Where to park an autonomous vehicle?

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Where to park an autonomous vehicle? Results of a stated choice experiment

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ABSTRACT

The future innovation and growing popularity of autonomous vehicles have the potential to significantly impact the spatiotemporal distribution of parking demand. However, little knowledge is gained on how people will choose to park their autonomous cars. In principle, an autonomous vehicle is not necessarily parked close by like traditional vehicles leveraging the automated driving and parking capability, still, the decision made by people is important for policymakers in urban and transportation planning. This study attempts to gain useful insights to understand people's parking location choices for autonomous vehicles. A stated choice experiment was designed, allowing people to choose a parking location for autonomous vehicles in varied contexts, including time windows, picking-up times, and the requirement for on-time arrival at the next activity. We found that similar to conventional cars people generally prefer cheaper and/or closer parking lots for autonomous vehicles. However, the distance between a parking lot and the activity location is relatively longer in the case of autonomous vehicles. The amount of time an autonomous vehicle spends in congestion while picking up the users influences the choice of parking locations. Moreover, substantial preference heterogeneity between individual people was found in the parking choice behavior. The maximum value of access time for autonomous cars is 34 $/h which is higher than the empirical value of walking time for conventional cars. Results of elasticity indicate that the influence of parking fees is larger than that of access time and congestion time.

1. Introduction

In many cities of the world, the cruising traffic induced by parking difficulties has been a significant contributor to the problems of congestion, emissions, and traffic safety (McCoy et al. 1990; Shoup, 2006; Chaniotakis & Pel, 2015). Providing a large number of parking spaces to solve the parking problem however requires valuable land space which could otherwise be used for other functionalities like retail, recreation, or social facilities (Zakharenko, 2016). This has been seen as not very sustainable in some city centers. Part of such a planning concept is enabled/restricted by the physical need of people to access their vehicle within an acceptable (walking) distance. However, the concept of parking in close proximity may undergo significant transformation with the advancement of autonomous driving and parking technology, because individuals will no longer need to physically walk to the parking location to

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retrieve their cars. Instead, autonomous vehicles (AV) are expected to pick up people at a specified activity location. It is thus highly relevant for urban and transportation planning to understand the extent to which autonomous vehicles can help solve parking problems.

Technically, automatic driving systems and parking assist systems of a fully autonomous vehicle enable the vehicle to drop off passengers at a certain destination and steer the vehicle into a parking space. This means people do not have to spend time searching for an available parking space or walking to their destination. Instead, they can simply get off the vehicle at the activity location and wait for AVs to pick them up when they are ready for the next trip (Hayes, 2011). This advantage of AVs may change people's parking behavior, which in turn influences the planning of land use and infrastructure. Firstly, car owners who traditionally park nearby with a relatively high parking fee, i.e., in a city center, may find a distant but cheaper parking lot for an AV. The change in parking behavior will essentially trigger the change in parking policy, including the setting of parking fees and the long-term planning of parking facilities. To facilitate informed decision-making regarding parking policies, it is crucial to gain a comprehensive understanding of how users make parking lot choices for autonomous vehicles. The knowledge gained by studying the parking behavior of AV users can serve as an important reference for land-use planning.

Therefore, in this paper, we attempt to gain further insights into the parking choice behavior of AV users. A stated choice experiment incorporating the main influential factors and the variables related to the contexts of AVs parking is designed. The questions about parking choices as well as the social demographics of the respondents were asked through an online questionnaire. Using the data collected in Dalian city, China, a mixed logit model is used to analyze people's preference in parking choices of AVs. Results not only enhance our understanding of the parking choice behavior of AV users but also quantify the magnitude of behavioral responses to the main influential factors.

In the following sections, we will discuss the existing literature on parking location choices which are particularly related to AV parking. Next, we will present the design of the choice experiment, followed by an analysis of the sample and the social characteristics of the respondents. Using the data collected in Dalian, the results of the mixed logit model will be presented, in combination with the analysis of the key indicators related to the value of access time and elasticities. The paper will be concluded with some discussions of future research directions.

2. Parking choice of autonomous vehicles

The topic of parking location choice has been extensively discussed in the existing literature. Parking fee is found an important factor influencing parking choice (Ahmadi Azari et al., 2013; Anderson et al., 2006; Axhausen & Polak, 1991) and may largely shape the parking patterns in CBD areas (Hensher and King, 2001). Moreover, the time spent during parking plays an important role in parking location choice, including access time to alternative parking lots (Bansal et al., 2016; van der Waerden et al., 1993), access time to destination (Anderson et al., 2006; van der Goot, 1982; van der Waerden & Oppewal, 1996), and the time of searching for a parking location (Ma & Xue, 2020; Martin & Shaheen, 2011; Soto et al., 2018). For example, Ibeas et al. (2014) found that access time to alternative parking lots and the destination has a significant and negative effect on parking location choice. Moreover, studies also investigated parking location choice in combination with travel decisions, e.g., parking location choice with a specific travel purpose (Chaniotakis & Pel, 2015; Hensher and King, 2001).

Studies on parking choices have unevenly focused on traditional vehicles rather than autonomous vehicles. The advantages of AVs in solving parking and land-use problems have been elaborated only to a limited extent. It is natural that people can save time finding a parking spot as well as walking to/from a parking spot by the use of AVs (Maurer et al., 2016). As a result, the demand for daytime parking could be shifted to the periphery, which may increase the intensity of economic activities and the land price of downtown areas (Zakharenko, 2016). From an economic perspective, part of the costs related to the parking spaces may be saved for society considering that AVs use fewer spaces and are shared. Fagnant and Kockelman (2015) found that $250 can be saved per new AV, assuming 10% of AVs are publicly shared.

Recent studies have started to explore the impacts of autonomous vehicles on urban mobility, including the issue of parking. Correia and van Arem (2016) investigated the overall impacts when privately owned autonomous vehicles replace conventional ones and how this change affects traffic delays and parking demand in a city. A so-called user optimum privately-owned automated vehicles assignment problem which dynamically assigns family trips in AVs from a user equilibrium perspective was solved. In the most recent studies, Bahrami et al. (2021) evaluated the parking policies through agent-based simulation for autonomous vehicles assuming people minimize their total parking cost based on Wardrop equilibrium, and identified how the overall vehicle kilometers traveled will be varied according to different parking fees.

Previous research on AV parking has generally overlooked the parking decision issue from a behavioral perspective. Many studies often discuss the benefits of AVs in parking without quantifying people's preferences. However, understanding preferences of AV users regarding the choice of parking locations is essential for developing effective parking-related policies and addressing traffic and land-use issues associated with parking. To this end, this paper is perhaps the first attempt to investigate the parking choice behavior of AV users. We wish to contribute to the rare literature and the understanding of parking decision-making of individual people in the case of autonomous vehicles. Because the parking data of AV cannot be observed yet in actual situations, we designed a stated choice experiment in the context of various settings which are specific to the use of autonomous vehicles, e.g., time to pick up users as the access time, time window, and on-time arrival at the next activity. To examine the preference heterogeneity between different people, a mixed logit (ML) model is estimated.

3. Experimental design and survey management

3.1. Experiment design

Previous studies investigating the parking choice of conventional vehicle users have observed that the decision-making process regarding parking is a complex one (Chaniotakis & Pel, 2015). In addition to the attributes related to parking location, people's decisions are also influenced by some context variables, such as travel purpose and time of day (Feng et al., 2013; Gu et al., 2021). To design the choice experiment, the relevant attributes and attribute levels were chosen based on the earlier studies and their relevance to the AVs. The parking location of AVs has a smaller impact on the current trip than that of traditional vehicles, while a bigger impact on the next trip, e.g., departure on time. To account for the influence of the travel context, the choice experiment assumes that the respondent is the user of the trip.

In particular, two time-related context variables are included in the experiment: time window and punctuality of the next trip. The time window refers to the available time interval of a certain activity before the next trip of AV users. A large time window would offer more flexibility for people to arrange to park, while a short time window would urge people to park nearby. The punctuality of the next tip reflects the urgency to conduct the next activity such as the requirement for on-time arrival. The extent of punctuality could be dependent on the types of activities, however, it also reflects the level of travel time uncertainty as people could assess punctuality differently. To be simplified, in our experiment, we define punctuality as the necessity of arriving on time for the subsequent trip.

According to previous research, parking fee, the access time from the parking lot to the destination, and the access time from the origin to the parking lot are important factors that influence people's choices of parking (Bansal et al., 2016; Ibeas et al., 2014; Lambe, 1996). AVs can drop off users at the activity location, drive to find a parking lot, and pick up the user before the next trip. Therefore, the access time from the origin to the parking lot is not considered in the experiment. Instead, we use the access time to denote the time that an AV spends to pick up the users. The levels of parking fees are set according to the actual prices in the research area, Dalian city. The highest price for public parking lots in Dalian is 12 ¥/h. Thus, the four levels of parking fees are set, including 0 ¥/h, 4 ¥/h, 8 ¥/h, and 12 ¥/h. To observe whether AV users would choose a parking lot that is much farther away from their activity location, a large value of access time (driving time of autonomous vehicles) from the parking lot to the users' location is considered in the experiment. The four levels of access time are 1 min, 10 min, 20 min, and 30 min, whereas 1 min indicates that the vehicle is parked at the same place as where people stay.

In addition, as AVs need to drive from the parking lot to the users' locations before the next trip, traffic congestion could be unavoidable in some cases, which affects vehicles' arrival time. When the uncertainty in travel time caused by traffic congestion is excessively high, users may refrain from utilizing remote parking options regardless of the price. To mimic the effects of such complexity, congestion time is included as an attribute. The level of congestion time is set referring to the average congestion delay index of Dalian City. Four levels (0 min, 3 min, 6 min, and 9 min) are defined.

In total, three main attributes (parking fee, access time, and congestion time) and two context variables (time window and punctuality of next trip) are included in the choice experiment, as listed in Table 1. The levels of attributes are set as four or two, which results in a total of $4^4 \times 2^1$ combinations in the case of a full-factorial design. Usually, optimal designs like *D*-efficient designs are generally considered superior (Guo et al., 2020). However, not all priori values of the parameters are empirically known. Moreover, a good investigation based on an orthogonal design could also serve the purpose of this study. Therefore, in this study, a fractional factorial design is created. A total of 128 profiles were generated, allowing us to estimate all the main effects and six two-way interaction effects. Because the choice alternatives are unlabeled, each of the 128 profiles is combined with another different profile to construct a choice set. In total, sixteen blocks were allocated to the 128 profiles so that each respondent is presented with eight choice tasks. A screenshot of the choice experiment is shown in Fig. 1.

Table 1
Attribute and attribute levels used in the stated choice experiment.

Variable	Attribute	Level
Main attributes	Parking fee	0 ¥/h
		4 ¥/h
		8 ¥/h
		12 ¥/h
	Access time (The time from the parking lot to users)	1 min
		10 min
		20 min
		30 min
	Congestion time to pick up AV users	0 min
		3 min
		6 min
		9 min
Contextual variables	Time window	1 h
		3 h
		5 h
		7 h
	Punctuality of next trip (On-time arrival or not)	Yes
		No

Imagine you are the next user of the AV, you will travel **3 hours later**, and **you must arrive on time**. Which parking lot do you prefer the AV to be parked?

Parking lot	A	B
Access time (the time from the parking lot to your location)	10min	30min
Parking fee	8￥/h	4￥/h
Congestion time	3min	0min
Your choice	○	○

Fig. 1. Screenshot of the choice experiment.

3.2. Survey deployment

The data was collected in 2018 in the city of Dalian, China. Dalian is a major city and seaport in Liaoning Province, with a total area of 12,574 square kilometers. The population of Dalian according to the 2021 census is 7.45 million. The city administers seven districts, two county-level cities, and one county. According to the statistics in 2018, car ownership in Dalian is 1.6 million. Parking difficulty is one of the urban problems. People often face a serious problem in finding a parking space, especially in the areas of shopping centers. At the same time, traffic congestion is another main issue. According to the "Traffic Analysis Report of Major Chinese Cities in the Third Quarter of 2020", the peak congestion delay index of Dalian was 1.789, which means the peak travel time was 1.789 times high than the normal state, and the average peak driving speed was only 26.5 km per hour.

In this paper, we implemented the survey through an in-house developed online questionnaire system. After that, the actual implementation of the survey was managed by a commercial marketing company that has a large panel. Respondents were randomly invited by the company from four central city districts of Dalian City: Zhongshan, Xigang, Shahekou, and Ganjingzi Districts. People who were invited would participate in the survey with the assistance of a face-to-face interviewer of the company to increase the data quality and response rate. The survey consisted of two parts: socio-demographic questions and a stated choice experiment. Before the survey, the contents of our questionnaire were ethically reviewed by the university committee. The general introductory information of the questionnaire, such as motivation, contact information, and particularly the instructions about how to engage in the choice experiments, was shown to the respondents to prevent any misinterpretation issues about the questions and the choice experiments. Among the 1,743 invited respondents, 708 completed the survey. In order to improve the reliability of the responses, the consistency and feasibility of answers were checked. For example, the observations completed within 10 min were considered invalid and deleted because the average time finishing the questionnaire was estimated to be 25–30 min. Moreover, the data in which people always gave the same answer multiple times in different choice experiments was also omitted. In the end, 552 of the questionnaires are considered valid. This results in a total of 4,416 observations used for analysis and model estimation. Relative to the minimum sample size defined in an orthogonal experiment (Orme, 2010, this is considered sufficient.

3.3. Sample and sample characteristics

Table 2 summarizes the socio-demographic characteristics of the respondents. According to the main data bulletin of the seventh national census in Dalian in 2021, the sample is representative of the population in Dalian City. It shows gender is equally distributed. In the sample, 47.6% own cars in their household, and 52.4% do not own a car. All respondents are older than 18 years old. 42.0% age range between 18 and 30, 39.2% between 31 and 50, and 18.8% are older than 50 years old. The distribution of household annual income shows that about 20% of the respondents are in the category of <50,000 ¥ and ≥130,000 ¥, respectively, leaving the majority in the middle range.

Table 2
Socio-demographic characteristics of respondents.

Variable	Category	Percentage (sample)	Percentage (Dalian population)
Age	<=30	42.0%	40.9%
	31–50	39.2%	34.7%
	>50	18.8%	33.3%
Gender	Male	49.7%	49.80%
	Female	50.3%	50.20%
Car ownership situation	have car	47.6%	
	no car	52.4%	
Household income (¥/year)	<50,000	21.8%	
	≥50,000&<90,000	30.8%	
	≥90,000&<130,000	27.6%	
	≥130,000	19.8%	

Table 3
Estimation results.

Variables	Levels	MNL			MNL+			Mixed logit model		
		Coef.	p-value		Coef.	p-value		Coef.	p-value	
Random parameters										
Parking fee (¥/h)	0	1.918	0.000	***	2.039	0.000	***	3.795	0.000	***
	4	0.317	0.000	***	0.430	0.000	***	0.897	0.000	***
	8	−0.765	0.000	***	−0.915	0.000	***	−1.542	0.000	***
Access time (min)	1	0.693	0.000	***	1.263	0.000	***	1.635	0.000	***
	10	0.629	0.000	***	0.218	0.000	***	0.535	0.000	***
	20	−0.231	0.008	**	−0.240	0.008	**	−0.580	0.005	***
Congestion time (min)	3	0.391	0.000	***	0.215	0.000	***	0.457	0.012	**
	6	−0.057	0.000		−0.029	0.966		−0.101	0.312	
	9	−0.715	0.000	***	−0.575	0.000	***	−0.923	0.000	***
Standard deviation of random parameters										
Parking fee(¥/h)	0							1.457	0.000	***
	4							0.692	0.033	**
	8							0.007	0.986	
Access time(min)	1							1.528	0.000	***
	10							1.311	0.000	***
	20							0.051	0.900	
Congestion time(min)	3							0.911	0.000	***
	6							0.497	0.022	**
	9							0.566	0.000	***
Two-way interaction										
Time window(1 h) * Parking fee (¥/h)	0				−0.405	0.000	***	−0.477	0.001	***
	4				0.080	0.745		0.065	0.759	
	8				0.238	0.021	**	0.269	0.008	***
Time window (3 h) * Parking fee (¥/h)	0				0.133	0.581		0.174	0.565	
	4				0.102	0.243		0.112	0.915	
	8				−0.148	0.098	*	−0.275	0.021	**
Time window (5 h) * Parking fee (¥/h)	0				0.210	0.001	***	0.296	0.021	**
	4				0.061	0.551		0.091	0.368	
	8				0.009	0.928		0.013	0.852	
Time window (1 h) * Access time (min)	1				0.275	0.021	**	0.521	0.014	**
	10				0.053	0.538		0.135	0.557	
	20				−0.093	0.312		−0.116	0.294	
Time window (5 h) * Access time (min)	1				−0.333	0.070	*	−0.309	0.028	**
	10				0.171	0.082	*	0.195	0.077	*
	20				0.071	0.731		0.059	0.881	
Punctuality (on-time arrival) * Parking fee (¥/h)	0				−0.325	0.000	***	−0.677	0.000	***
	4				−0.027	0.682		−0.064	0.519	
	8				0.203	0.000	***	0.415	0.000	***
Punctuality (on-time arrival) * Access time (min)	1				0.278	0.006	***	0.476	0.004	***
	10				−0.064	0.290		−0.006	0.584	
	20				−0.084	0.144		−0.110	0.238	
Punctuality (on-time arrival) * Congestion time (min)	3				0.012	0.810		0.011	0.894	
	6				−0.110	0.039	**	−0.218	0.018	**
	9				−0.002	0.979		−0.005	0.974	
Access time (1 min) * Parking fee (¥/h)	0				1.504	0.000	***	1.916	0.000	***
	4				0.100	0.476		1.433	0.000	***
	8				0.488	0.000	***	1.112	0.000	***
Access time (10 min) * Parking fee (¥/h)	0				1.226	0.000	***	1.721	0.000	***
	4				0.464	0.000	***	0.853	0.000	***
	8				0.361	0.001	***	0.416	0.000	***
Access time (20 min) * Parking fee (¥/h)	0				1.283	0.000	***	1.334	0.000	***
	4				0.466	0.023	**	0.521	0.001	***
	8				−0.445	0.000	***	−0.687	0.000	***
Age (<=30) * Access time (min)	1				0.117	0.273		0.491	0.003	***
	10				−0.161	0.023	**	−0.237	0.018	**
	20				−0.036	0.601		−0.034	0.661	
Age (>30&<=50) * Access time (min)	1				0.165	0.019	**	0.280	0.014	**
	10				0.040	0.566		0.059	0.596	
	20				−0.131	0.232		−0.133	0.440	
Income (<50000) * Parking fee (¥/h)	0				0.123	0.074	*	0.346	0. 053	*
	4				0.054	0.367		0.043	0.774	
	8				−0.188	0.044	**	−0.456	0.015	**
Income (>=50000&<90000) * Parking fee (¥/h)	0				0.365	0.004	***	0.583	0.000	***
	4				0.065	0.475		0.091	0.697	
	8				−0.217	0.008	**	−0.479	0.006	**
Have cars? (yes) * Congestion time (min)	3				−0.051	0.239		−0.065	0.396	

(continued on next page)

Table 3 (*continued*)

Variables	Levels	MNL			MNL+			Mixed logit model		
		Coef.	p-value		Coef.	p-value		Coef.	p-value	
	6				−0.023	0.674		−0.039	0.766	
	9				0.905	0.001	***	0.371	0.002	***
LL(0)					−2997.964			−2997.964		
LL(β)					−1900.31857			−1708.576		
Rho^2 adjusted					0.366			0.430		

***, **, * means the level of significance at 1%, 5% and 10%.

4. Mixed logit model

In the community of travel behavior, discrete choice models based on the random utility maximization theory are widely used, including the multinomial logit (MNL) model and mixed logit (ML) model. ML overcomes the strong assumption of IID made in MNL and can capture taste variation across decision-makers (differences across identical agents in their evaluation of an alternative's attributes) (Hess & Polak, 2009). To reflect the structure of the collected data and incorporate different sources of heterogeneity, the mixed logit model is used in this study to estimate the effects of the selected attributes and social-demographic variables.

To capture the deterministic taste variations, the effects of social-demographic variables and context variables are estimated through two-way interactions. The utility associated with each alternative $i(i \in I)$ is evaluated by the individual $n(n \in N)$ and can be presented below:

$$U_{ni} = \sum_{k \in K} \beta_{ik} x_{ik} + \sum_{k \in K} \sum_{m \in M} \beta_{ikm} x_{ik} x'_{nm} + \sum_{k \in K} \sum_{q \in Q} \beta_{ikq} z_{nq} x_{ik} + \varepsilon_{ni} \tag{1}$$

where x_{ik} is the k^{th} attribute of alternative i,x'_{nm} is the m^{th} context variable $(m \in M)$ for individual n, $x_{ik}x'_{nm}$ is the two-way interaction between attribute k and context m,z_{nq} is the $q^{th}(q \in Q)$ social-demographic variable of individual n, and $z_{nq}x_{ik}$ is the two-way interaction between attribute k and social-demographic variable q. β_{ik}, β_{ikm}, and β_{ikq} are parameters to be estimated.ε_{ni} is an error term that follows a Gumble distribution. Individuals are assumed to choose the alternative that maximizes their utility.

To reflect the preference difference between different people induced by the repeated choice experiments, the random parameter mixed logit model is adopted in this paper. The random parameter of attribute k of alternative i for individual n can be specified as follow:

$$\beta_{ik} = \overline{\beta}_{ik} + \delta_k \nu_{ik} \tag{2}$$

where $\overline{\beta}_{ik}$ is the population means, ν_{ik} is normally distributed random term with zero mean and a standard deviation of one. δ_k is the standard deviations of distributions of β_{ik}.

The unconditional choice probability of alternative i for individual n is:

$$P_{ni} = \int_{\beta} (P'_{ni}|\beta) f(\beta, \theta) d\beta \tag{3}$$

where θ is the parameters of the distribution to be estimated,P'_{ni} represents the conditional choice probability:

$$P'_{ni} = \frac{\exp\left(\sum_{k \in K} \beta_{ik} x_{ik} + \sum_{k \in K} \sum_{m \in M} \beta_{ikm} x_{ik} x'_{nm} + \sum_{k \in K} \sum_{q \in Q} \beta_{ikq} z_{nq} x_{ik}\right)}{\sum_{j=1}^{J} \exp\left(\sum_{k \in K} \beta_{jk} x_{jk} + \sum_{k \in K} \sum_{m \in M} \beta_{jkm} x_{jk} x'_{nm} + \sum_{k \in K} \sum_{q \in Q} \beta_{jkq} z_{nq} x_{jk}\right)} \tag{4}$$

The full loglikelihood function to be maximized is

$$LL = \sum_{n=1}^{N} \log \prod_{i=1}^{I} P_{ni}^{'\delta_i} \tag{5}$$

where δ_i equals 1 if alternative i is chosen, and 0 otherwise.

In this paper, we select all the main effects, parking fee, access time, and congestion time, as random variables. The effects of the context variables are specified through two-way interactions. As we mentioned before, considering the advantages of AVs in parking, a cheaper but distant parking lot could be more attractive to AV users. Thus, we explore the effects of the two-way interaction between the parking fee and access time. Note this interaction effect was already treated when generating the orthogonal design which allows the estimation of several interaction effects. We also considered the possible existence of interactions of the main effect attributes with socio-demographic variables, like gender, age, income level, and household car ownership.

5. Results and analysis

Nlogit was used to estimate an MNL model with the main effects only, an MNL + model with interaction effects and a mixed logit model. In the mixed logit model, the random parameters can be assumed to follow different distributions. Following several rounds of estimation using different distributions, the normal distribution is deemed the best according to the Rho-squared value and used for the model estimation. We used 1000 Halton draw in the simulated maximum likelihood estimation. The estimation results are presented in Table 3. All variables were effect coded. The estimate of the reference level (those without *p*-values in Table 3) was calculated based on the estimates of the non-reference levels. Compared to the MNL model, the mixed logit model has a relatively satisfactory goodness-of-fit in terms of Rho-squared value. The log-likelihood (LL) is −1900.32 for the MNL + model, and −1708.57 for the ML model. Rho-squared values increase from 0.366 (MNL model) to 0.430 (ML model). This means including the random parameters in the model improves the overall goodness-of-fit. The signs of all estimated coefficients are in line with theoretical expectations. Thus, in the following sections, we discuss the results by mainly focusing on the mixed logit model.

5.1. Results of the main attributes and interaction effects

5.1.1. Results of parking fee

Based on the estimates in Table 3, we can find almost all the attributes have a significant effect on the parking lot choice of AV users. For the convenience of presentation, we use bar charts to present the marginal utility for each main attribute, as presented in Fig. 2. It shows that the probability of choosing a parking lot decreases with increasing parking fees. In general, people prefer free parking the most ($\beta = 3.795$). When the parking price is 4 ¥/h, people are also likely to pay ($\beta = 0.897$). However, when the price increases to 8 ¥/h and 12 ¥/h, the probability of choosing a parking lot decreases dramatically. This means people generally consider the parking price of 8 ¥/h or more as expensive. This result is in line with previous findings in the cases of conventional vehicles where lower parking prices encourage drivers to park their cars (Chaniotakis & Pel, 2015).

The interaction effects between parking fees and context variables, as shown in Fig. 3. It shows that when time window is short (1 h), the effects of free parking decrease, which perhaps indicates that the intention to use paid parking is stronger if AV users need to leave for the next trip very soon. This finding is also confirmed in the cases of a higher parking fee because the additional utility underlying the short time window negatively adds to the marginal utility of the main effect. In another word, when the parking fee increases to 8 ¥/h or 10 ¥/h, people are still likely to pay if it is only a short stay (within one hour). This is understandable because, in the case of a short say, individuals tend to use nearby and convenient parking lots such that the uncertainties that could cause a delay in their subsequent trip can be minimized. When the time window becomes longer, consistent interaction effects are observed in relation to the main effects. When the time to leave for the next trip is relatively long (3 or 5 h), people in general do not choose the parking with high parking fees (8 ¥/h and 10 ¥/h). When the time window is longer, the intention to use free parking gets stronger. As shown in the bar chart, a longer time window increases the probability to use free parking lots.

Results of the interaction between on-time arrival and parking fee Fig. 3 show that the probability of using free parking decreases and the probability of using paid parking increases when on-time arrival is a condition. This result is not surprising because more expensive parking lots are normally equivalent to convenient services, considering the various factors related to access time, availability of parking spaces, and safety. In addition to the interaction effects between context variables and main effects, we also estimated the interaction effects between social demographical variables and parking fees (results are presented in Table 3). From the significantly estimated interaction effects Fig. 4 between household income and parking fees, one can see that people in the category of low

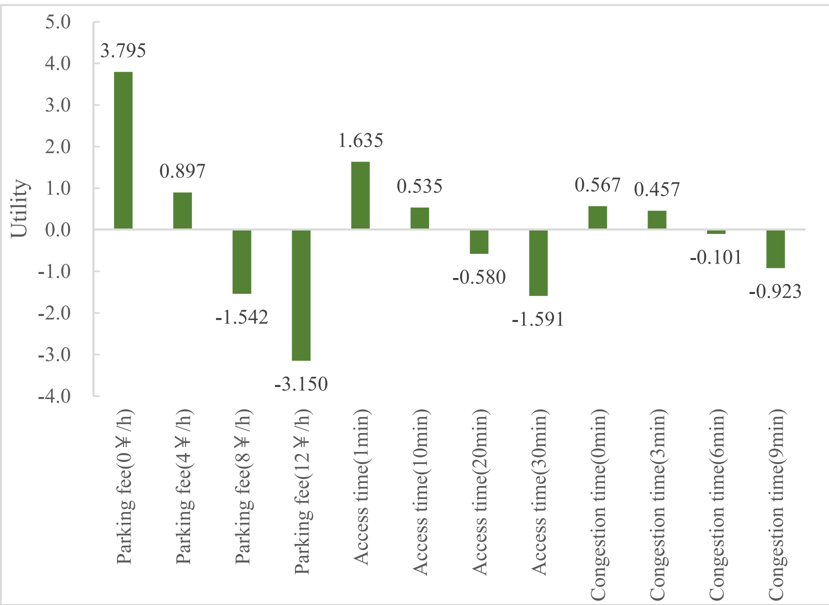

Fig. 2. Utilities of main effects.

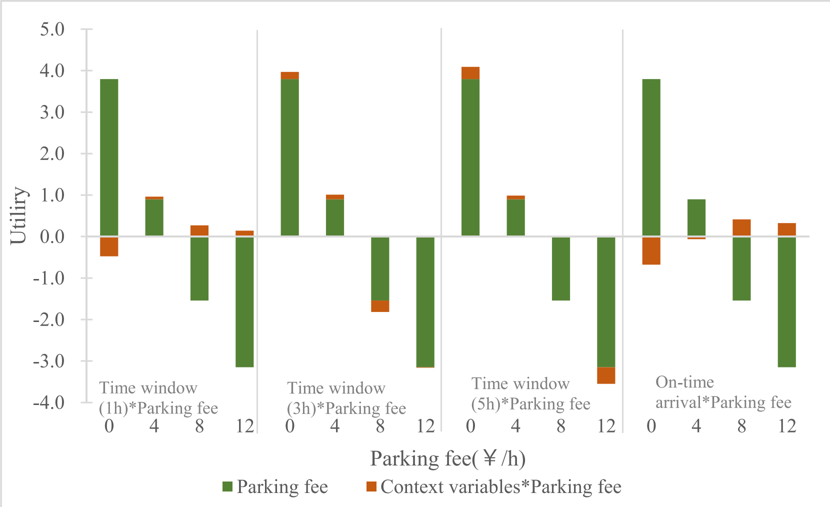

Fig. 3. Two-way interactions between parking fee and context variables.

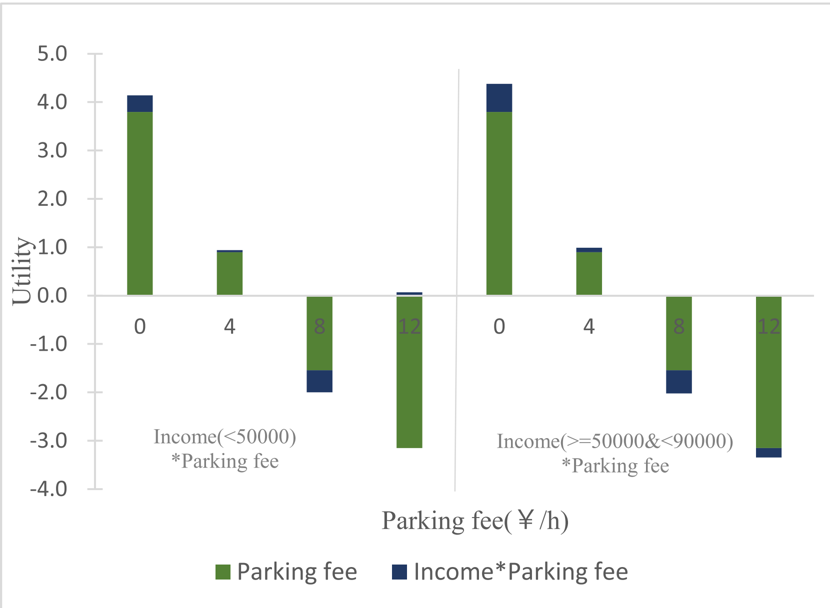

Fig. 4. Two-way interactions between parking fees and household income.

and middle-level income prefer free parking lots and are reluctant to use the parking lot with a fee higher than 8 ¥/h.

5.1.2. Results of access time

The effects of access time on the parking lot choice are presented in Fig. 2. It shows that people generally prefer the parking lot which is more accessible (the pick-up time of autonomous vehicles is shorter than ten minutes) regardless of the congestion. This means that even in the case of autonomous vehicle, people still prefer to shorter access time for the AVs to arrive and pick up users. This result is in line with the findings related to conventional vehicles (Chaniotakis & Pel, 2015). For example, in the case of conventional vehicles, a ten-minute walk from the parking lot to the destination is unacceptable to most conventional vehicle drivers (Ma et al., 2013a). However, the ten-minute access time was found to positively influence the parking location choice of autonomous vehicle drivers. This is understandable considering that ten-minute waiting for autonomous vehicles is relatively effortless. This means the distance from a parking lot to the activity location can be relatively long in the case of autonomous vehicles. This finding serves a valuable reference for parking space planning, as it highlights the distinct spatial distribution of parking demand between autonomous vehicles and conventional vehicles.

The interaction effects between access time and time window Fig. 5 show that, when the time window is as short as one hour, the

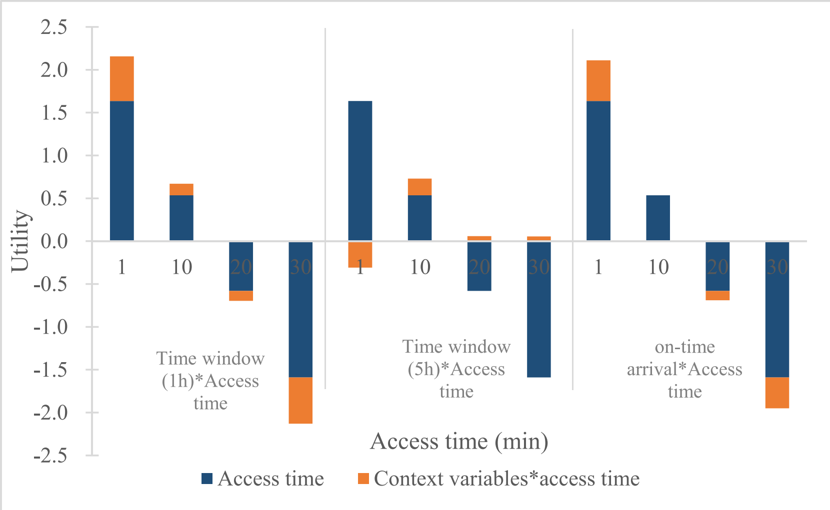

Fig. 5. Two-way interactions between Access time and context variables.

probability of choosing the most accessible parking lot is high (β = 0.521), and when access time becomes longer, the probability decreases, indicating that shorter access time is a priority for the users with temporal stopping. Interestingly, when the time window is sufficiently long (five hours), the probability of using the most accessible parking lot decreases (β = -0.296). While the probability increases when access time is ten minutes. This may be attributed to the fact when the time window is extended, individuals often make a trade-off by considering that a parking lot with a one-minute access time is typically more expensive, while a parking lot with a ten-minute access time is still considered sufficiently accessible.

Results of the interaction effects between on-time arrival and access time show a positive effect in the case of one-minute access time, indicating that the preference of people for the most accessible parking lot is strengthened when on-time arrival for the next trip is required.

In addition, we also estimate the interaction effects between access time and social demographical variables. However, only the interaction between age and access time is somewhat significant. We found that the parking lots with a ten-minute access time are not preferable for people younger than 30 years old. The most accessible parking lots are significantly preferable for people between 30 and 50 years old. While for other age groups, we did not find significant interaction effects.

5.1.3. *Results of congestion time*

In addition to the access time that an autonomous vehicle spends on roads to pick up users, congestion time defines the possible extra time caused by unexpected events like traffic jams. Results of the main effects show that the probability of parking location choice decreases with the increasing congestion time, which is understandable. People in general do not mind three-minute congestion time

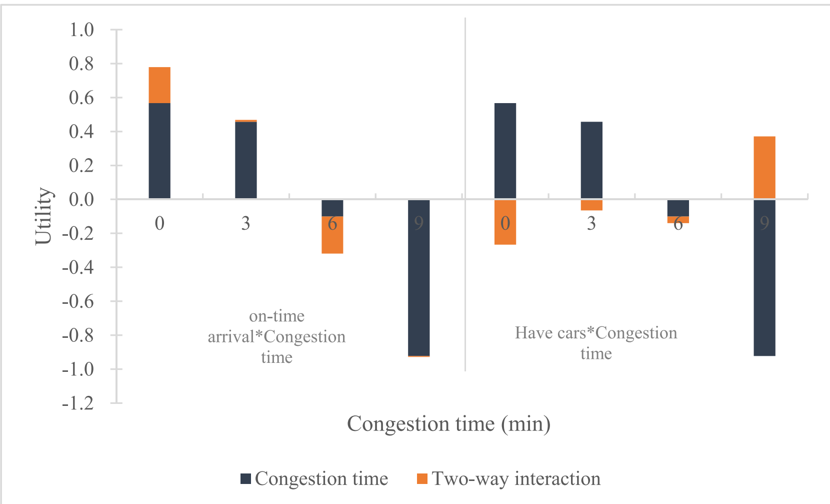

Fig. 6. Two-way interactions about congestion time.

when choosing a parking location for autonomous vehicles. However, the probability to choose a parking place with nine-minute congestion time gets decreased. This implies that there is a strong preference for minimizing congestion time, indicating a limited tolerance for congestion among AV users.

Furthermore, the congestion time of AVs may be highly relevant to the on-time arrival because sometimes the uncertainty underlying the possible congestion may override the choice of a parking place when on-time arrival is a must. Our results show consistent estimates as the probability of parking location choice in the case of six-minute congestion time will be further decreased when there is an on-time arrival requirement.

Because congestion time may have varying effects on different groups of people, especially those who experienced congestion and those who did not. To investigate the difference, we incorporated the interaction effects between car ownership and congestion time Fig. 6, anticipating that individuals who own a car may evaluate congestion time differently. Results show that indeed people who have a car can tolerate a longer congestion time (nine minutes). In another word, the negative effect of the nine-minute congestion time gets smaller for car owners.

5.1.4. Two-way interaction between parking fee and access time

The interaction effects between context variables and main attributes give additional information on the marginal effects influenced by specific contexts. As presented in the experimental design, there might be a potential dependency between the parking fee and access time of a parking location, which is true in many cities, e.g., city centers and rural areas. To explore the two-way interaction effects between parking fee and access time, we included the interaction variable in the model Fig. 7. The results demonstrate that users of autonomous vehicles consistently prefer free parking regardless of whether the access time is short or long. The parking lots with a fee of 4 ¥/h are generally preferable in the case of ten-minute and twenty-minute access time. When the parking fee is 8 ¥/h, individuals still prefer to use the parking lots with ten-minute access time, while the probability of using the parking lots with twenty-minute decreases. When the parking fee is 12 ¥/h, people are reluctant to use the parking lots regardless of the access time. This suggests that implementing a parking fee of eight RMB per hour will distinguish AV users based on their varying preferences for access time.

5.2. Results of the standard deviation of random parameters

As a part of the mixed logit model output, one can see that the standard deviations of random parameters are significant for the parking fee, access time, and congestion time. In case of the parking fee, significant heterogeneity exists among AV users when the parking fee is 4 ¥/h or lower, while no significant heterogeneity was found in the case of 8 ¥/h and 12 ¥/h parking fees. This indicates that, when parking fee gets expensive, the preference of AV users becomes homogeneous. Similarly, significant heterogeneity is also found for access time that is shorter than 10 min, and not for the longer access time (>10 min). This means that, in addition to the systematic heterogeneity analyzed above through the interaction effects, there is also significant unobserved heterogeneity in the sense that short access time will bring varying influences for different people. This is an interesting finding because, for example, some AV users may still not use a nearby parking lot even if the access time is short. This may be attributed to the relatively higher tolerance for long access time among AV users. They are more inclined to park at greater distances to save on parking fees, particularly when engaging in longer-duration activities such as work. In addition, significant taste variation is also found for the congestion time of AVs, indicating that AV users evaluate the uncertainty of picking-up travel time differently.

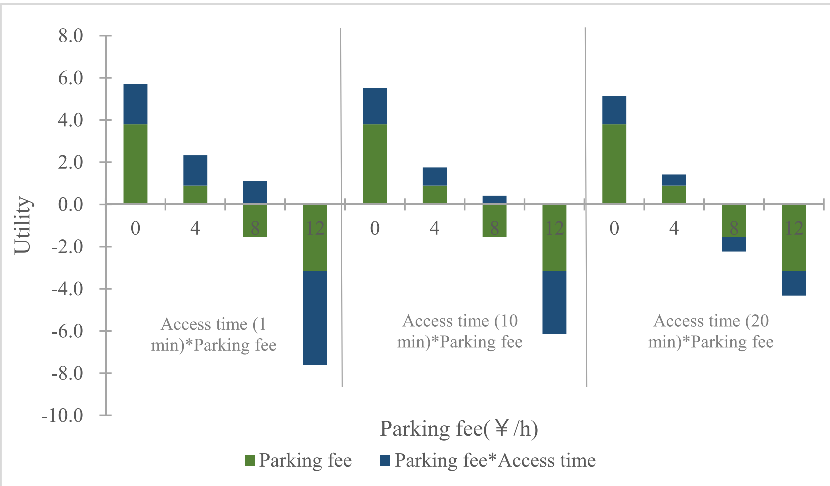

Fig. 7. The effects of parking fees and the two-way interactions between access time.

5.3. The value of access time

As presented above, people tend to choose a farther but cheaper parking lot than a near but expensive parking lot for their AV. Here, a practically relevant question is how much AV users are willing to pay for a parking lot which is varied by parking fee and access time. Thus, based on the results of the MNL model, we calculated the overall value of access time for parking without differentiating user profiles. We found that the value of time ranges from 0.29 RMB/min to 6.36 RMB/min, which is equivalent to 2.44 $/h and 53.4 $/h, respectively. In comparison to the findings of Harmatuck (2007), who observed a value of waking time ranging from 4 $/hour to 30 $/hour in the context of parking traditional cars, the range of value of time in our study is relatively large. Our maximum value of time (53.4 $/h) is bigger. This is perhaps because of the context of parking AVs, while Harmatuck (2007) emphasized the context of traditional vehicles, e.g., people need to walk to the parking places. We also calculated the value of time using an additionally estimated MNL model in which access time and parking fees are continuous values (keeping everything else the same), and we obtained the parameters of parking fee (-0.458) and access time (-0.073), which results to 6.28 RMB/min (52.82 $/h).

5.4. Elasticity of AV parking

Another practical relevance of people's parking decisions is to what extent the choice of parking is sensitive to the change of influential factors, like parking fees and access time. Elasticity is a popularly used indicator, which is defined to describe the change of probability relative to the value change of variables. Here, for the parking choice of AVs, we calculated the elasticity of the main effects, i.e., parking fee, access time, and congestion time. In the calculation, we allow the value of the main effects to change by 1% and check how the probabilities change. Results are shown in Table 4.

It is found that the elasticity of the parking fee of AVs is −0.428, indicating that a 1% increase in parking fee will lead to 0.428 reductions in the probability of choosing the parking lot, assuming all other influences are held constant. This result is well in line with the existing studies that also report the elasticity of parking with respect to the parking fee. In particular, Lehner and Peer (2019) conducted a *meta*-analysis of the price elasticity of parking. The elasticity of parking fee (price) has a value ranging from −0.2 to −2.73. These findings provide a reference for elasticity although they are based on traditional vehicles, while our results of elasticity are for autonomous vehicles.

Furthermore, we found the elasticity of AV parking is −0.304 for access time and −0.122 for congestion time which indicates that a 1% increase in access time and congestion time will respectively result in 0.304 and 0.122 percent decrease in the probability of choosing the parking lot. The elasticity of the parking fee is higher than that of the other two attributes. This perhaps indicates that parking fee has a greater impact on AV users' parking lot choice, compared with access time and congestion time. This result further suggests that AV users exhibit greater sensitivity to parking fees compared to access time.

6. Conclusions and discussions

With the aid of advanced sensors and rapid computing capabilities, the technology of autonomous parking has become mature. As the era of fully autonomous vehicles becomes a reality, AV owners will inevitably encounter the challenge of identifying a suitable parking location that aligns with their individual requirements and schedules, e.g., on-time arrival and short picking-up time. It is reasonable to assume/expect some individuals would park autonomous vehicles significantly farther compared to vehicles driven by human drivers. This is because the effort involved in retrieving a traditional car can be eliminated. By opting for remote parking, individuals can utilize the time saved in picking up the vehicle for other activities or enhance the efficiency of their current tasks. There is no doubt that people's decisions regarding parking autonomous vehicles will significantly impact the planning of parking infrastructures, e.g., price setting according to locations, fewer parking places in central areas, and more parking facilities in distant areas. Therefore, analyzing and understanding parking choice behavior of autonomous vehicle users is necessary and timely for policy decision-making in urban and transportation planning.

In this study, we designed a stated choice experiment to collect the data of the parking location choice of autonomous vehicle users. We attempt to assess the parking choice behavior of AV users with a specific focus on the heterogeneous behavior in different contexts of the current activity and the next trip. By estimating a mixed logit model which incorporates the interaction effects between main attributes and context variables, and the two-way interaction effects between the designed attributes, the taste variation between AV users was identified.

It is found that the attributes known to impact the parking choice of conventional car users also play a role in influencing the parking decisions of autonomous vehicles, including factors like parking fees. As anticipated, implementing a parking fee has proven to be an effective approach in influencing parking choices, including those made by autonomous vehicle users. Within the research area, a parking fee of four RMB per hour or lower is considered an acceptable rate for parking autonomous vehicles. The probability of parking lot choice decreases when the price increases to eight RMB per hour or higher. However, when the access time for picking up an autonomous vehicle is ten minutes, parking lots with an eight RMB per hour fee continue to be the preferred choice. Conversely, as the access time increases to twenty minutes, individuals are more likely to opt for parking lots that offer rates lower than eight RMB per hour.

To specifically address the use of autonomous vehicles, we incorporated the attributes of access time and congestion time during the picking-up trip. The results indicate a general preference for access times of ten minutes or less. However, when the time window is long, e.g., five hours, the most accessible parking lots (e.g., within one minute) are not preferred, which is probably because highly accessible parking lots often come with higher prices. In the case of a short time window (one hour), the probability of using the most

Table 4
Elasticity of main attributes.

Attributes	Elasticity
Parking fee	−0.428
Access time	−0.304
Congestion time	−0.122

accessible parking lot increases. Given that individuals are not constrained to personally retrieve their cars, they may choose to utilize parking lots located farther from their activity location, particularly when engaging in relatively long-duration activities. The findings hold significant implications for the planning and development of parking infrastructures.

Furthermore, the effects of AV-specific attributes are not examined in isolation but rather within the context of the subsequent trip, e.g., the requirement for on-time arrival. This is because the uncertain travel time of a picking-up trip may influence the arrival time at the next activity location. The congestion time of picking up trips is found to negatively impact the parking lot choice when the time is longer than six minutes. When on-time arrival is required, the effects of congestion time become larger. In other words, individuals who have the need to arrive punctually for their next trip are unlikely to opt for a parking lot that would result in congestion time of six minutes or longer. Furthermore, the effects of congestion time on parking lot choice vary between different people. The results reveal that individuals who own a car exhibit a higher tolerance for congestion time, specifically up to nine minutes. This is evidenced by the relatively smaller negative impact of a nine-minute congestion time on the probability of parking lot choice among car owners.

The findings presented in this paper have clear practical implications for policy decision-making. Firstly, policymakers have the opportunity to establish a distinct pricing scheme for autonomous vehicles, separate from the one applied to human-driven vehicles. Such a policy approach can be employed to effectively influence the traffic flow resulting from parking and picking-up trips. Secondly, the insights obtained regarding the access time of autonomous vehicles provide crucial guidance for the planning of parking locations. On one hand, parking locations should be easily accessible. On the other hand, efforts should be made to minimize uncertainties arising from congestion time during picking-up trips. Moreover, it is important to optimize the parking fee in conjunction with the access time to ensure that parking autonomous vehicles is guided effectively.

The topic of parking for autonomous vehicles is an important subject, however, there remains a scarcity of research that explores this subject from a behavioral perspective. Therefore, the current study is considered an initial exploration. In the future, further research is needed to incorporate the distinctive aspects of autonomous vehicle parking to a greater extent. For example, dedicated parking lots for autonomous vehicles only might impact the choice of parking lots. Moreover, people may need to decide between parking and cruising (sharing with other people), which seems to be a more critical issue relevant to traffic control. In addition, the results presented in this study are highly dependent on the local context and with a limited number of samples. Future studies should continue the effort by investigating the parking location choice of autonomous vehicles, e.g., in different cities and using larger samples. Ultimately, as the era of autonomous vehicles unfolds, actual data will provide a true depiction of the parking behavior exhibited by AV users. Nevertheless, we anticipate that additional insights into this line of research will be incrementally acquired over time.

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.

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