Citation: WANG Qian, GUO Jifu, GE Yu, LIANG Chao, XIAN Kai, DIAO Jingjing, ZHANG Lei, MA Yilin. Practice and Thoughts on Reservation Travel in Beijing Metro Stations [J]. Urban Transport of China, 2021 (1): 89–94.

Practice and Thoughts on Reservation Travel in Beijing Metro Stations

WANG Qian[1,2,3], GUO Jifu[1,2,3], GE Yu[4], LIANG Chao[4], XIAN Kai[1,2,3], DIAO Jingjing[1,2,3], ZHANG Lei[1,2,3], MA Yilin[1,2,3]

1. Beijing Transport Institute, Beijing 100073, China;
2. Beijing International Science and Technology Cooperation Base of Urban Transport, Beijing 100073, China;
3. Beijing Key Laboratory of Urban Transport Operation Simulation and Decision Support, Beijing 100073, China;
4. Beijing Municipal Commission of Transportation, Beijing 100073, China

Abstract: Excessively concentrated commuting passenger flow during peak hours presents a great challenge to urban rail transit operation and management. According to the historical passenger flow of the same period, Beijing adopted measures to limit passenger flow at several stations. During the prevention and control of COVID-19 in 2020, the high uncertainty of passenger flow makes it more difficult to manage passenger flow effectively. To acquire passenger travel demand in advance and decrease the possibility of passenger gathering while queuing, Beijing has carried out a trail of reservation at several rail transit stations, which can reduce the queuing and gathering of people outside the station caused by traditional flow restriction measures and meet the requirements of load factor control and precise traceability. In the first two pilot stations, the daily reservation users are about 6,000 during peak hours, which has helped save about 240 hours of waiting time outside the station for passengers. Practice has proved the effectiveness of the travel reservation strategy and provides experience for exploring new transportation management methods in the reservation mode. **DOI:** 10.13813/j.cn11-5141/u.2021.0107-en

Keywords: travel reservation; urban rail transit stations; passenger volume control; supply–demand balance

1 Background

Travel reservation refers to the demand-responsive travel service that serves travelers by optimizing the overall supply and demand with the help of the mobile Internet, wireless communication and other technologies in the transportation system. Drawing on the reservation modes for medical treatment, dining, parking, etc., the idea of travel reservation is to balance supply and demand to address the disorder and low-efficiency issue derived from the over-concentration of demand. Previous studies have proven through theoretical algorithms, simulation, application and practices that reservation can help balance supply and demand and improve travel efficiency. In Reference [1], a travel reservation model was constructed based on an adjustment model of congestion charges. The simulation results showed that reservation could reduce the waiting inefficiency by about 50%. In Reference [2], a comparative study was conducted on the advantages and disadvantages of the highway reservation system (HRS) and the flow control system for ramps on the basis of theoretical models. The results showed HRS was more advantageous than the flow control system for ramps. Reference [3] proposed that the reservation system could calculate vehicle locations on highways at the next instant of time based on their current locations and reserve space resources for them correspondingly. A simulation was conducted and verified that the proposed approach could significantly improve the efficiency of the transportation system. Based on the analysis of the market share for travel reservation, Reference [4] found that at least 15% of social cost during peak hours could be reduced if some autonomous vehicles made reservations before travel. In Reference [5], a bi-level optimization model for intersection rating was introduced to dynamic traffic assignment to minimize travel time, and case studies revealed that travel time could be reduced by 10% to 40% when the share of travel with reservation was 20% to 100%. Beijing Transport Institute adopted reservation to adjust the commute travel time during morning peak hours in the Huilongguan North Bridge area. It was found that each user could save 17 to 39 minutes in passing through congestion points and the transportation system could save 76 to 97 minutes for congestion on average [6]. However, these studies mainly focused on highway, parking and public transportation reservations, while the studies of applications or practices of reservation in the urban transportation system are lacking, especially for commuting passenger flows during peak hours. One of the reasons is the openness and randomness of the urban transportation system. Advanced scientific and technological achievements,

Received: 2020-06-05
First author: WANG Qian (1989–), female, from Bayan Nur of Inner Mongolia, master's degree, engineer, is mainly engaged in the research on transportation big data analysis and application as well as travel demand modeling. E-mail: wangq@bjtrc.org.cn

represented by the mobile Internet, are now applied widely in transportation. As a result, the transportation system is more controllable and information is more transparent to a certain extent, providing an opportunity for adopting travel reservation to mitigate the imbalance between supply and demand.

One of the key features of travel reservation is the refined control of passenger flow at the system level. Travel reservation can adjust demand distribution during peak hours when the demand is high, decentralize travel demand that is highly concentrated in time and space, and avoid disorder and congestion caused by excessive travel concentration. Due to its rapidness, punctuality and large capacity, urban rail transit transports a huge number of commuters during peak hours. At some stations, the instantaneous passenger flow during peak hours could even exceed the station capacity, resulting in an extreme imbalance between supply and demand. To avoid crowding on platforms and in stations, station operators usually limit the passenger flow outside stations by installing fences to control passenger density. Passengers have to queue up in long lines to exercise their rights to travel during peak hours. In 2019, there were 92 stations in the Beijing metro network that restrict passenger flow on a regular basis. Tiantongyuan Station on Line 5 is taken as an example: Around 26,000 passengers rush into the station during morning peak hours on workdays under normal conditions, severely exceeding the station capacity. The station operator has to control access to the station by installing fences outside the station and admit passengers in groups, and the average queuing time outside the station is 10 to 20 minutes. If the concept of reservation is adopted at stations that implement flow control and the passenger flow is adjusted before they arrive, the queuing outside the station can be mitigated and passengers can save massive waiting time.

During the special period of COVID-19 pandemic prevention and control, higher requirements are imposed on the density of passenger flow and the load factor of train cars, posing greater challenges to the management of metro passenger flow. On the one hand, uncertainty caused by changing situation of the pandemic has made it impossible to predict the potential increase in passenger flow demand. In the case of a surge in passenger flow, the requirements on the cross-sectional load factor will require flow restrictions outside the station, which will result in the gathering of people and will be detrimental to the pandemic prevention and control. On the other hand, passengers cannot know in advance when metro operators would implement flow restrictions or the queuing conditions outside the station. They can learn the situation only when they arrive at the station, so they can be at the risk of waiting for a long time outside the station. If travel reservation is introduced, demand can be mastered in advance and precise control of passenger flow can be realized so that transportation capacity can be arranged and passenger flow can be organized in a reasonable manner. Travel reservation not only improves passengers' travel experience but contributes to the rapid tracing for the benefit of the pandemic prevention and control. Therefore, Beijing selected the rail transit stations with large passenger flows to implement the idea of travel reservation during the period of pandemic prevention and control. In light of this practice, queuing outside stations was changed to queuing online due to reservation, which reduced the risk of people gathering outside stations.

2 System design for travel reservation in urban metro systems

To control the distribution of passenger arrivals at metro stations through travel reservation, metro station operators can rely on real-time communication and locating technologies and establish a reservation system on a scalable general-purpose cloud platform, so as to comprehensively manage travel demand and transportation resources. Travelers input their future travel demand in the reservation system before traveling. The system generates an optimized travel plan based on calculations that match supply and demand, gives feedback to travelers, and arranges the transportation capacity accordingly. For time periods and locations with concentrated travel demand, a reasonable and effective mechanism should be implemented to allocate remaining transportation capacity, or users should be encouraged to adjust their travel plans. During off-peak hours when demand is not high, flexible transportation services should be provided, including dispatching trains and arranging transportation capacity based on demand.

The difficulty in applying reservation-based access control is how to choose a reasonable management granularity for the system, namely the length of the time interval for the reservation. The length of the time interval should be able to ensure precise control of passenger flow and convenient travel. If the time interval is over short, it would be difficult for passengers to precisely control the time when they arrive at the station (hereinafter referred to as the "arrival time"), and the intended effect of reservation will therefore diminish greatly. If the time interval is over long, precisely controlling the passenger flow will be of no avail and the issue of people crowding in peak hours cannot be resolved. Therefore, the system needs to analyze passenger-flow big data across the whole urban metro network, study passenger travel behaviors and departure time, and pre-evaluate the results through simulation models. The system should also precisely manage and rationally adjust the distribution of passenger arrivals at stations and ensure passengers who have made reservations enter the station without waiting and get on the train in a safe and orderly manner, thereby enhancing passengers' travel experience.

In summary, the reservation system is mainly composed of the user platform, the data platform, the simulation platform, the optimization platform, the cloud server, the cloud database and other parts. It includes several key functional modules such as supply–demand matching, dynamic simulation, quota calculation cluster for the whole network and verification (Fig. 1). Among these key modules, the quota calculation cluster for the whole network is based on metro transportation capacity and historical number of passengers entering stations. It adopts a quota algorithm oriented to the whole network to calculate the reservation quota and dynamically adjusts the quota according to the actual passenger flow at each station. The calculated reservation quota will be updated on a regular basis to the reservation platform for quota distribution. The module of verification manages users who have made reservations by checking whether they enter stations as scheduled and sends verification information to reservation service, which provides the basis for subsequent travel records and reservation quotas.

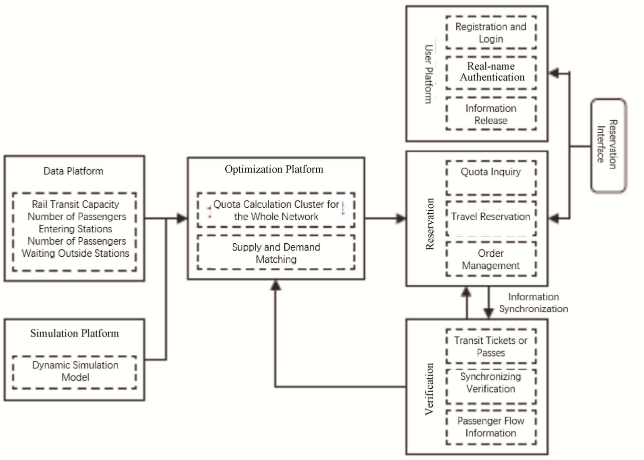

Fig. 1 Framework of travel reservation system of urban rail transit

3 Practice of travel reservation at Beijing metro stations

3.1 Selection of pilot stations

Considering the scale of passenger flow and the condition of stations that implement flow control during the pandemic, Beijing selected Shahe Station on Changping Line and Tiantongyuan Station on Line 5 as the first batch of pilot stations. The pilot study started officially on March 6, 2020. These two stations have the largest passenger entries on weekdays in the entire Beijing metro network, which is as high as 30,000 during the morning peak (6:30 am–9:30 am) and 12,000 during the peak hour. Under normal conditions, Shahe Station and Tiantongyuan Station implement passenger flow control during the morning peak, and passengers have to queue up outside the station. The queue could be as long as 500 meters and it could take passengers 10 to 20 minutes to enter the station. At the initial stage of the travel reservation, none of the Beijing metro stations had passenger flow back to pre-pandemic levels, but the passenger flow at Shahe Station and Tiantongyuan Station rebounded quickly, well above the average of the entire network. With the increase in passenger flow, these two stations are facing higher pressure on pandemic prevention.

3.2 Implementation rules

Rules were formulated before implementation based on the basic principle that these rules should ensure the smooth progress in the pilot study without interfering with passengers who do not participate in travel reservation. These rules cover time schedules and targeted population of the reservation service, allocation of reservation quota, and management of reserved entrances.

3.2.1 Time range and targeted population

Considering the passenger flow distribution during peak hours at pilot stations, the weekday morning peak was chosen to conduct the pilot study of travel reservation. From the first day of the pilot study, passengers who needed to take metro at a pilot station during weekday morning peak hours were able to make a reservation to enter the station.

Travel reservation at pilot stations was not compulsory but voluntary. Passengers who did not make a travel reservation could enter the station as normal. The elderly who are unfamiliar with smart phones and other special population groups can enter the stations to take metro through reserved entrances even if they did not make travel reservations in advance.

3.2.2 Arrangement and management of reserved entrances

Entrances exclusive to passengers with travel reservations were added at the pilot stations so that they could enter the stations without delay if arriving at the stations during reservation times. Verification devices were installed at the reserved entrance to check whether a passenger had made a reservation and whether the passenger's reservation was valid when they showed up at the reserved entrance.

According to the optimization algorithm and simulation results, as long as some passengers participate in travel reservation, the travel reservation strategy can reduce the passengers' queueing time at the system level by reasonably adjusting passengers' demand, even if there are no dedicated entrances (Fig. 2). Different types of reserved entrances were adopted on the basis of the actual condition of the pilot stations, so that their performances can be examined and the effective ones can be promoted at more stations. Shahe Station turned the entrance originally closed during peak hours into a reserved entrance, and passengers without reservations had to enter the station through other entrances. Tiantongyuan Station simply added a reserved lane at the ordinary entrance, so that passengers who had made reservations did not need to queue up along flow-control fences although they still had to enter the station through the same entrance as other passengers.

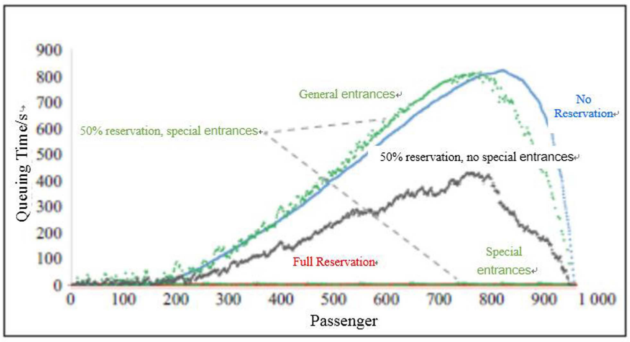

Fig. 2 Passengers' queuing time at different participation rates

3.2.3 Quota determination and allocation rules

The travel reservation system is built upon big data simulation. Its demand conditions are the total demand to enter the station during peak hours and the distribution of actual passenger entries in each time slot. Its supply conditions are the actual passenger-entry capacity of the pilot station for each time slot. The reservation system calculates the quota for the morning peak at pilot stations according to the predicted proportion of passengers who make reservations, i.e., the participation rate. It enables passengers with travel reservations to enter the station without queuing, under the premise that other passengers' entrance to the station is not affected. In the meantime, the reservation quota for each time slot is dynamically adjusted according to changes in the actual participation rate, which ensures that passengers can enter the station without delay if they arrive at the station during the reservation time.

In the pilot study, the reservation time slot was set to be 10 minutes. The system calculated the quota for each time slot of the next workday and made them available for reservation one day in advance. The granularity of the time slot represents a tradeoff between the precise control of passenger flow and the fulfillment of passengers' demand. It analyzed passengers' historical card swiping data and summarized passengers' travel patterns, including the proportion of regular passengers and the stability and flexibility of passengers' entrance time at stations. After the effects of different time granularities on controlling passenger flow were compared, the granularity of 10 minutes was finally taken as the time slot (Fig. 3).

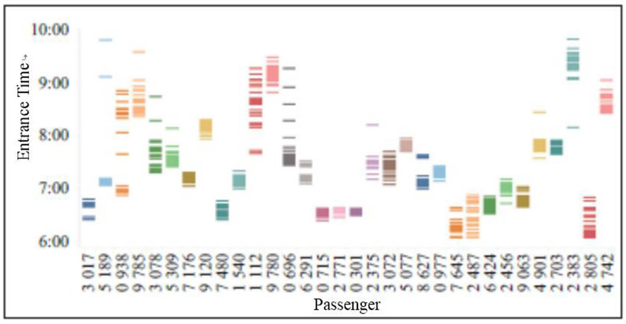

Fig. 3 Distribution of passengers' entrance time

3.2.4 Reservation channels and procedures

Passengers who need to take metro at the pilot stations during weekday morning peaks can access the reservation system by the WeChat official account, Beijing Metro App, Yitongxing App and other apps on a smartphone. In the reservation system, a passenger can check how many people can make travel reservations for each time slot and make a reservation for an available time slot. Once the reservation is successful, the system will show a QR code when the passenger is allowed to enter the station, and the QR code is limited to be used only by one person for one time. The passenger can enter the station rapidly by verifying the QR code at the dedicated reserved entrance, without being impacted by the requirement for queuing up outside the station due to passenger flow control.

Based on the big data analysis of passengers' habits of arriving at the station and passengers' acceptance, the reservation system adds 10 minutes before and after the reservation time slot as the grace period. The QR code is valid as long as the passenger arrives at the station in the grace period. For example, if a passenger has made a reservation to enter Shahe Station between 8:00 am and 8:10 am, this passenger can verify the QR code successfully and enter the station through the reserved entrance as long as arriving at Shahe Station between 7:50 am and 8:20 am. Passengers who fail to make reservations and miss the grace period are not able to enter the station through the reserved entrance. Instead, they need to queue up at other entrances to enter the station.

3.3 Simulation results and quota calculation

3.3.1 Simulation model for travel reservation

Firstly, on-site investigation and video surveillance were employed to collect relevant data from stations with passenger flow control. The data include the number of passengers arriving at the station, the number of passengers passing through the security check, and the number of passengers entering the station in different time slots on different days. Data processing and analysis were then employed to calculate the carrying capacities of platforms and trains, the capacity of security check, and the number of passengers entering the station in different time slots. The number of passengers in the queue outside the station due to passenger flow control was also calculated along with the queue length and the average waiting time.

Secondly, a simulation model for metro stations with passenger flow control was constructed according to the analysis of historical data. This model simulates the process for passengers to queue up to enter the station and compares the queuing situations in different reservation scenarios. It also verifies the effect of travel reservation at different participation rates, including no passengers making reservations, some passengers making reservations, and all passengers making reservations.

The results show that in the case that some passengers make reservations, passengers who have made reservations can save time waiting in the queue if arriving at the station during the reservation time, while the time it takes for passengers without reservations to enter the station is basically not impacted. The effect of reducing waiting time outside the station is more significant as more passengers make reservations. When 30% of passengers make reservations, the overall waiting time outside the station can be reduced by 22% and the queue length can be shortened by 23%. When 50% and 80% of passengers make reservations, the overall waiting time outside the station can be reduced by 44% and 78% respectively and the queue length can be shortened by 38% and 64% respectively (Fig. 4).

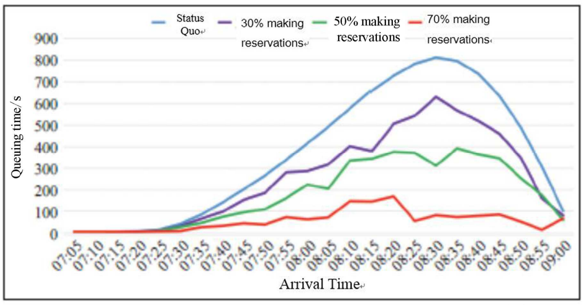

Fig. 4 Queuing time under different reservation scenarios

3.3.2 Calculation of reservation quota

Quota calculation is a process of calculating the entrance quota for different time slots to meet the requirements on the cross-sectional load factor of the metro network. The quota calculation follows three rules: maximization of system benefits, dynamic adjustment, and fairness and accessibility. The rule of maximization of system benefits means under the premise that the control objectives are met, the metro system should be utilized as much as possible so that the mobility utilities (including passenger turnover and degree of staggering passenger peaks) are maximized. The rule of dynamic adjustment indicates the reservation quota should be adjusted dynamically in light of carrying capacity of the metro system and changes in passenger demand. The rule of fairness and accessibility signifies the reservation quota should be available for each time slot and each station pair.

The process of quota calculation is to first calculate the marginal contribution of passenger entries in a unit time to the cross-sectional passenger volume on the bottleneck. The calculation of marginal contribution is based on the spatial-temporal distribution of passengers' travel demand and their selection of routes in the metro network. On the premise that the cross-sectional passenger volume on the bottleneck meets the load factor target and the utility is maximized, optimization algorithms are used to calculate flow control requirements at each station according to each station's marginal contribution to key cross-sections. The passenger entry quota for each station in a unit time can then be obtained and used to determine the reservation quota for each time slot in light of the proportion of passengers who make reservations. This proportion changes and should be used to adjust the reservation quota dynamically.

3.4 Results of the pilot study

Since the launch of the reservation service, increasing people participated in travel reservation and the reservation service has gradually gained recognition from more passengers. In less than six months, more than 68,000 users registered in the reservation system and made about 560,000 reservations. The actual number of passenger entries with reservations was 432,000, with the daily maximum of 6,604 (Fig. 5).

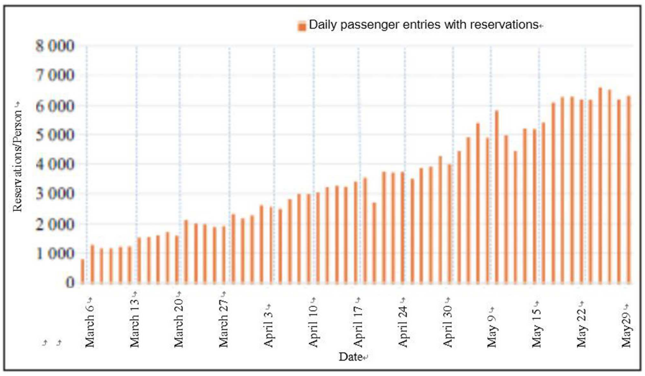

Fig. 5 Change in daily passenger loading volume under travel reservation

As the COVID-19 pandemic had been gradually put under control, the passenger entries were recovering at pilot stations. Queues emerged again outside the ordinary entrances at Shahe and Tiantongyuan stations and the queues due to passenger flow control were getting longer. As of July 2020, the average queuing time under flow control was 4 to 7 minutes during morning peak hours. In contrast, as the reservation quota was dynamically adjusted according to daily passenger flow and the capacity of reserved entrances, passengers who had made reservations could enter the station without queuing if they arrive during the reservation time. Their queuing time was therefore zero. Calculation was performed on the basis of the passenger entries with reservations in each time slot. The calculation result shows the total time saved by passengers who make reservations during peak hours at the two pilot stations is 240 hours per day. As passenger flow in the metro system continues recovering, travel reservation will play a bigger role at stations with flow control.

In an effort to verify the impact of travel reservation on individual travelers, a questionnaire was distributed through WeChat to passengers who made reservations to enter stations. A total of 750 valid responses were returned, among which 648 were from passengers at Shahe Station (86% of valid responses) and 102 were from passengers at Tiantongyuan Station (14% of valid responses).

The survey results show that most reservation users tend to enter the station during the reservation time although the

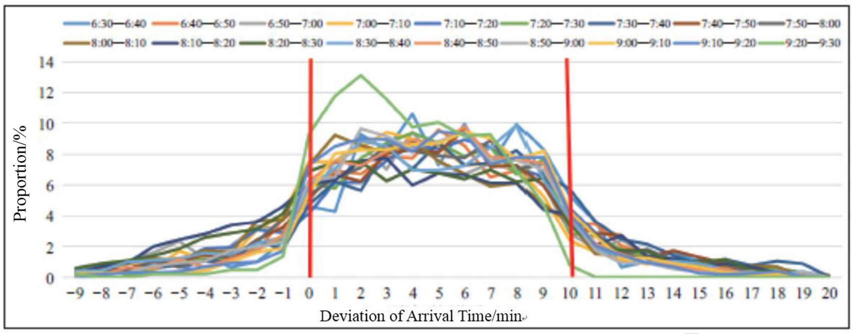

Fig. 6 Distribution of passengers' arrival time by reservation period

reservation system sets a grace period. Fig. 6 shows that the deviation of reservation users' arrival time follows a Poisson distribution. In detail, 55.7% of reservation users entered stations during their reservation times, while 20.2% entered stations within 10 minutes before their reservation times and 24.1% entered stations within 10 minutes after their reservation times. The results indicate that the selected time slot is reasonable.

After the launch of the travel reservation system, some passengers' travel habits have been changed. A comparison between passengers' travel habits before and after the launch of the travel reservation system shows that travel reservation can carefully adjust passengers' departure time and shorten the time it takes for them to enter the station. Among the respondents to the questionnaire, 42% departed later after the reservation system was launched and 77% spent less time on entering the station because travel reservations keep them from waiting in the queue. The analysis on the source of passengers who enter Shahe Station with reservations shows that 44% of them used to enter the station through other entrances before the reservation system was launched. This observation reveals that passengers are willing to change their travel habits if appropriate management approaches are adopted.

4 Conclusion

The implementation of travel reservation service in the Beijing metro system has changed the conventional and extensive management style of passenger flow control. Through refined passenger flow management, it reduces the number of passengers queuing outside the station, improves passengers' travel experience, and yields positive results. The results show that travel reservation has high recognition among passengers. Most users believe travel reservation is convenient for peak-hour travel and hope it will last. This observation further proves that travel reservation can be not only implemented during pandemic prevention and control but also used as a regular management measure for passenger flow control.

As a new type of travel service, travel reservation can precisely match supply and demand through technical means when transportation resources are limited. It is the future of transportation. In addition to metro, multiple urban transportation subsystems, such as the road system and the bus system, also face problems of uneven distribution of demand in time and space and the imbalance between supply and demand. If travel reservation could be implemented in the road system, it would improve information transparency on supply and demand and prevent traveling blindly caused by anxiety, which would decrease the capacity of the road system. The implementation of travel reservation in the bus system will facilitate the flexible arrangement of routes, stations and capacity, providing travel services at a lower cost and meeting travel needs better. The future research can explore the implementation of travel reservation in different subsystems, with the goal of gradually providing travel reservation service in the entire transportation network and for all subsystems.

With the rapid development of technologies on autonomous driving and smart roadside equipment, travel reservation will be driven by the evolvement of residents' travel habits, advancement in smart vehicles and progress in infrastructure informatization. As a result, travel reservation will be more convenient, integrated into daily life better, and much easier; it will gradually become the new normal. Under this trend, the study of travel reservation could be deepened from multiple aspects, such as technical research and standard formulation. In addition, the scope of travel reservation can be expanded further and travel reservation service can be provided in more scenarios so that the acceptance level of travel reservation can be improved continuously. With the help of travel reservation, how to engage passengers more widely in transportation governance should be explored for the purpose of promoting orderly transformation of the transportation system.

References

[1] Koolstra K. Potential Benefits of a Freeway Slot-Reservation System: Queuing Costs Versus Scheduling Costs [C]//Urban Transport Systems Conference, Lund, Sweden, June 7–8, 1999.

[2] Edara P, TeodorovićD. Model of an AdvanceBooking System for Highway Trips [J]. Transportation Research Part C: Emerging Technologies, 2008, 16 (1): 36–53.

[3] Chai Rong, Tang Lun, Xiao Min, et al. Dynamic Resource Reservation in High-Speed Transportation Communication System [J]telecommunications science, 2009, 25 (10): 48–51 (in Chinese).
[4] Lamotte R, de Palma A, Geroliminis N. On the Use of Reservation-Based Autonomous Vehicles for Demand Management [J]. Transportation research Part B: Methodological, 201799: 205–227.
[5] Patel R, Venkatraman P, Boyles S D. Optimal Placement of Reservation-Based Intersections in Urban Networks [J]. Transportation Research Record Journal of the Transportation Research Board, 2019, 2673 (1): 781–792.

(Translated by WANG Q)

