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A COMPARATIVE STUDY ON THE INDIVIDUAL BEHAVIOURAL MODE CHOICE MODEL FOR WORK TRIPS IN MIYAZAKI AND JOHOR BAHRU CITY

By Takeshi KUROKAWA, Haruo ISHIDA** and Mok You CHUA****

The issue of model transfer for the Individual Behavioural Model remains unresolved, This study is an attempt to test the transferability of work trips choice models of three travel modes of drive alone, bike and bus, calibrated at two geographical locations, namely the City of Miyazaki, Japan and Johor Bahru, Malaysia, Aggregate data show that both cities have very similar urban population sizes, growth trends and transport mode shares for their daily work trips. Using samples from recent person trips surveys, independent mode choice models are calibrated and their structures compared. Three statistical tests are performed to further ascertain the degree of transferability of the two models.

1. INTRODUCTION

Since its development, the individual travel behavioural model has proved to be an effective modelling technique for understanding and forecasting travel demand behaviour[6),10),12),15)]. Amidst its many successess, however, the issue of model transfer remains a heated debate inspite of many empirical studies[4),8),9),17)].

This paper has three objectives, firstly it attempts to apply the behavioural travel model to worktrips mode choice study in a developing country. Secondly, it seeks to compare and understand the differences or similarities if any that exist for work trips mode choice between Miyazaki and Johor Bahru City. Finally, this paper analyses the degree of model transferability of these two study areas.

The Individual Behavioural Model under study in this paper is the work trips mode choice model for the three modes of drive alone, bike and bus. As this is one of the early attempts in applying this new modelling technique to a developing country like Malaysia, work trips are preferred over the other trips as routes and destinations are easier to trace for the work trips. The specific property called the Independence from Irrelevant Alternatives of the Individual Behavioural Model[11),12)], allows us to select the more significant and important transport modes in the study areas without any loss of precision yet saving a great deal of time and cost in collecting and processing an otherwise larger load of data. The three chosen modes consist of the two main private modes and the main public transport mode of travel in both cities.

Johor Bahru City, located at the southern tip of Peninsular Malaysia, and Miyazaki City in eastern Kyushu are selected for this comparative study by virtue of their comparable urban size and similar mode

* Member of JSCE, Dr. Eng., Professor, Institute of Socio-Economic Planning, University of Tsukuba
** Member of JSCE, Dr. Eng., Assist. Professor, Institute of Socio-Economic Planning, University of Tsukuba
*** MSc. Planning, Fukuyama Consultant International

share characteristics for the total work trips. As can be seen in Table 1, both cities have an urban population of approximately a quarter of a million. The availability of up-to-date person trip survey data for the two cities further help in justifying their selection.

Table 1 Urban Area Population and Worktrips Mode Share for Miyazaki and Johor Bahru.

City	Urban Population	Work Trips Mode Share in %					
		Car	Bike	Bus	Wk/Cy	Truck	Others
Miyazaki	265 000	53.9	9.2	8.4	21.1	6.7	0.7
J. Bahru	247 000	41.1	24.4	8.4	17.4	5.7	3.0

Source : MCTPS, JUTMS.

2. DATA

A 12.5 % sample person trip survey was designed and conducted in Miyazaki in the second half of 1981 for the Miyazaki Comperhensive Transport Planning Study (MCTPS) by the Prefectural Department of Urban Planning. A total of 41 000 valid observations and 110 000 trip records were collected and stored in magnetic tapes. In Johor Bahru, a home interview survey was conducted as a supplementary survey to the vehicular owner OD survey for the Johor Bahru Urban Transport Master Plan Study (JUTMS) by the Japan International Cooperation Agency (JICA) in the first half of 1982. Though the OD survey has a 11.3 % sample, the home interview survey has only a 2.0 % sample yielding a total of about 10 000 observations and 14 000 trip records. Although, there are some differences in the questionnaire format for the two studies but basic tripmaker's household and socio-economic data are common.

The data available from these two transport studies are however not the ideal disaggregate data in the strict sense of the word as the origin and destination of each trip record are coded in the small traffic zone numbers instead of their exact locations. This limitation of the data as recorded on the available magnetic tapes hampers the preparation of accurate travel distances or times. The preparation of these level of service data however, need to be prepared by means of average travel speeds and road network data. Though travel times are reported in the surveys, they are not used for reason of their subjectivity[11,14] Moreover, times are rounded up to 10 minutes in the Johor Bahru survey. For Miyazaki, the average car travel speeds on the national routes are available from the results of actual car travel speed survey as reported in the "Existing Traffic Condition Survey 1981". No such similar survey on travel speeds exist for Johor Bahru and hence they have to be estimated from the results of the trip assignment in JUTMS. For bike, travel speed is estimated on site. It was found that bike travel speed is higher on the suburban roads than in the CBD areas. Consequently, a two tier travel speeds are estimated for preparing the level of service (LOS) data for bike. Distances travelled by car or bike were taken from road network base maps of scale 1 : 10 000 and the travel costs were computed using average fuel consumption rates of vehicles and the prevailing costs of gasoline in both cities. Out-of-vehicle travel time, such as times consumed in parking the vehicle and walking to the office were not prepared since exact parking lot and work places are impossible to locate with the given data.

In Miyazaki, a comprehensive bus timetable and fare charge booklet is published by the Miyako Bus Company. This booklet proved very useful in the preparation of the LOS data for bus. The printed bus time tables were checked by actual riding on some selected routes around the city during the site visit. Bus waiting time especially on overlapping routes and bus transfer time were likewise surveyed and estimated on site. Unfortunately, no such detailed and useful data are available for the case of Johor Bahru. Bus travel times had to be prepared from average bus travel speeds and bus routes surveyed in the JUTMS. The results of these surveys show that bus waiting time in Johor Bahru vary according to route location and ranges frem 2-3 minutes in the CBD to 25-30 minutes in the rural outskirts. The reason for such an astonishing variations in bus waiting times is the failure of buses to follow the scheduled timetables which is in turn caused by sporadic boarding or alighting of passengers in the rural outskirts or bus jamming at bus stops in the CBD areas. Bus waiting and transfer times in Johor Bahru were therefore estimated from the results of a rather constrained survey on buses, In both cities, out-of-vehicle travel time for bus is taken to be the sum of walking time to and from the nearest bus stops, waiting and transfer times.

In preparing the LOS data, the obvious setback in maintaining high accuracy of data by using only the zonal tripmaker records is the inability to pin-point the exact route taken by each tripmaker. In this study, therefore the guiding principle is to use the shortest travel time path. This problem is also the main reason why we have eliminated car shared ride trips in this study. The preparation of the LOS data is a tedious yet paramount task.

The sampling procedure employed in this study is the exogenous sampling method[2),3)]. High trip attraction zones, mainly the CBD or suburban centres were identified and designated as the destination zones ; while all traffic zones in the study area were treated equally as the trip generation zones. A total of 272 zone pairs were hence created for Miyazaki and 297 for Johor Bahru. All the available trip observations for these zone pairs of work purpose, that utilise either one of the three modes as the principal travel mode, in the morning peak were extracted from the master tapes. This sampling process yields a sample of 842 and 565 for Miyazaki and Johor Bahru study areas respectively. This sampling procedure is efficient in extracting the appropriate trip samples for the purpose of this study while cutting a reasonable amount of work load on LOS data preparation and avoid accruing further inaccuracies in trying to establish trip destination points for the large but low attraction zones, yet maintaining a reasonably wide range of trip lengths and variations in the samples.

We have difficulty concerning the determination of choice sets. Although the zonal trip maker records contain the information on car and bike ownership, there is no information on bus availability. Furthermore we cannot derive bus availability from network data because of lack of intormation on exact origin and destination points. Therefore if a bus is available at a zone centroid, all the samples in the zone were assumed to be able to use a bus and vice versa. Whereas "car" and "bike" can be eliminated from individual choice sets when necessary.

3. TRAVEL CHARACTERISTICS OF THE SAMPLE OBSERVATIONS

The exogenous sampling procedure inevitably produces more bus and less car trips in the samples for the simple reason that the CBD and the suburban centres are better served with bus routes. This explains why the mode share of the samples as shown in Fig. 1 has a higher bus share as compared to that for the overall work trips mode share in Table 1 above.

Comparing the two samples, the Johor Bahru sample has a slightly higher bike share and a smaller car share than the Miyazaki sample. The correlative characteristics of each socio economic features of the sampled observations to the three modes were analysed. The graphical distribution of the mode share in % by sex, age and occupation groups of the two samples for example, are shown in Fig. 2, 3, and 4.

Bike usage is equally shared by both the sexes in Miyazaki while females in Johor Bahru almost do not use bike to work. Passenger car usage is high among males in both study areas (Fig. 2), as well as among the 30-39 and 40-49 age groups (Fig. 3). Bus on the other hand is most popular among the elder age groups in Miyazaki but among the younger age groups in Johor Bahru. The V-shaped curves for

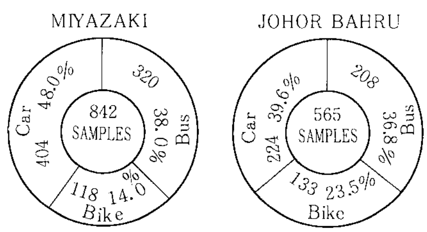

Fig. 1 Mode Shares of the Samples.

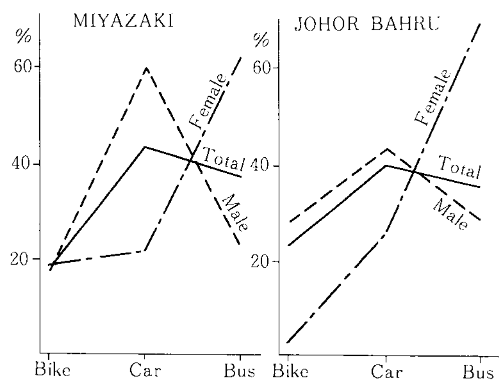

Fig. 2 Sex with Mode Share.

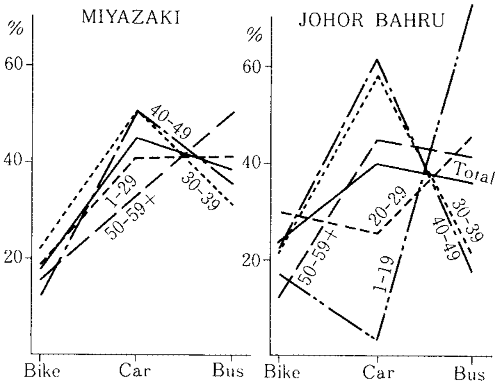

Fig. 3 Age Groups with Mode Share.

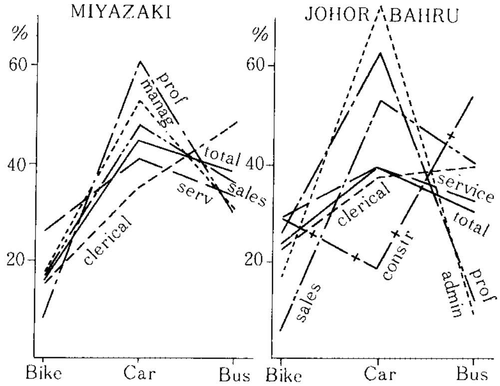

Fig. 4 Occupation Groups with Mode Share.

the younger age groups in Johor Bahru is an obvious difference from its Miyazaki counterpart. Furthermore, mode shares in general varied greatly among the age groups in Johor Bahru compared to those of Miyazaki which displayed rather similar shares.

A similar mode share characteristics can be seen for the occupation groups distribution in Fig. 4, Large differences in mode shares exist among the different occupation groups in Johor Bahru compared to those of Miyazaki. In both areas, however, the managerial and professional groups tend to prefer passenger car while the service group chooses bike more than the other occupation groups, Bus pre-ferences are however, different between the two areas. While bus is the most popular among clerical workers in Miyazaki, it is among the construction workers in Johor Bahru instead.

The results of this analysis show that there are both similarities as well as differences in the way socio-economic indicators affect travel mode choice behaviour in both study areas. On the whole, however, mode shares between different socio-economic groups tend to vary more in Johor Bahru than those in Miyazaki. This is to say that socio-economic features of tripmakers in Johor Bahru would seem to exert a greater influence on work trips mode choice.

4. ESTIMATION OF MODELS

The socio-economic indicators of the selected samples were extracted from the master tapes, recoded and matched up with the computed LOS data. This final data file is hence ready for model estimation using the multinomial logit model[3,11,12,15]. A total of 14 and 11 different combinatory specification of the independent variables are tried for Miyazaki and Johor Bahru respectively. With the usual most likelihood method of estimation employed in the logit model, the exogenous sampling was able to produce efficient and consistent yet unbiased estimates[2]. From these estimation results, an assessment on the model's specifications, parameter vector estimates and the goodness of fit indicators, the best performing model for each study area are selected[11,16] and shown in Table 2.

Both the selected models possess significant t-values for their estimated parameters. χ^2 and $\bar{\rho}^2$ values are significantly high in both models, indicating their satisfactory goodness of fit of the model specification. The two models also perform very well in mode choice prediction, with a total % correct of 75.1 % for Miyazaki and 82.5 % for Johor Bahru. In comparing the variable specifications of the two models, however, socio-economic variables are predominant in Johor Bahru Model while the LOS variables in addition are both found to be significant in the Miyazaki Model. Out-of-pocket travel cost (OPTC) for the three travel modes and out-of-vehicle travel time for bus (BOVTT) are all fairly significant independent variables in addition to the important mode specific variables such as MSEX (sex of biker) and CDES (car destination) in the Miyazaki Model. The Johor Bahru Model however, has only

Table 2 The Results of Model Estimation.

MIYAZAKI			JOHOR BAHRU		
Variables*	Parameter	t-values	Variables	Parameter	t-values
OPTC	−0.0031	−1.91			
MSEX	1.2693	4.98	MSEX	3.5892	3.48
MAGE	0.5146	1.99			
M A	0.0480	11.98	M A	0.0850	9.32
CSEX	0.9590	3.87			
CAGE	0.6929	3.11	CPIHH	2.0953	3.78
C A	0.0209	5.88	C A	0.0188	1.97
CDES	−2.3527	−8.43	CDES	0.9648	−1.64
BOVTT	−0.0984	−3.36	BOPTC	0.0057	−1.21
BRES	0.7884	3.42	BOCC	0.6667	2.04
MCON	−4.6749	−9.38	MCON	5.1763	−4.91
CCON	−1.1477	−2.19	CCON	−0.2915	−0.37
Sample Size	842		Sample Size	565	
x^2	798.89		x^2	866.96	
d. f.	10		d. f.	7	
$\bar{\rho}^2$	0.455		$\bar{\rho}^2$	0.710	
% Correct Bike	48.3		% Correct Bike	69.9	
% Correct Car	84.7		% Correct Car	80.6	
% Correct Bus	76.2		% Correct Bus	86.1	
% Correct Total	75.1		% Correct Total	82.5	

*Prefix =M : Bike, C : Car, B : Bus,
OPTC =Out of Pocket Travel Cost,
BOPTC =Out of Pocket Travel Cost for Bus,
BOVTT =Out of Vehicle Travel for Bus,
MSEX =Sex for Bike,
(1 : Male, 0 : Female)
MAGE =Age for Bike
(1 : 1-29, 0 : otherwise)
MA =Bike Availabilitv in %
$\left(\frac{\text{\# of bikes in the household}}{\text{\# of licence holder in the household}}\right)$
MCON =Constant for Bike,
CCON =Constant for Car,
BRES =Residential Location,
(1 : New Resideдtal Area)
(0 : Otherwise)
CSEX =Sex for Car,
(1 : Male, 0 : Female)
CAGE =Age for Car,
(1 : 30-49, 0 : otherwies)
CA =Car Availadilitv in %,
$\left(\frac{\text{\# of cars in the household}}{\text{\# of licence holders in the household}}\right)$
CDES =Destination for Car,
(1 : CBD, 0 : otherwise)
CPIHH =Position in the Household,
(1 : head, 0 : otherwise)
BOCC =Occupation Group for Bus,
(1 : construction, 0 : otherwise)

the BOPTC as the only LOS variable while MSEX, CDES, CPIHH (positon in the household), BOCC (occupation group of bus rider) are rather important socio-economic variables. The predominance of socio-economic variables in the Johor Bahru Model is consistent with the deduction from the results of the travel characteristics analysis described above.

5. MODEL TRANSFERABILITY TESTS

The comparative analysis of the two best performing models above has largely revealed their low geogroaphical transferability. Besides the difference in the specification sets, the magnitudes of the estimated parameter vectors for such common variables as MSEX, CDES, MA (bike availability) varied significantly.

To vigorously test their degree of transferability, three statistical tests were performed and the results of these tests are briefly described below ;

Test-1 : The estimated parameter vectors for each variable in the Miyazaki Model are directly "transferred" to the Johor Bahru data without model re-estimation and vice versa*. The goodness of fit indicators and the % correct of the "transferred" models are compared with the original models (Table 3).

Table 3 Results of Test-1.

Indicators		MIYAZAKI Model	Transferred JOHOR BAHRU Model	JOHOR BAHRU Model	Transferred MIYAZAKI Model
χ^2		787.09	384.56	862.72	758.05
$\bar{\rho}^2$		0.448	0.213	0.707	0.616
% Correct	Bike	50.3	66.0	69.9	52.6
	Car	84.9	85.2	86.6	86.6
	Bus	74.0	52.3	85.1	84.1
	Total	74.7	69.3	82.1	77.7

Table 4 Results of Test 2.

Indicators		Transfered JOHOR BAHRU Model		Transfered MIYAZAKI Model	
		Parameter	t-value	Parameter	t-value
α		0.6018	16.38 ($\alpha=0$) 10.84 ($\alpha=1$)	1.2947	16.06 ($\alpha=0$) 3.66 ($\alpha=1$)
β_b		−4.5115	−16.36	−4.0731	−15.41
β_c		−2.220	−13.42	−3.5801	−14.19
χ^2		385.25		782.34	
$\bar{\rho}^2$		0.220		0.636	
% correct	Bike	36.7		61.7	
	Car	72.6		83.5	
	Bus	67.5		77.9	
	Total	64.4		76.3	

χ^2 and $\bar{\rho}^2$ values for the "transferred" Johor Bahru Model are exactly halved from the original Miyazaki Model. The % correct for bus has dropped from 74.0 % to 52.3 %. For the 'transferred' Miyazaki Model, the results suggest a relatively high degree of transferability.

Test-2 : The estimated parmeter vector of the Miyazaki Model θ^m are applied to the Johor Bahru variables X^j for a re-estimation of the parameter vector α and β_i in,

$$P_i = \frac{e^{\sum_k \theta_k{}^m X_{ik}{}^j + \beta_i}}{\sum_j e^{\sum_k \theta_k{}^m X_{jk}{}^j + \beta_j}}$$

The results of this test are shown in Table 4. The value of α in both "transferred" Models are different

Table 5 Results of Test-3.

Variables		MIYAZAKI Model	transfered to J. B.	Variables		J. BAHRU Model	transferred to MIYAZAKI
		Parameter	Parameter			Parameter	Parameter
OPTC		−0.0033 (−2.042)	−0.0006 (−0.206)	MSEX		3.4969 (3.402)	1.1361 (4.740)
MSEX		1.2005 (4.779)	3.8961 (3.590)	M A		0.0849 (9.349)	0.0487 (12.06)
MAGE		0.5221 (2.036)	0.3932 (1.259)	CDES		−1.062 (−1.836)	−2.4618 (−8.866)
M A		0.0477 (11.95)	0.0820 (9.307)	CPIHH		2.1013 (3.805)	0.8046 (3.258)
CSEX		0.9055 (3.695)	0.5233 (0.649)	C A		0.0179 (1.891)	0.0197 (5.548)
CAGE		0.6547 (2.970)	1.4947 (2.649)	BOPTC		−0.0057 (−1.245)	−0.0047 (−3.741)
C A		0.0200 (5.705)	0.0231 (2.384)	MCON		−5.2901 (−5.03)	−3.9377 (−10.64)
CDES		−2.4023 (−8.67)	−1.0343 (−1.74)	CCON		−0.4219 (−0.55)	−0.1601 (−0.36)
BOVTT		−0.0796 (−2.81)	0.0006 (0.045)				
MCON		−4.6481 (−9.43)	−5.5015 (−4.74)				
CCON		−0.9922 (−1.93)	−0.4708 (−0.46)				
χ^2		787.09	858.59	χ^2		862.72	766.10
d. f.		9	9	d. f.		6	6
$\bar{\rho}^2$		0.448	0.702	$\bar{\rho}^2$		0.707	0.437
% Correct	Bick	50.3	71.4	% Correct	Bike	69.9	51.0
	Car	84.9	86.2		Car	86.6	82.8
	Bus	74.0	85.1		Bus	85.1	72.8
	Total	74.7	82.3		Total	82.1	73.4

( ) : t-value

* The alternative specific variables of BRES in the Miyazaki Model and BOCC in the Johor Bahru Model are each deleted during the transfers as there are no similar variables in the corresponding data sets.

from the desirable value of unity for the case of perfect model transferability. χ^2 and $\bar{\rho}^2$ for the "transferred" Johor Bahru Model are halved from the original Miyazaki Model. For the "transferred" Miyazarki Model, the results again tend to show a relatively high degree of transferability.

Test-3 : A similar set of variable specification from the Miyazaki best model is transferred to the Johor Bahru data for model reestimation and vice versa. The results are presented in Table 5. The parameter vectors hence estimated for each model are expressed as a simple ratio to a common parameter value for ease of comparative analysis. Although the 'transferred' model possess satisfactory χ^2, $\bar{\rho}^2$ and % correct values, further examination of the results indicates that BOVTT variable in the 'transferred' Johor Bahru Model for example has failed to come up with the correct sign for its parameter. Furthermore, the t-values of OPTC, CSEX and BOVTT are significantly low. The relative magnitudes of the parameter vectors also vary greatly between the original and the 'transferred' model. The same is also true for the 'transferred' Miyazaki Model. An addition test for the distribution of the two sets of parameters is also done and the results are shown in Table 6 (The Hotteling's Test). The F statistics computed for both cases are over the 1 % critical level indicating the significant dissimilarity of the two sets of parameter distributions.

Table 6 Results of Hotteling's Test.

Statistics	Transferred MIYAZAKI Model	Transferred JOHOR BAHRU Model
F-Statistics	3223.33	262.14
d.f.	11,1397	11,1397

Although the superficial results of Test 1 and 2 seem to show the high transferability of the Miyazaki Model to Johor Bahru, it is too simplistic to conclude that the Miyazaki Model is highly transferable. Considering the results of the comparative analysis in section 4 and Test 3, which are inconsistent with those of Test 1 and 2, we can say that the model transferability between two cities is low. The reasons behind the Miyazaki Model having a higher transferability than the Johor Bahru Model are worth exploring.

6. REASONS FOR LOW TRANSFERABILITY

It is immensely interesting to analyze the factors causing the low transferability of the two models and the relatively higher transferability of Miyazaki Model. We have indicated in the course of this study that Johor Bahru and Miyazaki City have very similar population, size of urban area and mode shares of the total daily work trips. The analysis of travel characteristics, however, has showed that there are some disparate effects of socio-economic factors on the travel mode choice between two cities. The estimated models futher showed that model structure are in fact quite dissimilar, with the Johor Bahru Model having a large bias towards the socio-economic variables.

The next main factor that accounts for the low model transfarability seems to lie in the difference in level of urban transport service between two cities. In Miyazaki, bus route coverage is wide and there are even direct services plying between the CBD and the new suburban residential estates. There are designated exclusive bus lanes in the CBD area, hence we find that the bus mode in Miyazaki is given the chance to compete with the private modes. The same cannot be said for Johor Bahru. No exclusive bus lanes are provided in the CBD area. Bus fleets are poorly maintainned resulting in frequent breakedowns. Moreover bus route coverage in Johor Bahru is poor. Commuters who happen to live far from certain corridors served by buses would have no choice but to consider private modes. The choice for the latter modes would depend much on the individual's socio-economic status and, hence, the bias of these factors in the Johor Bahru Model.

We can point out another reason for the low model transferability : the differences in perception of time value and travel attitude of the people in two cities. There are qualitative features that are difficult to quantify, but people in urban areas in developing countries like Johor Bahru still regard cars as a status symbol[18]. Such attitude is not conspicuous in Miyazaki. some car owners in fact still choose to use the public mode.

Finally, the LOS variables could be inaccurate, particularly in the case of Johor Bahru. Bus and car travel speed data, for example, are limited and the survey only covered certain sections on a few selected routes. IVTT of bus, car and bike are very difficult to measure precisely in Johor Bahru. This might be the reason why very few LOS variables could be introduced in the Johor Bahru Model, and possibly why the transferability of the Johor Bahru Model is much lower than that of the Miyazaki Model in Test 1 and 2.

7. CONCLUDING REMARKS

This study has shown the strength of the disaggregate modelling technique in understanding travel behaviour of work trips mode choice both in a developed as well as in a developing country.

Data for this study were limited and confined only to those recorded in the master tapes or traffic survey reports. Nevertheless, the overall model estimation results can be said to be rather satisfactory. Unfortunately, however, the zonal data of origin and destination location and the lack of specific travel routes, parking data for example have limited the preparation of more accurate LOS data.

The significance of OPTC and BOVTT in the Miyazaki Model is an important and interesting finding since this would permit analysis of transport policies such as bus fare adjustment or higher gasoline tax in affecting mode choice. The low % correct for the bike mode in both models is another important finding worth pondering. This could imply that there are still some inherent causal factors for the preference of this travel mode.

This study also supports the fact that disaggregate modelling does not require the large volume of data demand of the conventional transport models[1),6)]. To be effective however, more data, not volume but information should be collected preferably by specific survey with well designed questionnaire to collect such data as routing, parking location, parking charge, bus waiting and transfer times and fare.

The comparative analysis of the work trips mode choice models for Miyazaki and Johor Bahru City have shown that factors influencing travel behaviour differ between the two cities and hence the low-transferability of the two models. This seems to be attributed to the inherent divergence of socio-economic characterestics of trip makers and the level of urban transport services. For model application in actual planning studies, therefore analysis of these factors might give some useful clues as to the appropriateness of applying any 'borrowed' models.

As the results of Test 1 and 2 show, the Miyazaki Model, which has been estimated with considerably accurate values of LOS variables, has higher transferability than the Johor Bahru Model. This fact might suggest the probability of obtaining high transferability when more detailed and accurate data are available. It cannot be understated that further studies are necessary to check the veracity of the above statement.

ACKNOWLEDGEMENT

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APPENDIX (Note on the Hotelling's generalized T^2 Test)

The Hotelling's generalized T^2 statistics is a natural extension of the student's t-statistics and can be used for testing whether mean vectors of two populations are equal or not.

Suppose $X_1, X_2, \cdots, X_m$ and $Y_1, Y_2, \cdots, Y_n$ represent random samples from k-dimensional normal distribution with mean μ_1, μ_2 and dispersion matrix Σ_1, Σ_2, respectively.

$X_i \sim N_k(\mu_1, \Sigma_1) \quad (i=1,2,\cdots\cdots,m)$

$Y_j \sim N_k(\mu_1, \Sigma_2) \quad (j=1,2,\cdots\cdots,n)$

Our object is to test $H_0 : \mu_1 = \mu_2$ against $H_1 : \mu_1 \neq \mu_2$ with random samples. If Σ_1 and Σ_2 are known, then the χ^2-test can be used. In our case, however, Σ_1 and Σ_2 are not given, therefore we must employ the Hotelling's generalized T^2 test.

If $\Sigma_1 = \Sigma_2 = \Sigma$, then the Hotelling's generalized T^2 statistics is defined as

$$T^2 = (\overline{X} - \overline{Y})' \left\{ \left(\frac{1}{m} + \frac{1}{n} \right) \hat{\Sigma} \right\}^{-1} (\overline{X} - \overline{Y}) \quad \cdots\cdots \quad (A \cdot 1)$$

where $\overline{X}$ and $\overline{Y}$ are sample mean vectors of two populations, and $\hat{\Sigma}$ is an unbiased estimator of Σ. Let $\hat{\Sigma}_1$ and $\hat{\Sigma}_2$ be unbiased estimators of Σ_1 and Σ_2, respectively. Then $\hat{\Sigma}$ is given by

$$\hat{\Sigma} = \frac{(m-1)\hat{\Sigma}_1 + (n-1)\hat{\Sigma}_2}{m+n-2} \quad \cdots\cdots \quad (A \cdot 2)$$

If H_0 is true,

$$F_0 = \frac{m+n-k-1}{(m+n-2)k} T^2 \sim F_{k,m+n-k-1} \quad \cdots\cdots \quad (A \cdot 3)$$

when $F_0 > F_{k,m+n-k-1}(\alpha)$,

we reject $H : \mu_1 = \mu_2$ at the α level of significance.

The proof of (A·3) and various characteristics of T^2 are shown, for example, in Seber[19]

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