

Highway Investment Planning Model for Equity Issues

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Abstract: In the present study, we revised and expanded the basic model proposed in our previous study to better deal with equity issues in highway investment planning. The issues cover horizontal (intraregional) and vertical (interregional) equity of the accessibility or travel cost for cities as well as the equity of budget allocation among the cities. In this study, more constraints and decision variables were added to the model to handle the exclusive and complementary properties among alternatives. In addition, adjustments for travel cost measures and objective functions are proposed to justify the horizontal and vertical equity. The revised multiobjective model is estimated by fuzzy programming for the highway system in Taiwan. Our results indicate that the model is practical and effective for acquiring reasonable solutions for the goal of efficiency and equity in highway investment planning.

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Introduction

Highway investment planning involves making optimal decisions on the improvement and expansion of a highway network system to meet the growing demand for travel in order to select improvement or addition of links to an existing network under budget constraints for the maximization of social welfare. Traditional methods for solving this problem mostly focus on the issue of effi-

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ciency in cost or travel time instead of the issue of equity. However, for the equilibrium of regional development, the achievement of equity in highway investment is very important.

Equity implies social or political consensus about the fairness of the distribution of costs and benefits of a policy or program (Dear 1978). In the planning of highway investment, the concepts of horizontal equity and vertical equity should be adopted to justify the distribution of travel costs and benefits. Horizontal equity means that persons in like circumstances should be treated identically (Truelove 1993), and vertical equity refers to developing a rationale for allocating services among people who are in different circumstances and have various socioeconomic attributes (Chitwood 1974). In highway investment, horizontal equity should focus on people who live in the same region or in regions with similar circumstances, while vertical equity can focus on people who live in different regions of various sizes, population, income levels, or travel demands.

In planning for highway investment to facilitate equal regional development, we should provide people from every city in every region reasonable accessibility to the regional center. Accessibility can be measured by the travel cost or benefit along the shortest path from the city to the regional center. Based on the idea of horizontal equity, all the main cities in the same region should have the same travel cost or benefit to the greatest extent to connect with the regional center. Also based on the idea of vertical equity, accessibility of each city in different regions is expected to be as reasonably fair as possible. Consequently, while improving accessibility for all the cities to achieve efficient highway investment, we must simultaneously attend to equal accessibility among the cities to maintain both horizontal and vertical equity.

Based on this concept, a basic model was proposed for highway investment planning in our previous study (Feng and Wu 1999). In the present study, we have revised the basic model to make the planning process more reasonable and practical for the equity issues, namely, horizontal and vertical equity in accessibility for cities as well as equity in budget allocation among the cities. In the next section, the traditional methodology for highway investment planning will first be reviewed, and then the basic model used in our previous study, with its estimation algorithm, will be described briefly. After that, the new formulation of a revised model is developed and elaborated and tested in a case study of Taiwan's highway system to prove the contribution of the model. Finally, to expand the revised model for more flexible uses, equity in budget allocation for highway investment is discussed for a case, and potential alternative travel cost/benefit measures are proposed for future study.

Literature Review

Some transportation planners regard determining appropriate highway investment alternatives as a network design problem (NDP). Friesz (1985), Magnanti and Wong (1984), Boyce (1984), and Yang and Bell (1998) conducted comprehensive surveys on the modeling and algorithmic development of mathematical programming-based NDPs.

From those surveys, we observed that cost efficiency in travel time or budget was usually concerned in single-objective NDPs (LeBlanc 1975; Boyce and Jan-

son 1980; Suwansirikul et al. 1987; Chen and Alfa 1991), while various kinds of cost items were proposed in multiobjective NDPs. Current et al. (1987) considered the trade-off between operator cost for paths and user cost to reach the path. Tzeng and Chen (1993) evaluated the social cost by total travel distance, total travel time, and total air pollution. Tzeng and Tsaur's (1997) model concerned total travel time and total investment cost. Friesz et al. (1993) used total user transport costs, total construction costs, total vehicle miles traveled, and total dwelling units taken for rights-of-way. In those studies, researchers pursued the optimization of investment performance for the network only in view of efficiency, without considering equity issues; in general, the issue of equity is seldom mentioned in either single-objective or multiobjective NDPs.

Actually, it is difficult to solve the NDP since two sets of decision makers with different objectives are inherently involved (LeBlanc and Boyce 1986): the road users are engaged in user optimization at the lower level, and the government in system optimization at the upper level. According to past researches [for example, Tzeng and Tsaur (1997)], the bilevel model is nondeterministic polynomial hard (NP-hard), and that problem could not be solved by a polynomial algorithm. Especially for a nonlinear bilevel model, the problem becomes non-convex and the global optimal solution becomes even more unreachable. Therefore, only some heuristic algorithms [for example, Suwansirikul et al. (1987); Chang and Chang (1992)] have been used to solve large-scale NDPs.

Feng and Wu's Previous Study

Basic Model

Feng and Wu (1999) proposed the basic model for highway investment planning to deal with the issues of both equity and efficiency. The formulation of the basic model (M1) is as follows (see the notation):

$$TCM_{ij} = \sum_{l \in SPij} T_l^f = TT_{ij} - \sum_{l \in SPij} T_l^s \cdot x_l = \sum_{l \in SPij} T_l^c - \sum_{l \in SPij} T_l^s \cdot x_l$$

$$\text{Objective_}W_1: \min \frac{1}{\sum N_i} \sum_i \sum_j TCM_{ij}$$

$$\text{Objective_}W_2: \min \frac{1}{\sum N_i} \sum_i \sum_j \left(TCM_{ij} - \frac{1}{N_i} \sum_j TCM_{ij} \right)^2$$

$$\text{Objective_}W_3: \min \frac{1}{N} \sum_i \left(\frac{1}{N_i} \sum_j TCM_{ij} - \frac{1}{\sum N_i} \sum_i \sum_j TCM_{ij} \right)^2$$

subject to $\sum_l A_l \cdot x_l \leq B$; $x_l \in \{0,1\}$, \forall_l .

In this multiobjective model, Objective_ W_1 is to optimize accessibility for all the main cities in all regions, while Objective_ W_2 and Objective_ W_3 optimize horizontal (intraregional) and vertical (interregional) equity by minimizing the difference in accessibility of main cities in the same region and the difference among regions, respectively. Accessibility is measured by the travel time along

the shortest path SP_{ij} from each main city j of region i to the regional center. Actually, travel time serves as an antiaccessibility measure, and we may call it travel cost measure TCM_{ij} .

The $\sum_l A_l \cdot x_l \leq B$ is the budget constraint for investment, and the discrete decision variables x_l are used in the model; x_l will be equal to 1 when link l is selected to be improved. For a practical reason, links of the shortest paths are selected to be the alternatives for improvement, and those shortest paths are determined by the field survey of travel time.

The variable TCM_{ij} is defined as

$$\sum_{l \in SP_{ij}} T_l^f$$

the future travel time along the shortest path SP_{ij} . The value of

$$\sum_{l \in SP_{ij}} T_l^c$$

is derived from the difference between the current travel time

$$TT_{ij} \left(= \sum_{l \in SP_{ij}} T_l^c \right)$$

and the estimated saved travel time

$$\sum_{l \in SP_{ij}} T_l^s \cdot x_l$$

along SP_{ij} . The value of TT_{ij} can be obtained from the field travel survey. Estimation of T_l^s , the time saved by improvement of link l , requires information on future travel speed S_l^f along that link; ($T_l^s = \max(0, T_l^c - D_l / S_l^f)$ where T_l^c is the current travel time along link l , and D_l is the length of link l). The future travel speed could be assumed as a conservative value on account of the increasing demand for highway improvement.

Estimation Algorithm

In Feng and Wu's (1999) previous study, the estimation algorithm for the basic model is fuzzy programming proposed by Zimmermann (1978) and modified by Li and Lee (1990). In many research studies (Bit et al. 1992; Bhattacharya et al. 1992; Lee and Li 1993; Sasaki et al. 1995), fuzzy programming serves as a good method for finding compromise solutions for the multiobjective optimization problem. To follow the procedures of that method, we first need to get the ideal solution $\mathbf{I}^* = (W_1^*, W_2^*, W_3^*)$ and anti-ideal solution $\mathbf{I}^\# = (W_1^\#, W_2^\#, W_3^\#)$ for the basic model. Each W_s^* shows the independently optimal performance of its Objective_ $W_s (= \min W_s, s = 1, 2, 3)$, and each $W_s^\#$ shows the worst possible performance of its objective while optimizing other objectives. Both W_s^* and $W_s^\#$ are used as the reference points to define the membership function $DS_s(W_s)$, which indicates the degree of satisfaction for each Objective_ W_s . The membership functions are defined as follows:

$$DS_s(W_s) = \begin{cases} 1 & W_s \leq W_s^* \\ (W_s^\# - W_s) / (W_s^\# - W_s^*) & W_s^* < W_s \leq W_s^\# \\ 0 & W_s > W_s^\#; \quad s = 1, 2, 3 \end{cases} \quad (1)$$

The degree of overall satisfaction of the optimization is expressed as

$$\lambda = \min_s \{ DS_s(W_s) \mid s = 1, 2, 3 \} \quad (2)$$

Through maximization of the compromise grade λ in two-phase fuzzy programming (see the Appendix), we may get estimation results for the basic model (M1).

Development of Revised Model

Defining Exclusive and Complementary Properties among Alternatives

In the basic model, the links of those shortest paths are treated as the alternatives for improvement by default. Alternatively, any given set of links that serve as the substitute for the shortest path can be allowed to be the alternatives for improvement or addition. However, due to the lack of definition of exclusive alternatives in the basic model, we cannot evaluate those alternatives for the shortest path for a city in the model at the same time.

To evaluate all the alternatives together to optimize the objectives, we revised the basic model by introducing the new decision variable y_{ijk} to accommodate the exclusion property among alternatives for the shortest path for a city. The variable $y_{ijk} = 1$ while the alternative k for the shortest path SP_{ij} connecting the city to the regional center is chosen; otherwise, $y_{ijk} = 0$. The exclusive property of alternatives is specified in the constraint $\sum_k y_{ijk} = 1 \forall_{i,j}$. With this modification, we may simultaneously evaluate the links of all the substitution paths in the model and still follow the exclusive property among alternatives.

Besides, complementary alternatives should also be defined in the model to generate reasonable solutions. In real cases, relative links should be improved together to enhance highway performance, and they must be defined as complementary alternatives. Therefore, the new constraints $x_{l'} = x_{l''}$, $\exists_{l', l''} \in C_m$, \forall_m were added to the model to handle the complementary property; C_m represents the set of relative links that should be improved or added together to raise highway performance. Judgment for the set of relative links is dependent on professional experience, and those sets could be given for the model.

Adjusting Travel Cost Measures in Equity Objectives

In the basic model, travel time serves as the travel cost measure in all of the objectives, but it is not always a good measure for horizontal (intra-regional) equity, especially for big differences in travel distance from every city to the regional center. For similar reasons, travel time is not an appropriate measure for vertical (inter-regional) equity, especially when the area size of each region varies greatly. Average travel time from every city to the regional center is usually longer in a region with a large area than in a region with a small area.

To revise the model, $HTCM_{ij}$ and $VTCM_{ij}$ respectively serve as the travel cost measure for horizontal and vertical equity instead of TCM_{ij} . Both $HTCM_{ij}$ and $VTCM_{ij}$ are given as L_{ij}/TCM_{ij} where L_{ij} is the length of the chosen shortest path SP_{ij} . After this adjustment, both horizontal and vertical equity are measured by average travel speed rather than travel time. Average travel speed is a good indicator of highway service quality and a reasonable measure of equity in highway investment, even for regions of various shapes or area sizes.

Justifying Objective Formulas in Terms of Membership Functions

In the basic model (M1), the objective functions for horizontal and vertical equity are formulated in the form of an average square of the difference in travel cost measure. Actually, we intended to evaluate equity in terms of the difference rather than the square of the difference in travel cost measure. The reason for using the square operation is to eliminate the deduction effect of the signs (positive or negative) while accumulating items of difference for each city and region.

While using fuzzy programming for the basic model, the membership function $DS_s(W_s)$ defined in Eq. (1) indicates the degree of satisfaction for each Objective_ $W_s (= \min W_s)$. Using the form of square in objective function W_s ($s = 2, 3$) will underestimate the real degree of satisfaction for the achievement of that equity, as illustrated in Fig. 1. Owing to the increasing and concave-up curve of square function $W_s = (W'_s)^2$, the value of $DS_s(W_s)$ for the original objective function W_s is less than the value of $DS'_s(W'_s)$ for the new objective function $W'_s (= \sqrt{W_s})$. To refine the underestimated degree of satisfaction, we revised the objective function W_s ($s = 2, 3$) by applying operation of the square root (fractional exponent = 1/2) to their original formula; then the membership functions for these two objectives can genuinely reflect the extent to which horizontal and vertical equity can be achieved.

Formulation of Revised Model

With the above modifications, formulation of the revised model (M2) becomes the following:

$$TCM_{ij} = \sum_k \left[\sum_{l \in SP_{ijk}} (T_l^f) \right] \cdot y_{ijk} = \sum_k \left[\sum_{l \in SP_{ijk}} (T_l^c - T_l^s \cdot x_l) \right] \cdot y_{ijk}$$

$$HTCM_{ij} = L_{ij}/TCM_{ij}; \quad VTCM_{ij} = L_{ij}/TCM_{ij}; \quad L_{ij} = \sum_k L_{ijk} \cdot y_{ijk}$$

$$\text{Objective_} W_1 : \min \frac{1}{\sum N_i} \sum_i \sum_j TCM_{ij}$$

$$\text{Objective_} W_2 : \min \left[\frac{1}{\sum N_i} \sum_i \sum_j \left(HTCM_{ij} - \frac{1}{N_i} \sum_j HTCM_{ij} \right)^2 \right]^{1/2}$$

$$\text{Objective_} W_3 : \min \left[\frac{1}{N} \sum_i \left(\frac{1}{N_i} \sum_j VTCM_{ij} - \frac{1}{\sum N_i} \sum_i \sum_j VTCM_{ij} \right)^2 \right]^{1/2}$$

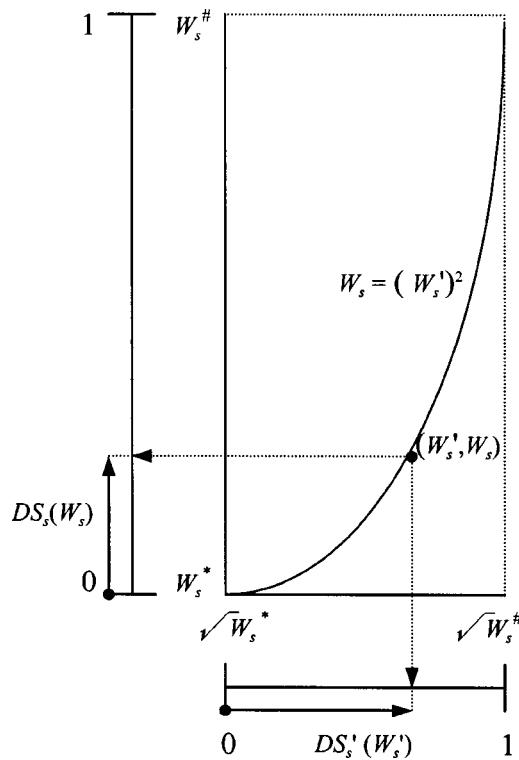


Fig. 1. Degree of satisfaction $DS_s(W_s)$ is less than $DS'_s(W'_s)$

subject to $\sum_l A_l \cdot x_l \leq B$; $x_l \in \{0,1\}$, \forall_l ; $y_{ijk} \in \{0,1\}$, $\forall_{i,j,k}$; $\sum_k y_{ijk} = 1$, $\forall_{i,j}$; and $x_{l'} = x_{l''}$, $\exists_{l',l''} \in C_m$, \forall_m .

In the revised model, Objective_ W_1 is to optimize the cost efficiency measured by average travel time from all the main cities to the regional centers, and Objective_ W_2 and Objective_ W_3 aim to optimize the horizontal and vertical equity, which are measured respectively by the intraregional and interregional differences in average travel speed from every main city to the regional center.

The symbols used in the model are listed in the notation; most of them are the same as those of the basic model. The new symbol SP_{ijk} represents the set of links that comprise the alternative k for the shortest path connecting the main city j in region i to the regional center; L_{ijk} represents the length of the shortest path SP_{ijk} , and L_{ij} is the length of the chosen alternative for SP_{ij} .

In summary, the revised model has the following key features in formulation:

1. With the new decision variables $y_{ijk} \in \{0,1\}$, constraints $\sum_k y_{ijk} = 1$, $\forall_{i,j}$, and $x_{l'} = x_{l''}$, $\exists_{l',l''} \in C_m$, \forall_m for handling the exclusive and complementary property among the alternatives, the model becomes more practical for the highway investment problem in the real world;

Table 1. Regions and Main Cities in Western Taiwan

Region	Regional center	Main city
North Region	Taipei City	Keelung City, Taoyuan City, Hsinchu City, I-lan City
Middle Region	Taichung City	Miaoli City, Nantou City, Changhwa City, Douliou City
South Region	Tainan City ^a	Chiayi City, Shinying City
	Kaohsiung City ^a	Pingtung City

^aSouth Region has two regional centers.

2. With the adjusted travel cost measure $HTCM_{ij} = VTCM_{ij} = L_{ij} / TCM_{ij}$, the horizontal and vertical equity are measured by the average travel speed, so the model becomes more flexible and reasonable for dealing with regions of various shapes or area sizes in highway investment planning; and
3. With operation of the square root for both original equity objectives, membership functions can genuinely reflect the degree of satisfaction of horizontal and vertical equity. Based on the justified membership function, the model can yield reasonable compromise solutions in view of both efficiency and equity.

Case Study for Taiwan's Highway System

The revised model is tested in highway investment planning for western Taiwan, which covers three regions with four regional centers and 11 main cities (Table 1). The highway network with 1,929 links (Fig. 2) is built in the geographic information system (GIS) using TransCAD, and the 1998 travel time data for links are collected by a field survey and stored in the GIS. Four types of highways are included in the test case: national, provincial, county, and connector highways. TransCAD was used to generate the shortest path that connects each main city to the regional center. After this procedure, the number of links that comprise all the shortest paths is 120, as illustrated in Fig. 3.

For testing, the values of parameters for the input of the revised model (M2) are given as follows: A_l = cost needed for improvement of link l ($= 5/\text{km} * D_l$, if link l is national or connector highway $A_l = 1/\text{km} * D_l$, otherwise), D_l = length of link l ; S_l^f = future travel speed along link l while it is improved ($= 80$ km/h, if link l is national highway $S_l^f = 45$ km/h, otherwise); and B = total budget ($= 200$).

We minimized the objectives W_s ($s = 1, 2, 3$) one by one and got the ideal solution $\mathbf{I}^* = (46.94, 7.11, 0.024)$ and anti-ideal solution $\mathbf{I}^\# = (56.31, 13.77, 5.27)$. Then the two-phase fuzzy programming was processed to derive the compromise solutions. Each process was executed by the Solver of Excel on a personal computer Pentium 3-733, and its computing time was less than 5 min.

According to the planning results (Table 2) from the revised model, the budget for highway investment is almost fully used, and the travel time saved for all the cities to the regional centers is 117.04 min in total. With highway investment, we may improve cost efficiency (from 59.85 to 49.21 min), horizontal equity (from 14.75 to 8.66 km/h), and vertical equity (from 3.88 to 1.08 km/h).

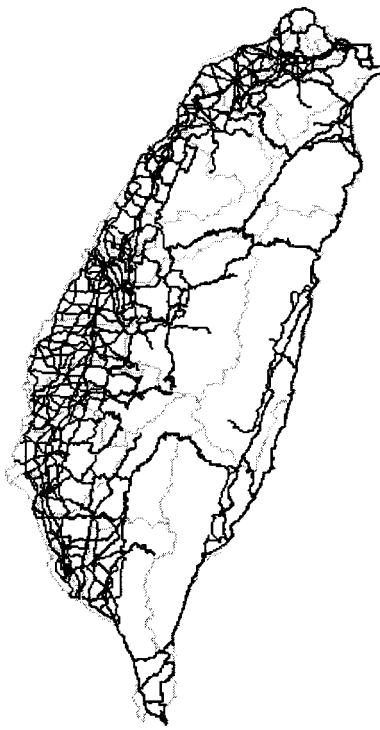


Fig. 2. Highway network in Taiwan in 1998

In the case study, the revised model not only improved the average travel speed of the shortest paths in every region, but also reduced the intraregional and interregional differences in average travel speed to improve horizontal and vertical equity (Table 3). In either the same region or different regions, the average travel speed of each shortest path connecting main cities to regional centers becomes closer through use of the revised model.

After adjusting the travel cost measure from travel time to travel speed in view of equity, the revised model has obtained properties superior to those of the basic model. To illustrate these properties, we compared the revised model with the basic model in the case study. The results (Table 4) indicate that the cost efficiency in terms of average travel time that resulted from the basic model ($W_1 = 50.34$ min) is similar to that obtained from the revised model (49.20 min), but the basic model yielded some unreasonable results in terms of equity. For example, with the basic model, the average travel speed was greatly improved from 66.38 to 82.04 km/h from Shinying to Tainan, but was only slightly improved from 26.58 to 27.84 km/h from Pingtung to Kaohsiung, even though these cities belong to the same region. Referring to Table 4, the revised model yields better results than the basic model because the service quality (average travel speed) of each shortest path has been equalized to some extent, as is also illustrated in Fig. 4.

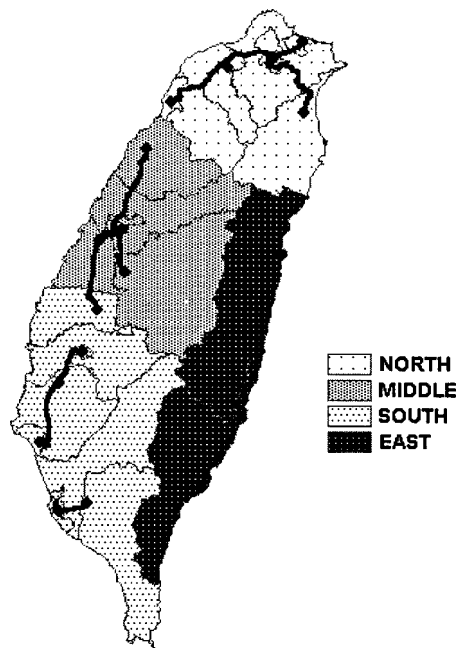


Fig. 3. Shortest paths with 120 links

This case study has proved that the revised model can be solved efficiently by fuzzy programming, and in addition, the estimated results indicated that it is a practical and effective model for acquiring reasonable compromise solutions for efficiency and equity of highway investment.

Expansion of Revised Model

Equity in Allocation of Budget for Highway Investment

Allocation of the budget for highway investment is another issue of equity but is not mentioned in the basic model. This issue can be considered by restricting the

Table 2. Summary of Results from Revised Model

Process results	Initial state	Minimum W_1	Minimum W_2	Minimum W_3	First phase	Second phase
Budget used	0.00	199.85	198.20	184.750	195.15	199.60
Time saved	0.00	141.94	78.33	38.830	114.89	117.04
Value of W_1 (minutes)	59.85	46.94 ^a	52.72	56.310	49.40	49.21
Value of W_2 (Δ km/h)	14.75	11.95	7.11 ^a	13.770	8.80	8.66
Value of W_3 (Δ km/h)	3.88	5.27	2.64	0.024 ^a	1.36	1.08

^aOptimal value.

Table 3. Effects of Revised Model on Regional Equity

Region	Average travel speed (km/h)		Intraregional difference (Δ km/h)		Interregional difference (Δ km/h)	
	Before	After	Before	After	Before	After
North	44.74	57.80	11.79	7.77	4.29	0.40
Middle	49.90	57.38	13.37	7.93	0.87	0.83
South	53.59	59.84	19.11	10.52	4.56	1.63

upper bound of the budget share for each city according to its socioeconomic attributes (for example, population, household income, household tax payment, or travel demand). The decision maker may adjust the budget share in response to some social or political consensus to achieve equity in highway investment. Here is an example.

We may use either household income or tax payment to calculate the percentage share of financial contribution CSH_{ij} ($\sum_{i,j} CSH_{ij}=1$) for each city j of region i . We may also use either population or travel demand to calculate another percentage share of travel need NSH_{ij} ($\sum_{i,j} NSH_{ij}=1$) for the city. The upper bound of budget UB_{ij} for improving the shortest path SP_{ij} can be assigned as the value of $\max(B*CSH_{ij}, B*NSH_{ij})$ where B is the total budget. Taking into consideration both the financial contribution and travel need of each city, the following budget-share constraints and total budget constraint ($\sum_i A_i \cdot x_i \leq B$) can be joined together in the revised model to improve the equity in budget allocation:

Table 4. Comparison between Results of Basic Model and Revised Model

Shortest path (main city \leftrightarrow regional center)	Travel time (min)			Average travel speed (km/h)		
	Initial status	Basic model	Revised model	Initial status	Basic model	Revised model
Keelung \leftrightarrow Taipei	42.56	31.47	26.70	35.03	47.37	55.85
Taoyuan \leftrightarrow Taipei	51.50	36.64	41.01	48.46	68.13	60.87
Hsinchu \leftrightarrow Taipei	72.26	64.50	66.39	62.39	69.91	67.92
I-lan \leftrightarrow Taipei	141.45	100.87	100.48	33.08	46.40	46.58
Miaoli \leftrightarrow Taichung	50.80	46.06	47.71	61.59	67.93	65.59
Nantou \leftrightarrow Taichung	38.95	37.61	34.71	48.98	50.73	54.97
Changhwa \leftrightarrow Taichung	35.49	35.50	22.16	28.40	28.40	45.49
Douliou \leftrightarrow Taichung	69.57	66.23	66.48	60.63	63.68	63.45
Chiayi \leftrightarrow Tainan	65.37	54.78	65.08	67.83	80.94	68.13
Shinying \leftrightarrow Tainan	42.03	34.00	42.03	66.38	82.04	66.38
Pingtung \leftrightarrow Kaohsiung	48.51	46.12	28.53	26.58	27.84	45.00
Average	59.86	50.34	49.20	49.03	57.58	58.20

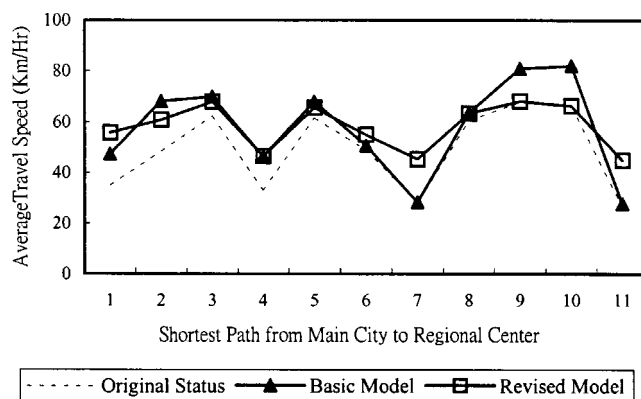


Fig. 4. Comparison between results of basic model and revised model

$$\sum_{l \in SP_{ij}} A_l \cdot x_l \leq UB_{ij}, \quad \forall_{i,j} \quad (3)$$

For testing this idea, the revised model with these new constraints was processed using the data from the above case study. We calculated the CSH_{ij} and NSH_{ij} by the 1998 household income and population of each city. With $CSH = (0.17, 0.15, 0.19, 0.04, 0.04, 0.04, 0.10, 0.03, 0.12, 0.03, 0.09)$ and $NSH = (0.17, 0.14, 0.16, 0.04, 0.04, 0.05, 0.10, 0.05, 0.12, 0.03, 0.10)$, the upper bound of the budget for each city was derived, and the budget-share constraints were added to the revised model.

However, after including the constraints for equity in the budget allocation, the performance of the objectives in the revised model could be sacrificed to some extent. Furthermore, the total budget could not be fully used through the enforcement of budget-share constraints. In this case, all the objective values ($W_1 = 51.95, W_2 = 10.74, W_3 = 1.47$) are worse than those ($W_1 = 49.21, W_2 = 8.66, W_3 = 1.08$) of the original revised model (M2). The time saved from highway investment is only 86.85 min, and only 149/200 of the total budget is used. According to the results obtained from the original revised model (M2), the time saved is 117.04 min, and the budget is almost fully used (Table 2).

Alternatives of Travel Cost/Benefit Measure

In the revised model, the travel time serves as the travel cost measure TCM for cost efficiency in highway investment. Alternatively, the average travel speed is chosen to be an adjusted TCM for horizontal and vertical equity. To make the revised model more flexible in practice, the planners may redefine the TCM. The travel time weighted by the travel demand would probably be considered an alternative to the TCM. The demand is increasing for the time saved by highway improvement, so it might be inappropriate to use a fixed demand (Asakura and Sasaki 1990), while using an elastic demand is not a good approach either be-

cause the latter could result in undesirable solutions involving less investment. The objective function could be minimized just through minimization of travel demand instead of travel time. Therefore, the alternative of TCM must be chosen deliberately.

Furthermore, instead of the TCM in the revised model, the consumers' surplus in travel demand could be an alternative to the travel benefit measure TBM for the highway investment. The use of consumers' surplus reflects an economic tradition that public investments should be operated to maximize social benefits. This measure has been suggested by many researchers (Kocur and Hendrickson 1982; Williams and Lam 1991; Yang and Bell 1997) to evaluate the benefits of transport systems but has never been proposed for the equity issue in highway investment. We may investigate alternative travel cost/benefit measures for the revised model in the future study.

Conclusion

The aim of achieving equity in highway investment is to provide people from every city in every region reasonable accessibility to the regional center. Accessibility can be measured by the travel cost or benefit along the shortest path from the city to the regional center. To facilitate equal regional development, optimization of highway investment considers not only cost efficiency but also horizontal and vertical equity.

In planning highway investment, horizontal and vertical equity should be considered to minimize the intraregional difference in accessibility for the main cities in the same region and to minimize that interregional difference among regions, respectively.

In this paper, we have proposed revising the basic model of our previous study (Feng and Wu 1999) to make the planning process more reasonable and practical for both efficiency and equity issues in highway investment. The modification has improved the capacity of the model in the following procedures:

1. Necessary decision variables and constraints are included to handle the exclusive and complementary properties among alternatives.
2. Travel cost measures are adjusted as the average travel speed for horizontal and vertical equity to deal with regions of various shapes or area sizes.
3. Both objective functions for equity are revised by applying operation of the square root to their original formulas to refine the underestimated degree of satisfaction for intended objectives.

To demonstrate the planning process, a case study of highway investment for western Taiwan was formulated in the revised model. Through the case study, we found the following outcomes:

1. The revised model can be solved efficiently by fuzzy programming;
2. The revised model can yield practical and reasonable results to achieve cost efficiency and horizontal and vertical equity in highway investment; and
3. The revised model can yield better results than the basic model in terms of equity.

For expansion of the revised model, equity in budget allocation is considered by restricting the upper bound of the budget share for each city according to its

socioeconomic attributes. However, according to our test, the budget-share constraints could lower achievement of the objectives.

To make the revised model more flexible in application, alternative travel cost/benefit measures were discussed and the consumers' surplus in elastic travel demand was proposed as a travel benefit measure in the future study.

Appendix

The details of two-phase fuzzy programming are described as follows:

For maximization of compromise grade λ , the basic model (M1) is transformed into the following problem in the first phase:

Maximum λ subject to $\lambda \leq (W_s^\# - W_s)/(W_s^\# - W_s^*)$, $s = 1, 2, 3$; $\sum_l A_l \cdot x_l \leq B$; $x_l \in \{0, 1\}$, \forall_l ; and $\lambda \in [0, 1]$.

After obtaining the optimal compromise grade λ in the first phase, a fully compensatory operator averaging is introduced in the second phase to find a nondominated solution by restricting $\lambda_s \geq \lambda$, $s = 1, 2, 3$. Then maximum $(\lambda_1 + \lambda_2 + \lambda_3)/3$ subject to $\lambda_s \leq (W_s^\# - W_s)/(W_s^\# - W_s^*)$, $s = 1, 2, 3$; $\sum_l A_l \cdot x_l \leq B$; $x_l \in \{0, 1\}$, \forall_l ; and $\lambda_s \in [0, 1]$, $s = 1, 2, 3$.

By solving this problem, all the value of compromise grade λ_s , compromise objective W_s , and link improvement decision variable x_l can be acquired.

Notation

The following symbols are used in this paper:

- A_l = cost needed for improvement of link l ;
- B = total budget;
- C_m = m th set of given links that are complementary;
- D_l = length of link l ;
- HTCM $_{ij}$ = adjusted travel cost measure for horizontal equity;
- L_{ij} = length of chosen alternative of shortest path SP_{ij} ;
- L_{ijk} = length of shortest path SP_{ijk} ;
- N = number of regions in problem;
- N_i = number of main cities in region i (regional center is not counted);
- S_l^f = future travel speed along link l while it is improved;
- SP_{ij} = set of links that comprise shortest path connecting main city j of region i to regional center;
- SP_{ijk} = set of links that comprise alternative k of shortest path SP_{ij} ;
- T_l^c = current travel time along link l ;
- T_l^f = future travel time along link l while it is improved;
- T_l^s = saved travel time along link l while it is improved ($T_l^s = \max(0, T_l^c - D_l/S_l^f)$);
- TCM $_{ij}$ = travel cost measure for city j in region i ;
- TT_{ij} = current travel time along SP_{ij} ;
- VTCM $_{ij}$ = adjusted travel cost measure for vertical equity;
- x_l = decision variable for improvement of link l ; and
- y_{ijk} = decision variable for choice of alternative k of SP_{ij} .

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