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Modeling of Bicycle Route and Destination Choice Behavior for Bicycle Road Network Plan

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A new modeling method that describes bicycle route or destination choice behavior is presented. Although there are numerous bicycle users in Japan, the urban transportation planning process often treats bicycles and pedestrians as a single mode. Therefore, a methodology by which to evaluate and analyze bicycle demand needs to be developed. A bicycle route choice model that describes the relationship between route choice behavior and facility characteristics (e.g., road width or sidewalk) has been proposed. This model can be applied to the planning of bicycle road networks. The data from a bicycle trip survey conducted in Japan are used to study the characteristics of the model. The model is applied to study access railway station choice (destination choice). The model can produce a better fit than can a conventional model.

In many developed countries, the bicycle has become an important transportation mode in recent years because of environmental problems or because of the increase in energy consumption associated with the use of automobiles. In European countries especially, the bicycle is treated as one of the major transportation modes in city areas, and there are many bicycle road networks. In Japan, although there are numerous bicycle users, urban transportation plans often treat bicycles and pedestrians as a single mode. In fact, adequate bicycle facilities do not exist in urban areas. Most projects or studies on bicycle transportation focus on the bicycle parking facilities near railway stations. For this reason, bicycles are mainly used as feeder transportation between homes and railway stations. In Japan, the "bicycle problem" is usually caused by bicycles that are left parked around stations. Only a few studies have been conducted on evaluation methods or demand analyses of bicycle road networks.

Many studies have analyzed automobile traffic demand modeling or level of service (LOS) of bicycle lanes [e.g., Landis (*1*) and Epperson (*2*)], whereas few behavioral model–based studies on bicycle or pedestrian road networks have been done. Since there are enormous numbers of bicycle or pedestrian routes in urban areas, a typical discrete choice model would not sufficiently explain actual behavior. Bovy and Stern (*3*) introduced the work of Ben-Akiva et al. (*4*) as an applicable route choice model. Called the labeling approach, the model proposed a method by which the number of alternatives could be reduced by the choice set generation function. The labeling approach can be applied to bicycle route choice models. However, this approach has the following shortcomings: the model has the independence from irrelevant alternatives property, and the choice set generation function is complicated.

Another methodology used to describe bicycle or pedestrian behavior is traffic network equilibrium modeling. However, a link performance function for bicycle or pedestrian facilities may not be clearly defined, because there are few congestion effects on a link velocity generally. A new modeling method is needed by which route choice behavior can be described and the bicycle or pedestrian road network evaluated.

In this study, a methodology for modeling bicycle route choice and access railway station choice behavior is suggested. This methodology can be used for planning bicycle road networks in urban areas. Data obtained from surveys in Japan are used to analyze the characteristics of the model.

CURRENT BICYCLE PLANNING IN JAPAN

In Japan, bicycles and pedestrians are often treated as a single mode. Few bicycle roads (Figure 1*a*) have been constructed in urban areas or in suburban areas to accommodate recreational uses. Consequently, most bicycle roads are constructed as bicycle and pedestrian roads, known as shared-use paths in the United States (Figure 1*b*). As for bicycle and pedestrian roads, the boundary between bicycle and pedestrian is not clearly defined (Figure 1*c*); moreover, bicycles are permitted on roads, sidewalks, and bicycle paths in Japan. Conflicts occur frequently and bicycles cannot travel unimpeded, especially on sidewalks. However, in recent years, the bicycle has gained considerable attention within the transportation policy area because its use can reduce automobile usage and relieve environmental problems. At this time, bicycle road networks are being planned and evaluated in several cities in Japan. On the other hand, huge numbers of bicycles left around railway stations cause serious congestion. Because of this, some decentralization of bicycle feeder demand should be considered. If adequate bicycle road network plans are introduced, the centralization problem will be solved.

OVERVIEW OF STUDY AREAS AND SURVEYED DATA

Characteristics of Study Areas

Bicycle travel behavior was surveyed in the city of Utsunomiya in 1996, and in the city of Kurume in 1995. Utsunomiya is the capital of the Tochigi prefecture, with a population of about 427,000. The person-trip survey was conducted in 1992, and the modal shares found are shown in Figure 2. The topography is flat, and the modal share of bicycles is higher than found in other cities in Japan. A diagram of

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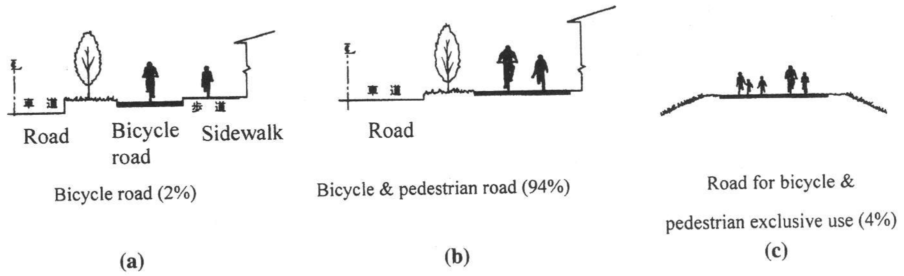

Bicycle road (2%)

(a)

Bicycle & pedestrian road (94%)

(b)

Road for bicycle & pedestrian exclusive use (4%)

(c)

FIGURE 1 Definition of bicycle road in Japan: (*a*) bicycle road; (*b*) bicycle and pedestrian road; (*c*) road for exclusive use by bicycles and pedestrians. (Pedestrian road means sidewalk.)

Utsunomiya is presented in Figure 3. There are two major railway stations, and a large school zone with seven to eight large junior high and high schools is located in the western section. During the morning peak, many students ride bicycles from the stations to their schools. In fact, the majority of bicycle users in Utsunomiya are high school students.

Kurume is the third largest city in Fukuoka Prefecture, with a population of 230,000 (a map of Kurume is shown in Figure 4). The topography is also flat, and the modal share observed from the person-trip survey in 1993 is summarized in Figure 2. There are three major railway stations (Figure 4). Many people commute to the central city of Fukuoka by using one of these stations, so there are many bicycles left around the stations. The feeder demand is especially concentrated at Kurume Station; therefore, some plans for switching concentration from Kurume Station to the other stations are considered. Construction of adequate bicycle roads is regarded as one of the policies. The railway station choice model (destination choice model), which also describes bicycle route choice behavior, can be used to evaluate this policy.

Summary of Bicycle Trip Surveys

Bicycle trip characteristics in Utsunomiya were surveyed in 1996, and those in Kurume were surveyed in 1995, in order that actual bicycle routes could be identified and the planned bicycle road network evaluated. In Utsunomiya, the survey questionnaires were handed out at high schools in the school zone, at bicycle parking facilities in the central business district (CBD), and at railway stations. In Kurume, questionnaires were handed out only at the three railway stations. The questionnaires asked the individual's characteristics and his or her usual bicycle routes and also asked him or her to draw the routes on a map. Total sample sizes were 502 in Utsunomiya and 252 in Kurume. The characteristics of the sample are summarized in Figure 5.

Bicycle Trip Characteristics

The links that exceed 10 m in width (excluding sidewalk width) in Utsunomiya are shown in bold lines in Figure 6. In the surveys, the bicycle routes for both trip directions (i.e., going and returning) were recorded. Figure 7 shows bicycle traffic volumes for going trips for all trip purposes in Utsunomiya. The majority of trips were found to be in the east-west direction, connecting JR Utsunomiya station, the CBD, and the school zone.

The relationship between link volumes (Figure 7) and road width (Figure 6) also shows that bicycle users tend to use roads with sufficient width.

Table 1 shows the detour rate for each trip purpose in Utsunomiya and in Kurume. The detour rate is the ratio of the actual trip length obtained from the survey to the length of the minimum path calculated by the computer. The actual trip length surveyed in this study is the length between home and school, office, or railway station; thus, some chained trips may be included. Therefore, the detour rate of the return trip is higher than that of the going trip, and the detour rate of the shopping trip is the highest of all trip purposes. Basically, the high detour rate suggests chained trips or intrinsic preference for wider roads. The comparison of Utsunomiya with Kurume shows that the characteristics of the detour are almost the same.

BICYCLE ROUTE CHOICE MODEL

Basic Model Concept

Bicycle link volumes might be calculated by the trip assignment models that were originally developed to estimate automobile traffic volumes. However, the latter often fail to incorporate the relationship between bicycle traffic volume and bicycle speed. In other words, the link performance function for bicycles is not defined. Another method of calculating bicycle link volumes is to assign bicycles to

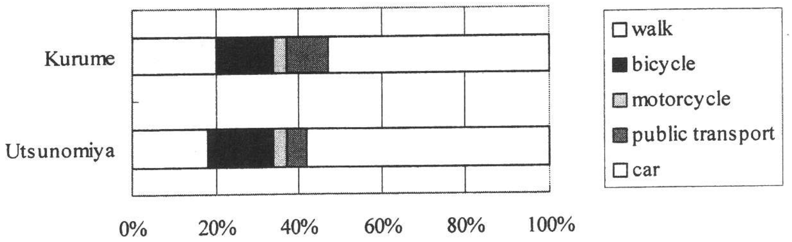

FIGURE 2 Modal shares in Kurume and Utsunomiya.

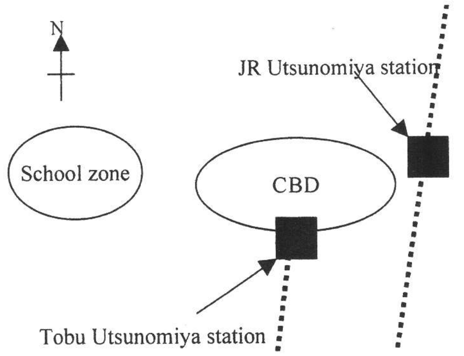

FIGURE 3 Utsunomiya, Japan (CBD = central business district; JR = Japan Railway).

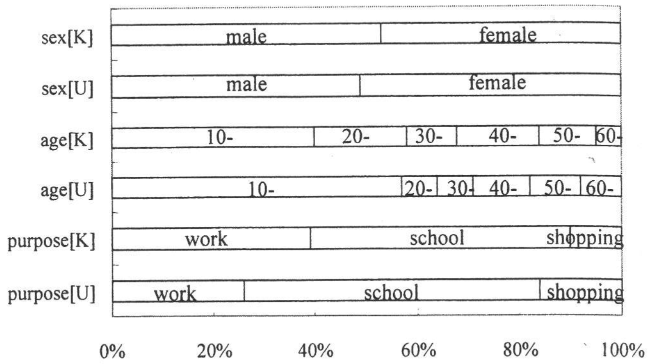

FIGURE 5 Sample characteristics for Utsunomiya and Kurume (U = Utsunomiya; K = Kurume).

the minimum distance paths without considering link performance. This method also has a shortcoming, because bicycle travelers do not always choose the minimum path. These characteristics of the existing methods warrant the development of a new modeling methodology suitable for bicycle route choice behavior. The following route choice model is therefore proposed. Its basic idea is similar to the impedance function in the choice set generation function proposed by Ben-Akiva et al. (*4*); however, its formulation is different and simple.

First, the actual trip length of the nth sample (X_n) is defined as

$$X_n = \sum_a \delta_{na} \cdot l_a, \tag{1}$$

where δ_{na} is the dummy variable (if the nth sample passes the ath link, δ_{na} is equal to 1; otherwise, δ_{na} is equal to 0) and l_a is the length of the ath link.

Figures 6 and 7 suggest that bicycle users tend to choose links with an ample width or a wide sidewalk. This means that users may perceive trips on wide roads to be shorter than they actually are. Under the assumption that perceived link length is affected by the link characteristics, the following relationship is proposed:

$$l^*_{an}(\theta) = l_a \cdot \exp\left[-\sum_k \theta_k z_{ank}\right] \tag{2}$$

where

$l^*_{an}(\theta)$ = the cognitive length of the ath link of the nth sample,
z_{ank} = the kth attribute (e.g., road width or width of sidewalk) for the ath link of the nth sample, and
θ_k = unknown parameter for the kth attribute.

Equation 2 illustrates that the physical attributes of a link affect the cognitive length of the link. Therefore, cognitive link length may be different for each traveler. The length of the cognitive minimum path of the nth sample, $Y_n(\theta)$, is defined as follows:

$$Y_n(\theta) = \sum_a \delta^*_{na}(\theta) \cdot l_a \tag{3}$$

where $\delta^*_{na}(\theta)$ is equal to 1 if the nth sample's cognitive minimum paths with parameter θ include the ath link, otherwise $\delta^*_{na}(\theta)$ is equal to 0.

If all the parameters equal 0 [i.e., $l^*_{an}(0)$], then $Y_n(\theta)$ becomes the ordinary minimum path calculated from the actual link length.

The unknown parameters, θ, in Equations 2 and 3, can be estimated by various methods. In this study, the following estimation procedure was employed.

Duplicate rate is introduced as a measure to be fitted. The duplicate rate is defined as

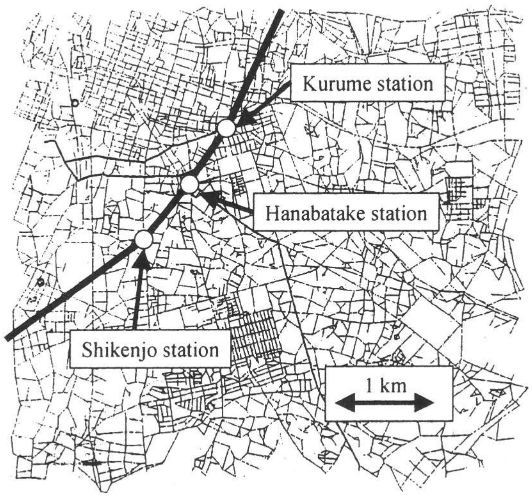

FIGURE 4 Kurume, Japan.

FIGURE 6 Links with widths more than 10 m.

FIGURE 7 Bicycle traffic volumes for going trips for all trip purposes, Utsunomiya.

$$D_n(\theta) = \frac{\sum_a \delta_{na} \cdot \delta^*_{na}(\theta) \cdot l_a}{X_n} \qquad (0 \le D_n(\theta) \le 1) \tag{4}$$

The numerator is the sum of the lengths of the links that are included in both the actual route taken as well as the cognitive minimum path determined using some arbitrary values for θ. The denominator is the length of the actual route taken (Figure 8). Therefore, if the duplicate rate is close to 1, then the model is describing the actual behavior of the *n*th sample well. Weighted duplicate rate is defined next, in order that the parameters for all samples may be estimated. The actual length, calculated by Equation 1, was used as the weighting factor.

$$D(\theta) = \frac{\sum_n X_n \cdot D_n(\theta)}{\sum_n X_n} = \frac{\sum_n \sum_a \delta_{na} \cdot \delta^*_{na}(\theta) \cdot l_a}{\sum_n X_n} \tag{5}$$

The unknown parameters, θ, are estimated by maximizing $D(\theta)$. And the value of $D(\theta)$ is named *D*-value.

Analysis of Model Characteristics with Single Parameter

The parameters, θ, are determined by maximizing $D(\theta)$ in Equation 5. However, the statistics of networks are generally discrete. Hence, Equation 5 cannot be differentiated with respect to θ. In this section, the value of the objective function, Equation 5, is studied so that the characteristics of the model may be clarified. The following variables, which describe road characteristics, were selected, and the change in $D(\theta)$ with respect to θ was observed.

Case 1: dummy variable, δ_{na}, is equal to 1 if the road width is more than given value; dummy variable, δ_{na}, is equal to 0 otherwise.

Case 2: dummy variable, δ_{na}, is equal to 1 if the sidewalk width is more than given value; dummy variable, δ_{na}, is equal to 0 otherwise.

In Japan, there are few bicycle roads in urban areas. Therefore, no variables that measure the quality of bicycle roads can be introduced. Instead, road or sidewalk width can be used as proxy variables. Of course, a continuous variable—for example, road width itself—can be introduced, but some variable transformation should then be required, and thus the above dummy variable is examined. Bicycle users in Utsunomiya usually use a sidewalk where possible. Other appropriate LOS variables suggested in Landis (*1*) or Epperson (*2*) should be examined. The dummy variables may be one of the alternative variables that explain the LOS. Figure 9 displays the curves of the objective functions. That the functions are not smooth and include several local optimum points is understood. The estimated parameters are identified by finding the maximum points of the curves in Figure 9. It is found that the differences of *D*-value are not so large around the maximum points; however, the differences cannot be tested statistically. In the future, a statistic should be developed for the purpose of identification of the global maximum points. Results are summarized in Table 2.

Since the duplicate rate is an index of probability, the maximum likelihood method may be applied to conduct the estimation. Unfortunately, the data from the survey include some samples that have no duplicate links. If the data contain even one sample with a duplicate rate of 0, the maximum likelihood method cannot be applied. Hence, the estimation procedure described above was adopted.

A performance measure similar to the aggregate log-likelihood ratio can be calculated from the result in Table 2. For example, the aggregate log-likelihood ratio of all purposes is about 0.2, which can be calculated as

$$\rho^2 = 1 - \frac{\ln 0.5839}{\ln 0.5113} = 0.1979 \tag{6}$$

This value was found to be satisfactory, especially compared with the researchers' experience with ordinary discrete choice models.

Table 2 also shows that the weighted duplicate rates, or *D*-values, for the models using sidewalk width and road width are quite similar. The purpose of the study is to develop an evaluation procedure for bicycle network planning in an urban area. In Japan, construction or improvement of a sidewalk is easier than widening a road; for that reason, the sidewalk width, rather than the road width, is included in the subsequent algorithm.

TABLE 1 Detour Rate for Each Trip Purpose, Utsunomiya and Kurume

	Utsunomiya		Kurume	
Trip purpose	Going	Coming back	Going	Coming back
All	1.07 (502)	1.08 (494)	1.06 (252)	1.09 (252)
Work	1.06 (138)	1.07 (133)	1.05 (101)	1.08 (101)
School	1.06 (286)	1.07 (284)	1.06 (113)	1.09 (113)
Shopping	1.10 (78)	1.14 (77)	1.06 (38)	1.16 (38)

( ): Number of samples

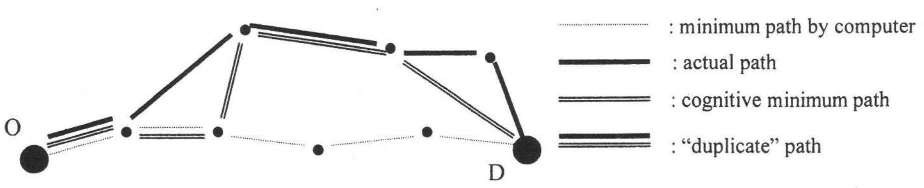

FIGURE 8 Diagram of model definitions (O = origin; D = destination).

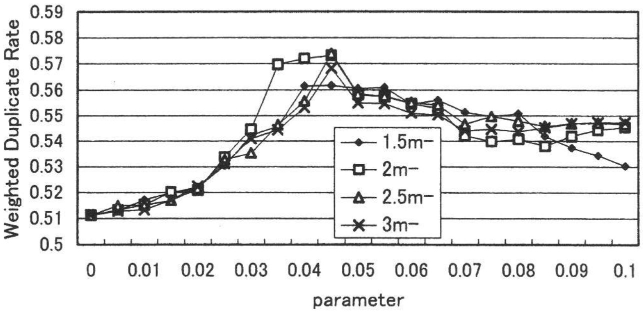

FIGURE 9 Relationship between parameter and weighted duplicate rate (sidewalk width).

Model Estimation Using Genetic Algorithm

Since the objective function of the proposed model is not unimodal, the parameters of the model were estimated with one variable by a heuristic method as described in the previous section. However, it is difficult to estimate more than two parameters by the heuristic method. In this paper, the genetic algorithm (GA) for calibration of models with many variables is introduced. One of the introduced variables is sidewalk width and another is a dummy variable. The dummy variable indicates whether the bicycle user uses Orion Street or not. An arcaded shopping street, Orion Street is located in the center of Utsunomiya. In the morning, all the shops are closed and cars are prohibited from using the street, which provides a safe environment for students to ride bicycles.

Here, each chromosome corresponds to an unknown parameter. The GA calculation conditions are shown in Table 3. Michalewicz (*5*) provides explanation of the technical terms in Table 3.

A model of all trip purposes is examined. It includes the sidewalk width and Orion Street dummy variables for each trip purpose, but other variables were not examined because of a lack of LOS data in this study. The estimation result is summarized in Table 4.

ACCESS RAILWAY STATION CHOICE MODEL

Necessity and Structure of Access Railway Station Choice Model

In Kurume, many commuters access one of the three railway stations by bicycle. All stations have bicycle parking lots, but most people concentrate at Kurume Station, which is the largest of the three stations. Therefore, serious congestion problems occur at the station, and some decentralization plans are required. One of the policies is to construct adequate bicycle roads to the other two stations. An access railway station choice model that involves bicycle road conditions can be used to evaluate this policy.

In this paper, the access railway station model, which has a hierarchical structure shown in Figure 10, is developed. The hierarchy is an analogy of the nested logit model. The lower level model is the bicycle route choice model proposed in the previous section, and the upper level is the conventional destination choice model. This model can describe bicycle road conditions and railway station conditions, such as number of parking lots or accessibility of the parking lots to the platforms.

Estimation Result

The model parameters of the lower and upper levels were estimated separately. First, the bicycle route choice model proposed in the previous section was estimated by the heuristic method. The result was as follows:

$$l_a^*(\theta) = l_a \times \exp[-(0.11 \cdot z_{a1} + 0.11 \cdot z_{a2})] \quad (7)$$

TABLE 2 Estimated Parameters for Single-Variable Model

Trip Purpose	Sidewalk width	Road width	Ordinary minimum path
All	0.045 [2.5m] (0.5839)	0.115 [10m] (0.5814)	(0.5113)
Work	0.045 [2.0m] (0.6010)	0.210 [8m] (0.5969)	(0.5322)
School	0.045 [2.5m] (0.5798)	0.115 [10m] (0.5961)	(0.5154)
Shopping	0.180 [2.5m] (0.5366)	0.225 [10m] (0.5424)	(0.4506)

[ ]: Threshold width for dummy variable that results in maximum D-value

( ): D-value ('Weighted Duplicate Rate')

TABLE 3 Calculation Conditions of GA

Number of bits for each chromosome	7
Population size	20
Number of generations	50
Crossover method	one-point crossover
Mutation rate	0.03
Scaling parameter	2.0 (linear scaling)

TABLE 4 Parameter Estimation Result by GA

Variable	Parameter
Sidewalk width [over 2.5m] (work)	0.1758
Sidewalk width [over 2.5m] (school)	0.1406
Orion Street dummy (school)	0.2148
Sidewalk width [over 2.5m] (shopping)	0.1016
Orion Street dummy (shopping)	0.3242
Initial Duplicate Rate (ordinary minimum path)	0.5113
Duplicate Rate (result of convergence)	0.5905

[ ] : Threshold width for dummy variable

( ) : Trip purpose

where z_{a1} is equal to 1 if the ath link has a pedestrian sidewalk and otherwise is equal to 0, and where z_{a2} is equal to 1 if the width of the ath link is over 25 m and otherwise is equal to 0.

By use of this model, the shortest cognitive path to the three railway stations is calculated for each sample. Then the access railway station choice model, the upper level model, is estimated. The form of the upper level model is the conventional logit model. The estimation results are summarized in Table 5. So that the proposed model may be compared with a conventional model, an access railway station choice model that uses the actual shortest path instead of the cognitive shortest path is estimated (see Column 3, Actual Distance Model, in Table 5). The results show that the proposed model has a better fit. Moreover, the sign of the actual distance parameter is not significant, whereas the cognitive distance parameter has sufficient statistical significance.

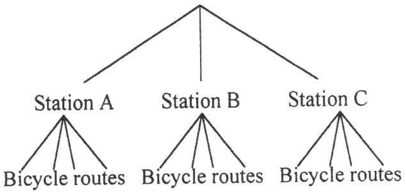

FIGURE 10 Structure of access railway station choice model.

If this model is used, bicycle access demand can be forecasted for improvement of bicycle facilities, such as construction of a bicycle road or bicycle parking lot. Each station's access demand was estimated by use of the trip generation volume of each zone in the studied area. Whether the switching of demand of a station's access behavior is derived from the construction of sidewalks or the widening of road widths was examined. Space limitations for this paper preclude the authors from including the results, which are available in Suzuki et al. (*6*).

CONCLUSIONS

The key results from this study are summarized as follows:

1. The proposed model can describe bicycle route choice and access railway station choice behavior sufficiently. From the examination of characteristics of the model, appropriate parameter estimation methods were developed and their efficiency was tested.
2. Data from actual bicycle behavior surveys were studied, and the procedure for bicycle demand analysis (survey, model building, and demand forecasting) was suggested.

The topics to be studied further are as follows:

1. One of the parameter estimation methods, GA, gives an approximate solution. Other methods that can provide a strict global solution

TABLE 5 Parameter Estimation Results of Access Railway Station Choice Model (*t*-Statistics)

	Cognitive distance model	Actual distance model
The shortest cognitive distance (m) [generic]	-0.00356 (-7.5)	- - -
The shortest actual distance (m) [generic]	- - -	0.02116 (0.1)
Hanabatake station dummy* [Hanabatake]	-1.710 (-2.2)	-2.647 (-3.6)
Shikenjo station dummy* [Shikenjo]	-2.101 (-2.9)	-1.831 (-3.4)
Constant [Kurume station]	2.663 (5.2)	1.305 (4.6)
Constant [Hanabatake station]	0.606 (1.3)	0.567 (1.7)
Number of samples	252	252
Likelihood ratio	0.3876	0.1078
Hit ratio (%)	80.2	69.1

* If the parking lot is located at the opposite side of the station from the origin, the dummy variable = 1, otherwise the dummy variable = 0.

should be developed. Also, a statistical index that indicates the significance of each parameter should be developed.

2. The model can also be applied to pedestrian route choice. The combinations of the route, mode, and destination choice models can be explored.

3. So that more precise data that can express LOS of a bicycle road may be introduced, additional surveys about road structure or the traffic situation (automobile traffic volume, speed, and so forth) should be conducted.

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