Engineering For Social Change
A. Cooper et al. (Eds.)
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doi:10.3233/ATDE240888

Sustainable Mobility Service Design Considering Economic and Transportation Efficiency in an Aging Society in Japan

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Abstract. In depopulated areas, public transportation services provided by municipalities are important for traffic-vulnerable people. Some municipalities need to scale back their services due to budget shortfalls. To tackle this social and technological problem, a transdisciplinary approach is necessary. The contribution of this paper is a methodology for considering sustainable public transportation services over uncertain long term and evaluate using it in Narita City, Japan. Narita City is a complex area where urbanization by the airport and rural farming villages coexist. To estimate the impact of various conditions under public transportation services, we use QoM index, which comprehensively quantifies the quality of an individual's mobility and can estimate the time-series changes of public transport-tation in the future. The simulation results show that residents' QoM values can be divided into two groups, with a higher percentage belonging to the lower group the more likely they are to live in rural areas or to be older, due to lower availability of transportation. In contrast, as the years passed, the average QoM in the urban area decreased, while that in the other areas increased. It means the elderly gradually clustered in the urban area as the years passed by natural population changes. Findings of our design proposal for a sustainable mobility service design in Narita City are to adopt demand-responsive transport like service to satisfy the small but uncertain future demand of traffic-vulnerable people in depopulated area at low cost.

Keywords. Local Public Transportation, Mobility, Transportation Service Planning

Introduction

In areas where the population is aging and declining, public transportation services provided by local governments are becoming more important for those who are vulnerable to transportation problems, even those who cannot afford the minimum necessary transportation for daily life. One such public transportation service is on-demand transportation. On-demand transportation is a shared-ride transportation system in which users can freely decide where and when to board and alight by making a reservation. In addition, since the service is based on reservations, there is no need to run vehicles when there are no passengers, which is highly valued from the standpoint of cost reduction. Due to these advantages, the number of municipalities introducing on-demand transportation is increasing every year, and seven hundred municipalities have introduced by FY2020 [1].

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However, even the on-demand transportation services, which is effective to such vulnerable people, may be difficult to continue due to the costs. Since on-demand transportation is generally introduced to alleviate the deficit incurred in the operation of a route bus, it is extremely difficult to turn a profit in depopulated areas. As a result, municipalities cannot even ignore the losses, and some decide a service reduction or elimination [2][3]. For such areas, it is important to combine public transportation services other than on-demand transportation to ensure transportation accessibility while reducing costs. In addition, municipalities set operational standards for public transportation services through regional public transportation plans every 5 years. However, the level of mobility of each resident is complex and difficult to figure out. Therefore, the supply of the established transportation services may not match actual demand, and it is difficult to easily change those services.

To solve these problems, this study proposes a method to search for a sustainable and better public transportation service for a period that is affected by uncertainty and complexity about the residents' mobility, such as about 10 years. Also, using the methodology, we evaluate the case of Narita City, Chiba Prefecture, and discuss the proposed operation of various transportation modes to achieve sustainable mobility services.

The contribution of this paper is to propose a methodology for considering sustainable public transportation services over the long term and evaluate using it.

The rest of the paper is structured as follows; Section 1 refers to previous research. Section 2 describes the methodology, and Section 3 presents the results and discussion of the case study based on it. Finally, Section 4 concludes.

1. Previous Research

Zhou et al. [4] investigated the determinants of public transportation and Shared mobility, which is now prevalent in many cities, use by examining behavior in densely populated urban areas in China. A comprehensive analysis of the various influences using a Markov Chain Monte Carlo model and a Bayes-Mixed Logit algorithm confirms that women are less likely to use Shared mobility from a safety perspective and that younger people are more likely to use bike sharing services. In contrast, the lack of connection between public transportation and shared mobility has led to a decline in the willingness to use public transportation, especially among residents suffering from "last mile." From this they concluded that establishing these transportation connections and combining the benefits of both would be a solution to the increasing mobility demands.

Ian and Graham [5] discussed the mobility characteristics of residents in rural areas of the United Kingdom, where the population is currently aging, to make sustainable mobility practical. As a result, car use among the elderly in rural areas is lower than average in areas where stores and hospitals are located within walking distance, but conversely above average in other areas. Therefore, they concluded that it is important for municipalities to intervene in spatial planning regarding the location of major facilities such as hospitals, and that a full discussion is needed on how much guarantee the public should receive for obtaining accessibility.

As mentioned above, there have been many studies that forecast demand for on-demand transportation as a public transportation service, but these are only evaluations at the current stage, and few of them consider the future and sustainability of the service. On the other hand, most studies that evaluate public transportation services in rural areas with a view to the future are limited to qualitative conclusions because of the small scale of these services and the unique geographic characteristics of each region.

Thus, while there are many studies that address the two issues of "quantitative evaluation of demand for shared transportation services" and "evaluation of transportation services considering future possibilities in underpopulated areas," respectively, there are few studies that combine both issues. However, in today's Japan, the need to evaluate sustainable transportation services for vulnerable populations is rising year by year due to the rapid aging of the population and other reasons. In short, the novelty of this study is “The evaluation of transportation services for vulnerable populations in underpopulated areas over an uncertain period of about 10 years.”

To solve this problem, we use a QoM index [6] and make a model about mobility changes with the aging. The QoM index can quantitatively calculate the mobility of the target population under various traffic conditions, thus the index allows quantitative comparisons. In addition, since the QoM index is calculated based on accessibility by purpose of travel, it can be evaluated with more emphasis on the purpose of travel, which is essential to life, and is also the existence value of public transportation services, especially for the vulnerable population. Furthermore, to assess the future potential of the service, we developed an Aging model that consider uncertainties such as the decrease in mobility due to the aging of the population. The population parameters through the aging model can be treated as situations, in which the population’s basic behavioral abilities have changed, and can therefore be evaluated by the QoM index.

The evaluation of mobility in the case of a flexible combination of various public transportation services can be quantitatively compared based on the future potential.

2. Methodology

This section describes the proposed methodology for comparing public transportation levels of service. A schematic diagram of the proposed method is shown in Figure 1.
In this approach, firstly we set the parameters of the model based on real-world input data (described in 2.1). Then, we set an arbitrary service situation and simulate one year at a time to calculate QoM (described in 2.2).

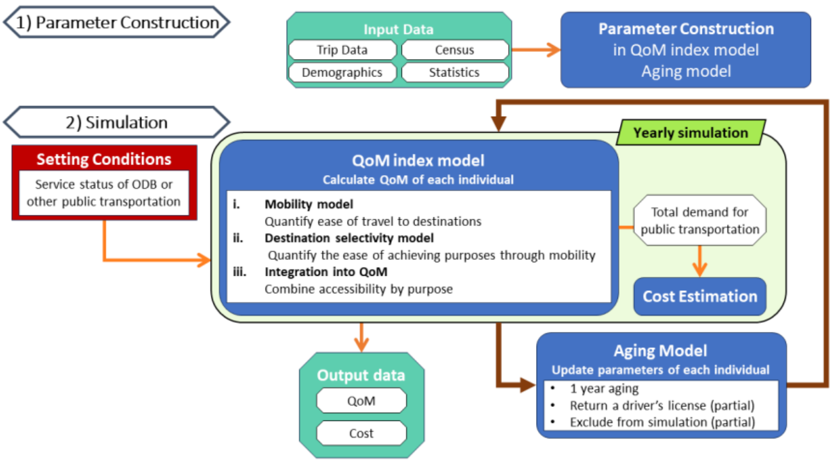

Figure 1. Schematic of the proposed method Parameter construction

Firstly, various data are used to set up each parameter within the QoM model and aging model. A summary of the data used for parameter setting and where it is utilized is shown in Table 1.

Table 1. Using Data

Data name	Outline
Tokyo Metropolitan Area ACT Model Data	The simulator uses a traffic behavior model based on activity from the 6th Annual Person Trip Survey conducted in FY 2018. The simulator is capable of outputting a person's daily travel, considering the various attributes of each person, district characteristics, and traffic conditions.
National Census	The most important and basic statistical survey of Japan, conducted every 5 years.
Economic Census	A statistical survey conducted to clarify the actual economic activities of establishments and companies in all industrial sectors in Japan.
Digital National Land Information	Geographic data related to national land planning, managed by the Ministry of Land, Infrastructure, Transport and Tourism.
Driver's License Statistics	A compilation of various data on driver's licenses provided by the National Police Agency, including the number of license holders and the number of licenses issued.
Demographics	Data on population provided by each municipality.

The following sections respectively outline the QoM model, cost estimation, and Aging model during the simulation.

2.1. Calculation of QoM index

This section will outline the QoM indicator, a quantitative measure of the overall quality of mobility for each individual citizen of interest. The QoM can be calculated through the following three steps.

1. Mobility model: Calculating estimated maximum utility, which quantifies the ease of traveling from an individual's place of residence to a certain destination.
2. Destination selectivity model: Calculate accessibility by purpose to quantify the ease of achieving individual mobility objectives based on ease of mobility.
3. Integration into QoM: Integrate accessibility by purpose.

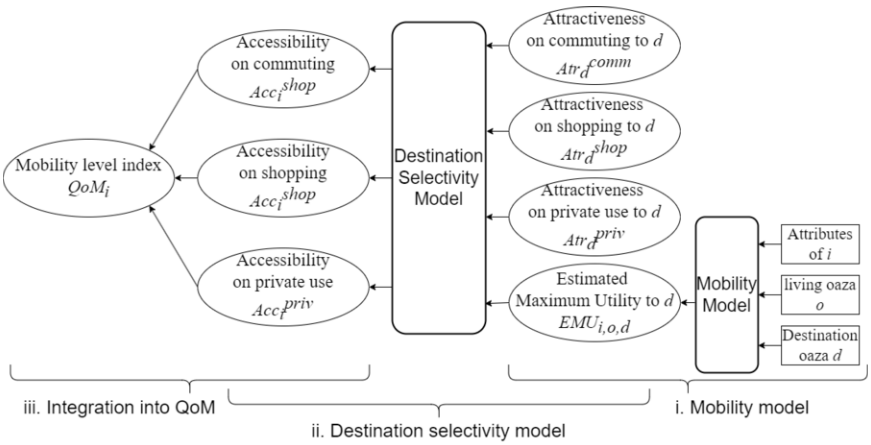

Figure 2. Overall structure of the Mobility Level Indicators

2.1.1. Mobility model

The mobility model calculates a quantitative measure of how easy it is for an individual to travel from his or her place of residence to a certain destination. In this part, the definite utility that an individual can obtain for each means of transportation when going to a certain destination is calculated based on personal attributes and transportation information (like satisfaction), and the expected maximum utility (EMU) at the time of transportation choice is considered as a quantified index of ease of travel. Here, EMU can be calculated by representing an individual's transportation choice using a multinomial logit model [7].

In the multinomial logit model, the individual *i* is assumed to choose one transportation mode with the highest utility among the *M = {Walk, Bicycle, Bus, Car, On-Demand Bus (ODB), Taxi}*. In this model, we model transportation behavior by assigning one type of transportation to each trip, using the concept of representative transportation in the person-trip survey. Furthermore, by considering the availability of transportation mode m, $\mathrm{Avail}_i(m) = \{0, 1\}$, the model represents a situation where a transportation mode that significantly affects the ease of travel cannot be chosen, due to aging or other factors.

Through this model, the utility obtained for each means of transportation is calculated according to individual attributes and transportation information, and the expected maximum utility from transportation choice is considered a quantified measure of an individual's ease of mobility.

Assume that individual i chooses the transportation mode m with the highest utility $U_{i,o,d}^{m}$ when traveling from origin o to destination d. The probability $\mathrm{Prob}_i(m|o,d)$ that individual i chooses transportation mode m when traveling from origin o to destination d is as in (1).

$$\mathrm{Prob}_i(m|o,d) = \mathrm{Prob}[U_{i,o,d}^{m} = \max_{m'}(U_{i,o,d}^{m'})] \quad (1)$$

Here utility $U_{i,o,d}^{m}$ of, (2) a term determined from the attributes of the individual and the transportation mode, as in $V_{i,o,d}^{m}$ and a term determined randomly at each choice $\varepsilon_{i,o,d}^{m}$ which is randomly determined each time a choice is made.

Here, utility $U_{i,o,d}^{m}$ is divided into a definite term $V_{i,o,d}^{m}$ consisting of the attributes of the individual and the transportation mode (represented in this model as a linear function of the preference parameter $\boldsymbol{\beta}$ and the characteristic variable vector $\boldsymbol{X}_{i,o,d}^{m}$), and a term $\varepsilon_{i,o,d}^{m}$ randomly determined at each choice.

$$U_{i,o,d}^{m} = V_{i,o,d}^{m} + \varepsilon_{i,o,d}^{m} = \boldsymbol{\beta} \cdot \boldsymbol{X}_{i,o,d}^{m} + \varepsilon_{i,o,d}^{m} \quad (2)$$

In this case, based on the assumptions of the logit model, the random term $\varepsilon_{i,o,d}^{m}$ is independent of the transportation mode *m*, each following a Gumbel distribution with independent expected value of 0 and variance μ. Here, $\mathrm{Prob}_i(m|o,d)$ that individual *i* chooses transportation mode *m* to get to destination *d* can then be calculated as (3), considering availability $\mathrm{Avail}_i(m) = \{0, 1\}$. This research uses the same parameter vector $\boldsymbol{\beta}$ for all moves.

$$\mathrm{Prob}_i(m|o,d) = \frac{\mathrm{Avail}_i(m) \cdot \exp(\boldsymbol{\beta} \cdot \boldsymbol{X}_{i,o,d}^{m})}{\sum_{m'} \mathrm{Avail}_i(m') \cdot \exp(\boldsymbol{\beta} \cdot \boldsymbol{X}_{i,o,d}^{m'})} \quad (3)$$

Then, due to the nature of the multinomial logit model, the expected value of the EMU can be calculated as in (4).

$$EMU_{i,o,d} = E\left[\max_{m}\left(U_{i,o,d}^{m}\right)\right] = \ln\sum_{m}\text{Avail}_{i}(m)\ \cdot\ \exp\left(\boldsymbol{\beta}\cdot\boldsymbol{X}_{i,o,d}^{m}\right) \quad (4)$$

Here, the availability of each transportation mode is shown in Table 2, and the definition of each characteristic variable in the transportation mode choice model is shown in Table 3. Here, l is a distance from o to d.

Table 2. Definition of availability $\text{Avail}_i(m)$

Walk	Bicycle	Bus	Car	ODB	Taxi
All 1	1 if under 85 years	All 1	1 if the individual has a license	1 if over 70 years	All 1

Table 3. Characteristic variable vectors $\boldsymbol{X}_{i,o,d}^{m}$

Name	Walk	Bicycle	Bus	Car	ODB	Taxi
Fee (per 1000 yen)	0	0.1	0.16+0.03l	0.016l	0.5	0.5 (l<1.155) +0.1 for every 239m thereafter
Riding Time (per 10 min.)	6l/4	6l/12	6l/25	6l/30	6l/20	6l/35
Access Distance (per 1 km)	0	0	Distance to bus stop	0	Distance to ODB stop	0
Egress Time (per 1 km)	0	0	Distance to bus stop	0	Distance to ODB Stop	0
Waiting Time (per 10 min.)	0	0	Determined by number of buses	0	0.5	1.5
Free Car Dummy	0	0	0	Have car = 1 Other = 0	0	0
Walk Zone Dummy	Within = 1 Other = 0	0	0	0	0	0
Bicycle Constant	0	1	0	0	0	0
ODB Ineffective Dummy	0	0	0	0	1	0
Taxi Ineffective Dummy	0	0	0	0	0	1

2.1.2. Destination selectivity model

The destination selectivity model considers the EMU and the attractiveness of each destination in achieving a certain objective and calculates a quantitative measure of how accessible a location is to satisfy that objective when an individual is trying to achieve a certain objective. To this end, we apply the Gravity Model, which explains the amount of traffic demand from one location to a certain destination using the attractiveness of each destination and the difficulty of traveling from one location to that destination.

We use the attractiveness level that emerges in this model to define the accessibility to a location that satisfies the objective.

Under this gravity model, the accessibility Acc_i^p can be expressed as (5).

$$\begin{aligned} Acc_i^p &= \ln\left[\sum_{d\in Z}\frac{Atr_d^p}{\sum_{d\in Z}Atr_d^p}\exp\left(-\gamma^p L_{o,d}\right)\right] \\ &= \ln\left[\sum_{d\in Z}\frac{Atr_d^p}{\sum_{d\in Z}Atr_d^p}\exp\left(-\gamma^p\left(\max_{i,o,d}EMU_{i,o,d} - EMU_{i,o,d}\right)\right)\right] \quad (5) \end{aligned}$$

Here, Atr_d^p is the relative attractiveness of destination d for achieving purpose p, Z is the range to be considered, and $L_{o,d}$ is the difficulty of the move, expressed in normalized EMU to allow for individual-specific calculations while maintaining relevance to the mobility model.

2.1.3. Integration into QoM

The QoM index is defined as a Cobb-Douglas type function [8] for accessibility per objective obtained in the previous section as in (6). As an allocation parameter for accessibility per purpose, we use the relative ratio of the total number of trips per purpose R_p. In this research, we consider 3 purposes: commuting, shopping, and other personal use. And since R_p is a relative ratio, $R_{comm} + R_{shop} + R_{priv} = 1$.

$$QoM_i = -(-Acc_i^{comm})^{R_{comm}}\left(-Acc_i^{shop}\right)^{R_{shop}}\left(-Acc_i^{priv}\right)^{R_{priv}} \quad (6)$$

As can be seen from these equations, the most ideal value of QoM_i for individual i is to be zero (equation (5) shows that this does not occur in most cases), and QoM_i is usually negative. Of course, the larger this value is, i.e., the smaller the absolute value, the higher the quality regarding mobility.

2.2. Updating Resident Parameters with Aging model

The QoM index and Cost are simulated not only for the present, but also for 10 years into the future. Therefore, after each yearly simulation, the following parameters will be updated for all the targeted population.

- Increasing age
- Return of car licenses for some individuals (car become inaccessible)
- To express population's moving out, exclude some population

3. Case Study

In this section, we estimate the QoM under current public transportation service conditions using simulations. And we examine how QoM will change in the future under the conditions and discuss how to operate better public transportation services in consideration of the future.

3.1. Case study subject

This study deals with Narita City, Chiba Prefecture, which is operating on-demand transportation services.

Narita City provides an on-demand transportation service. Table 4 shows the status of the service.

Table 4. Narita City On-demand Transportation Service (as of March 2023)

Status	Outline
User	Residents of Narita City, over 70 years, Able to get in and out of the car alone,
Usage fee	500 yen per ride
Operating date	Every Monday through Friday Except New Year's holidays and national holidays
Operating time	7:30~17:30
Vehicles in operation	7 vehicles with 4 passengers
Number of boarding stations	964

Narita City is currently divided into 10 statistical districts. As of March 2023, Narita City, Chiba Prefecture, has a population of 131,148 and the percentage of population over 65 years of 24.3%. Of these, major facilities are concentrated in Narita and Newtown, and those two areas account for nearly half of the total population.

3.2. Evaluation Results of current public transportation services

Firstly, the distribution of QoM in current public transportation services in Narita City is shown in Figure 3.

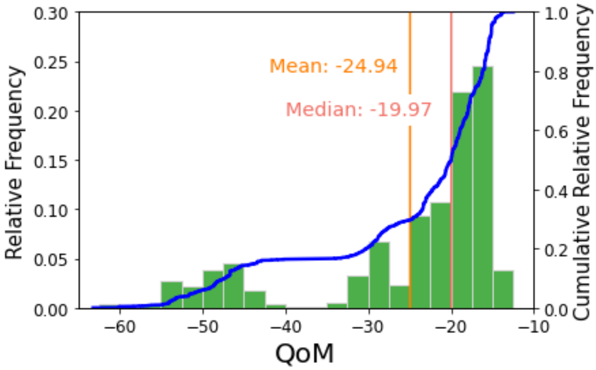

Figure 3. Distribution of QoM in current public transportation services

The individual mean value of QoM ($\overline{QoM}$) is -20.40. And Figure 3 shows that the mean value is closer to the maximum value and separated into two groups.

Next, the distribution of QoM by statistical district is shown in Figure 4.

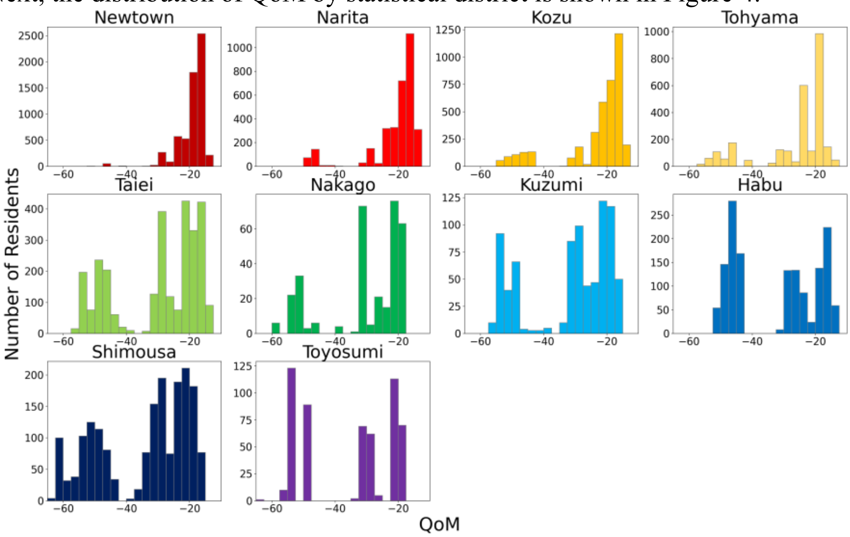

Figure 4. Distribution of QoM in current public transportation services

Figure 4 shows that the urban area has a higher QoM, and the further away from such areas, the higher the percentage of residents with low QoM.

Additionally, these 10 districts were then divided into 4 groups based on their $\overline{QoM}$ values, and the changes in the histograms at the present time, 5 years later, and 10 years later are shown in Figure 5. Future resident data were estimated using the method described in 2.3.

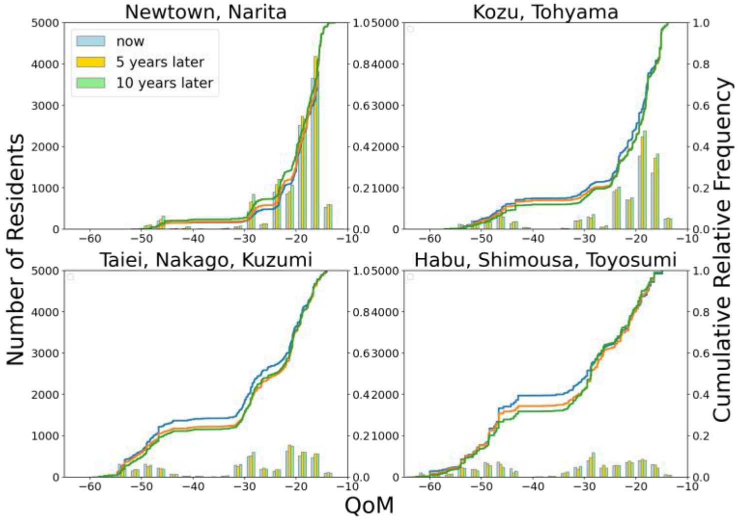

Figure 5. Distribution of QoM over 10 years for the 4 statistical district groups

The results show that areas with lower original $\overline{QoM}$ values have a higher percentage decrease in residents with lower QoM_i values, while areas with higher $\overline{QoM}$ values have a higher percentage of residents with lower QoM_i values as the years go by.

3.3. Discussion

The evaluation of the current service proposal has allowed us to identify the characteristics of the QoM_i values in each district. This section discusses the characteristics and future potential of each district.

First, Figure 4 shows that the $\overline{QoM}$ value is higher in districts called urban areas, and the further away from urban areas, the lower the $\overline{QoM}$.

Also, the cumulative frequency distribution in Figure 4 shows that in all districts, QoM_i once leveled off when the value is from -50 to -30. This indicates that the QoM_i value of Narita residents can be divided into 2 parts, but the cumulative frequency at this time shows that the urban area is less than 0.2, while Habu and Toyosumi, which are areas of inconvenient transportation, exceed 0.4.

However, when compared to 5 or 10 years later (Figure 5), the percentage of residents with low QoM_i values decrease as the years pass in all districts except urban areas, and this trend is more pronounced in areas with less convenient transportation. This movement is thought to be because the number of residents who were vulnerable to traffic declines more than the number of new elderly residents as the years go by. On the other hand, we observed that the percentage of residents with low QoM_i values increased as the years passed in Newtown and Narita, urban areas.

These changes are expected to occur because of the aging of residents who used to live in urban areas with good accessibility, while the number of residents in areas away from urban areas with relatively poor accessibility, especially older residents, declines with each passing year due to out-migration and deaths. In other words, the future population distribution of the elderly in Narita City will be concentrated in urban areas.

Next, we will discuss transportation services appropriate for Narita City.

The simulations confirm that the proportion of people with low QoM_i values is higher in more depopulated areas, but the number itself is smaller in Narita City as a whole. Based on this trend, our proposed transportation service proposal that Narita City should pursue is to adopt a lower-cost demand-responsive transportation service.

One specific example is the taxi subsidy system. Under this system, the municipality pays a portion of the cost of taxi. Taxi is relatively quick to meet the transportation needs of individuals, but are expensive to use, thus this system would reduce that disadvantage.

Another example is the introduction of personal mobility vehicles, which are small electric vehicles for one or two people that are suitable for short distances. This can expand the range of activities for people who are unable to travel even short distances on their own. However, due to the high price of the vehicles, if the municipality decides to subsidize them, they should carefully consider the proportion of the cost to be borne by residents.

4. Conclusion

The objective of this study was to propose and evaluate a method for studying public transportation services that can be sustainable over a long period of time, such as 10 years or so, subject to uncertainty and complexity in underdeveloped areas, where future transportation demand is expected to change significantly due to population decline and aging. Specifically, in Narita City, Chiba Prefecture, which operates an on-demand transportation system, we simulated the changes in the future.

The results suggest that the future distribution of Narita's elderly population will gradually cluster in urban areas. And our analysis of the results indicates that Narita City needs a demand-responsive transportation service that will meet the low cost, but uncertain future demand of vulnerable transportation users in underpopulated areas.

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