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Carpool-Based Parking Assignment Policy

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National Institute for Congestion Reduction
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16. Abstract

A new travel demand management (TDM) strategy is proposed that integrates ride-matching and parking management to tackle traffic congestion and air pollution problems that arise when the demand for parking spaces exceeds parking supply. The proposed strategy implements a centralized system that assigns parking spaces, free of out-of-pocket costs, according to users' reservation requests, users' travel schedules, and available parking supply. Concurrent to the parking assignment process, the system coordinates carpools by finding minimum travel cost matches between drivers whose parking requests were accepted and system participants that require transportation. This report presents an optimization model for the implementation of the proposed Parking Allocation-Ride-Sharing (PARS) system, an analysis of survey participant's perception of the strategy, and a discussion of a proof-of-concept application of the PARS system at the University of Puerto Rico at Mayagüez.

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Table of Contents

Figures

Tables

Abbreviations and Acronyms

ANOVA	Analysis of Variance
MIP	Mixed Integer Lineal Programming
MRS	Marginal Rate of Substitution
NP	Nondeterministic Polynomial Time
PARS	Parking Allocation and Ride-Sharing System
P2P	Peer-to-Peer
STM	Secondary Travel Mode
TDM	Travel Demand Management
UPRM	University of Puerto Rico at Mayagüez
USF	University of South Florida
WTA	Willingness to Accept

Executive Summary

This report presents the Parking Allocation and Ride-Sharing System (PARS), a new policy for mitigating traffic congestion and managing parking scarcity problems. In PARS, a centralized algorithm allocates parking spaces, which are free of out-of-pocket cost, to drivers who are willing to participate in a coordinated carpool. The algorithm is used to optimize the creation of carpools going to and returning from a particular venue and simultaneously reserve parking for these carpools at the venue. The individuals participating in PARS are self-classified as drivers and riders. Since all individuals must be included in a carpool, drivers who do not receive a parking reservation are included as a rider in another carpool. The report presents an optimization model to implement PARS, the results of a survey-based policy analysis, and a discussion of a real-world implementation of a PARS-type service at the University of Puerto Rico at Mayagüez (UPRM).

An efficient mixed integer linear programming (MIP) formulation is presented and two heuristics, namely Ride Decomposition (RD) and Quick Converge (QC), are proposed and compared via internally generated experiments. Experimental results show that a commercial solver can solve the MIP with thousands of individuals to optimality in minutes. For larger instances, the RD and QC heuristic algorithms can solve the problem, on average, 42.23% and 86.39% faster than the commercial solver and provide solutions that are 3.61% and 3.49% from optimal, respectively.

PARS is proposed as a more equitable travel demand management alternative than conventional parking pricing schemes. However, it is unclear to what degree commuters would prefer PARS, which introduces the possibility of having to travel in a carpool, over a parking pricing scheme. To examine people's preferences for PARS and parking pricing, a stated-preference survey was developed and distributed in two universities: UPRM and the University of South Florida (USF), Tampa Campus. Survey participants were presented with hypothetical choice scenarios in which they had to select between different parking and mode choice alternatives with varying attribute levels. Discrete choice analysis was used to estimate parking and mode choice models using the collected survey data. The model results suggest that females exhibit a stronger interest in carpooling as drivers when guaranteed parking is provided, the probability of selecting the carpooling alternative increases with higher parking costs, and the carpooling choice probability is relatively inelastic with respect to changes in parking cost. The results indicate that, in a situation in which PARS is implemented along with parking pricing, the parking costs serve as an effective incentive for PARS, especially in universities with limited transit services and parking supply.

A PARS prototype was launched at UPRM on March 7, 2024. The main prototype components are a mobile application called ROCS Carpool and a solar-powered mechanical parking gate that controls access to a 28-space section of the reserved parking area. ROCS operated for 27 days, with a peak use level of 27 parking reservation requests. A main lesson learned from this real-world experiment is that, even in a university context with significant parking problems, robust marketing and communications strategies are needed to overcome misconceptions about the carpooling service given comparisons against existing ride-hailing services (e.g., experiences with Uber or Lyft). Additionally, the main barrier to the use of ROCS was wariness of potential users due to the possibility of carpooling with an unknown person, even though the carpool driver and other passengers are members of the same institution.

Chapter 1. Introduction

Excess demand for parking in high-density areas is a perennial challenge. Often, increasing parking capacity is physically impossible, economically infeasible, or environmentally undesirable. Even when increasing parking capacity is viable, the long-term benefits of such projects are unclear given latent demand; more parking spaces invites more traffic, and its associated costs, and decreases space that could be available for other transportation modes or urban uses. As increasing parking supply is not a viable alternative, a more sensible response to parking demand problems in congested road networks is to implement travel demand management (TDM) strategies.

There are two parking dynamics that must be addressed by TDM strategies: the excessive use of parking and the inefficient distribution of demand across different locations (Small & Verho, 2007). Parking pricing has been proven effective in tackling both issues, which is why it has received considerable attention from economists, urban planners, and engineers, among others (e.g., D'Acierno et al., 2006; Inci, 2015; Qian & Rajagopal, 2014; Wang et al., 2022). Parking pricing has also led to successful parking management systems initiatives, such as San Francisco's SFpark initiative (Millard-Ball et al., 2014). However, implementing a parking pricing scheme remains a highly controversial proposition given that it is commonly viewed as a regressive tax that succeeds at the expense of lower-income users. The income-based equity argument is particularly relevant in environments in which drivers have few, if any, alternative modes of transportation on their way to performing mandatory activities (e.g., car-dependent commuters in low density, auto-centric communities). *Considering the equity concerns and accompanying political challenges associated with parking pricing, the primary objective of this report is to present a novel non-pricing parking control policy, called the Parking Allocation and Ride-Sharing (PARS) system.*

In the PARS policy, parking spaces are allocated, free of out-of-pocket cost, to drivers and riders who are willing to participate in a coordinated carpool going to a common venue or general area. The general idea in PARS is as follows:

i. There is a software platform where individuals requiring transportation from a location (e.g., their home) to a specific venue (e.g., the university), from the venue to a location, or both (to and from the venue), enter their request. These individuals are referred to as *riders*.

ii. Similarly, individuals that are interested in driving to that venue would use the software platform to request a reserved parking space at the venue. These individuals are referred to as *drivers*.

iii. A centralized algorithm combines the riders' and drivers' information to optimize the creation of carpools between drivers and riders, and reserve parking spaces for these carpools at the venue. A carpool would start at the driver's initial location, pick-up the riders specified by the centralized algorithm from their respective locations and complete the trip to the venue. At the venue, the carpool vehicle would have a guaranteed parking space. On the trip back, the carpool includes a potentially different set of riders specified by the algorithm that are to be transported from the venue to their respective locations.

Since not all potential drivers can have a guaranteed parking space, the algorithm will ensure that drivers who do not receive a parking reservation are included in a carpool as a rider. Also, all individuals must be included in a carpool going to, and returning from, the venue. Figure 1 summarizes the inputs and outputs of the PARS policy. Individuals, self-classified as drivers or riders, will provide to the system basic information regarding their pickup and drop-off location (i.e., depot) and the desired arrival and departure times at the venue. Individuals who seek to be drivers of the coordinated carpool will also need to provide information regarding their vehicle's passenger capacity. The PARS algorithm will use this input and the venue's parking capacity to construct carpools such that a cost metric (e.g., travel distances) is minimized and parking is reserved for the carpools. A carpool includes all the individuals who travel with a particular driver going to, and returning from, the venue, including the driver.

The right side of Figure 1 highlights two constructed carpools with six individuals that requested trips to PARS. In Carpool 1, the assigned driver will pick up two assigned individuals and take them to the venue. One of those individuals was self-classified as a rider and the other one as a driver. Since the algorithm did not grant a carpool to that individual as a driver, that individual was instead assigned to the carpool as a rider. Given the nature of the PARS centralized algorithm, the individuals in the carpool will have similar arrival times to the venue as the driver and will have starting locations that are relatively close to the driver's stating location. When the assigned driver leaves the venue, that individual will provide transportation to the two riders that were assigned to the carpool's return trip. The algorithm should ensure that these riders will have similar departure times from the venue compared to the driver and will have locations relatively close to the driver's starting location.

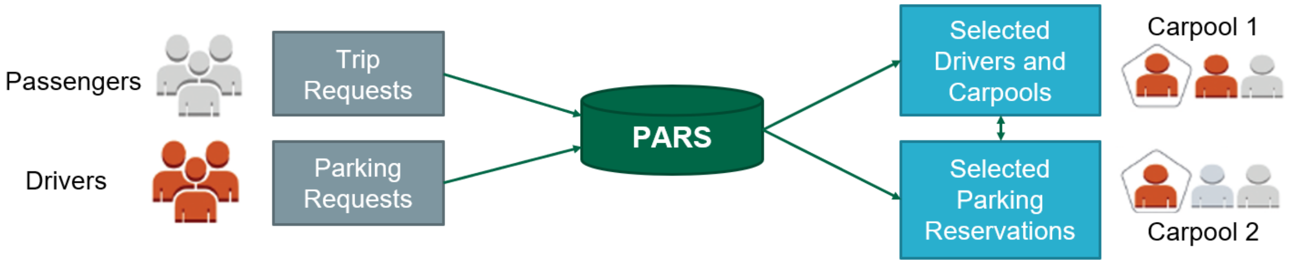


Figure 1. Inputs and outputs of the PARS policy

In areas with limited public transportation and parking scarcity problems, the PARS policy could improve the mobility and travel accessibility of targeted populations. Moreover, by coordinating trips and reducing the number of vehicles on the road, PARS has the potential of mitigating traffic and pollution problems caused by the mismatch between parking demand and supply. Examples of possible venues in which PARS could be implemented include universities, shopping malls, sports venues, or a downtown area with limited parking capacity. The ultimate congestion reduction and environmental impact of PARS in each of these venues would need to be carefully assessed considering multiple factors, including the complex dynamics that drive vehicle-generated air pollution (Pisoni et al., 2019). However, current evidence suggests that carpooling-based schemes have a positive environmental impact (e.g., Amatuni et al., 2020) and that the possibility of these impacts can motivate participation in this type of coordinated travel (Hartl et al., 2020).

The main contributions of this study are:

1. Introduction of PARS, as a novel travel demand management policy.
2. Mixed integer linear programming (MIP) formulation and two heuristics that may be used as the PARS centralized algorithm. The proposed policy extends previous work on ride-matching problems and peer-to-peer (P2P) ride-sharing systems by incorporating parking capacity consideration in the process of coordinating carpools.
3. Analysis of traveler preferences between PARS and parking pricing schemes based on discrete choice experiments.
4. A discussion of lessons learned from a real-world implementation of PARS.

The remainder of the report is organized as follows:

- *Chapter 2. Literature Review*: Incudes a review of previous work related to ride-matching, non-pricing parking management strategies, non-pricing travel demand management strategies, and parking management in universities.
- *Chapter 3. Model Formulation and Heuristic*: Discusses the proposed mathematical optimization model to implement the PARS policy, as well as heuristics to find solutions to the models. Results from numerical experiments using the models and heuristics are also presented in this chapter.
- *Chapter 4. Exploring Parking Policy Preferences Schemes*: Presents the development and results from a survey that was designed to examine people's preferences between parking pricing and PARS schemes. The survey was distributed among members of the University of Puerto Rico, Mayagüez (UPRM), and the University of South Florida (USF). The results from a discrete choice analysis made of the collected survey data are also discussed.
- *Chapter 5. PARS Prototype*: Discussed the development of the experimental test of the PARS system that was implemented at UPRM in May 2024. This chapter provides an overview of the system and lessons learned from its real-world operation.
- *Chapter 6. Conclusions*: Provides the main contributions, research limitations, and future directions of the project.

Chapter 2. Literature Review

This chapter provides a review of previous work related to ride-matching, non-pricing parking management strategies, non-pricing travel demand management strategies, and parking management in universities.

Ride-Matching Problems

The problem addressed in this study is an extension to static ride-matching problems that assume flexible customer roles (i.e., drivers or riders), multiple rider pick-ups (one-to-many matching), and guaranteed ride-back trips. This class of problem has been used in the development of ride-sharing systems that account for transit service transfers (Regue et al., 2016), pricing schemes and the use of HOV lanes (Lloret-Batlle et al., 2017), and rider transfers between drivers (Chen et al., 2019), among other types of systems. Peer-to-peer (P2P) ride-matching problems commonly consider objectives such as minimizing travel costs, individual delays, vehicles miles traveled, maximizing the number of service individuals, and they typically include time window constraints (Agatz et al., 2010; Tamannaei & Irandoost, 2019). The variety in service configurations and models has motivated the development of exact, approximate, and heuristic algorithms to efficiently search for problem solutions. For systems in which a driver can pick-up several riders, solution methods that have been considered include column generation (Baldacci et al., 2004), branch-and-bound (Thangaraj et al., 2017), mathematical formulations (Armant & Brown, 2014), simulated annealing, and tabu search (Xia et al., 2015), among other methods. For a detailed discussion of P2P ride-sharing problems and algorithms the readers may refer to (Tafreshian et al., 2020). Table 1 characterizes this work compared to the existing P2P ride-sharing academic literature.

Non-pricing Parking Management Strategies

The ride-matching problem proposed in this project differs from previous models in that it also allocates parking among the selected drivers, as part of a system ultimately aimed at managing parking and, more generally, travel demand. Non-pricing parking management systems can be broadly divided into two categories: *static systems* with cyclical allocation of parking slots and *dynamic systems* for real-time parking slot allocation. Examples of the former have existed for years in the form of period-long parking permits (e.g., university semester permits). Several mathematical models have been proposed to optimize this type of parking allocation approach. For university settings, Goyal & Gomes (1984) proposed a linear programming model to allocate permits among different individual classes with the objective of minimizing total walking distances from parking lots to final destinations, while Nadimi, Afsharipoor, & Amiri (2021) formulated an integer linear problem aimed at maximizing parking utilization. (Zhang et al., 2011) presented a theoretical model for managing parking demand using tradable permits. After an initial distribution of permits, individuals in this type of system are allowed to trade their assigned permits among themselves. The classic bottleneck model has been used to gain theoretical insights into systems that have partial or complete parking reservations, which are either *expirable* or *non-expirable* (Liu, Yang, & Yin, 2014; Liu, Zhang, & Yang, 2016; Yang, Liu, Wang, Zhang, 2013). Both the tradable permits and reservation systems were proposed with the objective of reducing congestion, and the theoretical results of these studies suggest that these non-pricing strategies can reduce total system travel times for peak travel periods. Like the static models, dynamic parking allocation models generally attempt to find parking distributions that maximize perceived parking utility such as walking distance, parking reliability, parking cost, etc. (Duan, Wu, & Li, 2019). Fairness in slot allocation (Alfonsetti et al., 2015), customer unpunctuality (Jiang & Fan, 2020), and aggregate measures of parking utility (Zhao et al., 2020) have also been considered in dynamic parking allocation models.

Table 1. Characterization of the peer-to-peer ridesharing academic literature

Study	Static	Dynamic	Single-Objective	One-to-Many Matching	Flexible Roles	Ride back	Parking Consideration
Baldacci et al. (2004)	✓			✓			
Agatz and Brown (2010)		✓	✓	✓	✓		
Armant et al. (2014)		✓	✓	✓	✓		
Xia et al. (2015)	✓		✓	✓			
Regue et al. (2016)	✓			✓		✓	
Lloret-Batlle et al. (2017)	✓				✓	✓	
Tamannaei and Irandoost (2018)	✓		✓	✓	✓		
Chen et al. (2019)		✓	✓		✓	✓	
Tafreshian and Masoud (2020)	✓				✓		
Tafreshian and Masoud (2022)	✓	✓	✓			✓	
Gao et al. (2022)		✓	✓				
This study	✓		✓	✓	✓	✓	✓

Non-pricing Demand Management Strategies

The new parking demand management strategy and model presented here also advance the study of non-pricing demand management strategies. Highway access booking systems (Edara & Teodorović, 2008; Ma, Van Zuylen, Chen, & Dalen, 2010; Liu et al., 2013), downtown space reservation systems (Zhao, Triantis, Teodorović, & Edara, 2010; Zhao et al., 2010), and tradable permits for road access (Fan & Jiang, 2013) are examples of non-pricing strategies proposed to address traffic congestion problem. Non-priced travel control measures to reduce vehicle-generated air pollution have been implemented in cities and explored in the academic literature (Goddard, 1997; Nagurney, 2000).

Carpooling Programs in Universities

In this project, the PARS model was implemented in an integrated carpooling-parking program at UPRM. Like in most places, parking can be a controversial issue in universities (Wiers & Schneider, 2022), including UPRM. Dissatisfaction with parking supply levels and/or parking costs is common in universities in North America, where many communities are dependent on the private automobile. One possible solution to this situation is parking pricing, although studies suggest that this strategy should be introduced along with incentives to use alternative travel modes (Proulx et al., 2014). Carpooling programs are another policy alternative to address congestion and parking problems in universities. Carpooling is an attractive strategy for universities as it aligns with institutional sustainability goals and, in theory, programs can be organized within institutional social networks, which should increase trust among potential carpool participants. Generally, research has found that commuters open to carpooling have flexible working hours, belong to younger age-groups, have convenient access to efficient public transit, and live in non-urban areas, among other attributes (Neoh et al., 2018). There are also role (passenger/driver) differences in the motivations for participating in carpooling. For instance, in a study using Ohio State University data, Park et al. (2018) found that "[p]eople favoring the passenger role emphasized safety, flexibility and parking cost-savings, whereas those favoring the driver role tended to find value in the convenience and opportunities for socializing through a carpool trip". In a study conducted at the University of Sannio, Italy, Gallo and Buonocore (2017) found that the main barrier for students to participate in carpooling was the mistrust of unknown people. This barrier can be addressed by creating systems that can match university members with people they know. An example of such a system was PoliUniPool, a web-based service created for the Università Statale and Politecnico di Milano, Italy, to coordinate carpools. The service allowed users to preselect carpool members and indicate if they preferred to carpool with friends (Bruglieri et al., 2011). As Chapter 5 will discuss, it appears that mistrust of unknown people is a major implementation barrier to the use of the UPRM PARS and, in response to this problem, community members have suggested features similar to those implemented in PoliUniPool.

Chapter 3. Optimization Model and Heuristics

This chapter presents the optimization model proposed to operationalize the proposed strategy, the heuristics to find solutions to the problem, and the results of numerical tests of the performance of the heuristics.

The PARS policy is designed as an equitable alternative to price-based parking demand management strategies. The basic idea behind PARS is that parking at a venue is reserved for carpools, which are optimized based on a centralized algorithm. Without loss of generality, it is assumed that there is a set of individuals that need to visit a venue (e.g., a university campus) with limited parking capacity. These individuals need to be transported from their initial location or depot (*e.g.*, their home), travel to the venue, and after some time in the venue, they need to travel back to their depot (*e.g.*, return home). Individuals are classified as *drivers* or *riders*. Drivers are individuals with a car that are willing to serve as a carpool driver. Riders are individuals that want to be included in a carpool as a passenger. Even though drivers have a vehicle, it is assumed that they are willing to be passengers in a carpool if they are not assigned a parking space. It is further assumed that each vehicle occupies one parking stall, that time may be discretized into periods, and that the number of drivers is much higher than the parking capacity.

In a real-world scenario, the PARS policy would require a virtual registration portal software platform where individuals provide the system with essential information, including their initial location, the acceptable arrival and departure windows to/from the venue, and their destination. Drivers would have to provide information regarding their vehicle, including the passenger capacity. A computer-based system would use the data collected in the virtual portal to simultaneously create carpools (who rides with whom to and from the venue) and provide a parking assignment for a block of time based on the acceptable arrival and departure times for everyone in the carpool.

The general idea is that once the algorithm conducts the allocation runs, each rider receives the driver information and estimated pickup time to-and-from the venue. In practice, after a carpool has been formed, the PARS system could operate day-to-day as follows. Drivers receive their carpool details, including departure time, the assigned riders' information going to-and-from the venue with driving directions and estimated pickup times, and the parking reservation times. Upon reaching the venue, drivers would present evidence of their reservation to the parking control system. The evidence could consist of an electronic reservation confirmation obtained after the riders confirm that the service was either provided (i.e., they are in the car) or declined before accessing their reserved parking stall. To enter or exit the reserved parking at the venue, everyone in the carpool must present electronic confirmation (e.g., a QR code) confirming that the service was provided (i.e., they are in the carpool vehicle). Other provisions would allow riders to cancel the service in case the ride is declined.

An interesting application of the PARS in this study is the university setting. Most universities experience parking scarcity during peak times that typically coincide with the most popular schedules of lecture times. Based on their class schedule and in-campus activities, individuals specify their latest arrival and earliest departure time. Potential benefits and drawbacks of the PARS policy are discussed in Chapter 6.

Optimization Model

The centralized algorithm in PARS concurrently establishes the carpool assignments and parking reservations. The centralized algorithm is essential for PARS, as without it, carpools would be limited to the individual networks of drivers and riders. This chapter proposes a linear mixed integer programming (MIP) formulation that can be used as the centralized algorithm in PARS.

The following modeling assumptions are made:

1. There is only one venue with finite and known parking capacity.
2. All information regarding drivers and riders is known (e.g., depot location, vehicle capacity, and desired arrival and departure times)
3. Each vehicle occupies a single parking stall.
4. The problem is solved for one day, which is divided into discrete time intervals (blocks) for parking stall reservations.
5. Drivers are to be considered riders if not assigned as drivers.
6. All individuals need to be assigned to a carpool going to, and returning from, the venue.
7. Instead of minimizing the total distance that needs to be traveled by drivers to pick-up all assigned riders, a proxy of the sum of the distances between drivers and riders' locations is used. The reason for this simplification is that the travel distance for each driver is a setup dependent scheduling problem (*i.e.*, Vehicle Routing Problem, VRP), which by itself is nondeterministic polynomial time (NP)-hard due to the subtour elimination constraints. The main consequence of this assumption is that drivers will get assigned to riders that are close to their depot location, but that are necessarily not guaranteed to be close to each other. It is argued that once the carpools are created using the proxy distances, the shortest route for each driver can be solved post-hoc as an independent Traveling Salesman Problem (TSP). In general, incorporating the actual sequence-dependent distances to the model can be easily done at the expense of a more complex model with the traditional VPR decision variables.
8. Users only provide their latest arrival and earliest departure times. This assumption was made given that incorporating time-window restrictions for each individual might be used to manipulate the model in practice and might result in problem infeasibility.

The model nomenclature is defined as follows:

Sets

J : all individuals that will either be drivers or riders, $J = \{1, \dots, |J|\}$ indexed over j

I : all individuals that will either be drivers, riders, or a dummy driver, $I = J \cup \{0\}$ indexed over i, where {0} is the dummy driver. The dummy driver is included to ensure the model is always feasible.

T : time intervals, $T = \{1, \dots, |T|\}$, indexed over t

Parameters

c_{ij} : travel distance (or cost) associated with individual i driving individual j to the venue, $i \in I, j \in J$, $c_{ii} = 0, c_{oi} = \infty$ (the cost related to the dummy driver).

c'_{ij} : travel distance (or cost) associated with individual i driving individual j from the venue, $i \in I$, $j \in J, c_{ii} = 0$, $c_{oi} = \infty$.

k_i : vehicle capacity associated with individual i (driver is included in the vehicle capacity), $i \in I$, $k_0 = \infty$, $k_i = 0$ if individual i is not a driver

p : venue's parking capacity measured in number of parking stalls

r_i : latest arrival time for individual i at venue, $i \in I$. For the dummy driver, $r_0 = 0$.

s_i : earliest departure time for individual i from venue, $i \in I$, $s_i > r_i$. For the dummy driver, $s_0 = |T|$.

p_{it} : 1 for $r_i \leq t \leq s_i$ for $i \in I$; 0 otherwise

M : very large positive number

Decision Variables

x_{ij} : binary variable = 1 if individual $i \in I$ drives individual $j \in J$ to the venue, = 0 otherwise

y_{ij} : binary variable = 1 if individual $i \in I$ drives individual $j \in J$ back from the venue, = 0 otherwise

h_{it} : binary decision variable = 1 if parking is assigned to individual $i \in I$ during period $t \in T$; 0 otherwise.

Next, the MIP formulation for the PARS problem:

$$Min\ z_{PARS} = \sum_{i \in I} \sum_{j \in J} (c_{ij} x_{ij} + c'_{ij} y_{ij}) \tag{1}$$

s.t.

$$\sum_{i \in I} x_{ij} = 1 \ \ \forall j \in J \tag{2}$$

$$\sum_{i \in I} y_{ij} = 1 \ \ \forall j \in J \tag{3}$$

$$\sum_{j \in J} x_{ij} \leq k_i x_{ii} \ \ \forall i \in I \tag{4}$$

$$\sum_{j \in J} y_{ij} \leq k_i y_{ii} \ \ \forall i \in I \tag{5}$$

$$x_{ii} = y_{ii} \ \ \forall i \in I \tag{6}$$

$$p_{jt} x_{ij} \leq h_{it} \ \ \forall i \in I, j \in J, i \neq j, t < r_i \tag{7}$$

$$p_{it} x_{ii} = h_{it} \ \ \forall i \in I, r_i \leq t \leq s_i \tag{8}$$

$$p_{jt} y_{ij} \leq h_{it} \ \ \forall i \in I, j \in J, i \neq j, t > s_i \tag{9}$$

$$h_{it} \leq h_{it+1} \ \ \forall i \in I, t < r_i - 1 \tag{10}$$

$$h_{it+1} \leq h_{it} \ \ \forall i \in I, s_i < \ t < T - 1 \tag{11}$$

$$\sum_{i \in I} h_{it} \leq p \ \ \ \forall t \in T \tag{12}$$

$$x_{ij}, y_{ij}, h_{it} \in \{0,1\} \ \ \forall i \in I, j \in J, t \in T \tag{13}$$

The objective function (1) is to minimize the total distance (or cost) between drivers and riders. Constraint sets (2) and (3) establish that each rider must be assigned to one driver going to and returning from the venue, respectively. Constraint sets (4) and (5) ensure that the total number of passengers in each vehicle does not exceed the vehicle capacity when going to and returning from the venue, respectively. Constraint set (6) states that individuals that are drivers going to the venue, must also be drivers when returning from the venue. Constraint set (7-9) are used to activate indicator variable h_{it}, the required parking reservation times. Constraint sets (7) and (9) incorporate the earliest arrival and latest departure of the riders, whereas Constraint set (8) incorporates the stay times of the driver. Constraint sets (10) and (11) are required to ensure the parking reservation is honored without skipping a time internal given that h_{it} is not in the objective function. Constraint set (12) enforces the parking capacity. Lastly, constraint set (13) delimits the decision variables.

Even though the PARS policy is designed to be equitable, the solution from the formulation might not be considered equitable among drivers as, for example, some drivers might be assigned more riders than others. These concerns might be incorporated into the formulation by means of additional (equity) constraints on the number of passengers, total travel distance required, or amount of earlier arrival or later departure a driver experiences due to riders.

Experimental results suggest that the commercial solver Gurobi 9.1 is able to solve the MIP formulation for large problem instances (3,000 individuals visiting a venue with parking capacity of 700 vehicles, and dividing a day into 16 time periods) in under half an hour, on a personal computer with an Intel Xeon quad-core with 2.80 GHz processors and 24 GB of RAM. On the other hand, equivalent instances with up to 1,000 individuals run on average in one and a half minutes.

Heuristic Solutions

By examining the MIP formulation one can identify the structure of an unbalanced transportation problem in Eqs. (2)-(5). The remainder of the formulation, associated with the parking assignment component, resembles a general resource scheduling problem with time-windows. Since the transportation problem and the parking assignment problems are both well-known *NP-hard* problems, it is straightforward to argue that the problem studied in this report is *NP-hard*. It is worth mentioning that in addition to the transportation and parking assignment problems, there is a mathematically complex, and somewhat unique problem, of determining which individuals will serve as drivers. Given the complexity of the problem, a heuristic solution is merited to solve large instances of the problem. Unfortunately, the large solution space of the problem makes traditional encoding methods used for metaheuristics impractical.

This section presents two heuristics for the PARS problem. The first heuristic, *Ride Decomposition*, is a decomposition-based heuristic that first solves a sub-problem associated with going to the venue, and given that solution, it solves the sub-problem associated with returning from the venue. The second heuristic, *Quick Converge*, finds minimum-cost solutions and manipulates them to consider parking capacity restrictions.

Ride Decomposition (RD) Heuristic

The Ride Decomposition (RD) heuristic decomposes the problem into two sub-problems: *going to*, and *returning from*, the venue. The problem is first solved to optimality considering all the information pertaining to going to the venue. Then, given the drivers selected in the first sub-problem, it determines the optimal carpools for the trip returning from the venue. The upper bound for the RD heuristic is obtained by adding the objective function values of the two sub-problems.

RD Sub-problem 1 - Going to Venue

The following formulation determines the carpool composition (including which individuals will serve as riders and drivers) and the parking assignment only considering the information associated with going to venue. The nomenclature from the MIP is reused.

$$Min\ z_{RD1} = \sum_{i \in I} \sum_{j \in J} (c_{ij} x_{ij}) \tag{14}$$

$s.t.$

Equations (2), (4), (7), (8), (10), (12)

$$0 \leq x_{ij} \leq 1 \ \ \forall i \in I, j \in J \tag{15}$$

$$h_{it} \in \{0,1\} \ \ \forall i \in I, t \in T \tag{16}$$

The formulation is similar to the original MIP formulation, without the parameters and decisions related to returning to the venue. As shown in Eq. (15), the x_{ij} decision variable may be relaxed for this sub-problem.

RD Sub-problem 2 - Returning to Venue

The drivers selected in RD sub-problem 1 will be the only drivers in RD sub-problem 2 (RD2). Two new sets are defined for sub-problem 2: set of riders R ($R \in I{:}\, x_{ii}^* = 0$) and drivers D ($D \in I{:}\, x_{ii}^* = 1$), where x_{ii}^* is the optimal decision variable for the drivers selected in RD1. A new parameter (h'_{it}) includes the optimal h_{it} values from formulation RD1 (i.e., $h'_{it} \equiv h^*_{it}$). The return sub-problem can be formulated as follows:

$$Min\ z_{RD2} = \sum_{i \in D} \sum_{j \in R} (c'_{ij} y_{ij}) \tag{17}$$

$s.t.$

$$\sum_{i \in D} y_{ij} = 1 \ \ \forall j \in R \tag{18}$$

$$\sum_{j \in R} y_{ij} \leq (k_i - 1) \ \ \forall i \in D \tag{19}$$

$$p_{jt} y_{ij} \leq h_{it} \ \ \forall i \in D, j \in R, t \in T{:}\, t > s_i \tag{20}$$

$$h_{it+1} \leq h_{it} \ \ \forall i \in D, t \in T{:}\, s_i < \ t < T - 1 \tag{21}$$

$$\sum_{i \in D} h_{it} + h'_{it} \leq p \ \ \ \forall t \in T \tag{22}$$

$$0 \leq y_{ij} \leq 1 \ \ \forall i \in D, j \in R \tag{23}$$

$$h_{it} \in \{0,1\} \ \forall i \in D, t \in T \tag{24}$$

The RD2 formulation is similar to the original MIP formulation, without considering the information pertaining to the trip going to the venue and assuming that the set of drivers and riders is known from RD1. The objective function in Eq. (17) only includes the distance (or cost) associated with the return trip. Constraint set (18) ensures all riders are assigned to a carpool. Constraint set (19) guarantees there is enough capacity in each vehicle for the return trip. Notice that that the vehicle capacity is discounted by one as the driver has already been assigned. Constraint set (20) ensures the parking for the carpool is held considering the riders' earliest departure. Constraint set (21) makes sure the parking reservation is honored for all required consecutive time periods. Constraint set (22) enforces the parking capacity constraint for all time periods. Constraint sets (23) and (24) delimit the decision variables. Once again, the decision variable regarding the carpool assignment may be relaxed.

The upper bound for the RD heuristic (z_{RD}) is obtained as $z_{RD} = z_{RD1} + z_{RD2}$. The decomposition done for the RD heuristic allows more efficient formulation of the sub-problems, which result in faster solution times. In addition, RD2 does not include the driver selection decision, which is mathematically complex. The quality of the solution of the RD heuristic depends on the quality of the driver assignments based on the going to venue portion. Non-optimal solutions may arise when individuals are not selected as drivers based on the RD1, but would have minimized the total cost when considering RD2.

Quick Converge (QC) Heuristic

Constraint sets in (2-5) of the original MIP formulation resemble a 3-dimensional transportation problem (3DTP), as defined in Bein, Brucker, Park, & Pathak (1995). Furthermore, the objective function in Eq. (1) is only associated with the variables from the 3DTP. Therefore, the problem can be viewed as a 3DTP subjected to parking assignment constraints. Based on this intrinsic mathematical property, the Quick Converge (QC) heuristic seeks to decompose the problem into a transportation problem and a parking assignment problem. The following subsections present the decomposition strategy and formalize the QC heuristic.

3D Transportation Sub-problem (3DTP)

This subsection presents a sub-problem that deals with determining the composition of the carpools. The transportation sub-problem (3DTP) assumes that the set of drivers and riders are known, so dummy drivers are not considered. Initially, the set of drivers and riders may be defined as:

- D set of drivers, indexed over d. $D = J: k_i > 0$.
- R set of riders, indexed over r. $R = J: k_i = 0$.

The remainder notation used in the 3DTP formulation is the same as in the original MIP formulation. The 3DTP may be formulated as a linear program as follows:

$$Min\ z_{3DTP} = \sum_{i \in D} \sum_{j \in R} (c_{ij} x_{ij} + c'_{ij} y_{ij}) \tag{25}$$

$s.t.$

$$\sum_{i \in D} x_{ij} = 1 \ \forall j \in R \tag{26}$$

$$\sum_{i \in D} y_{ij} = 1 \ \forall j \in R \tag{27}$$

$$\sum_{j \in R} x_{ij} \leq k_i \ \ \forall\, i \in D \tag{28}$$

$$\sum_{j \in R} y_{ij} \leq k_i \ \ \forall\, i \in D \tag{29}$$

$$x_{ij}, y_{ij} \geq 0 \ \ \forall\, i \in D, j \in R \tag{30}$$

Objective function (25) minimizes the total distance (cost) between drivers and riders, similar to the original objective function (1). Constraint sets (26) and (27) establish that each rider must be assigned to one driver going to and returning from the venue, respectively. Constraint sets (28) and (29) ensure that the vehicles' capacity is not exceeded when going to and returning from the venue, respectively. The variable declarations are defined in constraint set (30) as non-negative variables, although the optimal value of the variables will be binary due to the structural properties of the 3DTP.

Determining the Latest Arrival and Earliest Departure for each Driver

Given the optimal solution of the 3DTP sub-problem, one can easily determine the carpool composition and its latest arrival and earliest departure. Let, x_{ij}^* and y_{ij}^*be the optimal assignment in the 3DTP and let, n_i be the total number of riders carpooling with driver i, $i \in D$.

$$n_i \equiv \sum_{j \in R} (x_{ij}^* + y_{ij}^*) \tag{31}$$

For the optimal assignment in the 3DTP, one can compute the corresponding required carpool stay time (h_{it}^*) as follows:

$$h_{it}^* \equiv \begin{cases} 1 \ \forall t \in T\colon l \leq t \leq l', \text{where } l = \min\limits_{\forall j \in J: x_{ij}^*=1} \{r_j\} \text{ and } l' = \max\limits_{\forall j \in J: y_{ij}^*=1} \{s_j\} \\ \qquad\qquad\qquad\qquad 0 \text{ otherwise} \end{cases} \tag{32}$$

The n_i and h_{it}^* parameters are incorporated in the Parking Assignment sub-problem presented in the following sub-section.

Parking Assignment (PA) Sub-problem

The Parking Assignment (PA) sub-problem will reserve parking to carpools considering the number of individuals in the carpools. The PA may be formulated as a binary program using parameters n_i and h_{it}^* defined in the previous subsection and the parking capacity p measured in parking stalls. The decision variable for the PA sub-problem is:

- γ_i binary variable = 1 if driver i is assigned a parking stall, $i \in D$

$$Max\ z_{PA} = \sum_{i \in D} n_i \gamma_i \tag{33}$$

$s.t.$

$$\sum_{i \in D} h_{it}^* \gamma_i \leq p \ \ \forall t \in T \tag{34}$$

$$\gamma_i \in \{0,1\} \ \forall i \in D \tag{35}$$

The objective function in (33) maximizes the number of riders whose carpool receive a parking reservation. Constraint set (34) ensures that the maximum parking capacity is honored for each period. Constraint set (35) defines the decision variable. The PA sub-problem resembles a one-dimensional knapsack problem, which can be easily solved.

In the PA formulation, drivers are only denied parking due to capacity. Therefore, one can easily compute the drivers that are competing for a parking stall by examining the parking capacity at each time period.

Steps for the Quick Converge (QC) Heuristic

The Quick Converge (QC) heuristic can be described as follow:

1. Solve the 3DTP sub-problem in subsection 5.2.1 using $i \in D$ drivers and $j \in R$ riders and update the upper bound for the QC heuristic, $z_{QC} = z_{TP}$.
2. Compute the n_i and h_{it}^* parameters from Eqs. (31) and (32), respectively, to set up the PA sub-problem. Solve the PA sub-problem in Section 5.2.3.
3. If there are any drivers i' that did not receive a parking assignment, force them as riders (i.e., $D = D \backslash i'$, $R = R \cup i'$) and return to Step 1. If there are no unassigned drivers, then END as the solution is feasible.

The performance of the QC heuristic is expected to deteriorate as the parking demand dramatically exceeds the capacity since the heuristic greedily selects drivers based purely on cost. Carpools that require parking reservations for a shorter time tend to be avoided. On the other hand, it is easy to show that if the QC heuristic finishes in one iteration, then the minimum-cost assignment from the 3DTP is feasible, so the solution of the QC heuristic is optimal for the problem.

Experimental Results

The MIP formulation, the Ride Decomposition (RD) heuristic, and the Quick Converge (QC) heuristic were coded in Python 3.8. All mathematical formulations were solved by calling the Gurobi 9.1 solver. A computer powered by an Intel Xeon quad-core with 2.80 GHz processors and 24 GB of RAM was used for experimentation.

A full factorial experimental design was designed to compare the solution methods in terms of solution quality and runtimes under different scenarios, as shown in Table 2. The experimental factors considered are the number of individuals (γ = drivers+riders), the ratio of potential drivers to riders (D:R), and the ratio of potential drivers to parking capacity (D:p). Note that potential drivers are those who could serve as drivers if selected, which may be different from the actual drivers selected which is a decision variable. The experimental levels are organized in increasing complexity. The first factor (*No. of Individuals*), which is associated with the problem size, is limited to 1,000 individuals which are considered large instances. The experimental levels for the ratio of drivers to riders were limited to the case where the number of potential drivers is larger than the number of riders as would be expected in a practical implementation of the policy. Scenarios with more drivers than riders also help avoid infeasible scenarios due to vehicle capacities. Lastly, the driver to parking capacity factor was only considered when the former is larger than the latter to avoid trivial instances.

Table 2. Design of Experiments

Factor	Level 1	Level 2	Level 3
No. of Individuals (γ)	100	500	1000
Drivers:Riders (D:R)	2:1	4:1	-
Drivers:Parking Capacity (D:p)	2:1	3:1	4:1

For the computational experiments, the car capacity (k_i) was generated according to a Normal($\mu = 4, \sigma = \frac{1}{3}$) random variable, rounded to the nearest integer. The day was divided into 16 (30-minute) time intervals ($T = 16$). To avoid having carpools with impractical expectations for how long individuals must wait at the venue, an earliest arrival (r_j') and latest departure (s_j') period were generated. The individual's earliest arrival period was assumed Discrete Uniform(0, 3/4T). The latest arrival (r_j) was assumed as one period after the earliest arrival ($r_j = r_j' + 1$). The earliest departure (s_j) was computed by adding a Normal($\mu = 2, \sigma = 2$) time periods to the latest arrival. Similarly, the latest departure was assumed to be one period after the earliest departure ($s_j' = s_j + 1$). The individuals' depots were randomly selected in a 50×50 distance units rectangular map. The cost matrices (c_{ij} and c_{ij}') were computed as the rectilinear distance between the coordinates, d_{ij}. When there was no overlap between the earliest arrival and latest arrival time windows of individuals i and j, the c_{ij} cost was penalized by a constant equal to the maximum rectilinear distance between two individuals, plus the absolute value difference between the respective earliest arrivals and latest arrivals. More formally,

$$c_{ij} = \begin{cases} d_{ij} \; if \; arrival \; intervals \; overlap \\ d_{ij} + \max_{i,j}\{d_{ij}\} + |r_i - r_j| + |r_i' - r_j'|, otherwise \end{cases} \tag{36}$$

Similarly, the c_{ij}' values were penalized when the earliest departure and latest departure did not overlap.

$$c_{ij}' = \begin{cases} d_{ij} \; if \; departure \; intervals \; overlap \\ d_{ij} + \max_{i,j}\{d_{ij}\} + |s_i' - s_j'| + |s_i - s_j|, otherwise \end{cases} \tag{37}$$

Table 3 presents a summary of the experimental results for fifteen (15) replicates of each experimental condition. The first results column in Table 3 includes the average objective function percent difference (Ave z_{RD} and Ave z_{QC}) between each heuristic and the optimal solution from the MIP, computed as: $Ave \; z_{heuristic} = \sum_{k \in replicates} (\frac{z_k^{heuristic} - z_k^{opt}}{z_k^{opt}})/15$. Similarly, the average runtime (RT) percent difference for the heuristics compared with the optimal solution is also reported in Table 3. The runtimes for the MIP and the heuristics only include the solver runtime to remove any coding or Python-related inefficiencies when setting up and extracting the solution from the solver.

Table 3. Average percent difference of heuristics versus MIP for 15 replications

				Ride Decomposition		Quick Converge	
Index	γ	D:R	D:p	Ave z_{RD}	Ave RT_{RD}	Ave z_{QC}	Ave RT_{QC}
1	100	2:1	2:1	0.00%	-19.17%	0.00%	-90.76%
2	100	2:1	3:1	2.15%	-28.66%	3.10%	-87.32%
3	100	2:1	4:1	8.11%	-41.14%	6.97%	-89.72%
4	100	4:1	2:1	0.11%	-25.80%	0.00%	-88.25%
5	100	4:1	3:1	2.41%	-28.56%	3.37%	-85.89%
6	100	4:1	4:1	16.15%	-34.01%	14.39%	-81.11%
7	500	2:1	2:1	0.56%	-47.73%	0.00%	-87.38%
8	500	2:1	3:1	0.51%	-49.27%	0.25%	-90.08%
9	500	2:1	4:1	5.59%	-51.49%	5.90%	-90.02%
10	500	4:1	2:1	0.92%	-50.81%	0.00%	-87.78%
11	500	4:1	3:1	1.29%	-55.80%	0.03%	-86.53%
12	500	4:1	4:1	10.26%	-55.79%	12.52%	-89.57%
13	1000	2:1	2:1	0.60%	-45.63%	0.00%	-88.09%
14	1000	2:1	3:1	0.77%	-41.30%	0.00%	-83.73%
15	1000	2:1	4:1	5.27%	-45.34%	5.65%	-88.57%
16	1000	4:1	2:1	1.41%	-49.30%	0.00%	-83.42%
17	1000	4:1	3:1	1.94%	-39.36%	0.00%	-72.73%
18	1000	4:1	4:1	6.86%	-51.28%	10.68%	-84.15%

It can be observed from Table 3 that both heuristics performed reasonably well in terms of solution quality and solution time. Overall, on average, the RD heuristic yield solutions within 3.61% of the optimal and QC within 3.49%. By examining the raw data, it was determined that the RD heuristic found the optimal solution in 21.49% of the problem instances, whereas QC did so in 60.74%. In terms of average runtimes, RD was faster than the MIP by 42.23% and QC by 86.39%.

Table 4 presents the Minitab output for a paired t-test at a 95% confidence level for the individual runs' objective function percent differences. The percentage differences were used instead of the actual objective function values as a way to normalize the objective function values, which vary significantly according to the experimental conditions. The paired t-test fails to reject the hypothesis that the RD and QC are different ($Ha\colon \mu_{RD-QC} \neq 0$; with a *p-value* = 0.667). The corresponding statistical power for the paired t-test considering a difference of 2% ($\delta = 2\%$) with a 95% confidence level was 1.0000 (*i.e.*, Type II Error $(\beta) = 0.0000$). Based on the statistical power of the test, the 15 replicates used are considered enough replications. A similar t-test for the run times suggest that QC is statistically faster than RD (*p-value* = 0.00).

Table 4. Paired t-test for the objective function percent differences

N	Mean	StDev	SE Mean	95% CI	T	p-value
270	0.00114	0.04338	0.00264	(-0.00406, 0.00634)	0.43	0.667

A General Linear Model Analysis of Variance (ANOVA) performed to understand the effects of the main factors and their two-way interactions for the percent difference of the objective function (versus the MIP). As expected from the paired t-test results, the initial ANOVA at the 95% confidence level suggested that the method (*i.e.*, heuristic) was not statistically significant (*p-value* = 0.741). Therefore, all 2-way interactions including the method were also statistically non-significant. Furthermore, the Total Users*D:R interaction was also non-significant (*p-value* = 0.335). Table 5 presents the Minitab output for the follow-up ANOVA excluding all non-significant factors. It is observed that excluding the method factor in the experiment is equivalent to having a sample size of 30 for the remaining factors. The relative predictive power of the model (R^2) of the ANOVA was 55.06%, which is acceptable for our experiments. The ANOVA in Table 5 suggests that all remaining experimental factors are statistically significant at the 95% confidence level (*p-value* = 0).

Table 5. ANOVA for the objective function

Source	DF	Adj SS	Adj MS	F-Value	p-value
Total Users	2	0.03901	0.019504	12.17	0.000
D:R	1	0.05672	0.056725	35.40	0.000
D:p	2	0.82011	0.410053	255.90	0.000
Total Users*D:p	4	0.03757	0.009393	5.86	0.000
D:R*D:p	2	0.08331	0.041653	25.99	0.000
Error	528	0.84605	0.001602		
Lack-of-Fit	24	0.04162	0.001734	1.09	0.354
Pure Error	504	0.80443	0.001596		
Total	539	1.88277			

Figure 2 presents the interaction plot, which helps understand the two-way interactions of the experimental factors in the ANOVA. The response in the interaction plot is the average percentage difference of the two heuristics against the optimal solution. Non-significant interactions were removed from the interaction plot. From Figure 2 it can be observed that the performance of the heuristics: (1) improves as the number of individuals increases, (2) slightly worsens as the drivers-to-riders ratio increases, and (3) dramatically worsens as the drivers-to-parking capacity ratio increases. In general, these results suggest that the heuristics should perform satisfactorily for larger instances that the MIP is unable to solve.

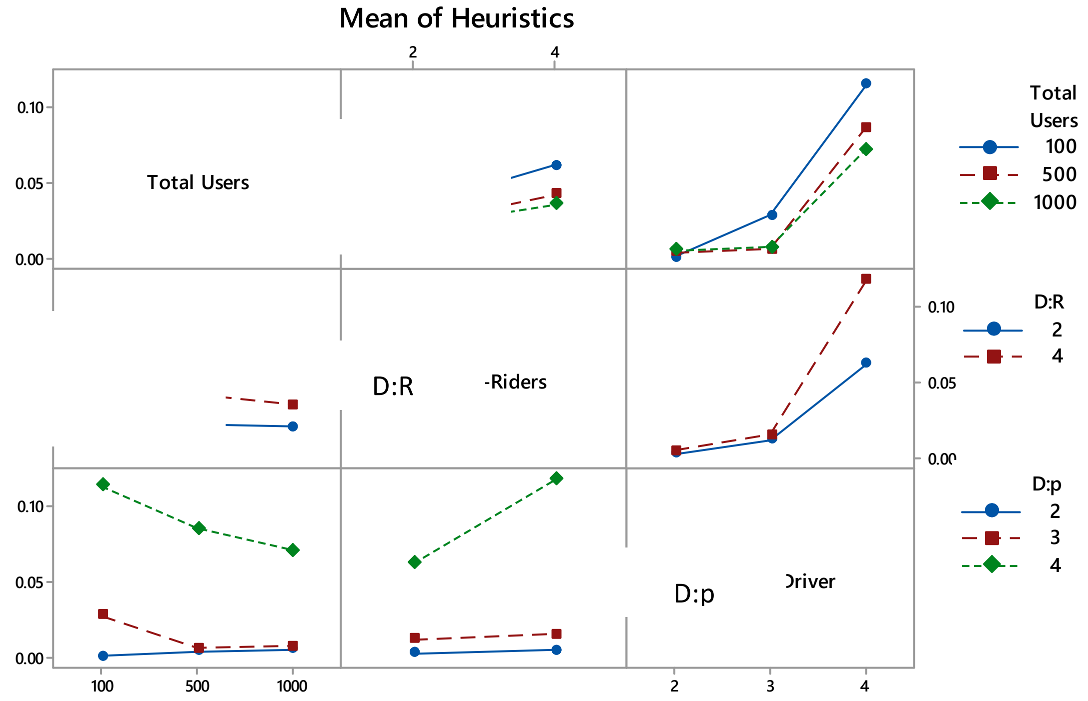


Figure 2. Interaction Plot from ANOVA

Closing Remarks

A MIP was proposed to implement the PARS policy. The model considers parking capacity, users schedules, vehicle capacities, and the need to ensure ride-back trips to all riders, among other constraints. Two problem-specific heuristics were also proposed. The first heuristic, Ride Decomposition (RD), is a decomposition-based heuristic that first solves the going to the venue sub-problem and given this solution it then solves the returning from the venue sub-problem. The second heuristic, Quick Converge (QC), finds minimum-cost solutions by solving a three-dimensional transportation problem and then solves a parking assignment sub-problem to incorporate parking capacity restrictions.

Internally generated experiments based on a full factorial experimental design were used to compare the proposed solution methods. It is concluded that on average, the RD heuristic yield solutions within 3.61% of the optimal solution and QC within 3.49%. The RD heuristic found the optimal solution in 21.49% of the problem instances, whereas QC did so in 60.74%. On average, RD was faster than the MIP by 42.23% and QC by 86.39%. Based on statistical analyses, it may be concluded that the methods perform similarly in terms of solution quality, but that QC is statistically faster than RD. Hence, QC would be the recommended heuristic. Lastly, it is concluded that the performance of the heuristics improves with the number of users, suggesting that the heuristics will perform satisfactorily in larger instances that the MIP is unable to solve.

Chapter 4. Exploring Parking Policy Preferences Schemes

PARS is presented as a more equitable alternative to parking pricing. However, would potential PARS users prefer a carpool-based system over the conventional parking alternatives? What factors determine people's preference for PARS-type services? These questions were examined in this project, in the context of universities, through a stated-preference survey and discrete choice analyses of responses. The survey's stated-preference questions presented respondents with hypothetical choice scenarios in which PARS-like and parking pricing alternatives were characterized by attributes with varying levels (see Appendix A for questionnaire). Multinomial logit models were estimated using the data. Willingness-to-accept measures and elasticities of the probability of selecting carpooling alternatives were estimated using the logit models.

This chapter is organized as follows. The next section provides an overview of the survey and data collected, followed a discussion of the methods used to analyzed the data. The chapter's third section presents the results of the discrete choice analysis. Lastly, the chapter closes with a discussion of the policy implications of the modeling results.

Survey and Data

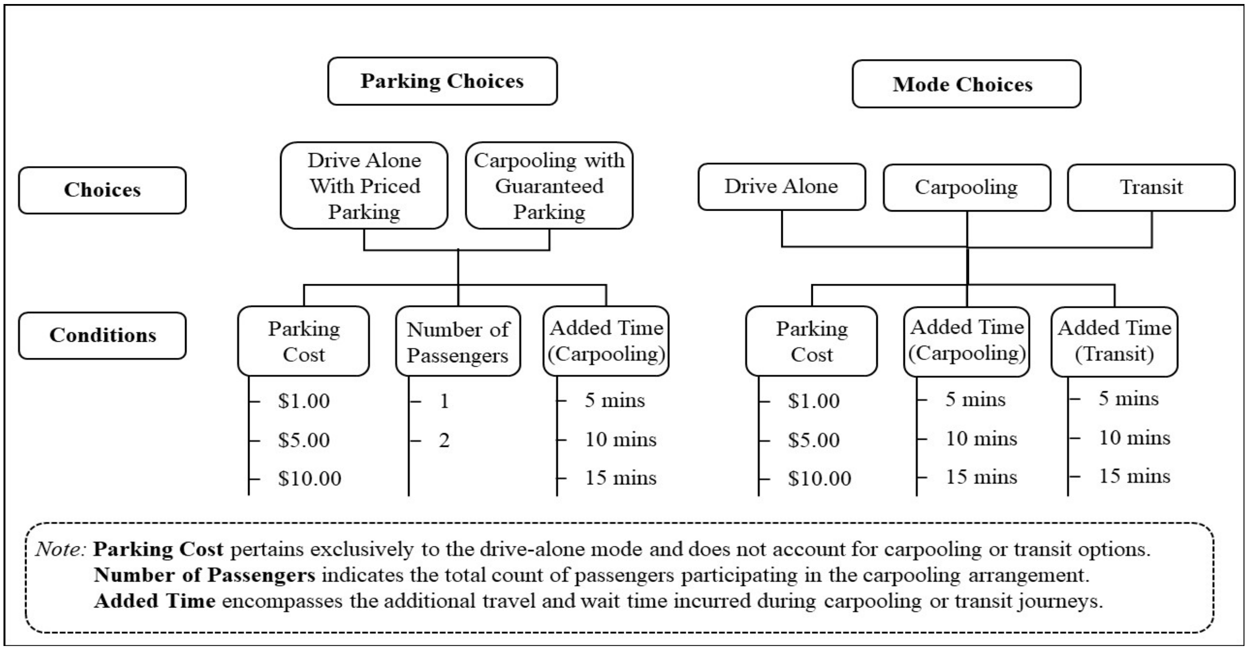
This study involved the formulation of two separate questionnaires to collect data from students, staff, and faculty members from the UPRM and the USF campuses. The transportation landscapes at UPRM and USF are similar in the high dependence in the use of private vehicles, but they significantly differ in two key aspects: firstly, USF manages its parking facilities using pricing, whereas UPRM uses a permit-based parking management system with no user charge. Secondly, carpooling is actively promoted at USF, whereas it is not at UPRM, making it a significant difference between the two institutions. This difference, in addition to the sociodemographic differences of the two campuses (e.g., the student body at UPRM is close to 100% Hispanic, the poverty rate in Puerto Rico is around 40%, relative to the 12% rate in Florida), provides a unique opportunity to capture variations in preferences across a diverse respondent base with markedly different backgrounds.

The questionnaires were designed based on factorial design theory (Montgomery, 2017) and aimed to gather information about respondents' parking preferences and mode choices for commuting to an university campus. Respondents were presented with stated-preference discrete choice experiments that described different travel scenarios, and they were asked to indicate their preferred choice from the given options, as illustrated in Figure 3. There were two sets of experiments. In the first experiment, participants were asked to imagine that there were planning to drive to the university and that they had two choices: driving alone with priced parking or carpooling with free guaranteed parking. For this first set of questions the respondent was the carpool driver. In the second experiment, participants were asked to imagine that they were travelling to the university, and they had three mode alternatives: driving alone and paying for parking, traveling as a passenger in a carpool, or using transit. Alternative attributes, such as parking cost, number of passengers, and additional travel and wait time, were considered in these conditions. Each respondent answered two stated-preference parking choice questions and two stated-preference mode choice questions respectively. Besides the stated-preference questions, the questionnaire included questions about sociodemographic factors and commute-related factors, as outlined in Table 6. A total of 456 people from UPRM and 261 people from USF participated in the survey. The survey was distributed via the institutional email system of the universities. A convenience sampling approach was used to recruit survey participants.

Table 6. Description of independent variables

Variables	Description
Sociodemographic factors	
Age	The respondent’s age, in years
Gender	The respondent’s gender: 1: male; 2: female
University status	The respondent’s current relationship with the university. 1: undergraduate student; 2: graduate student; 3: staff; 4: faculty
Location	The respondent’s location 1: UPRM; 2: USF
Years	How many years have the respondent been studying/working at USF/UPRM? For students, 1: 1 or less; 2: 2-3; 3: 4-5; 4: 6 or more. For employees, 1: 1 or less; 2: 2-5; 3: 6-10; 4: 11 or more
Commute-related factors	
Commute time	The respondent’s average commuting time (in minutes) to the university.
Main mode	Currently, what is the respondent’s main transportation option to travel to the university? 1: private vehicle as driver; 2: private vehicle as passenger; 3: transit; 4: non-motorized transportation (bike, walk, skateboard, scooter); 5: taxi & ride-hailing services (e.g., Uber and Lyft); 6: motorcycle; 7: others
Alt - drive	If secondary travel mode (STM) is "private vehicle as driver", 1; else, 0
Alt - passenger	If STM is "private vehicle as passenger", 1; else, 0
Alt - bike/walk	If STM is "non-motorized transportation (bike, walk, skateboard, scooter)", 1; else, 0
Alt - transit	If STM is "transit", 1; else 0
Alt - taxi	If STM is "taxi & ride-hailing services (e.g., Uber and Lyft)", 1; else 0
Alt - moto	If STM is "motorcycle", 1; else, 0
Attitude driver	The degree of agreement with following content: "I would be comfortable with giving a ride to a fellow student/faculty as part of a university coordinated carpooling program." 1: strongly disagree; 2: disagree; 3: neutral; 4: agree; 5: strongly agree
Attitude passenger	The degree of agreement with following content: "It would make me uncomfortable to travel as a passenger in a university coordinated carpool program if the driver is a person of a different gender than mine (assume that you do not know the driver prior to the trip)." 1: strongly disagree; 2: disagree; 3: neutral; 4: agree; 5: strongly agree

Note: “Alt” refers to alternative



Note: **Parking Cost** pertains exclusively to the drive-alone mode and does not account for carpooling or transit options.
Number of Passengers indicates the total count of passengers participating in the carpooling arrangement.
Added Time encompasses the additional travel and wait time incurred during carpooling or transit journeys.

Figure 3. Conceptual framework for modeling integrated parking choice and mode choice

Data Analysis Methodology

Discrete Choice Models

The binary logit and multinomial logit models (Koppelman & Bhat, 2006) were selected to model the respondent's parking and mode choice preferences. The parking choices and mode choices are the dependent variables in this study. The parking choices were categorized into two alternatives: 'driving alone with priced parking' and 'carpooling with guaranteed parking'. The mode choices were categorized into three alternatives: 'driving alone', 'carpooling', and 'transit'. The effect of sociodemographic factors, commute-related factors, and alternative-specific factors on the parking choices and the mode choices were analyzed using discrete choice models. Discrete choice models were estimated using linear-in-parameter deterministic utility functions and the logit probability function:

$$V_{ni} = \beta_{i0} + \sum_{k=1}^{K_i} \beta_{ik} X_{nik} \tag{38}$$

$$P_{ni} = \frac{\exp(V_{ni})}{\sum_{j=1}^{J_i} \exp\left(V_{nj}\right)} \tag{39}$$

where V_{ni} presents the utility of the i-th alternative for individual n; X_{nik} is the kth independent variable with the coefficient β_{ik}; K_i denotes the total number of independent variables associated with the ith alternative; P_{ni} represents the probability of selecting ith alternative; and J_i denotes the total number of choices. Equation 39 results from the assumption that the error terms in the utility function (i.e., $U_{ni} = V_{ni} + \varepsilon_{ni}$) is independently distributed, identically distributed, and Gumbel-distributed.

Marginal Rate of Substitution and Elasticities of Choice

One of the main hypotheses is that the additional travel time required for picking up a passenger as part of the carpooling option and the associated parking costs will have a direct effect on the driver's decision-making process. When a respondent opts for carpooling over driving alone, this choice can potentially result in cost savings with respect to parking fees. However, it may also entail an increase in travel time due to the additional waiting time and detouring required when picking up a carpooler. A similar situation arises when a respondent selects public transit. In this choice, the respondent avoids parking fees but may experience longer waiting times at bus stops and travel times.

Marginal rates of substitution (MRS) were computed to capture the trade-off between parking costs and the extra travel times of carpooling or transit use. In the context of the discrete choice models considered in this report, an MRS for two variables is computed as the ratio of deterministic utility function derivatives with respect to each variable. For example, assuming a linear-in-parameter utility function with no interactions relevant interaction terms, the MRS between the extra carpooling travel time and the parking cost can be computed as $\beta_{it^+}/\beta_{ic^-}$, where β_{it^+} is the coefficient of the additional travel time associated with an alternative i and β_{ic^-} is the coefficient for the parking cost savings of the alternative. Given that the parking cost savings could be viewed as price discounts aimed at motivating travel behavior changes, the term "willingness to accept" (WTA) will be used to refer to the $\beta_{it^+}/\beta_{ic^-}$ ratio (Hanemann, 1991; Kurri et al., 2000; Shogren et al., 1994). A higher WTA value indicates that respondents require greater parking cost savings to accept the extra travel time and remain at the same satisfaction level (Hanemann, 1991; Kurri et al., 2000). Since the survey included two different universities, the WTA value was estimated separately for each. This approach enables the examination of attitudes towards alternative travel options within each university setting.

Additionally, elasticities of choice were computed to explore the differences in participant preferences for both universities. Specifically, direct point elasticities (E_d) of the probability of carpooling (P_{n2}) with respect to the carpooling extra travel time (X_{n2T}) and the cross-point elasticities ($E_\times$) of the probability of carpooling with respect to parking cost (X_{n1c}) were computed for each university. The general expressions to compute direct point (3) and cross-point (4) elasticities are (Koppelman & Bhat, 2006):

$$E_d = \frac{\partial V_{n2}}{\partial X_{n2T}} X_{n2T}(1 - P_{n2}) \tag{40}$$

$$E_\times = -\frac{\partial V_{n1}}{\partial X_{n1c}} X_{n1c} P_{n1} \tag{41}$$

where $\partial V_{n2}/\partial X_{n2T}$ represents the partial derivative of the deterministic utility of the carpooling alternative with respect to its extra travel time attribute, $\partial V_{n1}/\partial X_{n1c}$ represents the partial derivative of the deterministic utility of the "drive alone" alternative, and P_{n1} is the probability that individual n selects the "drive alone" alternative.

Results

Descriptive Analysis

The survey included 717 respondents from both UPRM and USF to gather data on parking choices and mode choices. Among the respondents, 82.98% were students. The primary modes of transportation chosen by the respondents included a private vehicle as a driver, a private vehicle as a passenger, and biking/walking. Specifically, 86.47% of the respondents indicated a private vehicle as a driver as their primary mode of transportation. In contrast, only 2.09% of the respondents chose a private vehicle as a passenger as their primary mode. In terms of the secondary mode, most respondents (43.10%) chose the private vehicle as a passenger. Additionally, a mere 0.84% of respondents selected motorcycles as their secondary mode. A summary of responses to survey question data used to create model variables is presented in Table 7.

Table 7. Summary of Survey Data used as Model Variables (N=717)

Variables	Mean	St. D	Min	Max	Percentage of "1"
Social-demographic factors					
Age (years old)	26.720	12.403	17	76	
Gender: Male			0	1	56.90%
Undergraduate student			0	1	68.34%
Graduate student			0	1	14.64%
Staff			0	1	8.93%
Faculty			0	1	8.09%
UPRM			0	1	63.60%
USF			0	1	36.40%
Years	2.379	1.036	1	4	
Commute-related factors					
Commute time (min.)	24.424	22.416	0	180	
Private vehicle as driver			0	1	86.47%
Private vehicle as passenger			0	1	2.09%
Bike/walk			0	1	11.44%
Alt - drive			0	1	10.18%
Alt - passenger			0	1	43.10%
Alt - bike/walk			0	1	20.78%
Alt - transit			0	1	13.39%
Alt - taxi			0	1	11.44%
Alt - moto			0	1	0.84%
Attitude driver	3.202	1.174	1	5	
Attitude passenger	2.940	1.238	1	5	

Binary Logit Model Analysis for Stated Parking Choice Behavior

The estimated parameters of the binary logit model are presented in Table 8. These parameters can be used to analyze the effects of sociodemographic factors, commute-related factors, and scenario-related factors on parking choices. In terms of sociodemographic factors, females have a higher propensity to choose carpooling with guaranteed parking, relative to those who did not identify as female. In terms of commute-related factors, individuals who selected either the private vehicle as the driver or as a passenger and biking/walking as their secondary mode displayed a higher probability of choosing carpooling with guaranteed parking. Additionally, respondents who expressed a greater willingness to share a ride as drivers, showed a higher likelihood of opting for carpooling with guaranteed parking. Regarding factors specific to the different designed scenarios, a higher parking cost is positively correlated with the likelihood of individuals choosing carpooling with guaranteed parking. Conversely, increases in the number of passengers and in travel and wait time are negatively correlated with the probability of individuals selecting carpooling with guaranteed parking.

To capture the response differences between the UPRM and USF samples, a USF dummy variable was included in the carpooling alternative, as well as an interaction term between the USF dummy and the parking cost. Respondents from USF exhibited a lower likelihood of selecting carpooling with guaranteed parking compared to those surveyed at UPRM, as can be seen from the negative coefficient of the USF dummy variable. The sign of the interaction term indicates that USF respondents were more likely to choose carpooling as the parking cost increases.

Multinomial Logit Model Analysis for Stated Mode Choices Behavior

To investigate the effect of sociodemographic factors, commute-related factors, and scenario-specific factors on mode choices, a multinomial logit model was estimated. The three choices are ‘driving alone’, ‘carpooling’, and ‘transit’. The parameter results are summarized in Table 9. Regarding sociodemographic factors, older individuals were less likely to choose transit as an alternative to driving alone. Moreover, graduate students and faculty members displayed a lower preference towards carpooling compared to undergraduate students, but they exhibited a higher probability of selecting transit. Additionally, respondents from USF presented a lower likelihood of choosing transit compared to those from UPRM. In terms of commute-related factors, individuals who selected a private vehicle as a passenger or chose biking/walking as the secondary mode showed a higher probability of opting for carpooling. Additionally, respondents who expressed a higher level of comfort in providing rides displayed an increased likelihood of carpooling or using transit instead of driving alone. Regarding factors specific to the designed scenarios, higher parking costs were positively correlated with the probability of individuals choosing carpooling or using transit. Notably, the probability of using transit for individuals at USF showed a high and positive relationship with parking costs, a difference that could be explained by the relatively limited minor use of transit at UPRM. Conversely, increased travel and wait time were negatively correlated with the probability of individuals opting for carpooling or using transit.

Table 8. Modeling results for the binary logit model (parking choice model)

Variables	Estimate	P-value	Sig.
Intercept	2.868	<0.001	***
Sociodemographic factors			
Age	-0.010	0.327	
Gender: Female	0.458	0.001	***
Graduate student	-0.268	0.179	
Staff	0.026	0.941	
Faculty	-0.381	0.321	
USF	-1.354	<0.001	***
Years	-0.054	0.450	
Commute-related factors			
Commute time	-0.001	0.714	
Private vehicle as passenger	-0.525	0.274	
Bike/walk	-0.442	0.245	
Alt - drive	0.677	0.094	.
Alt - passenger	0.273	0.039	*
Alt - bike/walk	0.302	0.065	.
Alt - transit	0.068	0.730	
Alt - taxi	-0.057	0.787	
Alt - moto	0.014	0.983	
Attitude driver	0.546	<0.001	***
Attitude passenger	0.041	0.467	
Scenario design-related factors			
Parking costs ($ units)	0.124	<0.001	***
# of passengers	-0.335	0.006	**
Added travel time – carpooling (minute units)	-0.065	<0.001	***
Interaction Effects			
USF dummy*parking cost	0.084	0.019	*
Level of Significance: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1			
Model Accuracy			
AIC	1,645.580		
BIC	1,766.750		
Log-likelihood	-799.790	*(df=23)*	
McFadden R^2	0.161		

Table 9. Modeling results for multinomial logit model (mode choices)

Variables	Carpooling			Transit		
	Estimate	P-value	Sig.	Estimate	P-value	Sig.
Intercept	1.482	0.006	**	1.182	0.029	*
Social-demographic factors						
Age	0.007	0.609		-0.034	0.007	**
Gender: Female	0.248	0.110		0.087	0.570	
Graduate student	-0.723	0.005	**	0.790	0.001	***
Staff	-0.476	0.260		0.809	0.040	*

Variables	Carpooling			Transit		
	Estimate	P-value	Sig.	Estimate	P-value	Sig.
Faculty	-0.984	0.039	*	0.838	0.055	.
USF	-0.342	0.223		-1.003	<0.001	***
Years	-0.154	0.069	.	0.133	0.109	
Commute-related factors						
Commute time	-0.002	0.572		-0.005	0.175	
Private vehicle as passenger	0.002	0.997		-0.196	0.739	
Bike/walk	0.169	0.730		0.327	0.506	
Alt– drive	0.680	0.191		0.281	0.594	
Alt – passenger	0.517	0.001	***	0.088	0.574	
Alt – bike/walk	0.411	0.036	*	0.255	0.197	
Alt – transit	0.335	0.164		0.382	0.117	
Alt – taxi	-0.362	0.160		0.147	0.555	
Alt – moto	-0.115	0.893		0.324	0.653	
Attitude driver	0.508	0.000	***	0.185	0.006	**
Attitude passenger	-0.040	0.543		-0.072	0.266	
Scenario design-related factors						
Parking cost	0.111	<0.001	***	0.076	0.003	**
Added time – carpooling	-0.067	<0.001	***	0.008	0.634	
Added time – transit	0.025	0.167		-0.072	<0.001	***
Interaction effects						
Location: Parking cost	0.065	0.125		0.114	0.007	**
Level of Significance: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1						
Model Accuracy						
AIC	2,876.626					
BIC	3,118.964					
Log-likelihood	-1,392.313	*(df=46)*				
McFadden R^2	0.105					

Choice Probabilities, Willingness to Accept, and Elasticities

Controlling for confounding factors such as sociodemographic factors and commuting features, the probability of choices across various scenarios was calculated, as presented in Figure 4. These scenarios are created by different combinations of conditions, encompassing factors such as parking costs for solo driving, the number of carpoolers, the additional waiting and detouring time associated with carpooling, and the extra waiting and in-transit time when using public transportation.

In this study, respondents were provided choices regarding parking preferences and mode selection for their commuting journeys under specific conditions, resulted in nine scenarios. Figure 4 illustrates the predicted probability of choosing carpooling, as a driver from the parking choice model, with guaranteed parking, considering varying parking costs for solo driving, the number of passengers, and the additional time spent during carpooling. The findings indicate that, as expected, the highest carpool choice probability is observed when the parking cost is high, and the extra waiting and detouring time are minimal. The variation resulting from different numbers of passengers is minimal. Furthermore, the influence of parking cost on the probability of choosing carpooling with guaranteed parking diminishes. These results suggest that a higher potential for parking cost savings helps alleviate the negative impact of increased waiting and detouring time on the likelihood of selecting carpooling with guaranteed parking as a preferred option.

Figure 5 illustrates the predicted probability of selecting the alternative of carpooling as a passenger from the mode choice model, with scenarios based on parking costs for solo driving and additional time required for carpooling. Consistently, the highest probability is observed when the parking cost is high, and the additional waiting and detouring time is low. However, the magnitude of this effect changes accordingly as parking costs increase. Once again, these findings reaffirm the significance of utilizing parking pricing as a strategy to foster carpooling, and the adverse impact of waiting and detouring can be significantly alleviated.

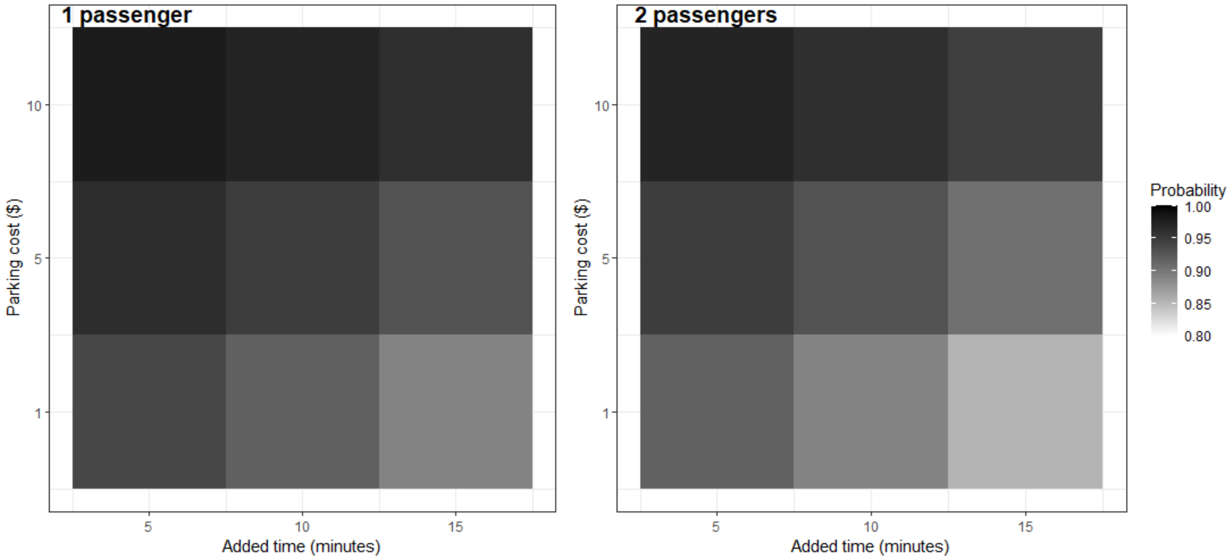


Figure 4. Predicted probability for carpooling choice as a driver with guaranteed parking under 18 scenarios

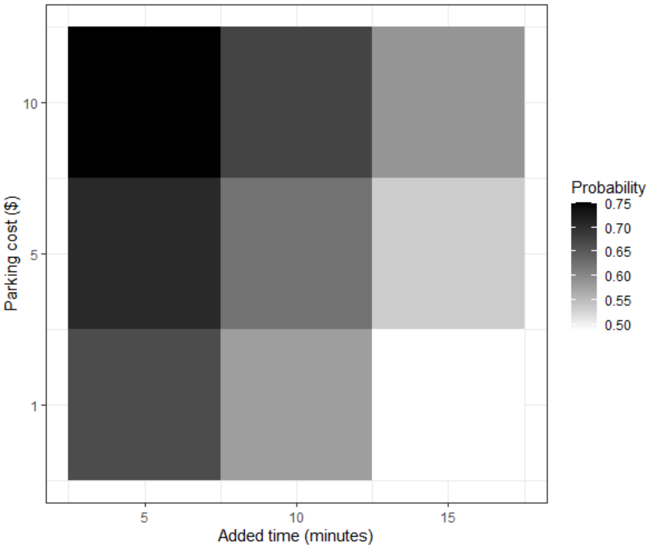


Figure 5. Predicted probability for carpooling choice as a passenger under 9 scenarios

Table 10 presents the computed WTA values. Individuals at UPRM require greater parking cost reductions to compensate for the disutility of the extra carpooling time, in contrast to their counterparts at USF. In the mode choices model, individuals at UPRM also exhibit a higher demand for parking cost savings when they choose transit as their preferred mode of transportation. Interestingly, both UPRM and USF participants show an equal willingness to accept carpooling as passengers as an alternative mode of transportation. These findings imply that the availability of guaranteed parking at USF significantly influences the preference for carpooling within its community. These results could reflect the real-world experiences that each sample has with parking policies and transit at their respective universities (e.g., UPRM has a transit service that mostly provides transport within the main campus, whereas USF is serviced by a more extensive transit system that connects adjacent communities to the university). The results emphasize the importance of considering university-specific parking policies when analyzing travel choices and advocating for sustainable commuting options.

Table 10. Willingness to accept (WTA) for modeling results ($/minutes)

University	Parking Choices	Mode Choices	
	Carpooling with Guaranteed Parking	Carpooling	Transit
UPRM	0.524	0.604	0.947
USF	0.313	0.604	0.379

The cross-point elasticities of the carpooling parking probability with respect to parking cost were computed for both university samples (Figure 6). The elasticities were computed using a reduced binary logit parking choice model that was estimated using only the variables that had statistically significant parameters in the full model reported in Table 3. The reduced model was estimated to obtain better estimates of the choice probabilities; ultimately, the parameters of the reduced model were comparable to those of the full model, with the main difference being in the magnitudes of carpooling alternative specific constant (the intercept changed from 2.868 to 0.901). The results reported in Figure 6 were computed assuming as a representative individual a female driver, with neutral attitude towards riding with a stranger and with the extra carpooling travel time attribute set to 5 minutes; similar trends would be obtained with other representative individuals. The results indicate that UPRM participants have a higher probability of selecting the “carpool with guaranteed parking” alternative, and that this probability increases as parking cost increases. For both university groups, the probability of choosing carpooling as a driver is relatively inelastic with respect to parking cost changes, although it is more elastic as the parking cost increases, and it is more elastic for URPM participants.

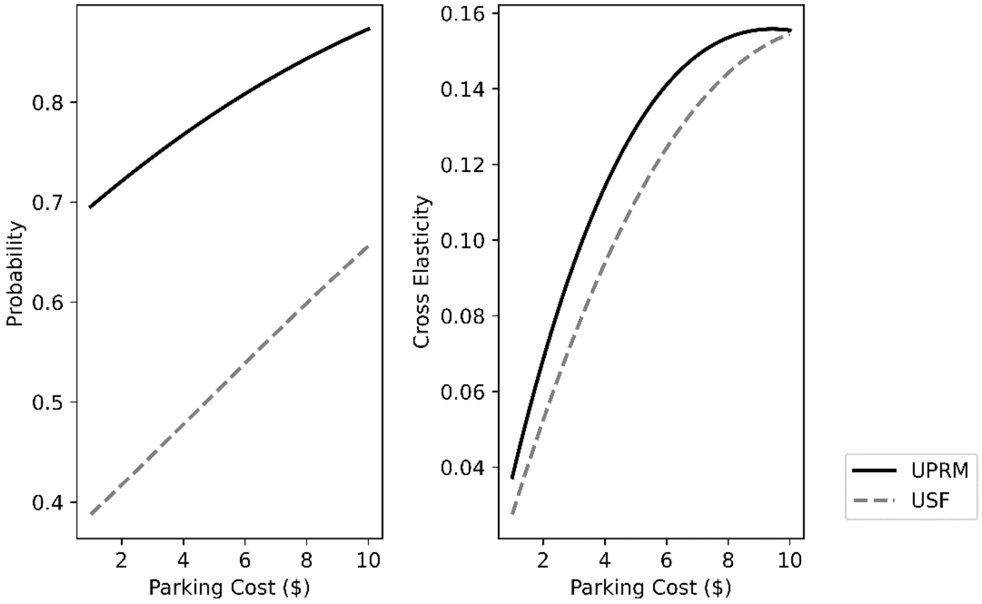


Figure 6. Probability of carpooling as a driver and its cross-point elasticity relative to parking cost

Using the reduced binary logit model, the direct point elasticities of the pooling parking probability with respect to extra carpooling travel time were computed, as reported in Figure 7. The results reported in Figure 7 were computed assuming as a representative individual a female driver, with neutral attitude towards riding with a stranger and with the parking cost attribute set to $5. Again, UPRM participants have a higher probability of selecting carpooling with guaranteed parking, which decreases as the carpooling travel time increases. The probability of carpooling as a driver is relatively inelastic with respect to the carpooling travel time, although USF participants had a higher sensitivity (i.e., higher magnitude elasticities) to the carpool travel time.

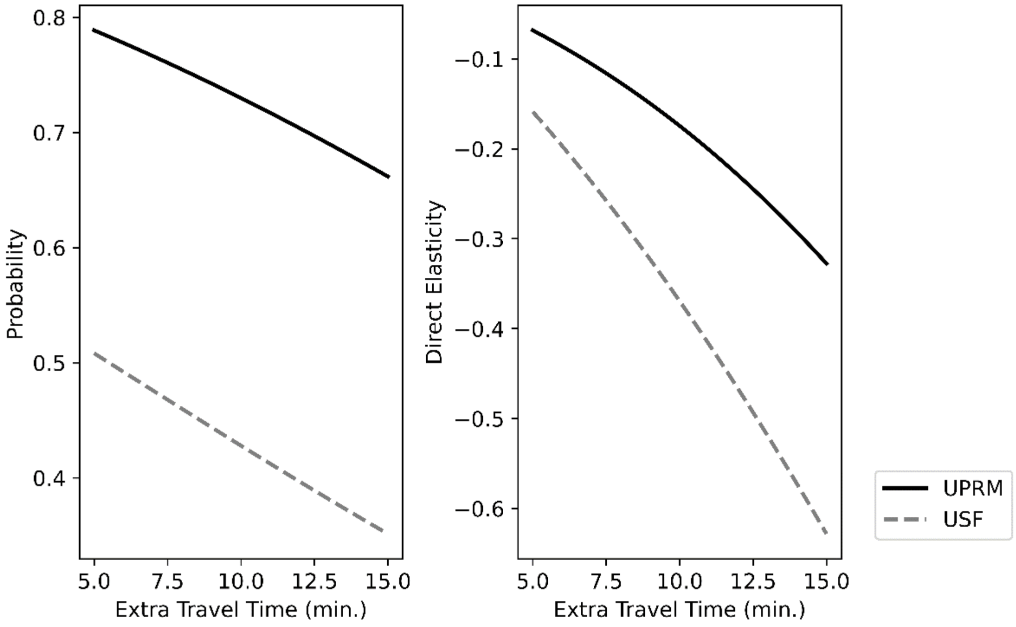


Figure 7. Probability of carpooling as a driver and its direct-point elasticity relative to carpooling travel time

In Figure 8, the cross-point and direct elasticities of the probability of selecting the carpooling mode as a passenger are presented. Elasticity values for each university were not computed as the model results do not suggest a difference in carpooling choice preferences. Like for the parking choice model, a reduced mode choice model was used to obtain the reported results, and the same representative individuals were used. The cross-point elasticity of the probability of selecting carpooling as a passenger with respect to parking cost is even more inelastic than the cross-point elasticity of selecting carpooling as a driver. The direct point elasticity of the probability of selecting carpooling as a passenger with respect to carpooling travel time has a higher magnitude than the cross elasticities, and the results are similar to those for the probability of selecting carpooling as a driver (see Figure 7) because the carpooling extra travel time parameters have similar values (around -0.065).

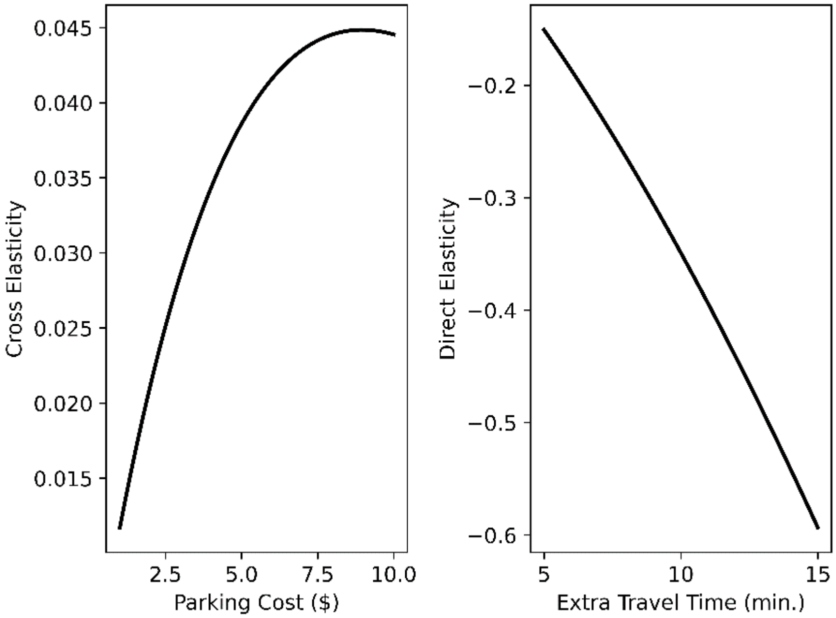


Figure 8. Cross-point and direct elasticities of the probability of selecting carpooling as a passenger

Discussion

Summary of Findings

The stated preference study focuses on exploring preferences towards carpooling with a PARS-like option versus parking pricing at a university. The study collected data through two questionnaires administered to students, staff, and faculty members at the UPRM and USF. The questionnaires were designed to gather information on parking preferences and mode choices for commuting, considering factors such as parking cost, number of passengers, and additional travel and wait time. The key findings of the study are discussed below.

Females exhibit a higher level of interest in carpooling with guaranteed parking. According to previous research, females are typically less inclined to carpool compared to males due to concerns related to safety and security (Delhomme & Gheorghiu, 2016; Matsuo, 2020). The convenience offered by guaranteed parking, coupled with the increased sense of security that arises from carpooling with individuals from the same university, could make carpooling with guaranteed parking more appealing. Sharing the ride with fellow university members could create a greater level of trust and openness to carpooling.

Older individuals are found to have a lower likelihood of utilizing transit, which contradicts findings in the existing literature (Su & Bell, 2009; Truong & Somenahalli, 2015). This finding may be attributed to sampling bias resulting from the specific empirical setting chosen for the study or the convenience sampling approach used.

Undergraduate students exhibit a higher tendency to engage in carpooling compared to graduate students. Several factors could explain this observation. The spatial distribution of undergraduate and graduate student residences could be different. Undergraduates typically have a larger peer network, which includes classmates and friends residing near the campus or with similar commuting patterns. These schedule and activity similarities make it more convenient for undergraduate students to establish carpooling arrangements and share rides, as they are more likely to find potential carpool partners within their existing social network. Carpooling presents a cost-saving opportunity for undergraduate students by sharing expenses related to fuel and parking, which can be more economical compared to driving alone or using other transportation options. Additionally, university campuses frequently experience limited availability of parking spaces during daytime hours when undergraduate courses are predominantly scheduled.

Increased parking costs incentivize people to opt for carpooling or public transit, with carpooling being a more attractive choice compared to public transit in the two university settings. In the case of both Mayagüez and Tampa, the spatial coverage of transit services is limited. Individuals may encounter lengthy waiting times of up to half an hour or even an hour if they miss a bus. In contrast, carpooling provides greater flexibility and convenience. Carpoolers have more control over their departure times, routes, and destinations as they can coordinate schedules with their fellow carpoolers (Neoh et al., 2018). This flexibility is particularly appealing for individuals with varying schedules or specific travel needs. It appears that current parking fees at USF are considered reasonable by both students and staff. A prudent modification of parking fees within a reasonable range could increase their enthusiasm for endorsing carpooling with guaranteed parking, given that both faculty and students perceive greater potential savings. The execution of this policy should be carefully evaluated, particularly in terms of affordability, to prevent public backlash.

Key Takeaways

The successful implementation of integrated parking and carpooling initiatives is highly context-specific and varies across different university environments. Each university may need to tailor the tools and strategies to fit their unique circumstances. Factors such as parking availability, cost, transit service quality, external traffic conditions like congestion, and the affordability of car ownership all play significant roles in influencing the decision to carpool. The provision of convenient and incentivized parking can serve as a strong motivator in encouraging individuals to shift towards carpooling as a preferred mode of transportation.

In the collected data, females and undergraduate students show a strong interest in the integrated parking and carpooling initiative, highlighting a significant potential for its promotion. To further enhance carpooling activities, specific actions targeted towards females and undergraduates can be implemented. These actions may include establishing designated and monitored areas for pick-up and drop-off, creating a female carpooler club, forming an undergraduate carpooler group, and prioritizing matching preferences for these groups. By implementing these tailored measures, the participation and engagement of females and undergraduate students in carpooling can be further encouraged.

While parking costs can help mitigate the negative effects of extended waiting and detouring time in carpooling, the influence of increasing parking costs on promoting integrated parking and carpooling has limitations. It is expected that excessively high parking fees may lead to criticism from the university population without significantly advancing this initiative. When parking fees are implemented, it is important to strike a balance and ensure that it is not set at an excessive level.

When implementing integrated parking and carpooling initiatives with incentives, it is crucial for other universities to carefully evaluate the potential benefits and costs, considering the potential impact on transit systems in the local area. It is important to ensure that these initiatives are designed to complement, rather than compete with, existing transit systems. By striking a balance and fostering collaboration between parking and carpooling options and public transit, universities can create a comprehensive and sustainable transportation ecosystem that meets the diverse needs of their communities.

Despite integrating parking and carpooling with incentives having many merits, this initiative remains largely theoretical and requires further real-world implementation and testing. The core of developing this initiative includes designing incentivized parking permits, developing a carpool matching system, and promoting marketing campaigns. Parking incentives may include discounted or prioritized parking permits, reduced parking fees, preferred parking locations, or guaranteed parking spots for carpooling groups. This initiative requires the development of a user-friendly online platform or mobile application that connects people looking to carpool based on their schedules, routes, and preferences. This platform should also integrate the incentivized parking system, allowing participants to easily access their parking benefits. To promote awareness, this initiative may launch comprehensive marketing strategies to promote the benefits of carpooling and incentivized parking program. It may also utilize various communication channels such as social media, flyers, posters, campus newsletters, and orientation sessions to reach a wide audience. The next chapter will present an overview of a real-world implementation of a PARS-type system.

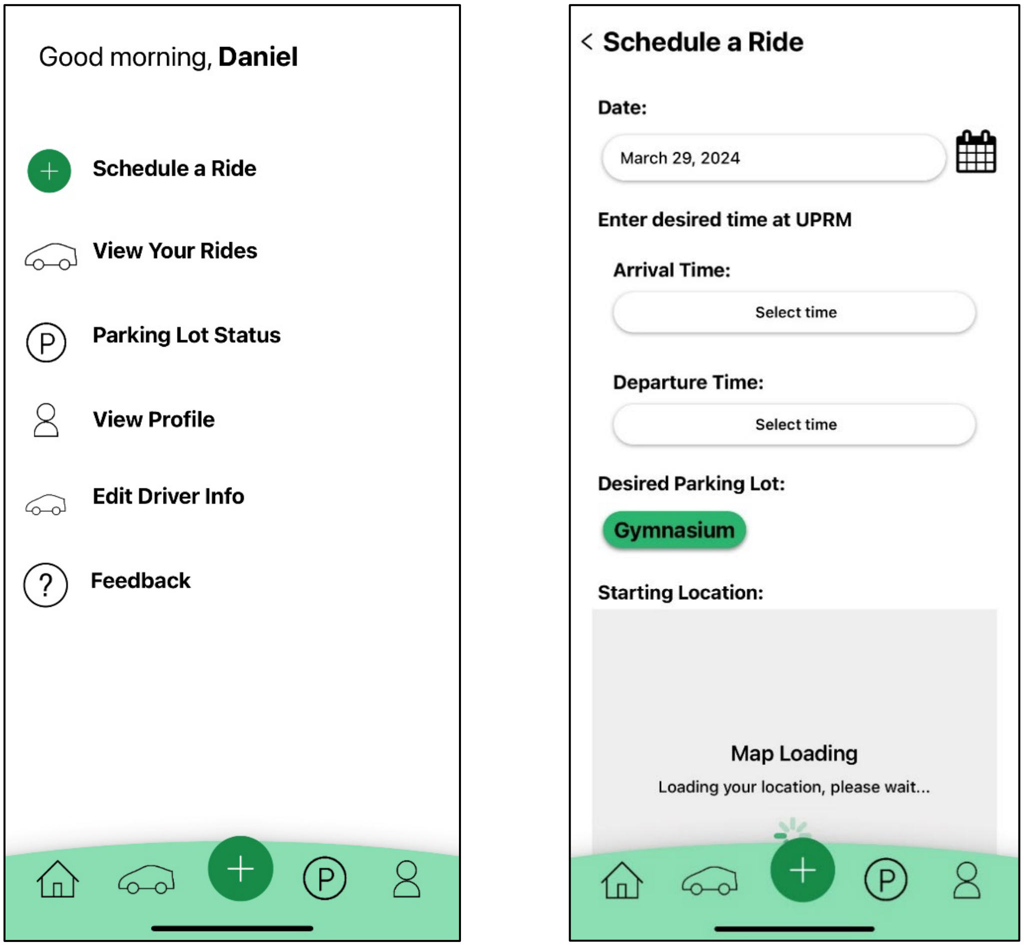
Chapter 5. PARS Prototype

The model proposed in Chapter 3 was implemented in the mobile application (app) called ROCS Carpool and it was launched as part of an integrated carpooling-parking service at UPRM. The system officially started providing services on March 7, 2024, although a soft launch was performed on November 28 and 29, 2023, to conduct preliminary technical tests with a selected group of UPRM users. The service operated for until April 19, 2024 (27 days not counting weekends and holidays) in a section of the main student parking lot with 28 parking spaces. The parking section was selected as it has a single entry/exit point, making traffic flow easy to control. The UPRM system is a prototype of the proposed PARS systems. A key difference between the prototype implementation and the assumptions that underpinned the PARS policy discussion is that students at UPRM had another parking alternative, namely the standard, free-of-charge student parking area. This chapter provides a brief overview of the prototype components, accounts of the experiences with the service's launch, and a discussion of lessons learned.

Main System Components and Procedures

The prototype's hardware components were a mechanical parking barrier gate, a single-panel photovoltaic energy system, a traffic barrier, and antennas that connected the parking barrier subsystems to the internet. The main prototype's hardware components can be seen in Figure 9. The main interface of the ROCS Carpool app is shown in Figure 10. After agreeing to the terms and conditions of the app, users were asked to complete their user profiles. Drivers also had to provide information about their vehicles, including the color, make and model, and license plate. After creating their profile, a user scheduled a ride by indicating the date, start and end time of their desired activities period at UPRM, and the starting location of their trip. The PARS algorithm ran on a cloud computing service. At the time of writing, only UPRM community members can create an account on ROCS Carpool. System operations were halted on April 22, 2024, due to the breakdown of a parking gate component.

Figure 9. Location of prototype launch


Good morning, **Daniel**

Schedule a Ride

Date: March 29, 2024

Enter desired time at UPRM

Arrival Time: Select time

Departure Time: Select time

Desired Parking Lot: Gymnasium

Starting Location:

Map Loading

Loading your location, please wait...

Figure 10. Main components of the ROCS Carpool user interface

Sequence of Events in the Use of a ROCS Carpool-Parking Reservation

At 9:00 PM of each day, the PARS algorithm was executed to determine the selected carpool and parking reservations given the received user requests. Once the program that implements the PARS algorithm completed its tasks, users received a notification with the status of their requests (accepted or rejected). Users who were assigned to a carpool were given the information about their carpooling partners (names, phone numbers, emails, pick-up locations, schedules). Carpool members were encouraged to contact each other and to coordinate details. From a user's perspective, the arrival/departure mechanics at the ROCS parking location are as follows:

- *Arrival*: the driver must open the parking barrier using ROCS Carpool. To do this, the driver must click on a button to verify their proximity to the barrier (at most 30-feet away from it), and once this is verified, an "Open" button is enabled on the app. When the driver is ready, they click on the "Open" button and the barrier opens. For carpools, all members of a carpool are required to use ROCS Carpool to verify their proximity to the barrier before the driver is given the option to open the barrier, thus ensuring that all carpool members are in the vehicle (or more precisely, that smartphones with each carpool member's ROCS accounts are close to the barrier). The ability to open the parking barrier is enabled 10 minutes before the start of the parking reservation period.

- *Departure*: Again, the driver must open the parking barrier using ROCS Carpool, following the previously described steps. The only difference compared to the arrival procedure, is that the driver can depart the parking lot at any time, unless the driver is part of a carpool, in which case all passengers must also confirm their proximity to the parking barrier using the app.

ROCS Carpool contains mechanisms to address unscheduled events, such as user cancellations and no-shows.

Overview of Launch Experience and Lessons Learned

At the time of this writing, the app has been downloaded 751 times. The number of reservations per day of operations is presented in Figure 11. In total, 98% of the 476 reservations that were submitted were approved by the system. Only 13% of the service requests were submitted by riders. Only rider requests were denied by the system, as there was always sufficient parking capacity for the number of driver requests. In total, 17% of ride requests were denied by the system. Ride denials were caused by the lack of drivers within the requested geographic locations and/or time windows. Once the system approved requests, approximately 71% (±22%) of drivers accepted their reservations (i.e., they did not cancel their reservations). Figure 12 presents the accepted reservations by the drivers. The lowest reservation acceptance dates are associated with a student assembly day in which classes were suspended from 12:00 pm onwards and days close to major holidays. On the 13th day of operations, the parking gate malfunctioned, which is why the acceptance percentage is reported as zero for that date.

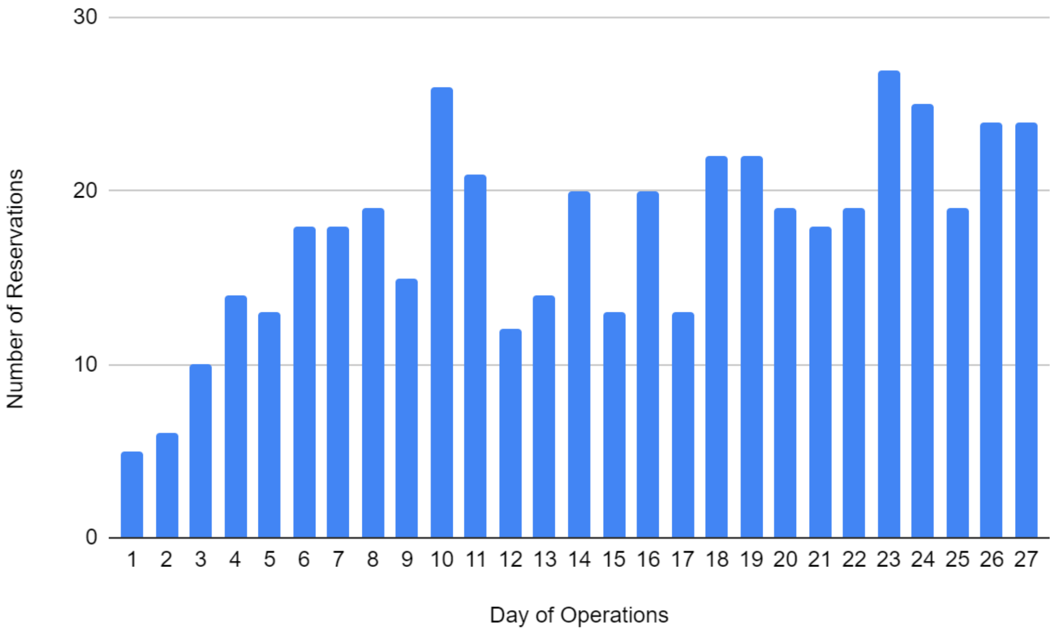


Figure 11. Number of reservations per day in ROCS

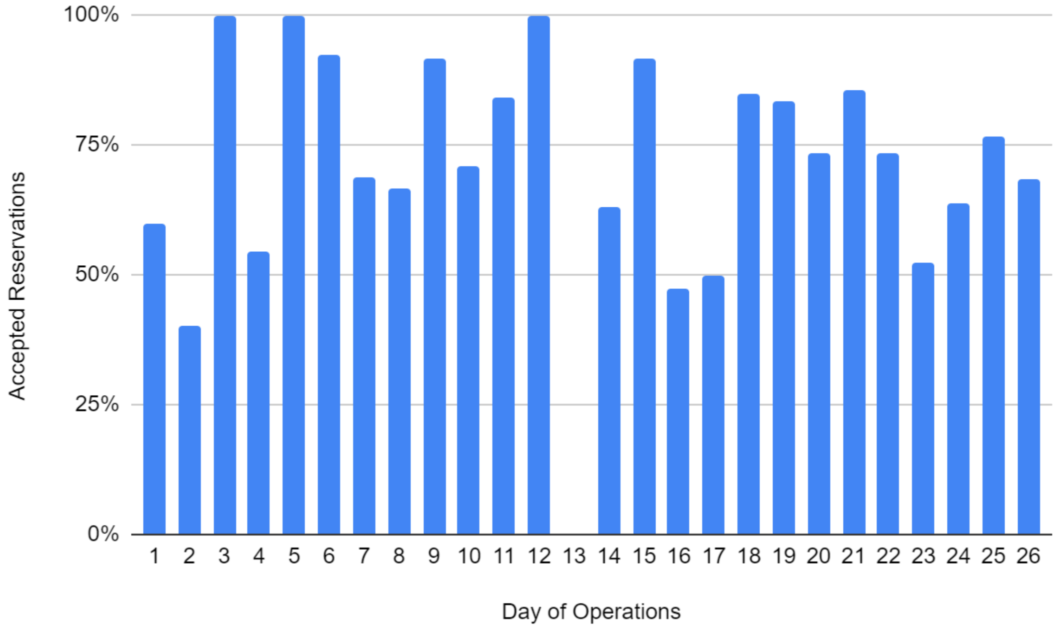


Figure 12. Accepted reservations by drivers in ROCS

The number of new users per day of operations is presented in Figure 13. On average, each day had 3.5 (±2.7) new users submitting requests. In total, there were 95 unique individuals who submitted parking or trip requests to ROCS.

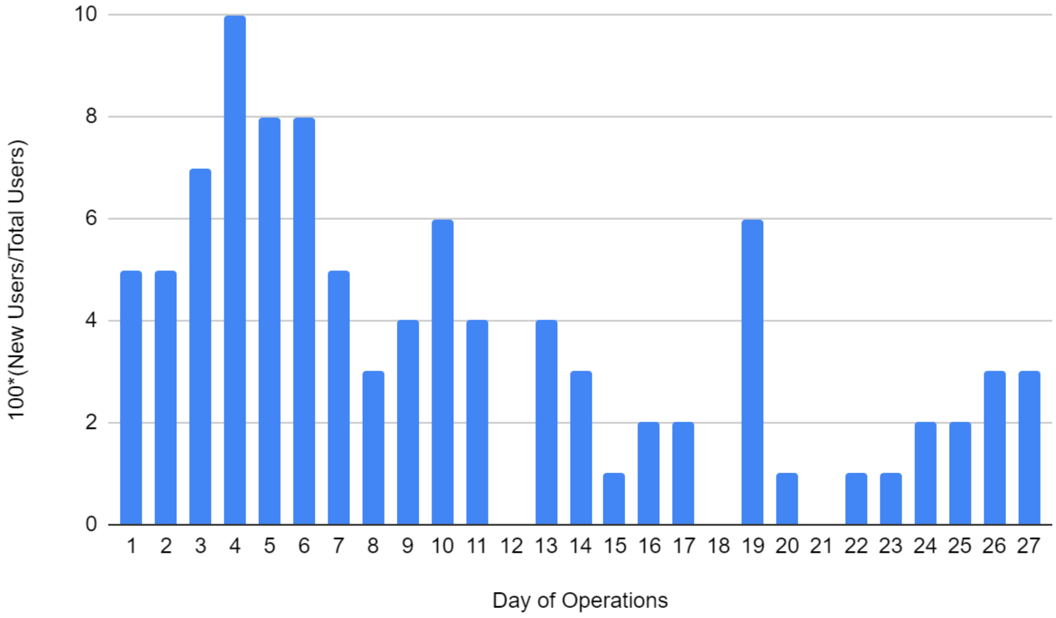


Figure 13. New users submitting service requests for each day of operations

Through informal conversations with UPRM community members and messages through ROCS social media accounts, the team noted the belief or concern that females were less likely than males to use the service due to safety concerns related to carpooling. Gender data was not available to explore if this was the case, in part because ROCS users were not asked to indicate their gender when registering in the app and because a survey was not conducted while ROCS was in operations to determine the reasons different groups were not using the system as much as others. However, a related question was explored: were males overrepresented among ROCS users? To answer this question, gender for each user was inferred based on their first name. It is assumed that, given the correlation between gender and types of first name in Puerto Rico, this approach would yield accurate results. Procedures for name-based gender inference are used commonly used in the absence of gender information (e.g., seeKarimi et al., 2016). Here, users were assigned into two groups: Female label and Male label. These terms are used, instead of Female and Male, to recognize the possibility of misgendering individuals based on their first name. Figure 14 presents the distribution of users by gender label for each day of operations. On an average day, 48% (±17%) of users submitting request to ROCS were Female label. For comparison, 45% of UPRM undergraduate students for the fall semester of 2023 were female. Therefore, the available data does not suggest an obvious overrepresentation of males among ROCS users.

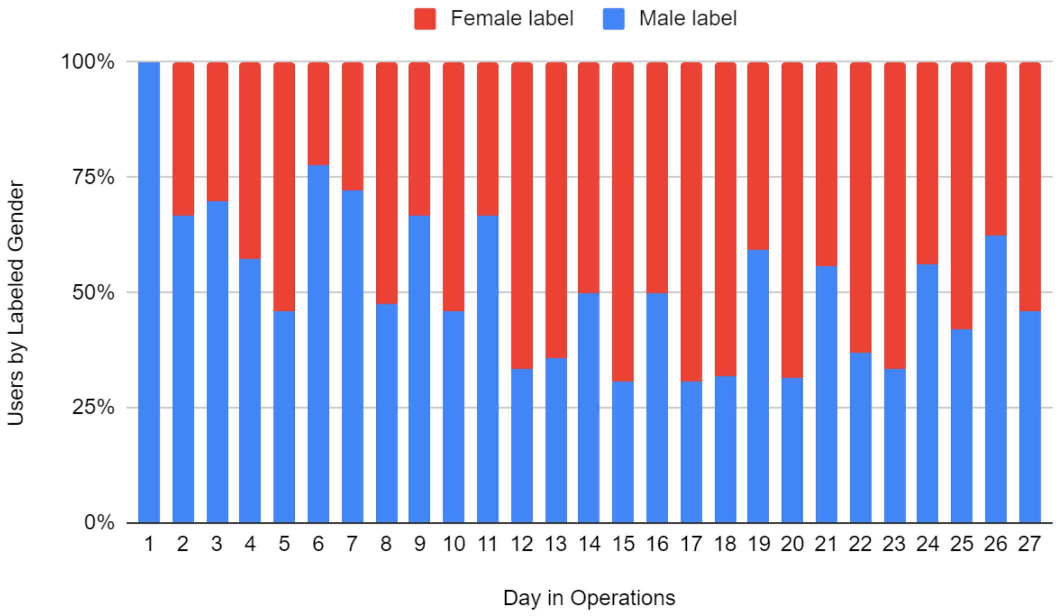


Figure 14. Users by labeled gendered for each day of operations

Based on the usage patterns, informal conversation with ROCS users and non-users, and feedback received through social media accounts, the main lessons learned from the 27 days of operations were:

- *Outreach and marketing are fundamental for carpooling programs*: Prior to the launch the team sent UPRM-wide emails about the service, distributed flyers, and created social media accounts for the service and posted messages, some of which were viewed more than 50,000 times. However, informal conversations with students reveal that there were many misconceptions about the service, the main being that it is an "UBER"-style service. The misconceptions include that drivers must make multiple trips in a day to transport people, that users need to pay to use ROCS, and that non-university people can use the system. Considerable work remains to communicate the features of the service and potential benefits. Future projects should consider designing outreach and marketing activities in parallel with the engineering activities, so that they are tested and ready for publication as soon as the system is operational.

- *It is not enough to state that only university members can use the system*: Like in the reviewed literature, one of the main barriers to the use of ROCS is the mistrust of unknown people. For example, the research team has received feedback stating that the system needs a "friend list" or that the system needs to control the sex or gender characteristics of carpools (e.g., only female passengers and drivers). The team is working on modifications to the ROCS system to allow users to specify their social network of accepted carpool participants. The team is also considering how existing online social networking data could be used to determine the similarity between travelers and potentially build trust among them (Xia et al., 2019). Lastly, the team is exploring introducing features to elicit user inputs that can be used to determine the level of compatibility between potential members of a carpool and/or to compute review scores (e.g., punctuality, vehicle cleanliness) (Caballero-Gil et al., 2015; Selker & Saphir, 2010).

Chapter 6. Conclusions

This study proposed a new non-pricing policy for managing parking demand called Parking Allocation and Ride-Sharing System (PARS). The proposed policy reserves carpool-dedicated parking stalls, free of out-of-pocket cost, to drivers who are willing to participate in coordinated carpools. Drivers who do not get a reserved parking are considered riders and incorporated into a carpool as a rider.

In PARS, a centralized algorithm is used concurrently to establish the carpool assignments and parking allocations. A mixed integer linear programming (MIP) formulation and two heuristics based on the structural properties of the problem are presented to perform this function.

Additionally, preference for a PARS service compared to parking pricing was examined through a stated preference survey. The discrete choice analysis of the collected data revealed that females were more likely to select the carpooling alternative in questions in which they were drivers, and the gender variable was not significant for the case where the respondent had to consider being a passenger. As expected, higher parking prices increased the probability of selecting the carpool alternative, while extra carpooling travel time decreased the probability of selecting the carpool alternative. In general, the analysis suggests that survey respondents were more willing to participate in a university-coordinated carpooling program as drivers rather than passengers.

Potential Benefits and Drawbacks of PARS

The main benefit for drivers under the PARS policy is that they could have a guaranteed parking space at a venue. On the other hand, drivers could have the inconvenience of carpooling with strangers and having extra travel to pickup and drop-off riders. It can be argued that for most drivers, a moderate amount of extra travel compensates for not having the uncertainty of not finding parking and having to wait and search for an open parking spot at the venue. Perhaps, the toughest burden for drivers will probably be the commitment to an arrival and departure schedule.

The main benefit of PARS for riders is that they get matched with a driver that picks them up, takes them to the venue, and drops them off for free (and, for some, without the need to take their own vehicle and drive to the venue). Clearly, the downside for riders is that they get matched to a stranger who will drive them, and the uncertainty of the driver complying with the commitment. In terms of commitment, riders have less responsibility than drivers as they can easily opt out of their return trip if they decide to stay longer, at the expense of finding their own way back. There is a subgroup of individuals that will identify themselves as drivers but are reassigned as riders because the system did not assign them parking. This sub-group can be interpreted as those that have the least utilitarian contribution as drivers.

One of the most interesting characteristics of the PARS policy is that the centralized algorithm creates the carpool compositions and reserves parking. Our hypothesis is that if the algorithm is perceived as unbiased and fair, individuals would be willing to sacrifice a little comfort for the benefit of the collectivity, including the reduced carbon footprint. It is observed that individuals with depots in close proximity that have a similar (r_i, s_i) windows would be considered a favorable match for the algorithm. Therefore, it is possible for individuals to conspire by providing identical (r_i, s_i) windows. Since the centralized algorithm makes decisions considering the greater good, this behavior is not discouraged.

There are multiple potential issues that threaten a practical implementation of PARS, including: (1) the practicability of establishing arrival and departure windows at the venue a priori, (2) risks and responsibilities assumed by drivers (*e.g.*, insurance, unfit riders, undesirable riders, rider with illicit drugs), and (3) managing driver or rider no-shows. The first risk (time windows) could be mitigated by running a dynamic re-allocation procedure to handle these situations. The other two risks are also faced by existing ride-sharing services, and they typically addressed by using a third-party insurance policy and implementing individual ratings or other systematic controls, respectively. Another concern that could arise is that since parking stalls are reserved, the capacity of the dedicated parking lot might not be fully utilized. Empty stalls could give the false impression that parking stalls are not being properly managed. Mitigation strategies for a practical implementation of PARS are beyond the scope of this work. Studying the public perception of the proposed PARS policy, as well as potential practical and implementation challenges, is the subject of ongoing research, but is beyond the scope of this study.

Another interesting feature of the PARS policy is that it is expected to balance itself as a consequence of supply and demand. For example, if there are fewer drivers than parking slots, then it would be convenient for drivers to artificially reduce the car capacity, which is an input in the registration portal. If the car capacity is set to 1 (i.e., only the driver), then the driver would get reserved parking without having to pick anyone up. Similarly, if a driver is not being awarded parking reservations, they would consider increasing the car capacity to match the true vehicle’s capacity or changing the arrival and departure schedule to avoid peak demand times.

Lastly, it is interesting to observe that the algorithm prioritizes based on the objective function, which is associated with minimizing total travel distances. For parking reservations that coincide with low parking demand periods, the system minimizes cost by allowing as many cars as possible. Hence, carpools will have unused capacity. However, if the parking reservation window for the carpools coincides with a high-demand period, the system is forced to prioritize carpools with more riders. Clearly, during these periods there will be an optimization tradeoff as adding riders to a carpool would likely extend the reservation requirement window for the carpool.

Future Research

Future research could focus on empirically understanding the practicality of the proposed PARS policy, including the perception of the unbiasedness and fairness of the algorithm. Also, it would be interesting to understand if individuals would be willing to sacrifice some comfort for the collective benefit, including the reduced carbon footprint. Our hypothesis is that the travel behavior factors motivating carpooling choices from academic literature will hold in PARS .

Future research may also focus on relaxing the fifth model assumption (drivers are to be considered riders if not assigned as drivers) in the model, extending the current PARS policy for more complex scenarios with different parking structures or parking requirements, or proposing a dynamic approach to solve the problem as new information requests and cancellations becomes available. Lastly, it would be interesting to understand the impact of incorporating time-windows instead of latest arrival and earliest departure times in terms of the solve time.

In terms of policy analysis, future research endeavors could conduct survey-based studies with experimental settings beyond universities, such as large employers. This would allow for a broader understanding of the effectiveness and applicability of the integrated parking and carpooling initiative in different contexts. By examining these settings, researchers can gain valuable insights into the potential benefits, challenges, and feasibility of implementing such initiatives beyond the low-density environments and the university settings.

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Appendix A. Survey Questionnaire

This appendix contains the general structure of the survey questionnaire. The USF team implemented the survey using Qualtrics, while the UPRM team implemented the survey using LimeSurvey. The USF questionnaire was written in English, while the UPRM questionnaire was in Spanish.

The questionnaire begins after the following horizontal line.

Section 1. General Information

1. Gender:
   - Female
   - Male
   - Other
   - Prefer not to answer

2. Age: ________ years

3. Currently, what is your main transportation option to travel to the university?
   - Private vehicle as driver
   - Private vehicle as passenger
   - Transit
   - Non-motorized Transportation (bike, walk, skateboard, scooter)
   - Taxi & ride-hailing services (e.g., Uber and Lyft)
   - Motorcycle
   - Other

4. Besides the main transportation option stated in the previous question, do you have other options to travel to the university? Select all that apply.
   - Private vehicle as driver
   - Private vehicle as passenger
   - Transit
   - Non-motorized Transportation (bike, walk, skateboard, scooter)
   - Taxi & ride-hailing services (e.g., Uber and Lyft)
   - Motorcycle
   - Other
   - None

5. What is your current relationship with the university?
   - Undergraduate student
   - Graduate student
   - Staff
   - Faculty
   - None/Other

6. What is your average commuting time (in minutes) when traveling to the university? _______

Section 1.5 Additional Demographic Questions

7. *[IF person identifies as student]* How many years have you been studying at USF/UPRM?
    - 1 or less
    - 2
    - 3
    - 4
    - 5
    - 6 or more

8. *[IF person identifies as worker]* How many years have you been working at USF/UPRM?
    - 1 or less
    - 2-5
    - 6-10
    - 11 or more

Section 2. Description of Alternatives

[IF person indicates in Question 3 that they travel to the university by driving their car, they will see the following paragraph]

> Next, you will be presented with several hypothetical parking option scenarios.
>
> In each scenario, there are two parking alternatives, along with a description of each alternative.
>
> You must select the alternative that you prefer.
>
> In Alternative 1, you must pay to have access to a parking lot. This alternative is called PRICED PARKING.
>
> *[IF person identifies as a student]* In Alternative 2, you have access to a reserved carpool parking space, but you must be available to provide a ride to a fellow student in your trip to the university. This alternative is called RESERVED CARPOOL PARKING.
>
> *[IF person identifies as a worker]* In Alternative 2, you have access to a reserved carpool parking space, but you must be available to provide a ride to a fellow university employee in your trip to the university. This alternative is called RESERVED CARPOOL PARKING.

[IF person indicates in Question 3 that they do not travel to the university by driving their car, they will see the following paragraph]

> For the following questions, imagine that you have the option to travel to the university by driving a private vehicle.
>
> You will be presented with several parking options scenarios.

In each scenario, there are two parking alternatives, along with a description of each alternative.

You must select the alternative that you prefer.

In Alternative 1, you must pay to have access to a parking lot. This alternative is called PRICED PARKING.

[IF person identifies as a student] In Alternative 2, you have access to a reserved carpool parking space, but you must be available to provide a ride to a fellow student in your trip to the university. This alternative is called RESERVED CARPOOL PARKING.

[IF person identifies as a worker] In Alternative 2, you have access to a reserved carpool parking space, but you must be available to provide a ride to a fellow university employee in your trip to the university. This alternative is called RESERVED CARPOOL PARKING.

Section 2.1. Stated-preference questions

9. Scenario 1: YOU ARE DRIVING to the university, and you have two parking choices, as described next:

Alternative Attributes	**Alternative 1: Priced Parking**	**Alternative 2: Reserved Carpool Parking**
Cost	[$1.00, $5, $10.00] per day	$0
Number of passengers to pick up in your trip	0	[1, 2, 3]
Additional travel time needed to pick passenger	0	[5, 10, 15] minutes
Guaranteed parking in campus	No	Yes

Which alternative do you prefer?

- Alternative 1. Priced Parking
- Alternative 2. Reserved Carpool Parking

[*The participant will see additional scenarios in this section, each scenario with a different set of attribute values. The levels are highlighted in green.]*

Section 3. Description of Alternatives [IF person indicates that they travel by car]

Next, you will be presenting with several hypothetical university travel and parking scenarios.

In each scenario, three travel alternatives are described. You must select the alternative that you prefer.

In Alternative 1, you drive to the university and you must pay to have access to a parking lot. This alternative is called PRICED PARKING.

In Alternative 2, you must travel to the university as a passenger in a carpool. YOU WILL HAVE A DRIVER for the trip to and from the university. This alternative is called CARPOOL.

In Alternative 3, you travel to the university using transit. This alternative is called TRANSIT.

Section 3.1. Stated-preference questions

10. Scenario 2: You have three travel options to the university. In Alternative 1, YOU ARE DRIVING and you pay for access to parking. In Alternative 2, YOU DO NOT DRIVE to the university. Instead, you travel as part of a university coordinated carpool in which a fellow student will drive you to the university. Assume that you have a carpool for your trip from the university. In Alternative 3, YOU USE TRANSIT.

Attribute	Alternative 1: Priced Parking	Alternative 2: Carpool	Alternative 3: Transit
Cost	[$1.00, $5, $10.00] per day	$0	$0.50
Guaranteed Parking	No	Does not apply	Does not apply
Compared to driving alone, additional travel and wait time	0	+[0, 5, 10] minutes	+[0, 5, 10] minutes

Which alternative do you prefer?
- Alternative 1. Priced Parking
- Alternative 2. Carpool Trip
- Alternative 3. Transit

[*The participant would see additional scenarios in this section, each scenario with a different set of attribute values. The levels are highlighted in green.]*

Section 4. Opinion Questions

[IF person identifies as an employee, the word "student" would be replaced by "employee" in the following questions.]

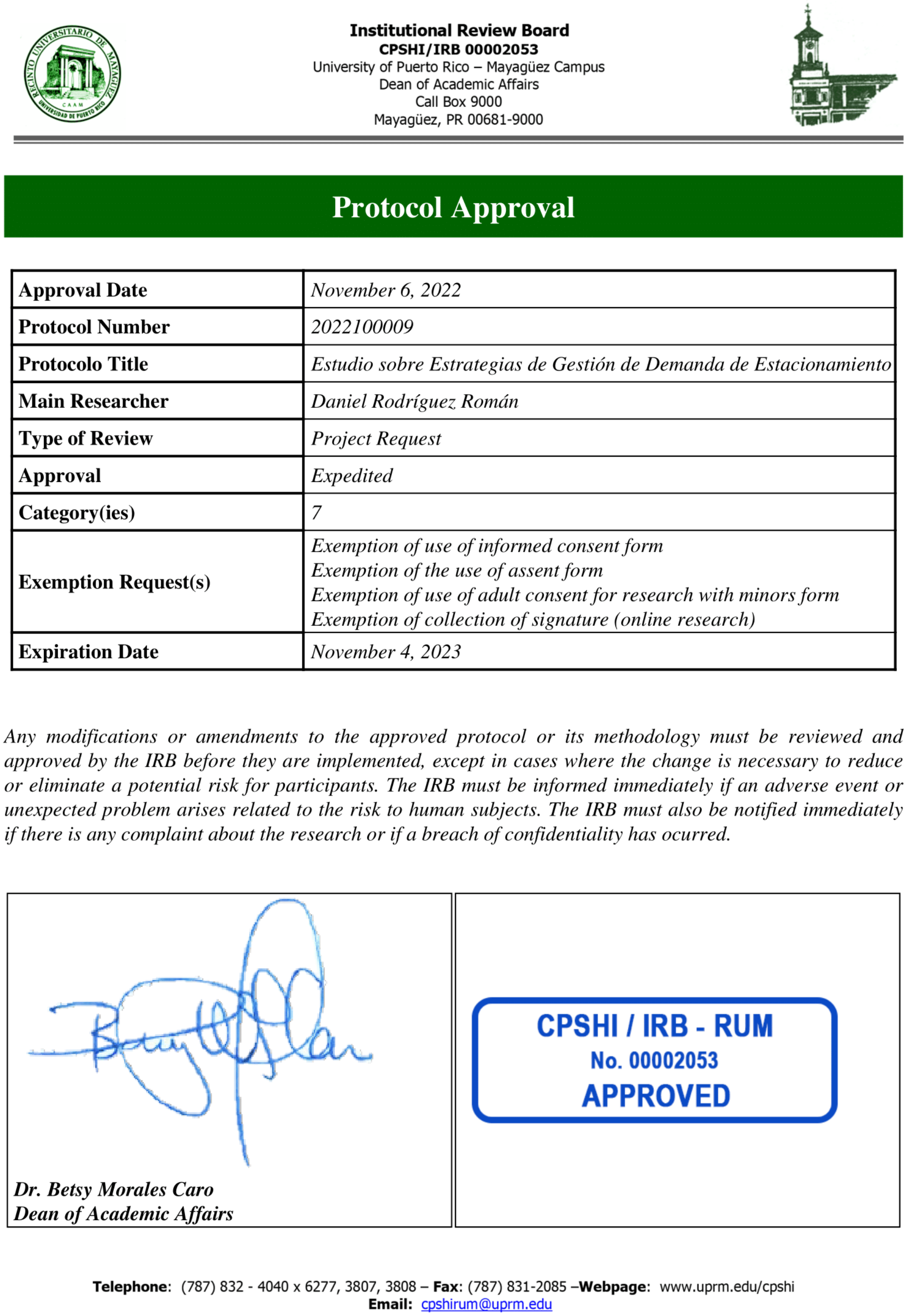
Please indicate whether you agree with the following statements.

11. I would be comfortable with giving a ride to a fellow student as part of a university coordinated carpooling program.
    - Strongly agree
    - Agree
    - Neutral
    - Disagree
    - Strongly disagree

12. It would make me uncomfortable to give a ride to a university student of a different gender than mine (assume that you do not know the person prior to the trip).
    - Strongly agree
    - Agree
    - Neutral
    - Disagree
    - Strongly disagree

13. I would be comfortable with being a passenger in a university coordinated carpool:
    - Strongly agree
    - Agree
    - Neutral
    - Disagree
    - Strongly disagree

14. It would make me uncomfortable to travel as a passenger in a university coordinated carpool program if the driver is a person of a different gender than mine (assume that you do not know the driver prior to the trip):
    - Strongly agree
    - Agree
    - Neutral
    - Disagree
    - Strongly disagree



Institutional Review Board
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Protocol Approval

Approval Date	*November 6, 2022*
Protocol Number	*2022100009*
Protocolo Title	*Estudio sobre Estrategias de Gestión de Demanda de Estacionamiento*
Main Researcher	*Daniel Rodríguez Román*
Type of Review	*Project Request*
Approval	*Expedited*
Category(ies)	*7*
Exemption Request(s)	*Exemption of use of informed consent form* *Exemption of the use of assent form* *Exemption of use of adult consent for research with minors form* *Exemption of collection of signature (online research)*
Expiration Date	*November 4, 2023*

Any modifications or amendments to the approved protocol or its methodology must be reviewed and approved by the IRB before they are implemented, except in cases where the change is necessary to reduce or eliminate a potential risk for participants. The IRB must be informed immediately if an adverse event or unexpected problem arises related to the risk to human subjects. The IRB must also be notified immediately if there is any complaint about the research or if a breach of confidentiality has ocurred.

Dr. Betsy Morales Caro
Dean of Academic Affairs

CPSHI / IRB - RUM
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