Feeder transit services in different development stages of automated buses: comparing fixed routes versus door-to-door trips

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Abstract

The arrival of automated vehicles could significantly reduce the operating cost of mobility services. This fact has encouraged researchers to propose door-to-door services instead of the current fixed routes. However, a comparison between these two alternatives is required in order to identify when (depending on the development degree of the automated vehicles) and where (depending on the characteristics of the area of service) the implementation of each service is the most competitive solution. This research compares the two types of transit services to supply first/last-mile solutions in suburban areas. By means of an analytical approach, the results show that fixed routes remain the most efficient alternative unless the new technology reaches a certain degree of development that allows a high reduction of operating costs. In this case, the applicability of door-to-door services will significantly increase under certain circumstances: small areas of service, short distance trips and high values of time.

Keywords: Automated buses; first/last-mile solutions; operating strategy of feeder transit services; fixed routes; door-to-door services

1. Introduction

The arrival of automated vehicles may significantly change mobility in different directions. In particular, the new technology may generate relevant changes in the cost structure of mobility services. This modification will mainly come from the removal of drivers. According to the levels of driving automation of SAE (2018), future vehicles will not require human driving in Level 4, although with some limitations, and with no constraints in Level 5. Driver salaries currently represent a high percentage of the service cost. Bösch et al. (2018) estimates that this cost is 88% of operating cost for taxis, and the cost per passenger and kilometer of an urban bus service would be a half of the current one if drivers were not required. In ATC (2006), the driver salaries represent around 50% of the total operating cost of a bus system. Some authors propose self-driving taxi fleets as substitutes of private cars (Burghout et al., 2015) or conventional buses (Merlin, 2017). However, the positive view of future mobility services based on the new automated vehicle also has detractors. UITP (2017) emphasizes the negative side that direct services with small vehicles would replace public transport, walking or cycling. Along the same lines, Currie (2018) criticizes this so-called shared mobility as a substitute of the real shared mobility, buses and trains.

Potential environments for early implementation of automated vehicles include suburban areas (residential zones, university campuses, business districts, etc.) because they present limited levels of demand, low levels of traffic, and a more affordable implementation of technical infrastructure equipment. Several trials of automated buses have taken place in this type of environments (e.g. Kista and Barkarby in Sweden and Vantaa in Finland). Thus, the last-mile problem to connect a suburban area with a station of a high capacity transit line becomes an interesting focus of research for future mobility based on automated vehicle technology. In this setting, some authors have proposed door-to-door services based on fleets of taxis to satisfy individual trips (Liang et al., 2016), shared taxis (Sheltes and Correia, 2017) and small, automated buses (Winter et al., 2016).

However, the applicability of these on-demand services to a wide range of scenarios has limitations due to high operating costs among other reasons (Enoch et al., 2006). Additionally, theoretical studies show that the applicability of door-to-door services is limited to scenarios of low demand density (Li and Quadrifoglio, 2010). Therefore, a comparison between this type of operation and fixed routes is required in order to clarify if door-to-door services will be more competitive in the era of automated vehicles. By means of a continuous approximation model, we discuss the applicability of these two operating services, including in the problem the degree of automation with regard to vehicle capabilities (or operating cost reduction) and manufacturing (i.e., acquisition cost increase).

There are different contributions in the literature for the modelling of feeder services. Some of them were focused on the design of a system of parallel fixed routes that connects a region with a rail corridor (Hurdle, 1973; Kuah and Perl, 1988), and others analyzed demand-responsive transport systems for door-to-door services.

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(Daganzo, 1978) or checkpoint dial-a-ride services (Daganzo, 1984). Chang and Schonfeld (1991) presented a comparison between fixed routes and door-to-door services in a many-to-one demand pattern. More recently, Kim and Schonfeld (2014) extended this model for scenarios where different areas of service are interconnected. Quadrifoglio and Li (2009) also contributed to the discussion about the critical demand density between both services. Other authors have analyzed hierarchical systems with a joint design of fixed routes as main transport network and on-demand services as a feeder service: zone-based strategies (Aldaihani et al., 2004) and line-based design (Chen and Nie, 2017).

The structure of the paper is as follows: the next section presents the analytical formulation used in this paper, Section 3 includes a numerical analysis, and Section 4 summarizes the main conclusions of the work.

2. Methodology

The objective of this study is to identify the applicability of fixed routes (FR) and door-to-door services (DtD) as last-mile solutions in different scenarios of development of automated vehicles. For this purpose, we choose an analytical model due to its usefulness for obtaining strategic guidelines about the behavior of transport systems.

2.1. Basics of the analytical model

The starting point for this model is Chang and Schonfeld (1991). We focus the analysis on a suburban area that needs to be connected with a main transit station. This area is a rectangle whose dimensions are $D_R$ and $D_W$ and its street pattern is a grid. A road of length $D_H$ connects this area with the station. The hourly demand density $\delta$ is deterministic, inelastic and uniformly distributed over the area. For this study, we assume that a half of the demand travels from the area of service to the station while the other half goes in the opposite direction.

On the other hand, Figure 1a shows the network layout of the fixed route feeder service: a group of parallel lines that cross the area from one side to the other, where they are gathered in the road to reach the station. Three decision variables determine the service: line spacing $s_l$, stop spacing $s_s$ and headway $H_l$. On the other hand, Figure 1b represents the door-to-door strategy. In this case, the area is divided into subareas that are served independently of each other. Buses are allocated to the different subareas, where they follow a route $r$ to pick up and drop off passengers at their origins or destinations. The decision variables are: dimensions of the subarea $l_{sa} \times w_{sa}$, and headway $H_{sa}$.  

![Fig. 1. Operation schemes of transit services compared.](image)

The transit technology is a bus with a variable size $S_r$ defined by demand requirements. The cruising speed in the area is $v$ and this speed is $s_f$ times higher on the road. At each stop, vehicles lose a fixed dwell time $\tau_s$, and every boarding and alighting requires an additional time $\tau_b$. For passengers, the walking speed is $v_w$.

2.2. Objective function

The criterion chosen to identify what type of operation is the most competitive solution is the system total cost. The first step for the comparison is to determine the optimal configuration that each alternative can provide in a given scenario, that is, the combination of values of the respective decision variables that provides the lowest system total cost. For this purpose, we minimize the objective function (1), which includes partial costs for agency and users. Agency cost involves distance traveled $K$ and fleet size $F$ per hour of service. There are two costs associated to the fleet size: vehicle acquisition cost and operating cost per hour. User cost covers the time of all the stages of the passenger journey: access $A$, waiting $W$, riding $R$, and time per stop and during the boarding/alighting process $S$.
min\{Z = C_a + C_d = [c_R \cdot K + (c_T + c_G) \cdot F] / \delta D_H W + VoT \cdot [\mu_A \cdot A + \mu_W \cdot W + \mu_R \cdot (R + S)]\} \tag{1}

All metrics are translated to monetary units for comparison. User expected times are multiplied by the value of time $VoT$ and weighted by the respective time perception $\mu_i$, where $i = A, W$ or $R$. Agency metrics are multiplied by the parameters $c_R, c_G$ and $c_T$, that is, the corresponding unit costs per kilometer traveled, hourly operating cost and acquisition cost per hour respectively. Then, agency cost is divided by the hourly demand to get this cost per passenger.

2.3. Partial costs of fixed routes

In a fixed route feeder service, every bus starts at the station and picks up passengers that travel from this point to the suburban area. The bus covers the entire road between station and area of service, where it runs on the border of that area to reach the served line. Once the bus arrives to its line, it travels to the end of the line and makes all the stops where passengers progressively get off. Finally, the bus runs in the opposite direction, following the same path and stopping at all the stops, but in the opposite direction from the area to the station. According to this operation, we derive the agency partial costs: total kilometers traveled by the entire fleet in one hour (2) and fleet size required to supply the service during that hour (3). They are obtained dividing the cycle length or time of one round trip by the service headway respectively.

$$K = 2(D_{wa}/s_i)\{D_l - s_i/2 + D_w/4 + D_h\}/H_1 \tag{2}$$

$$F = 2(D_{wa}/s_i)\{D_l - s_i/2 + D_w/4 + D_h/s_i\}/v + \tau_s(D_l/s_i + 1) + \tau_s\delta H_w H_s D_j/2 \tag{3}$$

From the user perspective, we work with the expected time across users for each component of the transit chain. Access cost (4) is the average between the closest user and the most distant user with regard to the bus stop. Regarding waiting time (5), we assume that the service works according to headways or schedules depending on the service headway. If the headway is small, users arrive at a stop following a Poisson process and the average waiting time is a half of the headway. Otherwise, users know the fixed timetable and arrive some minutes $h_i$ before the scheduled time; we assume certain coordination of transit services that allows users to adjust their arrivals. In this case, we add an extra time due to the low level of service since users cannot choose their departure times. This time is a fraction $f_i$ of the headway. Riding time (6) is the average between users at the first and the last stop of the line. To estimate the additional time at stops (7), some users make all the stops and wait for the boarding or alighting of the rest of passengers, and others only make the stop at station and do not wait for boardings or alightings.

$$A = (s_i + s_j)/4w_w : W = \min(H_2/h_2, h_2 + f_2) \tag{4}$$

$$R = (D_l/s_i + 1) + \tau_s\delta H_w H_s D_j/2 \tag{5}$$

Finally, a relevant metric for the estimation of system costs is the required vehicle size (8); that is, the highest level of demand in one of the directions allocated to the different lines and vehicles.

$$S_v = \delta H_w H_s D_j/2 \tag{8}$$

2.4. Partial costs of door-to-door service

In the on-demand service, the operation of a bus starts at the station and carries the users that go to the specific subarea assigned to that bus. When the bus arrives to that subarea, it covers a route determined by the requested origins and destinations. The bus drops off and picks up passengers during the same route. The former are the users who arrive at the station during the period of time between two vehicles (i.e., the headway). The latter are the users in the subarea that go to the station; they are always assigned to the next bus that will arrive to the subarea even if there is one en route at that moment. After this internal route, the bus goes back to the station to complete the cycle. Following this operation, we derive the total distance traveled in one hour of service (9) and required fleet size (10).

$$K = (D_{wa}/H_{aa}w_wa)\{D_l - l_{aa}\} + D_w/2 + 2D_h + r_l/H_{aa} \tag{9}$$

$$F = (D_{wa}/H_{aa}w_wa)\{D_l - l_{aa}\} + D_w/2 + 2D_h/s_j + r_s\delta H_{aa} l_{aa}w_wa + 2\} + 2\tau_s\delta H_{aa} l_{aa}w_wa\}/H_{aa} \tag{10}$$

An important metric in this design is the length of the internal route $r$. To estimate this length, we assume the non-backtracking routing strategy presented in Daganzo (1984) and reformulated by Quadrifoglio & Li (2009) for routes with few stops. The model works with one or other approximation depending on the number of stops $n_r = \delta H_{aa} l_{aa}w_wa$.

$$r = \left\{ \begin{array}{ll} 2\sqrt{(n_r + 2)l_{aa}w_wa/3} & \text{if } n_r \geq 12l_{aa}w_wa - 2 \tag{Daganzo, 1984} \\ 2l_{aa}(n_r + 1)/(n_r + 4)w_wa/6 & \text{if } n_r < 12l_{aa}w_wa - 2 \tag{Quadrifoglio and Li, 2009} \end{array} \right.$$ 

This system provides a door-to-door service; therefore, the access time is zero, $A = 0$. Regarding waiting time (12), we distinguish between users that travel from the station to the area of service and the users that travel in the opposite direction. The waiting time for the former group follows the same formulation as the fixed route service. However, the waiting time for the second group has two components. The first one is the time required to order a service. A vehicle accepts all requests received until the vehicle just arrives to its subarea. Therefore, this first
component depends on the headway as for the first group of users. The other component depends on the route in
the subarea. Once the vehicle starts that route, a user waits the time between the beginning of the route and when
the user is picked up. On average, this time is a half of the total routing time, which includes the running time and
the time at stops.

\[ W = \min\{H_{sa}/2; h_2 + f_i H_{sa}\}/2 + \min\{(H_{sa} + r/v + (\tau_s + \tau_d)\delta H_{sa} l_{sa} w_{sa})/2; h_2 + f_i (H_{sa} + r/v + (\tau_s + \tau_d)\delta H_{sa} l_{sa} w_{sa})\}/2\]  \( (12) \)

For the other two times where users are inside the vehicle (13) and (14), the expected time is the average
between the two extremes of trip length and number of stops made. The last metric to take into account is the
vehicle size (15). Assuming a conservative estimation, this size is the total number of passengers in both directions.

\[ R = [(D_k - l_{sa})/2 + D_{op}/4 + D_d/s_f + r/2]/v \ ; \ S = r_s (\delta H_{sa} l_{sa} w_{sa}/2 + 1) + r_s (3\delta H_{sa} l_{sa} w_{sa}/4) ; S_v = \delta H_{sa} l_{sa} w_{sa} \]  \( (13, 14 15) \)

2.5. Units agency costs with regard to maturity of automated vehicle technology

Agency costs depend on the bus size \( S_j \) following a linear relationship as in (16), where \( j = K, V, O \). As expected,
the arrival of the automated vehicle technology will generate changes in the operating costs of mobility services
and at the same time in the acquisition cost of these new vehicles. In this analysis, we assume that the variation of
unit costs will only occur in the fixed component while the other component will remain independent to the
evolution of the vehicle technology (Zhang et al., 2019). To capture this variation, parameter \( \Delta_o \) is included in (16).
This parameter can be positive or negative depending on whether the cost of the current buses increases or decreases.

\[ c_j = (1 + \Delta_o) \cdot a_j + b_j \cdot S_v \]  \( (16) \)

There is uncertainty about the evolution of these costs due to the arrival of automated buses. Regarding the
operating cost per hour, the most relevant change will occur in the driver cost for two main reasons: it is the highest
component of the system as commented above and this reduction could be total if the maturity of automated technology
allows the operator to remove drivers. Other costs such as energy consumption and maintenance have less weight
and possible variations will be smaller in comparison with labor costs. Therefore, we may assume that operating
cost will be smaller in the future, that is, parameter \( \Delta_o \) is negative and its range of values is \((\Delta_{OF}, 0)\), where \( \Delta_{OF} \)
represents the maximum reduction when the automated technology will reach its complete development. The evolution of this cost will have different stages: reduction of driver salaries, buses remotely driven from a control
center, and finally, no driver required in any case.

On the other hand, we expect that the vehicles will be more expensive than the current ones; at least the current
prototypes of automated vehicles have prices clearly higher (NCTR, 2016). For bus acquisition cost variation, the
range is \( \Delta_V \in (\Delta_{VF}, \Delta_{V0}) \), where \( \Delta_{V0} \) is the increase of the bus cost in the current automated bus prototypes and \( \Delta_{VF} \)
is that increase at the last stage of automation development. We assume that this cost will decrease with the
progressive improvement of the new technology and its mass production. Finally, the unit cost per kilometer is
mainly composed of fuel consumption, tires and maintenance. In this case, some authors predict a reduction due
to smoother driving behavior. However, this reduction will be limited in comparison with the previous costs
(Stephens et al., 2016). We assume that this cost will remain constant, that is, \( \Delta_k = 0 \).

In short, to describe the evolution of costs, we work with two parameters: reduction of operating cost per hour and
increase of acquisition cost. Figure 2 shows the domain of values for these two parameters \( \Delta_o \) and \( \Delta_V \).

![Fig. 2. Domain of values for parameters \( \Delta_o \) and \( \Delta_V \).](image-url)
3. Numerical analysis

In this section, we use the previous model to compare the applicability of the two feeder systems. The focus is on the effects of the variation of unit agency costs, that is, the domain of values in Figure 2. In this space, we focus the attention on four points: conventional vehicles $CV$ at point $(0, 0)$, current automated vehicles $AV_0$ ($\Delta V_0, 0$), intermediate evolution of automated technology $AV_I$ ($\Delta V_I, \Delta O_I$), and last stage on the development of the new technology $AV_F$ ($\Delta V_F, \Delta O_F$). According to the price of the current automated buses (NCTR, 2016), we can extrapolate that $AV_0$ is around 5. IHIS (2014) predict that the final price of an automated vehicle will be around 20% higher than for a conventional one, which means $\Delta V_F$ is 0.25. Finally, we consider that $\Delta O_F$ is -0.8 since the driver cost is 80% of the non-size-dependent part of the hourly operating cost. Table 1 includes all input parameters for the base case study.

Figure 3a shows the evolution of system total cost of both services with regard to demand density for the four points of the domain of cost variations. In general, for low levels of demand, the most competitive service is an on-demand system. However, fixed routes provide a service with a lower system total cost above a certain demand density. Thus, we identify the density threshold that determines the applicability of each type of operation. The evolution of unit costs with regard to the maturity of automated technology changes that threshold. In the current situation, where automated buses are expensive, the range of values where door-to-door services are the most competitive solution is narrower. However, the range is longer at point $AV_I$ and especially at point $AV_F$.

<table>
<thead>
<tr>
<th>Input parameter</th>
<th>Variable</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hourly demand density</td>
<td>$\delta$</td>
<td>pax/km$^2$-h</td>
<td>1 – 1000</td>
</tr>
<tr>
<td>Longitudinal dimension of the suburban area</td>
<td>$D_L$</td>
<td>km</td>
<td>2.5</td>
</tr>
<tr>
<td>Transversal dimension of the suburban area</td>
<td>$D_W$</td>
<td>km</td>
<td>1.2</td>
</tr>
<tr>
<td>Road length from station to suburban area</td>
<td>$D_R$</td>
<td>km</td>
<td>0.5</td>
</tr>
<tr>
<td>Value of time</td>
<td>$V_{ot}$</td>
<td>€/h</td>
<td>10</td>
</tr>
<tr>
<td>Time perception weight of access</td>
<td>$\mu_A$</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>Time perception weight of waiting</td>
<td>$\mu_W$</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>Time perception weight of travelling</td>
<td>$\mu_T$</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>Walking speed</td>
<td>$v_c$</td>
<td>km/h</td>
<td>4</td>
</tr>
<tr>
<td>Cruising speed in the suburban area</td>
<td>$v$</td>
<td>km/h</td>
<td>25</td>
</tr>
<tr>
<td>Speed factor in the road</td>
<td>$s_f$</td>
<td>-</td>
<td>1.8</td>
</tr>
<tr>
<td>Dwell time</td>
<td>$t$</td>
<td>h</td>
<td>12/3600</td>
</tr>
<tr>
<td>Boarding/alighting time</td>
<td>$t'$</td>
<td>h</td>
<td>1/3600</td>
</tr>
<tr>
<td>Safety waiting time</td>
<td>$t_I$</td>
<td>h</td>
<td>4/60</td>
</tr>
<tr>
<td>Home waiting time factor</td>
<td>$f_c$</td>
<td>-</td>
<td>1/6</td>
</tr>
<tr>
<td>Fixed unit operating cost per kilometer</td>
<td>$a_O$</td>
<td>€/veh-km</td>
<td>0.154</td>
</tr>
<tr>
<td>Size-dependent unit operating cost per kilometer</td>
<td>$b_O$</td>
<td>€/veh-km-pax</td>
<td>0.002</td>
</tr>
<tr>
<td>Fixed unit operating cost per hour</td>
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<td>€/veh-h</td>
<td>30.634</td>
</tr>
<tr>
<td>Size-dependent unit operating cost per hour</td>
<td>$b_O$</td>
<td>€/veh-h-pax</td>
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<td>Fixed unit acquisition cost per hour</td>
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<td>€/veh-h</td>
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<tr>
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<td>€/veh-h-pax</td>
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<tr>
<td>Variation of fixed unit operating cost per hour at intermediate stage of development</td>
<td>$\Delta V_I$</td>
<td>-</td>
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</tr>
<tr>
<td>Variation of fixed unit operating cost per hour at the final stage of development</td>
<td>$\Delta V_F$</td>
<td>-</td>
<td>-0.8</td>
</tr>
<tr>
<td>Variation of fixed unit acquisition cost per hour at current stage of development</td>
<td>$\Delta V_I$</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>Variation of fixed unit acquisition cost per hour at intermediate stage of development</td>
<td>$\Delta V_F$</td>
<td>-</td>
<td>2.5</td>
</tr>
<tr>
<td>Variation of fixed unit acquisition cost per hour at the final stage of development</td>
<td>$\Delta V_F$</td>
<td>-</td>
<td>0.25</td>
</tr>
</tbody>
</table>

In Figure 3b, we analyze the demand density threshold in the total domain of variation of hourly operating cost and acquisition cost. We observe that the former parameter $\Delta O$ has a greater impact on the variation of that threshold. However, this impact requires a high reduction of costs to produce a sharply growth of that demand density and the applicability of door-to-door services. For the base case study, when $\Delta O$ varies from 0 to -0.8, the density only increases from around 25 pax/km$^2$-h to 100 pax/km$^2$-h. To reach high density thresholds, the reduction of hourly operating cost would have to exceed 80%, from which on that density grows fast. The reason is the small difference between the system total cost curves at stage $AV_F$ in Figure 3a. Figure 3b also shows the boundary of applicability between conventional and automated buses, that is, the reduction of hourly operating cost required to compensate the higher acquisition cost.
Density threshold versus area size and shape

Area size $D_s = D_p$ (km$^2$)

Value of Time $V_{OT}$ (€/h)

Distance Area of Service - Station $D_p$ (km)

Distribution of costs for $\delta = 25$ pax/km$^2$-h

Distribution of costs for $\delta = 100$ pax/km$^2$-h

Density threshold versus road length and value of time

Fig. 3. Numerical results of system total cost, partial costs and demand density thresholds in different scenarios of automation maturity for fixed routes (FR) and door-to-door services (DdD).

Additionally, Figures 3c and 3d show the distribution of costs among the partial agency and user costs. In the optimal system configuration, door-to-door services provide a more balanced cost distribution between agency and users, for that reason, the operating cost reduction benefits this type of operation. On the other hand, the hourly operating cost is the greatest one in comparison with the operating cost per distance traveled or vehicle acquisition, therefore, its impact is more relevant in Figure 3b. From the user perspective, door-to-door services remove access cost at expenses of longer trips due to the internal route in the subarea and a higher waiting time due to the
dispatching strategy. The reduction of agency costs would allow the system to increase the fleet size (i.e., lower headways and more lines or subareas) and make the difference of both times between both services shorter.

Finally, Figure 3e and 3d present a sensitivity analysis of the density threshold with regard to four characteristics: area size and shape, distance between area of service and station, and value of time. The analysis is performed in three of the four stages of automation development: CV, AV_t, and AV_d. The variations between the current scenario and an intermediate development of automated vehicles would be limited in all the circumstances. The jump in the density threshold would arrive with a mature automated vehicle, but this change will only be decisive in some environments: relatively wide, small areas close to the station with high-income users.

4. Conclusions

The paper has compared fixed routes and door-to-door services as last-mile solutions to feed a transit station considering the impact on unit agency costs due to the arrival of automated buses. The results show that the range of applicability of door-to-door services would be wider, that is, the demand density threshold from which fixer routes are more competitive will be higher. However, this change will only be significant under some circumstances: high reduction of hourly operating unit cost, a limited increase in the acquisition vehicle cost, small areas of services, short trip lengths and high values of time. In these scenarios, the demand density threshold could reach values over 1000 pax/km²-h while this value is around 100 pax/km²-h for current scenario with conventional buses.

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