Safe Route Carpooling to Avoid Accident Locations and Small-Scale Proof of Concept in Japan

Hidenobu Hashikami, *Student Member, IEEE*, Ryotaro Kobayashi, Yu Li, Yoshiki Nakano, and Maiko Shigeno

***Abstract*—Carpooling, a transportation service that encourages employees to pick up and drop off co workers while driving to and from work, has the potential to decrease the number of private cars used to commute, eases commuter traffic congestion, and reduce CO_2 emissions. Despite this potential situation of severe traffic congestion in Japan, little work has gone into developing carpooling specifically for commuting with co-workers scenarios. To build a carpooling system that accommodates Japanese unique culture and regulations, receptivity, safety, and profitability would be essential success factors. A carpooling problem (CPP) is proposed in this article with a focus on safety to discover a safe route for each driver that picks up and drops off co-workers and drives to and from their workspace while avoiding high accident-frequency locations. The CPP defines the subsets of employees sharing each car and the routes the drivers should take to optimize and minimize the total distance. Accident location data define the risk and driving competence determined by the classification of driver's license and grade of automobile insurance; then, a driver's optimal route minimizes risk while decreasing the total distance sought in deriving the CPP. The effectiveness of the proposed CPP was demonstrated by an experiment using actual accident data. This article also reports the small-scale proof-of-concept (PoC) study conducted to verify the efficacy of the proposed CPP and highlight issues with its practical application. Ten employees with five drivers and five co-workers commuted via carpooling for two weeks using a mobile application with the CPP developed independently. Through the questionnaire survey conducted after the PoC, we validated the need for carpooling. We also identified some challenges: safe map navigation, incentives for the driver, and adaptation to Japanese culture when the carpooling system is in practical use.**

***Index Terms*—Accident locations, carpooling, carpooling problem (CPP), Japan, proof of concept (PoC), ride-sharing, safety.**

I. Introduction

COMMUTER traffic congestion is one of the urban transportation problems. According to a 2010 survey conducted by the Statistic Bureau of the Ministry of Internal Affairs and Communications of Japan, commuters that use private automobiles account for 46.5% of the total, the highest percentage of all modes of transportation [1]. Local cities with less convenient public transportation rely more on private cars for mobility. Most commuters use private cars in the suburbs, where several large-scale offices and factories are located, and public transportation is inconvenient, causing considerable commuter traffic congestion.

Ride-sharing, often known as carpooling, is gaining popularity as a mode of transportation demand management. Companies organize it, so employees can pick up and drop off co-workers while driving to and from work. Reducing the number of private cars traveling to and from the workspace, commuter traffic congestion, and CO_2 emissions is possible through carpooling. Carpooling service has already been implemented as a business in some countries [2]. Robert Bosch GmbH has joined the market by acquiring Splitting Fares Inc., which offers an enterprise carpooling platform [3]. Scoop Technologies, Inc. [4] in Silicon Valley has raised more than U.S. $100 million and offers convenient door-to-door carpools. If the schedule for carpooling is changed, backup commute options ensure every employee has a dependable way to and from the workplace daily. In Japan, a demonstration experiment of carpooling has begun. For example, Netz Toyota and Fujitsu Ltd. operated a ride-sharing service for employees using their idle vehicles. Mitsui Sumitomo Insurance Company Ltd. conducted a demonstration experiment in which its employees commuted by shared taxis [5].

For widespread use of carpooling services that accommodate unique Japanese culture and regulations, critical success factors are *receptivity*, *profitability*, and *safety* from some interviews for companies and municipalities. A study of ride-sharing in a low-density residential area in Japan reported that passengers' discomfort is one of the factors in unsuccessful ride-sharing and an obstacle to the sustainability of service [6]. A flexible carpooling system is required to reduce psychological resistance and satisfy user needs. As a result, Hashikami [7] proposed a technique to improve satisfaction for pairs of drivers and co-workers using their preferences. Another reason carpooling is not common in Japan is that paid passenger transportation with private cars requires a license from the Ministry of Land, Infrastructure, Transport, and Tourism under Japanese road transport law. It is to utilize existing transportation operators, such as buses and taxis, that have been licensed. Designing profitable carpooling using a private car in compliance with the regulation is necessary. Safety is essential to employees who commute by carpooling, and companies are introducing the service for employees. If the number of traffic accidents increases due to carpooling services, this becomes a disincentive to adopt the services. Actually, Fig. 1 shows a spot map of high accident frequency locations in Hiroshima,

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The authors are with the Department of Systems and Information Engineering, University of Tsukuba, Tsukuba 305-8577, Ibaraki, Japan (e-mail: s2130110@s.tsukuba.ac.jp; maiko@sk.tsukuba.ac.jp).

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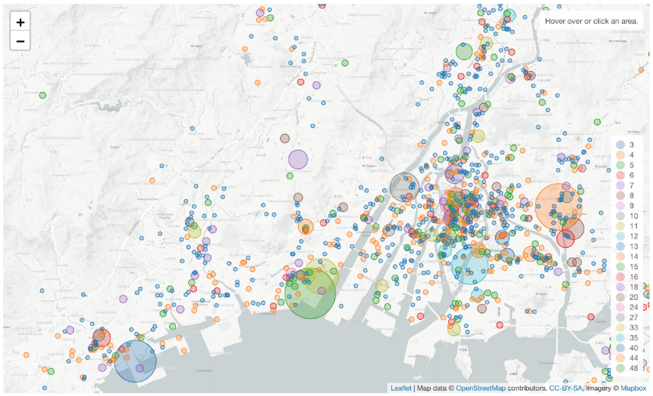


Fig. 1. Spot map of high accident frequency locations in Hiroshima, Japan, during 2020–2021. The circle represents the number of accidents. The accidents include both property damage and bodily injury.

Japan, from 2020 to 2021. Many accidents have occurred and are concentrated in urban areas and arterial roads, as indicated in Fig. 1, implying that employees may encounter accidents on their commute route. Reducing the probability of encountering a traffic accident on the commute route has numerous advantages not only for employees commuting but also for the company that hires them and insurance companies.

A system for carpooling services needs to provide an efficient route for each driver who picks up and drops off coworkers and drives to and from their workspace. The problem finding such routes is called carpooling problem (CPP). In this article, we focus on *safety* and develop the CPP to find safe routes to reduce the risk of traffic accidents while total distance is minimized. For finding safe routes, the risk is defined using accident location data and driving skills designed by classification of driver's license, grade of automobile insurance, and results of driving examinations. Some numerical experiments applying actual accident data showed that proposed routes reduced the risk of traffic accidents.

In this article, we also report small-scale proof of concept (PoC) to verify the feasibility of the proposed CPP and highlight challenges in its practical application under the cooperation of a company in Hiroshima, Japan. From November 5 to 18, 2021, ten employees, including five drivers and five coworkers, commuted via carpooling using a mobile application with the CPP developed independently. This article reports the results of the questionnaire survey conducted after the PoC and discusses the issues to be addressed when the carpooling system is implemented. The potential for practical application and the user needs for the carpooling service is confirmed by the PoC, which is expected to solve the commuter traffic congestion, a social need eventually.

The remainder of this article is organized as follows. In Section II, we review works relevant to the CPP and case studies of carpooling briefly. In Section III, we explain a problem description and formulation of a proposed safe route CPP for finding efficient routes while reducing the risk of traffic accidents. Section IV presents experimental results validating the proposed CPP. Section V explains the PoC conducted at a company in Hiroshima, Japan. Our conclusion and future works are provided in Section VI.

II. Related Work

A. Brief Review of the CPP

There are many surveys of actual carpooling services as a form of ride-sharing [8], and various types of CPP in [9]. The CPP is NP-hard since it contains a particular case of vehicle routing problem [10], [11] with unit customer demands. Based on two integer programming formulations of the problem, Baldacci et al. [12] proposed both an exact and a heuristic method for the CPP. The exact method is based on an abounding procedure that combines three lower bounds derived from different problem relaxations. The heuristic method obtains a valid upper bound, which transforms a Lagrangean lower bound's solution into a feasible one. Both approaches were tested on instances derived from the literature and yielded good results. Bruck et al. [13] proposed a practical daily CPP for minimizing CO_2 emissions. Experimental results attested a great potential in CO_2 savings using carpooling in the real-world scenario and newly generated instances. Tamannaei and Irandoost [9] proposed a model using a branch-and-bound algorithm efficiently. Based on the transportation network of Isfahan city, Iran, a computational experiment was conducted. These conventional studies help provide a formal definition of the CPP and provide solutions.

The model in the research described above is called the daily CPP, where users must agree on how to carpool daily. A long-term CPP involves employees forming groups and organizing shared rides that persist during a specific period. Varrentrapp et al. [14] gave a formal definition of the problem. Yan et al. [15] proposed a network flow formulation to systematically develop a long-term many-to-many carpooling model. They considered groups of individuals that would like to travel together rather than single individuals. Naoum-Sawaya et al. [16] also studied a long-term CPP derived from a company application. They proposed a stochastic model to solve the problem while considering events where a vehicle can be unavailable, possibly requiring rerouting. The proposed CPP in this article belongs to the daily CPP and is solved using integer programming.

B. Brief Review of the Case Studies of Carpooling

Inductive studies were conducted in several countries when researchers went into the field and analyzed existing carpooling initiatives. Cairns et al. [17] analyzed the efficacy of the travel plans of twenty employers in the United Kingdom. Their findings show that travel plans with parking management techniques can reduce the use of automobiles. Vanoutrive et al. [18] studied commuters' choices by clustering individuals by company in Belgium. This strategy is grounded on three arguments: 1) employers can foster internal commutation patterns among employees; 2) neighbor companies can have different accessibility options; and 3) companies are social settings where organizational culture and social norms can exert a significant influence on the individual choice to commute. The authors found that carpooling initiatives could be effective only where public transportation is either weak or absent, consistent with previous findings by Teal [19]. Abrahamse and Keall [20] conducted a study regarding Let us Carpool, a New Zealander initiative similar to a carpool zone but aimed at increasing vehicle occupation. This service is based on a website with an online ride-sharing algorithm that enables users to organize carpooling to and from work. Other match search options range from a maximum distance from home to different criteria, such as nonsmoking or gender. The website shows possible matches on a map with markers indicating trip starting and arriving points and generates a list containing partners' contact details. Users can then be free to contact potential matches. The study in [20] showed that the aspects of carpooling that make it preferable over public transportation are many, including money and time saving, reliability, and sociability. However, users also mentioned certain disadvantages of carpooling, such as lack of flexibility, absence of emergency cars, and complex arrangement of costs. A few studies concentrated on the assessment of individual opinions about carpooling. Through qualitative interviews and focus groups, Nielsen et al. [21] analyzed the perceptions of individuals from Denmark regarding carpooling. The authors highlighted that respondents never reported the environmental impact as a source of motivation for carpooling. Lee et al. [22] held a related study in the USA. The authors found that females and younger men are more inclined toward carpooling through survey data analysis. Furthermore, commuters from urban areas to country areas are more likely to participate in carpooling. Lehe et al. [23] examined increasing returns to scale in carpool matching by data from Scoop. As the number of requests to carpool in a specific market rose, the share of matches that users accept rises, while the extra distance traveled to accommodate these carpools declined.

No previous case study exists for commuter carpooling by private cars in Japan. This study is Japanese first PoC.

III. Problem Description and Formulation

We discuss the CPP for finding feasible routes that drive to the workspace by going around places where co-workers riding together are picked up. Driver error and traffic violations, vehicle types, weather and road condition during driving, and other factors contribute to traffic accidents. Thus, we propose a safe route CPP to find a commuter route to limit the risk specified by the accident locations data and driving skills. The CPP to work and the CPP from work are different problems and must be solved independently. In this section, we deal with the CPP to work. The CPP from work is explained in Appendix.

A. Problem Description

Let $V = \{1, \dots, n\}$ be a set of employees who participate in the carpooling and $V' = \{0\} \cup V$, where 0 represents the workplace. Each employee of V is identified as either driver (henceforth *server*) or co-worker to be picked up (hereafter called *client*). The servers represent drivers who provide their car in this carpooling, and the clients represent employees who desire to ride together in a driver's car. Therefore, the set of employees V is divided into the set of servers V_s and the set of clients V_c. Let $G = (V', E)$ be a directed graph, where edge set E is $\{(i, j) | i \in V, j \in V' \backslash V_s, i \neq j\}$. Each edge $(i, j) \in E$ corresponds to a potential pair of employees/the workplace for which route goes around in the order. A set of edges excludes pairs between servers $V_s \times V_s$ since no server may carry another. Each edge $(i, j) \in E$ holds distance $d_{ij} \geq 0$ and travel time $t_{ij} \geq 0$ from the place employee i gets on to the place employee j gets on or the workplace. The travel time t_{ij} satisfies the triangle inequality, i.e., $t_{ij} + t_{jk} \geq t_{ik}$.

The vehicle capacity must be considered when looking for routes in the CPP. The CPP also considers each server's maximum possible driving time when constructing practical routes. Let $Q^k \geq 1$ and $T^k > 0$ be the capacity of the car owned by server k and the maximum possible driving time of server k, respectively. Here, we assume that server's route found by the CPP is $P^k = (k, i_1, i_2, \dots, i_m, 0), k \in V_s$ in G starting from server $k \in V_s$, visiting clients $\{i_1, i_2, \dots, i_m\} \in V_c$ and ending at workplace 0. The restriction can be represented as $|P^k| - 2 \leq Q^k, k \in V_s$ and $\sum_{(i,j) \in P^k} t_{ij} \leq T^k, \; k \in V_s$. Employees must also arrive to work on time. Moreover, we consider the earliest time each employee can leave his/her home. Let $L_i > 0$ and $S_i \geq 0$ be the time at which employee i needs to arrive at the workplace and the earliest start time from which employee i can leave home, respectively.

To find a safe route so that a high possibility of traffic accidents is avoided as much as possible, we introduce the risk that each server goes to each edge. Assume that the statistical accident data was obtained. Let a'_{ij} be the number of accidents on edge $(i, j) \in E$ and s_k be the driving skill level of server k. Assume that the driving skill is designed so that the risk can be accurately quantified using the classification of the driver's license, the grade of the automobile insurance, the results of driving examinations, the results of video analysis from the drive recorder, and the results of questionnaire surveys. The driving skill is evaluated on $N_s + 1$ levels from 0 to N_s, representing the highest skill. Then the risk r^k_{ij} that server k goes through edge (i, j) is defined by

$$\begin{aligned} r^k_{ij} = \omega_a & \left(\frac{a'_{ij} - \min_{(i,j) \in E}(a'_{ij})}{\max_{(i,j) \in E}(a'_{ij}) - \min_{(i,j) \in E}(a'_{ij})} \right) \\ & + \omega_s \left(1 - \frac{s_k}{N_s} \right) \\ & + 1 \\ & i, j \in V, i \neq j, k \in V_s \end{aligned} \tag{1}$$

where ω_a and ω_s are weight coefficients adjusting the risk for the number of accidents and driving skills, respectively. The first term is the expression that normalizes the number of accidents to [0, 1], while the second term is the expression to normalize driving skill to [0, 1].

B. Formulation

The CPP to work is formulated as an integer programming problem. Two kinds of binary variables are employed. A binary variable $x^k_{ij} \in \{0, 1\}$ is equal to 1 if and only if $(i, j) \in E$ is traversed by a route of server $k \in V_s$. The other binary variable $y_i \in \{0, 1\}$ is equal to 1 if and only if client $i \in V_c$ is not picked up by any server. To represent time, two types of continuous variables are introduced. One is u_i^k at which server k's car leaves from the place for employee i. The other is v^k, at which server k's car arrives at the workplace. When server k departures at the time u, then they arrive at the workplace at $u + \sum_{(i,j)\ \in P^k} t_{ij}$, which must not be later than L_k. Since t_{ij} satisfies the triangle inequality, we have $S_k \le u \le L_k - \sum_{(i,j)\ \in P_k} t_{ij} \le L_k - t_{k0}$. As the same way, we have $S_i \le L_i - t_{i0}$ for client $i \in V_c$. A continuous variable $q_i^k > 0, i \in V, k \in V_s$ is introduced to reflect the number of people in the car. Each time the driver visits the client, the value for q_k increases.

The risk r_{ij}^k is incorporated into the objective function to select a server with low risk. The objective function is to minimize the risk and the total distance of routes that the servers drive to the workplace and the penalties when the client cannot ride together to a server's car, which is expressed as

$$\min \sum_{k\in V_s} \sum_{(i,j)\ \in E} r_{ij}^k d_{ij} x_{ij}^k + \alpha \sum_{i\in V_c} d_{i0} y_i \tag{2}$$

where α is the weight of the penalty term.

Constraints of the CPP are given as follows. Constraint

$$\sum_{j\in\{0\}\cup V_c} x_{kj}^k = 1, \quad k \in V_s \tag{3}$$

ensures that each server leaves the place they start, while constraint

$$\sum_{j\in\{k\}\cup V_c} x_{j0}^k = 1, \quad k \in V_s \tag{4}$$

ensures that each server arrives at the workplace. Continuity constraint for routes is

$$\sum_{j\in\{k\}\cup V_c} x_{ji}^k - \sum_{j\in\{0\}\cup V_c} x_{ij}^k = 0$$
$$i \in V_c, k \in V_s \tag{5}$$

which is known as the flow conservation constraint. Vehicle capacity constraint can be represented by

$$\sum_{(i,j)\ \in E} x_{ij}^k \le Q^k, \quad k \in V_s. \tag{6}$$

Maximum driving time constraint is represented by

$$\sum_{(i,j)\ \in E} t_{ij} x_{ij}^k \le T^k, \quad k \in V_s. \tag{7}$$

Departure time constraint is given by

$$u_i^k + t_{ij} - M(1 - x_{ij}^k) \le u_j^k$$
$$i, j \in V, k \in V_s \tag{8}$$

where M is a large number. If $x_{ij} = 1$, this inequality becomes $u_i^k + t_{ij} \le u_j^k$, indicating that the departure time u_j^k for j is no earlier than the time when the travel time t_{ij} has passed after leaving at u_i^k from i. If $x_{ij} = 0$, the inequality does not make sense because it is satisfied for any values of variables u_i^k and u_j^k. Furthermore, the departure time is not earlier than the earliest possible time S_i, therefore

$$S_i \le u_i^k \le L_i - t_{i0}, \quad i \in V, k \in V_s \tag{9}$$

where the upper bound comes from observing no later than his/her work. The time v^k arriving at the workplace is represented by

$$v^k \ge u_i^k + t_{i0} - M\left(1 - x_{i0}^k\right)$$
$$i \in V, k \in V_s. \tag{10}$$

It indicates that v_k is not earlier than when the travel time t_{i0} has passed after leaving at u_i^k from i visited immediately before the workplace. Arrival time constraint

$$v^k \le L_i + M\left(1 - \sum_{j\in\{0\}\cup V_c} x_{ij}^k\right)$$
$$i \in V, k \in V_s \tag{11}$$

ensures that employee i rides together server k has to arrive at the workplace at time compatible with L_i. If client i rides with server k, $\sum_{j\in\{0\}\cup V_c} x_{ij}^k = 1$ owing to (3). In this case, (11) becomes $v^k \le L_i$. The arrival time is also not earlier than the time when the server k has to arrive at the workplace, which is represented by

$$S_k + t_{k0} \le v^k \le L_k, \quad k \in V_s. \tag{12}$$

To prevent to create subtour, Miller–Tucker–Zemlin subtour elimination constraints [24]

$$q_i^k + 1 - Q^k(1 - x_{ij}^k) \le q_j^k$$
$$1 \le q_i^k \le Q^k$$
$$i, j \in V, k \in V_s \tag{13}$$

are introduced. When multiple clients are picked up at the same place, i.e., when $t_{ij} = 0$, (8) allows $u_{ki} = u_{kj}$, which implies the subtours may occur. As a result, we require the subtour elimination constraint separately from (8). The constraint

$$\sum_{k\in V_s} \sum_{j\in\{0\}\cup V_c} x_{ij}^k + y_i = 1, \quad i \in V_c \tag{14}$$

ensures that each client is picked up by a server or left unattended. In conclusion, the safe route CPP to work can be formulated by

$$\min \quad (2) \tag{15a}$$
$$\text{s.t.} \quad (3)\text{–}(14). \tag{15b}$$

When $\omega_a = 0$ and $\omega_s = 0$, the problem becomes without considering the risk. The problem is said to be a basic CPP. The server and client combination results in the safe route CPP are likely the same as for the basic CPP if the risks for each driver are similar.

This study's novelty is inventing the carpooling model considering user safety. The previous CPPs mentioned in Section II are exclusively concerned with route efficiency but cannot consider user safety. Unsafe carpooling becomes a disincentive for stakeholders of the service. The model is scalable and transferable to any city using its city's accident data. The model's feature is not only using accident locations but also driver skills. Since carpooling involves transporting someone, driving skill is an essential factor in maintaining

TABLE I
EXPERIMENTAL DATA OF THE WORKSPACE AND EMPLOYEES

ID	Type	Postal code	Address	Latitude and Longitude	Capacity Q^k	Max driving time T^k (minutes)	Driving skill s_k
0	workspace	731-5102	5998-1, Itsukaichi, Hiroshima	+34.419856+132.398009/	-	-	-
1	server	731-5103	3-79-74, Fujinoki, Hiroshima	+34.423290+132.364716/	5	60	4
			⋮				
6	server	731-0138	4-16-1, Gion, Asaminami, Hiroshima	+34.477047+132.461487/	5	60	3
7	client	731-3167	4-4, Ozukanishi, Hiroshima	+34.393257+132.348221/	-	-	-
			⋮				
20	client	731-0123	3-25-3, Furuichi, Hiroshima	+34.456894+132.469528/	-	-	-

TABLE II
PART OF ACTUAL ACCIDENT DATA

Accident location h	Granularity	Number of accidents a^h
+34.403152+132.341965/	house number	4
+34.377666+132.341049/	block code	3
+34.369671+132.344070/	house number	3
	⋮	
+34.36108+132.346207/	house number	5

safety. Another feature of our model is to provide routes that drivers drive efficiently. If just avoiding the accident location is needed, the shortest route that avoids the accident location is simply found when determining the route between the two points. However, such routes may not be familiar with drivers and give stress to the drivers. The model considered the accident location when determining the combination of servers and clients. The driver can drive the shortest route between clients, which is easier to operate.

IV. Experimental Evaluations

We studied the effectiveness and the validity of the safe route CPP for finding the safely feasible routes applied to artificial data based on the employee data of the company participating in the PoC and actual accident data. The safe route CPP is compared with the basic CPP in the experiment and is evaluated using efficiency and safety measures, perceptual route quality, and computational costs.

A. Setting for Experiments

An example of workspace and employee data is presented in Table I. The workspace is the company cooperating in the PoC described in Section V. The employee data had six servers and 14 clients whose addresses were selected within the same postal code by giving random latitude and longitude. The vehicle capacity of each server k was set to five, the maximum driving time T^k was 60 min, and the driving skill was set at five levels based on the driving skills of the PoC participants. The earliest start time S_i was 0, and the latest arrival time L_i was 60 min an hour after departure time for each employee i. The distance d_{ij} and travel time t_{ij} from i to j were computed by Google Map API.

Accident data was derived from the accident report, which detailed the occurrence of traffic accidents prepared by an insurance company. The report represented the accident location by address or street name. Each accident location dealt with latitude and longitude converted from the address. Accidents at the same place were counted in the number of accidents. Let a^h be the number of accidents in location h. The data has the granularity of conversion from address to latitude and longitude. Table II shows a part of actual accident data. Notably, the data cannot identify individual accidents. Preprocessing is essential because the accident locations are unidentified and scattered over a wide area. In accident data, there were 15 454 records in the table where two or more accidents had occurred. The accidents include both property damage and bodily injury. The 103 records in which four or more accidents had occurred and the address granularity that could identify the location known were used in the experiment. The accident location has been changed to the location on the closest road. Accident locations were aggregated at intersections or points on the road by map technology ArcGIS spatial join. Even though the accidents happened at the same intersection, this is to solve the problem caused by converting addresses near the junction to latitude and longitude.

According to the obtained accident data, we calculated the number of accidents a'_{ij} on each edge. We obtained the number of accidents determined to pass through the accident location by the following method because the accident location on the route was not updated accurately or because errors may occur on two-street routes. If the difference between distance d_{ij} of edge (i, j) and the distance of the route via the accident location h, $d_{ih} + d_{hj}$ was less than or equal to the tolerance $\epsilon \geq 0$, then location h was regarded to be on edge (i, j). The set of accident locations that were determined to locate on edge (i, j) is denoted by A_{ij}, i.e.,

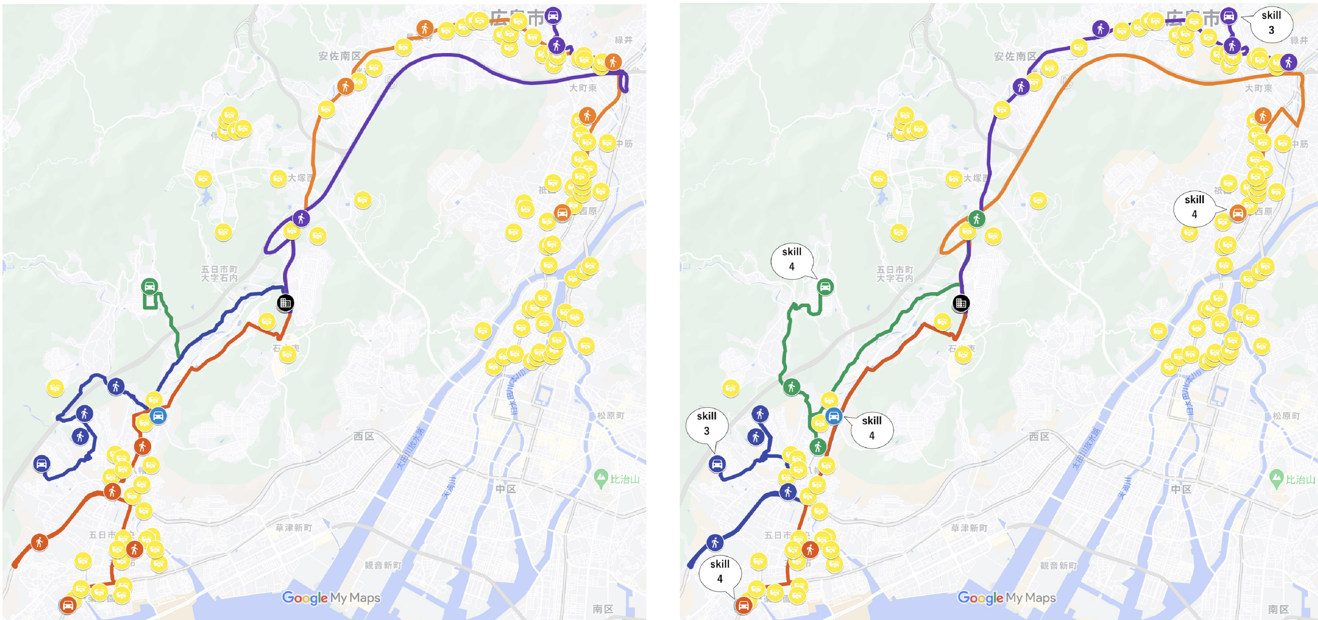
$$A_{ij} = \left\{h \middle| |d_{ij} - \left(d_{ih} + d_{hj}\right)| \leq \epsilon\right\}. \tag{16}$$

Then, the number of accidents a'_{ij} was given by

$$a'_{ij} = \begin{cases} \max\left\{a^h | h \in A_{ij}\right\}, & \text{if } A_{ij} \neq \emptyset, i \neq j \quad (17a) \\ 0, & \text{otherwise.} \quad (17b) \end{cases}$$

The ϵ was set at 40 m (0.000001 degrees) because the accuracy of the latitude and longitude of the accident location is in the 6 decimal place.

Google OR-Tools was used as the integer programming solver. The computational environment for solving the CPP using the solver was Intel Xeon 2.00-GHz CPU and NVIDIA GK210GL [Tesla K80] GPU with 12.0-GiB memory size running Ubuntu 18.04.3, with the program implemented in Python 3.6.9 programming language.



(a) (b)

Fig. 2. Comparison of feasible routes to work on map plotting workspace (office icon), server (car icon), client (person icon), and the high frequent accident location (collision icon) with $\alpha = 2.0$. (a) Basic CPP and (b) safe route CPP with $\omega_a = 1.5$ and $\omega_s = 0.5$. Numbers in bubbles represent driver skills with five levels. Each server's route is color-coded.

TABLE III
NUMERICAL COMPARISON FOR THE SAFE ROUTE CPP WITH $\alpha = 2.0$

	$\omega_a = 0.0$ $\omega_a = 0.0$ Basic	$\omega_a = 0.5$ $\omega_s = 1.5$	$\omega_a = 1.0$ $\omega_s = 1.0$	$\omega_a = 1.5$ $\omega_s = 0.5$
%m (%)	100.00	100.00	100.00	100.00
%tdr (%)	62.42	62.42	57.70	54.47
%tis (%)	67.05	67.05	62.13	64.30
%ala (%)	51.80	51.80	64.86	72.07

B. Results

The proposed safe route CPP was used to evaluate the performance of the obtained solution x, y using a matching rate of the combination of servers and clients

$$\%m = \frac{|\{y_i | y_i = 0, i \in V_c\}|}{|V_c|} \times 100 \tag{18}$$

the total distance reduction rate

$$\%\text{tdr} = \left(1 - \frac{\sum_{k \in V_s} \sum_{(i,j) \in P_k} d_{ij}}{\sum_{i \in V} d_{i0}}\right) \times 100 \tag{19}$$

where $P_k = \{(i,j) | x_{ij} = 1, (i,j) \in E\}$, driving time increase suppression rate

$$\%\text{tis} = \frac{\sum_{k \in V_s} t_{k0}}{\sum_{k \in V_s} \sum_{(i,j) \in P_k} t_{ij}} \times 100 \tag{20}$$

and accident location avoidance rate

$$\%\text{ala} = \left(1 - \frac{\sum_{k \in V_s} \sum_{(i,j) \in P_k} a'_{ij}}{\sum_{i \in V} a'_{i0}}\right) \times 100. \tag{21}$$

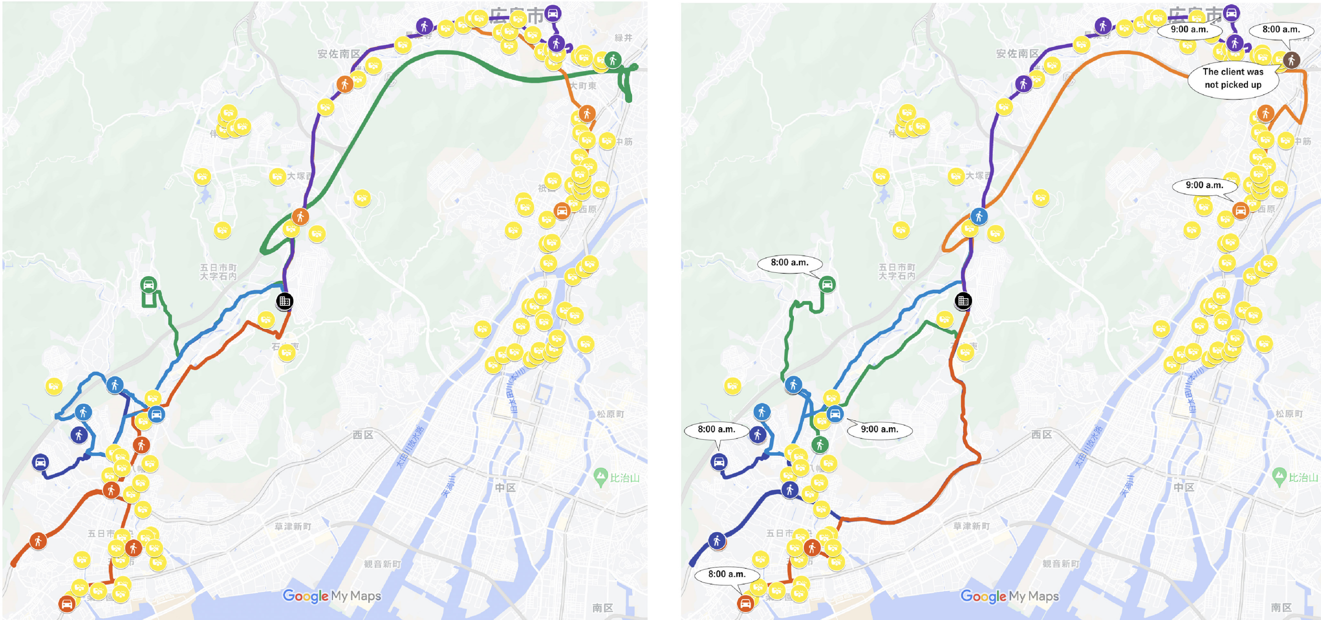
Higher values of these metrics, $\%m$, %tdr, %tis, and %ala are better results.

Table III shows the numerical comparison. The combinations of servers and clients were valid for all parameters. As shown in Table III, the expected effect can be confirmed that the result has an equal to or higher accident location avoidance rate than the basic, reducing the increase in total distance and travel time. In the case of $(\omega_a, \omega_s) = (0.5, 1.5)$, the server and client combination results were the same as for the basic CPP since the risks for each driver are similar values.

Fig. 2 shows an example of optimal routes for the CPPs on a map plotting the workspace, server, client, and the high frequent accident location. Each server in (a) basic CPP is heading toward the workspace via a short route, with other employees acting as clients. In (b) safe route CPP, we can see that the server located in the southwest picks up a few clients and drives them to work via a short route while avoiding accidents. The computational time required for the solver to complete the basic CPP was 27.1 s, displayed in Fig. 2. There were 72 067 branch-and-bound iterations until the solver was completed, and there were 948 branch-and-bound nodes. The computational time of the safe route CPP was 14.6 s. The total number of iterations was 16 408, and there were 202 nodes.

A case of two kinds of arrival times among employees additionally experiments. The arrival time of each server and client randomly is either. $\%m = 100\%$, $\%\text{tdr} = 43.52\%$, $\%\text{tis} = 51.76\%$, and $\%\text{ala} = 48.20\%$ by the basic. $\%m = 92.86\%$, $\%\text{tdr} = 43.69\%$, $\%\text{tis} = 59.83\%$, and $\%\text{ala} = 68.47\%$ by the safe route CPP with $\omega_a = 1.5$ and $\omega_s = 0.5$. Fig. 3 shows routes for the CPPs. Although one client could not be picked up, the safe route CPP matches drivers and clients at the exact arrival time and finds routes with higher accident location avoidance rates than basic ones without significantly lowering other rates.

Table IV shows the numerical comparison with the other numbers of servers and clients. Except for the case of



(a) (b)

Fig. 3. In the case of two kinds of arrival times among employees, comparison of routes on map plotting workspace (office icon), server (car icon), client (person icon), and the high frequent accident location (collision icon) with $\alpha = 2.0$. (a) Basic CPP and (b) safe route CPP with $\omega_a = 1.5$ and $\omega_s = 0.5$. Times in bubbles represent the arrival times of drivers and clients picked up. Each server's route is color-coded.

TABLE IV
NUMERICAL COMPARISON WITH DIFFERENT NUMBERS OF SERVERS AND CLIENTS FOR THE BASIC CPP AND SAFE ROUTE CPP. THE WEIGHTS WERE $\alpha = 2.0$, $\omega_a = 1.5$, AND $\omega_s = 0.5$, RESPECTIVELY

	$\lvert V_s \rvert = 1, \lvert V_c \rvert = 19$		$\lvert V_s \rvert = 2, \lvert V_c \rvert = 18$		$\lvert V_s \rvert = 3, \lvert V_c \rvert = 17$		$\lvert V_s \rvert = 4, \lvert V_c \rvert = 16$		$\lvert V_s \rvert = 5, \lvert V_c \rvert = 15$	
	Basic		Basic		Basic		Basic		Basic	
%m (%)	21.05	15.79	38.89	38.89	64.71	64.71	100.00	100.00	100.00	100.00
%tdr (%)	11.15	7.04	21.68	19.89	35.53	32.52	58.68	54.81	58.58	53.45
%tis (%)	22.67	20.26	28.20	31.55	41.28	40.02	45.92	43.71	52.09	47.89
%ala (%)	16.67	13.06	18.47	43.69	50.00	66.22	66.22	80.63	50.00	74.32

$|V_s| = 1, |V_c| = 19$, the safe route CPP has a higher accident location avoidance rate than the basic.

These experimental results show that for various situations in our instance, the safe route CPP appropriately avoids accident locations and reduces risks of traffic accidents without significantly reducing other ratings.

V. SMALL-SCALE PoC OF CARPOOLING IN JAPAN

Under the cooperation of a company in Hiroshima, Japan, we implemented the PoC to verify the feasibility of the proposed CPP and identify problems in its practical application.

A. Plan

1) Schedule: Ten business days (weekdays) from November 5 to 18, 2021.

2) Participants: Ten employees, including five servers and five clients.

3) Vehicle and System: The servers used their private cars. We installed a dash camera to record drive data and accidents in their automobiles. We initially used the iOS and Android mobile applications that developed the proposed CPP. Fig. 4 shows a wireframe and use case of the application in Fig. 5.

4) Legal Arrangement: We received confirmation from the Hiroshima Land Transport Office of the Chugoku District Transport Bureau on June 14, 2021. Because there is no payment or receipt of money between commuters, our PoC is no problem legal. In addition, participants consented to the terms of service and privacy policy that the lawyer requested.

B. Matching Result

As a countermeasure against Covid-19, every vehicle capacity was limited to two people to maintain a safe distance between passengers. Each pair of servers and clients stayed the same during the ten days. The parameters of the proposed CPP to and from work were $\alpha = 2.0$, $\omega_a = 1.5$, and $\omega_s = 0.5$, respectively. We used 563 accident occurrence locations corresponding to the granularity of house numbers and more than four traffic accidents. The driver competence was given based on a questionnaire survey before the PoC. We have found that the matching rate $\%m$ was 100%, the total distance reduction rate %tdr was 10.94%, the driving time increase suppression rate %tis was 69.30%, and the accident location avoidance rate %ala was 44.82% by the safe route CPP. As the reference, in the case of the basic CPP, $\%m$ = 100%, %tdr = 12.30%, %tis = 70.52%, and %ala = 43.35%.

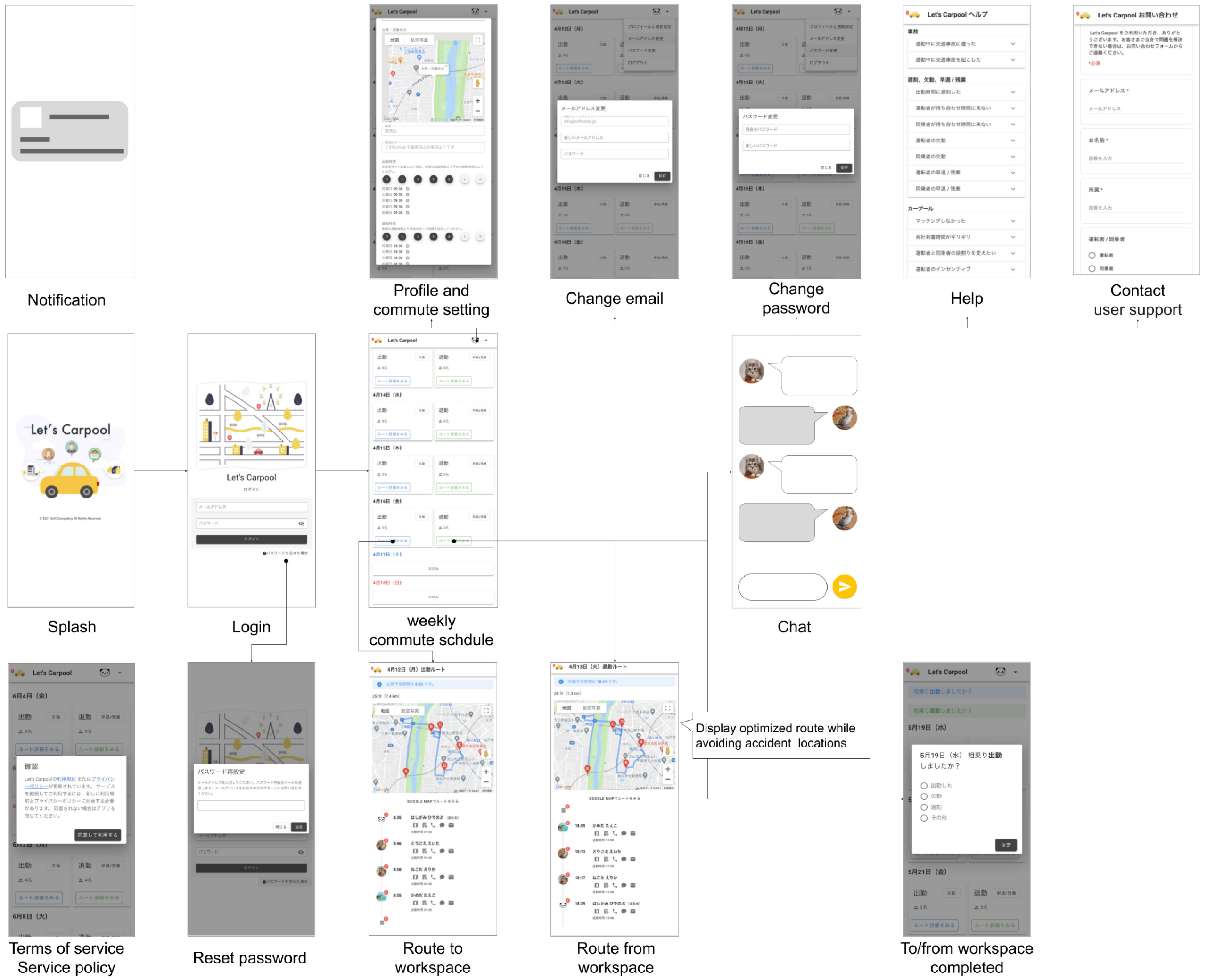


Fig. 4. Wireframe of the mobile application. When launching the application, a splash screen is first displayed. The weekly commute schedule screen appears after login in and agreeing once to the terms of service and privacy policy. Click the button for each day to display the route to and from the workspace screen, including map navigation. Predictive driving time has 3 min buffer for boarding and alighting time. The employee can communicate via a group chat. The employee can register a profile and commute setting with departure and arrival locations and days and times of use. Account management includes an email address change screen, a password change screen, and a password reset screen. For troubleshooting, help and user support are available.

TABLE V
DEMOGRAPHIC AND EXPERIENCE OF CARPOOLING TO COMMUTE IN ANOTHER CO-WORKER'S CAR

Type	ID	Age	Sex	Experience of carpooling To work	Experience of carpooling From work
Server	s1	20's	F		✓
	s2	20's	F	✓	✓
	s3	20's	F	✓	✓
	s4	40's	F		✓
	s5	50's	M	✓	✓
Client	c1	20's	F		✓
	c2	20's	M		✓
	c3	40's	M		
	c4	50's	F	✓	✓
	c5	50's	M		✓

TABLE VI
EXPECTATION FOR CARPOOLING BEFORE AND AFTER THE POC (1: HIGH AND 6: LOW)

Server ID	Server Before PoC	Server After PoC	Client ID	Client Before PoC	Client After PoC
s1	4	3 (+)	c1	3	3 (=)
s2	5	3 (+)	c2	1	1 (=)
s3	6	6 (=)	c3	4	3 (+)
s4	3	2 (+)	c4	6	6 (=)
s5	4	3 (+)	c5	3	1 (+)

C. Questionnaire Results

This section summarizes the result of the questionnaire survey after the PoC for participants whose demographic data are shown in Table V. Table V also shows experiences whether they have gone to or from work in a co-worker's car except for the CoP. The pairing of server and client with ID, s1 and c4, s2 and c5, s3 and c1, s4 and c2, and s5 and c3, respectively. People of various ages, genders, and company positions participated in the PoC. Almost participants have had experience carpooling to and from work. The office is located in the suburb of Hiroshima city, far from the bus stop and the station of the rubber-tired tram as public transportation.

Tables VI and VII and Fig. 6 show the consequence of the PoC. Table VI shows the expectation and opinions for carpooling before and after the PoC. Notably, carpooling expectations

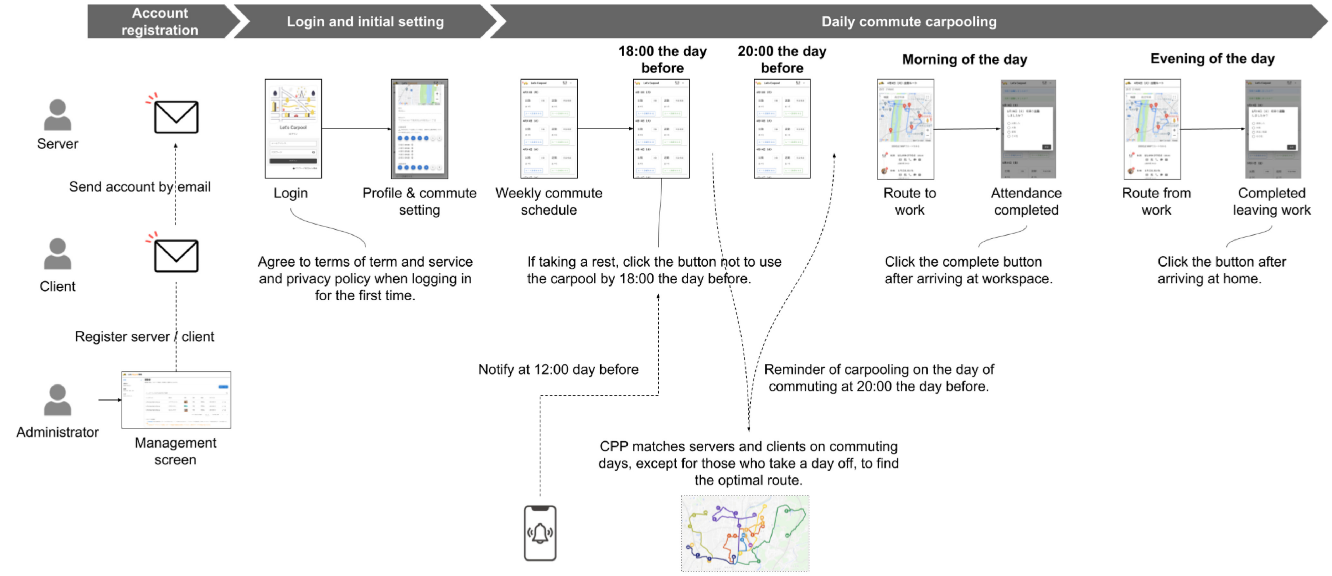


Fig. 5. Usecase, including account registration, login, initial settings, and daily commute carpooling. Administrator registers server and client accounts on the management application. After the server and client login into the account and register their profile and commute settings, they can use the application for daily commute carpooling.

TABLE VII
IN FIVE SERVERS, CHANGE OF ATTENTION TO THE SAFETY BETWEEN CARPOOLING AND USUAL DRIVING

Change of attention to the safety	Server
More careful in carpooling	2
Not changed	3
More careful in usual driving	0

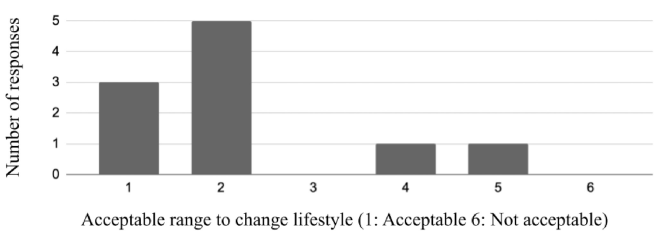


Fig. 6. Although changing the lifestyle of everyday commuting (time to wake up, time to leave home) was necessary, was it within your acceptable range? (1: Acceptable and 6: Not acceptable).

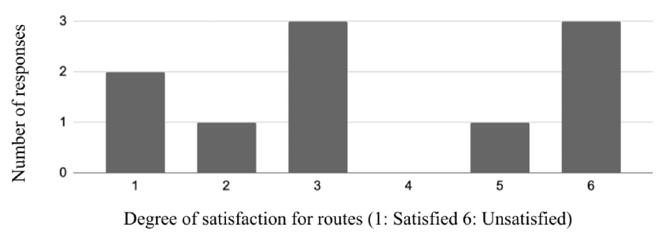


Fig. 7. Degree of satisfaction for recommended routes (1: Satisfied and 6: Unsatisfied).

TABLE VIII
DID YOU CHANGE A SUGGESTED ROUTE IN THE APPLICATION?

Change of suggested route	Number of responses
Changed suggested route	8
Did not change suggested route	2

remained the same as a result of the experience. Participants with both to and from work experience have low expectations, whereas those with only work experience have high expectations, making morning carpooling difficult.

We gathered opinions summarizing three positive aspects: the in-car user experience, time, and cost. As good points, participants as servers stated "was not lonely because of not alone," "it was a pleasure that we could talk about various things during commuting," "never be late for work," "the extra time was not a concern because of only one client," "the transportation cost was reduced." Clients stated, "it was easy because of no drive," "there was no stress because there was no need to drive," "could go home without working overtime." As bad points, "adjusting the time leaving work was difficult," "adjusting the commuting time in the morning was necessary," "it takes time to communicate about the arrival time at the place to pick up," "there is no time to spare (very close to the starting time)," "it was often delayed five to ten minutes than the scheduled time at the place to pick up, and it was cold to wait outside." Negative aspects mainly were opinions about time. Others were opinions about personal relationships that "made the atmosphere awkward."

Table VII shows the change of attention to the safety between carpooling and usual driving. Some servers were trying to drive more safely by riding with co-workers together. However, others did not change. There is room to increase safety by considering safe driving management in the risk assessment. As shown in Fig. 6, the participants embraced lifestyle change due to carpooling. This embracing could be one of the reasons why PoC's expectations for carpooling did not decrease.

Figs. 7 and 8 and Table VIII show the result related to the route in application. As shown in Fig. 7, some participants were not satisfied with the route. Participants expressed

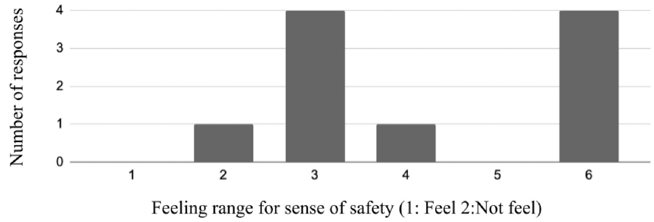


Fig. 8. Do you feel that the sense of safety in carpooling has improved, though we proposed the route considering the accident's frequent occurrence locations? (1: Feel and 2: Not feel).

TABLE IX
HOW OFTEN DO YOU WANT TO USE CARPOOLING IF YOUR COMPANY INTRODUCES IT?

Frequency of use	Server	Client
5 days a week	To/from work 1	To/from work 1 From work 1
4 days a week	0	0
3 days a week	0	To work 1
2 days a week	Only applicant 1	From work 1
1 day a week or not use	3	1

TABLE X
PREFERRED RIDE PARTNER IN CARPOOLING AS SERVER OR CLIENT

Preferred ride partner	Option of server as client	Option of client as client	Option of client as server
Identical undesignated co-worker ride together	1	2	1
Identical designated co-worker ride together	3	2	5
Specified randomly every day	4	5	2
Not use	1	0	1
Not sure	1	1	1

TABLE XI
DO YOU WANT TO RECOMMEND CARPOOLING TO OTHER CO-WORKERS?

	Server	Client
Recommend	2	4
Not recommend	3	1

TABLE XII
DO YOU ACCEPT CARPOOLING WITH OTHER COMPANY EMPLOYEES?

	Server	Client
Accept	0	3
Not accept	5	2

opinions on routes, such as "traffic congestion cloud not be avoided because of the fixed route" and "stopping by a convenience store was impossible." Participants stated that "a familiar route usually used may make driving easier than the provided routes," "the provided unfamiliar route is doubtful to reach the destination," "narrow roads was guided," "it was safer to take a familiar route rather than a very narrow one," "the mileage rose sharply," and "I chose a traffic conjunction route" as reasons for low satisfaction with the route. There is a main road with terrible traffic congestion near the workspace. The participant who commutes regularly knows and takes a shortcut route to avoid traffic congestion. The participants in the PoC were instructed to follow the suggested route as much as possible. However, many participants changed how often do you want to use carpooling if routes as shown in Table VIII. In practice, it is appropriate to operate a route that can be changed at the driver's judgment.

Fig. 8 shows the result of the sense of safety. The evaluation to feel safety was low generally because some participants said not to be concerned about safety so much, and other participants did not know that our provided route avoids high accident frequency locations as much as possible. Furthermore, as indicated in the route options, participants believed that the suggested routes were excessively unsafe. There was an opinion as "it was dangerous to guide a route as narrow as a sidewalk." Meanwhile, participants as clients expressed opinions, "since it was a narrow mountain road with various traffic routes, the sense of special safety was not improved" and "I did not know the function to present a safety route."

Tables IX–XII show the result about the future usage of carpooling. From the results, we could not obtain the expectation of positive use of carpooling, especially as a driver. We know from the result in Table VIII that almost all participants were dissatisfied with the suggested routes, which were unsafe, and changed their routes. These results imply that providing a route that is easy to drive is essential to service. We received the following reasons for using the service, "it minimizes travel cost and commuting time," "want to use it as a client because I do not mind driving," " it prevents overtime work," "I can go back to work early." Meanwhile, we have gathered opinions as reasons for not using the service, "it is awkward," "I do not like caring about fitting in with others and being cared for by others," "it is convenient sometimes but it is easy to ride alone," "I want to stop by a shop on the way to home," and "I despise predetermined routes." As shown in Table XII, carpooling among multiple companies is inappropriate in Japan because of the solid psychological resistance of users and the law restrictions.

D. Discussion

As shown in the matching result, although the low distance reduction rate was because of only ten participants and the limit of vehicle capacity, the accident location avoidance rate of the safe route CPP was better than that of basic CPP. The proposed model went well, as we expected. As shown in the simulation experiment with 20 participants, the performance of reducing the detour distance and increasing safety would be improved so that we can meet user needs flexibly.

Note that the qualitative analysis of the questionnaire survey in the PoC since a large sample was not available for statistical analysis. As shown in the questionnaire survey results, we can see that commuter carpooling is requested, especially by someone, to ride a driver's car. We can also identify five challenges so that a company can introduce the commuter carpooling system.

1) *Safe Map Navigation:* While the application we used to find routes from an origin to a destination is a map service considering traffic conditions, it occasionally proposes a narrow route based on route optimization. It is necessary to provide an easy-to-drive route, such as major roads.

2) *Incentive for the Driver:* While employees who are picked up can easily commute without driving, drivers take on a significant burden, such as loss of personal time in the car, longer detour distance, earlier arrival time at work, and later arrival time at home. The design of incentives other than allowances for drivers is an important issue related to profitability.
3) *To Participate Without Feeling Ill at Ease:* Since the Japanese are unfamiliar with the culture of ride-sharing, which is popular in many countries has not been spread in Japan. A portion of the participants in the PoC was uneasy since a specific pair of participants had to commute riding together for two weeks. Groups of participants riding together must be well-suited.
4) *To Drop in on the Way:* It is necessary to provide flexibility to the CPP so that participants drop anywhere.
5) *To Operate Flexibly:* An operational rule is needed when overtime work occurs suddenly. For a complaint that arrival and departure times have to be adjusted with other participants, as shown in the simulation experiment, it can be improved if the number of participants in the carpooling is increased. For a complaint that a driver lost private time, they can flexibly join or not by setting about days and times of use in the application.

VI. Conclusion

This study has proposed the safe route CPP for locating efficient routes while avoiding areas with high accident frequency. In deriving the CPP, the risk was determined by the accident location data and driving skills. The driver's optimized route that reduces risk while minimizing total distance was sought. The safe route CPP enhances accident location avoidance rate by an average of 1.6 times in the objective evaluation, according to a report based on real-world data in Japan. This study also reported the small-scale PoC to verify the feasibility of the proposed CPP and identify issues in its practical application under the cooperation of a company in Hiroshima, Japan. Through the questionnaire survey, we validated the need for carpooling and identified five challenges: 1) safe map navigation; 2) the incentive for the driver; 3) adaptation to Japanese culture; 4) drop-in on the way; and 5) flexible operation. In both results of the simulation experiment and demonstration experiment, the proposed model went as well as expected and would be possible to operate in practical use.

The CPP and application will be improved in the future by multiple PoCs of carpooling on various scales. Furthermore, we must design a business model to comply with the Japanese Road Transportation Act, which states that only employees of the same company might carpool with each other and have a fair driving allowance. To solve the commuter traffic congestion problem, we will establish a system for carpooling that accommodates Japanese culture and regulations.

Appendix
Formulation of the Safe Route CPP From Work

The safe route CPP from work that employees leave the workspace and go home is almost the same as the CPP to work. The directions of edges in G are reversed because it determines a route from the workspace to each server's place by going around some clients' places. Consequently, constraints (3)–(5) and (14) are replaced to

$$\sum_{j\in\{k\}\cup V_c} x_{0j}^k = 1, \quad k \in V_s \tag{22}$$

which ensures that each server leaves the workspace

$$\sum_{j\in\{0\}\cup V_c} x_{jk}^k = 1, \quad k \in V_s \tag{23}$$

which ensures that each server arrives at the home, continuity constraint

$$\sum_{j\in\{0\}\cup V_c} x_{ji}^k - \sum_{j\in\{k\}\cup V_c} x_{ij}^k = 0$$
$$i \in V_c, k \in V_s \tag{24}$$

which ensures that the routes for each server consist of the path not breaking in places for clients, and

$$\sum_{k\in V_s}\sum_{j\in\{0\}\cup V_c} x_{ji}^k + y_i = 1, \quad i \in V_c. \tag{25}$$

The CPP from work considers no time constraints because usually there is time room when going home. As a result, the constraints from (8)–(12) are unnecessary. The CPP from work will be the same result as the CPP to work if route distance, driving time, and same employees with leaving time are identical.

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Hidenobu Hashikami (Student Member, IEEE) received the M.Eng. degree in systems and information engineering from the University of Tsukuba, Tsukuba, Japan, in 2012, where he is currently pursuing the Ph.D. degree in policy and planning sciences.

From 2012 to 2016, he worked as a Software Engineer with Ricoh Company Ltd., Ebina, Japan. From 2016 to 2019, he worked as a Business System Architect with Mazda Motor Corporation, Hiroshima, Japan, and Mazda North American Operations, Irvine, CA, USA. From 2016 to 2021, he worked as a Chief Technical Officer with Pharma Cloud Inc., Tokyo, Japan. He is currently employed with Style Port Inc., Tokyo, Japan, for Web engineering and development team management. His research interests include carpooling as transportation demand management, operations research, and soft computing.

Ryotaro Kobayashi received the bachelor's degree in policy and planning sciences from the University of Tsukuba, Tsukuba, Japan, in 2021, where he is currently pursuing the master's degree in policy and planning sciences.

Especially, he has research interests in mobility services and operations research.

Yu Li received the bachelor's degree in logistics engineering from Shanghai Ocean University, Shanghai, China, in 2020. He is currently pursuing the master's degree in policy and planning sciences with the University of Tsukuba, Tsukuba, Japan.

Especially, he has research interests in big data analysis, mobility services, and operations research.

Yoshiki Nakano received the master's degree in systems and information engineering from the University of Tsukuba, Tsukuba, Japan, in 2022.

His research interests include combinatorial optimization and network optimization.

Maiko Shigeno received the Ph.D. degree in science from the Tokyo Institute of Technology, Tokyo, Japan, in 1996.

She is a Professor with the University of Tsukuba, Tsukuba, Japan. Her specialized research areas are operations research and mathematical optimization. Especially, she has research interests in combinatorial optimization and network optimization.