Potentialities of autonomous modular buses in branched lines with smart control strategies

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1 INTRODUCTION

Modular bus technologies are capturing the interest of transit practitioners due to their operational flexibility and commercial speed improvements, with prospective initiatives contributing to characterise the real performance of modular bus operation (Khan et al., 2023). However, there are still some doubts on the acceptability of the proposed strategies regarding the user experience and operational costs.

This research aims to explore the potential of modular buses in an urban bus route with branches, by comparing the operating cost and temporal performance of conventional bus technologies (S0) to two scenarios with modular bus operation. In Scenario S1 regular buses are replaced by modular bus convoys with a constant length. In Scenario S2, modular buses may couple and decouple each other for adapting the convoy length to the route shape and demand variability in route segments.

The modelled bus route presents a Y-shaped layout with different demand rates in each route segment. The branching scheme proposed is common in conventional transit services, when lines leave the crowded central areas in the city and branch out, providing affordable services in the city's periphery (see Daganzo, 2010). Despite the operating cost savings, the trips whose origins or destinations in the branches are served with low frequencies, worsening their waiting times, in comparison to the central segment. Hence, modular buses may neutralise the expected increase of waiting times by just decoupling modules at branching points. The main contribution of this paper is focused on the identification of the required situations where the scenario S2 would be cost-efficient.

2 METHODOLOGY

An optimization model is presented, aimed at minimising the system cost of the operation of modular buses in a given corridor (Eq. 1), as the sum of the cost incurred by the transit agency and the cost experienced by users. Users' perceived cost (Eq. 1.1) integrates in-vehicle travel time and waiting time while agency cost (Eq. 1.2) includes infrastructural cost for lanes and chargers of electric vehicles, and operating costs derived from fleet size and kilometres travelled. The decision variables of the optimization are headway (H) and slack time at the route terminals (θ) and are evaluated using a grid search procedure. The route is conceived to be operated by two independent fleets (one for each branch). In S2 we propose a single bifurcated line where each convoy splits to access both branches, operating the corridor with a homogeneous headway. Additionally, active control strategies are implemented to observe their effects on line design optimization.

$$\min\{Z_S = Z_u + Z_o\} \tag{1}$$

$$Z_u = \Lambda\beta t_u = \Lambda\beta[t_{IVTT} + t_W] \tag{1.1}$$

$$Z_o = \$_L L + \$_V V + (\$_M + \$_B)M + \$_{sc}N_{sc} \tag{1.2}$$

$$\text{s.t.} \quad H \geq Hmin;\ convoy\ length \leq max.\ convoy\ length;\ \theta \geq 0 \tag{1.3}$$

The different components of the objective function have been calculated by a complete simulation of the route performance metrics for the aforementioned scenarios of modular and conventional buses and the values of the decision variables under analysis. The simulation approach followed is strongly inspired by the previous work described in Estrada et al. (2021) and adapted to the modular operation schemes S1 and S2. S2 reproduces convoy splitting and reassembling at the route bifurcation, plus the possibility of reserving some pods to operate exclusively the main trunk. This homogenises headway along the branching segments, and adapts better supply to occupancy.

The model simulates the arrival and departure times of each vehicle at each stop and the respective dwell times. The arrival time to a stop is a function of the departure time from the previous stop and the travel time, that considers the bus movement and possible stops at signalised intersections. The bus movement depends on the distances to be travelled, as well as the desired cruising speed and the acceleration and deceleration rates.

The dwell time is calculated by the product of the boarding and alighting demand for each vehicle and the corresponding unit boarding/alighting time. At each stop, the occupancy of the vehicle in the new segment is recalculated. The computational method estimates the maximal occupancy along the route and calculates the corresponding length of the convoy for not exceeding the 80 % of the nominal vehicle capacity. The model assumes that all users willing to board a vehicle are able to do this operation. The modelling approach integrates random effects to resemble the real movement of buses. The arrival ratio of passengers at stops is randomly distributed with a Poisson distribution of parameter λ_{xy}, which is the aggregated hourly demand between each pair of stops x and y.

For each possible scenario and combination of values of the decision variables, the simulation is run several times in parallel, and subsequently the average values of the results are calculated. A verification is made to discard unacceptable solutions, that is, when in any of the tested iterations the convoy length exceeds the maximum permissible convoy length or the operating headway is less than the acceptable minimum (Eq. 1.3).

Finally, control strategies are implemented to study their comparative effect on conventional and modular technologies. In the C0 scenario, only slack times are considered as a control strategy. In the second scenario, C1, the slack times are modified to minimise the waiting times for coordination between branches when entering the central segment. Time departure coordination in branches enables tackling the instabilities generated by the difference in travel times between the two branches. The third scenario C2 integrates the C1 strategies plus an active headway control with two adaptive measures: traffic light priority for buses (+5 seconds in the stretch between two consecutive stops) to compensate for long headways (+20%) with the previous convoy, and extended stop times by 5% to offset short headways (-20%) from the preceding convoy.

3 RESULTS AND DISCUSSION

The model has been implemented in a Y-shaped corridor with a central segment of 8.75 km and two branches of 2.975 km and 4.60 km respectively. We have tested different levels of demand with the same spatial distribution, where 74% of trips start and end at the central corridor, while the rest have at least one point in the branches. In-vehicle travel time (IVTT) and waiting time are weighted by 1 and 2.1 respectively to a value of time of 12.5 EUR/pax-h. The minimal headway is established at 3 minutes and the maximal convoy length is 6 for modular solutions and 1 for conventional buses. All bus typologies are assumed to be autonomous, that is, no drivers are needed. The rest of parameters related to bus technology, bus corridor and the proxies of the system are defined in the following link UPC. The simulation is run ten times for each scenario.

Table 1 - *Line optimal design for Λ = 300 pax/h and Λ = 750 pax/h*

<table>
<tr><th colspan="2">Strategy C1</th><th colspan="2" rowspan="2">Minibus
18 pax/veh</th><th colspan="2" rowspan="2">Midibus
44 pax/veh</th><th colspan="2" rowspan="2">Standard
86 pax/veh</th><th colspan="2" rowspan="2">Modular S1
12 pax/pod</th><th colspan="2" rowspan="2">Modular S2
12 pax/pod</th></tr>
<tr><th>300 pax/h</th><th>750 pax/h</th></tr>
<tr><td colspan="2">Headway (min)</td><td>4</td><td>-</td><td>5</td><td>3</td><td>6</td><td>4</td><td>3</td><td>3</td><td>7</td><td>4</td></tr>
<tr><td colspan="2">Fleet size (veh)</td><td>18</td><td>-</td><td>15</td><td>24</td><td>13</td><td>18</td><td>24</td><td>48</td><td>20</td><td>36.6</td></tr>
<tr><td colspan="2">Convoy length Main/Branch/Branch</td><td>1/1/1</td><td>-</td><td>1/1/1</td><td>1/1/1</td><td>1/1/1</td><td>1/1/1</td><td>1/1/1</td><td>2/2/2</td><td>2/1/1</td><td>2.1/1/1</td></tr>
<tr><td colspan="2">Zs (EUR/pax)</td><td>4.64</td><td>-</td><td>5.17</td><td>4.00</td><td>5.47</td><td>4.16</td><td>4.42</td><td>4.10</td><td>4.87</td><td>3.85</td></tr>
<tr><td colspan="2">Zo (EUR/pax)</td><td>1.53</td><td>-</td><td>1.79</td><td>1.15</td><td>1.80</td><td>1.03</td><td>1.59</td><td>1.25</td><td>1.35</td><td>0.97</td></tr>
<tr><td colspan="2">Zu (EUR/pax)</td><td>3.11</td><td>-</td><td>3.38</td><td>2.85</td><td>3.67</td><td>3.13</td><td>2.83</td><td>2.85</td><td>3.52</td><td>2.88</td></tr>
<tr><td colspan="2">Avg. Waiting time (min/pax)</td><td>2.57</td><td>-</td><td>3.20</td><td>1.94</td><td>3.86</td><td>2.60</td><td>1.93</td><td>1.94</td><td>3.50</td><td>2.01</td></tr>
<tr><td colspan="2">Avg. In-Vehicle Travel time (min/pax)</td><td>9.51</td><td>-</td><td>9.52</td><td>9.58</td><td>9.50</td><td>9.58</td><td>9.53</td><td>9.58</td><td>9.56</td><td>9.62</td></tr>
</table>

In Table 1, the analysis considers two possible demand rates: 300 pax/h and 750 pax/h. For a total demand of 300 pax/h the optimal solution in terms of total cost is the modular bus strategy S1, followed by the minibus. Small buses or convoys adjust better the service capacity to the demand than midibuses or standard buses. On the other hand, operation S2 with modular vehicles is the most competitive solution for a demand of 750 pax/h. The main advantage of this operation is that waiting times in the branches are the same as in the central segment while it is double in the rest of alternatives. This allows the system to operate with higher headways to reduce the agency cost without increasing waiting times in the same proportion. S2 strategy for 750 pax/h is typically operable with a convoy length of 2 modules. However, some aleatory iterations request an extra pod in the convoy that is not needed in the branches. So, it is assigned to exclusively operate the main segment, increasing the fleet size.

The growth in the convoy length results in a considerable increase in the fleet size, as the length of all convoys in one unit is increased at the same time. In higher demand domains, the attractiveness of this solution gradually falls due to the high cost of operation per seat. The modular strategy with bifurcation and capacity adjustment (S2) has a very different behaviour. Firstly, the need to decouple the convoy in the bifurcation imposes a minimum convoy length of two units, which undermines the competitiveness of this strategy for low demands, where a conventional operation would be more favourable.

As it can be stated in Figure 1, modular strategies achieve additional operational leverage, thanks to the possibility of increasing capacity through a convoy extension, in addition to the classic reduction in headways. This strength extends their feasible demand domains to higher levels through an increase in the number of pods per convoy. This scalability has a counterpart in their cost. Modular solutions are more expensive in terms of unit operating costs.

In the direct comparison of technologies for a conventional operation (S0, S1), the modular technology is especially competent for very low demands, up to 300 passengers per hour in both directions. Below this demand threshold, S1 outperforms the system efficiency due to the lowest vehicle capacity and unit cost (as a 12-seat minibus fleet).

For a demand higher than 600 pax/h, where the potential demand domain of minibuses ends, Strategy S2 is optimal due to the increased frequency in the branches and the optimization of the fleet. This tendency is only maintained until we reach 1050 pax/h. When this threshold is exceeded, the bifurcation strategy S2 competes in terms of total system cost with a conventional strategy with standard buses up to 1500 pax/h demands.

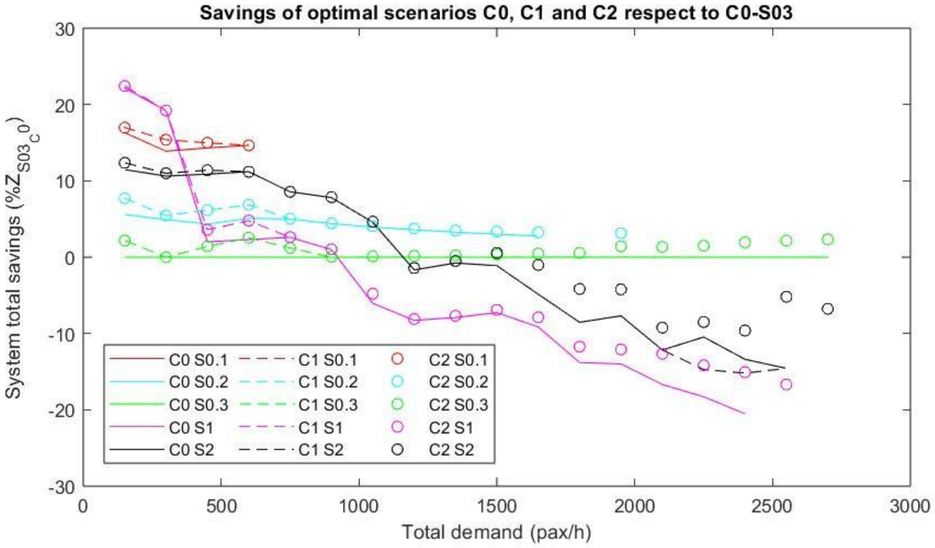

Figure 1 - Savings in the optimal scenarios with regard to standard buses reference cases.

Figure 1 also shows the effects of control strategies on savings averages. We can notice a relatively mild impact of route time coordination on branches (C1), which exists only for low demands where, therefore, the optimal intervals can be greater. On the other hand, the combination of branch-to-branch time coordination measures and active control measures has a significant impact that increases as demand levels rise. These measures are capable of significantly reducing system costs through two effects: improving regularity and, consequently, optimising occupancy. In addition, active regularity control is capable of increasing acceptable demand domains for all types of strategies and vehicle technology, but clearly a more noticeable effect is observed in high demands.

In conclusion, modular solutions allow us to, first of all, better adapt supply to demand along a corridor, in comparison to a conventional operation (S0 or S1). Secondly, these solutions are highly adaptable to find solutions both beneficial for users and operators in terms of perceived travel times and agency costs without highly impacting user experience and accessibility.

Each technology is capable of operating in an acceptable demand domain, defined by the limits associated with the minimum headway and capacity constraint. Conventional bus technologies usually achieve the lowest system cost by deploying low-capacity vehicles with an economic acquisition cost. The lower cost of the system for small vehicles is a consequence of the vehicle capacity adaptability (vehicles travel with fewer empty seats). Nevertheless, the feasibility of the low-capacity vehicles is only limited to narrower demand domains. The potential coupling and decoupling movements increase the bus route resilience, providing effective services in real situations, when the demand rates may vary significantly over the whole day.

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