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Dynamic Travel Permits Allocation Mechanism for Decreasing Traffic Congestion and Drivers' Dissatisfaction

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Abstract

An increasing number of people live in urban cities, and this trend is predicted to continue exponentially. However, such a tendency adversely influences infrastructure, such as roads, causing severe traffic congestion in some cities. In this paper, we present a new travel permit allocation mechanism to alleviate traffic congestion, especially during the rush hour of an urban area. This method aims to decrease drivers' dissatisfaction compared to existing odd-and-even license plate restrictions that mechanically assign the right of travel while maintaining the alleviated traffic congestion. To adequately allocate travel permits to each driver, we combined auction and personal trading to respond to time-series changes in the participants' schedules. We evaluated the efficiency of the mechanism by multi-agent simulation from the two perspectives of traffic congestion and agent satisfaction score, which represents the degree of matching between the agents' schedules and their actual acquisition status of the travel permits. We experimented in two cases in which agents' departure points were uniformly distributed and unevenly distributed, and confirmed that the proposed method improves the agent satisfaction score while limiting the number of vehicles to decrease traffic congestion.

Keywords: Dynamic allocation, Multi-agent simulation, Rush hour traffic congestion, Travel Permits

1 Introduction

Traffic congestion is becoming an increasingly serious problem owing to the growing population concentration in urban areas. According to a United Nations prediction, 55.3% of the world's population lived in urban areas in 2018, which is expected to increase to 68.4% by 2050 [1]. However, such a dense urban population contributes to escalating traffic congestion, mainly caused by a mismatch between the traffic supply and demand [2]. To eliminate such a mismatch, it is necessary to either expand the road capacity or decrease the traffic demand. However, increasing road capacity has been proven to be self-defeating in congested areas because the increased capacity is quickly absorbed by the induced travel demand [3][4]. Therefore, the current unrestricted traffic demand should be changed.

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There are two main types of transportation demand management schemes [5]. One is price-based regulation, such as road pricing and congestion pricing. This method requires payment for traversing certain roads during congestion. It is theoretically effective in reducing traffic jams and has been adopted in several cities, such as London, Stockholm, and Santiago de Chile. However, during actual adoption, such an approach can suffer a political backlash from citizens, including concerning revenue usage [6][7]. In addition, road pricing has the problem of information asymmetry. To determine the optimal toll price, the road manager needs accurate demand information of all users. Collecting such private information is almost impossible, so ensuring that the road pricing scheme has the correct effect is challenging [5].

The other scheme is quantity-based regulation, which limits the number of vehicles to less than the actual road capacity. Compared to price-based regulation, it is easier to control traffic flow in which the total number of vehicles can be predicted in advance. An example of this method, odd-and-even license plate restrictions, has been adopted in some cities, and its effectiveness has been analyzed in Jakarta [8], Beijing [9][10], and Bogotá [11]. However, it allocates "roadway-use rights" merely according to the license plate, and thus, it is hardly an efficient/effective method.

During the research of quantity-based regulation, which aimed at improving overall efficiency, Verhoef and Goddard proposed that road managers issue and allocate roadway-use rights [12][13]. This scheme deals with the transportation market as a collection of commodities of a shared economy and manages mobility demand with a proper rationing scheme [14]. To eliminate traffic congestion, it may be necessary to shift from the idea that roads can be used by anyone at any time without restriction to the belief that roads are common property, for which users should get rights in advance and use when needed.

In this study, we focused on commuting during the morning rush hour. We propose reducing congestion by issuing travel permits to vehicles to enter the city center from the suburbs/residence area. Here, travel permits are similar to the roadway-use rights, and only users who gained them are entitled to travel to urban areas. The main contribution is the presentation of a method that dynamically responds to the time-series changes in the participants' schedules. This study assumes that the participants reschedule dynamically from the travel permit allocation to the actual commuting time. The proposed method combines auctions with subsequent personal trading. It responds to the time-series rescheduling of participants more appropriately than the existing methods. In particular, it enables drivers who have changed their schedules to buy or sell permits in personal trading markets. Furthermore, this method proposes distributing the same number of dedicated coins to all participants for use in auctions and personal trading. This idea is similar to the travel credit scheme [15], described in Section 2. By incorporating the concept of travel credit into the study of travel permit allocation, we intend to increase equity and social acceptability. This paper is invited, modified, and expanded from our earlier conference paper [16], including the case in which the agents' departure points are uniformly distributed and the case in which they are unevenly distributed.

The remainder of this paper is organized as follows. The following section presents an overview of the related works. Section 3 describes the proposed method, which allocates travel permits effectively through auctions and personal trading. The evaluation results of the multi-agent simulation are presented in Section 4, and finally, Section 5 concludes the paper.

2 Related Works

Currently, there are two main types of studies that use roadway-use rights. One is a tradable travel credit scheme, which was first proposed by Yang and Wang [15]. Under this scheme, the government initially distributes a certain amount of credit to all eligible receivers/users and charges a link-specific amount of credit to travelers using each link. This scheme is more equitable than traditional road pricing because the same amount of credit is distributed to all users. However, it suffers from the same drawback as road pricing. The traffic volume cannot be completely controlled, and there is potential information asymmetry between road managers and users [5][17].

The other is the tradable bottleneck permits scheme proposed by Akamatsu et al. [18]. In this method, a road manager issues a right (bottleneck permit) that allows the permit holders to pass through a bottleneck during a pre-specified time interval and establish a permit trading market. Under this scheme, the number of permits is issued below the road capacity to eliminate queuing congestion completely [5]. This method was extended to the design of an auction mechanism for single bottleneck/general networks to implement a trading market for bottleneck permits [19][20][17]. However, such auction mechanisms have a problem in that they fail to consider the time-series change/variation of user preferences. In other words, it does not consider the possibility that the need for permits may change between the end of the auction and the actual commuting the next morning. To solve this problem, Wang proposed an implementation mechanism of tradable bottleneck permits with multiple purchase opportunities and showed that such multi-period markets could achieve more efficient resource allocation than single-period markets [5]. However, this study did not cover the case in which acquired permits become unnecessary over time.

3 Method

3.1 Preliminaries

This study proposes an approach for issuing travel permits to the central business district (CBD) and allocating them through auction and personal trading. This method assumes that the value of travel permits for each user changes over time. More specifically, these users reschedule with a certain probability during the time between the auction being conducted and their actual commute the following day. For such rescheduling, we design a personal trading market for those who have no permits but need them and those who have permits but no longer need them. This section explains the algorithms and concepts used in this study in detail.

3.1.1 Deferred Acceptance Algorithm

We adopt the deferred acceptance algorithm (DA algorithm), which was proposed by Gale and Shapley in 1962 [21]. It is a matching algorithm in which two kinds of people or things rank their preferences for each other. It makes stable and optimal matching for the proposing side by declaring true preferences [22][23]. However, it has a problem that optimal stable matching is not always obtained when preference ties occur in one group [24]. The implementation of this algorithm for the auction procedure considered in this study is discussed later.

3.1.2 Travel Permits

In this study, we assume that only users with travel permits can enter the CBD during rush hours. Multiple types of permits exist per entrance and time slot. Users must pass the entrance when the permits are specified. For simplicity, we implement a square virtual city with a central location defined as the CBD. There are four entrances at the CBD corners, and all users can flow into the CBD via one of these entrances, which is a type of bottleneck. Therefore, this study focuses on the bottleneck permits allocation problem. At the entrances, pre-installed surveillance cameras identify the license plate of each vehicle and evaluate the acquisition status of the users' travel permits.

3.2 Problem Definition

This study concentrates on a problem where multiple users (hereinafter, agents) commute from a residential area in the suburbs to their respective destinations in the CBD during rush hours. All agents are distributed with the same number of dedicated coins every week, which cannot be exchanged into actual money, to guarantee equal distribution and avoid the influence of each agent's financial situation on the acquisition of travel permits. These coins are used for bidding in auctions and personal trading only, and cannot be transferred to the following week. Each agent manages the coins according to their schedule.

The primary purpose of the proposed method is to eliminate traffic congestion during rush hours by limiting the total number of vehicles. Furthermore, it aims to achieve the optimal allocation of travel permits for individual schedules under quantity restrictions. We set two evaluation axes: (1) driving and stopping time and (2) satisfaction score by travel permit allocation. The driving and stopping time was used to evaluate the congestion level. In this study, we simulate the agent commutation, and measure each agent's departure and arrival time. Furthermore, the satisfaction score is used to evaluate the agent satisfaction, defined as the matching degree between each agent schedule and the actual permit acquisition status. The details are described in Section 5.

3.3 Approach Overview

The road manager conducts a travel permit auction and adjusts the number of issued travel permits. Therefore, it is possible to change the number of issued permits based on the traffic flow of the previous day. The road manager also administrates the personal trading market of permits, which is conducted via the server of the road manager. More specifically, this server randomly matches the possible buyers and sellers. An overview of the proposed travel permit allocation mechanism is presented in Figure 1.

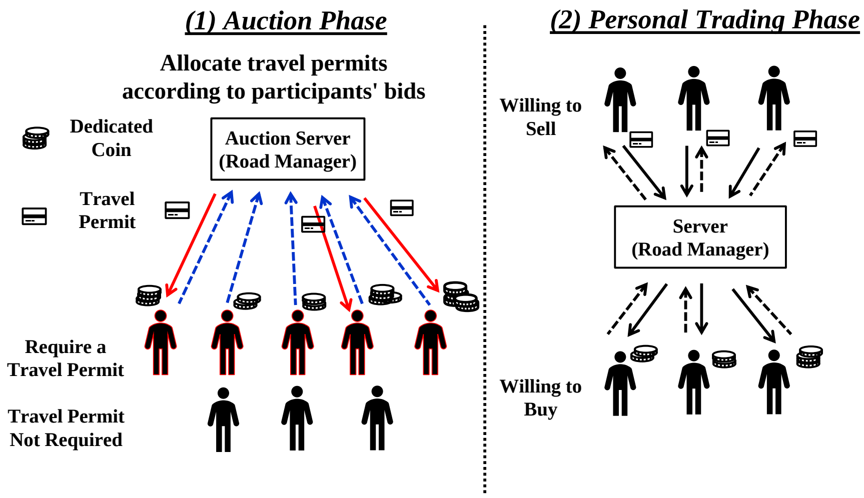

Figure 1: An overview of travel permits allocation mechanism

As shown in Figure 1, the proposed method has two phases. First, agents participate in travel permit auctions conducted daily at a fixed time (8:00 p.m., for instance). Because recurring congestion occurs mostly on weekdays, only weekdays are subject to travel permits in this study. Every auction is held one day before. Therefore, auctions are held from Sunday to Thursday each week, which determines the travel permit allocations for the next day. However, the agents reschedule dynamically, even after the auction. Thus, the road manager holds multiple travel permit markets between the auction and the starting commute.

3.4 Preparation for Auction

Before conducting an auction using the DA algorithm, it is necessary to determine the (1) agent preferences, (2) plans of bidding coins for each agent, and (3) road manager preference.

3.4.1 Agents' Preferences

The travel permit auction is a type of matching between agents and travel permits. Therefore, both sides need to present their preferences. Agents decide their preferred orders based on their policies. It is reasonable that they prefer the entrance, which shortens their travel route.

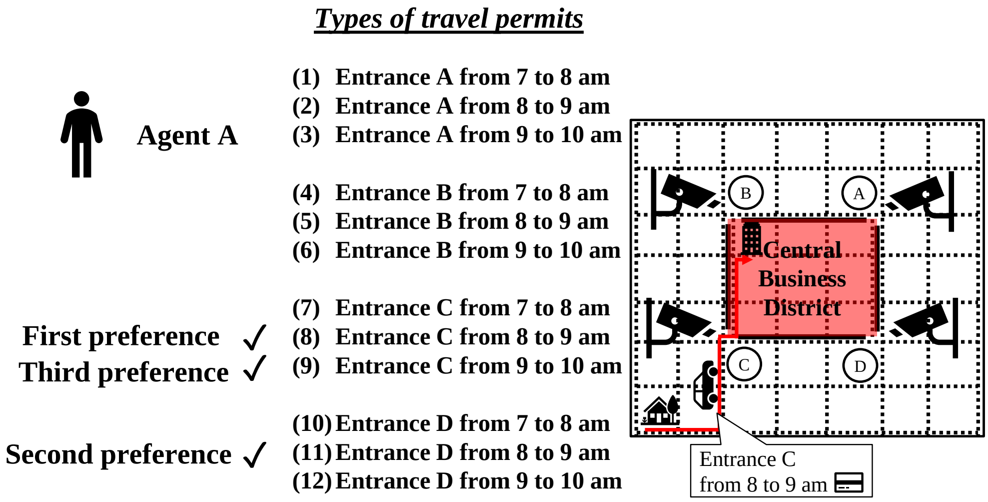

Figure 2: Example of an agent A's preference order

An example of the preference order of an agent is shown in Figure 2. Here, we assume that agents can present their first to third choices of travel permit type. Agent A's choices are (8), (11), and (9). The agent preferences are determined by their coordinates of origin and destination, and the time they want to enter the CBD.

3.4.1 Plans of Bidding Coins

All agents will make their weekly bidding plans according to their schedule and total coin amounts. In this study, the agents are assumed to have three types of schedule: (0) unnecessary (stay and work at home), (1) go to the CBD if possible, and (2) necessary to go to the CBD. For the simulation, the coin-distribution planning for the agents is calculated using Eq. (1).

$$B_i = \begin{cases} round\left(\frac{S_i}{\sum_j S_j} \times x_{coin}\right) & if \sum_j S_j \neq 0 \\ 0 & if \sum_j S_j = 0 \end{cases} \quad (1)$$

where $round(r)$ is a function that rounds a non-negative real number r to the nearest integer, S_i, $S_j \in \{0, 1, 2\}$ are the schedule weights of an agent, and indices *i* and *j* represent certain weekdays from Monday to Friday (0-4). Eq. (1) is the formula for distributing the coin B_i according to the schedule weights. x_{coin} is the total amount of coins that the agent has. If an agent receives a travel permit in an auction, they pay the same number of coins bidden at that auction. Before the auction, each agent reviews their plan and determines the number of bidden coins on that day.

3.4.2 Preference of Road Manager

The road manager ranks agents based on the corresponding number of bidden coins. A tie-break process is required in the DA algorithm when more than two agents bid for the same number of coins [25]. In this study, we adopted the simplest randomly ranked tie-breaking method. An example of the preferences of a road manager is illustrated in Figure 3.

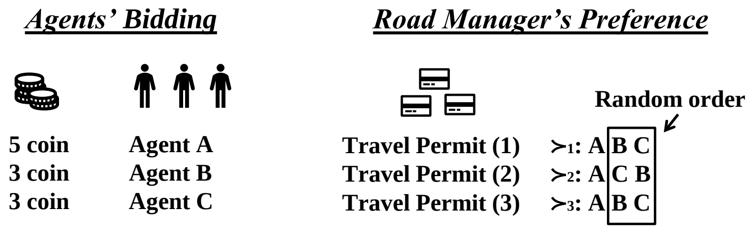

Figure 3: Example of preference order of road manager

3.5 Auction Phase

Once the agents and the road manager determine their respective preferences, the auction is conducted. The pseudocode of the auction is shown in Figure 4. First, all agents propose their most preferred travel permit in turn. All travel permits have a temporary acceptance list, the same length as the number of permits issued. Each permit accepts the agents listed in the temporary acceptance list as long as its capacity allows (Lines 6-7). When accepting an agent, the permit sorts the list according to its preference (Line 8). If the temporary acceptance list is full, the road manager compares the preference between the proposed agent and the last agent in its list (Lines 9-10). When the proposed agent is preferred to the last agent in the list, the proposed agent is replaced and registered (Lines 11-13). If replaced, the temporary acceptance list is sorted according to its preference (Line 14). In contrast, if the last agent is preferred to the proposed agent, this agent is rejected (Lines 15-16). The rejected agent will propose the second preferable permit, and this loop continues until the agent is accepted by a travel permit or rejected by all travel permits. If all travel permits reject an agent, the agent loses the right to propose. The process continues until each agent is accepted or rejected. Once all agents are accepted or have lost their right to propose, the auction is terminated, and the permit allocation is fixed.

Algorithm 1 Travel Permits Auction by DA Algorithm

```
procedure Auction (drivers, permits)
  const PREFERENCE_LENGTH, CAPACITY
  while len (drivers) > 0
    driver ← pop drivers[0]
    permit ← driver.preference[driver.rejectcount=0]
    if len (permit.list) < CAPACITY
      driver is accepted to permit.list
      sort permit.list by permit.preference
    elif len (permit.list) = CAPACITY
      compare driver with permit.list[-1]
      if driver is more preferred than permit.list[-1]
        rejectdriver ← pop permit.list[-1]
        driver is accepted and appended to permit.list
        sort permit.list by permit.preference
      else
        rejectdriver ← driver
    rejectdriver.rejectcount += 1
    if rejectdriver.rejectcount < PREFERENCE_LENGTH
      rejectdriver is appended to drivers
  for permit in permits
    for driver in permit.list
      driver.acquisition_status ← permit
      driver.coin −= driver.bidding
```

Figure 4: Pseudocode of travel permits auction by DA algorithm

3.6 Personal Trading Phase

Although an auction determines the permit allocation, agents can reschedule dynamically. This study assumes that agents continuously reschedule with a slight probability. After the auction, all agents always demonstrate their current status: (1) willing to sell, (2) willing to buy, or (3) not willing to trade. The road manager holds the personal trading market at any time if agents exist for both statuses (1) and (2). For example, when an agent with a travel permit changes their status from (3) to (1), and there exists at least one agent with status (2), the server of the road manager starts to search for the negotiation partners.

The pseudocode for personal trading is shown in Figure 5. In this method, agents with status (1) offer their permits to those with status (2). The server randomly determines negotiation partners based on each agent's status. The server randomly selects one agent of status (1) and their negotiation partners from agents of status (2) (Lines 5-6). The conditions for successful trading are: (i) the agent with status (2) can pay the same amount of coins the seller paid, and (ii) the travel permit type being sold matches the preferences of the negotiation partner (Lines 8-9). Here, the number of acceptable coins of each agent with status (2) is calculated using Eq. (1). The negotiation is repeated a certain number of times for one agent with status (1). If a trading is successful, the buyer pays the coins to the seller, and a permit is transferred from the seller to the buyer (Lines 10-13). Then, both statuses change to (3); they are unwilling to trade. However, if trading fails, the seller loses its trading chance at the market. This trading is repeated dynamically until the next morning, and the final allocation of travel permits is determined. Based on the acquired permits, agents enter the CBD at the designated entrance and time periods.

Algorithm 2 Personal Trading of Travel Permits

```
procedure Trading (status(1), status(2), permits)
 const MAX_NEGOTIATORS
 while status(1).list is empty
    n ← MAX_NEGOTIATORS
    seller ← randomly select 1 from status(1).list
    buyers ← randomly select n from status(2).list
    for buyer in buyers
       if buyer.acceptablecoins >= seller.biddingcoins and
                    seller.permit in buyer.preferences
          buyer.coin −= seller.biddingcoins
          seller.coin += seller.biddingcoins
          buyer.permit ← seller.permit
          seller.permit ← None
          break
    del seller from status(1).list
```

Figure 5: Pseudocode of personal trading of travel permits

4 Experimental Results

We evaluated the effectiveness of the proposed method using a multi-agent simulation, with Python 3.8 programming language for implementation. The evaluation axes are: (1) driving and stopping time, and (2) satisfaction score by travel permit allocation.

4.1 Traffic Simulation Specification

In this simulation, we developed a virtual city. For simplicity, we created a city with nine times nine roads laid out in a grid pattern, as shown in Figure 6. In the simulation, we defined the central 3 by 3 area as the CBD, with four entrances, namely A to D, located at its corners. The outside area was defined as a suburb. The length of one side was 225, with a total of nine roads, each of which had a length of 25. In Figure 6, all the roads look like a single track, but there exist two overlapping tracks for each road, right-to-left/left-to-right or up-to-down/down-to-up. These roads have connection information that takes direction into account.

The agents start from the suburban area and travel to their destinations in the CBD. Before applying the proposed method, the departure time was determined randomly. After applying the proposed method, the agent decides its departure time to arrive at the entrance during the time period covered by the travel permit. The agents search for the shortest route at the departure time. More specifically, the agents recognize the road that leads to their destination and first cover their departure venue. They then select one of the roads connected to the current road whose endpoint is closest to their destination and append/save the road information to their route list. This process is repeated until the last road is found, which covers the agent's destination. Because all agents can only enter the CBD through one entrance, they first head to the entrance, and then decide their direction to their destination.

Before adopting the proposed method, the agent goes through the entrance with the closest distance between the departure point and the destination. After adopting the proposed method, agents go through the entrance of the travel permits they acquire.

Traffic simulation is a cellular automaton model. Each agent advances to the coordinate in front of them for each tick while driving. Only one agent can be present in a single coordinate. Therefore, if another agent occupies a coordinate, the agent cannot move forward and remains in its current position.

In this simulation, the agents have six statuses. (1) The agent has not departed. Initially, all agents hold this status. Each agent shifts to (2) Departed when their predetermined departure time arrives. At this time, if there is another agent driving at its coordinates, the agent cannot yet depart. In this case, the agent goes to status (3) Waiting to start, and fails to move to status (4) Driving. In driving status, each agent moves forward one coordinate per tick. If another agent is in front of it, it cannot move forward and changes to status (5) Waiting due to congestion. In this status, when no other agents exist at the forward coordinates, it returns to the (4) Driving status and moves forward again. When its coordinate matches the destination, the agent arrives, and the status becomes (6) Arrived.

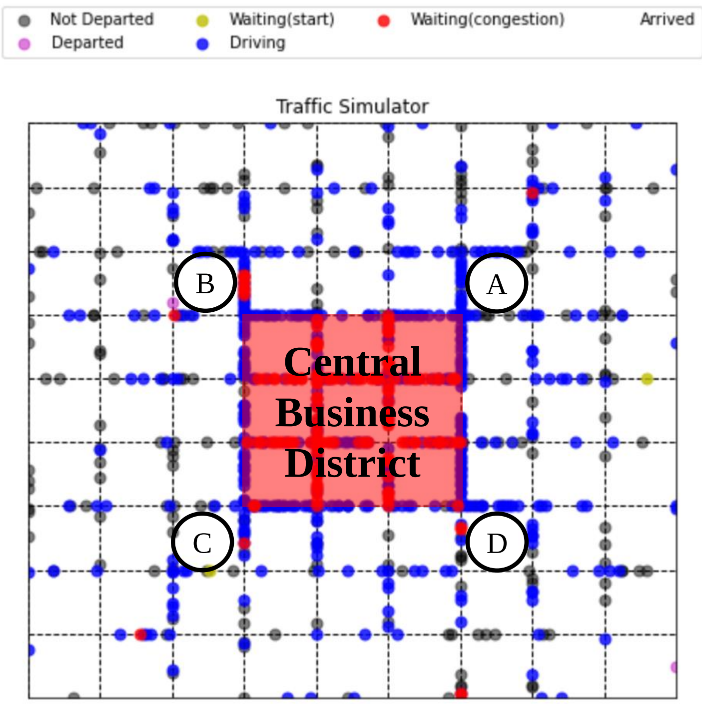

Figure 6: Animation output of simulation

One frame of the animation output is shown in Figure 6. One dot represents one agent, and the color identifies its status. In this simulation, the number of agents was integrated over time for evaluation. The driving and stopping time was calculated using Eq. (2) and (3), respectively:

$$T_{driving} = \frac{\sum_{a \in A} \sum_{t=0}^{T} n(a, s(4), t)}{|A|} \quad (2)$$

$$T_{stopping} = \frac{\sum_{a \in A} \sum_{t=0}^{T} n(a, s(3), t) + n(a, s(5), t)}{|A|} \tag{3}$$

where $T_{driving}$ and $T_{stopping}$ represent the average driving and stopping time per agent, respectively. $n(a, s(i), t)$ is 1 if agent $a \in A$ has status i at time t, and 0 otherwise.

4.2 Congestion Improvement Evaluation

The following three scenarios were compared and evaluated: (1) 50% restriction, (2) 75% restriction, and (3) no regulation. For example, a 50% restriction means that the proposed method allocates travel permits to half of the agents. The simulation results are presented in Figure 7. More than 100 simulations were performed, with average values shown on the graph, which were calculated based on Eq. (2) and (3), respectively.

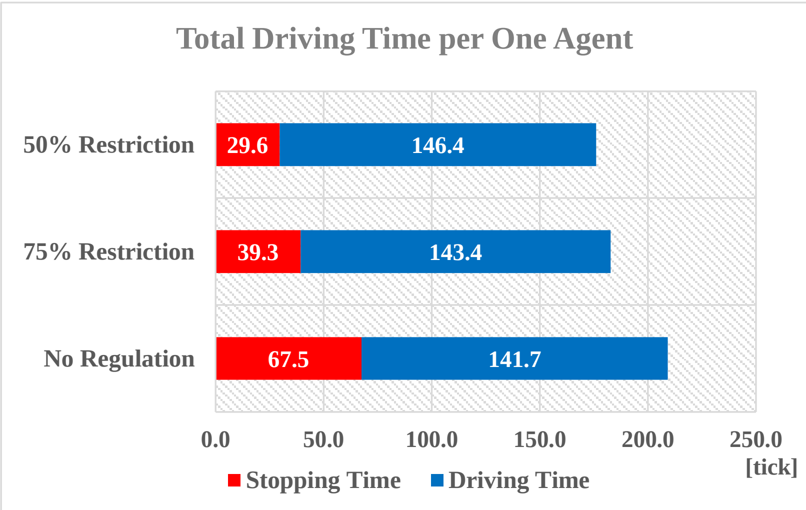

Figure 7: Simulation result about improvement in congestion

It can be observed from Figure 7 that limiting the number of permits issued to 75% of all agents reduced the stopping time to 58.2%. Similarly, by limiting the number of permits issued to 50%, the stopping time decreased to 43.8% of that in the no-regulation scenario.

The parameter settings for the simulation are listed in Table 1. In this simulation, the total number of agents was 3600, and the number of travel permit types was 12. Therefore, for example, 150 permits are issued corresponding to one permit type in the 50% restriction case.

Table 1: Simulation Setting Parameter (1)

Parameters	(1) 50% restriction	(2) 75% restriction	(3) No regulation
Number of Agents	3600	3600	3600
Total Number of Travel Permits	1800	2400	-
Total Number of Tick	800	800	800
Capacity of a Permit (*CAPACITY*)	150	200	-
Entrance Points	4	4	4
Time Frame for Travel Permits	3	3	-
Types of Travel Permits	12	12	-

4.3 Agent Satisfaction Evaluation

Subsequently, we evaluated the effectiveness of the proposed method in terms of agent satisfaction. The satisfaction score quantifies the coincidence between the agent's schedule and the travel permit acquisition status. The parameters used to calculate satisfaction scores are listed in Table 2. Schedule (1) implies going to the CBD if possible, while schedule (2) implies going to the CBD. Schedule (0), which represents unnecessary (stay and work at home), is not presented in Table 2 because it does not contribute to the satisfaction calculation. The simulation results are shown in Figure 8. The satisfaction score is the sum of all agents' satisfaction according to the setting parameters in Table 2.

Table 2: Simulation Setting Parameter (2)

Parameters	Para1	Para2	Para3	Para4	Para5	Para6
Number of Agents	3600	3600	3600	3600	3600	3600
Total Number of Travel Permits	1800	1800	1800	1800	1800	1800
Total Number of Tick	800	800	800	800	800	800
Capacity of a Permit (*CAPACITY*)	150	150	150	150	150	150
Entrance Points	4	4	4	4	4	4
Time Frame for Travel Permits	3	3	3	3	3	3
Types of Travel Permits	12	12	12	12	12	12
Number of Allocated Coins	10	10	10	10	10	10
Agents' Preference Length (*PREFERENCE_LENGTH*)	3	3	3	3	3	3
Number of Trading Available per Day	10	10	10	10	10	10
Max Negotiators (*MAX_NEGOTIATORS*)	20	20	20	20	20	20
Percentages of Schedule Change	5%	10%	15%	5%	10%	15%
Losing the appointment : Making the appointment	75:25	75:25	75:25	50:50	50:50	50:50
Satisfaction Score(schedule(2) * Acquired)	0	0	0	0	0	0
Satisfaction Score(schedule(1) * Acquired)	0	0	0	0	0	0
Satisfaction Score(schedule(2) * NOT Acquired)	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
Satisfaction Score(schedule(1) * NOT Acquired)	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2

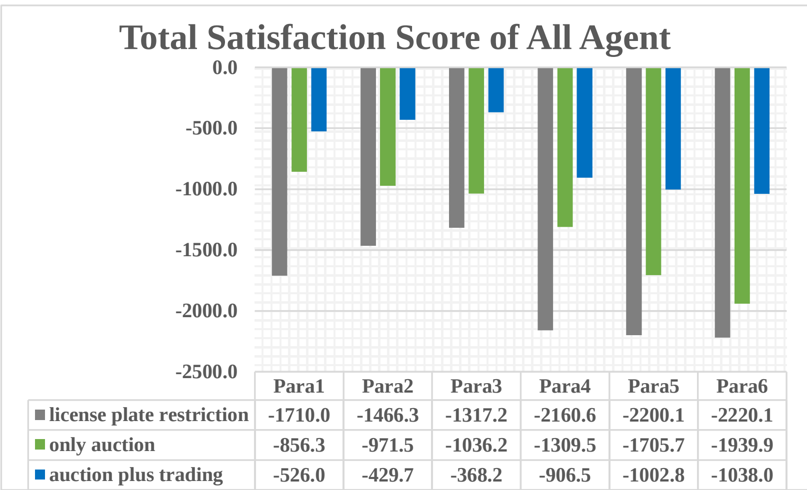

Figure 8: Simulation result about satisfaction score of total agents

The calculation formula is given as Eq.4.

$$S = \sum_{i}^{|I|} \sum_{a \in A} s_{a,i} \quad (4)$$

where S represents the total satisfaction score of all agents, index i indicates a particular weekday from Monday to Friday (0-4), and $s_{a,i}$ corresponds to the satisfaction score of an agent ($a \in A$) on day i, which is defined in Table 2.

These results differ in the percentage of schedule changes and how they change. The simulation assumes that the auction is held at 8:00 p.m., the night of one day before, and the commute starts at 7:00 a.m. the next morning. This simulation assumes a scenario where the agent's schedule changes each hour. In addition, personal trading is conducted hourly once there is a change in the agent schedule.

The parameters involved in this schedule change are (i) "the percentages of schedule change" and (ii) "Losing the appointment : Making the appointment." Parameter (ii) refers to the ratio of losing the appointment and making a new appointment. Because these two factors are difficult to measure/identify in practice, multiple values were assumed, and simulations were performed for all the selected patterns.

We describe the situation setting of parameter 1 as an example. This is the situation where the parameter (i) "the percentages of schedule change" is 5%, and (ii) "Losing the appointment : Making the appointment" is 75:25. This case could lead to 5% of all agents being rescheduled. The total number of agents was 3600, with 180 changing their schedule. Meanwhile, 75% of the agents will change their schedule to schedule (0), meaning they stay and work at home. On the other hand, 25% of the agents change their schedule to schedule (2), that is, they need to go to the CBD. When the schedule changed, the status of the agents changed to (1) willing to sell, (2) willing to buy, or (3) not willing to trade accordingly. Personal trading was conducted once the status changed, as mentioned in Section 4.

The comparisons among the three-parameter settings for evaluating the satisfaction score from parameters 1 to 6 are presented in Figure 8. The left bar represents the odd-and-even license plate restrictions. This method divides all agents into two groups: one group travels on Mondays, Wednesdays, and Fridays, and the other on Tuesdays and Thursdays. The center and right bars represent the distribution of travel permits by auction only and auction plus personal trading, respectively. The results demonstrate that the odd-and-even license plate restriction has the lowest satisfaction score in all parameter settings, followed by the auction approach. In contrast, auction plus personal trading achieved the highest satisfaction score. In this result, even though the number of travel permits issued is the same, the proposed method improves the agent satisfaction score.

Next, we investigate the effect of the difference in parameter (i) "percentages of schedule change." First, we compare parameters 1, 2, and 3, which have different percentages of schedule changes.

In the odd-and-even license plate restriction, an increase in the probability of rescheduling increases the satisfaction score. In this method, the number of travel permit holders does not change from the initial allocation. However, as the rescheduling probability increases, the number of agents who do not need travel permits increases. In other words, the number of agents who want travel permits but do not possess them, which negatively affects the satisfaction score, is relatively reduced. Therefore, the satisfaction score increases in proportion to the probability of a schedule change.

In contrast, in the "auction only" method, agents participate in the travel permit allocation auction according to their initial schedule, in which the travel permit acquisition status is determined. Therefore, an increase in the probability of rescheduling reduces the satisfaction score.

The "auction plus personal trading" results demonstrate that a higher rescheduling probability corresponds to a higher satisfaction score. This is because when the number of agents who release their travel permits due to rescheduling increases, agents who need travel permits can acquire them effectively through personal trading. Thus, a higher rescheduling probability makes the proposed method of auction plus personal trading more effective.

Finally, we evaluate the effect of the difference in parameter (ii) "Losing the appointment: Making the appointment." The difference between parameters 1 to 3 and parameters 4 to 6 is the possibility of losing the necessity of travel permits. More people release travel permits in parameters 1 to 3 due to schedule changes. For parameters 4 to 6, the satisfaction score worsens as the probability of schedule change increases for all methods. In parameters 4 to 6, the number of people in need of travel permits due to a schedule change is more extensive than in parameters 1 to 3. Even if rescheduling occurs, the number of agents who do not need the travel permit will be smaller, leading to fewer travel permits being sold. Therefore, the satisfaction score of "only auction" decreases as the rescheduling probability increases, similar to parameters 1 to 3. License plate restriction and auction plus personal trading also have lower satisfaction scores than parameters 1 to 3, regardless of the rescheduling probability. However, the "auction plus personal trading" method demonstrates the highest satisfaction score even in this case.

4.4 Change of Agent Distribution Density

We also conducted the same experiments based on skewed distribution density. In the previous simulation setting, the agents' departure points were assigned a uniform distribution; however, people's residential areas were often unevenly distributed in the actual world. Therefore, we changed the distribution density of the agents' departure points to resemble the real world. The changed distribution density of the traffic simulator is shown in Figure 9.

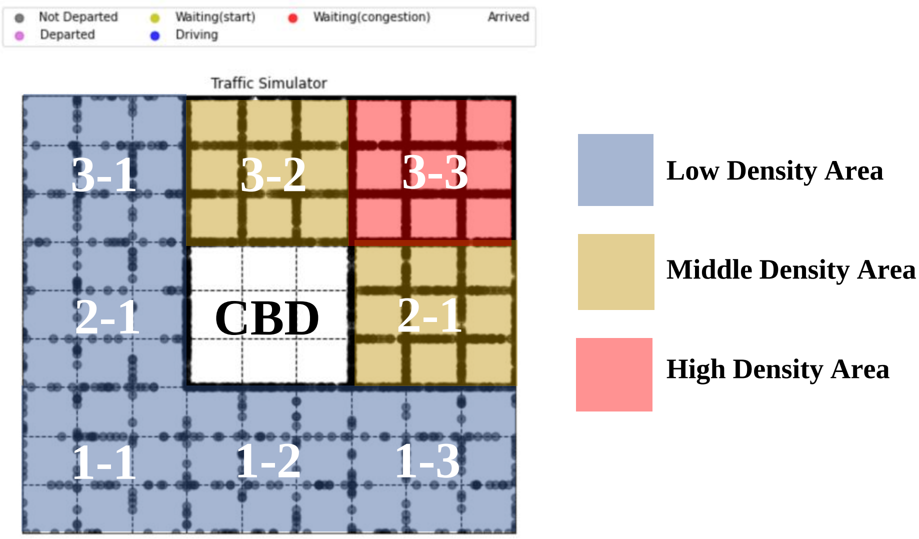

Figure 9: Unevenly distributed agents' departure point

We divided the suburban area into nine areas, as shown in Figure 9, and set 3-3 as a high-density area. The adjacent areas of 3-3 were designated as middle-density areas, and the remaining areas were low-density. In this simulation, we set the high-density area and middle-density area as twelve times and six times the number of agents, respectively, compared to the low-density area. The simulation results are shown in Figs. 10 and 11.

Figure 10 represents the stopping and driving time with Table 1 parameter settings on the skewed distribution of agents' departure points. Comparing Figure 10 with Figure 7, the stopping time increased in every case, even in the same parameter setting. We assumed that uneven agent distribution would cause more traffic congestion than a normal distribution, consequently increasing the stopping time. However, the 50% restriction reduced the stopping time to less than half of the no regulation in Figure 10; therefore, restriction by travel permit allocation reduces stopping time even when agents' departure points are unevenly distributed.

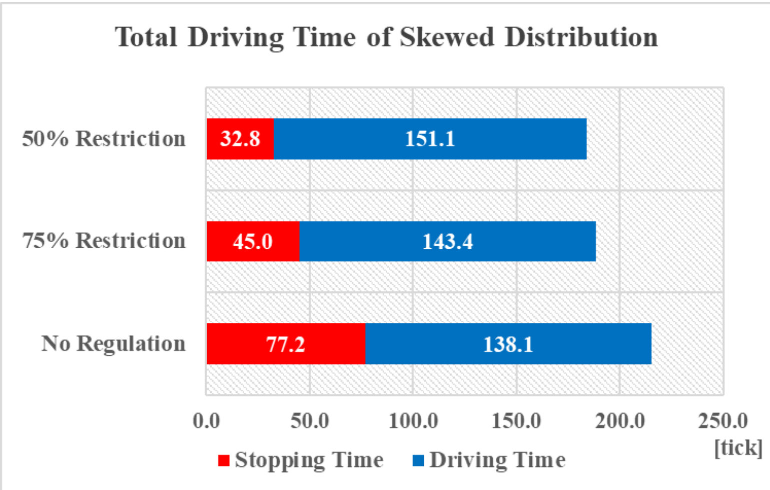

Figure 10: Simulation result about improvement in congestion on skewed distribution

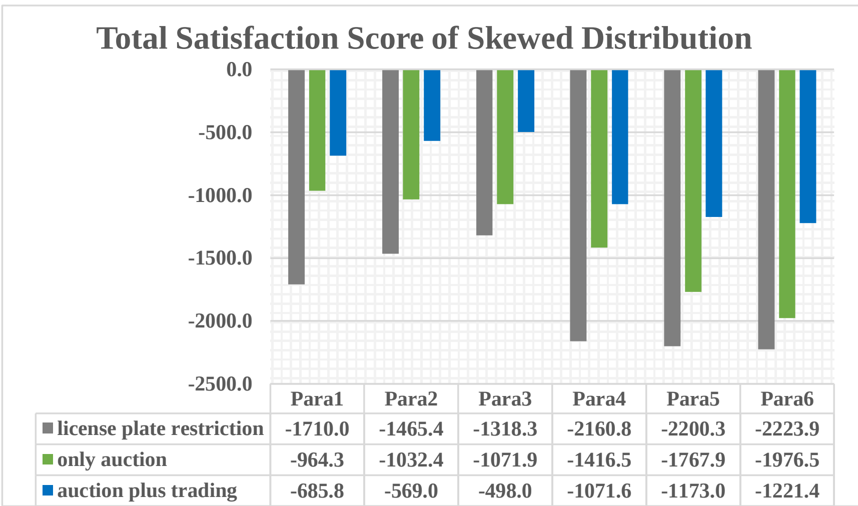

Figure 11: Simulation result about satisfaction score of total agents on skewed distribution

Figure 11 demonstrates the aggregated satisfaction score with Table 2 parameter settings on the skewed distribution of agents' departure points. Figure 11 has a similar tendency as Figure 8; on the other hand, the proposed methods have worse results in Figure 11, even though the license plate restriction has very similar values to Figure 8. This is because bidding for a particular entrance is concentrated under the proposed methods, and more agents could not acquire the travel permit. In contrast, agent distribution did not influence license plate restriction because the agents were allocated travel permits only by the license plate number. Even under this condition, the auction plus personal trading method had the highest satisfaction score compared to other methods, which shows that the proposed method is effective even when the agents' departure points are distributed unevenly.

5 Conclusion

We proposed a dynamic travel permit allocation mechanism to reduce traffic congestion in urban centers, which allocates travel permits based on the schedule of each driver while limiting the number of vehicles entering the urban center. The effectiveness of the proposed allocation mechanism was evaluated by simulating a simple virtual city. Future work will extend this method to a general network. The traffic simulator for the evaluation of traffic congestion also needs to represent an environment closer to the real world, such as an environment with actual map data or adopted traffic lights. We also believe that it would be useful to add the idea of automatic negotiation to personal trading markets and develop an algorithm to find a more appropriate number of coins to trade during each negotiation.

Our primary purpose is to propose an urban transportation system that reduces traffic congestion in urban centers and maximizes driver flexibility. The alleviation of traffic congestion could reduce economic losses and CO2 emissions. We hope that this study will maximize economic advantages, environmental sustainability, and personal benefits.

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