0.0040 | 2,917 | 92 | 3,861 |
| R01 | 23,645 | 8,324 | 4.03 | 13.0 | 87.00 | 18 | 0.0076 | 1,529 | 83 | 2,024 |
| R02 | 48,804 | 20,221 | 8.27 | 13.0 | 86.67 | 18 | 0.0037 | 3,150 | 94 | 4,169 |
| S01 | 37,834 | 17,208 | 5.17 | 14.5 | 97.00 | 18 | 0.0047 | 1,962 | 93 | 2,597 |
| S02 | 25,432 | 12,716 | 7.81 | 11.0 | 94.00 | 18 | 0.0055 | 2,321 | 98 | 3,071 |
| S03 | 37,576 | 18,788 | 6.70 | 10.0 | 300.00 | 18 | 0.0011 | 567 | 226 | 751 |
| S04 | 22,533 | 9,267 | 5.49 | 13.0 | 195.00 | 18 | 0.0036 | 929 | 156 | 1,230 |
| S05 | 33,572 | 14,768 | 13.87 | 16.0 | 20.00 | 18 | 0.0286 | 28,173 | 66 | 37,288 |
| S06 | 27,008 | 13,504 | 8.96 | 15.0 | 60.00 | 18 | 0.0111 | 5,687 | 79 | 7,528 |
| S07 | 34,947 | 15,474 | 15.93 | 11.0 | 95.00 | 27 | 0.0040 | 4,683 | 128 | 6,199 |
| S08 | 35,393 | 11,798 | 5.46 | 17.0 | 20.00 | 18 | 0.0288 | 11,784 | 45 | 15,596 |
| S09 | 66,179 | 22,059 | 10.99 | 17.0 | 20.00 | 18 | 0.0154 | 23,718 | 59 | 31,392 |
| S10 | 33,753 | 16,897 | 9.64 | 17.0 | 20.00 | 18 | 0.0302 | 20,796 | 55 | 27,525 |
| S11 | 27,547 | 13,785 | 7.30 | 17.0 | 20.00 | 18 | 0.0370 | 15,757 | 49 | 20,855 |
| S12 | 10,596 | 8,596 | 4.32 | 17.0 | 20.00 | 18 | 0.0963 | 9,321 | 42 | 12,337 |
| S13 | 45,121 | 40,121 | 21.21 | 17.0 | 20.00 | 27 | 0.0226 | 45,775 | 94 | 60,585 |

*Note: * NTD refers to New Taiwan Dollars. The fare is regulated as a fixed value in a specific spatial interval and it would be twice if the trip exceeds the interval. Accordingly, 50% passengers are assumed to take a trip exceeding the interval and the average fare of that route equals 18+0.5*18=27.*