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A Share-a-Ride Problem and Occasional Drivers

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Abstract. In recent decades technological advances have allowed the implementation of solutions designed for transportation problems. One of these proposals is the Share-a-Ride Problem (SARP), which creates shared travel environments among passengers and packages, served by a fleet of vehicles. The concept of occasional drivers has extended transportation problems, approaching the real last-mile transport scenarios. This work proposes a new formulation called SARP with occasional drivers (SARPOD). We defined as the occasional drivers to the entire vehicle fleet, with the addition of delay indicators in the drivers' service time. Tests and analyzes are carried out for small instances.

Keywords: Share-a-Ride Problem, Occasional Drivers, Mobility.

1 Introduction

Urban mobility has been modified by the integration with innovative technologies, bringing flexible solutions to the individual needs of customers. Companies, such as Uber and Lyft, use Mobility as a Service (MaaS) environments to provide travel on-demand for individuals and shared service, and more recently the exclusive transport of packages. Wording, there are already some examples of sharing among people and packages [1].

The concept of shared transportation among people and packages is treated in the literature by problems of ridesharing and crowdsharing [2]. However, only with the increasing technological escalation was possible to have successful applications. The ridesharing problem addresses the different types of vehicle sharing, while the crowdsharing problem searches efficient ways of transporting packages using the excess capacity existing in urban traffic. These problems are capable of positively influencing the reduction of pollutant gas emissions and congestion, as they increase the occupancy rate per vehicle. Furthermore, their approaches bring management policies at the planning stage and thus allow for different procedures [1].

As the crowdsharing problem seeks to integrate last-mile transport with existing and functioning structures (subways, buses, independent drivers), there are a great diversity of proposals. In Fatnassi et. al. [3] is modeled a goods transportation by subway during times of low usage. Some papers also search to use the support of drivers and cyclists in transit to transport small packages [4]. In this group of problems, we highlight the share-a-ride (SARP) problem, proposed by Liu et. al. [5] in 2014, as an extension of the Dial-a-Ride (DARP) problem that focuses only on people shared transportation.

SARP makes transportation shared among goods and people, where there are requests for travel between pickup and delivery stops and a fleet of vehicles for service. Each request can be classified as passenger or packages exclusively, making it possible to share the same vehicle for more than one request. Capacity restrictions, time window, length of service, etc. are also considered. Since then, some works have brought different modifications and applications. For example, the work by Nguyen [6] proposes a time-dependent model concerning the average speed of vehicles per period. Beirigo et. al. [6] present the share-a-ride with parcel lockers problem (SARPLP), in which it is possible to have passengers and packages in the same travel request. Yu et. al. elaborates on the General Share-a-Ride Problem (GSARP), which generalizes the formulation of SARP [7]. Also, work on related problems formulates different scenarios. The work of Parragh [8] who brings DARP with Split Requests and Profits. Also, Archetti et. al. [9] presents the concept of occasional drivers with the Vehicle Routing Problem with Occasional

Drivers (VRPOD).

This work is motivated by the models of GSARP and VRPOD, to formulate SARP with occasional drivers. It differs from the VRPOD proposal, since it takes all drivers in the fleet as occasional drivers and establishes the cost per delay in the drivers' maximum service time.

2 Mathematical formulation

In this section is presented a new formulation for the SARP, motivated by the General Share-a-Ride (GSARP) proposed in Yu et. al. [7], and by the Vehicle Routing Problem with Occasional Drivers (VRPOD), introduced by Archetti et. al. [9]. The SARP treats the transportation of passengers or parcels between specified origin and destination locations. A request is traditionally classified by a passenger or parcel, and is served by a fleet of vehicles, all vehicles must initialize and finalize its route at initial and final depots. However, in the traditional formulations of SARP, include the GSARP, the depots are defined as the same for all vehicles. In this paper it is considered a more realistic scenario, introducing to the GSARP the definition of occasional drivers initially proposed by work of Archetti et. al. [9], where the initial and final deposits are different. Although it is proposed in this paper that all vehicles have different deposits, and not just the occasional drivers.

Therefore, it is assumed as parameters a fleet of vehicles $K = K^1 \cup K^2$, where K^1 is the set of vehicles available for service at the beginning of the planning horizon, and K^2 is the set of vehicles that will be available for service after the initial planning horizon, called occasional drivers. Note that the information on which and when the occasional drivers will be available for the service is known beforehand. For each vehicle $k \in K$, an initial depot a_k and final depot b_k are associated, where $A = \{a_1, \cdots, a_k\}$ is a set of initial depots and $B = \{b_1, \cdots, b_k\}$ a set of final depots.

Each request has a origin and destination stops, where $V^o = \{1, \cdots, n\}$ is the set of origins stops and $V^d = \{n+1, \cdots, 2n\}$ the set of destinations stops. The problem is modeled on a graph $G = (V, A)$, where V is the set of all stops, such that $V = V^o \cup V^d \cup A \cup B$. Each arc (i, j) in $A = \{(i, j)\,; i, j \in V, i \neq j\}$ is associated to a distance d_{ij} and a travel time t_{ij}^k for a vehicle k.

For each stop $i \in V^o \cup V^d$, there is a time window $[e_i, l_i]$ to initialize the attendance, a service duration d_i and a quantity to load q_i^c of demand c, where $c \in \{P, F\}$ represents the type of request: $c = P$ for passenger request and $c = F$ for freight request. Else, for each vehicle k is defined $q_{a_k}^c = q_{b_k}^c = 0$, $q_i^c = -q_{n+1}^c$ and $d_{a_k} = d_{b_k} = 0$. For each vehicle $k \in K = K^1 \cup K^2$, let T_{a_k} be the time its available to perform a delivery from its initial depot a_k. Moreover, it is associated for each $k \in K$ the delay time h^k to finalize your route.

Parameters and input definitions:

$G = (V, A)$	A weighted and directed graph from problem
K	set of vehicles, $K = K^1 \cup K^2$
K^1	set of initial fleet
K^2	set of vehicles from occasional drivers
n	Number of requests
V	Set of all stops, include origins, destinations and depots, where $V = V^o \cup V^d \cup A \cup B$.
V^o	Set of origins stops, where $V^o = \{1, \cdots, n\}$
V^d	Set of destinations stops, where $V^d = \{n+1, \cdots, 2n\}$
$V^{p,o}$	Set of passenger origin stops
$V^{f,o}$	Set of freight origin stops
$V^{p,d}$	Set of passenger destination stops
$V^{f,d}$	Set of freight destination stops
V'	Set of just origin and destination stops, $V' = V^o \cup V^d$
C	Set of type of demands, being $c \in C = \{P, F\}$ a passenger or freights
a_k	Initial depot for vehicle k
b_k	Final depot for vehicle k
A	Set of initial depots, where $\|A\| = \|K\|$ and $A = \{2n+1, \cdots, 2n+k\}$
B	Set of final depots, where $\|B\| = \|K\|$ and $B = \{2n+k+1, \cdots, 2n+2k\}$
T_{a_k}	Instant time when vehicle k is available to perform to delivery from its initial depot a_k
T_{b_k}	Instant time when vehicle k must reach its destination b_k
q_i^c	Quantity of type c demand at stop i, where $C = \{P, F\}$
t_{ij}^k	Travel time of vehicle k between stops i and j
d_{ij}	Travel distance between stops i and j
s_i	Service duration of the request at stop i

$[e_i, l_i]$	Time window of stop i
Q^{kc}	Capacity of vehicle k for demand c, $k \in K$ and $c \in C$
M	A big number
α	Initial fare charged for delivering one passenger
β	Initial fare charged for delivering one package
γ_1	Fare charged for delivering one passenger per kilometre
γ_2	Fare charged for delivering one package per kilometre
γ_3	Average cost per kilometre for delivering requests
γ_4	Discount factor for exceeding the direct delivery time of passengers
γ_5	Discount factor for exceeding the time when vehicle k must finalize its route.

Decisions variables:

x_{ij}^k	1 if vehicle k travels on (i, j); 0 otherwise
u_i^k	Arrival time of vehicle k at stop i
w_i^{kc}	Amount of demand c in vehicle k when leaving stop i
r_i^k	Time spent by request i in vehicle k
p_i	Ratio between request i actual riding time and direct travel time.
h^k	Delay time to vehicle k finalize your route.

Objective functions:

- The total profit obtained from passenger deliveries:

$$f_1 = \sum_{i \in V^o} \sum_{j \in V} \sum_{k \in K} \left(\alpha + \gamma_1 d_{i,i+n} q_i^P\right) x_{ij}^k \tag{1}$$

- The total profit obtained from goods deliveries:

$$f_2 = \sum_{i \in V^o} \sum_{j \in V} \sum_{k \in K} \left(\beta + \gamma_2 d_{i,i+n} q_i^F\right) x_{ij}^k \tag{2}$$

- Cost per kilometre for delivering requests:

$$f_3 = \gamma_3 \sum_{i \in V} \sum_{j \in V} \sum_{k \in K} d_{ij} x_{ij}^k \tag{3}$$

- Discount factor for exceeding the direct delivery time of passengers:

$$f_4 = \gamma_4 \sum_{i \in V^o} (p_i - 1) \tag{4}$$

- Discount factor for exceeding the instant time when vehicle k must finalize its route:

$$f_5 = \gamma_5 \sum_{k \in K} h^k. \tag{5}$$

Then, the total benefits express in a function objectives is:

$$f = f_1 + f_2 - f_3 - f_4 - f_5 \longrightarrow \max . \tag{6}$$

The constraints for the SARP it's describe bellow:

- Each origin is served exactly once:

$$\sum_{j \in V'} \sum_{k \in K} x_{ij}^k = 1, \quad \forall i \in V^o \tag{7}$$

- Ensures each vehicle k initialize its route:

$$\sum_{i \in V^o} x_{a_k,i}^k = 1, \quad \forall k \in K \tag{8}$$

- Each vehicle finishes its route at final depot:

$$\sum_{i \in V'} x^k_{i,b_k} = 1, \quad \forall k \in K \tag{9}$$

- Impossible arcs:

$$\sum_{i \in V} x^k_{i,a_k} = \sum_{i \in V} x^k_{b_k,i} = 0, \quad \forall k \in K \tag{10}$$

- If a request is picked up by vehicle k, then it must be delivered by the vehicle k:

$$\sum_{i \in V} x^k_{ij} = \sum_{i \in V} x^k_{i,j+n}, \quad \forall j \in V^o, \quad \forall k \in K \tag{11}$$

- Flow conservation of route:

$$\sum_{j \in V} x^k_{ij} = \sum_{j \in V} x^k_{ji}, \quad \forall i \in V^o \cup V^d, \quad \forall k \in K \tag{12}$$

- Defines the arrival time in stops:

$$u^k_j - u^k_i \geq s_i + t_{ij} - M\left(1 - x^k_{ij}\right), \quad \forall k \in K, \quad \forall i, j \in V \tag{13}$$

- Ensures the load along of route not exceed the capacity of vehicle k:

$$w^{kc}_j - w^{kc}_i \geq q^c_i + t_{ij} - M\left(1 - x^k_{ij}\right), \quad \forall k \in K, \quad \forall i \in V, \quad \forall j \in V^o \cup V^d, \quad \forall c \in C \tag{14}$$

- Defines the ride time of requests:

$$r^k_i = u^k_{i+n} - u^k_i, \quad \forall k \in K, \quad \forall i \in V^o \tag{15}$$

- Establishes the time windows for each stop i:

$$e_i \leq u^k_i \leq l_i, \quad k \in K, \quad \forall i \in V^{'} \tag{16}$$

- Limits the variation of the load on the route:

$$\max\{0, q^c_i\} \leq w^k_i \leq \min\{Q^k, Q^k + q^c_i\}, \quad \forall k \in K, \quad \forall i \in V, \quad \forall c \in C \tag{17}$$

- Ensure the maximum value for ratio:

$$p_i \leq 1, \quad \forall i \in V^{p,o} \tag{18}$$

- Stipulate a value for a ratio to delivery passengers:

$$p_i \geq \sum_{k \in K} \frac{r^k_i}{\left(t^k_{i,i+n} + s_i\right)}, \quad \forall i \in V^{p,o}, k = \max\{t^1_{i,i+n}, \cdots, t^{|k|}_{i,i+n}\} \tag{19}$$

- For each vehicle k, the total service time limits, considering the time delay h^k:

$$u^k_{b_k} - u^k_{a_k} - h^k \leq T_{b_k}, \quad k \in K \tag{20}$$

- Establishes the time windows for depots:

$$T_{a_k} \leq u^k_i, \quad k \in K, \quad \forall i \in V \tag{21}$$

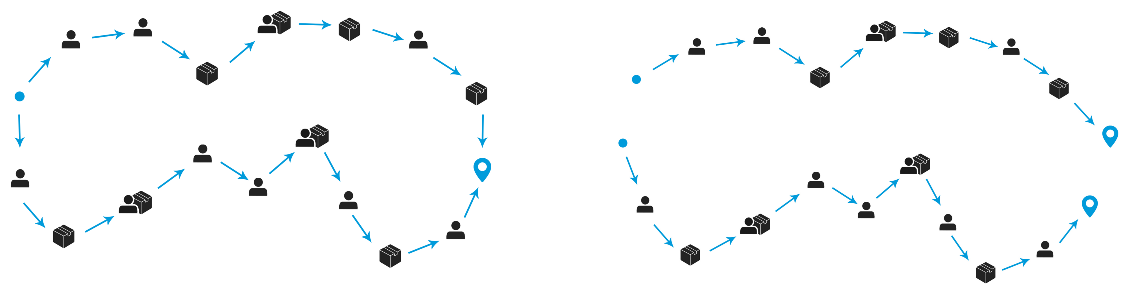
- Defines the binary decision variables:

$$x^k_{ij} \in \{0, 1\}, \quad \forall i, j \in V, \quad \forall k \in K. \tag{22}$$

2.1 Solution Example

A solution of DARP with occasional drives differs from a traditional DARP in considering different points of depots. In DARP with occasional drivers are two types the fleet. The first fleet is composed of drivers who leave from the same initial depot and arrive at our route on the same final depot. In this case, these drivers are available from the start to the last instant to the instance. The second fleet is composed of called occasional drivers, they are subsidiary drivers that work in their own free time, hereby they start work after that initial instant. The occasional drivers also start on different points of initial depots and finalize your routes on different points of final depots.

Figure 1 shows a little example comparing DARP and DARP with occasional drivers. Note that three types of clients, being just people, just package or people and package. In both examples, the fleet has two cars and consequently two routes, but the main difference is the points of initial and final depots. On the traditional DARP, there are just two points of depots, called initial and final depots, where all vehicles start on the same initial depot and finalize on the same final depot. However, on the DARP with occasional drivers, there are four depots points such that each vehicle is associate with a distinct point of initial and final depots.



(a) DARP Traditional

(b) DARP with occasional drivers

Figure 1. Examples of DARP and DARP with occasional drivers

3 Numerical Results

3.1 Experimental settings

This section describes how the formulation parameters were adopted and how the instances of the proposed model were generated. The scenarios of the instances were built to analyze the behavior of different factors and their influence on the result obtained, more specifically: 1) Have the occasional drivers been able to meet customer demand? 2) Did the total duration of the trip exceed the stipulated value? 3) What was the profit obtained by the scenario? 4) Were there large deviations from the passenger route? 5) What was the occupation level?

Since SARP is an NP-Hard problem, MILP model test configurations were limited to small instances [10]. Therefore, small fleets of sizes $|K| \in \{2, 3, 4, 8, 16\}$ and number of requests $\{8, 16, 20\}$ have been proposed. This informations are available in Table 1. The occupancy rate was calculated according to the share of seats occupied by the period of operation. However, the variation of the following sets of parameters was considered:

A. Fleet Composition: Vehicle compartments are split among passengers and packages, considering the occupancy of one seat per package. All vehicles can carry people and packages.

B. Time Windows: The time windows $[e_i, l_i]$ for each stop of passenger requests were established with an interval of 15 minutes, and for freight requests with an interval of 1 hour. Is defined T as the length of the planning horizon, during the one-day scenario. If i is a source, then the time window is generated by random choosing the value $l_n + i$ in the range $[60, T]$ and the value $e_n + i = l_n + i - 15$. While, if i is a destination, random choose the value e_i in the range $[0, T - 60]$ and the value $l_i = e_i + 15$.

C. Average speed: It is established a difference of 10% for the occasional drivers regarding the initial fleet.

D. The maximum time duration of routes: For the initial fleet is a fixed maximum route duration time duration of 6 hours and for the occasional drivers fleet value of 3 hours.

Table 1. Summary of scenario's parameters

Parameter	Values
Number of vehicles $\|K\|$	$\{2, 3, 4, 8, 16\}$
Number of requests	$\{8, 16, 20\}$
Maximum time duration of routes	3 and 6 hours

3.2 Results

Test instances were solved on an AMD Ryzen 5 3500U, 2.1GHz e 8Gb RAM computer. Gurobi 9.0.2 $c\#$ interface was used to implement the model.

The coordinates of the stops were generated randomly within the square $[-10, 10]x[-10, 10]$. Also, distance d is considered as Euclidean distance. The fare charged for delivering one passenger and one package are equals, $\gamma_1 = \gamma_2 = 1$, for each arc $(i, j) \in A$, and the average cost per kilometre $\gamma_3 = 0.3$. The discount factor for exceeding the direct time of passenger is $\gamma_4 = 0.1$ and for exceeding the maximum time duration of routes is $\gamma_5 = 0.1$.

Table 2 presents the results of the instances, specifying the profit and cost values for each objective function established in the formulation. Altogether were generated 42 scenarios, which were divided into an average of 5 scenarios for each specification. The column (#) indicates how many scenarios were used for each combination of the number of vehicles $|K|$ and the number of requests n. The column (Occ. (%)) shows the fleet occupancy rate. It is observed that the exact resolution of the adopted instances obtained resolution time in the interval of 15 minutes to 1 hour. Thus, the work focuses on the analysis of the behavior of the solutions obtained.

Table 2. Results of instances

#	$\|K\|$	n	Occ. (%)	Profit	Cost	f_1	f_2	f_3	f_4	f_5
5	2	8	29,9	174,1	50	105	119	50	0	0
5	2	16	29,5	284,3	84	206	162	84	0	0
5	2	20	31,2	364,5	104,5	251	217	99	4	1.5
5	3	8	29,2	253.7	76	144	185	76	0	0
5	3	16	29,6	385,6	110	234	261	110	0	0
4	3	20	30,1	489	142	309	322	139	0	3
5	4	8	28,1	380,9	112	237	255	112	0	0
5	4	16	27,4	478,7	142	315	305	142	0	0
3	4	20	28,8	532,3	172	343,3	361	168	1	3

In all scenarios, the vehicle fleet was able to attend customer demand, although there was a delay in finalizing routes for scenarios with the largest number of customers $n = 20$ in all values of the $K = \{2, 3, 4\}$. There were still discounts for exceeding the customer's travel time limit on instances of $K = \{2, 4\}$ and $n = 20$. Therefore, for cases with a higher number of travel requests, the discount factors for customer's travel time discount (f_4) and for the driver's service time (f_5) lightly influenced the objective function. Nevertheless, there were discounts for exceeding timeouts, although there were not large deviations from the passenger's route .

It is interesting to note that the problem was formulated in its static version, in which information is known beforehand, allowing vehicles with greater restrictions to be routed skilled time so as not to generate time inconsistencies. The dynamic version does not have all the information in the initial time and aims the best connections within a shorter planning time, not seeing opportunities for better future fittings. Thus, it is expected that in larger instances or dynamic scenarios there will be a greater influence of discount factors.

It is also observed that the increase in the total value of profits concerning the growth in the size of the vehicle fleet and the number of customer orders. This is in line with the fact that there is greater movement of traffic in the system. Finally, the discount rate followed approximately in the proportion of the growth of profits, also being a consequence of the definition of proportional calculation according to f_3. In future work, it is intended to develop a new discount rate that varies by traffic levels.

4 Conclusions

In this work, a formulation for the Share-a-Ride model with occasional drivers was proposed. Its implementation, even for small instances, brought first clarifications about the influence of the adopted parameters and their behavior. It was observed that the structure of occasional drivers was able to meet the demand for orders, slightly exceeding the maximum service time in the instances with the highest number of orders. It was also observed that the occupancy level averaged 30 $\%$ and therefore there was travel sharing among customers. Even though the influence of discount factors was small, it is expected that for larger instances there will be a greater impact. It should also be noted that the results are still highly dependent on the general parameters assumed. Different standards of parameters may obtain solutions that showed different patterns of distribution of care, penalizing long-distance travel. Future work concentrated efforts to determine such influence of the parameters on the model and to propose more complex scenarios.

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