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A reservation-based parking behavioral model for parking demand management in urban areas

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ABSTRACT

The rapid increase in car ownership has become a land-use problem in many cities which have limited land for parking. It also has adverse impacts on congestion, air quality, energy consumption, as well as losses in productivity, among other consequences. The problem worsens in some cities due to the adoption of inefficient mandatory minimum parking policies for new projects, according to a building's use and size, which incentivizes driving. Therefore, it is necessary to assess appropriate parking management policies that maximize social welfare. In this regard, this paper presents a reservation-based parking behavioral hybrid choice model for parking demand management policies in urban areas, that appropriately represents the behavior of private vehicle users when choosing their parking site. The proposed model is statistically significant and consistent with expected behavior and microeconomic theory. The results demonstrate that the possibility of reserving a parking space has a significant impact on car parking market share on- and off-street. The three latent variables included in the model (pro-parking attitude, perception of risk for parking on- and off-street) have a significant effect on the modal split and the evaluation of appropriate parking policies that consider heterogeneity. The latent variable that most impacts the modal shift is the pro-parking attitude, which can generate up to 7% change in the modal partition.

1. Introduction

Factors related to the rapid increase in car ownership, inefficient parking management policies, mandatory minimum parking requirements for new projects, and the widespread belief that parking is a right, have led to a significant problem in urban areas, since parking incentivizes driving [1]. Furthermore, with limited land available for parking and the inefficiency of public transport in developing economies, it has become progressively more difficult to meet the demand for more car parking [2,3]. As a result, traffic congestion has increased, leading to more fuel emissions, energy consumption, and productivity losses [4–6].

Initially, the parking policy paradigm for solving these problems was to increase the supply to meet the demand [3], which relies on parking minimums. However, the supply-focused approach has increased the likelihood of owning a car. It has also reduced the available public space for all city residents to access and enjoy physical activities, public transport, and other essential activities for recreation, social, cultural, and economic development. Nowadays, parking demand management is the most common way to deal with all these problems, by designing policies that decrease demand and influence modal shifts [7]. Users can respond to parking policies by changing their parking behavior, mode of transportation, destination, schedule, or activity [7]. This involves parking supply, pricing, and reservation strategies. Under this novel approach, instead of promoting minimum parking requirements, mandatory maximums parking is established.

The intelligent parking reservation system is a plausible alternative to parking demand strategies. According to this approach, price models are assessed according to users' willingness to pay for zero search time, thus increasing providers' revenue, while reducing drivers' search costs and total emissions [8]. One example of a parking reservation strategy is flexible reservations. This mechanism tolerates predetermined spatio-temporal flexibility, reducing service failures caused by late departures [9]. Parking reservation mechanisms reduce search times, fuel emissions, road congestion, and accidents [8–11]. However, to the best of our knowledge, there is a gap in the literature regarding the study of parking choice behavior when users can reserve parking.

Furthermore, intelligent devices and the Internet of Things

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technology are necessary to properly implement parking reservation mechanisms [11]. A technical team effort between the city as a whole and transport initiatives is also necessary to ameliorate living conditions, competitiveness, and sustainability [12]. These issues are challenging, especially in emerging economies where social, economic, geographical, and political constraints impose specific conditions for implementing appropriate parking policies.

This paper aims to fill these gaps by estimating and assessing a reservation-based parking behavioral hybrid choice model for parking demand management policies in urban areas. The modeling approach also includes the influence of pro-parking attitudes and the perception of risk for parking a car on- and off-street. These latent constructs capture population heterogeneity for a more accurate cost-benefit evaluation of different parking demand strategies. Using Colombia as a case study, the proposed model was estimated based on stated preference data collected through surveys of car users. This approach quantifies the factors, preferences, and attributes that determine the willingness to use a parking reservation scheme in urban areas and simulates potential policy scenarios. The findings from this study serve as a tool for policymakers and planners to design policies focused on enhancing the adoption of alternative parking plans to reduce negative externalities.

The paper is organized as follows: section 2 reviews the literature of previously estimated parking behavioral models; section 3 explains the research context; section 4 shows the methodology, describes the sample and profile of the respondents, the indicators used to form the individual attitudes, and the stated preference experiment; section 5 illustrates the model formulation and the choice model; section 6 displays the models estimated and their respective analysis, validation process and sensitivity, and economic indicators for parking management; section 7 summarizes the significant findings from the study; and section 8 contains our conclusions.

2. Literature review

Multiple authors have analyzed parking choice behavior in Intelligent Transportation Systems and parking demand management. Some researchers have assessed individual heterogeneity, considering location and trip purpose [13]. Others have studied socioeconomic factors instead, such as gender, age, occupation, level of education, income, cars per person in a household, car age, and car price [5]. Some researchers have estimated models considering parking choices between on-street, off-street, and underground parking [4], where on-street parking can either be free or have a cost [5].

The risk associated with illegal parking is also a matter of concern. Based on stated preference surveys conducted in the United Kingdom [13], one study demonstrated that most of the population was law-abiding. In contrast, studies in China concluded that the population was prone to illegal parking, possibly due to lack of law enforcement [14]. Furthermore, extensive research has examined travel itineraries, with attributes such as travel time, search time, and egress time among the most recurrent [15].

Parking lot attributes are also of interest within parking choice behavior [2]. explored consumers' preferences towards different shared parking features when considering and choosing a shared parking option. Studies regarding vehicle sharing systems have assessed parking choice behavior under some parking reservation policies [16]. Nonetheless, to the best of our knowledge, there is a gap in the literature regarding the study of parking choice behavior when users can reserve parking. Bearing this in mind, our model contributes to understanding the parking choice behavior of car users.

Car users could change their transport mode when facing more attractive mode alternatives than the status quo. Suppose an individual chooses a car option in a developing country. In that case, a subsequent decision is to choose a place where parking safety, whose available alternatives are usually on- or off-street. Whichever selected alternative, in a parking demand management policy, the individual could reserve a parking space at the destination. Following this line of thought, a choice tree is proposed in Fig. 1, where the transport mode is followed by the parking place and the reservation mechanism choice.

Although many studies have applied Discrete Choice Models (DCM) to study parking choice behavior [2,4,5,13,14,17,18], few authors have analyzed the effects of attitudes and perceptions on parking decisions. For instance, using a hybrid DCM [5], studied parking choice behavior among three parking type alternatives in downtown Cartagena, Colombia. They found that latent variables such as positive car care and risk-aversion were determinants in parking choice, these were the same as parking fee, search time, and egress time. In downtown Tunis, Tunisia [4], also examined parking choice behavior among three alternatives using a DCM: off-street, on-street, and underground parking. However, they did not consider latent variables.

[2] developed a latent class model to assess users' attitudes towards shared parking features in New South Wales, Australia. They used a multinomial logit model to show that a parking fee is the most effective shared parking policy. Additionally, they demonstrated the significance of egress time and suggested it should be considered in pricing policy schemes [19]. built a structural model for understanding users' acceptance of shared parking in China. They found that the construct that most favorably affected users' attitudes and intentions was the perceived usefulness of shared parking, which is highly influenced by perceived network externality, rather than perceived ease of use. Other authors, such as [20]; have explored the attitudes towards women-only parking spaces.

In short, several types of latent variables have been studied in discrete choice models, as listed in Table 1. These variables can either be attitudes or perceptions of the mode. Unlike other studies, which only ponder observable factors, this paper also considers individual attitudes and perceptions that may influence parking choice behavior. To the best of our knowledge, this is the first study to examine both a pro-parking attitude and perception of risk for parking on- and off-street. Moreover, this is the first study in emerging countries to consider both mode and parking choice in a hybrid DCM (see Table 1).

3. Context

This research took place in Cali, Colombia, the third-largest urban area in the country located in the southwest of the country with approximately 2.2 million inhabitants [21,22]. The city has approximately 700,000 motor vehicles, of which 64% are private cars, 31% are motorcycles, and the remaining percentage is divided between buses, taxis, and trucks. Motorized modes represent 62.3% of the 3.6 million urban daily trips. Most of them correspond to private vehicles (30.8%), including private cars and motorcycles, followed by official public transport (21.4%) and other modes (10.1%) [23]. The city's official public transport is SITM-MIO, a Bus Rapid Transit (BRT) system.

In 2019, a Special Regulation Parking Zones (SRPZ) policy was launched with a pilot scheme in an area in Cali popular with tourists. Its purpose was to raise funds to subsidize the public transport system, which has a significant financial deficit, affecting service quality and coverage. This policy allows the municipality to exploit street parking in twelve zones. In these zones there is a high demand for parking which is linked to business and service activities and needs comprehensive management for both on and off-street parking.

The SRPZ policy allows cars and motorcycles to park in some authorized places on-streets from Monday to Saturday between 09:00–21:00, paying a particular time-based rate per hour for cars and motorcycles, plus a fixed charge of USD 0.21 to finance the BRT deficit. Parking out of the authorized places in the delimited parking zones leads to a penalty fee of 122 USD and vehicle immobilization. This policy is expected to improve the city's mobility by regulating street parking usage in high-demand areas and to supply 17.5% of the resources to finance the BRT deficit by 2023 [24]. Nevertheless, under [25]; no guidelines are provided concerning the parking reservation policy,

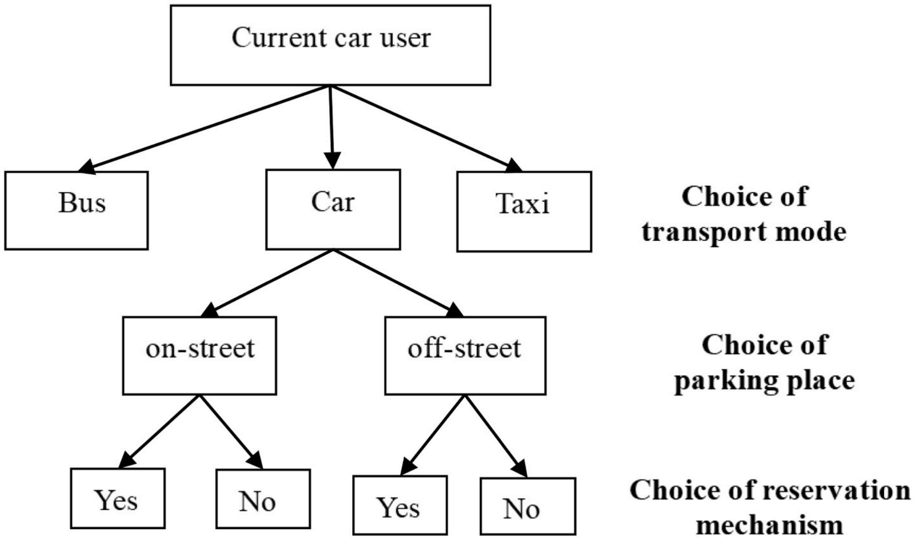

Fig. 1. The choice tree for car users.

Table 1
Latent variables in parking choice behavior.

Author (year)	Country	Latent variables	Reservation variable	Choice type
[13]	United Kingdom	Risk-aversion attitude	No	Parking
[5]	Colombia	Risk-aversion attitude, positive car care attitude	No	Parking
[9]	United States	Region flexibility attitude, time flexibility attitude	Yes	Reservation mechanism
[18]	China	Trust attitude towards parking apps	Yes	Parking
[2]	Australia	Preference towards shared parking features	Yes	Parking
[19]	China	Attitude and use intention, perceived usefulness and perceived ease of use, subjective norm and perceived behavioral control, perceived network externality, perceived risks for shared parking	Yes	Parking
[20]	China	Attitude towards women-only parking spaces	No	Parking
This paper	Colombia	Pro-parking attitude, perception of risk for parking on- and off-street	Yes	Mode, parking place, and reservation.

which could help to control parking problems by making the cost of parking changes based on demand.

In this context, a parking reservation strategy could match parking supply and demand better and eliminate the time spent searching for a spot and reduce congestion. In this sense, the proposed model presented in the following sections would help transport planners and decision-makers understand car users' parking behavior when it is possible to reserve a parking space.

4. Methodology

A Stated Choice (SC) survey was conducted in Cali to study the parking choice behavior of car users when they reserve a parking space. The SC was comprised of three different sections: (i) socioeconomic information for car users; (ii) nine individual indicators about a pro-parking attitude, and perception of risk for parking on- and off-street, as shown in Table 5; and (iii) a discrete choice experiment with nine hypothetical choice scenarios for traveling to public areas in downtown Cali (where SRPZs exist).

A number of essential aspects were considered to minimize bias in this study. The first was to conduct a focus group with car users to explore variables and other key factors influencing their decision to travel by car to their usual destination. Second, based on information gathered from focus groups, we tried to design a realistic and credible discrete choice experiment for respondents, avoiding the combination of attribute levels that cannot exist in the real world. Third, after conducting pilot tests, the resulting questionnaire was examined several times as part of the design process. Finally, the interviewers were trained to carry out the survey.

4.1. Sample and profile of the respondents

The SC survey was conducted in October 2021 among 309 car users who were randomly selected, whose main destination was downtown Cali. Concerning the socioeconomic characteristics of the respondents, the gathered information was demographically compatible with the characteristics of car users identified in the Cali mobility survey 2015 [23], as shown in Table 2. The gender and age population distributions are like our sample distribution, while the distribution of the level of income is close to the general population in Cali. A comparison between expected and observed frequencies for each socioeconomic category using the Chi-squared test, shows that the obtained Chi-square value is lower than the critical value at 95% confidence. Hence, our observed frequencies are significantly similar to the theoretically expected distribution. The discrepancies between the observed and expected frequencies are due to random sampling variation.

The respondents represented a broad range of socioeconomic conditions. Their levels of education were: 4% primary, 21% secondary, 55% college, and 20% graduate. The main employment status was employed (48%), then self-employed (39%), followed by retired people and students (6%), and unemployed (2%). The average age of the respondents was 46 years old. The gender difference was predictable, as

Table 2
Profile of respondents.

Characteristic	Level	Our sample (%)	Population distribution (%)[a]	χ^2_{value}	$\chi^2_{0.95;m-1}$
Gender	Male	77	77	0.0068	3.84
	Female	23	23		
Age	24 or less	6	3	8.305	11.07
	25–34	14	13		
	35–44	24	22		
	45–54	26	25		
	55–64	21	21		
	65 or more	9	17		
Level of income	1	0	6	11.049	11.07
	2	12	18		
	3	32	28		
	4	22	19		
	5	22	17		
	6 (maximum)	11	9		

[a] The population distribution is based only on the characteristics of car users identified in the Cali mobility survey 2015.

74% of driving licenses in Colombia and 77% of cars in Cali are owned by men [5,23]. In general, the sample distribution is representative of private vehicle users in Cali.

We hypothesize that parking choice behavior does not depend exclusively on observable factors. Thus, it can be associated with individual-specific latent constructs, such as a pro-parking attitude and the perception of risk for parking on- and off-street. To identify these attitudes and perceptions, we introduced the indicators shown in Table 3.

It seems logical that an individual with a pro-parking attitude would favor government policies that allow more street parking spaces. After all, the previous parking policy paradigm focused on meeting demand, not on promoting effective management of the current supply and ever-growing demand (Dave et al., 2019). Moreover, they would also probably agree that the city needs more parking buildings, increasing supply, which comes from the belief that parking is a right, and not a land-use issue that is subject to market forces. In the same way, people with a pro-parking attitude will probably feel more confident about arriving on time to carry out their activities if they can reserve parking, which is understandable, because parking reservations minimize parking search time. Thus, users will have more control over their schedule.

Table 3
Latent variable indicators and levels.

Latent variable	Type	Indicator	Description
Pro-parking attitude (Z1*)	Attitude	I_1	Local government should provide more street parking spaces.
		I_2	The city needs more parking lots
		I_3	The chance of reserving a parking space gives me the confidence that I will not arrive late to work/place of study.
Perception of risk for parking on-street (Z2*)	Perception	I_4	Chance of being robbed when parking on-street.
		I_5	Chance of vehicle damage when parking on-street.
		I_6	Chance of an accident while parking on-street.
Perception of risk for parking off-street (Z3*)	Perception	I_7	Chance of being robbed when parking off-street.
		I_8	Chance of vehicle damage when parking off-street.
		I_9	Chance of an accident while parking off-street.

Regarding the perception of risk when parking, it makes sense that users are concerned about robberies, vehicle damage, or accidents. For instance, street parking is especially vulnerable to robbery and vehicle damage as this parking option may or may not be supervised by a parking attendant. Moreover, as cars parked on-street are in direct contact with traffic, they are even more at risk of being involved in an accident. Car users may also feel concerned about parking off-street, although that may depend on its location and characteristics. According to Ref. [2]; the extra feature with the highest impact on parking choice behavior in shared-parking apps is closed-circuit television, followed by security patrol and security gates. Such behavior seems rational, as users are inclined to reduce risk, and these features provide a sense of security. Results also showed that the most popular parking type option was the “lockup garage” with a probability of 39% [2]. Once again, users demonstrated their likelihood to choose safer parking spaces.

The latent variable indicators in Table 5 were rated by respondents on a 5-point Likert scale ranging from “None” to “A lot” (1 = Nothing; 5 = A lot), as shown in Table 4. The higher the percentage, the darker the shade of green. The mean (M), standard deviation (SD), and minimum residual (MR) for each indicator are also given. In general, respondents agree with a more generous parking supply policy. On the other hand, contrary to the pattern shown for the perception of risk for parking on-street, car users perceive little chance of robbery, vehicle damage, and accidents when parking off-street.

In addition, an exploratory factor analysis (EFA) was developed with the indicators previously presented. EFA aimed to define the underlying structure among the latent constructs in the analysis. We calibrated the model by extracting three factors using the varimax criterion as an orthogonal rotation method. The latent constructs Z1, Z2, and Z3 were identified using minimum residual factor analysis, whose relative amounts of variance were 0.26, 0.40, and 0.34, respectively. Table 4 (MR column) shows that the latent constructs accounted for the maximum variance in its corresponding indicators. The model fit statistics are provided in the legend of Table 4, which indicates a good fit to the observed data [26,27]. The intention measured by the nine indicators and latent variables was included in the Hybrid Choice Model (HCM) shown in section 5.

5. Stated preference experiment

As indicated above, a discrete choice experiment was conducted to evaluate the parking choice behavior of car users when they reserve a parking space, which can be influenced by a pro-parking attitude and risk perception of parking on- and off-street. According to the study context, nine hypothetical choice scenarios for traveling to public areas in downtown Cali were shown to respondents. Each stated preference scenario included four options, as seen in Table 5: (i) Bus; (ii) Taxi; (iii) Car parking on-street; and (iv) Car parking off-street. The chosen observable factors were travel time, walking time at the destination, search time for parking at the destination, the possibility of reserving a parking space at the destination, the possibility of finding an available parking space at the destination, and cost. As indicated above, the attribute levels were set based on a focus group with car users.

Table 5 shows the attributes and levels for the experimental design. The off-street parking option has a higher cost per hour than the on-street option.

The main effects and interactions of all attributes required 36 choice situations following an orthogonal block design with level balance [28]. It was not feasible to develop this enormous number of choices, so a fractional factorial design was used. As a result, the orthogonal design was divided into four blocks using the Ngene® software [29].

The following choice behavior was observed: Bus (24%), Taxi (15%), Car parking on-street (21%), and Car parking off-street (40%). Concerning these last two alternatives, 15% of males and 6% of females chose parking on-street, while 31% of males and 9% of females chose

Table 4
Rating of indicators and Exploratory Factor Analysis.

Latent variable	Indicator	None	Very little	Somewhat	Quite a lot	A lot	M	SD	MR
Pro-parking attitude (Z1*)	I1	16%	29%	10%	32%	13%	2.98	1.33	0.13
	I2	1%	6%	11%	45%	37%	4.12	0.89	0.99
	I3	2%	9%	17%	34%	37%	3.94	1.06	0.34
Perception of risk for parking on-street (Z2*)	I4	3%	8%	28%	46%	15%	3.62	0.93	0.65
	I5	1%	5%	23%	53%	19%	3.84	0.81	0.76
	I6	4%	24%	37%	31%	4%	3.07	0.93	0.63
Perception of risk for parking off-street (Z3*)	I7	47%	40%	10%	2%	1%	1.68	0.77	0.74
	I8	37%	46%	14%	3%	0%	1.84	0.79	0.86
	I9	31%	46%	18%	4%	0%	1.95	0.82	0.57

Fit statistics: Tucker Lewis Index of factoring reliability (TLI) = .942; Goodness of Fit Index (GFI) = .99; Root mean square of the residuals (RMSEA) = .053; Root mean square of the residuals (RMSR) = .02

Table 5
Attributes and levels of experimental design.

Attribute	Bus	Taxi	Car parking on-street	Car parking off-street
Travel time [TT] (min)	20, 40, 60	15, 30, 60	15, 30, 60	15, 30, 60
Walking time at destination [WTd] (min)	5, 10, 15	0, 2, 4	3, 6, 9	3, 6, 9
Cost [C] (USD/hr)	0.51, 0.56, 0.61	1.46, 2.93, 4.39	0.37, 0.49, 0.61, 0.73, 0.85, 0.98, 1.10	0.73, 0.85, 0.98, 1.46, 1.59, 1.71
Search time for parking at destination [STp] (min)			0, 4, 7, 10	0, 5, 10, 15
Possibility of reserving a parking space [R]			No, Yes	No, Yes
Possibility of an available parking space [Pas]			High, Medium, Low	High, Medium, Low

*1 USD ≈ 3846 COP (October 2021).

parking off-street. The modeling in the next section was developed based on this data.

6. Modeling

We estimated an HCM based on the random utility theory to evaluate reservation-based parking behavior. The approach assumes that individuals seek to maximize their utility and have the most accurate information, so that they rationally select the alternative that maximizes their net utility [30]. Under these assumptions, the choice maker n faces a set of available alternatives J, each of which has an associated utility U_{jnt} from alternative j in choice situation t with the structure of Eq. (1).

$$U_{jnt} = V_{jnt} + \varepsilon_{jnt} \tag{1}$$

In Eq. (1), V_{jnt} is the systematic component of the utility, usually specified as a linear combination of measurable explanatory attributes X_{jnt}, whereas ε_{jnt} is a random error component. The logit model is derived if the random component is assumed to be Independent and Identically Distributed (IID) extreme value type I.

On the other hand, for the inclusion of attitudinal and perception factors, we estimated hybrid Latent Variable (LV) choice models [31]. The Multiple Indicators Multiple Causes (MIMIC) model allows modeling the latent variables using a structure with two components. On one side are the structural equations, Eq. (2), which relate the socio-economic characteristics of the individual n (S_n) with the latent variables l (Z_n). And on the other side, the measurement equations, Eq. (3), which relate the latent variables with the set of indicators (I_{nm}) shown in Table 3.

The model formulation included nine (9) measurement equations, one for the chosen alternative in the discrete choice model and one for each indicator given in Table 1 ($m = 1, \ldots, 9$). Each indicator in Table 1 included five categories, so the measurement equations were specified following ordered logit type models, based on Eqs. (3) and (4) [32]. For each indicator, k-1 thresholds ($\boldsymbol{\tau}$) were specified, among which a continuous latent variable would have the following value.

$$Z^*_{nl} = \boldsymbol{\lambda_l S_n} + \omega_{nl} \tag{2}$$

$$I_{nm} = \boldsymbol{\gamma_m Z^*_n} + \upsilon_{nm} \tag{3}$$

$$I^*_{nm} = \begin{cases} 1 & \text{if } \tau_{0m} < I_{nm} < \tau_{1m} \\ 2 & \text{if } \tau_{1m} < I_{nm} < \tau_{2m} \\ & \ldots \\ K & \text{if } \tau_{K-1m} < I_n < \tau_{Km} \end{cases} \tag{4}$$

I_{nm} is the continuous indicator m.
I^*_{nm} is the categorical indicator m.

The set of thresholds $\boldsymbol{\tau}$ must be estimated. For identification $\tau_{0m} = -\infty$ and $\tau_{Km} = +\infty$ are fixed.

Fig. 2 shows the general diagram of the hybrid choice model, in which rectangles represent observable explanatory variables, both from the individual and the alternatives [31], while ellipses represent latent variables since they are unobservable to the analyst. Solid arrows represent structural equations, while dashed arrows represent measurement equations. The DCM explains the chosen alternative, while the MIMIC model describes the relationships between the latent variables and their indicators and causes [33]. As the individual's utility for alternative j (U_{nj}) is an unobservable factor, it is also considered a latent variable.

The notation used in the Hybrid Choice Model is as follows:

Z_{n1}: Latent Variable "Pro-parking attitude" of individual n.
Z_{n2}: Latent Variable "Perception of risk for parking on-street".
Z_{n3}: Latent Variable "Perception of risk for parking off-street".
Y_{nj}: Choice indicator. 1 for the chosen alternative, 0 otherwise.
X_{n1}: 1 if the individual has a college degree, 0 otherwise.