

**Decision support methods
for constructing sustainable taxi business in
rural areas**

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ABSTRACT

In rural areas, it is anticipated that the use of public transportation will decline in the future due to the decrease in population and the widespread use of private cars. However, public transportation remains an essential means of transportation for the elderly who cannot drive and the young who do not have a driver's license. Therefore, even if the number of public transportation users decreases, it is necessary to maintain public transportation. Until now, local governments have utilized various means of transportation to maintain public transportation, but as the number of users continues to decrease, taxis are considered to be the central means of transportation suitable for the reality of rural areas.

However, in the taxi operator, not only is the number of passengers declining, but so is the number of taxi drivers. Therefore, even if there is an opportunity to increase the number of taxis users due to the conversion from local buses and railroads to taxis as the number of public transportation users declines, there is concern about whether current drivers can meet the demand of passengers. In such cases, it becomes necessary to determine how much service can be supplied by the regular taxis, and whether it is appropriate to introduce an alternative form of operation, such as the shared taxis if the feasibility of supply is in doubt by the regular taxis. Additionally, if there is little prospect of sustaining the business solely through passenger transportation services, expanding into new businesses such as freight-passenger integration, which transport both passengers and freight, and operators need to evaluate its feasibility appropriately.

However, taxi operators in rural areas are generally small-scale, and it is difficult to make such judgments and evaluations objectively. If these judgments and evaluations cannot be made there is a risk of missing opportunities for improving services or exploring new business possibilities, which could be a factor in undermining the sustainability of the business. Thus, this study will focus on taxi operators facing such challenges and develop a methodology to objectively evaluate factors related to sustainability, such as the possibility of supply by regular taxis, the conversion between operation modes, and the feasibility of new businesses as the purpose of this study. Specifically, this methodology comprises the following three components:

First, a method will be developed to grasp the amount of supply (Hereafter, this is referred to as "supply capacity".), that can be provided to passengers with a limited number of drivers under the operation format of general taxis. "Specifically, based on the reality of rural areas where drivers wait at the office until passenger reservations are received, a mathematical programming model for assessing supply capacity was constructed using mixed integer programming. Using this model, we objectively assessed the supply capacity of taxi operators in the target area of Jinsekikougenn Town.

Then, we focused on the scenario where taxi operators choose between operating a shared taxi or a regular taxi. In this selection, it is necessary to evaluate the superiority of shared taxis

compared to regular taxis. we proposed a method for objectively evaluating the superiority of shared taxis based on the viewpoint that the fewer the minimum number of drivers required to operate the taxis, the better the sustainability of the taxi operators. Specifically, given data on passenger origin-destination pairs and travel times, we formulated a mathematical programming model based on mixed integer programming that can calculate the number of drivers required for the operation of shared and general taxis. Then, using the results calculated by this model, we demonstrated that the superiority of shared taxis can be evaluated using statistical models. We also showed that this methodology can be used to examine the specific usage of shared and general taxis, such as selecting different operating modes on weekdays and weekends & holidays. Furthermore, we demonstrated that it is possible to clarify the operation methods in which shared taxis are superior. The methodology employs a combined approach of a mathematical programming model and a statistical model, and its effectiveness was also confirmed.

Finally, a mathematical programming model is developed to evaluate how much profit can be increased and whether there will be a shortage of manpower by implementing freight-passenger integration in rural areas. Specifically, we constructed a mixed integer programming model to simulate the transportation of passengers by taxi and the delivery of freight and developed a method to evaluate the implementation of freight-passenger integration from both profit and manpower perspectives based on the results of the model. Using operational history data and Wakasa Town in Japan as a case study area, we evaluated whether profits could be improved by implementing freight-passenger integration and whether there would be a shortage of labor, that is, how much supply capacity is available. As a result, it was possible to clarify that the profit per unit of cargo increases as the number of passengers increases, and how the possibility of driver shortages would be affected by the volume of deliveries. Through this analysis using the model, it became possible for taxi operators to objectively understand the change in sustainability for taxi operators with the introduction of freight-passenger integration.

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Life is fleeting, lasting only a hundred years. In the remaining 73 years, I will strive even harder, not to waste the precious time.

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Chapter 1

Introduction

1.1 Background

1.1.1 Current situation of rural areas

The decline in population and aging are serious problems that the world has never experienced before. Japan, which is at the forefront of the trend, there is no end in sight to population decline and aging. In Japan, the rural areas are leading this trend. Therefore, the experiences gained in rural areas are expected to provide valuable insights not only for Japan, but also for other countries around the world facing or will face population decline and aging in the future.

First, confirm the trend of population decline in Japan as a whole. According to the United Nations survey, major advanced countries such as Japan, Germany, and Italy are facing population decline, but as shown in Fig. 1.1 and 1.2, Japan has a particularly high rate among them. While the entire country is showing this trend, the trend is even more pronounced in the rural areas of Japan. Fig. 1.3 shows the population change in the towns of Wakasa in Tottori Prefecture and Jinsekikogen in Hiroshima Prefecture, both of which are rural areas. To compare with the national average, Fig. 1.4 shows the population trends for these areas and the entire country based on the population in 2015. From this figure, it is clear that the population in rural areas is declining rapidly compared to the national average.

Similarly, as for the aging, the change of the aging rate of the major developed countries under the United Nations data is shown in Figure 1.5. According to this figure, we can see that aging is progressing in all countries, but Japan has the highest aging rate among them. In Japan as a whole, aging in rural areas is even more serious. Figure 1.6 shows the aging rate trends in Wakasa Town and Jinsekikogen Town. In these areas, the aging rate was 40-50% in 2015, and it is estimated to be over 50% after 2025.

As population decline and aging progress, various problems arise in the areas. In particular, for the areas to sustain itself, it is important that there is a certain industry in the areas and economic circulation continues. However, population decline, and aging have a direct impact on this point., Especially since the outflow of the younger generation

is notable in population decline, the number of workers in local industry will become scarce, and it is difficult to nurture successors for local industries in the future. For companies, they face a harsh environment not only in terms of demand for goods and services but also in terms of labor needs. As a result, led company to relocation or withdrawal to other areas, and this will become a factor that further causes the outflow of the younger generation.

Even from the perspective of residents' daily lives, if commercial, medical, and educational facilities withdraw from the area, the attractiveness of the area will decrease, and it will become difficult to continue living there. Therefore, at milestone occasions, such as children's education or when parents receive nursing care certification, there are not a few people who decide to move to other areas. Especially in the event of a disaster in the area, it may become difficult to keep people in the area, and cases of population outflow may occur.

Thus, population decline, and aging are not merely a phenomenon of a decrease in the number of people and an increase in the aging population rate occur, but also social problems occur in a chain reaction, leading to the rapid vulnerability of the sustainability of the areas.

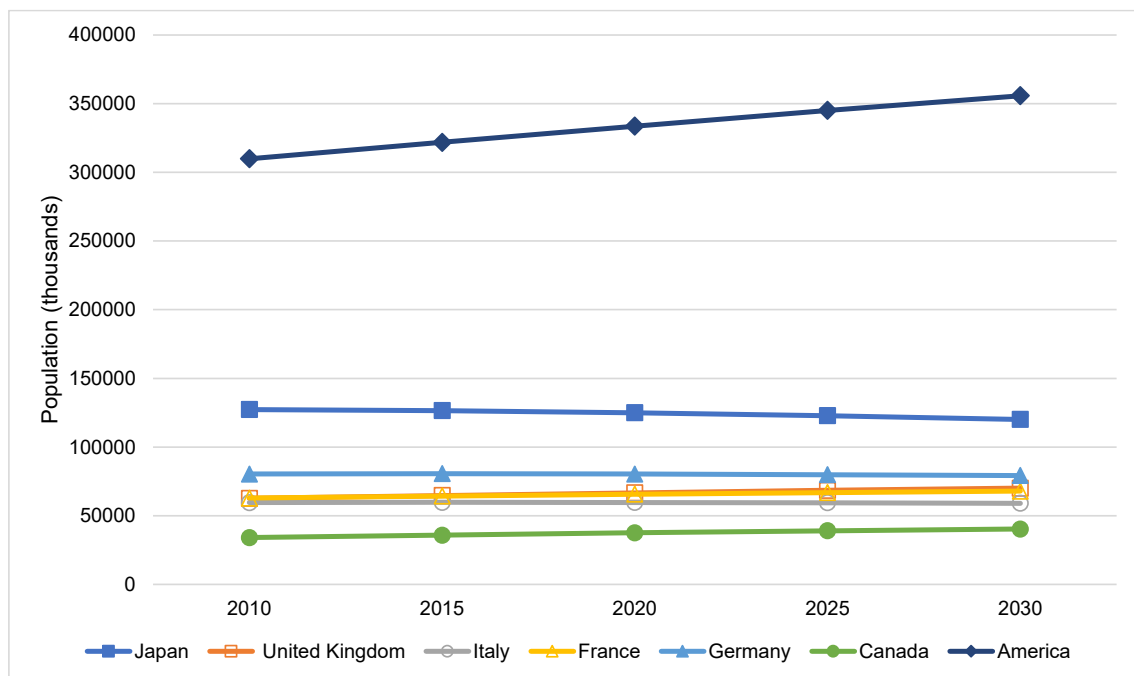


Fig. 1.1. Population trends in major advanced countries
(Created using data from World Population Prospects: 2015 Revision, United Nations)

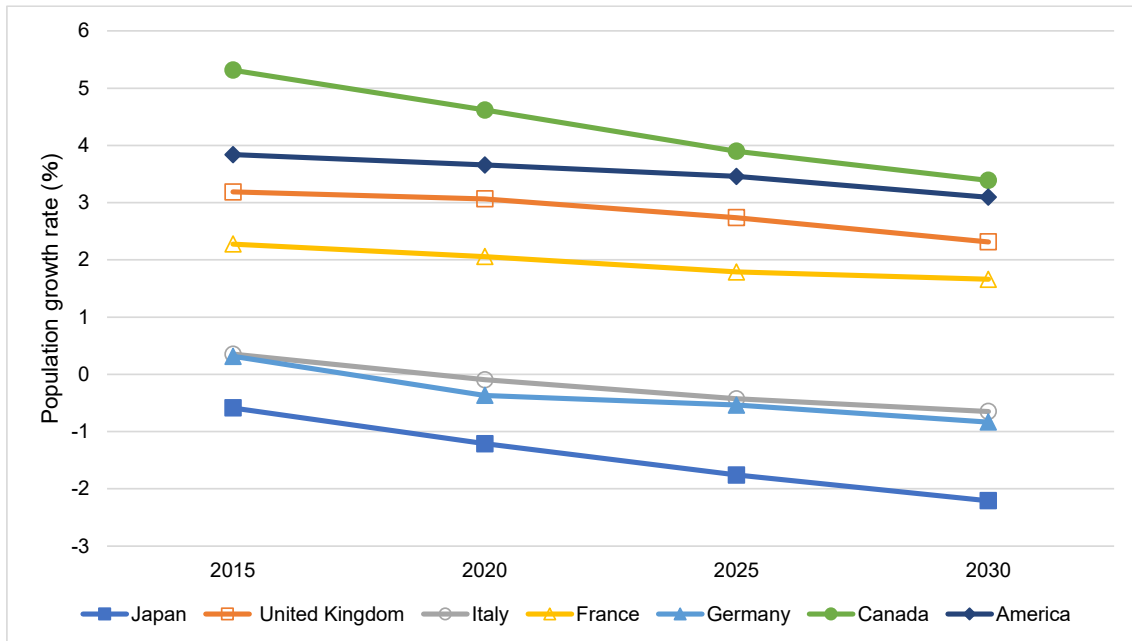


Fig. 1.2. Population growth rate trends in major advanced countries
(Created using data from World Population Prospects: 2015 Revision, United Nations)

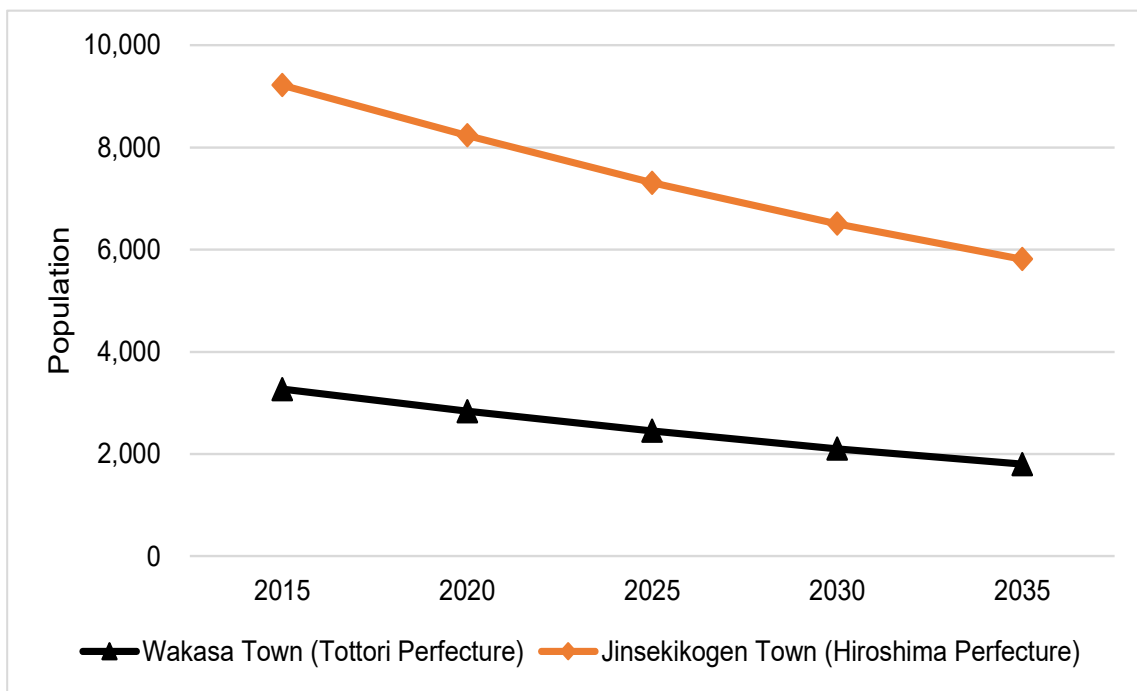


Fig. 1.3. Population trends in Wakasa Town and Jinsekikogen Town
(Created using data from Projected future population by region in Japan: 2018 estimated, National Institute of Population and Social Security Research)

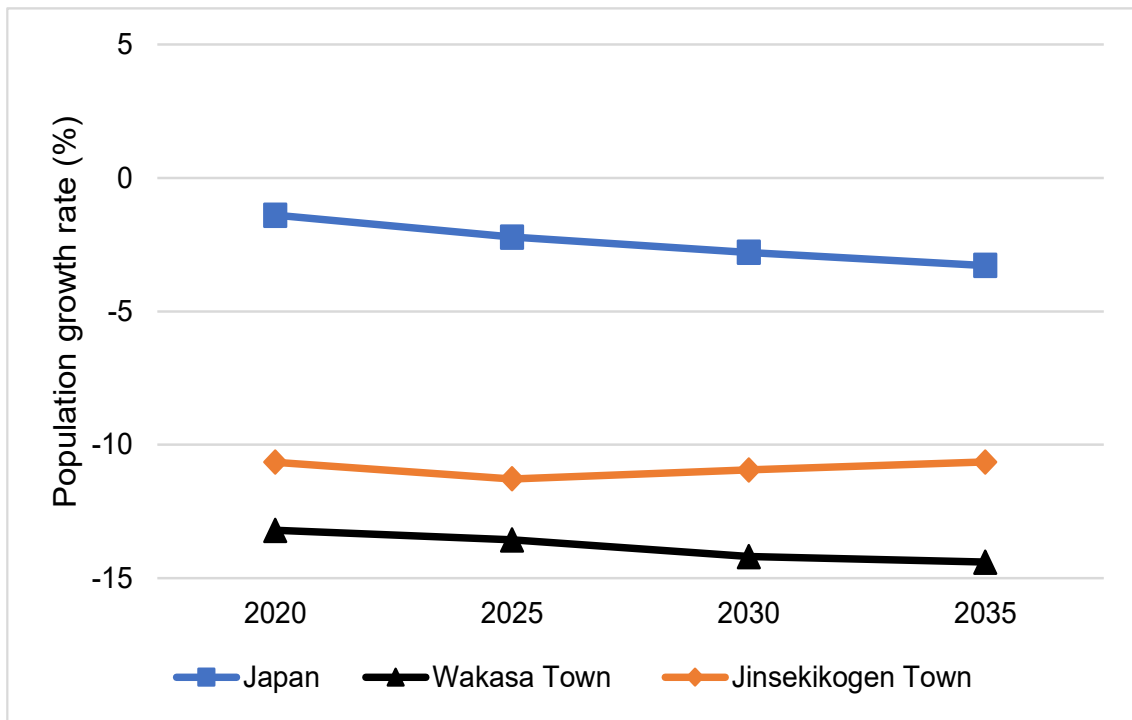


Fig. 1.4. Population growth rate trends in Japan, Wakasa Town, Jinsekikogen Town
(Created using data from Projected future population by region in Japan: 2018 estimated, National Institute of Population and Social Security Research)

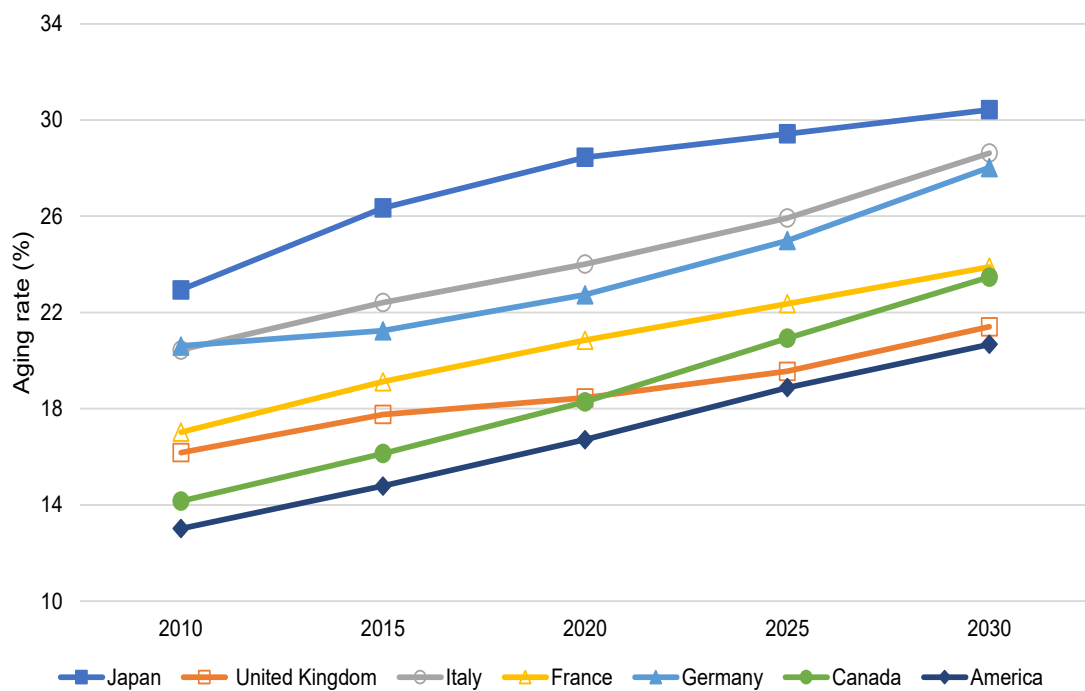


Fig. 1.5. Trends in aging rates in major advanced countries
(Created using data from World Population Prospects: 2015 Revision, United Nations)

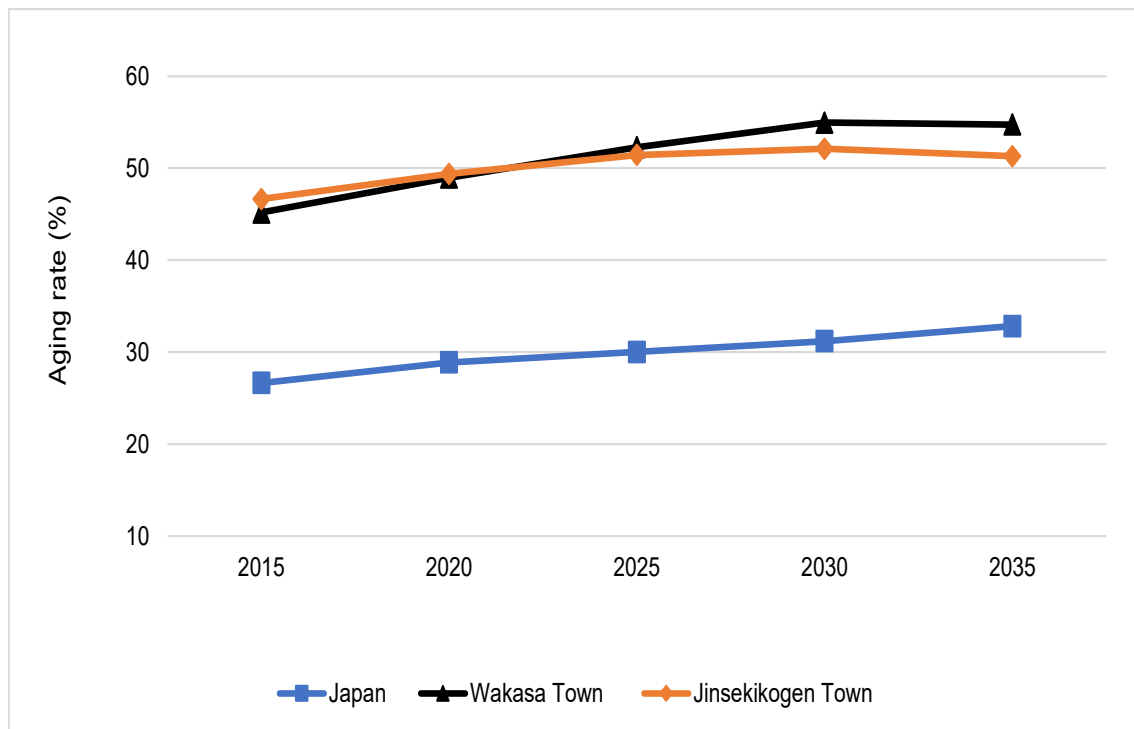


Fig. 1.6. Trends in aging rates in Japan, Wakasa Town, Jinsekikogen Town
(Created using data from Projected future population by region in Japan: 2018 estimated, National Institute of Population and Social Security Research)

1.1.2 Public transportation in rural areas

The impact of population declines, and aging extends to the transportation sector. In rural areas, there are many dispersed settlements scattered throughout the mountains, and the population size is also small, which means that many areas do not have sufficient public transportation services. As a result, private cars are the main means of transportation in rural areas, and only few people use public transportation. The number of people with driver's licenses will continue to increase, leading to a decrease in the number of people using public transportation.

However, as mentioned earlier, with the withdrawal of commercial, medical, and educational facilities, the distance from home to destination becomes farther, making transportation an increasingly important role. Especially for elderly people who cannot drive or students who cannot obtain a driver's license, public transportation is an important means of transportation, and its importance will remain the same in the future.

Thus, while public transportation is becoming increasingly important, demand is declining. Against this background, public transportation has been maintained by utilizing

various means. Fig. 1.7 summarizes the specific means. In summary, it is effective to use railways and bus when the number of users is large, and on-demand transportation or taxis when the number of users is small. In other words, by using different means depending on the number of users, it is possible to maintain the service of public transportation itself.

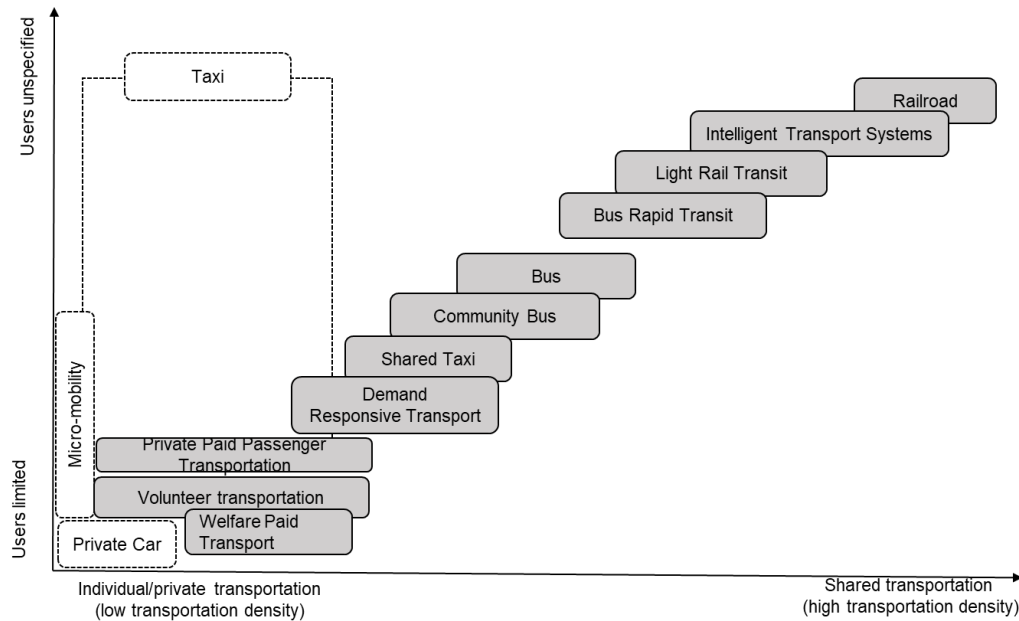


Fig. 1.7. Operational forms of diverse transportation systems ¹⁾

Based on this figure, the use of taxis will become more important in rural areas where the population is decreasing. However, taxis have not been considered as a form of public transportation in the past, and only recently have various regions begun to consider the possibilities for their use.

1.1.3 Challenges for taxi business

Despite there is a growing interest in utilizing taxis as a form of public transportation, the taxi industry cannot escape the effects of depopulation and an aging population. In other words, the number of users may be temporary increases, tend to decrease in the long term, which also applies to the human resources, taxi drivers, that operate the service.

Therefore, even if there is an opportunity to increase the number of taxis users due to the conversion from local buses and railroads to taxis as the number of public transportation users declines, there is concern about whether current drivers can meet the demand of passengers. In such cases, it becomes necessary to determine how much

service can be supplied by the traditional taxis, and whether it is appropriate to introduce an alternative form of operation, such as the shared taxis if the feasibility of supply is in doubt by the traditional taxis. Additionally, even if the number of passengers temporarily increases due to the conversion, it is necessary to appropriately evaluate the feasibility of continuing the business solely on passenger transportation services in the future, and if not feasible, what new businesses are promising while considering the risk of decreasing drivers.

However, taxi operators in rural areas are generally small-scale, and it is difficult to make such judgments and evaluations objectively. On the other hand, if these judgments and evaluations cannot be made there is a risk of remaining in the passive choice of maintaining the current situation or making incorrect choices. In this case, there is a risk of missing opportunities for improving services or exploring new business possibilities, which could be a factor in undermining the sustainability of the business.

1.2 Purpose of this study

This study will focus on taxi operators facing such challenges and develop a methodology to objectively evaluate factors related to sustainability, such as the possibility of supply by traditional taxis, the conversion between operation modes, and the feasibility of new businesses as the purpose of this study.

The methodology is as follows. First, a method will be developed to grasp the amount of supply (Hereafter, this is referred to as "supply capacity".), that can be provided to passengers with a limited number of drivers under the operation format of general taxis. Then, we focus on the situation in which, when it is determined that there is not sufficient supply capacity, a conversion to an alternative form of operation, i.e., shared taxis, is considered to improve the supply capacity. Specifically, a method will be developed to determine whether ridesharing taxis are superior to general taxis. Finally, attention will be given to the possibility of developing new businesses when the transportation of passengers alone cannot sustain the business, even with sufficient supply capacity. Specifically, A methodology will be developed to evaluate whether a new business can improve financial condition and whether the operator has the capacity to develop the new business with a limited number of drivers.

When utilizing these methodologies, data is required as input information. However, it is not always easy for small taxi operators to collect data that they have not collected outside of their normal operations. The data that taxi operators usually collect and hold is

the data from their work diary, which includes information on when and where passengers boarded and alighted. Therefore, the methodology developed in this study is based on an approach that can be evaluated using only this data.

Chapter 2

Basic concept of this Study

2.1 The current utilization status of taxis

The first step is to understand how taxis are utilized in the rural areas. In Jinsekikougen Town, Hiroshima Prefecture, a taxi subsidy system was introduced in 2017, and traditional taxis are being used as the center of public transportation. In addition, shared taxis are being introduced in cities such as Maibara Shi in Shiga Prefecture, Yamaguchi Shi in Yamaguchi Prefecture, Shizukuishi Town in Iwate Prefecture, and Kitakyushu Shi in Fukuoka Prefecture. Furthermore, taxi operators are developing a new business of transporting both passengers and freight. In Horonobe Town, Hokkaido Prefecture, taxis have been used to deliver Sagawa Express delivery freight to each delivery destination. And there are other initiatives in Asahikawa Shi, Hokkaido, which collaborates with Sagawa Express and taxi operators.

In addition to the above initiatives, fixed-price services and taxi dispatch applications are also being introduced. In many areas, traditional taxis, shared taxis, and freight-passenger integration are the main applications and there are a lot of research on these topics has also been accumulated. In the following sections, we will review research on traditional taxis, shared taxis, and freight-passenger integration, and then organize the structure of this study.

2.2 Previous research on traditional taxis

There is an amount of accumulated research on the utilization and operation of traditional taxi. Fukumoto *et al.*²⁾ analyzed digital daily report data to discuss public transportation policies that utilize traditional taxis. Suzuki *et al.*³⁾ are investigating the price sensitivity of initial taxi fares and examining the way services are provided. Suzuki *et al.*⁴⁾ studied the effect of taxi fare discounts on the outing behaviors and awareness of the elderly. Kato *et al.*⁵⁾ conducted a simple simulation on operating costs and determined that traditional taxis could be employed as local public transportation in situations with low transportation demand density. Yoshida⁶⁾ investigated the application of the flat-rate

taxi service. Sano *et al.*⁷⁾ formulated a time-constrained pickup and delivery planning problem and derived the needed number of vehicles and optimal patrol routes using the insertion method, a heuristic solution approach, to investigate the possibilities of improving operational efficiency.

However, all these studies were conducted under the assumption that taxi operators have sufficient supply capacity. In previous studies, no method has been established for grasping the supply capacity of taxi operators when operating traditional taxis.

2.3 Previous studies on shared taxis

There are many studies on the evaluation of shared taxis compared to traditional taxis for urban areas. Shared taxis in urban areas are evaluated primarily in terms of reduced travel distance and environmental impact. Cai *et al.*⁸⁾ and Yu *et al.*⁹⁾ evaluated shared taxis using taxi operation historical data in Beijing. The findings indicated that adopting shared taxis can reduce travel distance and the emission of air pollutants compared to traditional taxis. Choi *et al.*¹⁰⁾ also evaluated shared taxis in Seoul, Korea. The findings indicated that 48% of trips from hotspots where taxis pickup passengers can be shared, reducing the total vehicle-km traveled by 1.2 km per shared ride. Wang *et al.*¹¹⁾ performed a comprehensive simulation study based on real taxi booking data in Singapore, which indicates that shared taxis can reduce the average distance traveled by 2-3 km each taxi trip. In addition, some studies have been conducted in New York City, USA^{12),13)}; Shanghai, China¹⁴⁾, all of which showed that shared taxis can reduce travel distance.

Some studies indicated that shared taxis could reduce the number of vehicles in urban areas. Alonso-Mora *et al.*¹⁵⁾ demonstrated that 98% of the taxi rides currently served by over 13,000 taxis could be served with just 3,000 taxis of capacity four. In addition, Vazifeh *et al.*¹⁶⁾ also showed the reduction of vehicles in New York. Moreover, some recent research focuses on developing efficient algorithms for shared taxis in urban areas^{17) ~ 19)}.

There are few studies on shared taxis in rural areas. Elting *et al.*²⁰⁾ used a constraint programming formulation to quantify shared taxis' performance in terms of the number of served passengers under varying dynamic settings. The result demonstrated the impact of pre-booking on shared taxis' efficiency and service quality. Thao *et al.*²¹⁾ conducted a case study on how to effectively introduce ride-sharing transportation based on an empirical experiment of ridesharing done in Switzerland. Lygnerud & Nilsson.²²⁾ analyzed the business model for shared-ride transportation in rural areas of Switzerland

using the Business Model Canvas framework.

However, there are no studies that quantitatively evaluate the effectiveness of shared taxis in rural areas as in urban areas. In addition, there are no studies that evaluated the superiority of shared taxis compared to traditional taxi in the context of the shortage of drivers in rural areas.

2.4 Previous studies on freight-passenger integration

Research on freight-passenger integration is still in its infancy, but it has been on the rise in the last five years. A review paper by Cavallaro *et al.*²³⁾ detailed an overall picture of related research. This research has mainly focused on urban areas. Freight-passenger integration in urban areas was introduced to improve the efficiency of public transportation, traffic congestion, and environmental pollution²⁴⁾. Freight-passenger integration generally utilizes public transportation like buses, railways, and taxis.

Ghilas *et al.*²⁵⁾ discuss the integration of freight and passengers utilizing buses and rails. It is assumed that a portion of the freight transportation route is delivered by scheduled buses. Moreover, pickup and delivery vehicles deliver the first- and last-mile transportation. This problem is called The Pickup and Delivery Problem with Time Windows and Scheduled Lines (PDPTW-SL), and the model is built using mixed-integer programming. The findings demonstrate that integrating freight and passenger transportation may reduce freight transportation costs and CO₂ emissions. This model was extended by Ghilas *et al.*²⁶⁾ to account for uncertainty in freight demand and estimate the operational cost that may be decreased. Masson *et al.*²⁷⁾ identified the mixed urban transportation problem (MUTP) with buses, modeled it using mixed-integer programming, and compared it to classical freight transportation systems. For freight-passenger integration by rail, Behiri *et al.*²⁸⁾ focused on the Freight-Train-Transport-Scheduling-Problem (FRTSP) and constructed a mixed-integer programming model. The effects of freight-passenger integration on the components of the rail network (train, stations, and rail lines) were analyzed. Li *et al.*²⁹⁾ present an optimization framework for railway service design with integrated passenger and freight transportation and constructed a model assuming that freight may be transported on either dedicated freight rails or passenger rails.

Li *et al.*³⁰⁾ identified freight and passenger integration using taxis as the share a ride problem (SARP) and constructed a static SARP model based on mixed-integer programming. Furthermore, they created a dynamic SARP model and showed that its

performance was almost similar to that of the static SARP model and that the static model may replace the dynamic SARP model. Li *et al.*³¹⁾ extended a model that considers stochastic travel times and delivery locations. Nguyen *et al.*³²⁾ developed a model that considers parking between transportation based on Li *et al.*³⁰⁾ model. Moreover, it empirically demonstrated that freight-passenger integration is superior in profit, distance traveled, and the number of vehicles used, using taxi operators' Operational historical data. Do *et al.*³¹⁾, Ronald *et al.*³²⁾, and Linares *et al.*³³⁾ investigate freight-passenger integration by taxi as well. In addition to research on buses and taxis, there are also studies on freight-passenger integration via autonomous vehicles³⁴⁾.

There is comparatively less study in rural areas than in urban areas, but some has been collected. Qu *et al.*³⁵⁾ describe a bus-based system for the transportation of mixed freight and passengers linking rural and urban areas. Van Duin *et al.*³⁶⁾ introduce the Cargo Hitching project in the Netherlands. They demonstrate that this project has benefits, such as environmental benefits from CO₂ reduction and job promotion. Some studies also use data analytical approaches to evaluate the viability of freight and passenger integration and its implications. For instance, Mazzarino *et al.*³⁷⁾ investigated the feasibility of freight-passenger integration using public transportation by comparing the existing freight transport demand with the available capacity of the existing public transport system. Bruzzone *et al.*³⁸⁾ analyzed passenger and freight transport data from before and after integration to evaluate the effects of integration from operational, environmental, and social aspects.

However, previous studies have not taken into account the regional characteristics of rural areas. Additionally, there are no studies evaluating the feasibility of freight-passenger integration in terms of whether it can improve business conditions or supply capacity when implemented.

2.5 Structure of this study

As mentioned above, there are no studies evaluating the sustainability of taxi operators in rural areas, in terms of factors such as supply capacity of traditional taxis, the superiority of shared taxis as an alternative operating form, and the feasibility of a new business model, freight-passenger integration. Therefore, this study will examine the methodology for evaluating these factors as follows.

In Chapter 3, we construct a mathematical programming model based on mixed integer programming to quantitatively evaluate the supply capacity of taxi operators. Then, we

empirically evaluate the supply capacity of taxi operators in the town of Jinsekikougen using taxi operation history data and derive the general supply capacity of taxi operators. Additionally, taxi operators may adjust passenger reservations to accommodate their convenience, rather than dispatching according to the reservation of passengers. This adjustment is referred to as "reservation adjustment." Therefore, we also derive the supply capacity of taxi operators based on the model, considering reservation adjustments.

In Chapter 4, we focus on the scenario where taxi operators choose between operating the shared taxis or the traditional taxis. In this decision, it is necessary to evaluate whether shared taxis are superior to traditional taxis. Therefore, we propose a method for objectively evaluating the superiority of shared taxis based on the viewpoint that the fewer the minimum number of drivers required for operation, the better the sustainability of the taxi business. Specifically, we formulate a mathematical programming model based on mixed integer programming that can calculate the number of drivers required for shared and traditional taxi operations. Then, using the results calculated by this model, we demonstrate empirically that the superiority of shared taxis can be evaluated using statistical models.

In Chapter 5, a mathematical programming model is developed to evaluate how much profit can be increased and whether there will be a shortage of manpower by implementing freight-passenger integration in rural areas. Specifically, a model using mixed integer programming will be constructed to reproduce passenger transportation and freight delivery by taxi, and a method for evaluating the feasibility of freight-passenger integration from the perspectives of profit and manpower will be developed based on the results of the model.

Fig. 2.1 shows the structure of this thesis.

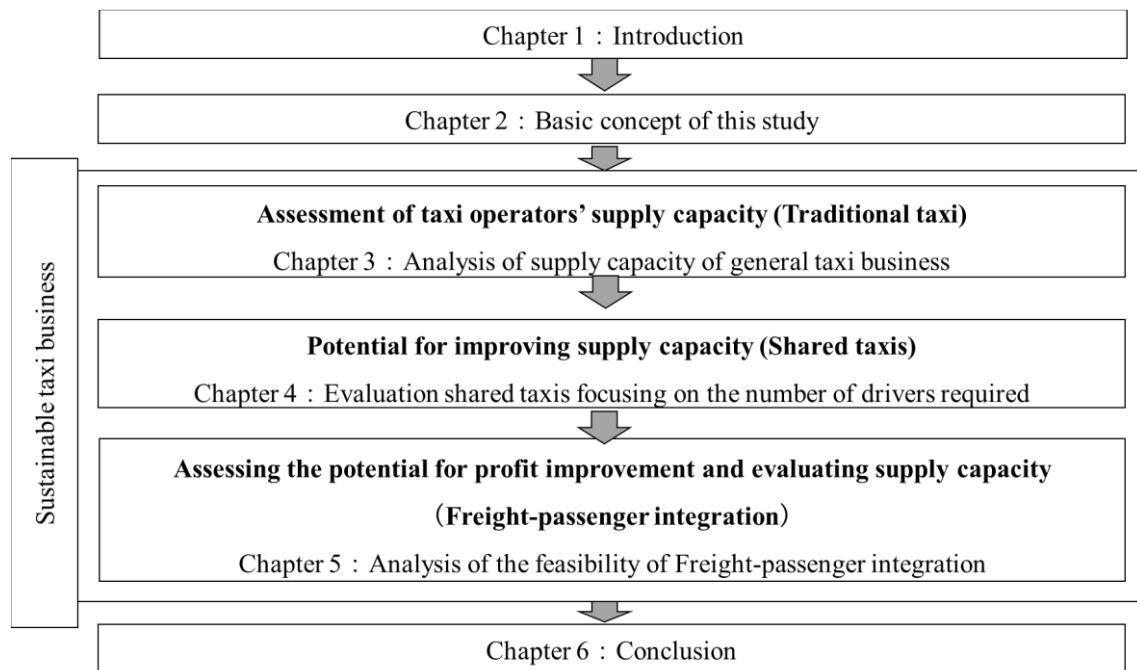


Fig. 2.1. Structure of this thesis

Chapter 3

Evaluating supply capacity of taxi business in rural areas

3.1 Introduction

In rural areas, there is an increasing number of municipalities that are exploring a shift from bus routes to taxis. However, in addition to a decline in the number of passengers, many taxi operators are facing a severe driver shortage. Therefore, when considering a shift from bus routes to taxis, if the taxi operator's supply capacity can be objectively assessed in advance, it will be evident how much demand can be handled by taxis and how many drivers should be maintained, thereby helping to promote constructive discussions. In this chapter, we will assess the supply capacity of taxi operators based on the characteristics of rural areas. Nonetheless, even if supply capacity could be determined, it would often be limited. It is meaningful to focus on the possibility that supply capacity can be improved by accommodating the passengers to the convenience of the operators, thereby improving the supply capacity by adjusting reservations to secure the necessary capacity for the area. Therefore, it would be useful to objectively assess this possibility as well.

In this study, we focus on the human resources aspect of taxi operators in rural areas and construct a methodology to quantitatively evaluate the supply capacity of taxi operators. Additionally, considering reservation adjustments, we use actual taxi operational history data to apply the developed methodology and empirically clarify the relationship between reservation adjustments and the supply capacity of the taxi operators.

3.2 Basic concept of this study

3.2.1 Previous studies

There are many studies on dispatch planning that has accumulated regarding the efficient use of limited resources, such as vehicles and drivers. If not limited to taxis, there is a considerable amount of accumulated research in the field of Operations Research on

the Vehicle Routing Problem. Many books have been published on this topic, including references ⁴⁴⁾ ~ ⁴⁶⁾, and many papers are available for review, e.g. Gansterer and Hartl⁴⁷⁾ developed a collective vehicle routing model, Baldacci *et al.*⁴⁸⁾ and Letchford and Gonzalez⁴⁹⁾ considered models with vehicle capacity constraints, Park and Kim⁵⁰⁾ addressed school bus routing problems, Cordeau and Laporte⁵¹⁾ focused on dial-a-ride problems, Desaulniers *et al.*⁵²⁾ tackled delivery planning problems with time window constraints, and Berhan *et al.*⁵³⁾ dealt with probabilistic vehicle routing models.

In addition, there are various types of models, including those using dynamic programming ^{54), 55)}, those using GA ^{56), 57)}, those using agent-based simulation ⁵⁸⁾, and those using machine learning such as deep learning ⁵⁹⁾, but the traditional and most widely used approach is mixed integer programming method. Taxis including shared taxis and many dial-a-rides, have also been modeled using mixed integer programming, with Desaulniers *et al.*⁶⁰⁾ as the most basic model. There are various derived models based on this model, such as Pierotti and Essen ⁶¹⁾ consider transfers, Tellez *et al.*⁶²⁾ consider changes in vehicle capacity due to accommodating wheelchairs, Ning *et al.*⁶³⁾ consider uncertainty in reservations, and Lu *et al.*⁶⁴⁾ address scheduling when there are electric and gasoline cars. In this study, we also use mixed integer programming to build a model. However, there is little study on the context of rural areas, such as Elting and Ehmke ⁶⁵⁾, which analyzes the possibility of rejecting reservations.

Therefore, in this study, while assuming rural areas, we construct a mathematical model based on the model developed by Desaulniers *et al.*⁶⁰⁾ to derive the operation of the taxi operator under given passengers and drivers.

3.2.2 Approach to understanding supply capacity

The data used in this study are past business journals related to taxi operations. Using this data, we derive the supply capacity of taxi operators by giving passenger demand as a fixed value and focusing on changes on the supply side. On the supply side, the service of providing spatial mobility to passengers is provided by drivers. In other words, taxi operators provide services to passengers using the resource of drivers. In the production activities in the rural areas with the background of shortage of drivers, taxi operators provide the minimum resources in response to passenger demand. The minimum number of drivers is the supply capacity of the taxi operator. The minimum number of drivers required needs to be calculated in the model. If the model can be constructed, setting a situation where the number of drivers is insufficient in response to daily passenger demand will result in a scene where passengers demand will be refused. The minimum

number of drivers just before this scene appears is the minimum number of drivers required. When focusing on daily operations to grasp the supply capacity of taxi operators, the number of drivers can be used as an indicator without any problem. However, the number of drivers cannot be used as a general indicator of supply capacity, which indicates that the supply capacity is a specific range of values for any operator. To understand the general supply capacity, we use a new indicator, which is the travel distance per driver. The travel distance is the distance the driver travels as a service provided to the passenger. Even if the number of drivers required daily and the demand of passengers are different, there is a limit to the distance that one driver can travel in a day. In the following, we use indicators of travel distance per driver to understand supply capacity.

The calculation of supply capacity is based on the following approach.

- Given the passengers of a particular operator on a given day, the model determines whether all passengers can be transported with a drivers and derives how many distances the operator will travel to transport all passengers.
- The travel distance is determined for each feasible number of drivers a that can transport all of the passengers. By this way, the number of drivers needed for transportation of all passengers and the travel distance under the number of drivers can be derived.
- If the number of drivers is sufficiently small, it will not be possible to transport all given passengers. The travel distance for the infeasible case is derived by the method described below.
- We focus on the interval between the maximum travel distance in the feasible optimal solution and the travel distance under the infeasible solution. In other words, there is a distance inside the interval that corresponds to the supply capacity.
- The above is calculated for all the days under consideration and for all the operators to find the supply capacity.

To implement the above approach, a model is required to derive the travel distance under the given number of drivers of taxi operators. The modeling concepts will be summarized in the following section.

3.2.3 Modeling assumptions

The following assumptions were made in constructing the model.

- Drivers start (start of work) and finish (end of work) at the location where the depot is located (hereinafter referred to as "business center").
- A single operator has only one business center.
- The driver takes a break for lunch at the business center.
- There is no passenger sharing.
- The driver performs the job within the prescribed working hours.
- If the next job is not determined at the end of a job, the driver returns to the business center and waits.
- The operator can't reject the passenger's reservation but can but requests an adjustment in the time of reservations within a predetermined time, and the passenger accepts the request.
- The passenger makes a reservation before departing. The passenger requests that the vehicles should be dispatched immediately. That is, the reservation is made just before the passenger's desired dispatch time from the passenger's departure place requested to the business office.

Among these, the assumption that "the driver returns to the business center to wait" is based on the characteristics of rural areas. In general, there are several places to wait, such as hospitals and supermarkets, which are facilities that serve as destinations for going out. However, where to wait may vary depending on the day or the operator. On the other hand, it is believed that the operator's office is not necessarily located in a remote area, but rather around areas where these facilities are concentrated. Therefore, if we assume that they wait at the business center, the result is not much different from the case where they wait at any location.

Furthermore, the final assumption, in practice, not all reservations are necessarily made at that time. If reservations are made at this time, it may be assumed that taxi operators cannot plan dispatches in advance, resulting in a disadvantaged situation for the driver's operation. Therefore, this assumption would set a pessimistic situation for operators, and the taxi supply capacity is evaluated from a safety perspective.

3.2 Model construction

Let the number of drivers in the business be denoted as m , and let any driver be represented as k . The set of drivers is denoted as $K = \{1, 2, \dots, m\}$. In the following,

passenger transportation and the driver's start of work (origin depot), and end of work (destination depot) are all expressed in terms of the word *job*. We denote the job related to transport passengers by $N = \{1, \dots, n\}$, the jobs related to take breaks by $U = \{n + 1, \dots, n + m\}$, and the start and end work by $i = 0, n + m + 1$ respectively. The set $\{0, n + m + 1\} \cup N \cup U$ is represented by V . Note that the distinction between jobs of transporting customers is also a distinction between passengers, so job $i (\in N)$ may also be referred to as passenger i .

The desired departure time (start time of job i) for passenger i is represented as $h_{i,in}$, the arrival time (end time of job i) is represented as $h_{i,out}$, and the occupied vehicle time is represented as $a_i (= h_{i,out} - h_{i,in})$. These are all constants. passengers inform the operator of their desired departure time to reserve a taxi. but the operator can postpone the pick-up time for passenger i by up to δ_i . However, δ_i has an upper limit, which is denoted by the constant δ (hereafter referred to as "adjustable time"). As a result of this adjustment, the actual departure and actual arrival times for passenger i are denoted as $d_{i,in}$, $d_{i,out}$, respectively. t_k and T_k are the start and end times of driver k , respectively, and D_{ij} is the time required from the end of job i to the start point of job j . If t_k and T_k are determined in advance, they are constants; otherwise, they are variables. Let r_k and R_k denote the start and end times of driver k 's breaks, respectively. Driver must take a break of at least Δr hours i. If r_k and R_k are predetermined, they are given as constants, but if not, they are treated as variables.

After completing job $i (\in N)$, if the driver has another job booked, he/she should go immediately to the location where the job starts, otherwise, he/she should return to the office to wait. The set of points passed on the way back from the location where job $i (\in N)$ was completed to the office is designated as A_i , the set of all points is designated as A , and any point is designated as s , with $s = 0$ designating the office. However, A_i includes the location where job i was completed and the office. The time required from the end location of job i to point s is represented by D_{is} , and the time required from point s to the starting location of job j is represented by D_{sj} .

The taxi operator minimizes the travel time. Then, the objective function of the taxi operator is given by Eq. (1). However, the first term is the travel time for the forwarding and the second term is the travel time for the occupied vehicle. The second term is a constant and hence unnecessary for optimization, but it is needed to calculate the supply capacity since the supply capacity is the sum of all travel times, regardless of whether the vehicle is empty or occupied. The travel time obtained here is converted to distance to obtain the travel distance.

$$\text{minimize } \sum_{i \in N} \sum_{j \in N} \sum_{s \in A_i} (D_{is} v_{is} + D_{sj} u_{sj}) + \sum_{i \in N} a_i \quad (1)$$

Subject to:

$$\sum_{i=0, i \neq j}^{n+m} x_{ij} = 1 \quad (\forall j \in N \cup U) \quad (2)$$

$$\sum_{j=1, j \neq i}^{n+m+1} x_{ij} = 1 \quad (\forall i \in N \cup U) \quad (3)$$

$$\sum_{j=1}^{n+m+1} x_{0j} = m \quad (4)$$

$$\sum_{i=0}^{n+m} x_{i, n+m+1} = m \quad (5)$$

$$\sum_{k=1}^m z_{ik} = 1 \quad (\forall i \in N \cup U) \quad (6)$$

$$z_{n+k, k} = 1 \quad (\forall k \in K) \quad (7)$$

$$z_{jk} \geq z_{ik} + x_{ij} - 1 \quad (\forall i, j \in N \cup U, \forall k \in K) \quad (8)$$

$$\sum_{s \in A_i} v_{is} = 1 \quad (\forall i \in N) \quad (9)$$

$$\sum_{s \in A} u_{sj} = 1 \quad (\forall j \in N) \quad (10)$$

$$u_{sj} \geq v_{is} + x_{ij} - 1 \quad (\forall i, j \in N, s \in A) \quad (11)$$

$$v_{i0} \geq \sum_{j=n+1}^{n+m+1} x_{ij} \quad (\forall i \in N) \quad (12)$$

$$u_{0j} \geq \sum_{i=n+1}^{n+m} x_{ij} + x_{0j} \quad (\forall j \in N) \quad (13)$$

$$h_{i, in} \leq y_{i, in} \leq h_{i, in} + \varepsilon_i \quad (\forall i \in N) \quad (14)$$

$$y_{i,out} = y_{i,in} + a_i \quad (\forall i \in N) \quad (15)$$

$$0 \leq \varepsilon_i \leq \varepsilon \quad (\forall i \in N) \quad (16)$$

$$y_{j,in} \geq y_{i,out} + \sum_{s \in A} (D_{is}v_{is} + D_{sj}u_{sj}) - M(1 - x_{ij}) \quad (\forall i \in N) \quad (17)$$

$$y_{i,out} + \sum_{s \in A} D_{is}v_{is} \quad (\forall i \in N) \quad (18)$$

$$y_{i,out} + \sum_{s \in A \setminus \{0\}} D_{is}v_{is} + Mv_{i0} \geq h_{j,in} - D_{0j} - M(1 - x_{ij}) \quad (\forall i, j \in N) \quad (19)$$

$$y_{i,in} \geq t_k + d_{0i} - M(1 - z_{ik}) \quad (\forall i \in N, \forall k \in K) \quad (20)$$

$$T_k \geq y_{i,out} + d_{i,n+m+1} - M(1 - z_{ik}) \quad (\forall i \in N, \forall k \in K) \quad (21)$$

$$r_k \geq y_{i,out} + d_{i,n+k} - M(1 - x_{i,n+k}) \quad (\forall i \in N, \forall k \in K) \quad (22)$$

$$y_{j,in} \geq R_k + d_{n+k,j} - M(1 - x_{n+k,j}) \quad (\forall j \in N, \forall k \in K) \quad (23)$$

$$r_k \geq t_k \quad (\forall k \in K) \quad (24)$$

$$T_k \geq R_k \quad (\forall k \in K) \quad (25)$$

$$R_k \geq r_k + \Delta r \quad (\forall k \in K) \quad (26)$$

$$x_{ij} \in \{0,1\} \quad (\forall i \in V, \forall j \in V) \quad (27)$$

$$z_{ik} \in \{0,1\} \quad (\forall i \in N \cup U, \forall k \in K) \quad (28)$$

$$v_{is} \in \{0,1\} \quad (\forall i \in N, \forall s \in A_i) \quad (29)$$

$$u_{sj} \in \{0,1\} \quad (\forall s \in A, \forall j \in N) \quad (30)$$

Any job must be done is represented by Eqs. (2) and (3). The presence of m drivers is equivalent to performing m jobs after start of drivers and before end of drivers. Therefore, Eqs. (4) and (5). hold. Except the start and end of the driver, any job is

completed by one driver alone. This condition is expressed by Eq. (6). All drivers take a break, which is expressed by Eq. (7). If job j is completed following job i , both jobs should be performed by driver k . This condition is expressed by Eq. (8).

When a reservation for the next job may come in while the driver is on their way back to the office after completing job i , they will head towards the next job from one of the locations included in A_i . However, if no reservation for the next job comes in while the driver is on their way back to the office, they will wait at the office and head directly towards the starting location of the next job after the reservation for the next job comes. From the above, Eq. (9) holds for v_{is} . Similarly, Eq. (10) holds for u_{sj} . If job j is performed after job i , and if the driver travels from the location where job i was completed to point s , then the driver will naturally travel to job j from point s . This condition is expressed by Eq. (11). If the next job after job i is a break or the end of the driver, the driver travels immediately to the office from the point where job i was completed. If the next job after the start of a driver or a break is job j , the driver goes from the office to the starting point of job j . This is expressed in Eqs. (12) and (13).

Eqs. (14) and (15) hold for the relationship between the desired departure time, arrival time, and the actual departure and arrival times for passengers. Eq. (16) holds the relationship between δ_i and δ . The condition that the start time of job j is after the end time of job i plus the time required for the travel to job j is expressed by Eq. (17), where M is a sufficiently large value. The time at which the driver passes point s on the way back to the business office after the completion of job i is expressed by Eq. (18). If job j is completed after job i , the driver cannot go to the starting point of job j until the reservation for job j is made. If the reservation is made later, received after the previous job has been finished and the vehicle has returned to the office, then the vehicle will go from the office to the beginning location of job j . This is represented by Eq. (19). However, as described in the previous section, passenger i 's reservation is made at a time D_{0i} (the time required to travel from the office to the location where passenger i departs the vehicle) earlier than the desired departure time. If driver k is in charge of job i after the start of driver k , the start time of job i is after the start time of driver k plus the travel time to job i . The same relationship holds for the end of drivers with job i . These relationships are expressed by Eqs. (20) and (21). The relationship between the times of these breaks and the times of the jobs completed before and after the break is expressed by Eqs. (22) and (23). The relationship between the start and end times of drivers and the time of breaks is expressed by Eqs. (24) and (25). Eq. (26) limit drivers' break times.

Binary variable x_{ij} indicates whether or not job j is executed after job i . Whether or not driver k is in charge of job i is represented by binary variable z_{ik} . Binary

variable v_{is} indicates whether or not to go to s from the point where job i is finished. Binary variable u_{sj} indicates whether or not to go from point s to the point where next job j is started.

Table 3.1 Model symbols.

Set	Explanation
N	Set of jobs to carry passengers and freight $N = \{1, \dots, n\}$
V	Set of all jobs plus breaks $V = \{0, 1, \dots, n + m + 1\}$
U	Set of breaks $U = \{n + 1, \dots, n + m\}$
K	Set of drivers $K = \{1, \dots, m\}$
A	Set of all points, where 0 is a business office $A = \{0, 1, 2, \dots, g\}$
A_i	Set of points to pass when returning to the business office from the point where job $i (\in N)$ is completed. $A_i \subset A$
Parameter	
$h_{i,in}$	Departure time desired by passenger $i (\in N)$
$h_{i,out}$	Arrival time desired by passenger $i (\in N)$
a_i	Time required for passenger $i (\in N)$ to move
D_{is}	Time required from the end point of job i to point s
D_{sj}	Time required from point s to the start of job j
D_{ij}	Time required from the end point of job i to the start point of job j
D_{0i}	Time required to travel from the office to the location where passenger i departs
δ	Adjustable time
Δr	Driver's break time
T	Driver's working hours
M	A sufficiently large value
Variable	
$d_{i,in}$	The actual departure for passenger i
$d_{i,out}$	The actual arrival times for passenger i
δ_i	The time to adjust from the desired time for passenger i
r_k	Driver k 's break start time
R_k	Driver k 's break end time
t_k	Driver k 's start time
T_k	Driver k 's end time
x_{ij}	Binary variable indicating whether to execute job j after job i : 1 if it

	is executed, 0 otherwise.
z_{ik}	Binary variable indicating whether driver k 's is in charge of job i : 1 if in charge, 0 otherwise.
v_{is}	Binary variable indicating whether to go to s from the point where job i is finished: 1 if it goes, 0 otherwise.
u_{sj}	Binary variable indicating whether to go from point s to the point where the next job j starts: 1 if it goes, 0 otherwise.

3.3 Supply capacity analysis

3.3.1 Overview of the target area

Jinsekikougenn town is in the northeastern part of Hiroshima Prefecture, bordering Okayama Prefecture, and is a town with an area of 381.98 km². As of June 2021, the number of households is 3,903, the population is 8,600, and the aging rate is 48.27%. The town's public transportation system includes the interaction taxi, and the town buses which operates two routes, the "Yuraki-Toyomatsu Route" and the "Kamiishi-Yuraki-Yuraki-Route". Additionally, there are eight taxi operators in the town."

3.3.2 Data and settings for analysis

In this study, we use operation history data from six taxi operators (referred to as taxi operator A-F) with at least two drivers. The number of drivers in each operator is 10, 4, 4, 4, 3, and 2, respectively. The data is from September 2 to September 30, 2019, and includes information such as date, departure /arrival time and location, and fare. We select five days of data, including the days with smallest, largest, and average number of customers per day on weekdays during the above period and two days between the days mentioned. The number of passengers for each day in ascending order is 81, 94, 106, 118, and 129.

Fig. 3.1 shows the relative frequency of passengers by departure time. With the time interval set to 30 minutes. we include the percentage of "travelers" in the social life basic survey (2016) for "village/town," "weekday," "unemployed," and "65 years and older," to compare the distribution in Jinsekikougenn town to the national average. The category "unemployed" is selected because it is considered that most of the employed persons in the towns travel by private car, and few travel by taxis. The data show that people in Jinsekikougenn Town tend to travel earlier in the day compared to the national average.

In fact, when the graph of the percentage of travelers is shifted one hour earlier, the trend generally aligns. Furthermore, when comparing the relative frequencies of morning and

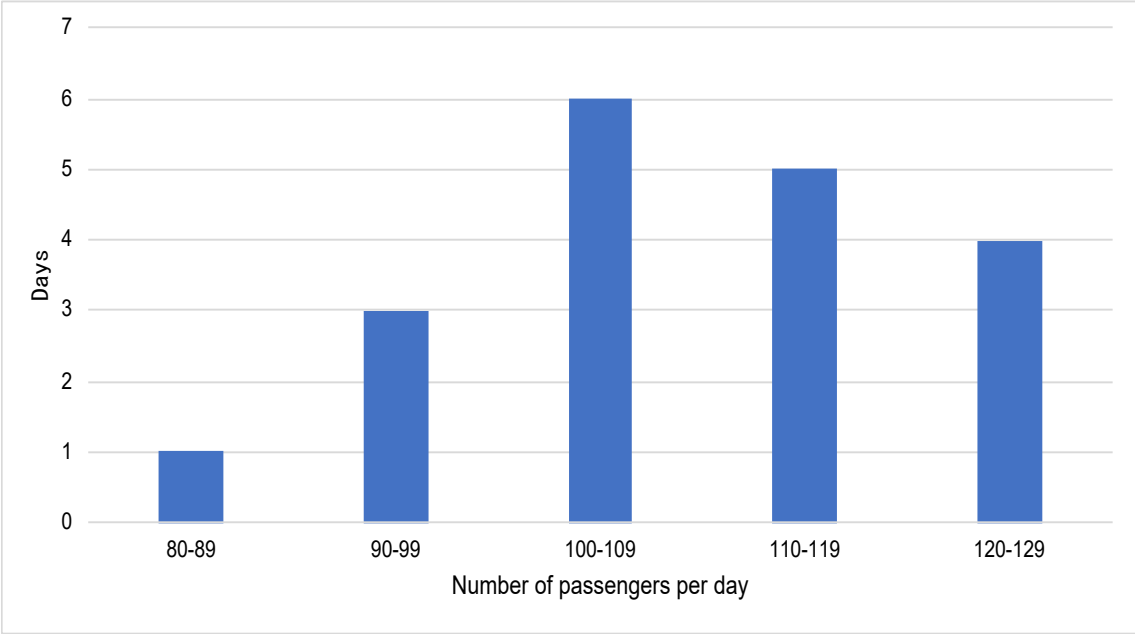


Fig. 3.1. Number of passengers per day

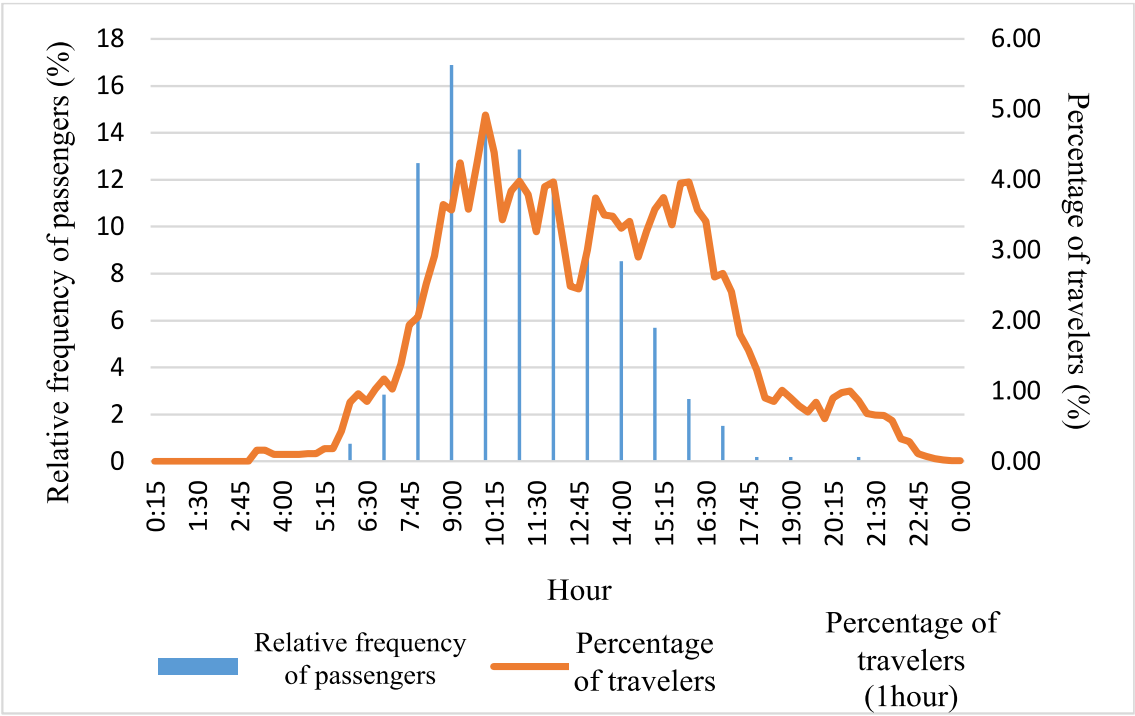


Fig. 3.2. The relative frequency of passengers by departure time

afternoon, Jinnsekikougenn Town shows a slight bias towards the morning, with a relatively sharp peak.

In addition to the historical data, we use data on the location of each taxi operator's office and the number of drivers. Both are based on information from 2019. We assume that the drivers work for 9 hours per day and take 1 hour break between 11:00 and 14:00. That is, for any driver k , $T_k - t_k = 9$, $r_k \geq 11$, $R_k \leq 14$, $\Delta r = 1$. Considering that the most frequently taken trips in the historical data were from Kamitoyomatsu district to the Jinnsekikougenn Hospital, Google Map was used to measure the distance and travel time between the Kamitoyomatsu Community Center, which is the center of the Kamitoyomatsu district, and the Jinnsekikougenn Hospital. Based on the results, the average speed was given as 40 km/hour. The representative landmarks are considered as typical locations for the settlements, and the distance between settlements is given by the shortest distance on the road network. The travel time between settlements is calculated based on the distance between them and the average speed. For the following calculations, gurobi 9.12 was used.

3.3.3 Supply capacity of taxi operators

First, let's evaluate the supply capacity for each taxi operator. Specifically, if there is a solution to the model under the condition of the number of drivers a , then all passengers can be transported by a driver. However, if there is no solution, not all passengers can be transported by a driver, which means there is a shortage of drivers. If there is no shortage of drivers, the distance that a driver travels in a day can be obtained by converting the objective function of the model, which is time, to distance. Even if there is a shortage of drivers, the travel distance can be calculated using the method described later. Therefore, the travel distance that serves as the boundary for whether or not there is a shortage of drivers can be determined and can be calculated as the supply capacity of the taxi operator.

Due to the possibility of differences in supply capacity between operators with a high number of drivers and those without, we will focus on the number of drivers and divide them into two groups: Operator A and Operator B - F. We examine three cases for the adjustable time: 0, 30, and 60 min, and calculate the supply capacity for each case. Note that in the case of 0 min for the adjustable time, it represents the operation mode of a traditional taxi service.

Then, let's consider the results for the first group, which is Operator A, as shown in Figs. 3.3 to 3.5. The interpretation of the figures is as follows: For example, let's focus on a day with 38 passengers in Fig. 3.3. For this day, assuming there are 10 drivers, the model

is calculated, and a feasible optimal solution exists. Under this solution, the travel distance per driver is approximately 85 km per day, which is represented by a black plot labeled "10 drivers" in the figure. Feasible optimal solutions also exist for 9, 8, and 7 drivers, and the results are depicted by black plots in the figure. However, when there are only 6 drivers, there is no feasible optimal solution. In such cases, the infeasible travel distance is calculated using the following method and represented by red plots in the figure. As mentioned before, there is a travel distance equivalent to the supply capacity between the maximum travel distance in the feasible optimal solution and the infeasible solution. Therefore, the supply capacity for this day ranges from 125 to 155 km per day.

If there is no feasible solution in the model, it is naturally impossible to calculate the travel distance without some modifications. In such cases, one possible approach is to relax the certain constraint (e.g., constraints on driver working hours) to seek a feasible solution and determine the travel distance under that solution. However, with this approach, if there are n passengers need be transported at the same time and m drivers ($n > m$), even with relaxed constraints, no feasible solution would exist. Therefore, in the following, we identify solutions that are clearly infeasible and derive the driving distance under those solutions."

Specifically, it is assumed that all passengers are transported from the business center to the point of departure, after transporting the passenger, the drive return to the business center. The distance required for this transportation is considered as the travel distance. In other words, if the number of drivers is enough, transportation can be conduct by this form, and the above travel distance is feasible. However, with a predetermined number of drivers, this transportation cannot be conduct, which meaning the travel distance is an infeasible value with the predetermined number of drivers. Based on this method, we calculate the travel distance when the model has no feasible solution. It should be noted that transporting all passengers in this form is the most inefficient form of transportation and has the longest travel distance among all forms of transportation. Therefore, the supply capacity is existed between the maximum feasible travel distance and the infeasible travel distance.

The same interpretation can be applied for other days and for cases where the adjustable time is not 0 min. Therefore, it can be visually confirmed that the supply capacity for an adjustable time of 0 min is around 150 (km/day), for 30 min is around 240 (km/day), and for 60 min is around 280 (km/day). However, this is only a provisional visual confirmation. Thus, a method that does not rely on visual inspection is used to derive the supply capacity.

We focus on the cumulative relative frequency of travel distance per driver. For

example, Fig. 3.5 shows the cumulative relative frequencies when the adjustable time is 0 min. This figure focuses on the "red plot" and the "black plot with the largest distance traveled" for each day, and the cumulative relative frequencies are obtained by pooling the travel distance under these plots for all days (5 days). Here, the function $F_1(d)$, written in black, is a function drawn using the feasible solution (black plot) as data, and represents the percentage of days when the travel distance is greater than or equal to d (km). Similarly, the function $F_2(d)$, written in red, is the frequency with which the infeasible solution (red plot) is drawn as data, representing the percentage of days when the travel distance is less than d (km). Thus, the intersection of $F_1(d)$ and $F_2(d)$ is the travel distance where the probability of being feasible and the probability of being infeasible are in conflict, and this can be regarded as the supply capacity. However, the figure shows that the cumulative relative frequencies at the intersections are as low as 20%, and in most cases the infeasible travel distances are higher than this. Given that there are cases in which the vehicle may be able to travel as far as 170 (km/day), the supply capacity is estimated to be 155-170 (km/day), leaving a margin of safety.

Using the above method, the supply capacity of the operator can be obtained as 155-170 (km/day) for the adjustable time of 0 min, 240-260 (km/day) for 30 min, and 240-320 (km/day) for 60 min. Next, the same analysis is conducted for Operator B to F. The results, including those for Operator A, are shown in Figs. 3.7 to 3.9. The alphabetical and numerical values on the horizontal axis represent the operators and the number of drivers, respectively. It is important to note that there are cases where a single driver can transport all passengers (indicated by the absence of red plots).

Based on these results, the supply capacity corresponding to the adjustable time is summarized in Table 3.2. From this table, it is evident that providing an adjustable time significantly improves the supply capacity. It should be noted that in actual taxi operations, some level of reservation adjustment is already being carried out. Therefore, the supply capacity with an adjustable time of 0 min represents a conservative estimate of the actual supply capacity. Consequently, the supply capacity within the range of 0 to 30 min of adjustable time is considered to be closer to the actual values.

Table 3.2 Supply capacity (unit: km/day)

Operator	Adjustable time		
	0 min	30 min	60 min
Operator A	155~170	240~260	240~320
Operator B~F	115~150	145~180	245

3.3.4 Validity verification

To assess the validity of the supply capacity, a comparison with actual statistical data is performed. According to statistical data from the Management Indicators for Automobile Transportation Businesses ⁶⁶⁾, there is data available on "average daily kilometers per operating vehicle" categorized by regional divisions. The regional divisions include "major cities," "core cities," "small and medium-sized cities," and "other regions." As Jinnsekikougenn Town falls under the "other regions" category, which represents areas with a population of fewer than 100,000 people. In the "other regions" category, the average daily kilometers per operating vehicle was 150 km per day during the years 2013 to 2015. Since this value is considered to be a close indicator of the per-driver daily distance, it will be used as a reference value for comparison in the following analysis.

Generally, this reference value is influenced by larger-scale operators, making it appropriate to compare it with Operator A in Jinnsekikougenn Town. Therefore, the following analysis compares the reference value with the supply capacity of Operator A. Considering that some level of adjustment is already being carried out in practice, it is reasonable to assume that the supply capacity of Operator A is at least 155 km per day and close to 200 km per day. Thus, the supply capacity exceeds the reference value of 150 km per day, indicating a valid and reasonable calculation of the supply capacity.

3.3.5 Relationship between reservation adjustment and supply capacity

The relationship between reservation adjustment and supply capacity has been found to be effective in improving the supply capacity of taxi businesses, and the reason behind this is the smoothing of peak demand. In other words, by smoothing the dispatch timings, it became possible to transport a large number of passengers with fewer drivers.

To confirm this point specifically, Fig. 3.1 illustrates the relative frequencies of passengers by departure time, based on the case where the adjustable time is 0 min. Therefore, by plotting the same relative frequencies for the cases where the adjustable time is 30 and 60 min, we can understand how the departure time have changed due to the adjustments. However, there are two issues in plotting this information.

The first issue is that in the aforementioned model, it is not possible to obtain a unique solution for the departure times. Therefore, in calculating the departure times, the objective function in Eq. (1) was modified and recalculated as follows. Specifically, by setting $\lambda(> 0)$ to a sufficiently small value, we ensure that it does not affect variables

other than the departure times, while also minimizing the deviation δ_i between the dispatch time and the desired time. This allows the operators to determine departure times under the realistic assumption of minimizing the deviations as much as possible during operations.

$$\sum_{i=1}^n \sum_{j=1}^n \sum_{s \in A} (D_{is}v_{is} + D_{sj}u_{sj}) + \sum_{i=1}^n a_i + \lambda \sum_{i=1}^n \delta_i \rightarrow \min \quad (31)$$

The second issue is that the departure times for a 30 min or 60 min adjustable time can vary depending on the number of drivers available. For example, in Fig. 3.3, the departure times for each passenger on a day with 38 passengers can differ when there are 7, 8, 9, or 10 drivers. Therefore, in the following analysis, we focus on the departure times when each driver has the longest travel distance. Specifically, we consider the scenario where the number of drivers is the minimum among the feasible solutions (represented by the black plots in the figure), which ultimately leads us to examine the departure times for the scenario with the fewest number of drivers among the feasible solutions.

Based on the above, Fig. 3.10 illustrates the relative frequencies according to the adjustable time. Focusing on the relative frequencies for 0 min, there is a peak at 9 o'clock. However, when the adjustable time is increased to 30 or 60 min, it can be observed that the relative frequency at 9 o'clock decreases. Furthermore, while the peak occurs at 9 o'clock for 0 and 30 min, it shifts to 9:30 for the 60 min. The height of the peaks follows the order of “the 0 min > the 30 min > the 60 min”, indicating a smoothing effect. Therefore, through the adjustment of reservations, peak demands are smoothed out, and the utilization time is dispersed, resulting in increased supply capacity for the operator.

3.3.6 Supplementary analysis regarding the spatial distribution of passengers

In the previous section, it was shown that adjustment of reservations allows for the control of passengers' temporal distribution, leading to the smoothing of peak demand and improvement in the supply capacity of taxi services. However, the supply capacity is influenced not only by the temporal distribution of passengers but also by their spatial distribution. The following section provides a supplementary analysis on the impact of passengers' spatial distribution on supply capacity.

Given that passenger demand can vary in different days and among different operators,

the previous analysis considered various spatial distributions of passengers that could occur in Jinnsekikougenn town to determine the supply capacity. However, it is not necessarily evident whether the same supply capacity can be achieved for other areas. Therefore, we consider areas with different sizes than Jinnsekikougenn town to determine the supply capacity. Specifically, we hypothetically set regions where the distances between each point in Jinnsekikougenn town are 0.5 and 1.5 times larger, and then conduct sensitivity analysis to determine the supply capacity for these regions. In this analysis, we focus on Operator B and, to minimize the impact of temporal dispersion of passengers, we examine the case with the least constraint, which is when the adjustable time is 60 min.

The results of the supply capacity are presented in Fig. 3.11. The left side of the figure represents the case where the distance is multiplied by 0.5, the center represents a multiplier of 1.0, and the right side represents a multiplier of 1.5. Here, we focus on the boundary between the black and red plots. In all cases, the supply capacity ranges from 200 to 250 km/day, which includes the value of 245 km/day shown in Table 3.2. This indicates that there is little difference in supply capacity when changing the scale of the region. While this result does not immediately imply that the supply capacity is the same in every region, it confirms that the supply capacity is not significantly affected by the spatial distribution.

3.4 Conclusion

In this study, we constructed a mathematical model based on mixed integer programming to derive the operation of taxi operators in rural areas. We used the results of the model to determine the supply capacity of taxi operators. The model was designed to reflect the reality of rural areas where drivers wait at the office when there are no passengers. Using this model, we focused on Jinnsekikougenn Town and used the operational history data of taxi operators to determine the number of drivers required for passenger transportation. Subsequently, we empirically evaluated the supply capacity of the taxi operator. Furthermore, we used the model to derive the supply capacity according to the adjustment of reservations. The results show that reservation adjustments contribute to improving supply capacity by smoothing peak demand and the magnitude of the improvement is also quantified.

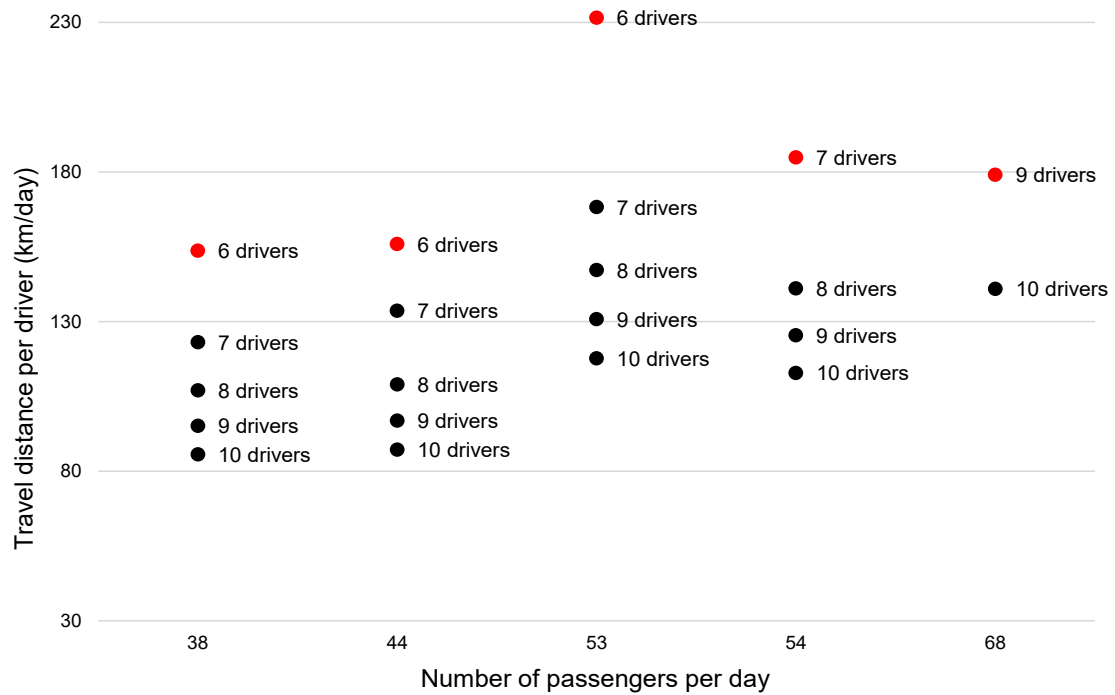


Fig. 3.3. Travel distance per driver
(Operator A, adjustable time : 0 min)

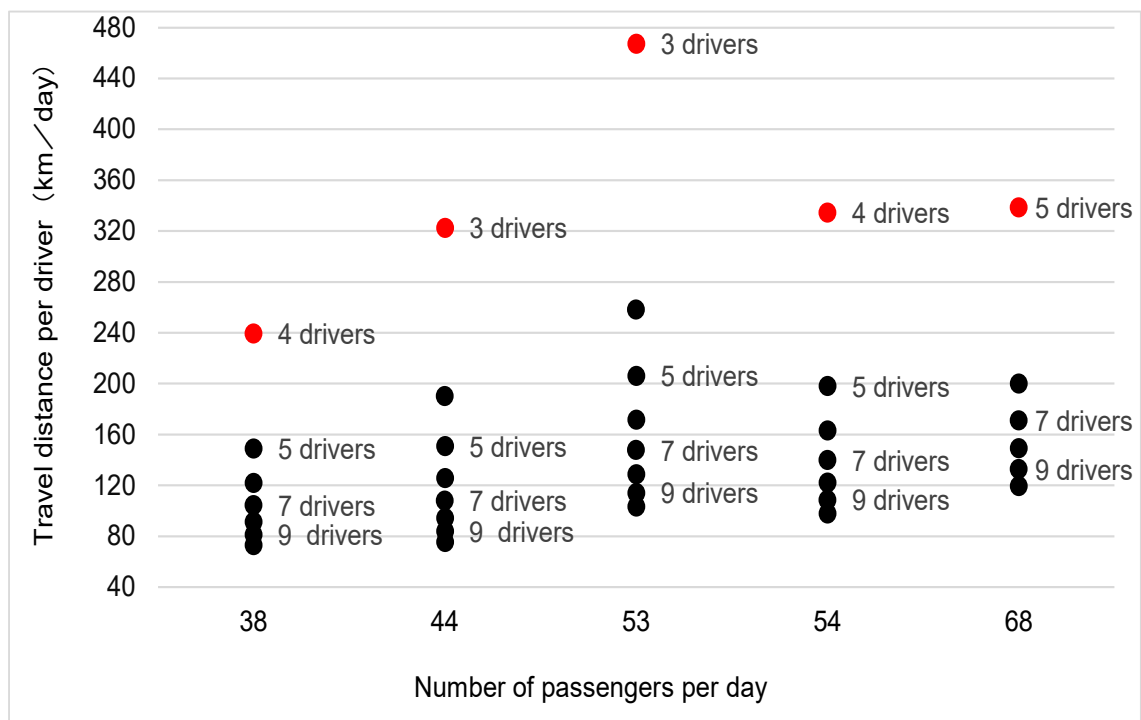


Fig. 3.4. Travel distance per driver
(Operator A, adjustable time : 30 min)

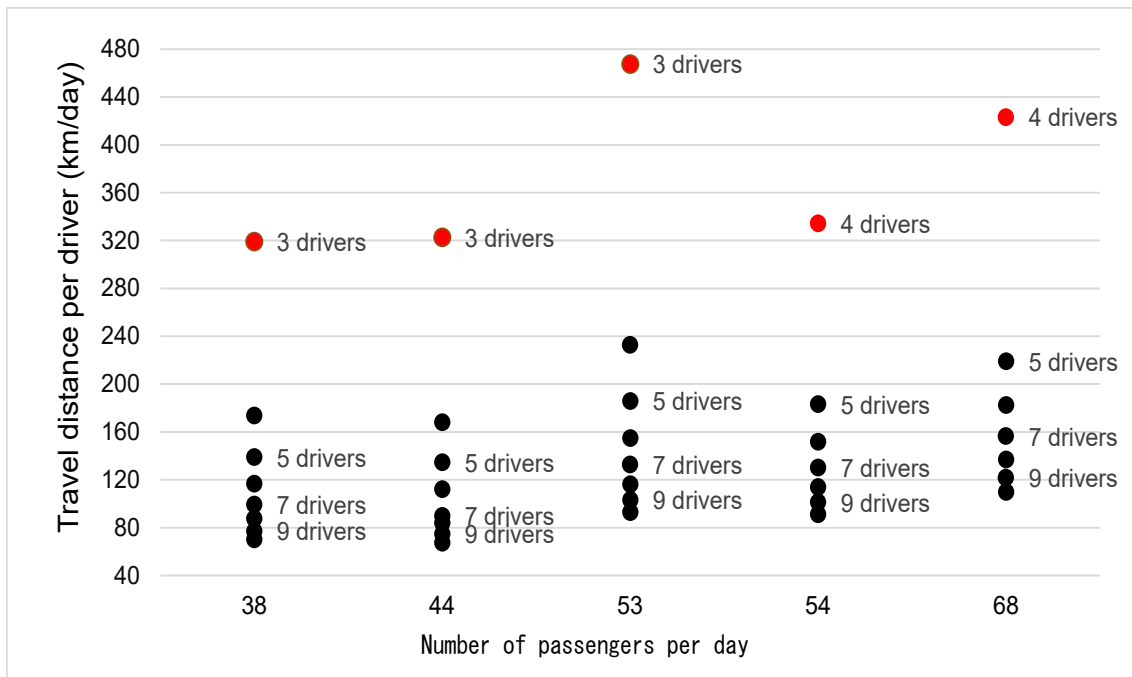


Fig. 3.5. Travel distance per driver
(Operator A, adjustable time : 60min)

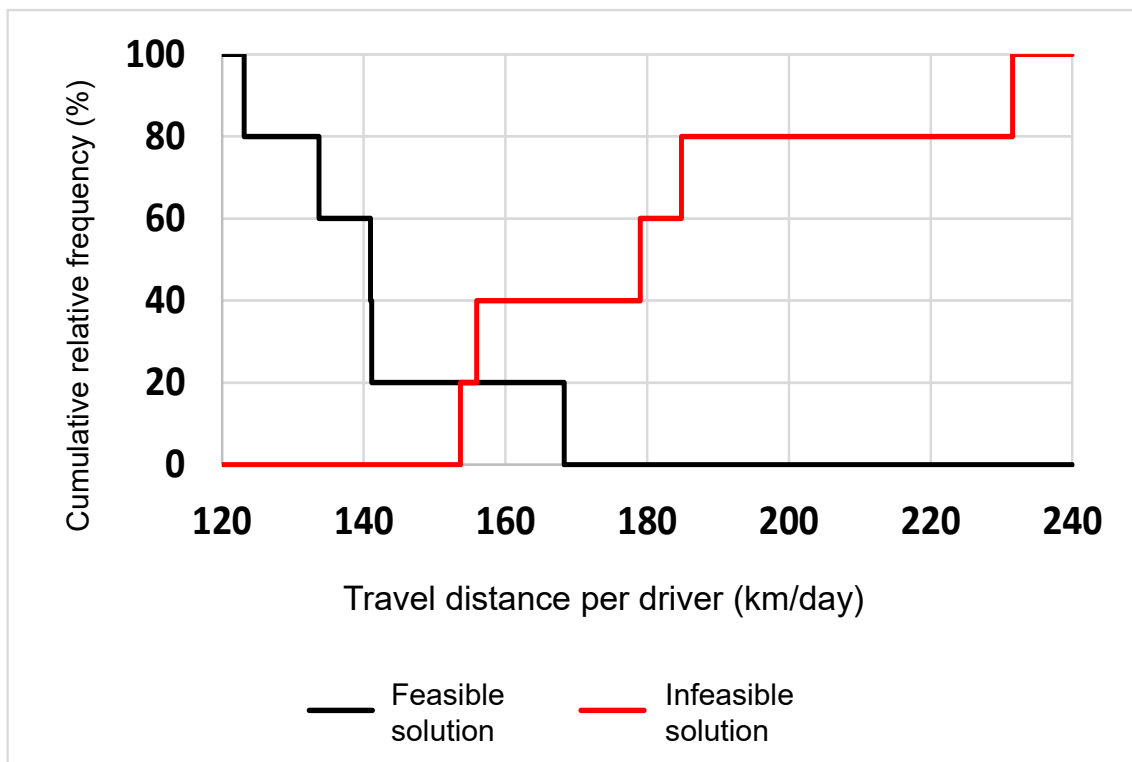
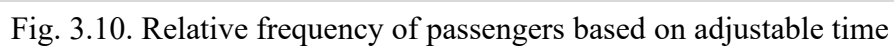
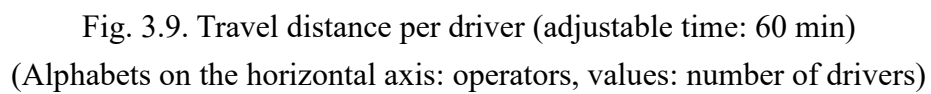


Fig. 3.6. Cumulative relative frequency of travel distance
(Operator A, adjustable time: 0 min)



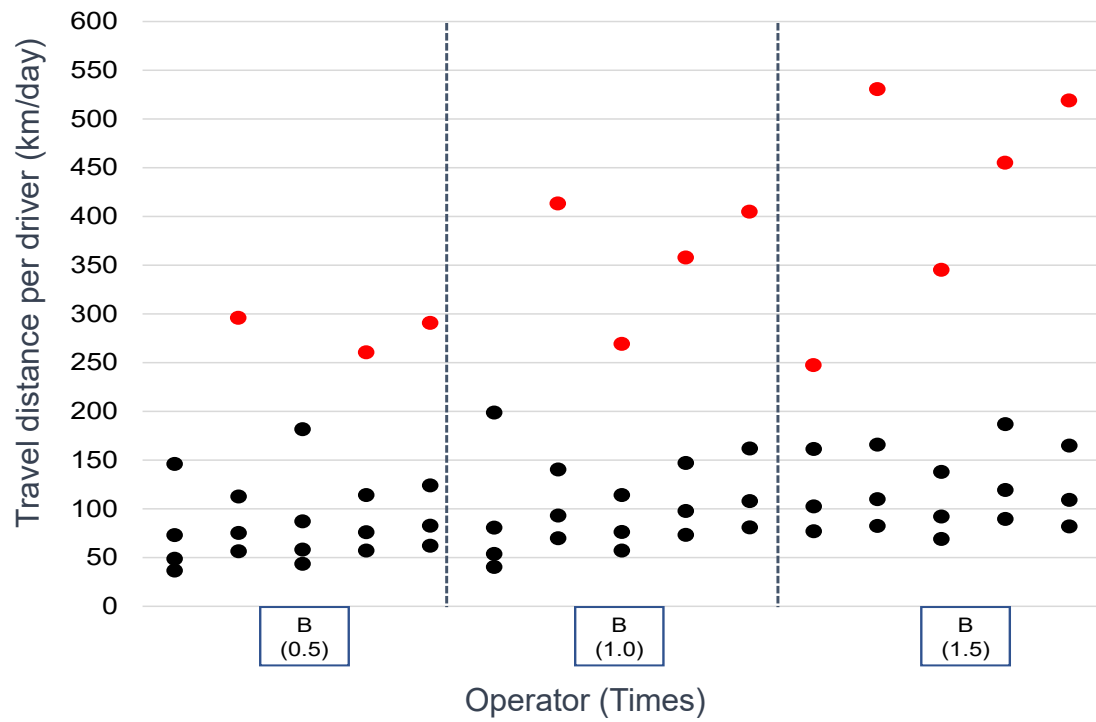


Fig. 3.11. Relationship between the spatial distribution and travel distance per driver

Chapter 4

Evaluating shared taxis focusing on the number of drivers

4.1 Introduction

The business environment for the taxi operators in rural areas is severe, and many operators suffer supply and demand challenges. In other words, the number of passengers tends to decrease because the population is declining in many rural areas, and there is a shortage of drivers on the supply side.

One of the measures to deal with the shortage of drivers is to introduce shared taxis. It is possible to operate with a smaller number of drivers in shared taxis by matching passengers to the convenience of the operator. Therefore, when there is concern about the shortage of drivers, taxi operators will be motivated to introduce shared taxis. Meanwhile, some operators have already introduced shared taxis. Nonetheless, if the demand continues to decline, it is futile to continue operating shared taxis. In other words, as the demand decreases, the need for passengers to accommodate the operator's convenience also decreases. Therefore, operators are motivated to switch from shared to traditional taxis. As mentioned above, taxi operators need to choose between shared and traditional taxis in response to business environment changes. To do this, it is necessary to evaluate whether shared taxis are better than traditional taxis.

In this study, we develop a mathematical programming model based on mixed integer programming that can calculate the number of drivers needed for shared and traditional taxi operations. Moreover, the results calculated by the model are used to estimate statistical models for evaluating shared taxis from the perspective that the lower the minimal number of drivers needed for operation, the more sustainable it is. Then, we demonstrate that the statistical models can be utilized to quantify the superiority of shared taxis for the case study area.

4.2. Mathematical programming model

4.2.1 Model assumptions

The model is constructed with the following assumptions.

- Passengers must make a reservation to use a taxi. When a passenger makes a reservation, he/she informs the operator of where and when to go.
- At the beginning of the day, all passengers' reservations on that day are known to the taxi operator.
- The operator does not refuse any reservations of passengers and transports all passengers.
- In the case of shared taxis, a vehicle can transport multiple passengers. However, the number of passengers must be within the vehicle's capacity.
- In the case of shared taxis, the operator can dispatch a vehicle later than the passenger's desired departure time. However, there is an upper limit to the delay time.
- In the case of shared taxis, the passenger's travel time may be increased due to sharing the vehicle with other passengers. However, this increase is limited.
- In the case of traditional taxis, passengers are transported separately at the time they desire.
- Drivers begin work at the location of the depot (hereafter referred to as "business center") and return to the business center to complete the work.

4.2.2 Model construction

Based on the assumptions described in the section 4.2.1, we built a model for the shared taxi. Note that the traditional taxis can be treated as a particular case of the shared taxis.

There are m drivers, each driver is denoted by k , and the set of drivers is indicated by $K = \{1, 2, \dots, m\}$. In the following, passenger transportation, the driver's start (origin depot), and end (destination depot) are all expressed in terms of the word *job*. Let i represent any job and n represent the number of passengers transported on any given day. Under this, let $N_1 = \{1, 2, \dots, n\}$ denote passengers' departure and $N_2 = \{n + 1, n + 2, \dots, 2n\}$ denote passengers' arrival, and $N = N_1 \cup N_2$ denote all jobs related to passengers. Note that $i \in N_1$ and $n + i \in N_2$ indicate the same passenger's departure and arrival. In this sense, $i \in N_1$ is also a passenger identification number. Therefore, i is used to identify the passenger in the following. $i = 0$ indicates the start of drivers. To distinguish between different drivers, the end of any driver k as $i = 2n + k$, and the set

of the drivers' end is denoted by $U = \{2n + 1, \dots, 2n + m\}$. $V = \{0\} \cup N \cup U$ represents the set of all jobs.

d_i represents the passenger i 's desired departure time, and d_{n+i} represents the desired arrival time. In the following, the gap between the passenger's desired departure time and the actual departure time is referred to as "deviation from the desired time", denoted by ε_i . ε represents the maximum deviation set by the operator. Passengers may be unable to go straight to their destination if they share a vehicle. The increase in travel time due to the detours is referred to as "increase in travel time" and is represented by λ_i . λ is the maximum increase in travel time set by the operator. t_i represents the time a passenger actually departs, and t_{n+i} represents the time a passenger actually arrives. c_{ij} represents the time required to travel from job i to job j , and L_{ij} represents the distance. The vehicle's capacity is represented by Q . u_i indicates the number of passengers in the vehicle after job i . The above variables and parameters are summarized in Table 4.1.

Table 4.1: Model symbols.

Set	Explanation
N	Set of jobs related to all passengers $N = \{1, 2, \dots, 2n\}$
N_1	Set of jobs related to passengers' departure $N_1 = \{1, 2, \dots, n\}$
N_2	Set of jobs related to passengers' arrival $N_2 = \{n + 1, n + 2, \dots, 2n\}$
V	Set of all jobs $V = \{0, 1, \dots, 2n + m\}$
U	Set of the end of drivers $U = \{2n + 1, 2n + 2, \dots, 2n + m\}$
K	Set of drivers $K = \{1, 2, \dots, m\}$
Parameter	
d_i	Desired departure time for passenger $i (\in N_1)$
d_{n+i}	Desired arrival time for passenger $i (\in N_1)$
ε	Maximum deviation from the desired time
λ	Maximum increase in travel time
c_{ij}	Time required to travel from job i to job j
L_{ij}	Distance required to travel from job i to job j
M	A sufficiently large value
Q	Vehicle's capacity
ω_1, ω_2	Weight coefficient
Variable	
t_i	Actual departure time for passenger $i (\in N_1)$
t_{n+i}	Actual arrival time for passenger $i (\in N_1)$
ε_i	Deviation from the desired time for passenger $i (\in N_1)$

λ_i	Increased travel time for passenger $i (\in N_1)$
u_i	Number of passengers in the vehicle after the transportation of the job i
x_{ij}	Binary variable for whether job j is executed after job i : 1 if it is executed, 0 otherwise.
z_{ik}	Binary variable for whether driver k is in charge of job i : 1 if it is, 0 otherwise.

The model formulation is shown below. Taxi operators minimize the distance traveled under the given drivers. Since the distance traveled is proportional to the largest variable cost for the operator, the assumption also means that taxi operators would like to minimize costs. Nonetheless, the operators also consider passengers satisfaction. Specifically, deviations from the desired time and increases in travel time are minimized. However, it is assumed that these minimizations have a lower priority than distance minimization, which expressed in weights. The objective function is expressed in Eq. (1) based on the above. The weights $\omega_1, \omega_2 (\geq 0)$ are set to make the second and third terms have a lower order than the first.

$$\text{minimize } \sum_{i \in V} \sum_{j \in V} L_{ij} x_{ij} + \omega_1 \sum_{i \in N_1} \varepsilon_i + \omega_2 \sum_{i \in N_1} \lambda_i \quad (1)$$

Subject to:

$$\sum_{j \in V} x_{0j} = m \quad (2)$$

$$\sum_{i \in V} x_{i, 2n+k} = 1 \quad (\forall k \in K) \quad (3)$$

$$\sum_{i \in V/U} x_{i0} + \sum_{k \in K} \sum_{j \in V} x_{2n+k, j} = 0 \quad (4)$$

$$\sum_{j \in V, j \neq i} x_{ij} = 1 \quad (\forall i \in N) \quad (5)$$

$$\sum_{i \in V, i \neq j} x_{ij} = 1 \quad (\forall j \in N) \quad (6)$$

$$z_{ik} = z_{n+i, k} \quad (\forall i \in N_1) \quad (7)$$

$$z_{jk} \geq z_{ik} + x_{ij} - 1 \quad (\forall i, j \in N \cup U, \forall k \in K) \quad (8)$$

$$z_{2n+k, k} = 1 \quad (\forall k \in K) \quad (9)$$

$$\sum_{k \in K} z_{ik} = 1 \quad (\forall i \in N \cup U) \quad (10)$$

$$t_j \geq t_i + c_{ij} - M(1 - x_{ij}) \quad (\forall i \in N, \forall j \in N) \quad (11)$$

$$t_{n+i} - t_i \geq 0 \quad (\forall i \in N_1) \quad (12)$$

$$0 \leq t_i - d_i \leq \varepsilon_i \quad (\forall i \in N_1) \quad (13)$$

$$\varepsilon_i \leq \varepsilon \quad (\forall i \in N_1) \quad (14)$$

$$t_{n+i} - t_i \leq d_{n+i} - d_i + \lambda_i \quad (\forall i \in N_1) \quad (15)$$

$$\lambda_i \leq \lambda \quad (\forall i \in N_1) \quad (16)$$

$$0 \leq u_i \leq Q \quad (\forall i \in N) \quad (17)$$

$$u_0 + \sum_{i \in U} u_i = 0 \quad (18)$$

$$u_j \geq 1 + u_i - M(1 - x_{ij}) \quad (\forall i \in V, \forall j \in N_1) \quad (19)$$

$$u_j \geq -1 + u_i - M(1 - x_{ij}) \quad (\forall i \in V, \forall j \in N_2) \quad (20)$$

$$x_{ij} \in \{0,1\} \quad (\forall i \in V, \forall j \in V) \quad (21)$$

$$z_{ik} \in \{0,1\} \quad (\forall i \in N \cup U, \forall k \in K) \quad (22)$$

The drivers begin work before transporting any passengers and end work after transporting all passengers. Eqs. (2) and (3) illustrate this condition. Eq. (4) indicates that there is no job before the start of drivers or after the end of drivers. Eqs. (5) and (6) illustrate that the operator must transport all passengers. Eq. (7) constraints that the driver who picks up a passenger to also drop off that passenger. If job j is executed after job i , the same driver should transport both jobs, as shown by Eq. (8). Eq. (9) indicates that driver k should undertake the end of driver k . Eq. (10) represents that any job except the start of drivers should be completed by a driver alone. The arrival time of job j must be later than the departure time of the previous job i plus the travel time between job i and j . Eq. (11) expresses this condition, where M is a sufficiently large value. Passengers' actual arrival time is after their actual departure time, which is constrained in Eq. (12). Constraints on the deviation from the passenger's desired time and the increase in travel time are indicated in Eqs. (13) ~ (16). Eq. (17) represents the vehicle's capacity. Passengers cannot depart at the start and end of drivers, which is represented by Eq. (18). As illustrated in Eqs. (19) and (20), the number of passengers in a vehicle increases by one when a passenger departs and decreases by one when a passenger arrives. The binary variable x_{ij} represents whether job j is executed after job i . $x_{ij} = 1$ denotes that job j is to be executed after job i . $x_{ij} = 0$ shows otherwise. Whether or not driver k accomplishes job i is indicated by the binary variable z_{ik} . $z_{ik} = 1$ denotes that driver k accomplishes job i . $z_{ik} = 0$ shows otherwise.

If the number of drivers given to the model is insufficient, there will be no feasible solution in the model. In contrast, there exists a minimum number of drivers need for the model to have feasible solutions. Therefore, the minimum number of drivers needed for

operation can be derived by putting the number of drivers into the model parametrically and checking for the existence of feasible solutions.

4.3 Evaluation of shared taxis based on statistical models

4.3.1 Overview of the evaluation

In this section, using the results calculated by the model constructed in the previous section, we evaluate shared taxis from the perspective that the less the minimum number of drivers needed for operation, the more sustainable the operator. Specifically, we demonstrate that the logistic regression models can be used to generally evaluate shared taxis in the case study area.

4.3.2 Case study area

The target area in this study is the Sanwa District, Jinsekikogen Town, Hiroshima Prefecture, Japan (see Fig.4.1). The Sanwa district is one of the four districts that comprise Jinsekikogen Town, and around 42% of the Jinsekikogen Town's population is concentrated in this district. As of January 2023, the number of households is 1,486, the total population is 3,504, and the aging rate is 41.8% in this district. Sanwa district is approximately 127.46 km².

4.3.3 Calculation of the mathematical programming model

(1) Passenger Data

This section describes the passenger data used to calculate the mathematical programming model. In the following analysis, we utilize the operation history data of a taxi operator that has a business office in the Sanwa district and mainly operates in the Sanwa area. The data is 21 days, from September 1 to September 21, 2019, including the date, times of departure and arrival, and locations of departure and arrival. The distribution of departure times for all passengers over the 21 days is shown in Fig. 4.2. The peak times for transportation in the morning and afternoon are between 10:00 ~ 11:00. and 14:00~15:00, which will determine the minimum number of drivers needed for operation. In the following, we extract the data of passengers transported between 9:00 and 16:00 and apply those to calculations. Fig. 4.3 shows the number of passengers extracted for each day.

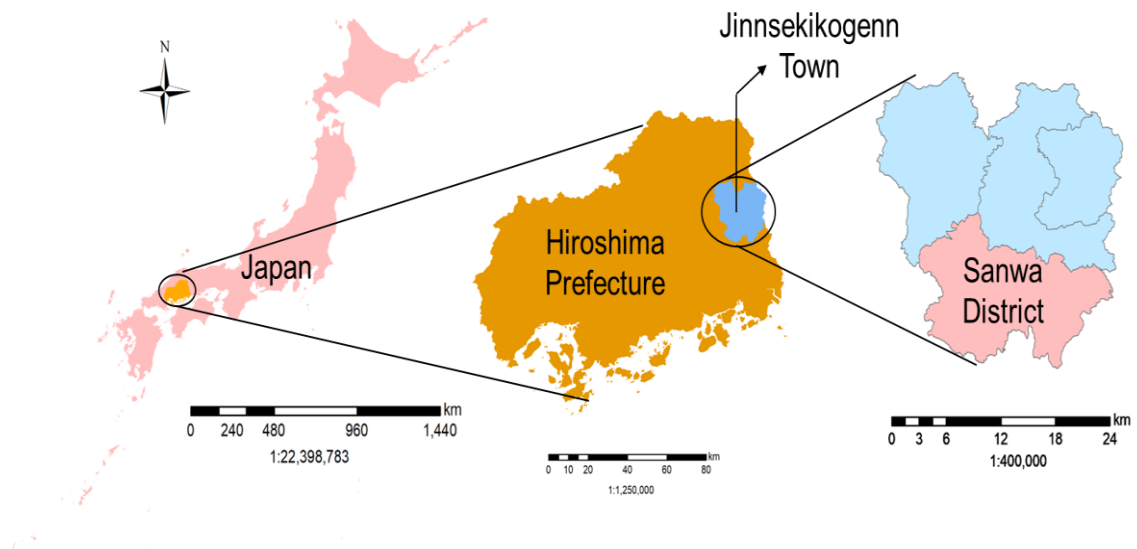


Fig. 4.1. Location of Sanwa District

Note that: this map is created based on administrative areas data ⁶⁷⁾

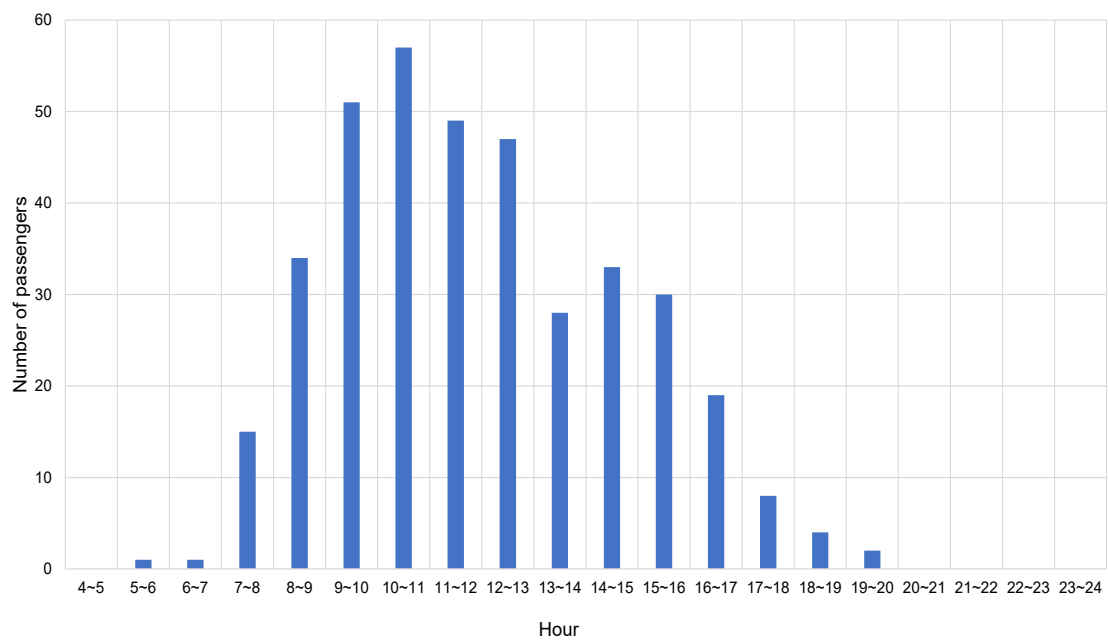


Fig. 4.2. Distribution of departure times

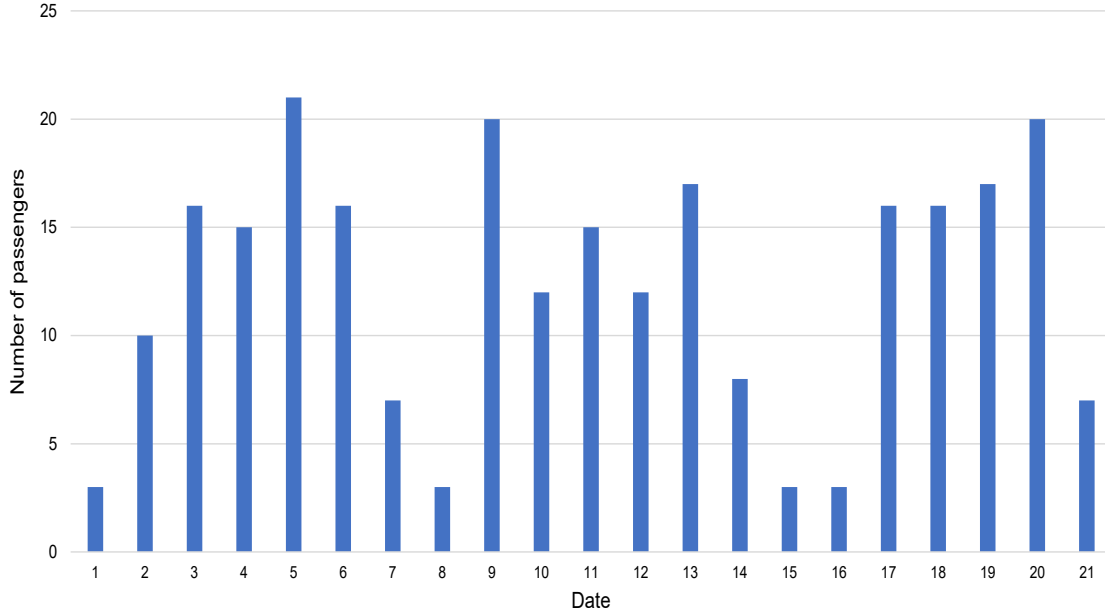


Fig. 4.3. Number of passengers on each day

(2) Set of mathematical programming model

The distance used in the analysis is the shortest distance on the road network. Assuming the average taxi speed is 40 km/h, the travel time is computed based on the distance and the speed. The maximum deviation from the desired time is set to 5,10,15 minutes (that is $\varepsilon = 5,10,15$ minutes). Similarly, the maximum increase in travel time is set to 5, 10, 15 minutes (that is $\lambda = 5,10,15$ minutes). Therefore, there are 9 combinations of ε and λ , since the traditional taxi $(\varepsilon, \lambda) = (0,0)$ is a particular case of shared taxis, a total of 10 combinations are applied to the mathematical programming model. Note that (ε, λ) is a value set by the operator for operating the shared taxis, it is referred to as the operation rule below.

Fig. 4.4 illustrates the minimum, mean, and maximum number of passengers per hour for all days used in the calculations. From this figure, the maximum number of passengers who can share a vehicle is around seven. At least in Japan, there are several instances where the vehicles with a capacity of seven or more passengers are used. Therefore, the following calculations omit the constraint equation related to the capacity to reduce the computational complexity. The software used for the calculations was gurobi 9.5.0 and was implemented in python. The calculations were performed on an Intel® Core™ i7-10750H CPU@2.60GHz 2592Mhz 6core PC. In some instances, the computations needed almost 24 hours, but in most of instances, they were finished in under three hours.

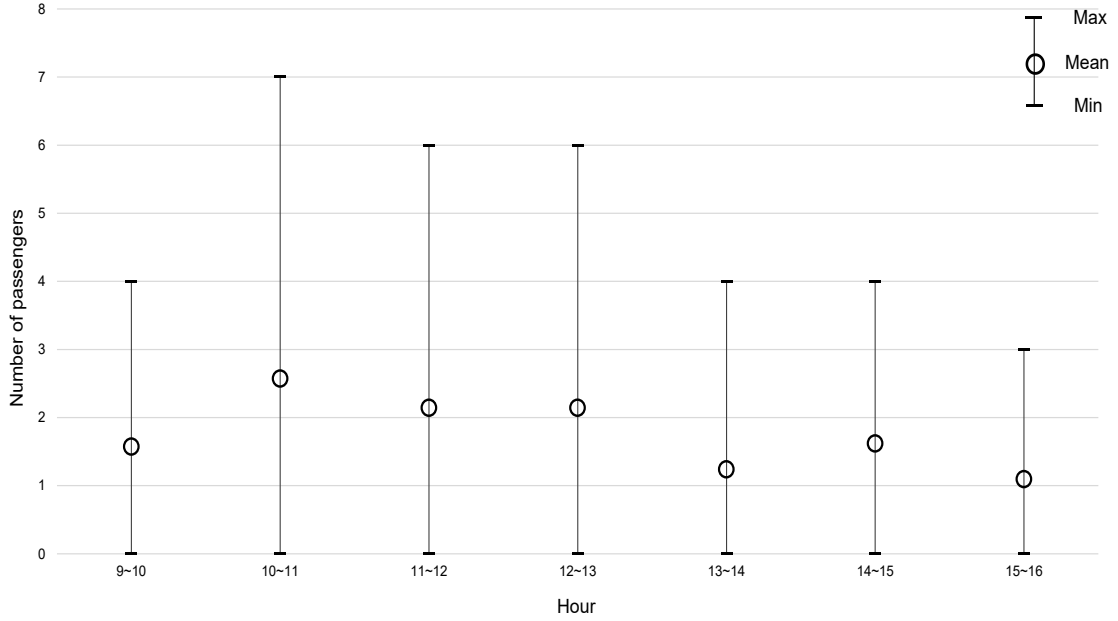


Fig. 4.4. Number of passengers per hour

(3) The minimum number of drivers needed for operation

The mathematical programming model calculated the minimum number of drivers needed for operation every day for the above 10 combinations. Fig. 4.5 shows the calculation results where the operation rules (ε, λ) are $(0,0)$, $(5,5)$, $(10,10)$, and $(15,15)$. In the following, the minimum number of drivers is abbreviated as MND, the MND of the shared taxis under the operation rule (ε, λ) is represented as $MND^{st}(\varepsilon, \lambda)$, and the MND of the traditional taxis is represented as $MND^{tt}(0,0)$.

From Fig. 4.5, it can be shown that MND decreases as the values of ε and λ increase. In the case of traditional taxis, there is a day that $MND^{tt}(0,0) = 5$, but in the case of shared taxis, $MND^{st}(5,5) \leq 4$, $MND^{st}(10,10) \leq 3$, and $MND^{st}(15,15) \leq 3$ are observed for all days. The maximum MND of shared taxis is lower than that of traditional taxis.

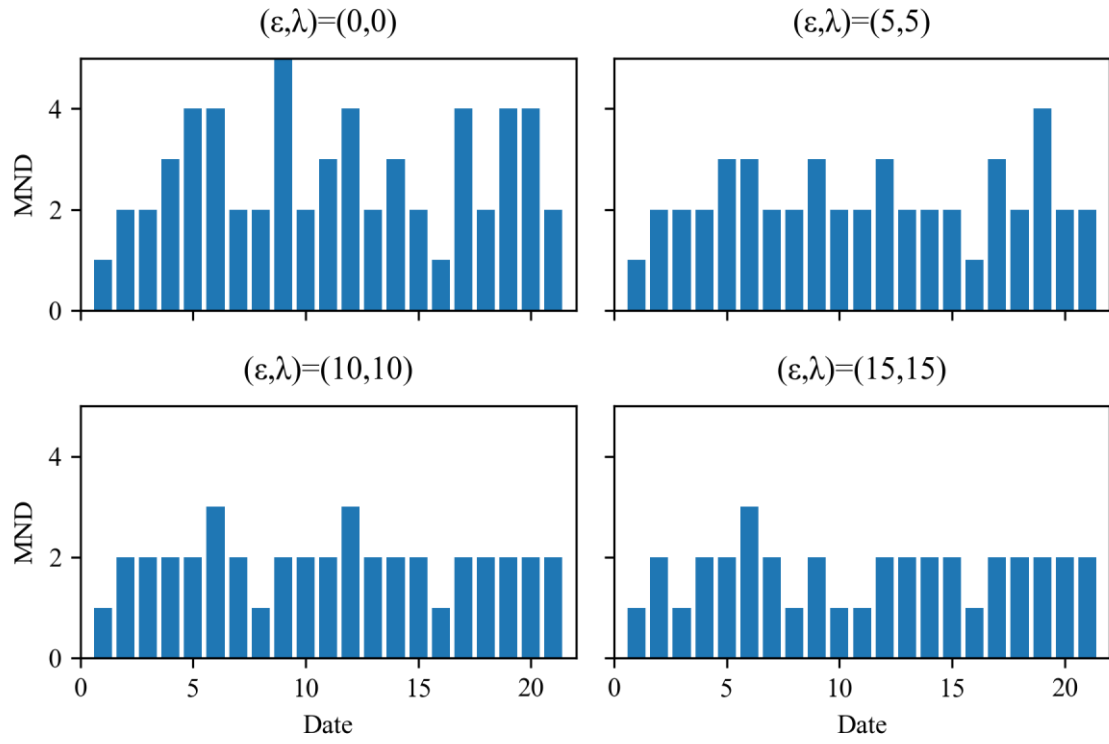


Fig. 4.5. MND (minimum number of drivers)

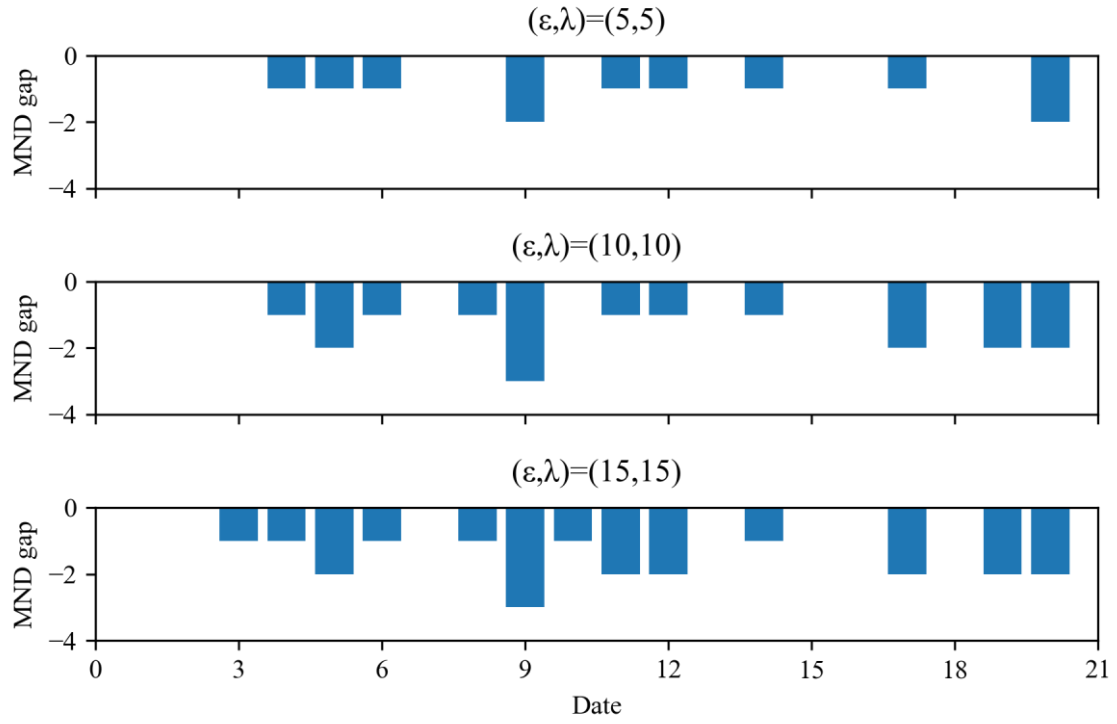


Fig. 4.6. MND gap

The MND gap between shared and traditional taxis each day is shown in Fig. 6. There are 9 days out of 21 days when $MND^{st}(5,5) < MND^{tt}(0,0)$, and the MND for shared taxis is 1-2 fewer than those of traditional taxis. Similarly, there are 11 days out of 21 days, $MND^{st}(10,10) < MND^{tt}(0,0)$ and 13 days out of 21 days, $MND^{st}(15,15) < MND^{tt}(0,0)$, and on these days, the MND for shared taxis is 1-3 fewer than those of traditional taxis. Shared taxis are superior these days.

On the contrary, if $MND^{st}(\varepsilon, \lambda) = MND^{tt}(0,0)$, shared taxis are not superior and traditional taxis are suitable. From Fig. 6, we can identify such days. There are 12, 10, and 8 days for $(\varepsilon, \lambda) = (5,5), (10,10), (15,15)$, respectively. Most of these days are weekends & holidays.

As described above, it is possible to understand the superiority of shared taxis for the days calculated using the mathematical programming model. However, the superiority on days that the model did not calculate is unknown. If data is provided for these days, it is possible to confirm the superiority by calculating with the model, but a significant amount of time and effort is required to compute using the model. Consequently, it would be useful if a statistical model could be estimated using the results calculated by the mathematical programming model for a limited number of days as sample data, and then evaluate the superiority with the statistical model. In the next part, we will evaluate the superiority of shared taxis using logistic regression based on this approach.

To evaluate the superiority of shared taxis, we focus on two cases. In the first case, we analyze the superiority of shared taxis under the assumption that the traditional taxi is presently in operation. The second case assesses the superiority of shared taxis under the assumption that shared taxis are currently operating. The former will be referred to as Case A and the latter as Case B in the following.

4.3.4 Evaluation of shared taxis using a statistical model (Case A)

(1) Estimation of the logistic regression model

The mathematical programming model calculates the results for 210 samples over 21 days and 10 operation rules. We estimate a logistic regression model with a binary variable as the explained variable, where 1 indicates that the MND of shared taxis is less than that of traditional taxis, and 0 indicates the otherwise. Through the logistic model, we can derive the conditions under which the MND of shared taxis is smaller than that of traditional taxis. In other words, we can determine the conditions under which shared taxis are superior.

Fig.4.5 and 4.6 show that operation rules affect MND gap. Hence, we include them as

explanatory variables in the logistic regression model. In addition to operational rules, the explanatory variables include several other indicators. One is the number of passengers per day. Given that shared taxis have the advantage of requiring less MND even when the number of passengers is large, it is appropriate to include this variable as an explanatory variable. Even though the number of passengers is large, the MND of traditional taxis may be small if passenger requests are well distributed in space and time. This situation is reflected in the indicator of occupied vehicle distance per driver. The occupied vehicle distance is the sum of the shortest origin-to-destination distances requested by passengers on a given day. If passenger requests are well distributed, the distance that can be transported by a single driver increases, resulting in a larger occupied vehicle distance per driver. Therefore, adding the occupied vehicle distance per driver is appropriate as an explanatory variable. In this section, the number of drivers, divided by the occupied vehicle distance, is the MND of traditional taxis, given that we assume that traditional taxis are now in operation.

The logistic regression model is expressed in Eqs. (23) ~ (24), where y is the explained variable, the variable p is the number of passengers per day, $odist_D$ is the occupied vehicle distance per driver, $\alpha_0 \sim \alpha_4$ are parameters, and X is a vector of explanatory variables. The explained variable mentioned y (1 or 0) is calculated by the mathematical programming model, ε and λ are input variables when using the mathematical programming model for computation, p and $odist_D$ are variables derived from the data given to the mathematical programming model for computation.

$$Pr(y = 1|X) = \frac{1}{1 + \exp(-f(X))} \quad (23)$$

$$f(X) = \alpha_0 + \alpha_1 \varepsilon + \alpha_2 \lambda + \alpha_3 p + \alpha_4 odist_D \quad (24)$$

A logistic regression model was estimated using the 210-sample data. The estimation results are shown in Table 4.2. Except for the intercept, all explanatory variables are statistically significant at the 5% level, the signs of the parameters are consistent with the hypotheses, and the results are reasonable. The accuracy and recall rates of the regression model are shown in Table 4.3. The accuracy rate of the regression model is 82.9%. The recall rate is 81.8% when the explained variable is 1 and 83.3% when the explained variable is 0. The McFadden R^2 is 0.43.

From the above, when $f(X)$ is positive, it is assumed that the MND of shared taxis would be less than that of traditional taxis, indicating that shared taxis are superior to traditional taxis. When $f(X)$ is negative, shared taxis are not superior to traditional taxis.

Table 4.2 Estimation results of the logistic regression model (Case A)

Explanatory Variables	Regression coefficient (t-value)
Intercept	-1.218 (-1.448)
Maximum deviation from desired time (hour)	10.529 (3.814) **
Maximum increase in travel time (hour)	6.304 (2.391) *
Occupied vehicle distance per driver (km/person)	-0.186 (-5.937) **
Number of passengers per day (person)	0.336 (6.480) **

Note that *: p-value ≤ 0.05 ; **: p-value ≤ 0.01 ; AIC: 175.17, McFadden R^2 : 0.43

Table 4.3 Accuracy and recall rates of the regression model (Case A)

		Predicted values			Recall rate
		1	0	Total	
Actual values	1	81	18	99	81.8%
	0	18	93	111	83.8%
	Total	99	111	210	82.9% (Accuracy rate)

(2) Operation rules of shared taxis

The estimate results of the logistic regression model indicate that the superiority of shared taxis depend on the operation rule. Consequently, the regression model can be used to identify which operation rule will make shared taxis superior. The approach is described below.

Fig. 4.7 shows 21 days of data in a two-dimensional coordinate system, with the number of passengers per day on the horizontal axis and the occupied vehicle distance per driver on the vertical axis. The blue plots represent data for weekends & holidays, and the orange plots represent weekdays. We focus on the point that when $f(X)$ is zero, that is, the following equation holds, the superiority between traditional taxis and shared taxis are indifferent. It is noted that $\alpha_0^* \sim \alpha_4^*$ are the estimated parameters.

$$\alpha_3^*p + \alpha_4^*odist_D = -(\alpha_0^* + \alpha_1^*\varepsilon + \alpha_2^*\lambda) \quad (25)$$

The line represented by this equation is called the decision boundary. The decision boundaries for the operating rules (ε, λ) of (5,5), (10,10), and (15,15) are overlaid in Fig. 4.7 and shown in Fig. 4.8. Plots below the decision boundary indicate that shared taxis are superior, while plots above the decision boundary indicate that they are not.

Fig. 4.8 shows that when the operating rule is set to $(\varepsilon, \lambda) = (5, 5)$, given that shared taxis are not superior for all plots on the weekends & holidays, and it is appropriate for shared taxis to only operate on weekdays & holidays. On the other hand, for weekdays, there is a mix of plots where shared taxis are superior and those where they are not. Therefore, under this operation rule, the benefit of fewer MND can only be enjoyed by the operator on limited days, and shared taxis are not necessarily appropriate for weekdays. The same conclusion holds for $(\varepsilon, \lambda) = (10, 10)$. When the operation rule is set to $(\varepsilon, \lambda) = (15, 15)$, almost all plots on weekdays are dominated by shared taxis, and the operator can enjoy the benefit of shared taxis on all weekdays. Although some plots on weekends & holidays are dominated by shared taxis, their number is limited, and the traditional taxis are appropriate.

From the above, it is appropriate to employ traditional taxis for weekends & holidays and shared taxis with $(\varepsilon, \lambda) = (15, 15)$ as the operation rule for weekdays. Thus, by using the regression model, we can evaluate the superiority of shared taxis and determine the operation rule that can enjoy the benefits of shared taxis and the appropriate use of shared and traditional taxis.

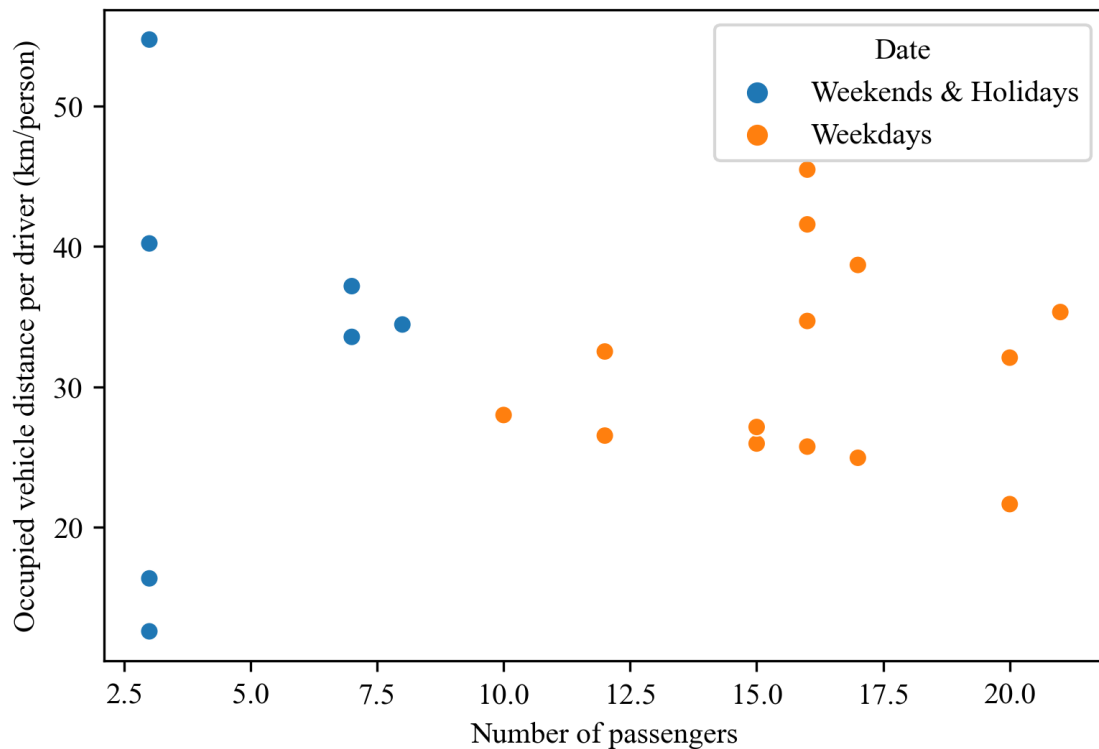


Fig. 4.7. Occupied vehicle distance per driver and number of passengers per day

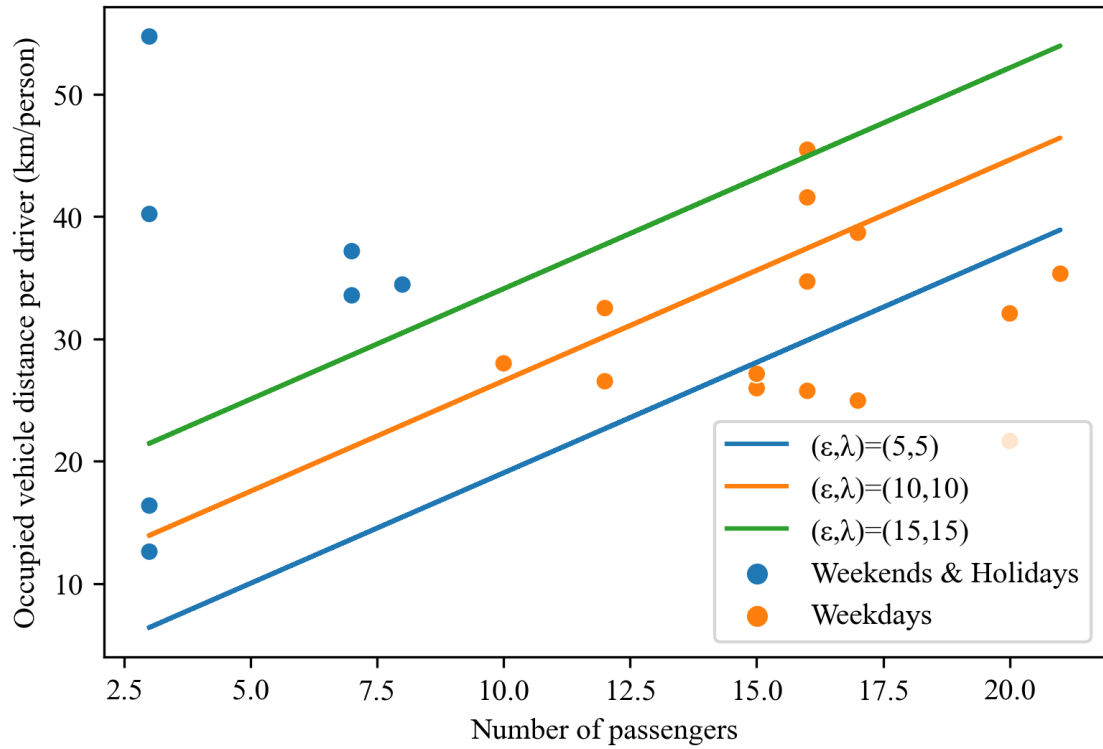


Fig. 4.8. Operation rules and decision boundaries

4.3.5 Evaluation of shared taxis using a statistical model (Case B)

(1) Estimation of the logistic regression model

As in the section 4.3.4, a logistic regression model is estimated using the results for the 210 samples obtained by the mathematical programming model to derive the condition under which shared taxis are superior.

The explained variable is a binary variable set to 1 when the MND of traditional taxis is bigger than the MND of shared taxis and 0 otherwise. when the explained variable is 1, shared taxis are considered superior because the MND increases when they are substituted for traditional taxis. For the explanatory variables, the variable that represents the situations where there is a high possibility that MND will increase when replacing shared taxis with traditional taxis should be included. Such situations are considered to be when the function of ridesharing is effective. Therefore, it is preferable to use variables reflecting such situations as explanatory variables.

Specifically, the operation rule could be included as an explanatory variable. The operation rule is only set for shared taxis, and as previously mentioned, the larger the value, the fewer the MND for shared taxis. In addition, the function of ridesharing is

effective when the driver's workload is significant. The number of passengers per day and the travel distance per driver can be considered specific indicators of the driver's workload. Based on the above, the explanatory variables include the operation rule, the number of passengers per day, and the travel distance per driver. Nevertheless, the number of drivers, divided by the distance traveled, is the MND of shared taxis, given that we assume the case in which shared taxis are currently in operation.

From the above, the logistic regression model replaces $f(X)$ in eqs. (23) and (24) with $g(X)$ in the following equation, where $t\text{dist}_D$ is the travel distance per driver and $\beta_0 \sim \beta_4$ are parameters. The explanatory variable $t\text{dist}_D$ is the variable computed by the mathematical programming model.

$$g(X) = \beta_0 + \beta_1 \varepsilon + \beta_2 \lambda + \beta_3 \text{cus} + \beta_4 t\text{dist}_D \quad (26)$$

The estimation results of the logistic regression model are shown in Table 4.4. All variables are statistically significant at the 5% level. The signs of the parameters are consistent with the hypotheses above, and the result is reasonable. Table 4.5 shows the accuracy and recall rate of the regression model. the accuracy rate of the regression model is 75.2%. The recall rate is 73.7% when the explained variable is 1 and 76.6% when it is 0. And the McFadden R^2 is 0.28.

From the above, when $g(X)$ is positive, it can be considered that MND will increase if operated by traditional taxis. That is, the shared taxis are superior. On the other hand, if $g(X)$ is negative, shared taxis are not superior.

Table 4.4 Estimation results of logistic regression model (Case B)

Explanatory Variables	Regression coefficient (t-value)
Intercept	-6.240 (-6.531) **
Maximum deviation from desired time (hour)	6.358 (2.692) **
Maximum increase in travel time (hour)	4.752 (2.070) *
Travel distance per driver (km/person)	0.028 (3.206) **
Number of passengers per day (person)	0.194 (5.728) **

Note that *: p-value ≤ 0.05 ; **: p-value ≤ 0.01 ; AIC: 175.17, McFadden R^2 : 0.28

Table 4.5 Accuracy and recall rate of the regression model (Case B)

		Predicted values			Recall rate
Actual values		1	0	Total	
	1	73	26	99	73.7%
	0	26	85	111	76.6%
	Total	99	111	210	75.2% (Accuracy rate)

(2) Operation rules of shared taxis

The estimation results of the logistic regression model indicate that the superiority of shared taxis depend on their operation rule. Therefore, as in the section 4.3.4, the regression model can also be employed to determine which operation rule should be used to make the shared taxis superior. The following explains the approach.

The decision boundary of superiority between traditional and shared taxis is expressed by Eq. (27), where $\beta_0^* \sim \beta_4^*$ are the estimated parameters.

$$\beta_3^*p + \beta_4^*tdist_D = -(\beta_0^* + \beta_1^*\varepsilon + \beta_2^*\lambda) \quad (27)$$

The 21-day data is plotted on a two-dimensional coordinate system with the number of passengers per day on the horizontal axis and the travel distance per driver on the vertical axis, and a decision boundary is drawn when the operation rule is $(\varepsilon, \lambda) = (5, 5)$, what is shown in Fig. 4.9. When the operation rule varies, the travel distance per driver and the location of the plots will change. Therefore, if the operation rule is not $(\varepsilon, \lambda) = (5, 5)$, the decision boundary cannot be drawn in Fig. 4.9. The decision boundaries with $(\varepsilon, \lambda) = (10, 10), (15, 15)$ operation rules are separately represented in Figs. 10 and 11. Plots above the decision boundary indicate that shared taxis are superior, while plots below the decision boundary are not. From Figs. 4.9-4.11, most of the plots on weekends & holidays are located below the decision boundary, indicating that shared taxis are not superior. Normal taxis are appropriate for weekends & holidays. In the following, we focus on weekdays to discuss the operation rules of shared taxis.

When the operation rule is set to $(\varepsilon, \lambda) = (5, 5)$, there is no clear superiority of shared taxis compared to traditional taxis, as the plots on weekdays are distributed almost equally on both sides of the decision boundary. For this reason, it is not appropriate to set the operation rule as $(\varepsilon, \lambda) = (5, 5)$. On the other hand, when $(\varepsilon, \lambda) = (10, 10)$, shared taxis are superior on all but three days, and when $(\varepsilon, \lambda) = (15, 15)$, shared taxis are superior on all but one day. For this reason, it is appropriate to set $(\varepsilon, \lambda) = (15, 15)$. However, under this operation rule, there are two days that traditional taxis are not superior on

weekends & holidays. Therefore, considering both weekdays and weekends & holidays comprehensively, $(\varepsilon, \lambda) = (10, 10)$ is also appropriate.

4.4 Conclusion

In this study, we focused on the scenario where taxi operators choose between operating a shared taxi or a traditional taxi. In this selection, it is necessary to evaluate the superiority of shared taxis compared to traditional taxis. We proposed a method for objectively evaluating the superiority of shared taxis based on the viewpoint that the fewer the minimum number of drivers required to operate the taxis, the better the sustainability of the taxi operators. Specifically, given data on passenger origin-destination pairs and travel times, we formulated a mathematical programming model based on mixed integer programming that can calculate the number of drivers required for the operation of shared and general taxis. Then, using the results calculated by this model, we demonstrated that the superiority of shared taxis can be evaluated using statistical models. We also showed that this methodology can be used to examine the specific usage of shared and general taxis, such as selecting different operating modes on weekdays and weekends & holidays. Furthermore, we demonstrated that it is possible to clarify the operation methods in which shared taxis are superior. The methodology employs a combined approach of a mathematical programming model and a statistical model, and its effectiveness was also confirmed.

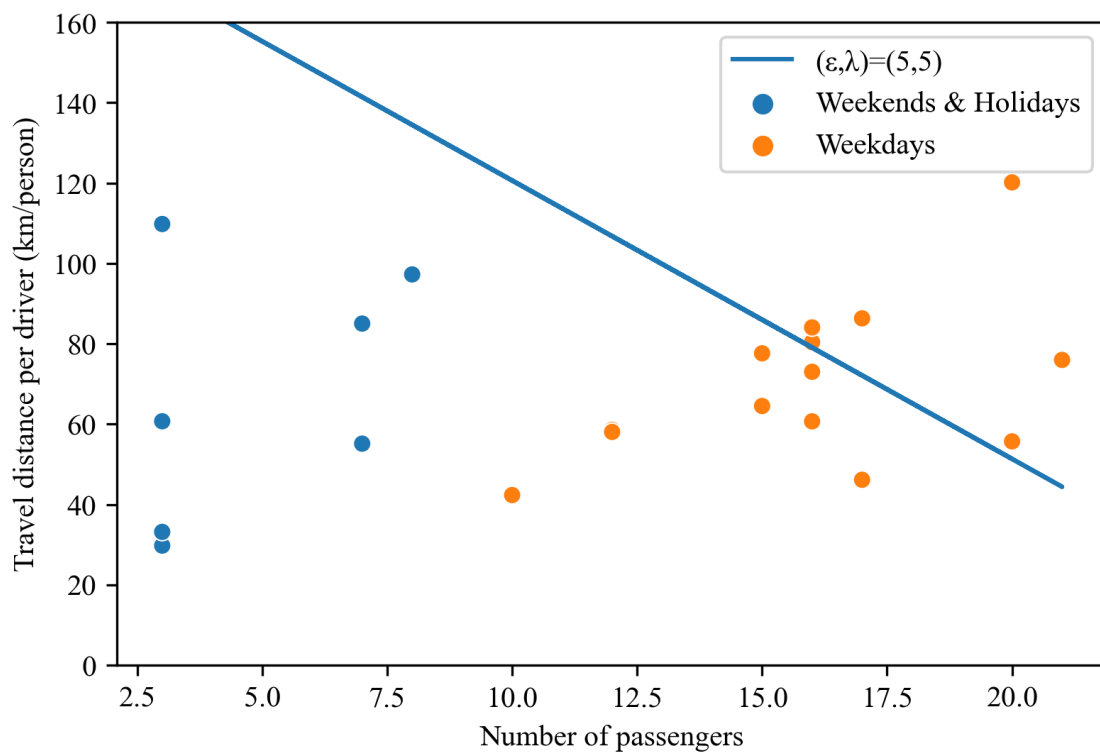


Fig. 4.9. Decision boundary (operation rule: $(\epsilon, \lambda) = (5, 5)$)

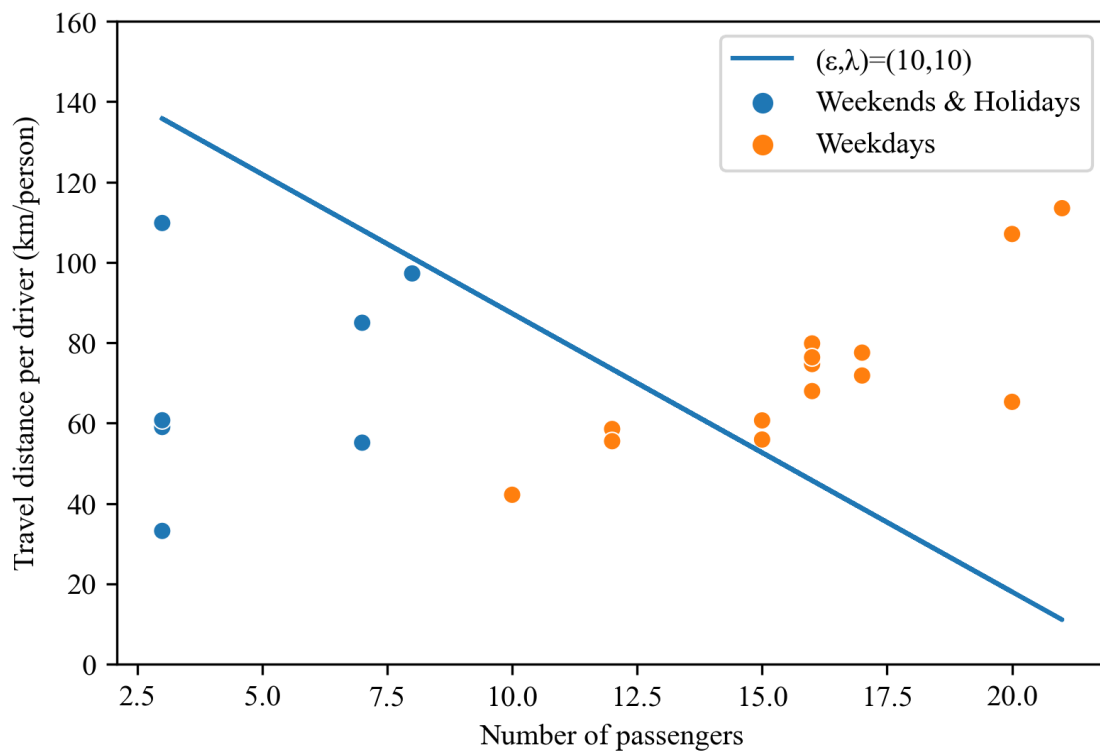


Fig. 4.10. Decision boundary (operation rule: $(\epsilon, \lambda) = (10, 10)$)

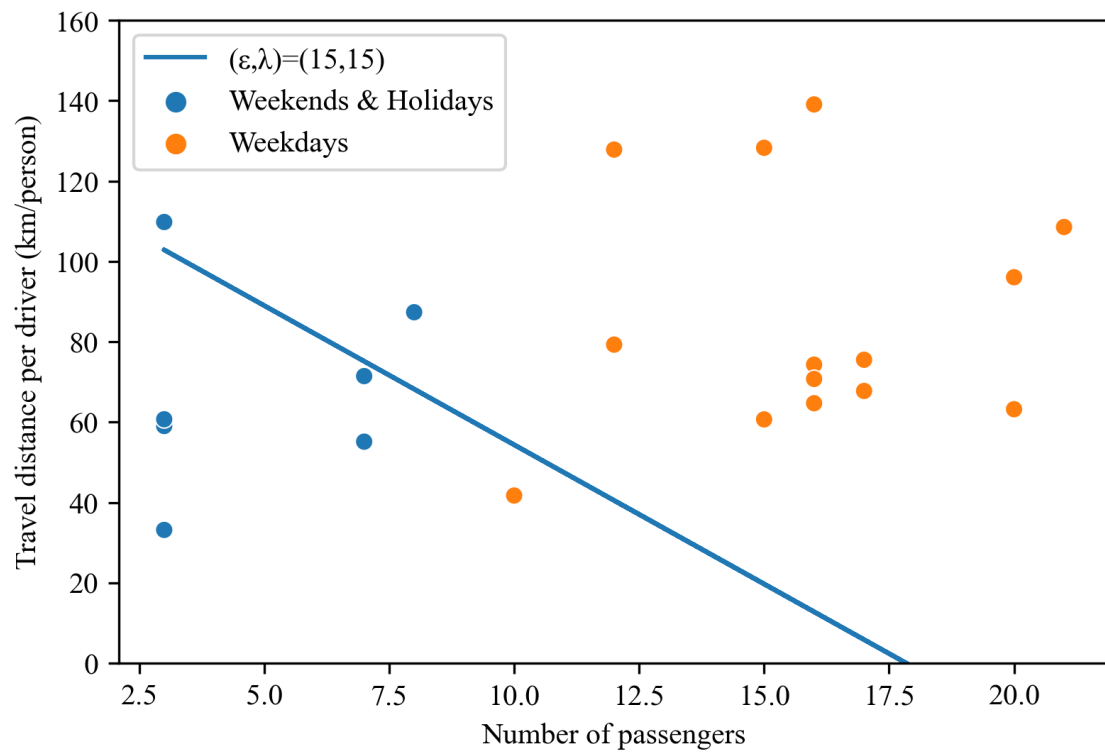


Fig. 4.11. Decision boundary (operation rule: $(\epsilon, \lambda) = (15, 15)$)

Chapter 5

Analysis of the feasibility of freight-passenger integration

5.1 Introduction

In rural areas, there are many small taxi operators. When the operators that currently have sufficient supply capacity experience a decrease in users and their business situation deteriorates, it becomes impossible for them to continue supplying services if profits are not sufficient. To improve this situation, it is effective to develop a new business, which is introducing freight-passenger integration.

However, taxi operators need to evaluate whether they can earn sufficient profit by introducing freight-passenger integration. Additionally, even for taxi operators who currently have enough drivers, there is a possibility of a shortage of drivers due to the introduction of freight-passenger integration. Therefore, it is necessary to reassess the supply capacity of taxi operators after the introduction of freight-passenger integration.

Therefore, in this study, we developed a mathematical model based on taxi-operation historical data to evaluate whether introducing freight-passenger integration would cause a shortage of labor and how much profit would increase. Specifically, a model based on mixed-integer programming was used to reproduce passenger transportation and freight delivery by taxi. According to the results, feasibility is evaluated in terms of profit and labor perspectives.

5.2 Model assumptions

We constructed a model based on the following assumptions.

- The driver starts working at depot (hereinafter referred to as "business office"), and returns to the business office to finish the work.
- The driver takes a break for a predetermined time in a predetermined time zone in the business office.

- The driver works within the prescribed working hours.
- If the subsequent transportation is not decided when the transportation of passengers and freight is completed, the driver returns to the business office and waits.
- The logistics company brings the freight to the business office before the driver's work starts or before the break is over.
- The driver delivers the freight within the specified time zone. The freight must be received by the consignee. No need for redelivery.
- Passengers will be transported on time according to their request. For this reason, the freight is delivered in-between passengers' transportation.
- There is no passenger sharing.
- Freight may be simultaneously transported while passengers are being transported, but the freight will not be delivered at the destination.
- Passengers make reservations as an immediate request for vehicle dispatch. In other words, the reservation is made prior to the desired time of the passenger, and the required time from the passenger departures point to the business office is considered the advance time. In reality, passengers make reservations for dispatch at various times. However, it is here assumed that the reservation is made at the most restrictive timing in the sense that the driver cannot make a delivery plan in advance, and the feasibility of the freight-passenger integration is evaluated from the safety side.
- The driver does not refuse to carry any passengers and freight.
- When delivering multiple numbers of freight to the same village, the driver transports them together.
- Freight capacity in the vehicle is not considered. This is because i) the taxi vehicle is small, so the freight-passenger integration by the taxi handles only small freight in the first place, and ii) the number of freights in rural areas is low.

In rural areas, the number of passengers is small, so the driver spends a lot of time idle. During this time, the drivers will have to wait for their next job somewhere, and generally they will have to wait in a place where they can easily park. Examples of such places are stations, hospitals, business offices, etc., but it is not always evident where to wait. Note that the business office is not necessarily a remote place. Actually, it is considered to be located around an area where waiting facilities, such as train stations and hospitals, are concentrated. Therefore, in this study, it is assumed that the driver waits at the business office for convenience which is assumption 4) above. In rural areas, drivers repeatedly move to the waiting place when they are idle, resulting in inefficient operation. In the following, a model will be constructed based on this characteristic.

5.3 Model construction

An arbitrary driver is represented by k , while $K = \{1, \dots, m\}$ denotes the set of drivers. In the following, in addition to passenger transportation and freight delivery, the driver's start of work (origin depot), and end of work (destination depot) are all expressed in terms of the word *job*. Let i be any job, the job of transporting passengers is symbolized by $N_1 = \{1, \dots, n_1\}$, the job of transporting freight is denoted by $N_2 = \{n_1 + 1, \dots, n_1 + n_2\}$, and let $N = N_1 \cup N_2$. The driver's start of work (origin depot), and end of work (destination depot) are denoted by $i = 0, n + m + 1$. The break of driver k is represented by $i = n + k$, whereas the set of breaks is represented by $U = \{n + 1, \dots, n + m\}$. The set $\{0, n + m + 1\} \cup N \cup U$ is represented by V . Due that job $i (\in N_1)$ involves the transportation of a single passenger, job number i is also a number that identifies the passenger. Therefore, in the following, i is also used as a passenger identification number.

Let $h_{i,in}$, $h_{i,out}$ be the desired departure time (start time of job i), and the desired arrival time (end time of job i) of passenger $i (\in N_1)$. The time required for movement is represented by a_i . Similarly, $y_{i,in}$ signifies the time at which the delivery of freights begins at the home of consignee $i (\in N_2)$. $y_{i,out}$ denotes the time at which the delivery concludes, and b_i denotes the delivery time needed. Freight i shall begin to be delivered between times e_i and f_i . The work start time, work end time, break start time, and break end time of driver k are represented by t_k , T_k , r_k , and R_k , respectively. In addition, the driver takes a break of Δr hours or longer in a day, and the working hours including the break are within T hours.

If a request for another job is made before the driver finishes job $i (\in N)$, the driver can go directly from the point where job i is finished to the point where another job is started; otherwise, we assume that the driver will return to the business office and wait. A_i indicates the set of points passed by the driver when returning to the business office from the point where job $i (\in N)$ is completed, A denotes the set of all points, let s be an arbitrary point, and $s = 0$ represents the business office. A_i includes the point at which job i is completed and the business office. The time required from the point where job i ends to point s is expressed by D_{is} , and the time required from point s to the point where job j starts is expressed by D_{sj} . The time required from the point where job i ends to the point where job j starts is expressed by D_{ij} . The above variables and parameters are summarized in Table 5.1.

Table 5.1 Model symbols.

Set	Explanation
N	Set of jobs to carry passengers and freight $N = \{1, \dots, n\}$
N_1	Set of jobs to transport passengers $N_1 = \{1, \dots, n_1\}$
N_2	Set of jobs to transport freight $N_2 = \{n_1 + 1, \dots, n_1\}$
V	Set of all jobs plus breaks $V = \{0, 1, \dots, n + m + 1\}$
U	Set of breaks $U = \{n + 1, \dots, n + m\}$
K	Set of drivers $K = \{1, \dots, m\}$
A	Set of all points, where 0 is a business office $A = \{0, 1, 2, \dots, g\}$
A_i	Set of points to pass when returning to the business office from the point where job i ($\in N$) is completed. $A_i \subset A$
Parameter	
$h_{i,in}$	Departure time desired by passenger i ($\in N_1$)
$h_{i,out}$	Arrival time desired by passenger i ($\in N_1$)
a_i	Time required for passenger i ($\in N_1$) to move
b_i	Time required to deliver freight to consignee i ($\in N_2$)
$[e_i, f_i]$	Time window to start delivering freight i ($\in N_2$)
D_{is}	Time required from the end point of job i to point s
D_{sj}	Time required from point s to the start of job j
D_{ij}	Time required from the end point of job i to the start point of job j
Δr	Driver's break time
T	Driver's working hours
M	A sufficiently large value
Variable	
$y_{i,in}$	Time to start delivering freight to consignee i ($\in N_2$)
$y_{i,out}$	Time to finish delivery of freight to consignee i ($\in N_2$)
r_k	Driver k 's break start time
R_k	Driver k 's break end time
t_k	Driver k 's start time
T_k	Driver k 's end time
x_{ij}	Binary variable indicating whether to execute job j after job i : 1 if it is executed, 0 otherwise.
z_{ik}	Binary variable indicating whether driver k 's is in charge of job i : 1 if in charge, 0 otherwise.
v_{is}	Binary variable indicating whether to go to s from the point where job i is finished: 1 if it goes, 0 otherwise.

u_{sj} Binary variable indicating whether to go from point s to the point where the next job j starts: 1 if it goes, 0 otherwise.

The model formulation is described below. It is assumed that the taxi operator maximizes profit. However, due that the amount of passengers and freight are given, maximizing profit is equivalent to minimizing cost. The cost is proportional to the mileage, and assuming that the taxi speed is constant, the cost is also proportional to the travel time. Therefore, in this study, the travel time is used as the objective function, and its minimization is performed as defined by Eq. (1). the second term of Eq. (1) is a constant, it does not affect the minimization, but it is a term necessary for calculating the cost, so it is intentionally included in the objective function.

$$\text{minimize } \sum_{i \in N} \sum_{j \in N} \sum_{s \in A_i} (D_{is}v_{is} + D_{sj}u_{sj}) + \sum_{i \in N_1} a_i \quad (1)$$

Subject to:

$$\sum_{j \in V \setminus \{0\}, j \neq i} x_{ij} = 1 \quad (\forall i \in N \cup U) \quad (2)$$

$$\sum_{i \in V \setminus \{n+m+1\}, i \neq j} x_{ij} = 1 \quad (\forall j \in N \cup U) \quad (3)$$

$$\sum_{i \in V \setminus \{n+m+1\}} x_{i,n+m+1} = m \quad (4)$$

$$\sum_{j \in V \setminus \{0\}} x_{0j} = m \quad (5)$$

$$\sum_{k \in K} z_{ik} = 1 \quad (\forall i \in N \cup U) \quad (6)$$

$$z_{n+k,k} = 1 \quad (\forall k \in K) \quad (7)$$

$$z_{jk} \geq z_{ik} + x_{ij} - 1 \quad (\forall i, j \in N \cup U, \forall k \in K) \quad (8)$$

$$\sum_{s \in A_i} v_{is} = 1 \quad (\forall i \in N) \quad (9)$$

$$\sum_{s \in A} u_{sj} = 1 \quad (\forall j \in N) \quad (10)$$

$$u_{sj} \geq v_{is} + x_{ij} - 1 \quad (\forall i, j \in N, \forall s \in A) \quad (11)$$

$$u_{0j} \geq \sum_{i \in U \cup \{0\}} x_{ij} \quad (\forall j \in N) \quad (12)$$

$$v_{i0} \geq \sum_{j \in U \cup \{n+m+1\}} x_{ij} \quad (\forall i \in N) \quad (13)$$

$$h_{i,out} = h_{i,in} + a_i \quad (\forall i \in N_1) \quad (14)$$

$$y_{i,out} = y_{i,in} + b_i \quad (\forall i \in N_2) \quad (15)$$

$$e_i \leq y_{i,in} \leq f_i \quad (\forall i \in N_2) \quad (16)$$

$$h_{i,out} + \sum_{s \in A \setminus \{0\}} D_{is} v_{is} + M v_{i0} \geq h_{j,in} - D_{0j} - M(1 - x_{ij}) \quad (\forall i, j \in N_1) \quad (17)$$

$$y_{i,out} + \sum_{s \in A \setminus \{0\}} D_{is} v_{is} + M v_{i0} \geq h_{j,in} - D_{0j} - M(1 - x_{ij}) \quad (\forall i \in N_2, \forall j \in N_1) \quad (18)$$

$$h_{j,in} \geq h_{i,out} + \sum_{s \in A} (D_{is} v_{is} + D_{sj} u_{sj}) - M(1 - x_{ij}) \quad (\forall i, j \in N_1) \quad (19)$$

$$h_{j,in} \geq y_{i,out} + \sum_{s \in A} (D_{is} v_{is} + D_{sj} u_{sj}) - M(1 - x_{ij}) \quad (\forall i \in N_2, \forall j \in N_1) \quad (20)$$

$$y_{j,in} \geq h_{i,out} + \sum_{s \in A} (D_{is} v_{is} + D_{sj} u_{sj}) - M(1 - x_{ij}) \quad (\forall i \in N_1, \forall j \in N_2) \quad (21)$$

$$y_{j,in} \geq y_{i,out} + \sum_{s \in A} (D_{is} v_{is} + D_{sj} u_{sj}) - M(1 - x_{ij}) \quad (\forall i, j \in N_2) \quad (22)$$

$$h_{j,in} \geq t_k + d_{0j} - M(1 - z_{jk}) \quad (\forall j \in N_1, \forall k \in K) \quad (23)$$

$$T_k \geq h_{i,out} + d_{i,n+m+1} - M(1 - z_{ik}) \quad (\forall i \in N_1, \forall k \in K) \quad (24)$$

$$y_{j,in} \geq t_k + d_{0j} - M(1 - z_{jk}) \quad (\forall j \in N_2, \forall k \in K) \quad (25)$$

$$T_k \geq y_{i,out} + d_{i,n+m+1} - M(1 - z_{ik}) \quad (\forall i \in N_2, \forall k \in K) \quad (26)$$

$$r_k \geq h_{i,out} + d_{i,n+k} - M(1 - x_{i,n+k}) \quad (\forall i \in N_1, \forall k \in K) \quad (27)$$

$$h_{j,in} \geq R_k + d_{n+k,j} - M(1 - x_{n+k,j}) \quad (\forall j \in N_1, \forall k \in K) \quad (28)$$

$$r_k \geq y_{i,out} + d_{i,n+k} - M(1 - x_{i,n+k}) \quad (\forall i \in N_2, \forall k \in K) \quad (29)$$

$$y_{j,in} \geq R_k + d_{n+k,j} - M(1 - x_{n+k,j}) \quad (\forall j \in N_2, \forall k \in K) \quad (30)$$

$$r_k \geq t_k \quad (\forall k \in K) \quad (31)$$

$$T_k \geq R_k \quad (\forall k \in K) \quad (32)$$

$$R_k \geq r_k + \Delta r \quad (\forall k \in K) \quad (33)$$

$$T_k - t_k \leq T \quad (\forall k \in K) \quad (34)$$

$$x_{ij} \in \{0,1\} \quad (\forall i \in V, \forall j \in V) \quad (35)$$

$$z_{ik} \in \{0,1\} \quad (\forall i \in N \cup U, \forall k \in K) \quad (36)$$

$$v_{is} \in \{0,1\} \quad (\forall i \in N, \forall s \in A_i) \quad (37)$$

$$u_{sj} \in \{0,1\} \quad (\forall s \in A, \forall j \in N) \quad (38)$$

Eqs. (2) and (3) indicate that all jobs related to passenger transportation and freight

delivery are performed, and that all drivers take a break. According to Eqs. (4) and (5), there are m drivers. Eq. (6) shows that any job except the start and end of work should be accomplished by one driver alone. Eq. (7), together with Eqs. (2) and (3), indicates that all drivers take breaks. Eq. (8) demonstrates that both jobs should be delivered by the same driver when job j is performed after job i .

After the driver finishes job i , they will move on to the next job from one point included in A_i . Here, A_i includes the point where job i is completed, so when going directly from the point where job i is finished to another job point, $v_{iq_i} = 1$ ($s = q_i$, q_i : the point where job i is finished). Also, given that A_i includes business office, $v_{i0} = 1$ ($s = 0$ represents business office) if there is no request for the next job before returning to business office and waiting. According to the above conditions, Eq. (9) holds. Similarly, Eq. (10) holds for u_{sj} . If job j is performed after job i , and job i is completed, the driver will head toward point s , and will headed from point s to job j . This condition is expressed by Eq. (11). When taking a break or ending driver's work after job i , the driver returns to the business office from the point where job i ends, which is defined by Eq. (12). Similarly, when going from a break or the start of work to job j , the driver starts from the business office, as expressed by Eq. (13).

Eqs. (14) and (15) hold for the relationship between the start time, end time, and implementation time of jobs related to passengers and freight. The time window at which the freight starts to be delivered is expressed by Eq. (16). When job j related to the transportation of passengers is carried out after job i , the driver cannot move to the job j starting point until the request for job j is received. Also, if the timing of the request is late, the request is received after the previous job has been completed and the driver has returned to the business office. To fulfill the request, a driver will then proceed from the business office to the starting point of passenger j . This is expressed by Eqs. (17) and (18). However, based on the premise (10) in Section 3, passenger j shall make a request at the time just before D_{0j} on which he / she gets on, that is, $h_{j,in} - d_{0j}$. The start time of job j is after the time that adds the time required for forwarding to job j to the end time of job i , which is expressed by Eqs. (19) to (22). Note that M is a sufficiently large value.

The constraint formula for the driver's work is explained below. If driver k is in charge of job i after the start of work, job i will begin after the start time of the work plus the transfer time to job i . A similar relationship holds for the end of jobs and the end of work. These are denoted by Eqs. (23) to (26). Eqs. (27) to (30) expressed the relationship between the start and end times of breaks and the times of jobs performed before and after breaks. The relationship between the start and end times of work and the start and end

times of breaks is indicated by Eqs. (31) and (32). Equations (33) and (34) limit drivers' break times and working hours.

Binary variable x_{ij} indicates whether or not job j is executed after job i . Whether or not driver k is in charge of job i is represented by binary variable z_{ik} . Binary variable v_{is} indicates whether or not to go to s from the point where job i is finished. Binary variable u_{sj} indicates whether or not to go from point s to the point where next job j is started.

Note that this model is based on the assumption that all passengers' demands are known before starting the day's business. However, in reality, the passenger's demand is not known until the passenger's request is received. Thus, to prevent some non-realistic driver's behaviors in the model that the driver will leave for the passenger's boarding location before the passenger's request is received, we added Eqs. (17) and (18). Moreover, idle drivers usually wait at the business office until they are notified of a passenger's reservation. Eqs. (17) and (18) also ensure this normal behavior.

5.4 Model application

5.4.1 Overview of the target area

The target area in this study was Wakasa Town, Tottori Prefecture, Japan. Wakasa Town is a town with an area of approximately 200 km² located at the southeastern tip of Tottori prefecture in Japan. As of March 1, 2022, the number of households was 1,286 and the total population was 2,924. The aging rate was 48.6% in 2020. Forests occupy approximately 95% of the total area. The area around Wakasa Station of Wakasa Railway Co., Ltd. is the center of the town, and most of the villages are formed along the main roads. The distance between the center and the farthest village is approximately 10 km, which can be covered in approximately 20 minutes by car.

5.4.2 Analysis data

(1) Passenger data

Currently, there is no taxi operator in Wakasa Town, but there used to be one in the past. The operation historical data of this operator were used as the data related to the transportation of passengers. These data extend for one month, from November 1, 2005 to November 30, 2005, and includes the date, boarding / deboarding times, boarding / deboarding locations, etc. In this month, there were 19 days with passengers; no

passengers were registered the rest of the days. In the following, data for 20 days in total are used, including the 19 days with passengers and one day without passengers.

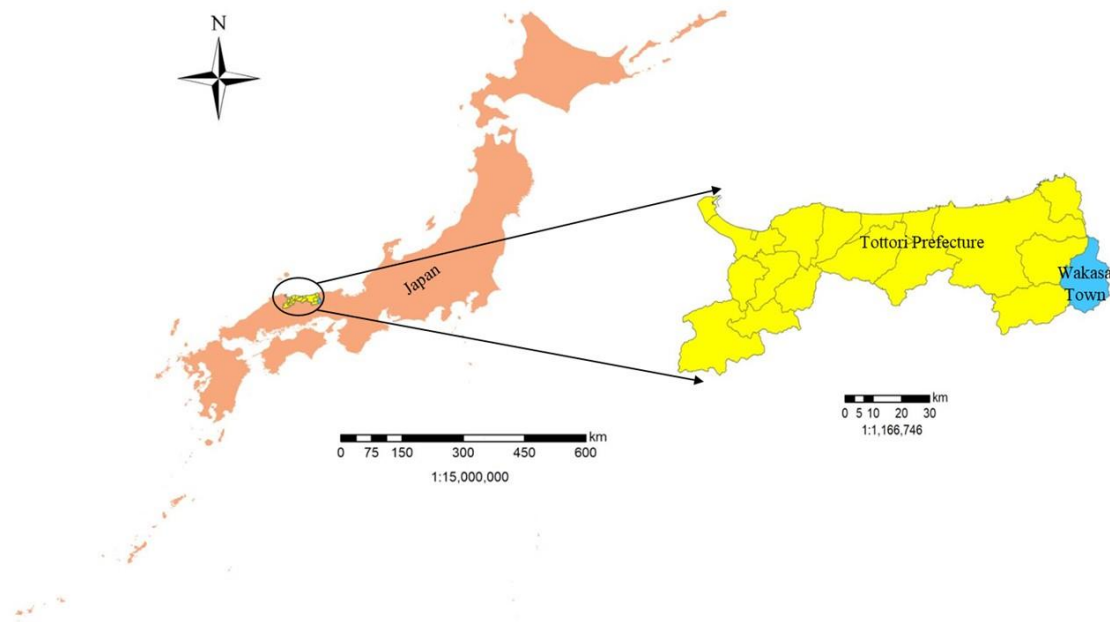


Fig. 5.1 Location of Wakasa Town.

(2) Freight data

In the following, it is assumed that the freight will be delivered to the village in Wakasa Town. Based on interviews with logistics companies that deliver freight to this town, it is assumed that Wakasa Town has an average delivery quantity of 50 pieces/day out of which 20 pieces/day are packages addressed to companies. Based on this delivery quantity, Poisson random numbers were used to generate five cases' delivery quantity and spatial distribution of freight delivery destinations according to the ratio of population and the number of business establishments in each village. In addition, other logistics companies besides those interviewed maybe request freight delivery. Therefore, based on the same approach, we also created cases in which the average delivery quantity was 60 pieces/day, 70 pieces/day, and 80 pieces/day. Table 5.2 shows all cases.

Table 5.2 List of cases related to freight delivery.

Case identification number (Delivery quantity-spatial distribution)	Number of villages at the delivery destination (morning)	Number of villages at the delivery destination (afternoon)	Delivery quantity
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50-1	10	13	49
50-2	11	10	50
50-3	13	8	48
50-4	14	9	49
50-5	10	10	49
60-1	10	11	61
60-2	13	9	62
60-3	12	16	58
60-4	10	12	58
60-5	8	11	59
70-1	12	15	69
70-2	14	9	69
70-3	12	16	71
70-4	11	12	70
70-5	13	13	71
80-1	14	16	82
80-2	18	17	80
80-3	16	16	79
80-4	15	12	81
80-5	14	17	79

(3) Preparation of analysis data

Wakasa Town was divided into 31 villages ($g = 31$, $A = \{0,1,2, \dots, g\}$, note that the business office 0 is located in village 1), as shown in Fig. 5.2. It is assumed that each village is represented by one point, where passengers get on and off and freight is received. The representative point is the main bus stop of the village, and the distance between villages is given by the shortest distance on the road network. Assuming that the average speed of a taxi is 40 km/h, the travel time between villages is calculated based on this speed and the distance between villages. Freight i begins to be delivered between 8 and 12 o'clock or 13 and 20 o'clock (that is, $(e_i, f_i) = (8,12)$ or $(13,20)$). The time required for freight delivery was set to 6 minutes for one freight.

The lunch break was set as one hour taken between 11:00 and 14:00 (i.e., $r_k \geq 11$, $R_k \leq 14$, $\Delta r = 1$ for any k). The working hours of the driver were set to 9 ($T = 9$). According to the operation historical data, there were three drivers working for the taxi operator. Thus, the number of drivers was set to 3. The software used for the calculations

was gurobi 9.12 and was implemented in python. All cases were calculated on two Inter core 24 Xeon Silver 4214R 2.40 GHz, CPU 64 RAM computers. Although a fraction of cases required almost 24 hours to calculate, most of cases required less than three hours.

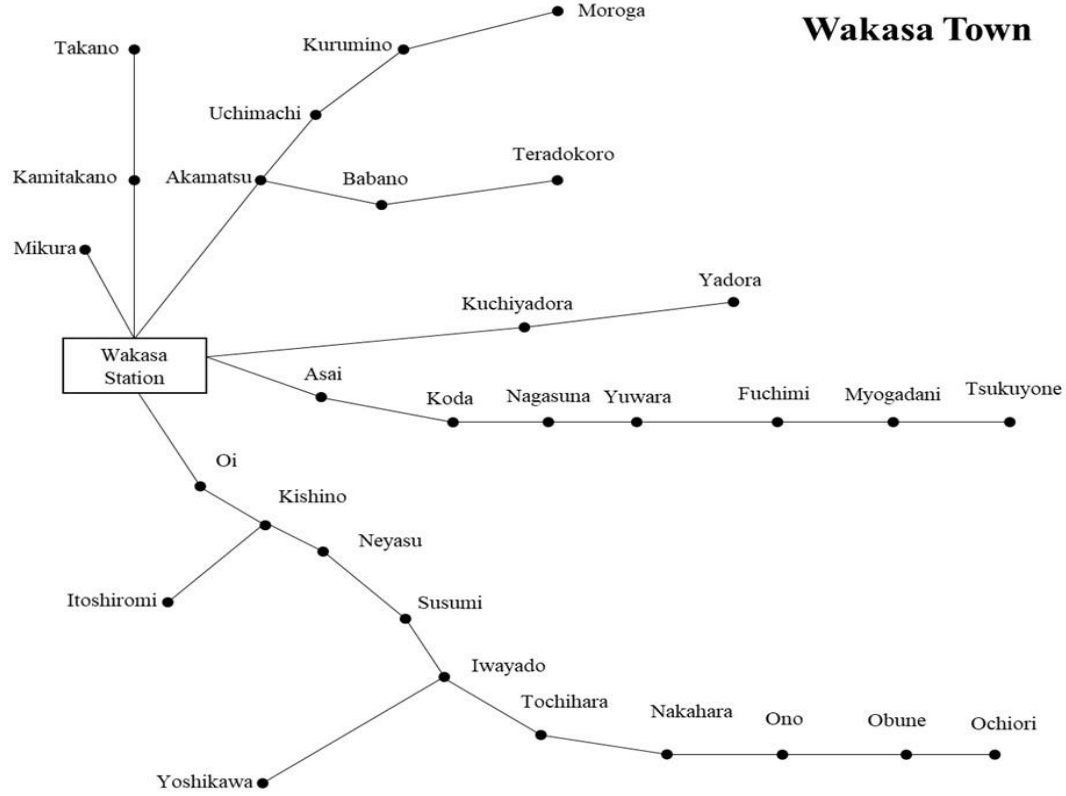


Fig. 5.2. Distribution of villages in Wakasa Town.

5.4.3 Method for calculating the profit of freight-passenger integration

In the model shown in Section 5.3, the travel time was derived as the value of the minimized objective function. As mentioned earlier, the cost is proportional to the travel time, under the assumption of constant taxi speed. Therefore, if the case identification number is p , the travel time when freight-passenger integration is introduced under any case p is $C_1(p)$, and the cost per travel time is λ , then the cost can be calculated as $\lambda C_1(p)$. In order to compute the cost before introducing freight-passenger integration, we run the model with the freight delivery quantity set to zero, and the cost may be expressed as λC_0 when the value of the objective function shows a travel time C_0 .

When w is set as the unit price per parcel delivery, and $E(p)$ represents the delivery quantity in any case p , then the income generated by freight-passenger integration are

expressed as $wE(p)$. The increase in daily profit from freight-passenger integration may be defined using the equation below. This π is referred to as "profit," which means the increase in daily profit in the following.

$$\pi = wE(p) - \lambda(C_1(p) - C_0) \quad (39)$$

The values of w and λ were set as follows. In Japan Post, if the pick-up location is specified at the post office when sending parcels, a shipping fee discount of 100 yen is applied ⁶⁸⁾. Therefore, based on this value, $w = 100$ yen/piece. Furthermore, according to the Annual Statistics Report on Automobile Fuel Consumption (2019) published by the Ministry of Land, Infrastructure, Transport and Tourism, fuel consumption is 0.141 (L/km) ⁶⁹⁾. According to Statista ⁷⁰⁾ and ELGAS⁷¹⁾, the average price of LP gasoline in 2019 was 89 yen/L. All in all, $\lambda = 12.549$ yen/km.

5.4.4 Calculation results

Using the aforementioned data for 20 days, the daily profit was calculated. The results of profit are shown in Fig. 5.3. Given that the profit of each day differs, it is represented by a box plot. the red plots illustrate the daily profit when the average delivery quantity is 50 pieces/day; for the cases 60, 70, and 80 pieces/day, the daily profit is showed by the blue plots, the yellow plots and the green plots. The result for no passengers is shown on the 20th day located on the right extreme of the figure. The figure clearly shows that the introduction of freight-passenger integration will generate benefits any day. Specifically, if the average delivery quantity is 50 pieces/day, the profit is approximately 3,800 yen/day; for the cases 60, 70, and 80 pieces/day, the profits are 4,900, 5,900, and 6,400 yen/day, respectively.

With three drivers, no shortage of drivers ever occurred, in other words, three drivers can carry all passengers and freight. However, if the number of drivers decreases for some reason, it may not always be possible to carry all passengers and freight. Therefore, when the number of drivers was decreased by one, that is, when the number of drivers was two, we confirmed whether shortage of drivers occur. Specifically, we calculated the model and confirmed whether there was a feasible solution on each day. The results are shown in Fig. 5.4.

We calculated 5 cases per day under the given delivery quantity shown in table 5.1. Here, the diamond-shaped blue plots illustrate one or two cases of driver shortage out of the above-mentioned five cases; the circular green plots show the shortage for all five

cases; and the circular black plots indicate when there is no shortage for all five cases. There were no cases in which there was a shortage in 3 or 4 cases out of the 5 cases. Fig.5.4 shows that there are enough drivers on most days, but there is a shortage on a few days, especially when the amount of freight to be delivered is large.

5.4.5 Discussion

As seen in Figs. 5.3 and 5.4, profit and driver shortages vary on a daily basis. Therefore, we will discuss under which conditions the profit will increase and drivers will be in short supply.

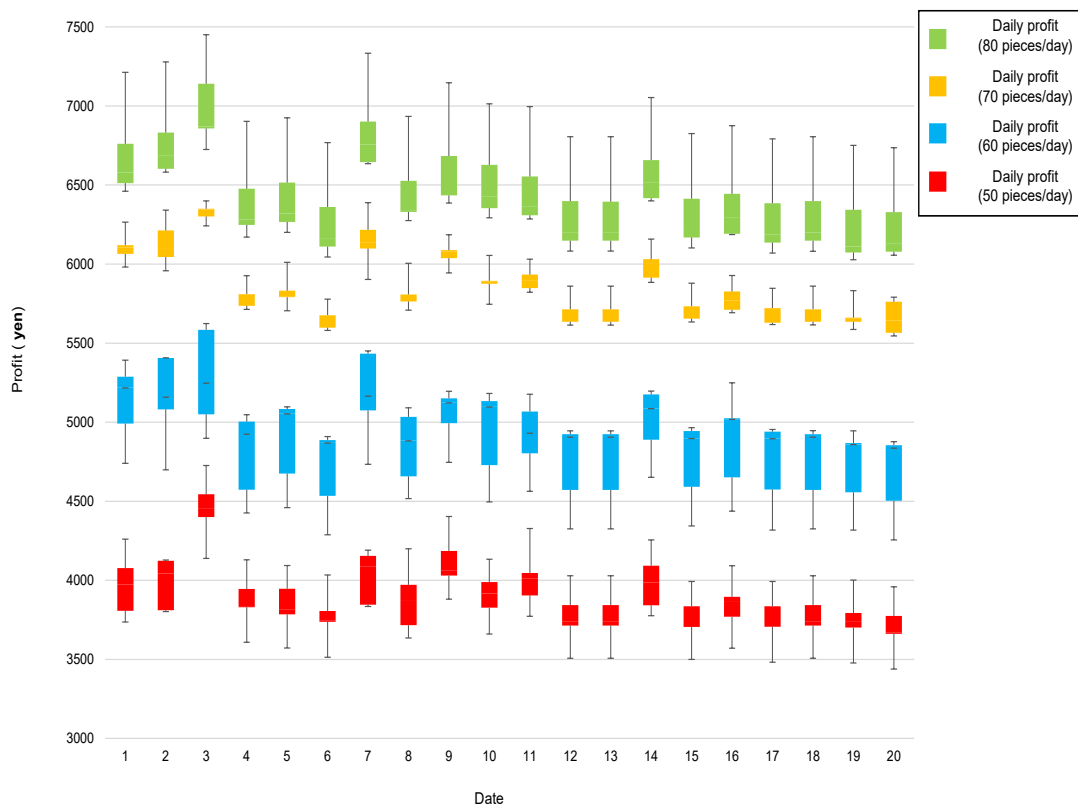


Fig. 5.3. Daily profit

(1) Profit

Fig. 5.3 shows that the profits on days without passengers (data in the figure correspond to the 20th day) are smaller than on other days. If there are no passengers, it is necessary to operate the vehicle from the business office to the delivery destination only for freight. By contrast, if there are passengers, freight can be transported along with the

transportation of passengers which is considered more efficient, less costly, and high transportability. More generally, it is thought that the profit will be greater when there are more passengers. Therefore, we used a figure to represent the relationship between the number of passengers and profit. However, it is clear that a large amount of freight delivery will result in a large amount of income, and hence profit. Thus, we used the profit per freight to reduce the influence of freight quantity on profit. As a result, Fig. 5.5 is obtained. This figure shows that the profit per freight tends to increase as the number of passengers increases. Thus, a large number of passengers has a positive effect on profit.

(2) Shortage of drivers

In general, in days when there is a lot of passenger transportation job, which is the main business activity, it is not always possible for a given driver to carry all freight. In other words, it is thought that there will be a shortage of drivers. The amount of passenger transportation job can be expressed by the passenger travel distance. Therefore, the plots in Fig. 5.4 were rearranged according to the order of passenger travel distance. The results are shown in Fig. 5.6.

Here, we focused on the case in which the delivery quantity was 80 pieces/day. All plots with the passenger travel distance less than 70 km are not associated to a shortage of drivers (hereinafter referred to as “black plots” for convenience according to the colors in the figure). By contrast, all plots with the passenger travel distance of at least 90 km are associated to a shortage of drivers (called “green plots” for the same reason as above). Therefore, it is considered that the passenger travel distance, which is the boundary between whether or not there is a shortage of drivers, exists between 70 km and 90 km. In other words, there is a boundary in the section width of the passenger travel distance in which the black and green plots coexist. Given that the diamond plot is the result of a mixture of cases in which there are insufficient drivers and cases in which there is no shortage, this plot can be interpreted as a mix of black and green. Consequently, the boundary of whether or not there is a shortage of drivers is considered to be between the two plots surrounded by the dotted line in Fig. 5.6, that is, from 72 to 88 km.

Based on the same concept, it seems possible to consider cases in which the delivery quantity is 50, 60, and 70 pieces/day. However, in these cases, it is unclear how many kilometers the passenger travel distance will be, and all plots will become green plots. This problem is solved by changing the conditions in the model. Specifically, we created a virtual area in which the distance between the villages was uniformly longer than the areas previously targeted. This means that the data related to distance and time are uniformly multiplied by a magnification factor. Then, a figure similar to that in Fig. 5.6

is derived for this area. By doing this, even if the green plot cannot be sufficiently observed in the original area, it can be eventually observed by supplementing data in a virtual area. Fig. 5.7 shows the results for virtual areas. The virtual area was calculated assuming that the distance was 1.5 times that of the original area. In Fig. 5.7, the “standard” on the vertical axis indicates the original area, and the “standard x 1.5” on the vertical axis indicates the virtual area. According to Fig. 5.7, when the delivery quantity is 70 pieces/day, the passenger travel distance ranges from 82 to 147 km as the boundary of whether or not there is a shortage of drivers. when the delivery quantity is less than 70 pieces/day, the boundary of whether or not there is a shortage of drivers is from 96 to 147km.

Concerning profit, note that a large number of passengers has a positive effect on the profit of freight-passenger integration, but an excessive number of passengers causes a shortage of drivers and makes freight-passenger integration infeasible. This is a qualitative finding, but by using the model, it can be determined that there is no driver shortage with three drivers, but two drivers may be insufficient to deliver all passengers and freight. For two drivers, if the delivery quantity is less than 70 pieces/day, there is a boundary of whether or not there will be a shortage of drivers when the passenger travel distance ranges from 96 to 147 km, whereas if the delivery quantity reaches 70 pieces/day, then the distance value decreases to the range 82 to 147 km and the distance value decreases to the range 72 to 88 km when the delivery quantity is 80 pieces/day.

5.5 Conclusion

In this study, a mathematical programming model is developed to evaluate how much profit can be increased and whether there will be a shortage of manpower by implementing freight-passenger integration in rural areas. Specifically, we constructed a mixed integer programming model to simulate the transportation of passengers by taxi and the delivery of freight and developed a method to evaluate the implementation of freight-passenger integration from both profit and manpower perspectives based on the results of the model. Using operational history data and Wakasa Town in Japan as a case study area, we evaluated whether profits could be improved by implementing freight-passenger integration and whether there would be a shortage of labor, that is, how much supply capacity is available. As a result, it was possible to clarify that the profit per unit of cargo increases as the number of passengers increases, and how the possibility of driver shortages would be affected by the volume of deliveries. Through this analysis using the

model, it became possible for taxi operators to objectively understand the change in sustainability for taxi operators with the introduction of freight-passenger integration.

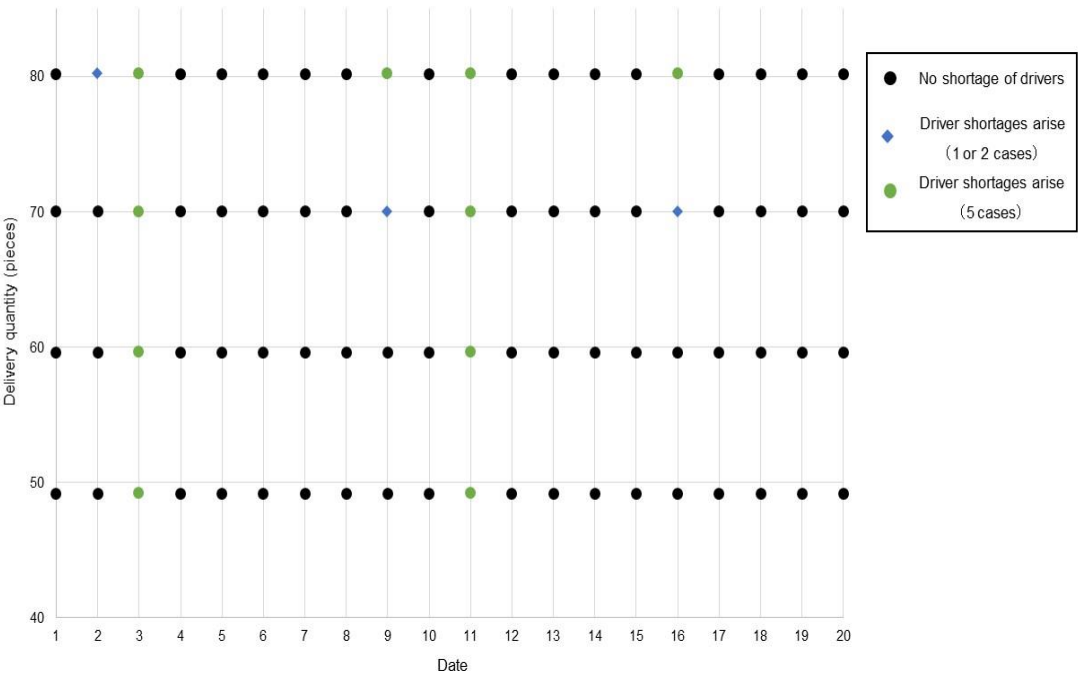


Fig. 5.4. Daily shortage of drivers (Number of drivers: 2)

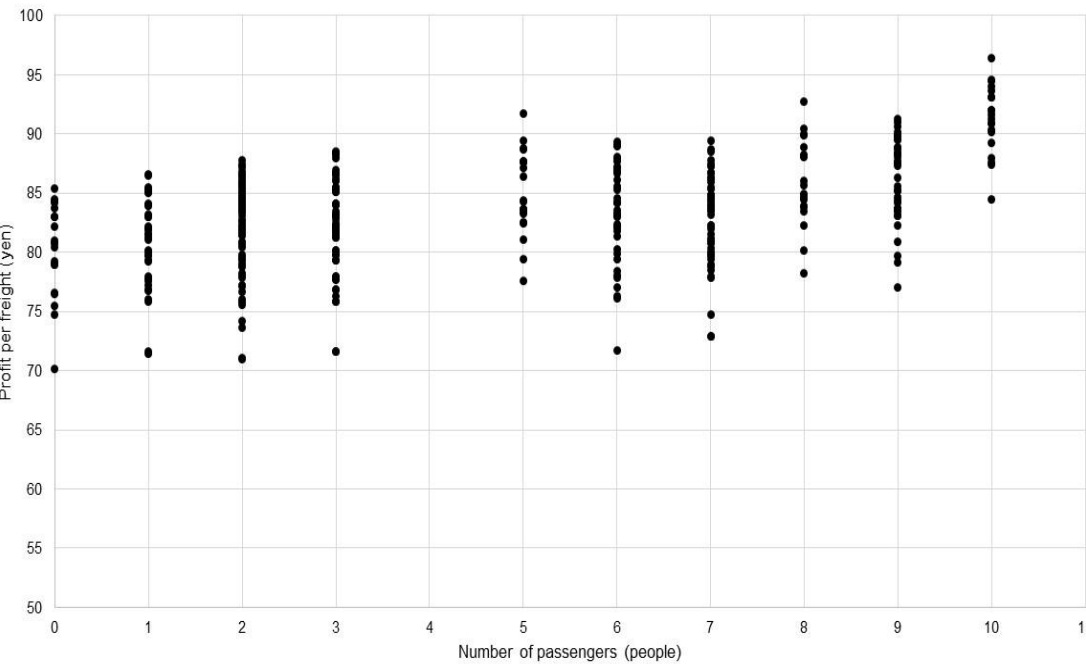


Fig. 5.5. Profit per freight and number of passengers

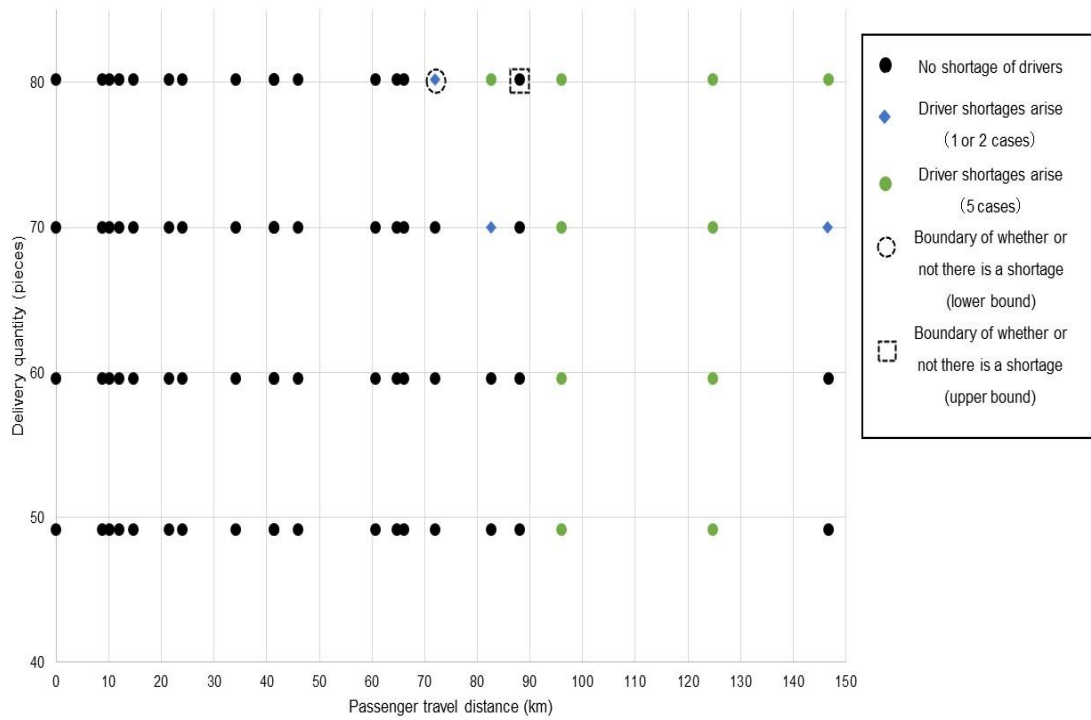


Fig. 5.6. Passenger travel distance and shortage of drivers (Number of drivers: 2)

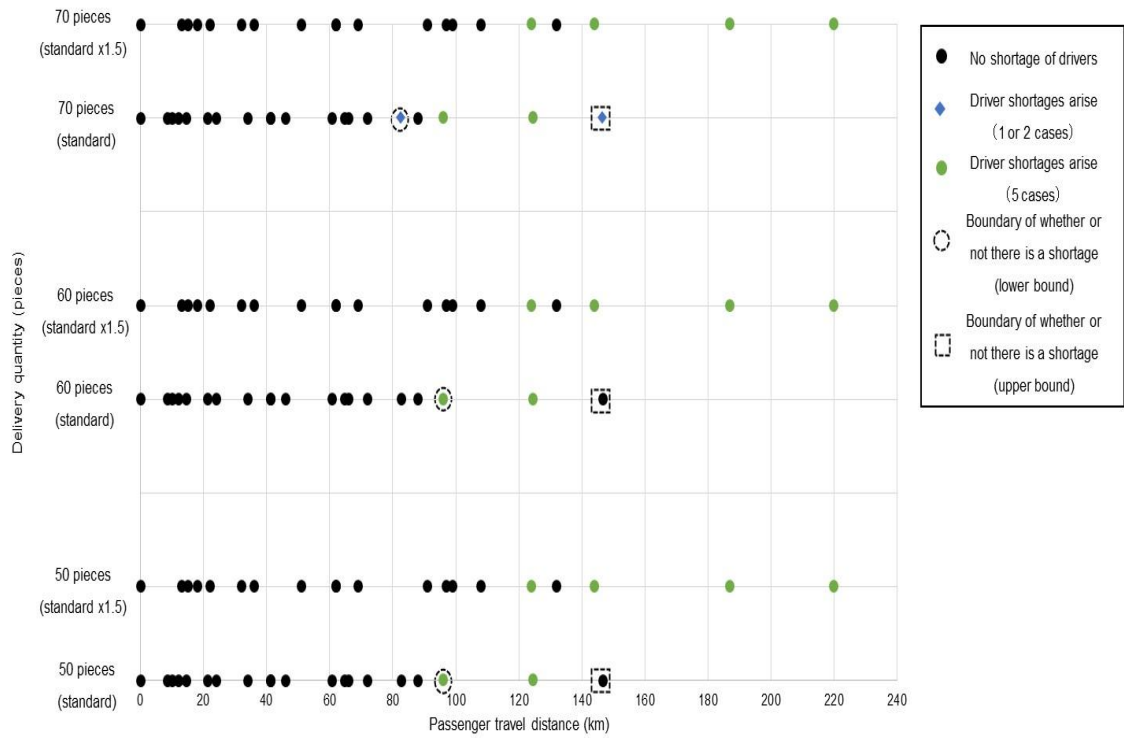


Fig. 5.7. Passenger travel distance and shortage of drivers in a virtual area
(Number of drivers:2)

Chapter 6

Conclusion

In Chapter 3, we constructed a mathematical programming model based on mixed integer programming to evaluate the supply capacity of taxi operators in rural areas. In this model, we took into account the actual situation of rural areas where drivers wait at the business center during periods with no passengers. Using this model, we objectively assessed the supply capacity of taxi operators in the target area of Jinsekikougenn Town by using the operation history data of the taxi operators. Furthermore, the model was also used to derive the supply capacity of the taxi operators with reservation adjustment taken into account. As a result, we clarified that reservation adjustments contribute to improving supply capacity due to the smoothing of peak demand, and we were able to quantitatively grasp the degree of the improvement.

In chapter 4, we focused on the scenario where taxi operators choose between operating a shared taxi or a traditional taxi. In this selection, it is necessary to evaluate the superiority of shared taxis compared to traditional taxi. we proposed a method for objectively evaluating the superiority of shared taxis based on the viewpoint that the fewer the minimum number of drivers required to operate the taxis, the better the sustainability of the taxi operators. Specifically, given data on passenger origin-destination pairs and travel times, we formulated a mathematical programming model based on mixed integer programming that can calculate the number of drivers required for the operation of shared and general taxis. Then, using the results calculated by this model, we demonstrated that the superiority of shared taxis can be evaluated using statistical models. We also showed that this methodology can be used to examine the specific usage of shared and general taxis, such as selecting different operating modes on weekdays and weekends & holidays. Furthermore, we demonstrated that it is possible to clarify the operation methods in which shared taxis are superior. The methodology employs a combined approach of a mathematical programming model and a statistical model, and its effectiveness was also confirmed.

In chapter 5, a mathematical programming model is developed to evaluate how much profit can be increased and whether there will be a shortage of manpower by implementing freight-passenger integration in rural areas. Specifically, we constructed a

mixed integer programming model to simulate the transportation of passengers by taxi and the delivery of freight and developed a method to evaluate the implementation of freight-passenger integration from both profit and manpower perspectives based on the results of the model. Using operational history data and Wakasa Town in Japan as a case study area, we evaluated whether profits could be improved by implementing freight-passenger integration and whether there would be a shortage of labor, that is, how much supply capacity is available. As a result, it was possible to clarify that the profit per unit of cargo increases as the number of passengers increases, and how the possibility of driver shortages would be affected by the volume of deliveries. Through this analysis using the model, it became possible for taxi operators to objectively understand the change in sustainability for taxi operators with the introduction of freight-passenger integration.

However, these studies were limited to the two rural areas of Jinsekikougen Town, Hiroshima Prefecture and Wakasa Town, Tottori Prefecture. In the future, it is necessary to expand the target areas for evaluation and confirm whether similar conclusions can be obtained, and if not, what conditions are influencing the results.

In this study, we used a mathematical programming model based on mixed-integer programming. However, in this model, the computation time may become longer due to the large amount of data, and in some cases, it may not be possible to calculate. Therefore, approaches that do not rely on mixed integer programming can be used, and one such approach is machine learning. Machine learning learns patterns from data and creates a prediction model. By using a pre-trained model instead of a mathematical programming model, it is possible to process data quickly with less computation. However, it is not clear what should be learned and how accurately the model should be, so verifying the substitutability of machine learning approaches is also a future research topic.

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Appendix

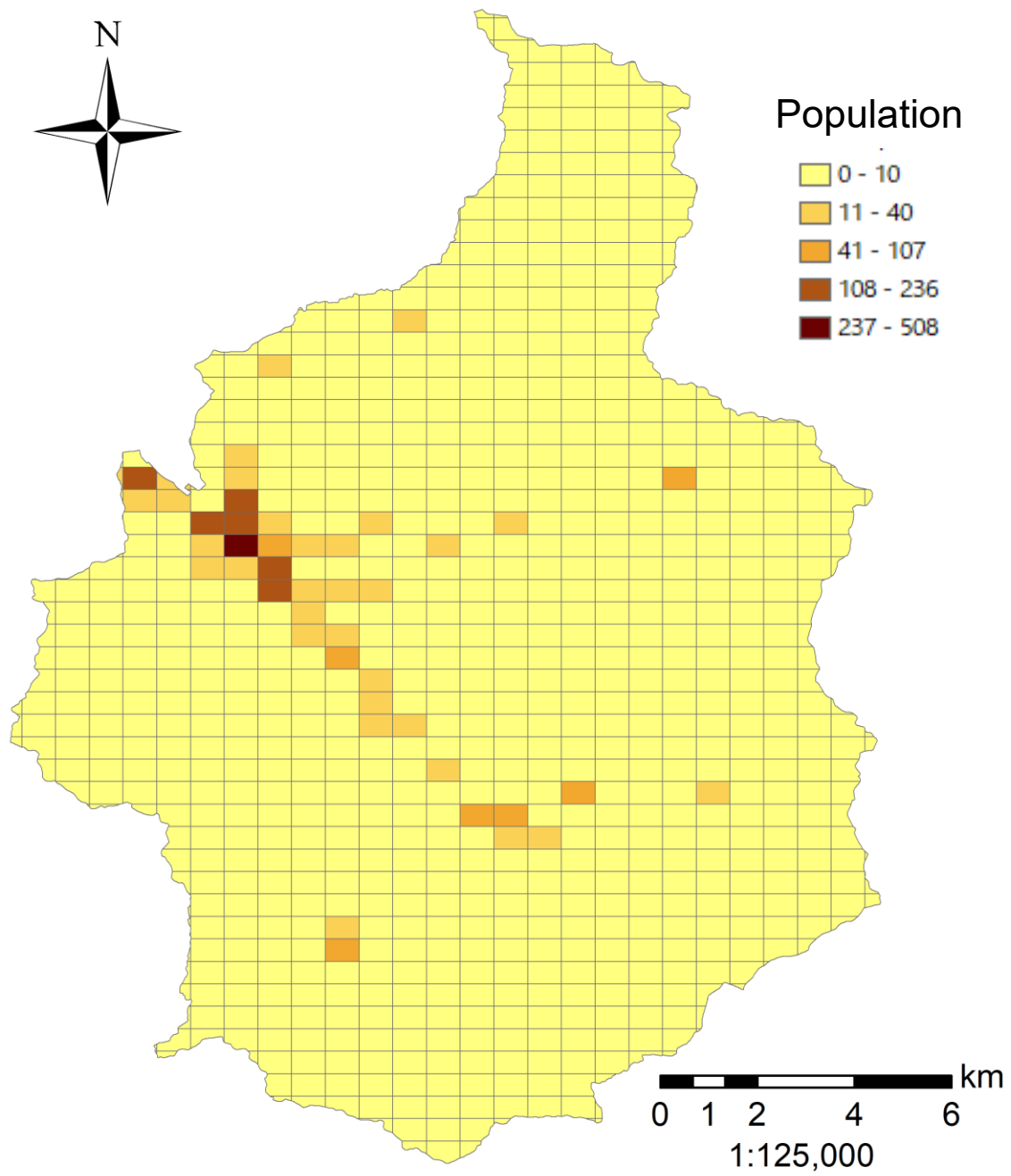


Fig. A.1. Population distribution of Wakasa Town

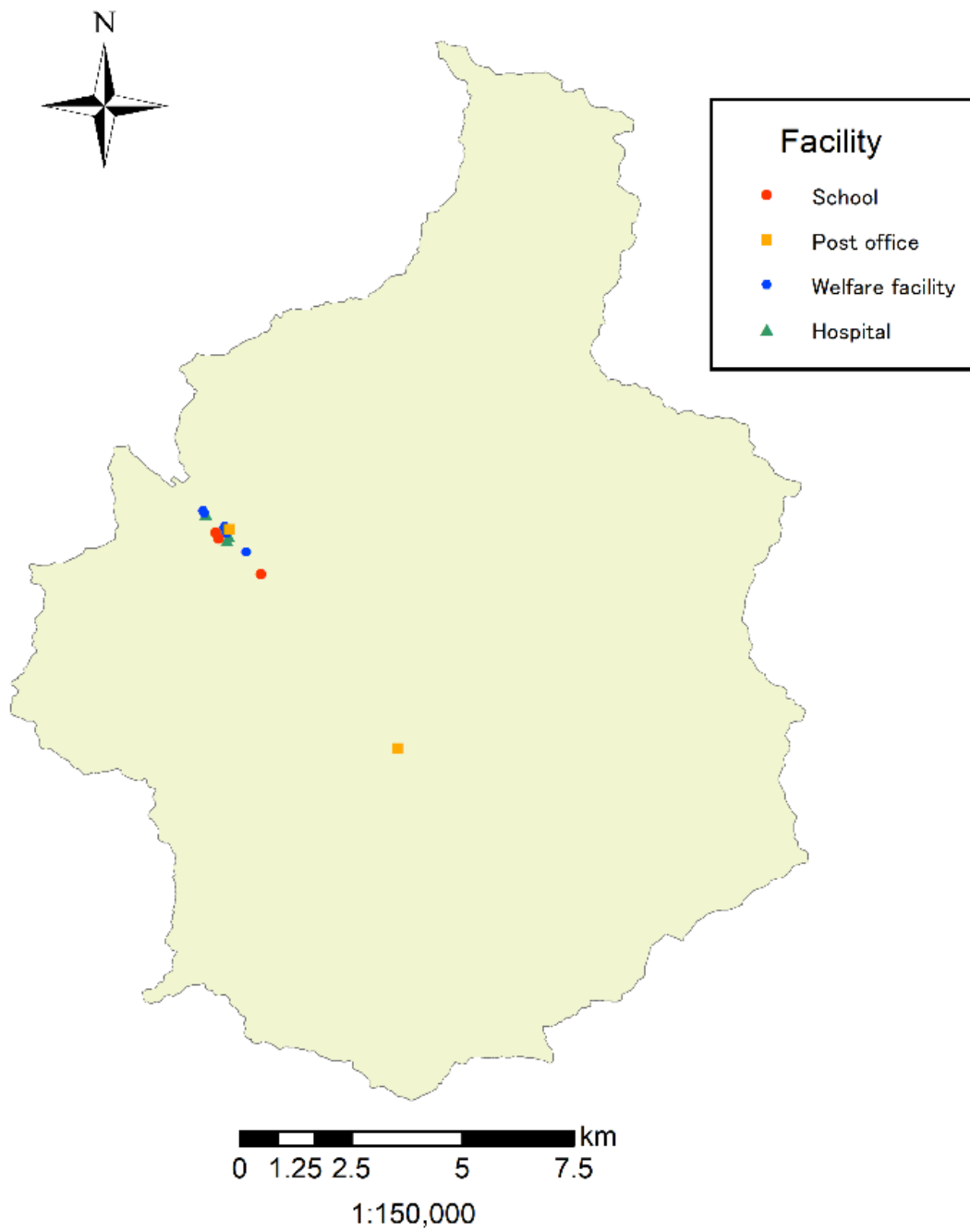


Fig. A.2. Location of facilities (Wakasa Town)

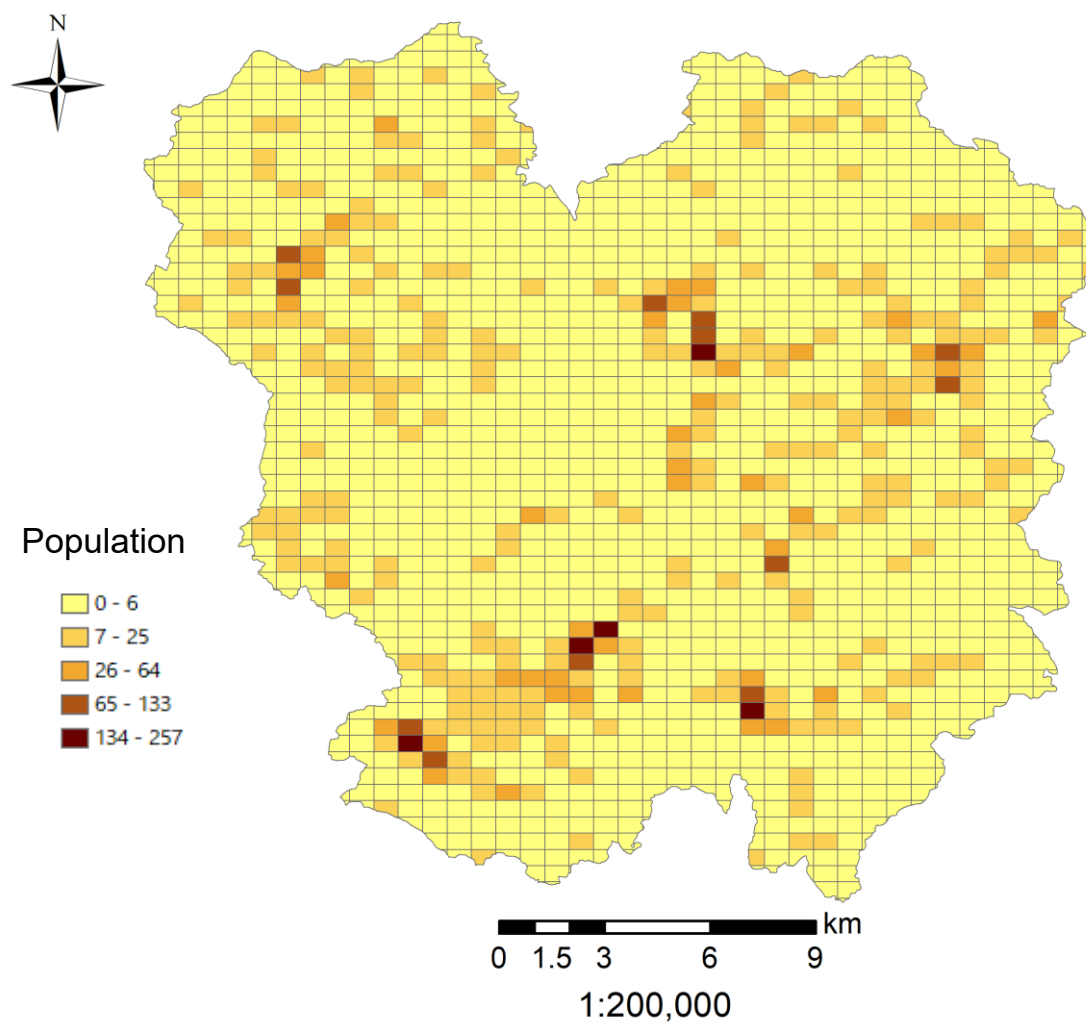


Fig. A.3. Population distribution of Jinsekikogen Town

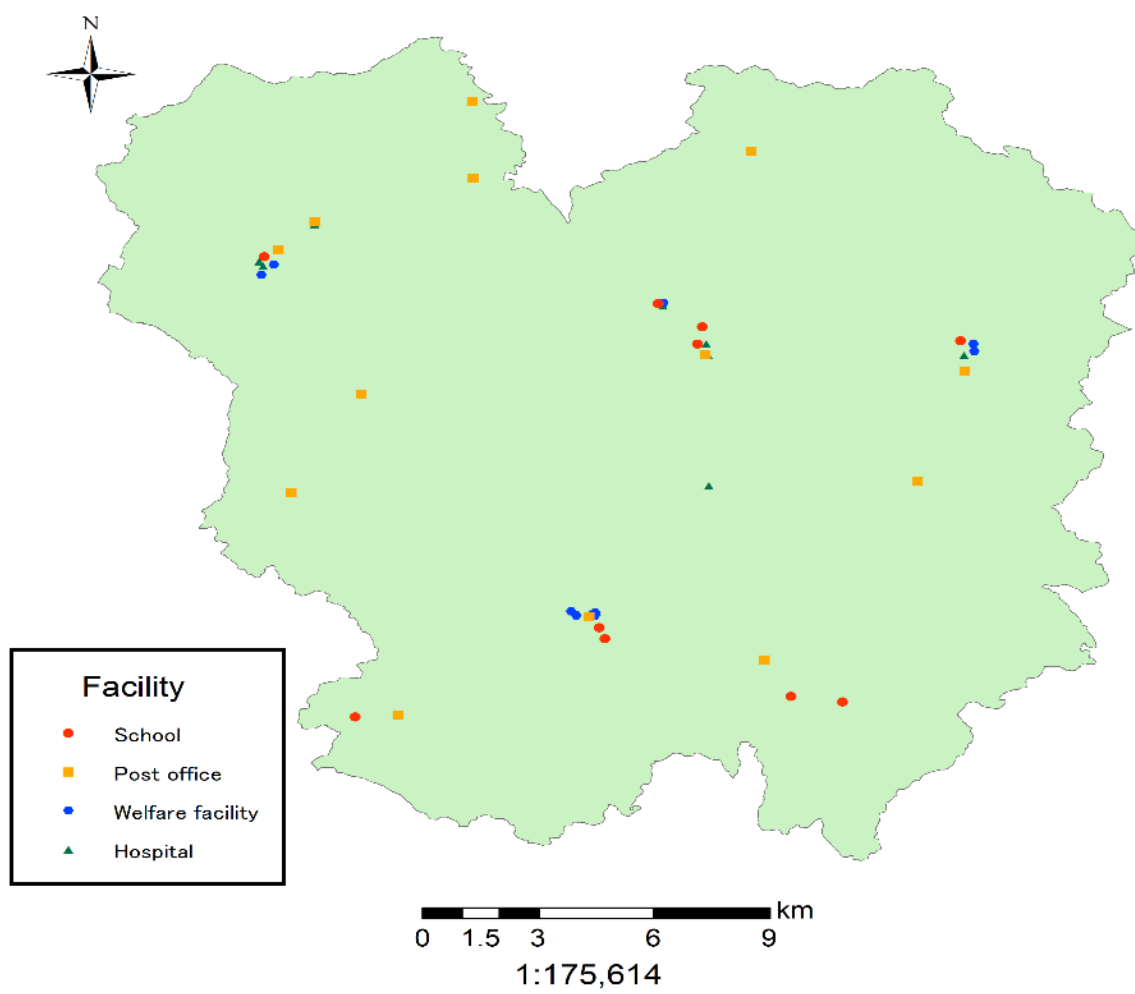


Fig. A.4. Location of facilities (Jinsekikogen Town)