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Modeling the joint choice behavior of commuters' travel mode and parking options for private autonomous vehicles

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A B S T R A C T

Difficulty in finding parking spaces and high parking fees discourage private car usage. Fully autonomous vehicles (AVs) capable of self-parking away from destinations will likely remove this barrier. Despite extensive survey-based research on AVs in recent years, existing literature has not sufficiently addressed the potential impact of new parking options on the demand for these vehicles. This study explores commuters' joint choice of travel mode and parking for private autonomous vehicles (PAVs). To this end, a stated choice (SC) experiment was designed and deployed in the city of Beijing, China. Attitudinal statements were also designed to measure four latent variables: perceived ease of use, perceived usefulness, perceived safety, and attitude toward waiting. Using a hybrid choice model framework, the estimation results reveal that the choice of letting the PAV self-park at a non-destination location is significantly influenced by the location of such parking, the potential delay in re-taking the vehicle, and the fuel/energy consumption to and from the non-destination parking place. Attitudes toward AVs also play a crucial role, with perceived safety and perceived usefulness having the greatest impact. Our results can help managers and planners understand how PAVs affect people's travel mode choices and the corresponding parking options and assist them in developing strategies in preparation for the widespread use of AVs.

1. Introduction

Autonomous vehicles (AVs) are expected to become available in our transportation system in the foreseeable future (Nieuwenhuijsen et al., 2018). Currently, automakers such as Tesla, Mercedes-Benz, Volkswagen, BMW, Hyundai, and Toyota, as well as IT companies like Google, Apple, and Baidu are developing and testing AVs. For instance, the Apollo autonomous car, developed by Baidu Inc., has been tested for more than 60 million kilometers on real roads in more than 30 cities in China, including Beijing (Apollo, 2023). Therefore, it is crucial to explore people's mode choice behavior regarding these vehicles and understand the significance of their unique characteristics.

Nowadays, travelers in downtown areas of big cities often encounter difficulties in finding available parking spaces and face high

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parking fees when driving private cars due to limited and expensive parking land supplies (Yan et al., 2020). Taking Beijing as an example, the number of motor vehicles is 6.85 million (Beijing Municipal Bureau of Statistics, 2022), and the total number of parking spaces in the city is only 4.27 million (Beijing Municipal Commission of Transport, 2017), with a gap of 2.58 million. There is a serious imbalance between the supply and demand of parking spaces. These parking-related issues greatly limit people's driving and prompt them to choose other modes to travel, such as public transport (Okeke, 2020; Rotaris and Danielis, 2014; Van Exel and Rietveld, 2009), which is indeed positive in terms of sustainability. However, in the context of vehicle automation, particularly full automation (Level 5 under the SAE classification system, SAE International, 2021), which does not require a human to be inside a vehicle, the benefits it brings in terms of parking might become the turning point that leads to a significant shift in demand from public transport to private cars.

Private autonomous vehicles (PAVs), which in this paper will be Level 5 vehicles, can drop off their owners at their trip destination and then self-park at an available parking space, regardless of the distance from the destination. In contrast, drivers of private conventional cars must first drive to a parking spot and then walk or use other modes of transportation to reach their destination. Parking fees in farther locations can potentially be cheaper than those right next to the trip destination (Correia and van Arem, 2016; Liu, 2018). As a result, PAVs can, in principle, relieve the pressure on finding a parking space that stresses many drivers today, provide lower parking costs, and eliminate the need to walk between the parking place and the destination.

Considering that parking costs and parking-related issues have been found to significantly influence people's choice of travel mode (Evangelinos et al., 2018; Rotaris and Danielis, 2014; Van Exel and Rietveld, 2009; Washbrook et al., 2006), the emergence of PAVs may attract travelers from sustainable travel modes, such as public transport. This shift could potentially exacerbate traffic congestion and energy consumption, which is risky for sustainable development and should not be overlooked. Additionally, it may reshape urban parking because, on the one hand, it will increase the parking demand for those who shift to travel by PAVs from non-driving travel modes, and on the other hand, those who regularly travel by driving may also change their parking locations.

Because AVs have not yet been widely popularized in the market, survey-based research on AVs has grown tremendously in recent years, with individuals' opinions and perceptions of AVs and their willingness to use/purchase AVs being two of the most prevalent research topics (Gkartzonikas and Gkritza, 2019). However, studies on travel mode choice that include PAVs have instead received considerably less attention. Remarkably, these studies have rarely considered the unique parking characteristics of PAVs in the survey, except for a notable one, which may result in a biased estimated share of PAV users compared to what may occur in the future.

Haboucha et al. (2017) set the parking cost of the PAV mode not higher than that of the private conventional car in the stated choice (SC) experiment design in order to express the potential savings. They also included a statement related to how AVs can make people's life easier by eliminating the need to search for parking, measuring the so-called Pro-AVs attitude. However, they did not explicitly explain to the respondents that the lower parking cost of PAV was the result of its ability to park at locations other than the destination. In addition, they did not consider the uncertainty regarding any potential delay in getting the vehicle back for another trip. In fact, vehicles in dense urban areas may, with a very high probability, encounter traffic jams on the way to pick up passengers. And this delay may impact people's decision regarding whether to allow the PAV to self-park elsewhere away from the destination and, if they choose to do so, where to let it park. Also ignored was the fuel/energy cost for traveling to and returning from farther parking places. We believe that the trade-off between the parking cost (decreasing with the distance) and the relocation cost (increasing with the distance) cannot be neglected, and it may have a very strong effect on how land use and transportation will be tuned in the future.

Moreover, only a very limited number of studies have explored the parking choice behavior of AVs, and these studies solely focused on parking choices without considering the mode choice. Similarly, these studies did not account for the potential delay in re-taking the AV if it was self-parked far away from the destination.

Therefore, given the importance of parking behavior in the mode choice of PAVs versus normal cars and the fact that it has hardly been addressed in the literature, it is critical to better understand the unique parking advantages of PAVs since these can potentially change the utility of using private cars and attract travelers from sustainable transportation modes. We argue that since the parking cost of PAVs is related to their parking location, the travel mode choice of PAVs and the corresponding parking option choice should be studied jointly. Moreover, the potential delay in re-taking the vehicle and the fuel/energy cost to and from the parking location to the destination for PAV self-parking elsewhere from the destination should also be considered in the parking choice model.

Consequently, in this study, we propose a SC experiment to collect data on the joint choice behavior of commuters' travel mode and parking options. Data were collected in Beijing, China. The following are the main contributions of our paper:

- We design a novel experiment that considers the unique parking characteristics of PAVs in the joint choice behavior of travel mode and parking options, taking into account the coexistence of conventional travel modes and the PAV.
- We propose perceived safety and attitude toward waiting, combined with the Technology Acceptance Model (TAM), to measure commuters' attitudes toward PAVs and their distinctive parking characteristics.
- We analyze the trade-off between saving parking costs and experiencing potential delays in re-taking the vehicle for travelers who choose to let the PAV self-park away from the destination.
- We provide policy recommendations for managers and planners, such as formulating road charging policies and redesigning parking pricing and parking space layout.

The remainder of this paper is organized as follows: In Section 2, we review research findings on the travel mode choice of PAVs and the parking choice of AVs. In Section 3, we introduce the survey and describe the data collected. In Section 4, we present the model specification. In Section 5, we discuss the results of the model estimation and analyze the relative impact of the level-of-service attributes on the joint choice preference of PAVs. Finally, in Section 6, we conclude the paper and provide relevant policy insights.

Table 1
Previous studies on travel mode choice with the private autonomous vehicle in the choice set.

Authors	Study area	Choice set	Level-of-service variables	Socio-demographics	Attitude variables	Travel purpose	Models
Yap et al. (2016)	The Netherlands	PCV, PAV, SAV, walk, bike	Travel time, travel cost, waiting time	Age, gender, income	Included	Last mile of train trips	Hybrid choice model
Haboucha et al. (2017)	United States, Canada, Israel	PCV, PAV, SAV	Travel time, travel cost, parking cost, purchase/subscription cost	Age, gender, education level, number of children	Included	Commuting	Nested logit kernel model
Steck et al. (2018)	Germany	PAV, SAV, PT, walk, bike	Travel time, travel cost, waiting time, access time, ridesharing	Age, income, driving license, PT pass	Not included	Commuting	Mixed logit model
Correia et al., 2019	The Netherland	PCV, PAV	Travel time, travel cost, walking time, travel companions, in-vehicle activity	Age, gender, income, education level, driving license, daily business, car ownership	Included	Commuting	Hybrid choice model
Stoiber et al. (2019)	Switzerland	PAV, automated taxi, automated PT	Travel time, travel cost, waiting time, walking distance, ridesharing, level of reliability	Age, gender, income, PT pass, car ownership	Not included	Leisure (50 km)	Generalized estimating equation ordinal logistic model
Kolarova et al. (2019)	Germany	PCV, PAV, SAV, PT, walk, bike	Travel time, travel cost, waiting time, access/egress time, ridesharing	Income, driving license, PT pass	Not included	Commuting, leisure/shopping	Mixed logit model
Saeed et al. (2020)	United States	PCV, PAV, SAV, hired AV service	Not included	Age, gender, education level, family size, retirement	Included	Not mention	Mixed logit model
Kolarova and Cherchi, (2021)	Germany	PAV, SAV, PT, walk, bike	Travel time, travel cost, waiting time, access/egress time, ridesharing	Age, gender, education level, PT pass, experience with ADAS	Included	Commuting	Hybrid choice model
Jabbari et al. (2022)	United States	PCV, PAV, SAV, ride-hailing, PT, walk, bike	Travel time, travel cost, waiting time, parking fee, monthly car payment	Age, gender, income	Included	A trip during one workday	Hybrid choice model

Note: PCV = Private conventional vehicle, PAV = Private autonomous vehicle, SAV = Shared autonomous vehicle, PT = Public transport, AV = Automated vehicle, ADAS = Advanced Driving Assistance System.

2. Literature review

In this section, we review the literature on the travel mode choice behavior of PAVs and parking choice behavior of AVs, respectively, to summarize the major findings and identify the specific research gaps.

2.1. Studies on travel mode choice behavior of PAVs

Table 1 provides a summary of previous studies on travel mode choice that include PAVs in the choice set. From Table 1, we can see that most of the previous studies considered the coexistence of conventional vehicles (CVs) and PAVs (Correia et al., 2019; Haboucha et al., 2017; Jabbari et al., 2022; Kolarova et al., 2019; Pudāne and Correia, 2020; Saeed et al., 2020; Yap et al., 2016). Notably, almost all of these studies focused on Western countries, such as the United States and several European countries, while developing countries have received far less attention.

Regarding the factors considered in these studies, most have included the level-of-service attributes of the travel modes and socioeconomic characteristics of the respondents. Some have also examined the influence of attitudinal factors on travel mode choice, finding that people's attitudes significantly affect their travel mode choice. However, except for Haboucha et al. (2017), which has been mentioned in the introduction, other studies have seldom taken into account the distinctive parking characteristics of PAVs.

2.2. Studies on parking choice behavior of AVs

In terms of SC research on the parking choice behavior of AVs, we have found only two very recent works, both of which only studied the parking choice and did not consider the mode choice. Jia et al. (2022) explored current private car drivers' parking relocation preferences for PAVs after the vehicle delivers the passenger to the destination, using an SC experiment conducted in Seattle and Kansas City in the United States. The experiment included three alternatives: parking at the destination, relocating the vehicle to park elsewhere with a lower parking fee, and an opt-out option of sending the vehicle to another family member. Two attributes, parking cost and relocation time, were considered. After completing the SC experiment, respondents were asked whether they had considered the relocation fuel/energy cost in their decision-making. The results show that the parking relocation will induce empty vehicle miles traveled in both cities, and the awareness of the relocation fuel/energy cost can lower the willingness to relocate the PAV for respondents in Seattle. However, for respondents in Kansas City, this effect was found to be statistically insignificant. This study only considers the choice of parking but not the choice of PAV versus a normal car, and this study did not consider the potential delay in re-taking the PAV if it was self-parked far away from the destination. Such delay may impact people's decision to relocate their car and, if they choose to relocate, where to relocate it. Simultaneously, the fuel/energy cost of traveling to and from the parking place should also be included in the total parking cost of the alternative of relocating the PAV to park elsewhere because this fuel/energy consumption can be easily estimated by the vehicle, and it may also affect people's choice of parking option for PAVs.

Ye et al. (2022) used SC experiments to study the parking choice behavior of SAVs conducted in China. They asked respondents' parking choice of SAVs based on travel times and parking durations. The experiment included five parking alternatives: cruising on the road, serving other passengers, nearby parking, peripheral parking, and returning to the origin. To describe these alternatives, the study considered travel time, parking duration, travel cost, parking fee (applied to nearby parking, peripheral parking, and returning to the origin), cruising cost (only applied to cruising on the road), waiting time (only applied to serving other passengers), and traffic emissions (expressed by impact degree). The study design set higher travel costs for peripheral parking and returning to the origin than nearby parking to reflect the fuel or energy expenses associated with traveling to and from non-nearby parking locations. The results revealed that during long-term parking, travelers tend to prefer having the SAV serve other passengers. However, for short-term parking, they are more inclined to choose peripheral parking or cruising on the road. It's worth noting that this study also did not study the mode choice but only the parking choice, and did not account for potential delay in re-taking the vehicle when it was parked far from the destination. This delay could significantly impact travelers' SAV parking choices because they would need to wait for the vehicle to pick them up for the next trip and the waiting time has been identified as a crucial factor influencing the usage of SAVs (Krueger et al., 2016).

3. Stated choice experiment

The SC experiment consists of a joint choice of the commuting mode choice and the corresponding parking option choice. To ensure realism, in addition to PAVs, shared bikes, public transport, and private conventional cars were included in the experiment. We did not include private bikes because incorporating one's personal bicycle into the experiment would limit the sample to those who actually own a bike. In contrast, shared bicycles are accessible to a broader range of individuals, and we believe that commuters who frequently use shared bicycles are more likely to be affected by AVs than those who use private bicycles. This is because regular private bicycle users do not incur usage fees, except for the initial purchase cost, while shared bicycles require payment during use. Last not least, Beijing witnessed a significant increase in the proportion of bike trips (from 9.4% in 2014 to over 17% in 2022) which has been attributed to the emergence of shared bikes (China City News, 2023). We assume that if the respondent chooses to commute by private conventional cars, he/she needs to park the vehicle at or near the workplace, which serves as the destination for the commuting trip. In the case of PAVs, the respondent can let the vehicle self-park either at or near the workplace, or away from the workplace. However, we did not include cruising as an optional parking choice for PAVs in our study. This decision is based on our study's specific focus on commuting trips, as opposed to journeys involving shorter stays at the destination, such as leisure, shopping, and other activities. It also takes into account the typical work patterns in China, where the majority of individuals with full-time jobs work on-site for eight hours or more. An 8-h cruising duration is somewhat unrealistic and quantifying the fuel/energy consumption costs for such an extended period of cruising presents significant challenges. Additionally, if a commuter allows his/her PAV to cruise on the road after reaching the workplace, this prolonged cruising period could result in substantial fuel/energy consumption and potentially worsen traffic congestion. Therefore, our experiment provided respondents with five alternatives: shared bike (BIKE), public transport (PT), private conventional car with parking at the workplace or nearby (CAR), private autonomous vehicle with self-parking at the workplace or nearby (PAV1), and private autonomous vehicle with self-parking away from the workplace (PAV2).

3.1. *Attributes in the stated choice experiment*

Eight attributes were identified based on an extensive literature review and three focus groups conducted between June and July 2022 in Beijing, China, with each group consisting of five to ten participants. These attributes include four classic level-of-service attributes (travel time, travel cost, waiting time, and walking distance) and four parking-related attributes specifically designed for private conventional cars and PAVs (parking cost, time to find a parking place, distance of the parking space, and delays). Specifically, travel time and travel cost were included in all five alternatives. Waiting time and walking distance to and from transit stops were considered for the public transport alternative. The walking distance between the parking place and the workplace (destination) was instead taken into account for the private conventional car alternative since these commuters typically need to park their cars first and then walk to the workplace. Previous studies have shown that walking distance influences drivers' parking location choices (Harmatuck, 2007; Hunt and Teply, 1993).

Regarding the attributes designed for private conventional car and PAVs, the parking cost reflects the price charged for staying parked at the parking place and was included in the private conventional car alternative and the "PAV with self-parking at the workplace or nearby" alternative. However, for the "PAV with self-parking away from the workplace" alternative, whose parking location is away from the workplace, its parking cost includes both the charge for staying parked at the parking place and the fuel/energy cost for traveling to and from the parking place to the workplace. The time to find a parking place measures the difficulty of

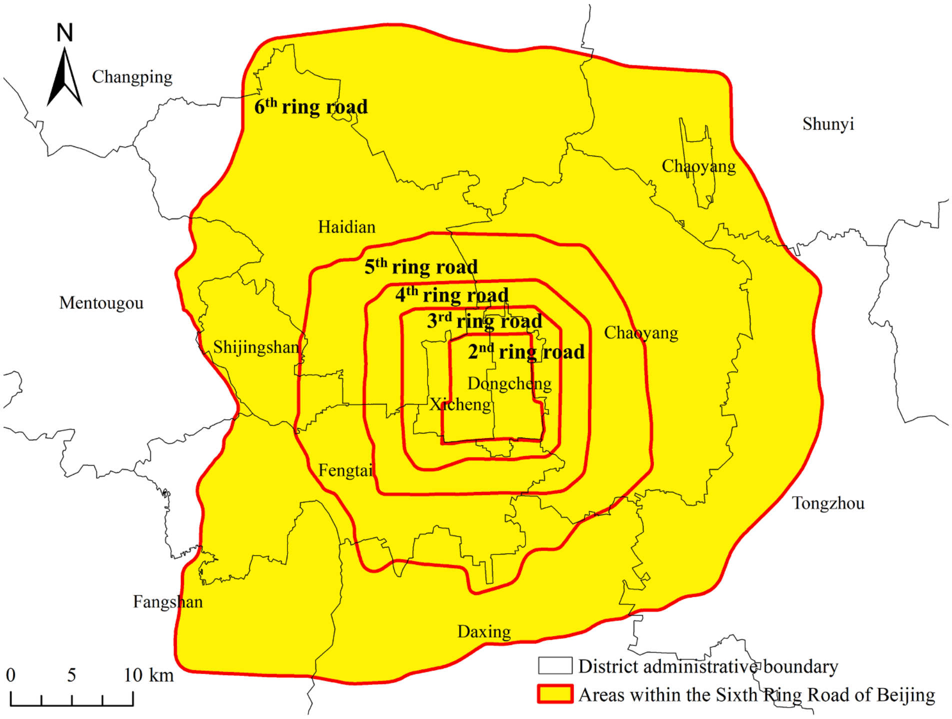


Fig. 1. Ring roads in Beijing.

finding an available parking space at or near the workplace for the private conventional car alternative. The distance of the non-destination parking space from the workplace indicates the location of the non-destination parking place for the "PAV with self-parking away from the workplace" alternative. Some participants in the focus groups expressed their concern about the non-destination parking location. For instance, one person mentioned worries about potential accidents during the process of the PAV self-parking or returning to pick up if it is parked far away. Finally, the delays in picking up the owner after work for the "PAV with self-parking away from the workplace" alternative, capture the potential uncertainty in re-taking the vehicle if it self-parks away from the workplace. Several participants during the focus groups raised concerns about letting the car self-park elsewhere. For example, two participants mentioned that although they were aware they could call the PAV in advance to pick them up before they finished work if the vehicle self-parked at a distant location, it might encounter traffic jams on the way to pick them up, resulting in long waiting times.

Due to the potentially harmful impact of hypothetical bias commonly observed in SC experiments, particularly when testing innovations (Yin and Cherchi, 2022), and considering that PAVs, with their distinctive parking features, are relatively unfamiliar to respondents, we opted to offer respondents a tailored SC experiment.

More explicitly, based on the literature review and the focus groups, we considered four types of commuting trip distances in the SC experiment design: trips of less than 10 km, 10–20 km, 21–30 km, and longer than 30 km. For each length of commuting trip, we provided separate designs. We did not include the shared bike as an available alternative for commuting trips of 10 km or more, as long-distance rides on shared bikes are physically demanding and uncommon for commuting purposes.

We provided two designs for those who travel to work during the peak time and those who travel outside the peak time. We also built two different designs for individuals who have a driving license, have and can use a private car to commute, and for those who cannot use a private vehicle to commute, in order to improve the realism of the experiment. In addition, considering that the unit price of motor vehicle parking charges is generally influenced by the parking location, taking the unit hourly parking prices charged on the curbside or on public parking lots in Beijing as an example, the parking fee for areas within the third ring road is approximately 10 CNY per hour. In the area between the third ring road and the fifth ring road, the parking fee is about 6 CNY per hour, while outside the fifth ring road, it decreases to approximately 2 CNY per hour (the schematic diagram of ring roads in Beijing is depicted in Fig. 1). We set up three designs according to the location of the respondents' workplaces and the area classification of parking charges in Beijing.

From the focus groups, we also learned that the waiting time for Beijing metro passengers and bus passengers differs somewhat because buses generally have less frequent service than the metro and are more likely to be affected by road traffic conditions. Therefore, we have also developed two designs for individuals who actually or conveniently commute by metro and those who actually or conveniently commute by bus or "bus + metro." As a result, there are a total of 96 segments (4 commuting distances $\times$ 2 peak/off-peak times $\times$ 2 private car availability $\times$ 3 workplace locations $\times$ 2 waiting times for public transport) in the SC designs.

For each of the four commuting trip distances considered in the SC experiment, we selected three typical commuting corridors in Beijing as reference and calculated the average value of travel time, travel cost, and walking distance for each travel mode (shared bike, public transport, and private conventional car) as benchmark values with the help of Gaode Map API. These benchmark values

Table 2
Levels of attributes used in experiments.

Attributes	Alternatives	Segment	Attribute levels			
			<10 km	10–20 km	21–30 km	>30 km
Travel time in vehicle/bike (min)	BIKE	In peak	25/40/55	–	–	–
		Off-peak	25/40/55	–	–	–
	PT	In peak	30/50/70	40/65/90	50/80/110	60/100/140
		Off-peak	30/45/65	35/60/85	45/75/105	55/90/125
	CAR	In peak	15/20/30	20/30/45	30/50/70	45/70/100
		Off-peak	10/15/20	15/25/35	25/40/55	35/55/75
	PAV1, PAV2	In peak and with private car availability	15/20/25/30	20/30/35/40/45	30/35/45/50/55/65/70	45/50/65/70/80/90/100
		Off-peak and with private car availability	10/15/20	15/25/35	25/40/55	35/55/75
	PAV1, PAV2	In peak and without private car availability	15/20/30	20/30/45	30/50/70	45/70/100
		Off-peak and without private car availability	10/15/20	15/25/35	25/40/55	35/55/75
Travel cost in vehicle/bike (CNY)	BIKE		2/3/4	–	–	–
	PT		2/4/6	3/5/7	4/7/10	5/8/11
	CAR		2/3/4	4/7/10	8/14/20	12/20/28
	PAV1, PAV2		2/4/6	6/10/14	12/20/28	17/28/39
Waiting time (min)	PT	Actual or accessible bus and "bus + metro" commuter, in peak	4/9/14			
		Actual or accessible bus and "bus + metro" commuter, off-peak	7/12/17			
		Actual or accessible metro commuter	2/6/10			
Walking distance to and from transit stops or the vehicle (m)	PT		300/600/1000	300/700/1200	300/800/1400	300/900/1600
	CAR		100/300/500/1000			
Time to find a parking space (min)	CAR		5/10/20			
Distance of the non-destination parking space (km)	PAV2		2/6			
Parking cost of accessing and staying parked (CNY)	CAR, PAV1	Workplace located within the 3rd ring road	25/36/47			
		Workplace located between 3rd to 5th ring road	17/24/31			
		Workplace located outside the 5th ring road	8/12/16			
	PAV2	Workplace located within the 3rd ring road and PAV self-parks 2 km away	If CAR/PAV1 = 25, PAV2 = 9/20; If CAR/PAV1 = 36, PAV2 = 11/27; If CAR/PAV1 = 47, PAV2 = 13/34			
		Workplace located within the 3rd ring road and PAV self-parks 6 km away	If CAR/PAV1 = 25, PAV2 = 11/16; If CAR/PAV1 = 36, PAV2 = 12/20; If CAR/PAV1 = 47, PAV2 = 13/24			
		Workplace located between 3rd to 5th ring road and PAV self-parks 2 km away	If CAR/PAV1 = 17, PAV2 = 6/12; If CAR/PAV1 = 24, PAV2 = 7/15; If CAR/PAV1 = 31, PAV2 = 8/19			
		Workplace located between 3rd to 5th ring road and PAV self-parks 6 km away	If CAR/PAV1 = 17, PAV2 = 9/12; If CAR/PAV1 = 24, PAV2 = 10/14; If CAR/PAV1 = 31, PAV2 = 11/16			
		Workplace located outside the 5th ring road and PAV self-parks 2 km away	If CAR/PAV1 = 8, PAV2 = 4/6; If CAR/PAV1 = 12, PAV2 = 4/7; If CAR/PAV1 = 16, PAV2 = 5/8			
		Workplace located outside the 5th ring road and PAV self-parks 6 km away	If CAR/PAV1 = 12, PAV2 = 9/10; If CAR/PAV1 = 16, PAV2 = 9/11			
Delays in picking you up after getting off work (min)	PAV2	PAV self-parks 2 km away	0/5/10			
		PAV self-parks 6 km away	0/5/10/15			

Note: BIKE = shared bike, PT = public transport, CAR = private conventional car with parking at the workplace or nearby, PAV1 = private autonomous vehicle with self-parking at the workplace or nearby, PAV2 = private autonomous vehicle with self-parking away from the workplace. The dash "–" indicates the attribute does not take values in this travel scenario.
CNY = Chinese Yuan, the currency unit of China; 1 CNY = 0.133 Euro = 0.145 US dollars in April 2023.

were used to differentiate the attribute levels. It is important to mention that the travel time for each mode was collected separately during peak time and outside peak time. The Gaode Map is a popularly used map search engine in China, similar to Google Maps.

Since PAVs are not yet available on the market, we used a generic design to set the difference in travel time between private

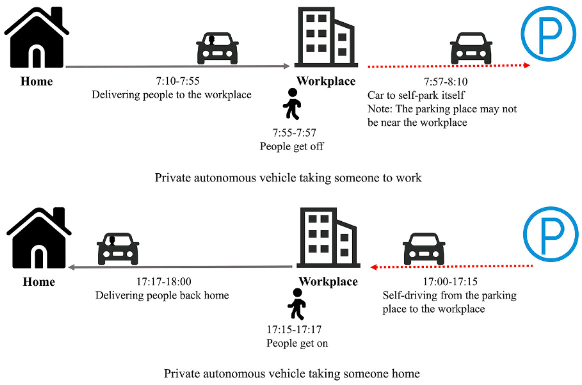


Fig. 2. The schematic diagram of the private autonomous vehicle delivering people to and from the workplace provided in the survey (translated from Chinese).

conventional cars and PAVs in the SC experiment to reduce the number of choice tasks. More explicitly, we set the difference to be 0 and ±5 min for trips of less than 10 km, 0 and ±10 min for trips of 10–20 km, 0 and ±15 min for trips of 21–30 km, and 0 and ±20 min for trips longer than 30 km. For the travel cost of the PAV, we set its benchmark value to be higher than the corresponding travel cost of the private conventional car (approximately 1.4 times). This decision takes into account the additional equipment such as radar and sensors that the PAV will be equipped with, as well as the associated maintenance and wear and tear costs. Additionally, we established two different levels of travel cost for the PAV based on the benchmark value.

For attributes such as parking cost at the workplace in different areas, waiting time for buses and metros during peak and non-peak hours, time to find a parking space, and walking distance from the parking space to the workplace, we obtained benchmark values from a combination of the Gaode Map API and real travel experiences gathered from the focus groups. We also differentiated the attribute levels based on these benchmark values. Insights gathered from focus groups suggest that a distance of 2 km or less between the non-destination parking place and the destination is considered close, and more than 5 km deemed far. This is consistent with the spatial layout of Beijing's ring roads (e.g., the shortest straight-line distance between the 2nd and 3rd ring roads in Beijing is approximately 2.2 km, between the 3rd and 4th ring roads is also around 2.2 km, and between the 4th and 5th ring roads is about 3.8 km as depicted in Fig. 1), and the current location-based parking charges at the ring road level. Based on these insights, we devised two non-destination parking locations for the experiment. These locations are situated 2 km and 6 km away from the destination (workplace), representing non-destination parking places in close proximity and at a greater distance from the destination, respectively. It should be noted that when determining the parking fee at non-destination parking places, we set this fee in proportion to the corresponding charge at the destination parking place. We have also introduced two levels of this ratio for each non-destination parking place. The specific ratio is determined based on the location (ring road level) of the respondent's workplace. As a result, in certain scenarios, the parking fees for distant non-destination parking places (6 km away from the destination in our study) are nearly equivalent to free parking, which can represent free parking in distant places, such as returning home for free parking. However, due to the fuel/energy consumption of vehicles traveling to and from this distant parking place, the total parking cost may not be that low. Furthermore, based on the input received from the focus groups, we determined the attribute value and level for delays in picking up passengers after work. The attributes and their respective levels considered in the SC experiments are summarized in Table 2.

Given the substantial number of scenario combinations generated by the alternatives and attributes considered in our study, we selected the D-efficient design as an efficiency criterion during the construction of the SC experiments using the experimental design software Ngene (ChoiceMetrics, 2021). The priors we employed for this efficient design were derived from the model estimated in the pilot survey. To ensure the practicality of the design, we applied constraints to exclude some unreasonable scenarios. 24 choice tasks were generated for each of the 96 segments defined and randomly divided into four blocks, each with six choice tasks.

3.2. Questionnaire and data collection

The questionnaire we set up for collecting data consisted of four sections:

Section 1: Screen out, commuting trip information, and knowledge and experience of AVs. Since the survey targeted Beijing commuters, we set up screening questions to select only respondents who have a full-time job and work on-site on average for more than three days per week. Additionally, both their residence and workplace should be located in Beijing to ensure they are familiar with commuter trips in Beijing.

This section also contains questions about respondents' commuting information, such as their commuting distance, regular main commuting mode, and whether they travel from home to work during peak times. For the question regarding the regular main commuting mode, we provided respondents with options including private car as a driver, private car as a passenger, bus, metro, "bus + metro," taxi or car-hailing, my own bike, shared bike, electric bicycle, walking, and others. Since our SC experiments only include options for driving private conventional cars, taking private autonomous vehicles, riding shared bikes, and using public transport in the mode choice, respondents who regularly commute using modes other than the private car as a driver, bus, metro, "bus + metro,"

	Shared bike	Public transport	Private conventional car with parking at the workplace or nearby	Private autonomous vehicle	
				Self-parking at the workplace or nearby	Self-parking 6km away from the workplace
Travel time in vehicle/bike (min)	40	50	15	20	20
Time to find a parking place (min)			20		
Waiting time at the station for public transport (min)		9			
Delays in picking you up after getting off work (min)					5
Travel cost in vehicle/bike (CNY)	2	6	2	6	6
Parking cost of accessing and staying parked (CNY)			25	25	11
Walking distance to and from transit stops or the vehicle (m)		1000	100		
Please make your choice:	☐	☐	☐	☐	☐

Fig. 3. Example of one choice task provided to respondents in the survey (translated from Chinese).

and shared bike were screened out.

In addition, we asked respondents about the location (ring road level) of their residence and workplace, possession of a driving license, household car ownership, personal car availability, and their knowledge and experiences of AVs. We also inquired about the availability of parking space at their workplace for those who do not typically commute by private cars. If a parking space was available, we further investigated whether the associated parking cost was considered acceptable.

Additionally, for those whose regular commuting mode is non-public transport, we asked about their most accessible public transport mode for commuting between their residence and workplace, providing four options: bus, metro, "bus + metro," and "I don't know." If the response was "I don't know," we also excluded the corresponding sample. Furthermore, for those with a commuting distance shorter than 10 km, we asked if they can ride a bike. If they can, we further inquired whether they need to bring heavy or oversized equipment to work to check if they can choose the shared bike alternative in the SC experiment. These questions help customize the later choice task experiment.

Section 2: The customized SC experiment. In this section, respondents were first introduced to PAVs (both what they are and their unique parking characteristics) and how they deliver people to and from work in an objective text, as shown in italics in Appendix A (translated from Chinese), and a corresponding picture, as illustrated in Fig. 2.

Afterward, respondents were asked to imagine that they had to make a trip to work and could choose from the travel alternatives provided in the SC scenarios. They were asked to select the alternative they preferred the most for each scenario. Each respondent had six customized SC scenarios to answer based on their commuting distance, whether they commute during the peak time, the availability of a private car, the location of their workplace, and their regular main commuting mode. Since this research focuses on future-oriented travel, precautions were taken to prevent the respondents' recent COVID-19 experience from affecting their decision-making on future travel scenarios. For example, during the COVID-19 pandemic, some people might choose to use less public transport due to safety concerns. To address this, respondents were informed that the scenarios provided in the survey were future travel scenarios and were considered "zero-COVID." This explanation was given to them before they answered the SC scenarios.

We also reminded the respondents that the parking cost of each travel alternative in the experiment was the total parking cost. This means that for PAVs with self-parking away from the workplace, the parking cost displayed in the experiment comprises both the parking charge for the duration of parking at the designated location and the fuel/energy consumption costs for the vehicle's round trip from the parking place to the workplace. This reminder was provided before they answered the SC scenarios. Fig. 3 depicts a choice task that respondents who are capable of riding a bike, possess and can use a private car for commuting, and regularly commute using "bus + metro" during peak hours, with a commuting distance of less than 10 km may answer as an example to illustrate the format of the choice tasks presented in the SC experiment.

Section 3: Attitudinal statements. In this section, we requested respondents to indicate their level of agreement with fourteen attitudinal statements using a five-point Likert scale, ranging from "strongly disagree" to "strongly agree," to capture their attitudes and perceptions regarding PAVs and the unique parking characteristics.

These attitudinal statements were defined by extending the classic Technology Acceptance Model (TAM) with two new constructs: perceived safety and attitude toward waiting. TAM (Davis, 1989) is regarded as one of the most effective methods for investigating the acceptance of new technologies (King and He, 2006), and it is widely used to explore factors affecting people's intention to use and acceptance of AVs (e.g., Lee et al., 2019; Nastjuk et al., 2020; Panagiotopoulos and Dimitrakopoulos, 2018; Wu et al., 2019; Zhang et al., 2019).

Considering both the operation of PAVs and their self-parking are safety–critical tasks, and the emerging nature of PAVs, particularly for their self-parking function, individuals' perception of safety is expected to greatly influence their mode choice and parking option preference for PAVs. Simultaneously, allowing PAVs self-park elsewhere may incur delays in re-taking the vehicle, requiring people to wait for the car at their workplace. Hence, people's perception of waiting at the workplace would also play a significant role

Table 3
Designed and used attitudinal statements in the study.

Expected latent variables	Attitudinal statements
Perceived ease of use (PE)	
PE1	Learning to operate a private autonomous vehicle to commute would be easy for me.
PE2	It would be easy for me to become skillful at using the private autonomous vehicle to commute.
PE3	I would find it easy to let the private autonomous vehicle do what I want it to do.
Perceived usefulness (PU)	
PU1	I think private autonomous vehicles' automatic parking function eases my burden of finding a parking space.
PU2	Private autonomous vehicles' automatic parking function can save my commute time.
PU3	Private autonomous vehicles allow me to engage in other activities (such as rest, entertainment, work, etc.) while commuting, thereby improving the efficiency of my time use.
PU4	Private autonomous vehicles make my commute easier.
Perceived safety (PS)	
PS1	I generally have concerns about letting the private autonomous vehicle park itself.
PS2	I'm worried about the failure or malfunctions of private autonomous vehicles' automatic parking functions.
PS3	I'm worried that letting the private autonomous vehicle park itself may cause accidents.
PS4	I think I cannot depend on private autonomous vehicles for safe commuting.
Attitude toward waiting (AW)	
AW1	I think it is acceptable to wait for a while at the workplace for my family to pick me up after getting off work.
AW2	I think it is acceptable to wait at the workplace for a while for my booked taxi.
AW3	I will get very angry if I booked a taxi to pick me up when I get off work, and the driver is late due to a traffic jam. (reversed)

in deciding where to let the PAV park. Consequently, we constructed statements to measure the perceived safety and attitude toward waiting. Since the classic TAM already considers the impact of perceived ease of use and perceived usefulness on individuals' behavioral intention (Davis, 1989), the latent variables considered in our study include perceived ease of use, perceived usefulness, perceived safety, and attitude toward waiting, measured through fourteen attitudinal statements. Table 3 shows the fourteen attitudinal statements designed and employed in the study and presented to respondents in a random order in the survey.

Section 4: Demographic profile. This section includes information on the socio-demographic characteristics of the respondents, such as age, gender, education level, profession, personal monthly income, and whether respondents have a Beijing permanent residency, etc. For respondents whose families own private cars, we also inquired about the presence of Driver Assistance Systems (DAS) in their vehicles.

Data collection. We entrusted the implementation of the survey to a professional online survey company, Changsha Ranxing Information Technology Co., Ltd. As our study focuses on commuting trips, individuals who commute in Beijing were eligible to participate. In September 2022, the company that ran the survey conducted an online pilot survey in Beijing to assess its clarity among the target audience and to support an efficient design for the full survey. This pilot survey was built using an orthogonal design and was distributed to 150 people, resulting in 135 valid responses. Subsequently, the final survey was carried out between December 2022 and February 2023, with 2500 respondents being recruited for this purpose.

Respondents with logical errors in their responses, such as stating that their regular main commuting mode is driving private cars despite not having a driver's license or access to a private car, were also removed from the sample. After filtering out invalid responses, 2203 individuals with 13,218 SC scenario responses and 2203 attitudinal responses were collected. Table 4 presents a summary of the sample characteristics and collected information. Since we did not find specific statistics regarding working individuals in Beijing, we utilized the overall population statistics of Beijing as a reference.

Since our survey targeted working individuals, the majority of respondents consisted of young and middle-aged individuals, and the educational level of the respondents surpassed that of the overall population in Beijing. Regarding the respondents' commuting information, the far majority of the sample uses public transport (53.5%) and private cars (45.3%) as their regular main commuting mode. It is interesting to note that, despite the vast majority of the sample having availability of private cars, there are still more individuals who regularly commute by public transport rather than by driving.

In terms of knowledge and experience of AVs, 80.5% of respondents were aware of AVs, and 37.0% had ridden in AVs prior to participating in the survey. The high level of knowledge aligns with previous studies (Yin and Cherchi, 2022), while the relatively high riding experience with AVs can be attributed to the operation of automated taxis and minibuses in Beijing before the survey took place. The majority (74.8%) of the interviewees live outside the 3rd ring road of Beijing (i.e. outside the city's core area) but work within it (50.0%). In the urban area of Beijing (i.e. within the 5th ring road), particularly in the core area, there is a noticeable imbalance between parking supply and demand, resulting in high parking fees.

Table 5 reports the statistical results of the responses to the attitudinal statements collected from 2203 respondents in the survey, while Table 6 reports the estimation results of an exploratory factor analysis (EFA) conducted to verify the rationality of the current design of these fourteen attitudinal statements. EFA was performed using the orthogonal varimax rotation method on the expected four latent variables. The estimation results show that the factor loadings of all selected attitudinal statements exceed 0.4, indicating that these designed attitudinal statements can be utilized to measure the intended latent variables. The third attitudinal statement of attitude toward waiting (AW) was expressed reversely in the survey. For sake of convenience in comparison and calculation, in both tables below, it has been reversed.

Table 4
Sample summary statistics.

Attributes	Description	Frequency	Percentage (%)	Population in Beijing
Socio-economic characteristics				
Gender	Male	1070	48.6	51%
	Female	1133	51.4	49%
Age	18–25	270	12.2	15–24: 8%
	26–30	795	36.1	25–29: 8%
	31–40	962	43.7	30–39: 21%
	41–50	141	6.4	40–49: 15%
	51–60	32	1.5	50–59: 15%
	>60	3	0.1	≥60: 20%
Education level	High school and below	51	2.3	44%
	Associate degree	208	9.4	22%
	Bachelor degree	1619	73.5	26%
	Master degree	302	13.7	7%
	Doctorate	23	1.1	1%
Profession	Production equipment operator	43	2.0	53% of people have a job
	Sales and service personnel	135	6.1	
	Government and public institution employee	176	8.0	
	Private-owned enterprise employee	1001	45.4	
	State-owned enterprise employee	431	19.6	
	Foreign capital enterprise employee	283	12.8	
	Others	134	6.1	
Personal monthly income (CNY)	<6000	161	7.3	13,876 on average for working people
	6000–9000	422	19.2	
	9001–12,000	537	24.4	
	12,001–15,000	450	20.4	
	15,001–20,000	335	15.2	
	>20,000	298	13.5	
Beijing permanent residency	Local household registered	1197	54.3	65%
	Others	1006	45.7	35%
Driving license possession	Yes	2105	95.6	55%
	No	98	4.4	45%
Private car availability	Yes	1913	86.8	–
	No	290	13.2	
Have a car equipped with Driver Assistance Systems (DAS) in the family	Yes	1235	56.1	–
	No	968	43.9	
Commuting characteristics				
Frequently used commuting mode	Shared bike	27	1.2	–
	Bus	89	4.0	
	Bus+metro	531	24.1	
	Metro	559	25.4	
	Private car as a driver	997	45.3	
Commute during peak time	Yes	2143	97.3	–
	No	60	2.7	
Commuting distance (km)	<10	717	32.6	13.3 on average
	10–20	972	44.1	
	21–30	388	17.6	
	>30	126	5.7	
Knowledge of and experience in automated vehicles				
Know about automated vehicles	Yes	1773	80.5	–
	No	430	19.5	
Have ridden in automated vehicles	Yes	816	37.0	–
	No	1387	63.0	
Built environment attributes				
The residential location	Within the 3rd ring road	555	25.2	14%
	Between 3rd to 5th ring road	1189	54.0	29%
	Outside the 5th ring road	459	20.8	57%
The working location	Within the 3rd ring road	1102	50.0	–
	Between 3rd to 5th ring road	873	39.6	
	Outside the 5th ring road	228	10.4	
Do not have an available parking place at the workplace[a]	Yes	241	20.0	–
	No	965	80.0	
The parking fee at the workplace is not acceptable[b]	Yes	157	16.3	–
	No	808	83.7	

Note: The dash "–" indicates that this data part is unknown.
Beijing's driving license possession data is from Beijing Traffic Management Bureau (2022), the average commuting distance data and residential population distribution (ring road level) data are from Beijing Transport Institute (2021), and other statistics of the overall population of Beijing is from Beijing Municipal Bureau of Statistics (2022).

[a]The row of statistics pertains to respondents who do not drive for their daily commute.
[b]The row of statistics pertains to respondents who do not drive for their commute but have access to parking spaces at their workplace. The percentages presented in these two rows[(a, b)] are calculated specifically for these two distinct groups of individuals and are not representative of the entire survey population.

4. Model specification

A hybrid choice model (HCM) framework is utilized in this study, as illustrated in Fig. 4. The HCM framework consists of three components, including a structural model, a measurement model, and a discrete choice model.

4.1. Latent variable model

Four latent variables, namely PE, PU, PS, and AW, were included in the HCM model. The structural model of LV_n^q, the latent variable n of commuter q, is defined as:

$$LV_n^q = \alpha_n + \beta_n SK_q + \varphi_n^q,\ \ \varphi_n^q \sim N(0, \sigma_{\varphi_n}) \quad (1)$$

where SK_q is a vector of socio-demographics and knowledge and experience of AVs of commuter q; α_n and β_n are the intercept and the coefficients of the SK_q; φ_n^q is the stochastic error term of latent variable n assumed to be normally distributed with the mean value of zero and standard deviation σ_{φ_n}.

For the measurement model, since the attitudinal statements were rated on a five-point Likert scale, we employ the ordered probit model to specify the observed values of the indicators as follows:

Table 5
Statistics of responses to the attitudinal statements.

Expected latent variables	Mean	Std dev	Percentage (%)				
			Strongly disagree	Disagree	Neutral	Agree	Strongly agree
Perceived ease of use (PE)							
PE1	4.06	0.624	0.05	1.04	13.21	64.18	21.52
PE2	4.09	0.769	0.14	2.23	18.02	47.84	31.77
PE3	4.07	0.759	0.18	2.27	17.52	50.16	29.87
Perceived usefulness (PU)							
PU1	4.58	0.619	0	0.73	4.81	29.91	64.55
PU2	4.39	0.701	0.14	1.27	8.03	40.76	49.80
PU3	4.31	0.659	0	1.23	7.40	51.02	40.35
PU4	4.29	0.596	0	0.50	6.04	57.78	35.68
Perceived safety (PS)							
PS1	2.39	0.887	14.26	43.35	33.18	7.26	1.95
PS2	2.92	1.187	12.17	26.78	28.96	20.79	11.30
PS3	2.70	1.107	14.16	30.78	33.36	14.25	7.45
PS4	2.21	0.873	19.65	47.48	26.51	4.54	1.82
Attitude toward waiting (AW)							
AW1	4.20	0.705	0.14	1.86	10.44	53.11	34.45
AW2	3.96	0.647	0.14	2.54	14.53	66.77	16.02
AW3	3.77	0.805	0.36	6.17	26.06	51.25	16.16

Table 6
Exploratory factor analysis results.

Attitudinal statement	F1. Perceived ease of use	F2. Perceived usefulness	F3. Perceived safety	F4. Attitude toward waiting
PE1	0.542			
PE2	0.674			
PE3	0.489			
PU1		0.613		
PU2		0.507		
PU3		0.458		
PU4		0.436		
PS1			0.669	
PS2			0.787	
PS3			0.782	
PS4			0.563	
AW1				0.520
AW2				0.608
AW3				0.568

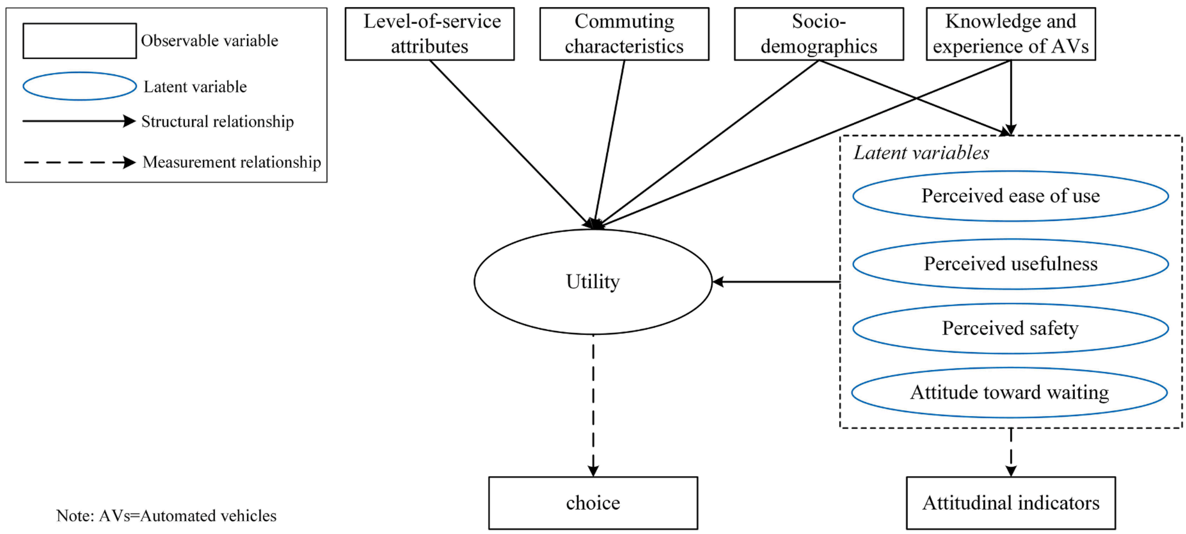


Fig. 4. Illustration of the hybrid choice model framework for this study.

$$IND_{n,r}^{q*} = \delta_{n,r} + \theta_{n,r} LV_n^q + \zeta_{n,r}^q, \zeta_{n,r}^q \sim N\left(0, \sigma_{\zeta_{n,r}}\right) \tag{2}$$

$$IND_{n,r}^{q} = \begin{cases} j_{n,r}^1, & if \tau_{n,r}^0 < IND_{n,r}^{q*} < \tau_{n,r}^1 \\ j_{n,r}^2, & if \tau_{n,r}^1 \leqslant IND_{n,r}^{q*} < \tau_{n,r}^2 \\ \vdots \\ j_{n,r}^k, & if \tau_{n,r}^{k-1} \leqslant IND_{n,r}^{q*} < \tau_{n,r}^k \\ \vdots \\ j_{n,r}^5, & if \tau_{n,r}^4 \leqslant IND_{n,r}^{q*} < \tau_{n,r}^5 \end{cases} \tag{3}$$

where $IND_{n,r}^{q*}$ is the indicator of the r - th attitudinal statement of the latent variable n from commuter q; $\delta_{n,r}$ and $\theta_{n,r}$ are the intercept and coefficient of LV_n^q to be estimated for the r - th attitudinal statement; $\zeta_{n,r}^q$ is a stochastic error term assumed to be normally distributed with the mean value of zero and standard deviation $\sigma_{\zeta_{n,r}}$; $IND_{n,r}^q$ is the actual response to the r - th attitudinal statement of the latent variable n from commuter q; $j_{n,r}^k$ is the k - th ordinal scale of the r - th attitudinal statement of the latent variable n, $k = \{1, 2, \cdots, 5\}$. $\tau_{n,r}^{k-1}$ and $\tau_{n,r}^k$ are the lower and upper thresholds of $IND_{n,r}^{q*}$, respectively. In the case of our five-level response scale, four thresholds need to be used in the measurement model. Because the whole set of thresholds cannot be estimated, we set $\tau_{n,r}^0 = -\infty$, $\tau_{n,r}^1 = 0$, $\tau_{n,r}^5 = +\infty$, and estimate the difference between thresholds (Daly et al., 2012) as:

$$\tau_{n,r}^k = \tau_{n,r}^{k-1} + \gamma_n^{k-1} \tag{4}$$

In this way, the probability of commuter q reporting $j_{n,r}^k$ to the r - th attitudinal statement of the latent variable n can be expressed as:

$$P_r^q\left(IND_{n,r}^q = j_{n,r}^k\right) = P\left(\tau_{n,r}^{k-1} \leqslant IND_{n,r}^{q*} < \tau_{n,r}^k\right) \tag{5}$$

And the probability P_r^q can be obtained by:

$$P_r^q\left(IND_{n,r}^q = j_{n,r}^k\right) = \Gamma\left(\frac{\tau_{n,r}^k - \delta_{n,r} - \theta_{n,r} LV_n^q}{\sigma_{\zeta_{n,r}}}\right) - \Gamma\left(\frac{\tau_{n,r}^{k-1} - \delta_{n,r} - \theta_{n,r} LV_n^q}{\sigma_{\zeta_{n,r}}}\right) \tag{6}$$

where $\Gamma(\cdot)$ represents the cumulative distribution function of standard normal distribution.

4.2. Discrete choice model

In the discrete choice component of the proposed HCM framework, a two-level nested logit (NL) model is developed. As depicted in Fig. 5, the NL model consists of an upper level representing the mode choice model and a lower level representing the parking option

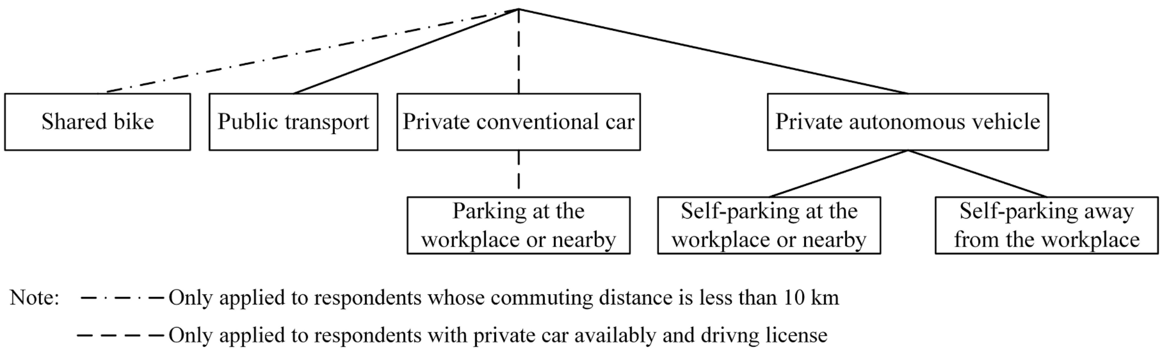


Fig. 5. Nested structure of the five alternatives in this study.

choice model.

The tailored SC experiment provided to respondents for the sake of realism resulted in different numbers of alternatives for different groups of respondents, which in turn led to four distinct groups in our dataset. Specifically, the first group comprises respondents who were presented with a SC experiment with the following three alternatives: PT, PAV1, PAV2. The second group includes respondents with the following four alternatives: BIKE, PT, PAV1, and PAV2. The third group includes respondents with the following four alternatives: PT, CAR, PAV1, and PAV2, and the fourth group encompasses respondents with all five alternatives: BIKE, PT, CAR, PAV1, and PAV2.

Given that variations in the set of alternatives could potentially lead to differences in scale (e.g., as discussed by Caussade et al., 2005; Meyerhoff et al., 2015), we specified a heteroskedastic NL (HNL) model with different scales for groups with different numbers of alternatives. Let δ_{qg} be an indicator used to categorize each commuter q into a specific group g, as described in Eq. (7) and Eq. (8):

$$\delta_{qg} = \begin{cases} 1 & \textit{if } q \textit{ belongs to } g \\ 0 & \textit{otherwise} \end{cases} \tag{7}$$

$$\sum_{g} \delta_{qg} = 1 \text{ for all } q \tag{8}$$

The probability of commuter q in group g choosing mode m and parking option i in choice task t can be expressed as the product between the conditional probability of commuter q in group g choosing parking option i under mode m, as adopted in choice task t, and the marginal probability of commuter q in group g adopting mode m in choice task t:

$$P_{imt}^{q\in g} = \frac{\exp\left(\lambda_g V_{i|mt}^{q\in g}\right)}{\sum_{j=1}^{A_m^{q\in g}} \exp\left(\lambda_g V_{j|mt}^{q\in g}\right)} \times \frac{\exp\left(\mu_g \widetilde{V}_{mt}^{q\in g}\right)}{\sum_{d=1}^{N^{q\in g}} \exp\left(\mu_g \widetilde{V}_{dt}^{q\in g}\right)}, \quad (i,j) \in A_m^{q\in g} \tag{9}$$

$$\widetilde{V}_{mt}^{q\in g} = \frac{1}{\lambda_g} \ln \sum_{j=1}^{A_m^{q\in g}} \exp\left(\lambda_g V_{j|mt}^{q\in g}\right), \quad m \in N^{q\in g} \tag{10}$$

where μ_g is the scale parameter for the upper level, specific for each group; λ_g is the scale parameter for the lower levels, specific for each group. Since there is one nest with two alternatives and four other single alternatives that represent degenerated nests, we constrained all the scales in the lower level such as $\lambda_{sg} = \lambda_g \quad \forall s = \{1,2,3,4\}$. Since we have 4 groups, we have 4 upper level scales (μ_g) and 4 lower level scales (λ_g) with $g = \{1,2,3,4\}$. We normalised $\lambda_{g=1} = 1$, i.e. the scale parameter for the first group of respondents (presented with three alternatives) to one and estimated the scale parameters for the other three groups $\lambda_g \quad \forall g = \{2,3,4\}$ for the lower level and $\mu_g \quad \forall g = \{1,2,3,4\}$ for the upper level. That is, the normalization work of the HNL model is done from the bottom. $V_{i|mt}^{q\in g}$ is the part of the utility that commuter q in group g associates to parking option i under the mode m in choice task t; $A_m^{q\in g}$ is the set of alternatives under the mode m for the commuter q in group g; $\widetilde{V}_{mt}^{q\in g}$ is the expected maximum utility among all the parking options available if using PAV (log-sum term); and $N^{q\in g}$ is the set of mode choices for commuter q in group g.

In our HCM-HNL, $V_{imt}^{q\in g}$, the utility for commuter q in group g in choosing mode m and parking option i in choice task t, encompasses six components: level-of-service (LOS) attributes, latent variables (LVs), individual-related variables, alternative specific constants (ASCs), error term, and model parameters. More explicitly, the LOS attributes considered in the study consist of travel time (included in all alternatives, with coefficients specific among travel modes and between commuting distance within or above 10 km because shared bicycles are only provided in scenarios for trips within 10 km), travel cost (included in all alternatives, with coefficients specific among travel modes), walking distance (included in public transport and private conventional car alternatives, with the same coefficient), parking cost (included in private conventional car and PAV alternatives, with coefficients specific by parking locations), waiting time (included in the public transport alternative), time to find a parking space (included in the private conventional car alternative), and

Table 7
Model calibration results for mixed HNL and the choice model component of the HCM-HNL.

	Applies to	Mixed HNL		HCM-HNL	
		Value	*t*-test	Value	*t*-test
Scale parameters					
Upper level for the groups:		0.396	9.98	0.347	10.10
g1: 3 alternatives (PT, PAV1, PAV2)					
g2: 4 alternatives (BIKE, PT, PAV1, PAV2)					
Upper level for the groups:		0.532	12.70	0.464	12.80
g3: 4 alternatives (PT, CAR, PAV1, PAV2)					
g4: 5 alternatives (BIKE, PT, CAR, PAV1, PAV2)					
Lower level for the groups:		1.200	13.30	1.210	13.50
g2: 4 alternatives (BIKE, PT, PAV1, PAV2)			(2.22)*		(2.34)*
g3: 4 alternatives (PT, CAR, PAV1, PAV2)					
g4: 5 alternatives (BIKE, PT, CAR, PAV1, PAV2)					
Level-of-service variables					
Travel time in vehicle/bike (min)					
Travel time for shared bike	BIKE	−0.305	−8.42	−0.338	−8.45
Travel time for public transport (<10 km)	PT	−0.102	−8.08	−0.113	−8.07
Travel time for private conventional car (<10 km)	CAR	−0.156	−6.67	−0.172	−6.85
Travel time for private autonomous vehicle (<10 km)	PAV1, PAV2	−0.120	−6.85	−0.126	−6.74
Travel time for public transport (≥10 km)	PT	−0.104	−9.59	−0.111	−9.65
Travel time for private conventional car (≥10 km)	CAR	−0.123	−8.97	−0.129	−8.99
Travel time for private autonomous vehicle (≥10 km)	PAV1, PAV2	−0.109	−9.22	−0.115	−9.24
Travel cost in vehicle/bike (CNY)					
Travel cost for shared bike	BIKE	−0.437	−3.33	−0.527	−3.60
Travel cost for public transport	PT	−0.190	−5.10	−0.206	−5.09
Travel cost for private conventional car	CAR	−0.197	−7.70	−0.203	−7.65
Travel cost for private autonomous vehicle	PAV1, PAV2	−0.179	−8.92	−0.194	−8.96
Walking distance to and from transit stops or the vehicle (100 m)	PT, CAR	−0.175	−8.35	−0.186	−8.33
Waiting time for public transport (min)	PT	−0.197	−7.74	−0.487	−4.55
Waiting time * Attitude toward waiting	PT	–	–	0.073	2.85
Time to find a parking space (min)	CAR	−0.143	−8.13	−0.153	−8.16
Parking cost of accessing and staying parked (CNY)	CAR, PAV1	−0.121	−12.40	−0.117	−12.60
	PAV2	−0.126	−11.50	−0.121	−11.50
Parking cost * Beijing permanent residency	CAR, PAV1	0.017	3.70	0.014	3.09
	PAV2	0.026	3.56	0.019	2.56
Distance of the non-destination parking space (km)	PAV2	−0.109	−7.53	−0.106	−7.52
Delays in picking you up after getting off work (min)	PAV2	−0.128	−12.20	−0.126	−12.40
Alternative-specific constants (ASCs)	BIKE	5.450	5.31	5.250	4.91
	PT	−0.458	−0.86	−1.290	−2.39
	PAV1	1.310	4.00	−2.540	−2.93
	PAV2	1.480	4.30	−3.750	−3.95
Standard deviation for error components	BIKE	2.830	7.01	2.850	6.76
	PT	2.970	8.69	2.660	8.72
	CAR	1.990	7.65	1.310	5.58
	PAV1	1.210	10.70	1.120	10.20
	PAV2	1.420	11.80	1.370	11.60
Latent variables					
Perceived ease of use	PAV1, PAV2	–	–	0.332	2.71
Perceived usefulness	PAV1, PAV2	–	–	0.957	5.36
Perceived safety	BIKE, PT, CAR	–	–	1.050	7.67
Attitude toward waiting	PAV2	–	–	0.357	4.02
Individual-related variables					
Commute distance longer than 20 km (1 yes; 0 no)	CAR, PAV1, PAV2	1.550	4.51	1.440	4.28
Regularly commute by shared bikes (1 yes; 0 no)	BIKE	1.670	2.09	1.830	2.23
Regularly commute by public transport (1 yes; 0 no)	PT	0.745	3.24	0.893	3.87
Do not have an available parking place at the workplace (1 yes; 0 no)	BIKE, PT, PAV2	0.329	2.24	0.405	2.90
The parking fee at the workplace is not acceptable (1 yes; 0 no)	BIKE, PT, PAV2	0.378	2.14	0.382	2.36
Personal monthly income of more than 20,000 CNY	PAV1	0.427	3.26	0.321	2.67
Have an available private car	CAR, PAV1, PAV2	1.640	4.91	0.855	2.75
Have a car equipped with Driver Assistance Systems in the family	CAR, PAV1, PAV2	0.843	4.09	0.455	2.36
Have ridden in automated vehicles	PAV1, PAV2	0.803	5.02	0.333	2.31
Residing within the 3rd ring road of Beijing	BIKE, CAR, PAV1	0.471	4.33	0.522	5.05
Model summary					
Number of draws		500		500	
Final log-likelihood		−12121.85		−12088.80	
Adjusted rho-squared value		0.350		0.351	
Akaike Information Criterion (AIC)		24327.70		24271.60	
Bayesian Information Criterion (BIC)		24642.25		24623.60	
Number of individuals		2203		2203	
Number of observations		13,218		13,218	

Note: The “Applies to” column shows the alternative where the variable is included in the utility function.
*The values in parentheses in the *t*-test column represent the *t*-test against 1, while the value outside of the parentheses is the *t*-test against zero.
BIKE = shared bike, PT = public transport, CAR = private conventional car with parking at the workplace or nearby, PAV1 = private autonomous vehicle with self-parking at the workplace or nearby, PAV2 = private autonomous vehicle with self-parking away from the workplace.
The dash “–” indicates that the variable is not modeled in the specification.
The overall statistics reported in the table are computed only for the discrete choice model. For the entire HCM-HNL, including also the latent variable model, the final log-likelihood is −43426.98, the adjusted rho-squared value is 0.363, the AIC is 87079.96, and the BIC is 87926.25.

two dedicated attributes for the “PAV with self-parking away from the workplace” alternative: distance of the non-destination parking space and delays in picking you up after getting off work.

For the LVs, PE and PU, constructed based on TAM to measure commuters’ perceived easiness and perceived usefulness of commuting by PAVs, both are expected to positively affect the adoption of PAVs for commuting. We specify them in the utility functions of the two PAV alternatives. The third LV, PS, reflects people’s perceptions that commuting by PAVs is unsafe. We hypothesize that a higher PS leads to an increase in the perceived utility of non-autonomous driving modes. Thus, PS is included in the utility functions of the shared bike, public transport, and private conventional car alternatives. The fourth LV, AW, which captures people’s perceptions toward waiting at the workplace, is expected to have a positive relationship with the choice of the “PAV with self-parking away from the workplace” alternative. Therefore, it is incorporated into its utility function.

The individual-related variables, categorized into four groups - socio-demographics, experience with AVs, commuting trip characteristics, and built environment attributes - are incorporated into the utility functions. Specifically, socio-demographics are included in the utility functions of private vehicle alternatives (both conventional and autonomous). Experience with AVs is incorporated into the utility functions of the two PAV alternatives. Commuting trip characteristics and built environment attributes are included in the utility functions of all alternatives. A full set of ASCs is included, using the “private conventional car with parking at the workplace or nearby” alternative as a reference.

Finally, we added a set of error components (ECs), η_{im}^{q} (normally distributed with a mean zero and standard deviation $\sigma_{\eta_{im}}$), in the utility function of each alternative to reveal the potential alternative specific inter-individual heterogeneity, accounting for intra-individual correlation among choice tasks.

Hence, the unconditional probability of commuter q in group g selecting the sequence of choices $t = (1, \cdots, T)$ can be calculated by integrating the SC conditional probability $P_{im}^{q\in g}\left(LV\left(\varphi_n^q\right), \eta_{im}^q\right)$ across the distribution of φ and η:

$$P_{im}^{q\in g}\left(LV\left(\varphi_n^q\right), \eta_{im}^q\right) = \prod_{t=1,\ldots,T} P_{imt}^{q\in g}\left(LV\left(\varphi_n^q\right), \eta_{im}^q\right) \tag{11}$$

$$L = \int_{\eta,\varphi} P_{im}^{q\in g}\left(LV\left(\varphi_n^q\right), \eta_{im}^q\right) \prod_{n=1,2,3,4} f_{LV}\left(\varphi_n^q\right) \prod_{r=1,\ldots,R_n} f_{IND}\left(IND_{n,r}^{q*} | LV\left(\varphi_n^q\right)\right) f(\varphi) f(\eta) d\eta d\varphi \tag{12}$$

where f_{LV} stands for the probability density function of the latent variables, while f_{IND} represents the probability density function of the indicators.

The log-likelihood function is calculated as the logarithm of the product of the unconditional probabilities in Eq. (13) across the entire sample:

$$LL = \sum_{q=1}^{Q} \ln(L) \tag{13}$$

5. Results and discussion

This section presents the results of model calibration using the aforementioned model specification and analyzes the relative impact of LOS attributes on the joint choice preferences of PAVs, based on the estimated model.

5.1. Model estimation results

We estimated the proposed HCM-HNL model with Monte Carlo simulation using Pandasbiogeme (Bierlaire 2020), and we also estimated the corresponding mixed HNL model for comparison. Notably, for the HCM-HNL model, we simultaneously estimated the parameters of both the latent variable model and the discrete choice model through simulated maximum likelihood. This full-information estimation was performed with 500 normal draws for each individual while accounting for the panel effect of observations. The results of the estimated mixed HNL and the discrete choice model component of the HCM-HNL are reported in Table 7.

Comparing the mixed HNL model with the discrete choice model component of the HCM-HNL, we observe that all the coefficients and the *t*-tests have similar values, with the exception of the ASCs that are affected by the inclusion of the latent variables. In addition, AIC and BIC are lower in the HCM-HNL than in the Mixed-HNL, indicating an improved model fit after considering latent variables. Therefore, we discuss the model results based on the estimation of HCM-HNL.

It should be noted that we initially estimated models with all identifiable scales and found no significant differences between the upper-level scale of the first group ($\mu_{g=1}$) and that of the second group ($\mu_{g=2}$), as well as between the upper-level scale of the third group

($\mu_{g=3}$) and the fourth group ($\mu_{g=4}$). Additionally, no significant differences were identified among the lower-level scales of the second, third and fourth groups ($\lambda_{g=2}$, $\lambda_{g=3}$, $\lambda_{g=4}$). Consequently, we proceeded to re-estimate the model imposing constraints such as $\mu_{g=1} = \mu_{g=2}$, $\mu_{g=3} = \mu_{g=4}$, and $\lambda_{g=2} = \lambda_{g=3} = \lambda_{g=4}$.

When comparing the estimated scales across different groups, we observe that $\mu_{g=1}$ (also $\mu_{g=2}$) is significantly different from $\mu_{g=3}$ (also $\mu_{g=4}$) (*t*-test $>$ 2.576), and $\lambda_{g=2}$ (also $\lambda_{g=3}$, $\lambda_{g=4}$) is significantly different from 1 ($\lambda_{g=1}$) (*t*-test $>$ 1.96). Thus, the number of alternatives does indeed affect certain scales in our study, and our constructed model effectively controls for the impact of this scale heterogeneity. Notably, the scale parameters of the model (μ_g/λ_g) for all groups fall between 0 and 1, indicating an internal consistent nest structure setting. Next, the estimated standard deviations of the error component terms are highly significant, suggesting that the panel effect existing in repeated choice tasks of the SC experiment cannot be ignored.

Regarding the LOS variables, we find that all tested variables are highly significant at a confidence level of more than 95%, and all their marginal utilities align with the micro-economic conditions. More explicitly, we note that for commuting by private conventional cars, the time spent searching for a parking space has a more considerable negative impact on the perceived utility than travel time for trips of 10 km or more (*t*-test $>$ 1.65), indicating that people care more about the time spent finding an available parking space than the time it takes to travel in the vehicle for commuting trips of 10 km or more. Moreover, for commuting by PAVs with self-parking elsewhere, the delays in re-taking the vehicle exert a similar adverse effect on people's perceived utility as travel time does for trips within 10 km and trips of 10 km or more, highlighting that individuals also place great importance on this delay. Furthermore, we find that the coefficient for the cost of parking the vehicle at or near the workplace is similar to that of parking elsewhere for respondents, whether they have Beijing permanent residency or not. This suggests that the total cost of parking the PAV elsewhere, which includes the fuel/energy consumption costs to and from the non-destination parking space, has a similar negative impact on people's perceived utility as the cost of parking the vehicle at or near the destination. This finding underscores the importance of considering the fuel/energy consumption associated with parking in a non-destination parking lot and highlights the need to include it in the overall calculation of the total parking cost.

Regarding the latent variables, we found that all of them have a high level of significance (above 99%), and their impact on the corresponding perceived utility aligns with expectations. Specifically, perceived ease of use and perceived usefulness positively affect the choice of PAVs. This means that individuals who perceive commuting by PAVs as effortless and beneficial are more inclined to adopt PAVs for commuting. Perceived safety is found to have a positive impact on the choice of non-autonomous travel modes for commuting, confirming that individuals who have concerns about the safety of PAVs and their unique parking characteristics are less willing to commute by PAVs. The attitude toward waiting at the workplace positively influences the choice of commuting by PAVs and letting the vehicle self-park elsewhere, indicating that respondents with a positive attitude toward waiting at the workplace are more likely to choose PAVs to commute and let the vehicle self-park away from the workplace. And if we compare the influence of each latent variable on the perceived utility, it can be noted that the perceived safety and perceived usefulness have a more noticeable impact than the attitude toward waiting and perceived ease of use (*t*-test $>$ 2.576). This indicates that respondents seem to be mostly concerned about the safety and benefits of commuting by PAVs.

From the estimation results of individual-related variables, we can assess which scenarios or individuals are more likely to choose PAVs for their commute. We note that individuals with a commuting distance of more than 20 km are generally more inclined to choose private cars (conventional or autonomous) for their commute. Simultaneously, people who regularly commute by shared bikes or public transport tend to continue choosing these modes of transportation.

We also found that people who lack parking spaces at their workplace or consider the cost of parking at their workplace unacceptable are more likely to choose shared bikes, public transport, or PAVs with parking the vehicle elsewhere. This indicates that PAVs do provide a privately motorized travel choice for people who lack parking space at the workplace or find the parking charge to be unacceptable. This is noteworthy as it may attract former so-called "green travelers" to switch to commuting by private cars, and it could also increase road traffic due to PAVs parking elsewhere.

Moreover, individuals with higher incomes (personal income greater than 20,000 CNY per month) show a greater willingness to commute by PAVs by letting the vehicle self-park at or near the workplace. Respondents with access to private cars or with vehicles equipped with Driver Assistance Systems (DAS) in the household are more likely to commute by private vehicles (conventional or autonomous). This finding is reasonable since respondents with available private cars may have experienced the comfort and convenience of traveling in their own vehicle. Similarly, respondents with family vehicles equipped with DAS may have enjoyed a pleasant travel experience with advanced features.

Furthermore, individuals who have previously ridden in AVs show a greater inclination to commute by PAVs. This suggests that the riding experience influences people's choice of autonomous driving. It also inspires automakers to organize events during the initial promotion stage of PAVs to allow the public to experience PAVs firsthand. In addition, people living within the 3rd ring road of Beijing are more likely to commute by shared bikes, private conventional cars, and PAV with parking the vehicle at or near the workplace. This could be attributed to the higher concentration of job opportunities within the 3rd ring road, resulting in shorter commuting distances for residents. Moreover, individuals residing within this area tend to have higher income levels given how expensive is to live there, enabling them to afford relatively higher parking costs at or near their workplace.

In addition, we have identified that the attitude toward waiting at the workplace influences the marginal utility of waiting time for public transport. Specifically, respondents with a positive attitude toward waiting at the workplace are less sensitive to public transport waiting time compared to those without a positive attitude. Besides, we have discovered that respondents with Beijing permanent residency exhibit lower sensitivity to the parking cost of private cars (both private conventional cars and PAVs) compared to non-local household registered respondents.

Table 8
Results for structural and measurement model components of the HCM-HNL model.

Variables	Perceived ease of use (PE)			Perceived usefulness (PU)				Perceived safety (PS)				Attitude toward waiting (AW)		
	PE1	PE2	PE3	PU1	PU2	PU3	PU4	PS1	PS2	PS3	PS4	AW1	AW2	AW3
Measurement model component														
Coefficients for the attitudinal indicator	1.0	1.340 (16.00)	1.100 (14.40)	1.0	0.770 (12.50)	0.646 (12.70)	0.566 (12.40)	1.0	1.500 (29.70)	1.420 (29.90)	0.920 (24.70)	1.0	0.918 (13.50)	1.030 (12.70)
Intercept for the attitudinal indicator	0.0	−1.590 (-3.83)	−0.383 (-1.01)	0.0	0.527 (1.95)	0.832 (3.53)	1.120 (4.93)	0.0	0.035 (0.37)	−0.216 (-2.40)	−0.208 (-2.88)	0.0	−0.166 (-0.63)	−0.870 (-2.85)
Interval for the ordinal scales	1.710 (9.19), 1.970 (23.20), 2.390 (31.50)			1.250 (6.45), 1.040 (17.80), 1.650 (24.70)				1.920 (38.20), 1.600 (36.80), 1.160 (27.20)				1.320 (12.40), 1.170 (25.10), 1.860 (34.50)		
Structural model component														
Male	0.175 (3.74)													
Age 18–30								0.293 (6.07)						
Bachelor degree or above												0.170 (2.86)		
Employees in government, public institutions, state-owned enterprises, or foreign capital enterprises				−0.167 (-3.50)										
Personal monthly income ≤ 9000 CNY				−0.264 (-4.91)										
Personal monthly income > 20,000 CNY	0.263 (3.76)													
Have the Beijing permanent residency	0.144 (2.99)													
Have a driving license	0.682 (5.78)			0.308 (2.77)										
Have an available private car								−0.424 (−5.72)						
Have a car equipped with DAS in the family	0.174 (3.47)							−0.262 (−4.93)						
Know about AVs				0.398 (6.42)								0.246 (4.93)		
Have ridden in AVs	0.196 (3.79)							−0.328 (−6.17)						
Intercept for the latent variable	4.010 (17.10)			3.920 (15.30)				2.100 (22.80)				3.520 (23.60)		
S.d. for the latent variable	0.844 (15.20)			0.830 (13.50)				1.110 (24.70)				0.696 (13.90)		

Note: The value in parentheses is the *t*-test value for the coefficient.
DAS = Driver Assistance Systems, AVs = Automated vehicles.

Table 9
Willingness to pay for level-of-service variables.

Variables	Willingness to pay
Travel time for shared bike	38.48 (CNY/h)
Travel time for public transport (<10 km)	32.91 (CNY/h)
Travel time for private conventional car (<10 km)	50.84 (CNY/h)
Travel time for private autonomous vehicle (<10 km)	38.97 (CNY/h)
Travel time for public transport (≥10 km)	32.33 (CNY/h)
Travel time for private conventional car (≥10 km)	38.13 (CNY/h)
Travel time for private autonomous vehicle (≥10 km)	35.57 (CNY/h)
Walking distance to and from transit stops	9.03 (CNY/km)
Walking distance to and from the car	9.16 (CNY/km)
Waiting time for public transport	60.01 (CNY/h)
Time to find a parking space for the car	45.22 (CNY/h)
Distance of the non-destination parking space	0.55 (CNY/km)
Delays in picking you up after getting off work	38.97 (CNY/h)

The estimation results for the measurement and structural model components of the proposed HCM-HNL are presented in Table 8. In the measurement model, we note that the coefficients for the attitudinal indicators exhibit high significance levels (greater than 99%). Additionally, the signs of these indicators align with our expectations, and the threshold parameters also demonstrate high significance levels (greater than 99%). All the coefficients in the structural model are highly significant (more than 99%). In terms of perceived ease of use, we found that males, individuals with high incomes (personal monthly income > 20,000 CNY), Beijing permanent residents, individuals with a driving license, individuals who have ridden AVs, and those who have a car equipped with DAS in their family exhibit a higher level of perceived ease of use.

For perceived usefulness, people who are knowledgeable about AVs and possess a driving license are found to have higher levels of perceived usefulness. On the other hand, employees in government, public institutions, state-owned enterprises, or foreign capital enterprises, as well as those with lower incomes (personal monthly income ≤ 9000 CNY), are noted to exhibit a lower level of perceived usefulness. This may be because individuals in the aforementioned occupations generally have higher incomes and better welfare benefits, such as access to workplace parking spaces, some of which are even provided free of charge. Consequently, they do not face difficulties with parking while driving, resulting in a lesser appreciation for the benefits of commuting by PAVs. Individuals with lower incomes may perceive commuting by PAVs as too expensive.

Regarding perceived safety, we found that people who have a private car, have a family vehicle equipped with DAS, or have ridden in AVs express lower safety concerns toward PAVs compared to other groups. Surprisingly, individuals aged 18 to 30 exhibit higher safety concerns. This could be attributed to the fact that younger respondents have easier access to news about accidents in previous automated vehicle tests, particularly through social media, which makes them more concerned about the safety of PAVs. Furthermore, concerning the attitude toward waiting, the model results indicate that individuals with a bachelor's degree or higher education level and those who are knowledgeable about AVs exhibit a more positive attitude toward waiting at the workplace.

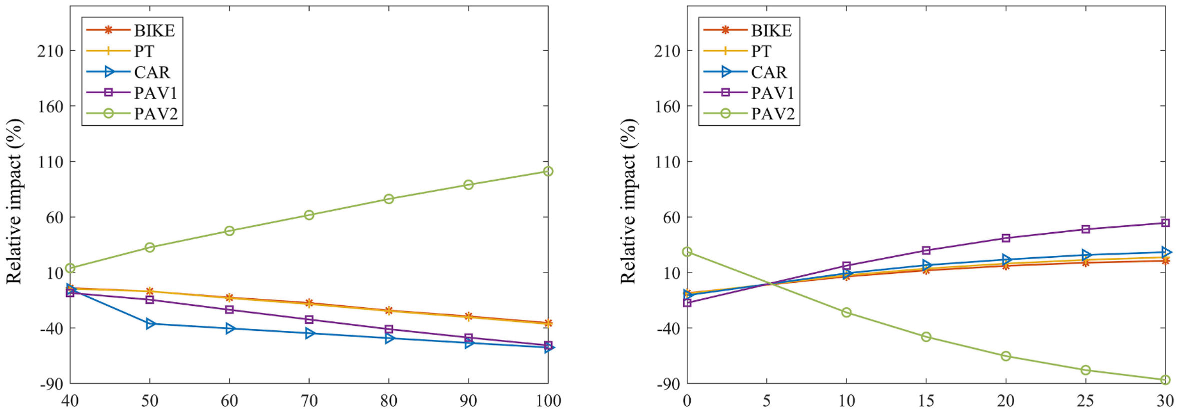
To provide a clearer analysis of the trade-off among the tested LOS variables, we have calculated the willingness to pay (WTP) of decision-makers for modifying non-cost variables in the model. The WTP for variable h (excluding waiting time for public transport) is calculated using Eq. (14) as shown below, while the WTP for waiting time for public transport is determined through simulation because it has interacted with the attitude toward waiting in the model specification. The results are presented in Table 9.

$$WTP_h = \frac{\frac{\partial V_{imt}^{q\in g}}{\partial x_h}}{\frac{\partial V_{imt}^{q\in g}}{\partial x_c}} = \frac{\beta_h}{\beta_c} \tag{14}$$

where β_h and β_c in our model, are the marginal (dis)utilities for variable h and travel cost of the corresponding travel mode, respectively.

We note that respondents are willing to pay more to save 1 h of travel time on private vehicles (both conventional and autonomous) than on public transport. This is in line with the literature on mode choice and the difference can be attributed to the fact that users of private vehicles generally belong to higher-income groups. Similarly, for trips within 10 km, the WTPs for private vehicles are higher than those for shared bikes. Additionally, we found that people are willing to pay more to save 1 h of shared-bike rides compared to 1 h of travel on public transport, likely due to the increased physical exertion required for cycling.

We note that the WTP for saving travel time for PAVs is lower than that for conventional cars. This is because PAVs do not require people to drive manually, allowing them to engage in other activities during the journey and utilize their time more efficiently. These results are consistent with previous research conducted in the Netherlands and Germany, evaluating the impact of AVs on the value of travel time saving (Correia et al., 2019; Kolarova et al., 2019). Furthermore, focusing on the estimated WTP value for saving travel time on PAVs, we find that our result (38.97 CNY/h for trips within 10 km and 35.57 CNY/h for trips of 10 km or more) is similar to the value of 3.61 Euros/h (equivalent to 27.54 CNY/h according to the exchange rate) for saving an hour of travel time in automated taxis obtained in a recent study also conducted in China (Yin and Cherchi, 2022). Additionally, we observe that individuals with commuting distances less than 10 km are willing to pay more to reduce the travel time of their chosen travel mode by 1 h compared to those with longer commuting distances. This tendency may arise from the fact that individuals with shorter commuting distances typically reside



(a) Discounts on non-destination parking fees (%)

(b) Delays in re-taking the PAV of parking elsewhere (min)

Note: BIKE = shared bike, PT = public transport, CAR = private conventional car with parking at the workplace or nearby, PAV1 = private autonomous vehicle with self-parking at the workplace or nearby, PAV2 = private autonomous vehicle with self-parking away from the workplace.

Fig. 6. The relative impact of discounts on non-destination parking fees and delays in re-taking the PAV for parking elsewhere on the market share.

in urban centers with greater job opportunities and higher incomes, making them more willing to invest in reducing travel time.

Furthermore, we find that, on average, people are willing to pay 9.03 CNY to reduce the walking distance to and from transit stops by 1 km, and 9.16 CNY to reduce the corresponding access and egress distance for private conventional cars by 1 km. This is due to the less favorable in-vehicle experience of public transport compared to private cars, which includes factors such as overcrowding, reduced privacy, and the absence of guaranteed seats. Moreover, lengthy walking distances to and from transit stops further diminish the appeal of public transport as a viable commuting option. Consequently, individuals place a relatively equal importance on access and egress walking distance of public transport as they do for private conventional cars. Additionally, when comparing individuals' WTP for reducing the access and egress walking distance by 1 km for private conventional cars to their WTP for the PAV with self-parking 1 km closer to the destination when parking the vehicle elsewhere (0.55 CNY), we observe that the former is 16.65 times the latter. This suggests that people highly value the walking distance from parking for private conventional cars as well.

We also notice that, on average, respondents are willing to pay 60.01 CNY to save 1 h of waiting time for public transport. This value represents the highest levels of WTP among all the LOS variables. Additionally, respondents, on average, are willing to pay 45.22 CNY to save 1 h of searching time for an available parking space for private conventional cars, which is 1.19 times the corresponding WTP for saving travel time for trips of 10 km or more.

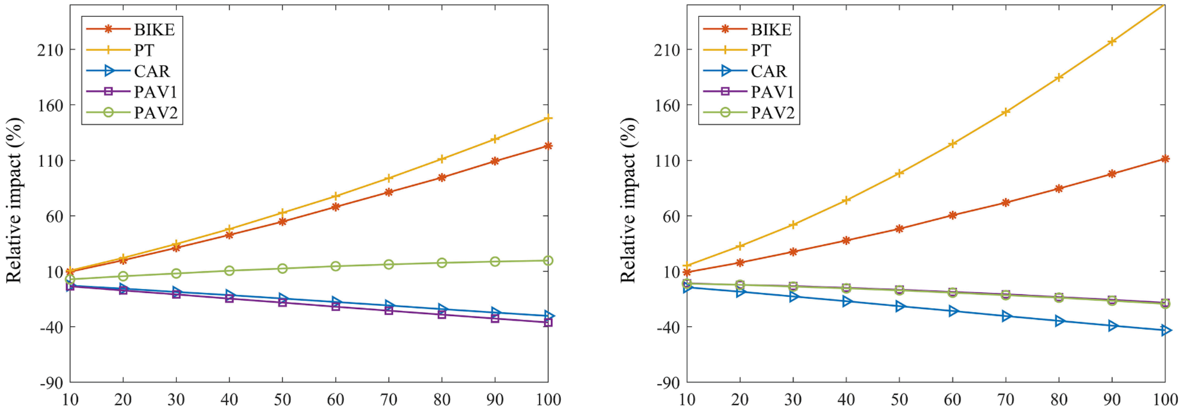
Looking at the delays for PAVs parking elsewhere in picking up at the workplace, our results show that respondents are also willing to pay 38.97 CNY to save 1 h of delay, which is 1.00 and 1.10 times the corresponding WTP for reducing in-vehicle travel time in PAVs for trips within 10 km and trips of 10 km or more, respectively. This indicates that the potential delay in re-taking the PAV if the vehicle self-parks elsewhere cannot be neglected, as people attach great importance to this variable.

5.2. Policy analysis

Based on the estimated results of the proposed HCM-HNL model, we conducted a sensitivity analysis to examine the relative impact of the LOS attributes on the probability of the joint choice of travel mode and parking options. In this analysis, we considered a sample of 2203 respondents who participated in the survey. Specifically, we define their commuting scenarios based on their actual commuting characteristics (commuting distance, availability of a private car, whether they commute during peak time, the location of their workplace, and their regular commuting mode) and adopt the corresponding benchmark values of LOS attributes from survey design as the values for each service level in their respective commuting scenarios. The attribute levels used in the sensitivity analysis are presented in Appendix B.

It should be noted that the focus of this analysis is not on determining absolute market share or demand forecasting but on assessing the relative change in market share caused by policies involving selected factors that we consider to be crucial for shaping future policy decisions. Computing the absolute market share requires adjusting the ASCs, which is not feasible due to the absence of a market for the alternatives we tested. Even if we had such data, it would likely represent early adopters and would not provide a valid market share for long-term policy analysis.

Since we focus on the use of PAVs in this analysis, we primarily discuss the effects of the parking charge at the non-destination parking place, delays in re-taking the vehicle for parking the PAV elsewhere, the increasing urban parking fee, and the increasing travel time of private vehicles. We believe that these analyses can be instrumental for urban planners and managers in shaping relevant policies. To elaborate, the sensitivity analysis of the first two factors can offer insights into their relative impact on the potential



(a) Increasing urban parking fees (%)

(b) Increasing travel time of private cars (%)

Note: BIKE = shared bike, PT = public transport, CAR = private conventional car with parking at the workplace or nearby, PAV1 = private autonomous vehicle with self-parking at the workplace or nearby, PAV2 = private autonomous vehicle with self-parking away from the workplace.

Fig. 7. The relative impact of increasing urban parking fees and increasing travel time of private cars on the market share.

demand for "PAVs with self-parking away from their destination". The sensitivity analysis of the third factor can assist in assessing the relative effectiveness of existing traffic demand management measures following the allowance of PAVs to self-park elsewhere. Furthermore, the sensitivity analysis of the fourth factor can aid policymakers in gauging the relative impact of congestion (a possible outcome of widespread usage of PAVs) on the potential demand for PAV use.

Fig. 6(a) shows how the relative impact varies with the discount of the parking charge for non-destination parking places. In this scenario, we assume that commuters can let the PAV self-park in a parking lot located 3 km away from the workplace, and if they let the vehicle self-park at this non-destination parking place, the delay time for the PAV in picking them up after getting off work is 5 min. We define the parking charge for staying parked in this non-destination parking place by the discount on the corresponding parking charge for parking at or near the workplace. We vary this discount from 30% to 100% (completely free) and calculate the relative impact on the market share of a 30% discount for each alternative through sensitivity analysis. When calculating the parking cost of PAVs slef-parking away from the workplace, we also consider the fuel/energy cost for traveling to and from the non-destination parking place.

From Fig. 6(a), we note that in this scenario, as the charge for the non-destination parking place decreases, the relative impact on the market share of a 30% discount for people choosing to commute by "PAVs with self-parking the vehicle away from the workplace" increases. In contrast, for people choosing to commute by other alternatives, especially private conventional cars or "PAVs with self-parking the vehicle at or near the workplace", the relative impact decreases.

We can also notice that in this scenario, the relative impacts of the discount on non-destination parking fees on the market share for people choosing to commute by shared bikes and public transport are relatively smaller compared to those who choose to commute by private vehicles, whether conventional or autonomous. This suggests that if the parking charge at the non-destination parking place is cheaper, although some "green travelers" may switch to commute by "PAVs with self-parking the vehicle elsewhere", which is not a positive effect in terms of sustainability, a greater number of travelers who use private conventional cars or "PAVs with self-parking the vehicle at the workplace or nearby" will switch to commute by "PAVs with self-parking the vehicle elsewhere".

Fig. 6(b) illustrates the relative impact of the delay time in re-taking the PAV for letting the vehicle self-park elsewhere on the market share. In this scenario, it is also assumed that people can let the PAV self-park at a non-destination parking place located 3 km away, with the parking charge at this location being 70% of the charge for parking at or near the workplace. We also use the market share with a delay time of 5 min as the benchmark, consistent with the benchmark used in the first scenario, to calculate the corresponding relative impacts on market share for different delay times.

It can be observed that in this scenario, as the delay time increases, the relative impact on the market share of choosing to commute by the PAV and letting the vehicle self-park at a non-destination parking place decreases significantly. Conversely, the relative impact on the market share of commuting by other alternatives, particularly "PAVs with self-parking at or near the workplace", increases. This finding highlights the significance of delay time in re-taking the PAV when individuals make decisions regarding commuting by the "PAV with self-parking the vehicle elsewhere".

Fig. 7(a) illustrates the changes in the relative impacts on the market share as urban parking fees increase. In this scenario, we also assume that commuters have the option to let the PAV self-park in a parking place located 3 km away from the workplace, with a 30% discount on the parking charge compared to parking at or near the workplace. Additionally, if they choose to commute by the PAV and let the vehicle self-park at this non-destination parking place, the delay time for the PAV in picking them up after work is 5 min. The benchmark used for calculating the relative impact is consistent with the one employed in the previous scenarios.

From Fig. 7(a), it can be observed that as urban parking fees increase, the relative impacts on the market share of commuting by

Table B1
Levels of attributes used in the sensitivity analysis.

Attributes	Alternatives	Segment	Attribute level			
			<10 km	10–20 km	21–30 km	>30 km
Travel time in vehicle/bike (min)	BIKE	In peak	40	–	–	–
		Off-peak	40	–	–	–
	PT	In peak	50	65	80	100
		Off-peak	45	60	75	90
	CAR	In peak	20	30	50	70
		Off-peak	15	25	40	55
	PAV1, PAV2	In peak	20	30	50	70
		Off-peak	15	25	40	55
Travel cost in vehicle/bike (CNY)	BIKE		3	–	–	–
	PT		4	5	7	8
	CAR		3	7	14	20
	PAV1, PAV2		4	10	20	28
Waiting time for public transport (min)	PT	Actual or accessible bus and "bus + metro" commuter, in peak	9			
		Actual or accessible bus and "bus + metro" commuter, off-peak	12			
		Actual or accessible metro commuter	6			
Walking distance to and from transit stops or the vehicle (m)	PT		600	700	800	900
	CAR		300			
Time to find a parking space (min)	CAR		5			
Parking cost of accessing and staying parked (CNY)	CAR, PAV1	Workplace located within the 3rd ring road	36			
		Workplace located 3rd to 5th ring road	24			
		Workplace located outside the 5th ring road	12			

Note: BIKE = shared bike, PT = public transport, CAR = private conventional car with parking at the workplace or nearby, PAV1 = private autonomous vehicle with self-parking at the workplace or nearby, PAV2 = private autonomous vehicle with self-parking away from the workplace. The dash "–" indicates the attribute does not take values in this travel scenario.

"PAVs with self-parking the vehicle at or near the workplace" and commuting by a private conventional car decrease significantly. On the other hand, the relative impacts on the market share of commuting by public transport and shared bikes increase substantially, while the relative impact on the market share of commuting by "PAVs with self-parking the vehicle elsewhere" slightly increases. These results indicate that increasing urban parking fees can indeed significantly discourage people from commuting by private cars and parking the car at the workplace. However, since PAVs can self-park in a cheaper parking place away from the destination, increasing urban parking fees has a limited impact on people's choice of commuting by "PAVs with self-parking the vehicle elsewhere".

Fig. 7(b) demonstrates the changes in the relative impacts on the market share as the travel time of private cars increases, simulating the potential congestion that may occur with an increased number of private vehicles on the road after the emergence of autonomous driving in the future. In this sensitivity analysis, we assume that the travel time of public transport and shared bikes remains unchanged due to the relatively independent nature of urban rail transit systems and the presence of dedicated bus lanes and bicycle lanes. Furthermore, we assume that individuals can choose to let the PAV self-park in a parking place located 3 km away from the workplace, with the parking charge being 70% of the charge for parking at or near the workplace. If the PAV is self-parked at this non-destination parking place, the delay time for re-taking the vehicle is 5 min, which is the same benchmark used for calculating the relative impact in the above three scenarios.

Fig. 7(b) shows that in this scenario, as the travel time of private cars (both conventional and autonomous) increases, the relative impacts on the market share of commuting by private cars decrease significantly. Conversely, the relative impacts on the market share of commuting by public transport and shared bikes increase remarkably, particularly for public transport. When comparing the relative impacts of traffic congestion on the market share for two types of private cars, we find that private conventional cars are more affected than PAVs (regardless of parking location). This could be attributed to the advantages offered by PAVs, such as allowing commuters to engage in other tasks during the trip, eliminating access/egress distances, and avoiding the need to search for parking spaces when compared to driving private conventional cars.

It should be noted that our sensitivity analysis assumes that every commuter in the sample of 2203 respondents can commute by PAVs, aiming to analyze their maximum potential impact on traffic. However, in the future, particularly during the initial stages of PAVs introduction to the market, their influence on traffic will not be as significant due to a lower ownership rate among people.

6. Conclusions

While previous studies have focused on mode choice in the presence of both PAVs and conventional travel modes, limited attention has been given to the influence of PAVs distinctive parking advantages on mode choice. These advantages include the ability of PAVs to automatically find a parking space and the option to self-park at a location away from the destination to minimize parking expenses. This study aims to address these research gaps by investigating the impact of PAVs' unique parking advantages. Furthermore, by using the extended TAM, this study examines how attitudes influence people's decision-making regarding the emerging mode of PAVs and their novel self-parking feature. This study develops an HCM-HNL model based on a large sample of SC data collected in Beijing, China. It takes into account factors such as level-of-service attributes, individual socioeconomic attributes, knowledge of and experience with AVs, commuting characteristics, built environment attributes, and attitudes to analyze commuters' joint choice behavior concerning travel mode and parking options for PAVs.

The findings reveal several important conclusions. Firstly, level-of-service attributes related to PAVs' parking characteristics such as total parking cost (including fuel/energy consumption to and from non-destination parking places), potential delays in retrieving the vehicle from a non-destination parking place, and the location of the non-destination parking place, significantly influence the joint choice of travel mode and parking options for PAVs. This highlights the need to consider the fuel/energy cost associated with non-destination parking and the potential delay in vehicle retrieval when studying mode and parking option choices for PAVs.

Secondly, individuals who have previous experience riding AVs, own a private car, own a family vehicle equipped with DAS, or have longer commuter distances (over 20 km) are more likely to choose PAVs for their commute. Higher-income groups (with a personal monthly income exceeding 20,000 CNY) and individuals living in the 3rd ring road of Beijing also show a higher inclination to commute using PAVs while parking the vehicle at or near their workplace. Conversely, individuals without workplace parking or those who find the parking cost at their workplace unacceptable are more likely to opt for PAVs with self-parking elsewhere. These findings suggest that these specific groups represent potential early adopters of PAVs and support the notion that PAVs can provide a travel mode for individuals lacking parking spaces at their destination or those who find parking charges unfavorable.

Thirdly, we found that travelers' attitudes significantly influence the choice of travel mode for PAVs and preferences for parking options, with perceived safety and perceived usefulness having the greatest impact. These findings emphasize the importance of highlighting the safety of PAV technology and the benefits of autonomous driving when promoting PAVs.

Furthermore, the study reveals that people are willing to pay less for a certain reduction in travel time when using PAVs compared to private conventional cars. This might be because PAVs allow individuals to engage in non-driving activities during the trip, thereby reducing perceived disutility. Additionally, PAVs eliminate the need for searching for parking spaces and walking to and from parking locations, further enhancing the appeal of traveling in PAVs compared to driving private conventional cars, particularly when the cost difference is not significant.

The study also finds that increasing urban parking charges can significantly reduce the probability of commuting by private conventional cars and PAVs with parking at or near the workplace in sensitivity analysis scenarios. However, the impact on commuting by PAVs with self-parking elsewhere is limited. This suggests that certain travel demand management policies, such as establishing no-parking zones or raising parking fees, may become less effective with the introduction of PAVs if they are allowed to self-park away from the destination. Furthermore, allowing PAVs to self-park elsewhere could potentially lead to increased traffic on the roads and worsen congestion.

Taking these points into consideration, PAVs, particularly their unique parking capabilities, significantly influence people's choices of travel mode and parking options. While earlier studies have suggested that PAVs can enhance traffic efficiency (e.g., Fagnant and Kockelman, 2015), their impact on traffic efficiency might have been overestimated if they are allowed to self-park away from the destination. This could result in a shift in parking behavior for regular private car users who typically park at their destinations, as well as a potential transition of passengers from sustainable transportation modes like public transport to PAVs, leading in increased traffic congestion. Additionally, this shift would contribute to higher fuel/energy consumption and emissions. As a consequence, public transport companies would experience reduced fare revenues, adding financial strain, while governments and car park owners would experience a decline in parking fee revenues as individuals opt to let PAVs self-park elsewhere, potentially even returning home for free parking. Therefore, it is crucial for transportation planning and management departments to formulate appropriate policies and strategies. Looking toward a future with PAVs, if self-parking away from the destination is permitted, we recommend that urban planners and managers explore the implementation of road tolls or redesign the pricing and layout of existing parking lots. These measures should be carefully crafted, taking into consideration factors such as their impact on parking revenue, public transport fare revenue, the effects of PAVs on traffic and the environment, and the fairness of policy formulation. It should be noted that certain attributes in our study, such as the waiting time for public transport and the time to find an available parking space for private conventional cars, were not subject to uncertainty. We made this assumption due to the availability of widely used mobile phone applications, such as Gaode Map and the Beijing Transport App, which provide good quality real-time information on public transport and parking space availability to travelers in Beijing. However, in cities where such information is not easily accessible to travelers, the uncertainty associated with these attributes might have to be considered.

CRediT authorship contribution statement

Fei Xue: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft. **Enjian Yao:** Conceptualization, Funding acquisition, Resources, Supervision, Writing – review & editing. **Elisabetta Cherchi:** Conceptualization, Methodology, Project administration, Resources, Supervision, Writing – review & editing. **Gonçalo Homem de Almeida Correia:** Conceptualization, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A

Introductions employed in the survey to describe fully private autonomous vehicles.

"In the future, fully autonomous (also known as self-driving) vehicles will become a reality and will constitute a transportation option available to people. Fully autonomous vehicles will free the driver's hands and automatically control the vehicle's operation. As a result, people can engage in other activities while traveling in the vehicle, such as resting, playing, or working. The vehicle can also park itself automatically. This means that in addition to private conventional cars that require manual driving, there will be private autonomous vehicles.

A fully private autonomous vehicle can take you to your destination. Then the vehicle automatically finds a parking place near or far from your destination and parks itself based on the availability of parking locations. When you arrive at your destination, you get out of the vehicle directly without having to go to the parking place to participate in the subsequent parking process. Similarly, when you need the vehicle, it will automatically drive from the parking place and pick you up at the time and place of your appointment. However, there may be some delays when the vehicle comes to pick you up if it is parked away from the destination due to uncertainties like traffic jams. In such cases, you will need to wait for the vehicle. Once the vehicle arrives at the appointed place, you need to be there ready to take the vehicle. If you are late, the vehicle will leave, and you will need to request it to come and pick you up again."

Appendix B

Table B1

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