Research Article

Nonlinear Influence of Commute Time Tolerance Threshold on Commute Mode Choice Based on the Semicompensatory Model

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Received 7 December 2021; Revised 5 January 2022; Accepted 10 January 2022; Published 28 April 2022

The tolerance threshold of commute time (TTCT) reflects the longest commute time that commuters can tolerate from home to the workplace. When the commute time exceeds the TTCT, the commuting utility significantly reduces, which has a nonlinear influence on commuting mode choice. To reveal the nonlinear relationship between the commuting utility and commute time, the TTCT is introduced to constrained multinomial logit (CMNL) model based on the semicompensatory decision-making mechanism. In addition, an empirical study is carried out on 405 commuters in Kunming, China. The results show that the CMNL model has a higher fitting accuracy than the MNL model, which indicates that the TTCT is a significant explanatory variable for the commuting mode choice. Moreover, the commuting utility does not decrease linearly with the commute time. An appropriate commute time range (about 5–25 min) could bring positive commute utility to the commuters, but the commute utility is negatively impacted when the commute time is larger than the TTCT. Therefore, it is necessary importing the TTCT in the utility function to improve the predictive power of the commuting mode choice model.

1. Introduction

Providing high-quality travel experience for commuters is one of the goals of the intelligent transportation system. Therefore, the exploration of travel behavior has become the focus of researchers and developers of the intelligent transportation system [1]. Studying commute mode choice is not only beneficial for formulating sustainable urban transportation development policies but also for developing and designing the intelligent transportation system [2]. The discrete choice model based on random utility maximization is one of the main methods used for analyzing commute mode choice [3]. Currently, the utility function of the commute mode choice is generally based on the compensatory decision-making mechanism. The compensatory mechanism holds that the utility of the various explanatory variables of the commute mode compensates for each other [4]. Taking commuting by bus as an example, the lost utility of the longer commute time spent on the bus can be compensated for by the lower commuting costs.

However, when commuters make mode choice decision, a noncompensatory mechanism might be used to eliminate commute mode alternatives. In other words, when the attribute value of the commute mode exceeds its attribute threshold, the utility of this commute mode may change significantly [5]. The noncompensatory mechanism has been validated in the studies that related to travel mode choice [6]. For instance, Cantillo et al. [7] used a two-stage choice sets generated model which proved the existence of noncompensatory mechanism in the travel mode choice. Cascetta et al. [8] regarded the mode choice set as a fuzzy set and adopted the membership degree to express the comprehensive availability of the commute mode. The lower the membership degree, the more pronounced the non-compensatory effect. Based on the membership degree model, Martinez et al. [9] improved the utility function and established a constrained multinomial logit (CMNL) model to describe the nonlinear change of the utility caused by the travel attribute threshold. CMNL model was then applied to analysis the commute mode choice and the route...
choice [10, 11]. Yao et al. [12] analyzed the influence of the threshold of the number of transfers on people’s subway route choice. Then, Zhang et al. [13] introduced the thresholds of commute time and the number of transfers to construct a semicompensatory mixed logit model, which effectively improved the prediction accuracy of the subway route choice.

The above studies showed that attribute thresholds have an obvious influence on the travel mode choice and the travel route choice. Yet, few studies have been done on the nonlinear relationship between the psychological threshold of commuting attribute and the commuting utility, as well as its influence on the commute mode choice. Researchers have found that commuters subjectively have a tolerance upper for commuting time. For instance, through semistructured interviews, Milakis et al. [14-15] validated the existence of acceptable travel time. He et al. [16] carried out an empirical analysis on the distribution characteristics of the tolerance threshold of commute time (TTCT) and its influencing factors. It should be noted that when the actual commute time (ACT) approaches or exceeds the TTCT, commuters may change their workplaces or residence locations or commute modes to shorten the commute time to their tolerable range. Clark et al. [17] found that people’s tolerance of commute time affected their choice of workplaces or residence locations. Vale et al. [18] found that commuters were more likely to drive a car to keep the commute time within a tolerable range when the commuting distance increased. All these studies revealed the existence of the TTCT, as well as its distribution characteristics. But, studies about the influencing of the TTCT on the commute mode choice remain scarce.

The objective of this study is to analyze the influence of the TTCT on the commute mode choice and to reveal the nonlinear relationship between the commuting utility and the commute time. Applying the decision-making mechanism of the semicompensatory, the utility penalty function is established to describe the negative utility generated when the TTCT is exceeded, and this function is integrated with the MNL model. Finally, an empirical analysis is carried out to study whether the TTCT has more utility than any other alternative, which is expressed in the following equation:

$$P_{ni} = 	ext{Pr}(V_{ni} + \epsilon_{ni} \geq V_{nj} + \epsilon_{nj}, \forall j \in A_n),$$

where $A_n$ is the choice set of commute modes for the commuter $n$. Assuming that the error term $\epsilon$ follows the Gumbel distribution, then the probability $P_{ni}$ of the commuter $n$ choosing the $i$ is

$$P_{ni} = \frac{1}{\sum_{j \in A_n} \exp \left( \sum_{k=1}^{K} p_{nkj} (x_{njk} - x_{nik}) \right)}.$$  

It is easily found that the utility function of the MNL model follows the compensatory mechanism, that is, when a specific explanatory variable does not meet the needs of commuters (e.g., a long commute time), the utility can be compensated by other explanatory variables (e.g., a low commuting cost). However, when the commute time of a certain commuting mode exceeds the TTCT, the commuters’ perceived utility decreases rapidly. In such a case, no matter how low the cost is, the commuter will not choose this commuting mode. Therefore, the real possibility of choosing this mode is less than the estimation value obtained with the MNL model.

2. Methodology

The semicompensated model is a combination of compensatory model and noncompensating model, so this part first introduces the multinomial logit (MNL) model, then analyzes the noncompensating effect of the TTCT on commuting utility, and finally explains the theoretical framework of the semicompensated model, considering the TTCT.

2.1. The Multinomial Logit Model. The MNL model is one of the discrete choice models [19]. Its mathematical expression is as follows:

$$U_{ni} = V_{ni} + \epsilon_{ni},$$  

$$V_{ni} = \sum_{k=1}^{K} p_{nk} x_{nik},$$

where $U_{ni}$ is the total utility that commuter $n$ obtains from commute mode $i$, $V_{ni}$ is the deterministic part, and $\epsilon_{ni}$ is the random error. $V_{ni}$ is represented by the linear function shown as equation (2). $x_{nk}$ is the explanatory variable of the commuting utility. $p_{nk}$ is a coefficient which needs to be estimated. $K$ is the number of explanatory variables.

According to the principle of utility maximization, the probability of the alternative $i$ is chosen by commuter $n$ which refers to the probability that the alternative $i$ has much more utility than any other alternative, which is expressed in the following equation:

$$P_{ni} = \text{Pr}(V_{ni} + \epsilon_{ni} \geq V_{nj} + \epsilon_{nj}, \forall j \in A_n),$$

2.2. The Semicompensatory Model considering the TTCT. The CMNL model proposed by Martnez et al. [9] demonstrates that there is a noncompensatory effect on utility when the attribute value exceeds the threshold. Moreover, the CMNL model is continuously derivable at the threshold point. Therefore, based on the CMNL model, a logarithmic function is integrated with the MNL model to express the punitive effect of the TTCT on the total utility. In other words, when the ACT of a certain commute mode exceeds
the TTCT, the total perceived utility of commuters significantly decreases, thus leading to a decrease in the probability of choosing this commute mode. Figure 1 presents the theoretical framework of the CMNL model, which is used to illustrate the utility penalty when the TTCT is violated by the ACT. Since the CMNL model considers both compensatory mechanism and noncompensatory mechanism, the CMNL model is referred to as a semicompenatory model. The total utility of the CMNL model is as follows:

$$U_{ni} = V_{ni} + \ln(\phi_{ni}(x_{ni})) + \epsilon_{ni},$$  \hspace{1cm} (5)$$

where $V_{ni}$ is a compensatory term, $\ln(\phi_{ni}(x_{ni}))$ is a non-compensatory term; it represents the punitive effect on the total utility $U_{ni}$.

The TTCT reflects the tolerable upper of the commuter for commuting time that in spent from home location to the workplace. The ACT, on the other hand, refers to the actual commute time that is spent from the place of residence to the place of work. When the ACT is less than the TTCT, the level of commute tolerance is high. When the ACT is near the TTCT, the level of commute tolerance is relatively lower. When the ACT exceeds the TTCT, the level of commute tolerance decreases rapidly. In order to effectively express the relationship among the level of commuting tolerance, the ACT, and the TTCT, as shown in equation (6), a binomial logit function is established.

$$\phi(x_{time}) = \frac{1}{1 + \exp[\omega(x_{time} - b_{time} + \rho)]},$$  \hspace{1cm} (6)$$

where $\phi(x_{time})$ is the level of commute tolerance, $x_{time}$ is the ACT, $b_{time}$ is the TTCT, and $\rho$ and $\omega$ are parameters to be calibrated. Then, $P_{ni}$ is deduced from the CMNL model:

$$P_{ni} = \frac{1}{1 + \sum_{j \neq i} \exp[(V_{nj} - V_{ni}) + \ln(\phi_{nj}/\phi_{ni})]}.$$  \hspace{1cm} (7)$$

Equation (7) shows that the choice probability of commute mode is not only related to the difference in the linear utility (the part of compensatory utility) but also related to the ratio of the level of commute tolerance (the part of noncompensatory utility).

As shown in Table 1, when the commute time $x_{time}$ is less than the threshold $b_{time}$, the level of tolerance $\phi(x_{time})$ is 1, and $\ln[\phi(x_{time})]$ is 0, then the punitive effect of the non-compensatory part is 0. When the commute time is near the TTCT, $\phi(x_{time})$ decreases from 1 to 0, and $\ln[\phi(x_{time})]$ is negative, which means that the part of noncompensatory utility exerts a punitive effect on the total utility. As the commute time continues to increase, $\phi(x_{time})$ tends to 0, $\ln[\phi(x_{time})]$ decreases rapidly, and the part of noncompensatory utility accounted for the majority of the total utility.

3. Data Analysis

A survey of commuters was carried out using the stratified random sampling method in Kunming, China. A total of 493 questionnaires were obtained, 88 invalid questionnaires were excluded, and 405 questionnaires remained. The questionnaire mainly includes three parts, i.e., personal attributes, commuting attributes, and the TTCT. In this section, the variables are described, then the statistical distribution characteristics of the TTCT are presented, and finally the parameters of the level of commuting tolerance are calibrated.

3.1. The Description of the Variables. The dependent variable is the commute mode, explanatory independent variables are individual attributes, commuting attributes, and the TTCT. In the questionnaire, the commuting mode refers to the most frequently used travel mode by respondents from their place of residence to place of work. The sample statistic shows that the main commuting modes of respondents are bicycle, E-bike, public transit (bus and subway), and car. E-bike is an important travel mode in Kunming, thus E-bike is classified as separate category in this study [20].

In the questionnaire, respondents are asked to answer the question “how long is the maximum commute time you can tolerate?” through this question, the respondents’ TTCT is obtained. Similarly, “how many minutes do you spend from where you live to where you work?” based on this question, the respondents’ ACT is obtained. Personal attributes include “gender, age, annual family income, whether there are children under the age of 13 years old in your family, and the number of people employed in your family.” Among these attributes, age, and the number of people employed in your family are treated as dummy variables. The definition of each variable is shown in Table 2.

3.2. The Distribution Characteristics of the TTCT. Table 3 shows the distribution of the TTCT. The TTCT are mainly concentrated in the range of 20–50 min (73%). Remarkably, the TTCT of the 30% of respondents is 30–40 min. It is calculated according to the intermediate value of each interval; the average TTCT is 37.5 min, which is taken as fixed threshold in the CMNL model and denoted as $b_{time}$.

As shown in Table 4, the ACT of all respondents is compared with $b_{time}$. The ACT of 96 samples exceeds $b_{time}$, accounting for 23.7% of all samples. The ACT of 18 samples is approximately equal to $b_{time}$, accounting for 4.5% of all samples. The ACT of 291 samples is less than $b_{time}$, accounting for 71.8% of all samples.

3.3. Parameter Calibration of the Level of the Commute Tolerance. In order to first calibrate the parameter $\rho$ of the commuting tolerance level $\phi(x_{time})$, define the value of $\phi(x_{time})$ when the ACT is around the TTCT as the proportion of the sample where the ACT is approximately equal to $b_{time}$ and it is denoted as $\lambda$; then,

$$\phi(b_{time}) = \frac{1}{1 + \exp[\omega(b_{time} - b_{time} + \rho)]} = \lambda = 0.045.$$  \hspace{1cm} (8)$$

It can be derived from equation (8) that
Table 4: Comparative distribution characteristics of the ACT and the TTCT.

<table>
<thead>
<tr>
<th>Classification</th>
<th>$x_{time} - b_{time} &gt; 0$</th>
<th>$x_{time} - b_{time} \approx 0$</th>
<th>$x_{time} - b_{time} &lt; 0$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samples</td>
<td>96</td>
<td>18</td>
<td>291</td>
<td>405</td>
</tr>
<tr>
<td>Proportion</td>
<td>23.7%</td>
<td>4.5%</td>
<td>71.8%</td>
<td>100%</td>
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</table>
4. Results and Discussion

The maximum likelihood estimation method is used to estimate the parameters of the MNL model and the CMNL model in the Biogeme 1.8 software. The parameter estimation results are shown in Table 5.

According to the estimation results, the utility functions of the four commuting modes in the CMNL model are shown in the following equations:

\[
\begin{align*}
U_{\text{bike}} &= 0.135x_{\text{biketime}} - 1.19S_{\text{gender}} - 0.459F_{\text{income}} + \ln \left\{ \frac{1}{1 + \exp \left[ 0.167 \left( x_{\text{biketime}} - 37.5 \right) + 3.06 \right]} \right\}, \\
U_{\text{E-bike}} &= 0.135x_{\text{E-biketime}} - 1.19S_{\text{gender}} + \ln \left\{ \frac{1}{1 + \exp \left[ 0.167 \left( x_{\text{E-biketime}} - 37.5 \right) + 3.06 \right]} \right\}, \\
U_{\text{Public}} &= -3.85 + 0.135x_{\text{pubtime}} + 0.577A_{\text{age1}} + 0.804T_{\text{cost}} + 0.962N_{\text{job1}} \\
&+ \ln \left\{ \frac{1}{1 + \exp \left[ 0.167 \left( x_{\text{pubtime}} - 37.5 \right) + 3.06 \right]} \right\}, \\
U_{\text{Car}} &= -3.27 + 0.135x_{\text{cartime}} - 1.19S_{\text{gender}} + 0.509A_{\text{age2}} + 0.804T_{\text{cost}} + 0.513F_{\text{income}} \\
&+ \ln \left\{ \frac{1}{1 + \exp \left[ 0.167 \left( x_{\text{cartime}} - 37.5 \right) + 3.06 \right]} \right\}.
\end{align*}
\]

It can be seen from equations (12)–(15) and Table 5 that, first of all, the fit goodness of the MNL and the CMNL model is 0.242 and 0.249, respectively, indicating that the CMNL model considering the TTCT has a better explanatory ability. The result of statistical significance suggests that the TTCT has a significant influence on the commute mode choice.

Secondly, \( \varphi \) is the estimated coefficient of the difference between the ACT and \( b_{\text{time}} \), which is 0.167. The larger the difference, the smaller the level of commute tolerance \( \varphi \), the greater the negative impact of utility penalty \( \ln (\varphi) \), and the smaller the total utility \( U \), which indicate that the TTCT has a significant negative impact on the utility in the CMNL model.

In addition, the estimated coefficient of the ACT changes from negative in the MNL model to positive in the CMNL model, which proves that the commute time and utility are not in a simple negative linear relationship. When the TTCT is considered in the CMNL model, the commute time has a nonlinear impact on the commute utility. Specifically, if the ACT exceeds the TTCT, the increase in the commute time will exert a negative impact on the commute utility. While the ACT is less than the TTCT, the commute time has a positive impact on the commuting utility. The result overthrow the view that the commute time only produces negative utility and provides support for the insight that if commute time is within a reasonable range, the commute time will bring positive utility to commuters [21–23].

To intuitively demonstrate the nonlinear influence of the TTCT on commuting utility, explanatory variables in the utility function of the CMNL model, except commute time and TTCT, are controlled. According to the parameter estimation results, the relationship between commute time and commute utility in the MNL and the CMNL models is plotted in Figure 2.

In contrast to the negative linear relationship between utility and commute time in the MNL model (Figure 2(a)), the utility of the CMNL model first increases with the commute time and then decreases when the TTCT is exceeded, demonstrating a nonlinear relationship (Figure 2(b)). An appropriate commute time (about 5–25 min) could bring positive commute utility to the commuters, and the commute utility is negatively impacted when the commute time is larger than 30 min. The main contribution of this study is that it supports the idea that “the commuting utility changes nonlinearly with the commute time” [15].

Lastly, the parameter estimation results show that the probability of the women choosing bicycle, E-bike, and car as the commuting modes is smaller than that of the men. Commuters in the age group of 18–29 years old are more
inclined to select public transportation. In addition, families with only one person employed are more likely to choose public transportation. It is found that the higher the acceptable commuting cost or the higher the annual household income, the greater the probability of choosing car for commuting, which is consistent with economic laws. The estimation results of these individual and household attributes are in good agreement with expectations.

5. Conclusion

To explore the nonlinear influence of the TTCT on the commute mode choice, the tolerance level for the ACT of commute mode is integrated with the linear MNL model, thus the semicompensatory CMNL model is established. After conducting an empirical study of commuters in Kunming, China, the following conclusions are obtained.

![Figure 2: (a) The linear relationship between commuting utility and commute time. (b) The nonlinear relationship between commuting utility and commute time.](image-url)

Table 5: The coefficient estimated results of CMNL and MNL model.

<table>
<thead>
<tr>
<th>Models</th>
<th>CMNL</th>
<th></th>
<th></th>
<th>MNL</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical indicators</td>
<td>Coefficient</td>
<td>s.d.</td>
<td>t</td>
<td>Sig.</td>
<td>Coefficient</td>
<td>s.d.</td>
</tr>
<tr>
<td>Constant</td>
<td>-3.850</td>
<td>0.657</td>
<td>-5.86</td>
<td>0.00</td>
<td>-3.260</td>
<td>0.626</td>
</tr>
<tr>
<td>Public transit</td>
<td>-3.270</td>
<td>0.488</td>
<td>-6.70</td>
<td>0.00</td>
<td>-3.310</td>
<td>0.483</td>
</tr>
<tr>
<td>Car</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The estimate coefficient of variables</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Actual commute time</td>
<td>0.135</td>
<td>0.028</td>
<td>4.76</td>
<td>0.00</td>
<td>-0.042</td>
<td>0.011</td>
</tr>
<tr>
<td>Accepting commute expenses</td>
<td>0.804</td>
<td>0.143</td>
<td>5.63</td>
<td>0.00</td>
<td>0.812</td>
<td>0.142</td>
</tr>
<tr>
<td>Gender</td>
<td>-1.190</td>
<td>0.242</td>
<td>-4.93</td>
<td>0.00</td>
<td>-1.180</td>
<td>0.240</td>
</tr>
<tr>
<td>Age 1 (18–29 years)</td>
<td>0.577</td>
<td>0.286</td>
<td>2.02</td>
<td>0.04</td>
<td>0.590</td>
<td>0.285</td>
</tr>
<tr>
<td>Age 2 (30–39 years)</td>
<td>0.590</td>
<td>0.296</td>
<td>1.99</td>
<td>0.05</td>
<td>0.567</td>
<td>0.296</td>
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<tr>
<td>Whether there are children under the age of 13 in your family</td>
<td>0.271</td>
<td>0.283</td>
<td>0.96</td>
<td>0.34</td>
<td>0.293</td>
<td>0.281</td>
</tr>
<tr>
<td>Annual income of the family (car)</td>
<td>0.513</td>
<td>0.121</td>
<td>4.24</td>
<td>0.00</td>
<td>0.542</td>
<td>0.119</td>
</tr>
<tr>
<td>Annual income of the family (bicycle)</td>
<td>-0.459</td>
<td>0.151</td>
<td>-3.04</td>
<td>0.00</td>
<td>-0.190</td>
<td>0.119</td>
</tr>
<tr>
<td>One person in your family is employed (transit)</td>
<td>0.962</td>
<td>0.298</td>
<td>3.23</td>
<td>0.00</td>
<td>0.953</td>
<td>0.295</td>
</tr>
<tr>
<td>The estimate coefficient of $\varphi(x_{time})$</td>
<td>0.167</td>
<td>0.022</td>
<td>7.38</td>
<td>0.00</td>
<td>18.32</td>
<td></td>
</tr>
<tr>
<td>$\omega$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\beta_{time}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L(0)$</td>
<td>-560.063</td>
<td></td>
<td></td>
<td></td>
<td>-560.063</td>
<td></td>
</tr>
<tr>
<td>$L(\rho)$</td>
<td>-408.8</td>
<td></td>
<td></td>
<td></td>
<td>-413.2</td>
<td></td>
</tr>
<tr>
<td>The likelihood value</td>
<td>302.3</td>
<td></td>
<td></td>
<td></td>
<td>292.8</td>
<td></td>
</tr>
<tr>
<td>$\rho^2$</td>
<td>0.270</td>
<td></td>
<td></td>
<td></td>
<td>0.261</td>
<td></td>
</tr>
<tr>
<td>Adjusted $\rho^2$</td>
<td>0.249</td>
<td></td>
<td></td>
<td></td>
<td>0.242</td>
<td></td>
</tr>
</tbody>
</table>
Firstly, the TTCT has a significant influence on the commute mode choice; the CMNL model considering the level of commute tolerance effectively improves the explanatory ability of the commute mode choice model. Secondly, there is a nonlinear relationship between the commute time and the commuting utility, with the TTCT as the inflection point. When the actual commute time (ACT) is smaller than the TTCT, there is a positive impact of commuting time on commuting utility. While the ACT exceeds the TTCT, the impact of commute time on commuting utility is negative. Lastly, gender, age, and household income are also significant explanatory variables for commuting mode choices.

These conclusions provide enlightenment for urban planning. The government needs to be aware of the long commute time caused by urban expansion. The commute time exceeding the TTCT may not only seriously affect the commuting experience but also encourage commuters drive car to work, which runs counter to the advocacy of public transportation and green travel. In addition, when formulating urban transportation policies, it is necessary to distinguish between commuter groups with different demographic economic attributes.

The limitation of this study is that the tolerance parameter used in the model was calibrated using the average of the TTCT of the surveyed samples. However, the TTCT is characterized by individual heterogeneity; therefore, the parameter calibration of the level of tolerance needs to consider individual heterogeneity in future studies. In addition, the model established in this study only considered the TTCT. In the next step, the ideal commute time will be introduced into the model to explore whether there is a more complex nonlinear relationship. That will be a problem worthy of research.

Data Availability

The data used to support the findings of this study are available from the authors upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (No. 71861017).

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