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Locating Method for Pick-up and Drop-off Spots for Shared Autonomous Vehicle-based Mobility Services

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Abstract
To provide safety to users and not disturb traffic flow, autonomous vehicles in shared on-demand mobility services cannot stop everywhere; thus, pick-up and drop-off (PUDO) spots must be dedicated or established for them. Our research objective is to propose a method to locate the PUDO spots for shared autonomous vehicle-based mobility services as this topic has been barely studied. The number of required PUDO spots is calculated, and the location is chosen considering the urban environment, walking radius, vehicle occupancy, and time for boarding and alighting among other parameters. Different from some methods applied to shared mobility, we consider the existing infrastructure (e.g., parking spaces) as potential locations for PUDO spots. The method is applied to a study case, demonstrating the applicability and providing the main findings: (i) the required number of PUDO spots decreases if willingness to walk increases; (ii) with a 3-min walking radius, 83% of curbside parking spaces can be repurposed, and 100% is reached with a 10-min walking radius; (iii) the minimum of 55% of curbside parking spaces can be repurposed with 10-min walking radius and without locating PUDO spots in private parking. Using our method, cities can determine the quantity of PUDO spots and their locations, being prepared in advance for the required changes in the existing infrastructure as well as the freed-up space to be repurposed.
Keywords
shared mobility, autonomous vehicles, pick-up and drop-off, spatio-temporal, urban space

1 Introduction

Technology advancements may result in a strong demand for Shared Autonomous Vehicle (SAV)-based mobility services [1]; a transition from the use of private vehicles to shared mobility services is anticipated [2]. The number of pick-up and drop-off activities will increase significantly; thus, they will need to be considered during the planning, development, and operation of mobility services [3].

Pick-up and drop-off (PUDO) spots are designated areas to serve pick-up and drop-off activities; they can be located either in parking spaces or on roads. The PUDO spots serve only short-time boarding/alighting to pick up and/or drop off travelers. Their establishment ensures the optimization of urban space, traffic and traveler safety, and high service quality.

The following PUDO spot types are distinguished:

- private parking opened for the public (e.g., shopping malls, supermarkets),
- curbside, and
- on road lane (temporal).

Even though the impact of PUDO spots on urban space [2, 4], and the importance of an appropriate design [5] are tackled by some studies, forecasting the number of PUDO spots is limited (e.g., [6]). Also, there is no available method to place PUDO spots.

We aim to provide a calculation and locating method for PUDO spots to be used by the SAV-based mobility services. The proposed service is nearly door-to-door because users may walk to take the vehicles at PUDO spots; also, a pooling option (i.e., seat-sharing) is available in the service. We consider all the current car-based trip demand to be served.

Limitations applied: (i) a macroscopic approach is considered (the exact location of a PUDO spot in a parking area has been disregarded); (ii) vehicle attraction rates of POI types from the literature are used in simulation, (iii) the PUDO spots are used only for pick-up and drop-off (not for parking), (iv) SAV mobility service replaces entire car traffic; no modal shift from public transport or

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micro-mobility to SAV is assumed, (v) feeder service is neglected, so the time interval of PUDO activities is not related to the schedule of public transport.

Our research questions are:

- How many PUDO spots are necessary and where to deploy them?
- How much urban space can be freed up?

The paper is structured as follows. The literature is reviewed in Section 2. The locating method is explained in Section 3. The method is applied as a case study through a simulation. The results and discussion are presented in Sections 4 and 5, respectively. Conclusions are drawn in Section 6.

2 Literature review

The literature review aimed to identify how certain on-demand shared mobility service types are planned according to the facility location problem and location-allocation models. The revealed conclusions have been used during the elaboration of our method. A facility location problem supports selecting the location of an activity or a service. Limitations of a facility (e.g., the product demand served) are dealt with by a capacitated facility location problem [7]. Location-allocation models determine who is served by which facility [8]. Therefore, the capacitated facility location problem is the basis of our locating method, and the location-allocation model determines which PUDO spot serves the trip demand at points of interest (POIs).

For *car-sharing*, the location of stations was determined using location-allocation models, and the spatial distribution of the travel demand was generated by a GIS-based method. A 10-minute walking radius from the main routes and economic activities were considered [8]. Alternatively ordering, population data, and POI were used to calculate the demand. The location of stations was determined by statistical models [9].

For *ride-sourcing/ride-hailing* services, to avoid detours and enhance service efficiency, passengers usually walk to a pick-up point. The location of pick-up points was defined by an algorithm and heuristics in which walking costs and unchangeable drop-off points were considered [10]. Also, to avoid deadheading trips (i.e., trips between dropped-off and picked-up passengers), PUDO locations were modeled using a nonlinear-in-parameters multinomial logit considering the built environment and sociodemographic characteristics [11]. For *taxi* stands, spatial-temporal analysis of demand data, construction costs, walking distance, and demand coverage were considered [12].

To choose the locations of *bike-sharing* stations metaheuristic algorithms can be applied [13]. The shortest path was used to determine the distance between consumers and the bike stations. The population was grouped in the center of neighborhoods, and station activity was used to calculate the demand. Similarly, locations were defined considering the distance between the centroids of districts and the walking distance. The exact location was selected by a model considering the travel costs to reach the station, implementation, and maintenance costs [14].

People's daily walking average from/to public transport varies significantly. It ranges from 2 to 30 min [15–17]. Characteristics such as terrain, suburban areas, weather, security and so on may be decisive for the willingness to walk.

The most significant problem with *free-floating* shared services is improper parking [18]. Therefore, virtually designated areas for parking (i.e., geo-fence) may be a solution.

The parking demand for *bike-sharing* services based on the volume of rides made inside a certain region was determined. The location of geo-fences was determined by a location-allocation model [19]. Likewise, an algorithm was applied to *scooter-sharing* located parking facilities based on historical demand data [20]. The parking facility was placed in the center of the zone.

In conclusion, the main findings of the literature review are:

- access and egress time, represented mainly by walking time, are decisive aspects for placing stations, PUDO spots, and parking;
- locations are chosen in many cases based on the usage of urban space and its costs.

3 Methodology

We considered the PUDO spots as the center points of the zones to be served by them. The radius represents the willingness to walk. Where many PUDO spots are available together (e.g., parking area in a shopping mall), we refer to multiple PUDO spot. Otherwise, it is a single PUDO spot.

For multiple PUDO spots, the centroid of the parking area becomes the center point and the number of PUDO spots are summed up. The number in italics in Fig. 1 next to the PUDO spots represents the number of PUDO spots available. The numbers next to the POIs indicate the quantity of PUDO spots required to attend to the trip demand in the peak time interval. The peak time interval refers to the period when the biggest trip demand occurs.

The novelty of our model is that we apply a supply-oriented approach. We consider the existing parking spots as potential PUDO spots and investigate the covered area

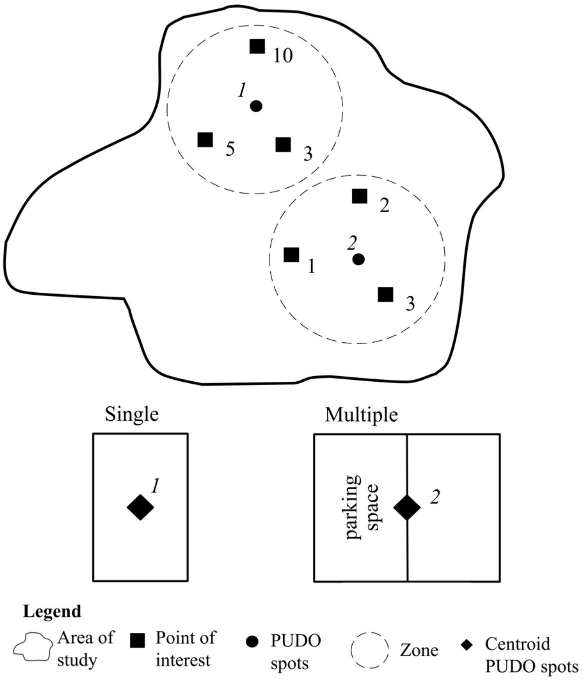

Fig. 1 Physical model

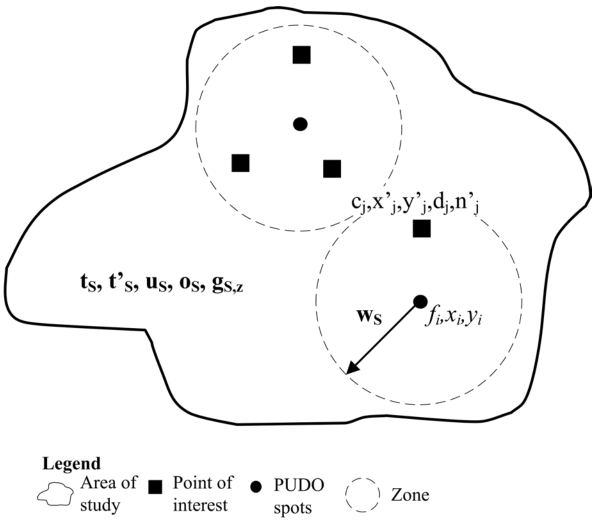

Fig. 2 Attributes of the model

including POIs with their trip demand (i.e., number of cars arriving at a location or leaving the location). Thus, the least disturbance to urban space and a reduction in investment costs are achieved. In addition, we consider the user's parameters and evaluation by decision-makers, being in line with other locating method studies [21]. Fig. 1 shows the elements considered in our physical model.

Fig. 2 summarizes the attributes of PUDO spots, POIs, and an area with a scenario. Attributes of a PUDO are indicated in italics, attributes of an area for scenario S are indicated in bold, and the remaining attributes refer to POIs. The attribute descriptions are summarized in Tables 1–3.

The method is composed of several steps. The simplified flowchart is presented in Fig. 3.

3.1 Supply description

3.1.1 Potential PUDO spot identification

Location (coordinates) and types are identified as main attributes (Table 1).

Furthermore, we use the aggregated value m_{fi} which indicates the sum of potential PUDO spots with type f_i.

3.2 Demand description

3.2.1 Identification of POIs and their trip demand

Location (coordinates), trip demand (i.e., number of vehicles visiting the POI) in the peak 15-min interval, and the POI's category are identified as main attributes (Table 2).

Table 1 Attributes of potential PUDO spots

Sign	Definition	Unit
f_i	type of PUDO spot *i* (1: private parking, 2: curbside, 3: on road lanes)	
x_i	easting of PUDO spot *i* centroid	[degrees]
y_i	northing of PUDO spot *i* centroid	[degrees]
n_i	number of available PUDO spots in a multiple PUDO spot *i*	[un]

Table 2 POI attributes

Sign	Definition	Unit
c_j	category of POI *j* (1: university, 2: bank, 3: restaurant, etc.)	
x_j'	easting of POI *j* entrance	[degrees]
y_j'	northing of POI *j* entrance	[degrees]
d_j	conventional vehicle trip demand in the peak 15-min interval for the POI *j*	[veh/15min]

Table 3 An area for scenario *S*

Sign	Definition	Unit
w_S	average willingness to walk	[min]
$g_{S,z}$	weight of criteria z of the multicriteria assessment; determined by the decision makers and society, and the sum of weights is 100%; $z = 1,...,v$ (1: urban space disturbance, 2: traffic flow disturbance, etc.)	[%]
t_S	average time for boarding/alighting defined by the service provider	[min]
t_S'	additional time for boarding/alighting defined by the users	[min]
u_S	proportion of users requiring additional time for boarding/alighting	[%]
o_S	average pooling rate of autonomous vehicle	[veh/un]

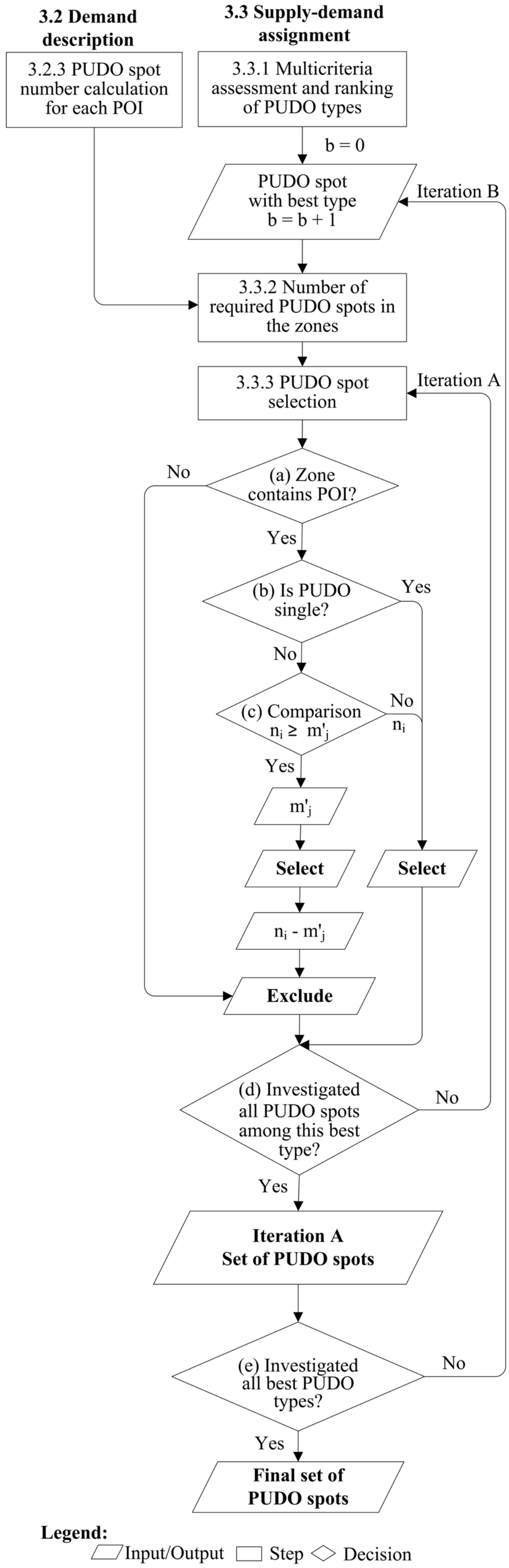

Fig. 3 Model flowchart

3.2.2 Identification of service and users input parameters

Table 3 shows the attributes (as input parameters) describing an area for a scenario.

To illustrate the average pooling rate, if trips of 5 conventional vehicles (5 persons) are accommodated in one vehicle which consequently needs one PUDO spot, the pooling rate is 5 veh/un. The pooling rate can be increased by boosting travelers' motivation to accept a shared service.

3.2.3 PUDO spot number calculation for POI j, in scenario S (Eq. (1))

$$n'_j = \frac{d_j}{o_S} \cdot \left(t_s + u_S \cdot t'_S \right), \tag{1}$$

where:

- n_j' number of required PUDO spots to serve POI j peak trip demand;
- d_j conventional vehicle trip demand in the peak 15-min interval for the POI j;
- t_s average time for boarding/alighting defined by the service provider;
- t_s' additional time for boarding/alighting defined by the users
- u_s proportion of users requiring additional time for boarding/alighting;
- o_s average pooling rate of autonomous vehicle.

3.3 Supply-demand assignment

3.3.1 Ranking of PUDO types

We used a flexible (adaptable) multicriteria evaluation method to rank the PUDO types. This part of the method can be adapted according to the study area and the criteria to be considered. The following criteria (as variables) have been considered:

- urban space disturbance,
- traffic flow disturbance,
- user safety and comfort, and
- operator costs.

We established a scale from 1 to 3 for the performance value of PUDO types; 1 means that PUDO type f_i is not beneficial for criterion z, and 3 means that it is beneficial.

The proposed performance values are presented in Table 4.

Eq. (2) is used to evaluate PUDO spot types in scenario S.

$$e_{f_i} = \sum_{z=1}^{v} g_{S,z} \cdot a_{f_i,z}, \tag{2}$$

where:

e_{f_i} Evaluation value of PUDO type f_i,

$g_{S,z}$ Weight of criteria z in scenario S,

$a_{f_i,z}$ Assessment value of PUDO type f_i considering criterion z.

The PUDO types are ranked according to the evaluation values in descending order. The highest evaluation value indicates the first-best PUDO type b (1: first-best, 2: second-best, 3: third-best, etc.).

3.3.2 Number of required PUDO spots in the zones

We draw circles (zones) with a walking radius for PUDO spots with the first-best PUDO type.

We select a PUDO spot randomly. Then, we calculate the distance between POIs and the selected PUDO spot using their coordinates in the Haversine formula [22]. If the distance is smaller than or equal to the walking radius (namely, located within the zone), the POI is assigned to the zone of the selected PUDO.

Then we repeat this step for the remaining PUDO spots until we have selected all of them (Fig. 4).

If there are POIs with the same peak time interval within a zone, the number of required PUDO spots is summed up and assigned to the zone. Otherwise, the number of required PUDO spots for a zone equals the biggest number of required PUDO spots of a POI within the zone. Therefore, we use the aggregated value m_j', which indicates the number of required PUDO spots in a zone.

In this study, due to simplification, morning (6 a.m. to 12 p.m.), afternoon (12 p.m. to 6 p.m.), and night (6 p.m. to 12 a.m.) were defined as time intervals for the zones.

The output of this step serves as input for step 3.3.3. As 3.3.3 is an iterative process for analyzing all best PUDO types, 3.3.2 is performed again for the second-best PUDO type and so on (for every Iteration B).

3.3.3 PUDO spot selection

This step determines the PUDO spots that are selected. We randomly select a PUDO spot from the set of first-best PUDO types. We investigate it to decide whether it belongs to the final selected PUDO spots set or not. Substeps are indicated between parentheses.

If the zone does not contain any POI (Fig. 3(a)), the potential PUDO spot is excluded. Otherwise, we need to identify if the PUDO spot is single or multiple (Fig. 3(b)); single PUDO spots in zones containing POIs are always selected, but multiple PUDO spots are further evaluated.

Table 4 Assessment value of PUDO types ($a_{f_{i,z}}$)

Criteria z / Alternative - PUDO types f_i	Urban space disturbance	Traffic flow disturbance	Safety comfort	Cost
Private parking (f_1)	3	3	3	1
Curbside (f_2)	1	2	2	2
On road lane (f_3)	2	1	1	3

Legend: scale from 1 to 3; 1 – not beneficial and 3 – beneficial.

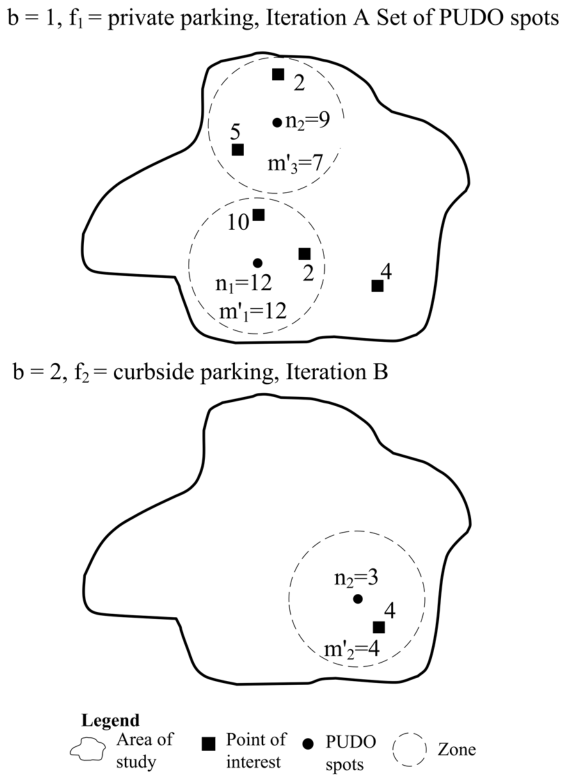

Fig. 4 Number of required PUDO spots in the zones

To find out how many multiple PUDO spots are selected, the number of available PUDO spots n_i is compared to the number of required PUDO spots in a zone m_j' (Fig. 3(c)).

Fig. 5 shows a hypothetical result of Iteration A for the first-best PUDO type.

If there are more PUDO spots than the required number ($n_i > m_j'$), the required number (m_j') is selected, and the excess ($n_i - m_j'$) is excluded; the same process is valid if the number of required and available PUDO spots are the same. Otherwise, the available number of PUDO spots n_i is selected; it means that if there are fewer PUDO spots than the required, the number of required PUDO spots will not be fulfilled. The PUDO spots to be excluded are chosen based on the shape of the area, the repurposing project, etc.

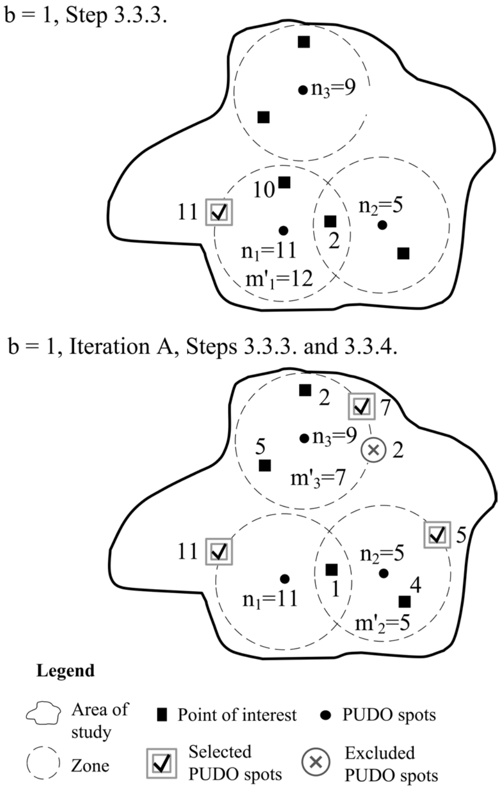

Fig. 5 Set of PUDO spots with Iteration A

In the evaluation of subsequent potential PUDO spots with the first-best PUDO type (Fig. 3(d)), only POIs with an unfulfilled number of required PUDO spots are considered (Iteration A). After evaluating all PUDO spots within the best type, the set of selected PUDO spots for this best type is revealed.

The process is repeated (Fig. 3(e)) for all potential PUDO spots following the ranking of PUDO types (Iteration B). In the end, the final sets of selected and excluded PUDO spots contain the number and location of PUDO spots for each PUDO type. The number of excluded PUDO spots in the final set can be compared to the number of potential PUDO spots according to the type m_{f_i}, indicating the percentage of PUDO spots that can be repurposed.

4 Results

A study case is performed in Budapest, Hungary in order to prove method applicability and results' validity. To calculate the number of PUDO spots and decide about their locations, three scenarios (S_1, S_2, S_3) have been simulated. Due to the page length limit, we shortened the analyses. Thus, for all scenarios, the average time for boarding/alighting defined by the service provider, the additional time for boarding/alighting defined by the users, the proportion of users requiring additional time for boarding/alighting, and the average pooling rate of autonomous vehicles do not vary (t_s =1, t_s' =1, u_s = 20%, and o_s = 5). For each scenario, weight $g_{S,z}$ and three variations in willingness to walk w_S were considered, which affect part 3 of the method; namely, 'Supply-demand assignment'. The nine cases are presented in Table 5. The cases are indicated by the letter S followed by 2 digit numbers; the first one indicates the scenario and the second one the variation in the willingness to walk.

Scenario 1 (S_1) focuses on reduced disturbance in urban space, using existent infrastructure and less disturbance in the traffic; thus, higher weight factors are attributed to aspects 1 and 2. Scenario 2 (S_2) focuses on the user, enhancing comfort and safety, and considering the cost of these benefits for operators and users. Hence, aspects 3 and 4 received higher weight factors. Finally, Scenario 3 (S_3) aims to benefit the operators and the service, choosing options for PUDO with the least cost and traffic disturbances. The results of the model for each step are presented as follows. Scenario 1 is described in detail to illustrate the application of the model.

Table 5 Scenarios

	Scenarios Urban space (1)		
	S_{11}	S_{12}	S_{13}
w_S	3	5	10
$g_{S,z}$			
Urban space disturbance	0.7	0.7	0.7
Traffic disturbance	0.2	0.2	0.2
Safety/Comfort	0.05	0.05	0.05
Cost	0.05	0.05	0.05
	Scenarios User (2)		
	S_{21}	S_{22}	S_{23}
w_S	3	5	10
$g_{S,z}$			
Urban space disturbance	0.05	0.05	0.05
Traffic disturbance	0.05	0.05	0.05
Safety/Comfort	0.7	0.7	0.7
Cost	0.2	0.2	0.2
	Scenarios Operator (3)		
	S_{31}	S_{32}	S_{33}
w_S	3	5	10
$g_{S,z}$			
Urban space disturbance	0.05	0.05	0.05
Traffic disturbance	0.2	0.2	0.2
Safety/Comfort	0.05	0.05	0.05
Cost	0.7	0.7	0.7

4.1 Supply description

4.1.1 Potential PUDO spot identification

Five multiple PUDO spots in private parking (from PP1 to PP5) have been identified (shopping mall, office building, and three areas of the university) as potential PUDO spots. The total number of potential PUDO spots in the area of study is 2 948; m_{f_1} = 1 584 in private parking, m_{f_2} = 1 350 on the curbside, and m_{f_3} = 14 on road lanes.

4.2 Demand description

4.2.1 Identification of POIs and their trip demand

The location and category of POIs were identified through OpenStreetMap and Google Maps, and the peak time of each POI was via Google popular times data. The POI category trip demand (d_j) was based on previous studies [23–28].

4.2.2 Identification of service and users input parameters

Values of service and user's parameters were determined based on characteristics of public transport, capacity of an ordinary vehicle, and different walking radius.

4.2.3 PUDO spot number calculation for each POI

We calculated the number of required PUDO spots for each POI category n_j' using Eq. (1); the results are shown in Table 6. If data are available to each single POI, then the categories can be eliminated.

4.3 Supply-demand assignment

4.3.1 Ranking of PUDO types

Table 7 shows the evaluation values (e_{f_i}) for the scenarios. The highest value means ranking as the first-best PUDO type.

4.3.2 Number of required PUDO spots in the zones

Considering S_1 and its first-best PUDO type (i.e., private parking), the zone for 3-min willingness to walk was drawn and the number of required PUDO spots at the peak time intervals was calculated. Table 8 presents the number of required PUDO spots for the zones of PP1 to PP5. Four small shops (n_j = 10) with the same peak time interval are within PP1's zone; thus, m_j = 40.

4.3.3 PUDO spot selection

Considering S_1, its first-best PUDO type, and 3-min willingness to walk, we selected randomly PP1. Its zone contains POIs and PP1 is a multiple PUDO spot with n_i = 200 available PUDO spots. Therefore, PP1 has more PUDO spots than the required number. As a result, m_j = 40 PUDO spots are selected, and $n_i - m_j$ = 160 PUDO spots are excluded. The process is repeated for the remaining PUDO spots with private parking types; PP2 to PP5.

The number of required PUDO spots in the zone of PP3 was unfulfilled, hence, the respective POI was considered in the next iterations. Its location was within the zone of PP5 and the remaining number of required PUDO spots was considered (37 PUDO spots). Thus, the number of required PUDO spots in PP5's zone increased. Table 9 shows the number of selected PUDO spots for each private parking (first-best PUDO type).

Although 130 PUDO spots were selected for PP5, the number of required PUDO spots for the previous POI was still unfulfilled (12 PUDO spots). As all potential PUDO spots with the first-best type were evaluated, we continued the evaluation for potential PUDO spots on road lanes, and on curbside.

We calculated the results for all the cases (see Table 10). The excluded PUDO spots can be repurposed. If PUDO spots on private parking are prioritized, more curbside parking spaces can be repurposed. Fig. 6 illustrates the quantity and location of PUDO spots for S_{11}.

Table 6 Number of required PUDO spots for each POI category

Point of Interest category (c_j)	University	Shopping mall	Post office	Bank
PUDO spots [un] (n_j')	315	13	11	12
Point of Interest category (c_j)	Restaurant	Fast food	Café, pub	Small shop
PUDO spots [un] (n_j')	5	14	1	10

Table 7 Evaluation values of PUDO types for scenario 1

Scenario	Private parking (f_1)	Curbside (f_2)	On road lanes (f_3)
S_1	2.9	1.3	1.8
S_2	2.6	1.95	1.95
S_3	1.6	1.45	2.45

Table 8 Number of required PUDO spots within a 3-min walking radius

PP1	PP2	PP3	PP4	PP5
40	30	105	116	105

Table 9 Number of selected PUDO spots

PUDO spot private parking	Available	Required	Selected	Excluded
PP1	200	40	40	160
PP2	1078	30	30	1048
PP3	68	105	68	-
PP4	108	116	108	-
PP5	130	130	130	-

Table 10 Results - Number of PUDO spots

		Number of selected PUDO spots				Number of excluded PUDO spots			
Case	Walking radius	Private parking (f_1)	Curbside (f_2)	Sections of a street (f_3)	Total	Private parking		Curbside	
S_{11}	3 min	376	232	14	622	-1 208	-76%	-1 118	-83%
S_{12}	5 min	447	67	14	528	-1 137	-72%	-1 283	-95%
S_{13}	10 min	497	0	0	497	-1 087	-69%	-1 350	-100%
S_{21}	3 min	376	246	0	622	-1 208	-76%	-1 104	-82%
S_{22}	5 min	447	81	0	528	-1 137	-72%	-1 269	-94%
S_{23}	10 min	497	0	0	497	-1 087	-69%	-1 350	-100%
S_{31}	3 min	0	608	14	622	-1 584	-100%	-742	-55%
S_{32}	5 min	0	514	14	528	-1 584	-100%	-836	-62%
S_{33}	10 min	0	503	14	517	-1 584	-100%	-847	-63%

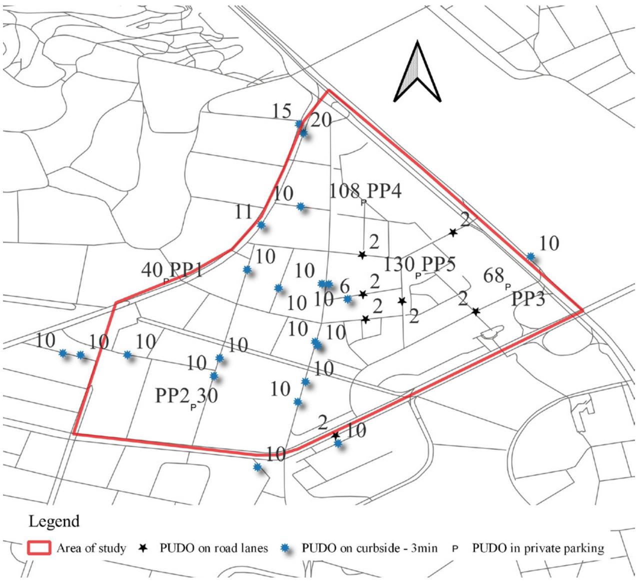

Fig. 6 Location and quantity of PUDO spots for S_{11}

5 Discussion

As the walking radius increases, the possibility of zones without any POI decreases and more PUDO spots may be selected. For example, 376 PUDO spots located in private parking are necessary in S_{11}, while 447 PUDO spots in S_{12}.

In S_{11}, 83% of curbside parking spaces can be repurposed. Moreover, by increasing the walking radius from 3 to 5 minutes, the total number of PUDO spots on the curbside is reduced to around 71% (from 232 to 67). Finally, S_{13} presented the lowest impact on urban space; the existing 1,350 curbside parking spaces could be repurposed because PUDO spots on private parking fulfilled the number of required PUDO spots at the peak time interval.

Even though S_2 was focused on the user, the number of curbside parking spaces that can be eliminated is significant, being 1% smaller than S_1's results.

In S_3, although the reduction of costs for operators is prioritized over the disturbance of urban space, a minimum of 55% of curbside parking spaces can be repurposed. Hence, the use of SAV and the implementation of PUDO spots within a walking radius represent a significant benefit for repurposing urban space. Our results are aligned with the existing literature; high vehicle occupancy (i.e., high pooling rate) reduces the number of vehicles and, as a result, the amount of space required for PUDO spots [29].

6 Conclusions

Pick-up and drop-off activities will increase significantly as AV will be able to drop travelers off and park themselves. The main contribution of this study is a supply-oriented method to determine the number of pick-up and drop-off (PUDO) spots for shared AV-based mobility services and then to determine their location based on the current infrastructure. We considered the urban environment, mobility service parameters, and users' preferences in the method.

The key findings are:

- Reduction of 71% in the number of required PUDO spots when increasing the walking radius from 3–5 min.
- A 10-min walking radius presented the lowest impact on urban space because 100% of curbside parking spaces can be repurposed.
- 83% of curbside parking spaces can be repurposed within a 3-min walking radius when the reduction of urban space disturbance is prioritized.
- A minimum of 55% of curbside parking spaces can be repurposed within 10-min walking radius and without locating PUDO spots in private parking.

We are going to address the following topics in the future research:

- adapt the model to feeder services, where public transport's schedule is considered.
- add new parameters to the method such as willingness to wait, AV acceptability [30, 31], and booking of PUDO spots in advance [32].
- model the choice to switch from exact pick-up and drop-off locations in shared mobility services to flexible locations within a walking radius; utility model will be used considering the willingness to walk, use and pay for the SAV services; inputs for the model elaboration, calibration and validation will be gathered through a stated preference survey.

For practical applications and accurate results, it is recommended to use the vehicle trip demand of the area of study and collect the average pooling rate through a survey.

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