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Heterogeneous fleet sizing for on-demand transport in mixed automated and non-automated urban areas

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Abstract

The era of intelligent transportation with automated vehicles (AVs) is coming. Nonetheless, the transition to this system will be a gradual process. On the one hand, some zones in the city may be dedicated to AVs with a fully intelligent traffic management system geared toward high performance. On the other hand, automated and conventional vehicles may have to be allowed to drive in the remaining zones of the urban network in a transition stage. In this paper, we consider a situation where AVs are deployed by a taxi operating company to serve door-to-door travel requests. Facing this transition period, a strategic flow-based vehicle routing model is developed to determine the optimal fleet size of automated and conventional taxis as a function of the gradually increasing coverage of the AVs-only dedicated area. Traffic congestion is considered through flow-dependent travel times. Two taxi company service regimes are tested: the User Preference Mode (UPM) and the System Profit Mode (SPM). In the UPM, passengers can choose their preferred vehicle type according to their preference. In the SPM, the taxi company will take charge of the vehicle assignment to maximize the system profit. The developed model formulations are applied to a case study of a large toy network. The results give insight into the performance of the heterogeneous taxi system on a hybrid network. Strategies are presented on how to adjust the fleet size of automated and conventional taxis to get the best system profit while satisfying the mobility demand. The SPM can bring more profit to the operating company by reducing the detour and relocation cost of taxis, reducing the salaries for drivers through a bigger fleet size of AVs, and reducing the delay penalty, compared to the UPM.

Keywords: Vehicle routing problem; automated vehicles; mixed-driving environment; on-demand mobility service; traffic congestion; AVs-only zone.

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1. Introduction

In recent years, various technologies for automated driving have been developed and extensively tested, which leads to believe that automated vehicles (AVs) are coming to the market soon. This will revolutionize people's travel

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patterns. For example, the emergence of shared automated vehicles (SAVs) will challenge the usage of privately-owned cars and public transport as they can provide on-demand door-to-door service to meet personal mobility needs. Novel business models using SAVs may emerge and be deployed globally, providing app-based on-demand service. This will allow passengers to make online requests providing their desired trip information including the origin and destination. The operating system will then assign passengers' requests to vehicles and determine the vehicles' route in the transportation network.

Many papers focus on optimizing the profit from the operator's perspective (Liang et al. (2017); Liang et al. (2020)). However, most of them consider the situation where all travel requests are served by SAVs. By this, they ignore the fact that the transition to such an intelligent automated transportation system will be a slow and gradual process. Many researchers hold the view that some critical locations or zones, such as the city centre or locations where it is easy to have traffic bottlenecks, are likely to be the first to be dedicated to AVs thus establishing AVs-only zones to improve traffic efficiency (Chen et al. (2017)). Within an AVs-only zone, AVs will follow the route guidance given by the operating company realizing a fully automated driving environment. The human-driven vehicles would therefore be prohibited from entering the AVs-only zone to avoid randomness brought by human drivers. In the remaining part of the network, AVs and conventional vehicles (CVs) used as shared taxis are very likely to cooperate to satisfy the travel requests. Considering the gradual expansion process of intelligent infrastructure in the city, it is much more realistic at this point to build models that consider vehicle routing in mixed traffic conditions (automated and human-driven).

To determine a new strategy for a taxi company when facing the upcoming SAVs era, we develop a strategic flow-based vehicle routing model in a time-space network to determine the optimal fleet size of automated taxis (ATs) and make adjustments to the existing fleet size of conventional taxis (CTs) as the coverage of the AVs-only zone expands. We assume that ATs at level 5 automation and CTs co-exist to serve the total mobility demand in a city. Due to the restriction of an existing AVs-only zone, CTs cannot drive in the whole network whilst ATs can drive in both the AVs-only zone and outside the AVs-only zone. Traffic congestion is considered in the model by making travel times dependent on the vehicle flows. Furthermore, two service regimes are considered. The first one is a User Preference Mode (UPM) where passengers are allowed to choose the vehicle type (AT or CT) if their origin and destination are both outside the AVs-only zone. The user's preference towards the vehicle type makes sense since many people may prefer low levels of automation as they worry about the potential risk of the AVs without human supervision (Ha et al. (2020)). The second one is a System Profit Mode (SPM) in which the taxi company will take charge of the vehicle assignment to maximize the profit.

This paper is organized as follows: Section 2 establishes a flow-based routing model for heterogeneous vehicles in a mixed automated and non-automated zone network incorporating different service regimes. Section 3 presents the numerical results of a case study with a large toy network. Section 4 draws our conclusions.

2. Methodology: mixed-integer linear programming (MILP) models

The aim of this paper is to develop a method to determine the fleet size of ATs and CTs for a taxi company in a city while the AVs-only zone is expanding. To characterize the performance of a taxi system during a general day of operations, one must be able to assign travellers to taxis and to determine vehicle routes under a mixed driving environment subject to AVs-only zone constraints. The interplay between the route choice of vehicles and dynamic travel time considering traffic congestion is also incorporated in this model.

We have the following assumptions for this future scenario: (1) ATs are allowed to move empty in the network without a human driver; (2) Vehicles can only park at certain nodes which are defined as the parking depots provided by the taxi company; (3) To keep a high-quality service, the taxi company cannot reject any travel request; (4) Only the taxi company uses AVs, so travellers are assumed not to be able to use private AVs; (5) The background traffic flow generated by privately-owned human-driven cars outside the AVs-only zone is simplified. Constants are used to represent the average value of such background traffic. Considering the driving restrictions imposed on CVs, trips received by the on-demand mobility system should be assigned to the appropriate type of vehicle based on three types of trips: 1) a trip with origin and destination inside the AVs-only zone which should be served by an AT; 2) a trip with origin and destination outside of the AVs-only zone which can be served by either an AT or CT; 3) a trip with origin/destination inside the AVs-only zone and destination/origin outside the AVs-only which should be served by an AT. Next, the mathematical models for UPM and SPM are presented.

Nomenclature

Sets

T	Set of time instants in the operation period.
N	Set of nodes.
L	Set of road links between nodes in set N.
G	Set of links in the time-space network.
M	Set of vehicle types, with option 1 being the conventional taxi (CT) and option 2 being the automated taxi (AT).
R	Set of groups of requests, where each group of requests $r \in R$ has the same origin, destination, desired departure time, and latest arrival time at the destination.
N^m	Set of nodes that can be used by vehicles of type $m \in M$ with $N^m \subseteq N$. CTs can use the nodes outside the AVs-only zone and the nodes located at the border of the AVs-only zone; ATs can use all the nodes.
N_P^m	Set of nodes allowing parking for vehicles of type $m \in M$ with $N_P^m \subseteq N^m$.
G^m	Set of links that can be used by vehicles of type $m \in M$ in the time-space network.
R^m	Set of groups of requests served by vehicles of type $m \in M$ with $R^m \subseteq R$.

Parameters

n^r	Total number of requests for group of requests $r \in R$.
o^r	Origin node for group of requests $r \in R$.
d^r	Destination node for group of requests $r \in R$.
a^r	Desired departure time for group of requests $r \in R$.
b^r	Latest arrival time for group of requests $r \in R$.
f_{ijt}	Background traffic flow on road link $(i, j) \in L$ at time instant $t \in T$.
Q_{ij}	Capacity of road link $(i, j) \in L$ in vehicles per time unit.
$C_{i_{t_1} j_{t_2}}$	Spatial capacity of road link $(i, j) \in L$ in vehicles that fit on the road link from time instant t_1 to t_2, where $(i_{t_1}, j_{t_2}) \in G$.
$t_{ij}^{\max}$	Maximum travel time on road link $(i, j) \in L$.
$t_{ij}^{\min}$	Minimum travel time on road link $(i, j) \in L$.
p^0	Initial base fare in euros for using the taxis.
p^m	Price per kilometre in euros/km for using vehicle type $m \in M$.
co^m	Unit driving operational cost in euros/km for vehicle type $m \in M$.
cd	Delay cost in euros/time instant.
cp	Salary of a driver in euros/time instant.
cf^m	Depreciation cost in euros/vehicle/time step for using vehicle type $m \in M$.
l_{ij}	Length of road link $(i, j) \in L$.
std^r	Shortest travel distance for group of requests $r \in R$.
stt^r	Shortest travel time assuming free flow speed for group of requests $r \in R$.
s	Total number of time instants in the operation period.

Decision variables

$PF^r_{i_{t_1} j_{t_2}}$	Passenger flow in group of requests $r \in R^m$ served by vehicle type $m \in M$ in road link (i, j), from time instant t_1 to t_2. Only defined for $(i_{t_1}, j_{t_2}) \in G^m, a^r \leq t_1 < t_2 \leq b^r$. If $t_1 = a^r$, then $i = o^r$.
$PF^{rm}_{i_{t_1} j_{t_2}}$	Passenger flow in group of requests $r \in R$ served by vehicle type $m \in M$ in road link (i, j) from time instant t_1 to t_2. Only defined for $(i_{t_1}, j_{t_2}) \in G^m, a^r \leq t_1 < t_2 \leq b^r$. If $t_1 = a^r$, then $i = o^r$.

Auxiliary variables

V^m	Taxis fleet size of type $m \in M$.
E^{rt}	Total number of passengers in group of requests $r \in R^m$ for vehicle type $m \in M$ arriving at time $t \in T$.
$TF^m_{i_{t_1} j_{t_2}}$	Total number of taxis of type $m \in M$ in road link (i, j) from time instant t_1 to t_2, where $(i_{t_1}, j_{t_2}) \in G^m$.
$TP^m_{i_t}$	Total number of taxis of type $m \in M$ parking at node $i \in N_P^m$ from time instant t to $t + 1$, with $t \in T$.

$X_{i_{t_1} j_{t_2}}$	Binary variable which is 1 when vehicles travel in road link (i, j) from time instant t_1 to t_2, where $(i_{t_1}, j_{t_2}) \in G$ and 0 otherwise.
F_{ijt}	Traffic flow on road link $(i, j) \in L$ at time instant $t \in T$.
P^{rm}	Total number of requests in group of requests $r \in R$ served by vehicle type $m \in M$.
E^{rmt}	Total number of passengers in group of requests $r \in R$ served by vehicle type $m \in M$ arriving at time $t \in T$.

2.1. User preference mode (UPM)

As explained before, in this on-demand mobility service system, we consider a service regime called ‘user preference mode’ in which travellers can choose the vehicle type by themselves if the requests can be served by both types of vehicles. While for the trips of type 1 and type 3, there is no option for the passengers and they always have to use an AT. In this case, we assume that all the passengers have known the available options and will adjust their behaviour to the on-demand mobility system. Thus, the requests for the vehicle type will always be feasible and no request will be rejected. This mode takes users’ preference into account which will increase the users’ satisfaction with the on-demand mobility service system. A mixed-integer linear programming model is developed with the objective of maximizing the total profit of the whole system.

2.1.1. Base formulation

The travel requests in group $r \in R^m$ have the same origin and destination node. Even though the vehicles serving group $r \in R^m$ depart at the same time, they may arrive at the destination at different times. Constraints (1)-(3) make sure that, for each group $r \in R^m$, the passenger flows departing from the origin node o^r at time a^r and arriving at the destination node d^r should be equal to the total number of requests.

$$\sum_{j_t | (o^r_{a^r}, j_t) \in G^m} PF^r_{o^r_{a^r} j_t} = n^r, \forall r \in R^m, m \in M \tag{1}$$

$$\sum_{t \in T | a^r + stt^r \le t \le b^r} E^{rt} = n^r, \forall r \in R^m, m \in M \tag{2}$$

$$E^{rt} = \sum_{i_{t_1} | (i_{t_1}, d^r_t) \in G^m} PF^r_{i_{t_1} d^r_t}, \forall r \in R^m, m \in M, t \in T \tag{3}$$

Constraints (4) and (5) ensure that the passenger flows are generated in the origin node and absorbed in the destination node. The passenger flow conservation in the intermediate nodes is described in Constraints (6). The total number of passengers on road link (i, j) traveling from time instant t_1 to time instant t_2, should be less than or equal to the total number of taxis on the same link as some taxis might drive without passengers, as in Constraints (7).

$$\sum_{j_{t_2} | (d^r_{t_1}, j_{t_2}) \in G^m} PF^r_{d^r_{t_1} j_{t_2}} = 0, \forall r \in R^m, m \in M, t_1 \in T, a^r + stt^r \le t_1 \le b^r \tag{4}$$

$$\sum_{i_{t_1} | (i_{t_1}, o^r_{t_2}) \in G^m} PF^r_{i_{t_1} o^r_{t_2}} = 0, \forall r \in R^m, m \in M, t_2 \in T, a^r \le t_2 \le b^r \tag{5}$$

$$\sum_{j_{t_0} | (j_{t_0}, i_{t_1}) \in G^m} PF^r_{j_{t_0} i_{t_1}} = \sum_{j_{t_2} | (i_{t_1}, j_{t_2}) \in G^m} PF^r_{i_{t_1} j_{t_2}}, \forall r \in R^m, m \in M, t_1 \in T, t_0 < t_1 < t_2, i \in N^m, i \neq o^r, i \neq d^r \tag{6}$$

$$\sum_{r \in R^m} PF^r_{i_{t_1} j_{t_2}} \le TF^m_{i_{t_1} j_{t_2}}, \forall (i_{t_1}, j_{t_2}) \in G^m, m \in M \tag{7}$$

At the beginning of the service period, the total number of taxis driving on road link (i, j) plus the total number of taxis parked at depot $i \in N_P^m$ should be equal to the fleet size of AT and CT as specified in Constraints (8). Constraints (9) and (10) describe the vehicle flow equilibrium for the nodes that allow and do not allow vehicle parking, respectively. Outside the AVs-only zone, the traffic flow of road link (i, j) at time instant t is calculated by the background traffic flow generated by privately owned conventional vehicles together with the flow generated by ATs and CTs, while in the AVs-only zone, the value of background traffic flow is zero and the traffic flow will be generated only by ATs. Constraints (11) calculate the traffic flow on every link.

$$\sum_{(i_0,j_t)\in G^m} TF^m_{i_0 j_t} + \sum_{i\in N_P^m} TP^m_{i_0} = V^m, \forall m \in M \tag{8}$$

$$\sum_{(j_{t_1},i_t)\in G^m | t_1<t} TF^m_{j_{t_1} i_t} + TP^m_{i_{t-1}} = \sum_{(i_t,j_{t_2})\in G^m | t<t_2} TF^m_{i_t j_{t_2}} + TP^m_{i_t}, \forall t \in T, i \in N_P^m, m \in M \tag{9}$$

$$\sum_{(j_{t_1},i_t)\in G^m | t_1<t} TF^m_{j_{t_1} i_t} = \sum_{(i_t,j_{t_2})\in G^m | t<t_2} TF^m_{i_t j_{t_2}}, \forall t \in T, i \in N^m \setminus N_P^m, m \in M \tag{10}$$

$$F_{ijt} = f_{ijt} + \sum_{m\in M} \sum_{t_2\in T|(i_t,j_{t_2})\in G^m} TF^m_{i_t j_{t_2}}, \forall t \in T, (i, j) \in L \tag{11}$$

2.1.2. *Traffic congestion*

We use the formulation of van Essen and Correia (2019) to include traffic congestion in our model. Based on the Bureau of Public Roads (BPR) function, we calculate the spatial capacity $C_{i_{t_1} j_{t_2}}$ of road link (i, j) from time instant t_1 to time instant t_2 by Equation (12). Note that if the difference between t_2 and t_1 equals the minimum travel time of road link (i, j), the value of $C_{i_{t_1} j_{t_2}}$ will be zero. To avoid this, we add in this case 0.5 to t_2 to obtain a nonzero value. To match the road link flow with the spatial link capacity, binary variables $X_{i_{t_1} j_{t_2}}$ are introduced. Constraints (13) describe the allowed total flow on road link (i, j) at time instant t_1. Constraints (14) ensure that at most one travel time for road link (i, j) starting from time instant t_1 can be chosen. Constraints (15) ensure that there is only vehicle flow from time instant t_1 to at most one time instant t_2. The first-in first-out Constraints (16) ensure that the vehicle that enters the road link first will leave the road link first, which means that vehicles cannot pass one another when driving on a link.

$$C_{i_{t_1} j_{t_2}} = (t_2 - t_1) Q_{ij} \left(\frac{1}{a} \left(\frac{t_2 - t_1}{t_{ij}^{\min}} - 1 \right) \right)^{\frac{1}{b}}, \forall\, (i_{t_1}, j_{t_2}) \in G \tag{12}$$

$$\sum_{t_2\in T} \left\lceil C_{i_{t_1} j_{(t_2-1)}} \right\rceil X_{i_{t_1} j_{t_2}} \leq F_{ijt_1} \leq \sum_{t_2\in T} \left\lfloor C_{i_{t_1} j_{t_2}} \right\rfloor X_{i_{t_1} j_{t_2}}, \forall\, (i, j) \in L, t_1 \in T \tag{13}$$

$$\sum_{t_2|(i_{t_1},j_{t_2})\in G} X_{i_{t_1} j_{t_2}} \leq 1, \forall (i, j) \in L, t_1 \in T \tag{14}$$

$$X_{i_{t_1} j_{t_2}} \geq \frac{\sum_{m\in M} TF^m_{i_{t_1} j_{t_2}}}{C_{i_{t_1} j_{t_2}}}, \forall\, (i_{t_1}, j_{t_2}) \in G \tag{15}$$

$$t_1 + \sum_{t\in T} X_{i_{t_1} j_t} (t - t_1) \leq t_2 + \sum_{t\in T} X_{i_{t_2} j_t} (t - t_2) + M \left(1 - \sum_{t\in T} X_{i_{t_2} j_t} \right), \forall t_1 < t_2 \in T, (i, j) \in L \tag{16}$$

2.1.3. *Objective function*

From the operator's point of view, the aim is to maximize the total profit of the whole system, which includes the taxi fares paid by passengers, the operational cost (including fuel, cleaning, maintenance, etc.) of the fleet, the delay penalization, the salaries for drivers, and the depreciation cost of the taxis. The taxi fares paid by passengers are constant in Equation (17) as the number of requests served by ATs and CTs are known beforehand. This term is included in the objective function to be able to compare with the SPM in which the vehicle type serving a request is determined by the model.

$$\begin{aligned} \max \quad & \sum_{m\in M}\sum_{r\in R^m}\left(p^0\cdot n^r + p^m\cdot n^r\cdot std^r\right) - \sum_{m\in M} co^m\cdot\left(\sum_{(i_{t_1},j_{t_2})\in G^m} TF^m_{i_{t_1}j_{t_2}}\cdot l_{ij}\right) \\ & - cd\cdot\sum_{m\in M}\sum_{r\in R^m}\left(\sum_{t\in T} E^{rt}\cdot t - a^r\cdot n^r - stt^r\cdot n^r\right) - s\cdot cp\cdot V^{CT} - \sum_{m\in M} s\cdot cf^m\cdot V^m \end{aligned} \tag{17}$$

2.2. *System profit mode (SPM)*

The UPM may lead to higher customer satisfaction, but a lower revenue for the operating company, because of additional relocations of vehicles. From the operator's point of view, the best way to maximize the system profit is to decide on the vehicle to assign to each client. In this mode, the set of groups of requests R can be divided into three subsets R_1, R_2, R_3, representing the set of groups of requests of type 1, type 2, and type 3, respectively. For trips of type 1 and 3, the vehicle type is known beforehand, whereas the mode of vehicles serving trips of type 2 is determined by the model.

The requests in group $r \in R_2$, which have the same trip information, might be assigned to different vehicle types to maximize the system profit. Constraints (18) ensure that the number of requests P^{rm} in group $r \in R$ served by vehicle type $m \in M$ in total equals the number of requests in group $r \in R$. Constraints (19) impose that the requests of type 1 and 3 should only be served by ATs. Constraints (1) and (2) are replaced by Constraints (20) and (21). For each group of requests $r \in R$ served by different vehicle types $m \in M$, the variables E^{rt} and $PF^r_{i_{t_1}j_{t_2}}$ in Constraints (3)-(7) should be replaced by E^{rmt} and $PF^{rm}_{i_{t_1}j_{t_2}}$, respectively. The objective function for the SPM should also be modified. When calculating the total taxi fares paid by passengers and the delay penalization, the total number of requests n^r in group $r \in R$ in Equation (17) should be replaced by P^{rm}. The set of groups of requests R^m should be replaced by R.

$$\sum_{m\in M} P^{rm} = n^r, \forall r \in R \tag{18}$$

$$P^{rm} = 0, \forall r \in R_1 \cup R_3, m = CT \tag{19}$$

$$P^{rm} = \sum_{j_t|(o^r_{a^r},j_t)\in G^m} PF^{rm}_{o^r_{a^r}j_t}, \forall r \in R, m \in M \tag{20}$$

$$P^{rm} = \sum_{t\in T|a^r+stt^r\le t\le b^r} E^{rmt}, \forall r \in R, m \in M \tag{21}$$

3. Computational results

We test the models on a large toy network consisting of 64 nodes and 112 links (two-way circulation allowed). Each road link has an equal length of 2 kilometres. We use several networks with different AVs-only zone coverage rate of the road network, namely 10%, 30%, 50%, 70%, and 90%, as shown in Fig. 1. The time step is set to 2.5 minutes. The shortest travel time and the longest travel time for each road link are 2.5 minutes and 10 minutes, respectively. The background traffic flow outside the AVs-only zone is generated randomly within the capacity restriction. 600 requests and their trip information including origins, destinations, departure time, latest arrival time, number of passengers in each group, shortest distance, and shortest travel time, are generated randomly with equal probability, to emulate the travel demands in the peak hour. Assuming that the acceptance of users towards AVs in level 5 is low, more than 80% of the requests with a preference for CVs are generated. In this case study, the value of the parameters are as follows: the initial base fare p^0 for using the taxis is 2.66 euros and is based on the price rate of a ride-hailing company in the Netherlands; the prices p^m for using CTs and ATs are 1.95 euros/km and 1.8 euros/km, respectively; the unit operational costs co^m for using CTs and ATs are 0.24 euros/km and 0.32 euros/km, respectively, calculated according to the methodology proposed by Bösch et al. (2018); the delay cost cd is 0.5 euros/time instant based on Liang et al. (2020); the salary cp of a driver is 10 euros/hour according to the minimum wage in the Netherlands, resulting in 0.42 euros/time instant; the depreciation costs cf^m for CTs and ATs are 0.04 and 0.05 euros/time instant/vehicle, respectively, which is calculated as the price of a taxi divided by its statutory lifespan. The estimation parameters a and b of the BPR function are set to 2 and 4, respectively, based on van Essen and Correia (2019). We solve these models using the Python interface of Gurobi 9.0.2 on an Intel(R) Core(TM) i5-6500 CPU @3.6GHz 8.0GB RAM computer. A comparison of the UPM and SPM in scenarios with a different coverage rate of the AVs-only zone is given in Table 1.

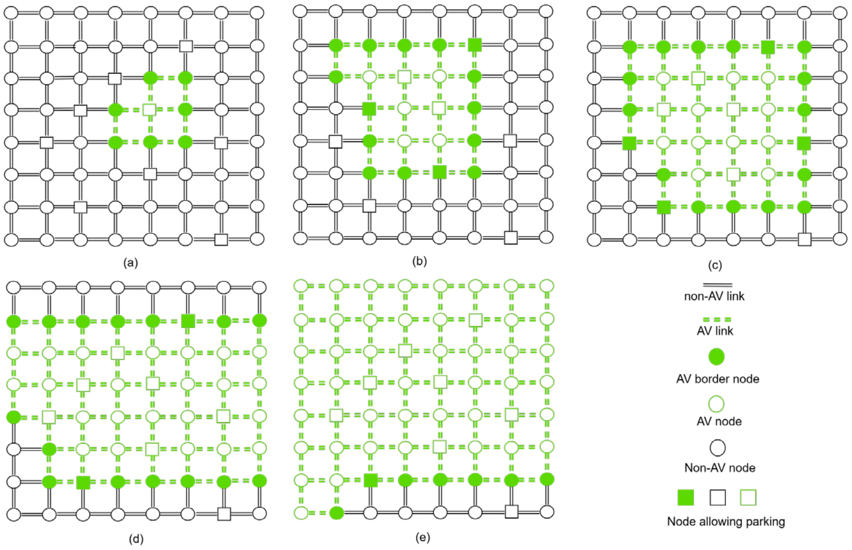

Fig. 1. Networks with different AVs-only zone size: (a) 10% (b) 30% (c) 50% (d) 70% (e) 90%

Table 1. Optimal results for the different coverage rates of the AVs-only zone.

AVs-only zone coverage rate %	Service mode	Obj. value	Total fleet size	AT fleet size	CT fleet size	Satisfied requests by ATs	Satisfied requests by CTs	Total travel distance (km)	Relocation distance (km)	Detour distance (km)	Delayed time (time step)	CPU time (minutes)
10%	UPM	4526.6	160	20	140	40	560	4870	1354	276	160	6.9
	SPM	5836.0	123	123	0	600	0	4348	1072	36	18	12.5
30%	UPM	3831.5	260	100	160	200	400	4980	1444	296	229	5.8
	SPM	5846.7	122	122	0	600	0	4332	1068	24	12	10.6
50%	UPM	3917.4	260	120	140	320	280	5122	1746	136	188	5.5
	SPM	5852.5	122	122	0	600	0	4320	1064	16	8	9.9
70%	UPM	4906.3	181	121	60	480	120	4910	1570	100	170	6.1
	SPM	5856.0	121	121	0	600	0	4292	1044	8	4	8.1
90%	UPM	5283.2	160	120	40	520	80	4544	1292	12	86	6.3
	SPM	5856.0	121	121	0	600	0	4292	1044	8	4	8.1

The total profit increases with the coverage rate of the AVs-only zone in most cases. This happens, first of all, because the privately-owned conventional vehicles are not allowed to drive inside the AVs-only zone, resulting in a lower delay cost caused by traffic congestion when the AVs-only zone enlarges. Secondly, in the SPM, the total travel distance decreases with the increase of the AVs-only zone coverage, as less detour and relocation kilometres are needed when the congestion effect diminishes. For UPM, the total travel distance increases at the early stage as the CTs have to detour more on the road network because of the driving restriction. When the AVs-only zone is big enough, fewer CTs are required and their total travel distance decreases correspondingly. In addition to this, a smaller fleet size of taxis is needed when the AVs-only zone expands, as fewer CTs are needed and the usage rate of ATs increases. This leads to less depreciation cost of the taxi fleet. A larger AVs-only zone means that more requests can be served by ATs instead of CTs which will also reduce the salary cost. The total profit does not decrease a lot in the SPM with different AVs-only zone sizes, as traffic congestion is the only factor that impacts the profit and the fleet size. When the AVs-only zone enlarges up to 70%, there is no variation in the performance of this model because the congestion effect has already been greatly reduced. Even though there exist privately-owned vehicles, ATs can always make use of the links within the AVs-only zone and find an alternative path to reduce the congestion effect. If the coverage rate of the AVs-only zone is 100%, there is no difference between UPM and SPM as all the requests will be assigned to ATs. An exception happens in the UPM when the AVs-only zone enlarges in the initial stage. The total profit falls steeply, with the coverage of the AVs-only zone increasing from 10% to 30%. This is due to the longer relocation and detour distance of CTs. Without permission to drive across the AVs-only zone, the CTs should detour more to satisfy the users' requirements and drive empty for a longer distance for the next requests. Once a CT detours, a delay cost is obtained as the CT should spend more time to serve the requests. Thus, more CTs are needed to fulfil all the mobility needs, resulting in a higher salary cost for drivers. When comparing the UPM with the SPM, it is evident that the SPM can bring more profit than the UPM. All the requests are assigned to ATs in SPM, as ATs services are more profitable due to less detour and relocation cost, no salaries for drivers, and less delay penalization. In terms of the computation time, the SPM takes longer than the UPM as also the vehicle type for each request in R_2 needs to be determined.

4. Conclusions and future work

In this paper, we introduced a mixed-integer linear programming model to determine the fleet size under different service regimes and study the impact of an AVs-only zone on the taxi service system performance. In general, ATs can bring more profit than CTs. The operating company should deploy more ATs when the AVs-only zone emerges if they do not consider the users' preference towards the type of taxis. UPM brings less profit than SPM but can satisfy passengers' demand if they prefer to ride in a conventional vehicle. In the long run, it is still worthwhile to consider users' preference. At the early stage, the emergence of the AVs-only zone will lead to a longer detour and relocation distance for CTs. So a well-designed construction strategy of the AVs-only zone can be beneficial to help diminish the negative effects for conventional human-driven vehicles. When the coverage rate of the AVs-only zone is relatively large, the traffic congestion will be largely reduced and the taxi operating company can gain more profit by using ATs. Further research should be done in real case studies, considering the impact of the AVs-only zone on privately-owned vehicles in a global view. Also, a sensitivity analysis of the parameters should be performed.

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