Efficiency of Semi-Autonomous Platooning Vehicles in High-Capacity Bus Services

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Abstract. We analyze the efficiency of semi-autonomous platooning vehicles as an alternative to conventional vehicles in bus and BRT (bus rapid transit) systems. Four each service type, optimal bus size, service headway and platoon length are obtained by minimizing total generalized cost, which includes passengers' and the service provider's costs. Results show that as the demand level increases, semi-autonomous vehicles can be introduced to enable a better service in both traditional bus and BRT systems. The benefits of semi-autonomous buses become more significant as the capacity upper bound decreases.

Keywords: semi-autonomous vehicle, platooning, public transport, BRT

1 Introduction

Several studies investigate the possibility of using fully (Level-5) autonomous vehicles as a supplement to current public transport system to serve personalized travel requests (e.g., autonomous taxis and autonomous on-demand bus services with flexible routes) [4,6]. However, it is impractical to serve large demands with small vehicle capacities without fixed routes [8]. Therefore, some studies also consider replacing conventional buses with autonomous buses [3].

For high-demand scenarios, bus rapid transit (BRT) systems can deliver passengers efficiently on segregated roads with corresponding infrastructure. BRT can become a competitive public transport mode unless the demand is very low and sparsely distributed. Compared with traditional bus transit (in mixed traffic), BRT can avoid congestion to a large extent [7] .

Since fully autonomous buses are not yet ready to be implemented in practice due to safety concerns and low driving speed, this paper considers the adoption of semi-autonomous (Level-4 automation) buses as a more ready solution. Unlike fully autonomous buses, semi-autonomous buses need to operate as platoons[1] without drivers in the follower vehicles but with a driver in the leading vehicle.

[1] In this context, a platoon is a string of vehicles which drive closely to each other, with vehicle-to-vehicle communication and adaptive cruise control (ACC) or cooperative adaptive cruise control (CACC) technologies to maintain safety with short inter-vehicle distance. The number of vehicles contained in a platoon is called *platoon length*.

By platooning, the labor cost is reduced, and the platoon capacity can adjust to demand without introducing significant operating cost fluctuations.

To compare the performance of semi-autonomous buses with conventional buses, we formulate the operating problem as a constrained optimization problem and solve it analytically. Numerical results are provided, with sensitivity analysis regarding different demand levels and capacity upper bounds.

2 Problem formulation

Consider a corridor of length l where the hourly directional demand q is uniformly distributed along the line. The directional hourly demand at position x is $2q(lx - x^2)/l^2$. The maximum demand, $q/2$, appears at $l/2$.

The problem is to minimize the generalized cost C_{tot}, which is the sum of passengers' cost and the service provider's cost, by optimizing bus size s, platoon length N and service headway h. The passengers' cost includes access time cost C_{access}, waiting cost C_{wait} and riding cost C_{ride}, while the service provider's cost is composed of operating cost C_{oper} and capital cost C_{cptl}.

There are two types of buses, namely conventional buses ($i = \text{conv}$) and semi-autonomous buses ($i = \text{sa}$), which can be used in either traditional bus transit ($j = \text{bus}$) or BRT systems ($j = \text{BRT}$). The difference between traditional bus transit and BRT lies in the driving speed, stop spacing, and capital cost (mainly land cost and infrastructure cost). Assuming that the bus fleet is homogeneous, there are four possible combinations (i, j) of services in total.

2.1 Cost components

Access cost Given the distance between two consecutive bus stops d^j, the walking distance on average is $d^j/2$ for each user. The hourly access time cost for all users is:

$$C^j_{\text{access}} = c_{\text{access}} \frac{d^j}{2v_{\text{walk}}} 2q, \tag{1}$$

where c_{access} is the value of access time and v_{walk} is the walking speed.

Waiting cost Assuming passengers arrive randomly to the stop, the average waiting time is half of the service headway h. Therefore, the hourly waiting cost is

$$C_{\text{wait}} = c_{\text{wait}} h q, \tag{2}$$

where c_{wait} is the value of waiting time.

Riding cost The value of in-vehicle time is modeled as a linear function of the occupancy rate ϕ, $c_{\text{iv}}(\phi) = c_{\text{ride}} + c_{\text{dcf}}\phi$, where c_{dcf} measures the discomfort caused by crowding [5].

Integrating over the demand distribution along the line, the total riding cost is

$$C^j_{\text{ride}} = \frac{2ql}{v^j}\left(\frac{c_{\text{ride}}}{3} + \frac{2}{15}\frac{qhc_{\text{dcf}}}{Ns}\right), \tag{3}$$

where Ns is the capacity of the bus platoon, and v^j is the driving speed.

Operating cost Vehicles are operated jointly in a bus platoon of $N \geq 1$ vehicles. To serve the demand with conventional buses, the hourly operating cost per vehicle is $c_{\text{oper}} + b_{\text{oper}}s$, where c_{oper} and b_{oper} are the fixed operating cost and marginal operating cost with respect to vehicle size s, respectively. For semi-autonomous buses, each platoon follower will experience a reduction η^{sa} in the labor cost. In general, the hourly operating cost is

$$C^{ij}_{\text{oper}} = \frac{2l\{[1 + (N-1)(1-\eta^i)]c_{\text{oper}} + Nb_{\text{oper}}s\}}{v^j h}, \tag{4}$$

where $\eta^{\text{conv}} = 0$.

Capital cost The capital cost includes infrastructure, land and rolling stock cost. Since BRT requires segregated lanes to ensure higher vehicle diving speed than traditional bus transit, we assume a fixed capital cost term c_0^{BRT} to capture the extra infrastructure and land needed by BRT. For conventional buses, the hourly capital cost per vehicle is $c_{\text{cptl}} + b_{\text{cptl}}s$, where c_{cptl} and b_{cptl} are the fixed capital cost and marginal capital cost with respect to vehicle size s, respectively. For semi-autonomous vehicles, there is an additional fixed capital cost β^{sa}. The hourly capital cost is:

$$C^{ij}_{\text{cptl}} = c_0^j + \frac{2lN[(1+\beta^i)c_{\text{cptl}} + b_{\text{cptl}}s]}{v^j h}, \tag{5}$$

where $c_0^{\text{bus}} = 0$ and $\beta^{\text{conv}} = 0$.

2.2 Generalized cost minimization

For each of the four bus service scenarios, the cost minimization problem can be formulated as

$$\min_{h,N,s} C^{ij}_{\text{tot}} = C^j_{\text{access}} + C_{\text{wait}} + C^j_{\text{ride}} + C^{ij}_{\text{oper}} + C^{ij}_{\text{cptl}} \tag{6}$$

subject to

$$2Ns - hq \geq 0, \tag{7}$$
$$s_{\text{ub}} - s \geq 0, \tag{8}$$
$$N - 1 \geq 0, \tag{9}$$

where (7) ensures that the service is able to serve the maximum load, (8) limits the bus size to its upper bound and (9) ensures that there is at least one vehicle in the bus platoon.

We can divide the analysis into eight cases based on the KKT complementarity conditions, and obtain the optimal solution in three relevant cases:

Case 1: (7) and (8) are inactive while (9) is active gives

$$N = 1,\ s = \sqrt{\frac{4qlc_{\text{dcf}}[c_{\text{oper}} + (1+\beta^i)c_{\text{cptl}}]}{15v^j c_{\text{wait}}(b_{\text{oper}} + b_{\text{cptl}})}},\ h = \sqrt{\frac{2l[c_{\text{oper}} + (1+\beta^i)c_{\text{cptl}}]}{qv^j c_{\text{wait}}}}. \tag{10}$$

Case 2: (7) and (9) are inactive and (8) is active gives

$$\begin{aligned} N &= \sqrt{\frac{4ql\eta^i c_{\text{oper}} c_{\text{dcf}}}{15c_{\text{wait}} v^j s_{\text{ub}}[(1-\eta^i)c_{\text{oper}} + (1+\beta^i)c_{\text{cptl}} + (b_{\text{oper}} + b_{\text{cptl}})s_{\text{ub}}]}}, \\ s &= s_{\text{ub}},\ h = \sqrt{\frac{2l\eta^i c_{\text{oper}}}{c_{\text{wait}} q v^j}}. \end{aligned} \tag{11}$$

Case 3: (7) is inactive and (8) and (9) are active gives

$$N = 1,\ s = s_{\text{ub}},\ h = \sqrt{\frac{30ls_{\text{ub}}[c_{\text{oper}} + (1+\beta^i)c_{\text{cptl}} + (b_{\text{oper}} + b_{\text{cptl}})s_{\text{ub}}]}{15v^j s_{\text{ub}} c_{\text{wait}} q + 4q^2 l c_{\text{dcf}}}}. \tag{12}$$

3 Numerical analysis

Studies show that the in-vehicle time cost increases by 50% if the bus is full [2]. Therefore, we use $c_{\text{dcf}} = c_{\text{ride}}/2$. Other parameters[2] are from [3,1,7]: $\beta^{\text{sa}} = 0.2$, $b_{\text{oper}} = 0.75$ SEK/hour/vehicle, $b_{\text{cptl}} = 1.01$ SEK/hour/vehicle, $c_0 = 60824$ SEK/hour, $c_{\text{access}} = 66.1$ SEK/hour, $c_{\text{wait}} = 79.35$ SEK/hour, $c_{\text{ride}} = 56.28$ SEK/hour, $c_{\text{dcf}} = 28.14$ SEK/hour, $c_{\text{oper}} = 334.6$ SEK/hour/vehicle, $c_{\text{cptl}} = 14.24$ SEK/hour/vehicle, $d^{\text{BRT}} = 0.8$ km, $d^{\text{bus}} = 0.4$ km, $l = 15$ km, $v_{\text{walk}} = 4$ km/h, $v^{\text{BRT}} = 30$ km/h, $v^{\text{bus}} = 15$ km/h.

Results with respect to different demand levels q are shown in Fig. 1. As demand increases, the optimal bus size increases until the upper bound s_{ub} is reached. The capacity of semi-autonomous bus platoons may exceed the upper vehicle size bound due to platooning (Fig. 1(b)). The headways in all four scenarios decrease as q increases (Fig. 1(c)). For low demand levels, BRT provides shorter headways than traditional bus transit, e.g., 5 min when $q = 100$ pax/hour. For high demand levels, semi-autonomous buses yield slightly longer headways (within 1 min given $q = 6000$ pax/hour) than conventional buses in both BRT and bus transit.

The occupancy rate of conventional buses increases as q increases (except when $q < 400$ pax/hour), while for semi-autonomous buses, it is fixed to 0.51

[2] Units are converted from AUD to SEK (1 AUD=6.41 SEK).

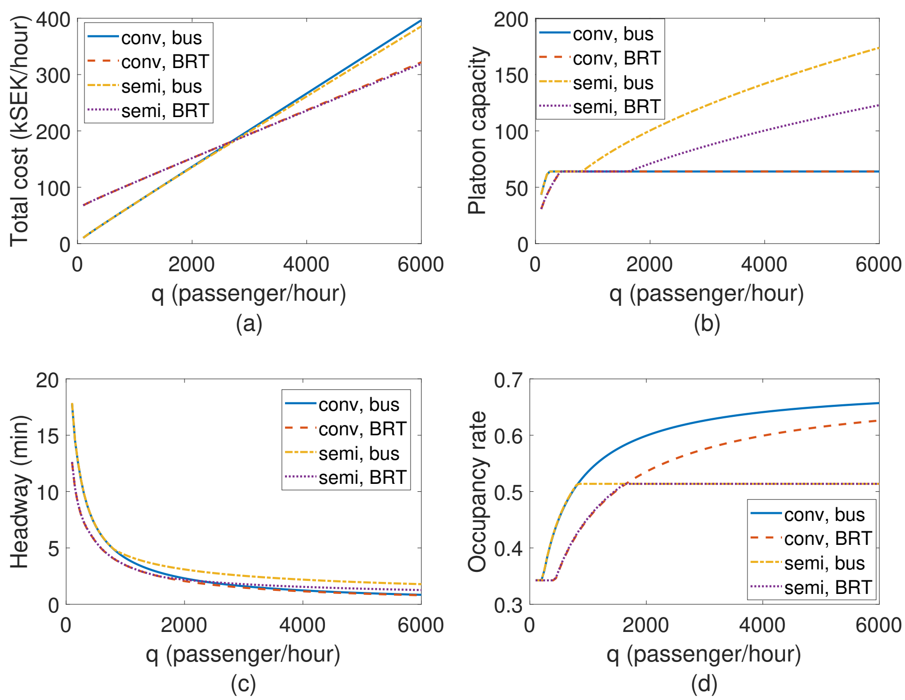

Fig. 1: Results with respect to different demand levels, $s_{\mathrm{ub}} = 64$ pax.

beyond 850 and 1650 pax/hour, for bus and BRT, respectively (Fig. 1(d)). This indicates that semi-autonomous buses may offer a better riding experience when q is high. The total cost savings by using semi-autonomous bus can be up to 10.8 kSEK/hour in bus transit and 2.8 kSEK/hour in BRT ($q = 6000$ pax/hour). Semi-autonomous buses reduce both passengers' costs and the service provider's costs. However, semi-autonomous buses start to lose advantage when s_{ub} becomes larger (see Fig. 2). For example, given $q = 4000$ pax/hour, semi-autonomous buses in BRT can save 2.0 kSEK/hour when $s_{\mathrm{ub}} = 50$, but are 51.2 SEK/hour more expensive when $s_{\mathrm{ub}} = 100$.

4 Conclusion

The study shows that semi-autonomous bus can be implemented to serve medium and high demands, in traditional bus transit and BRT respectively. The optimal service mode to use is dependent on the specific demand level and the bus capacity upper bound. If large buses are not allowed in the transit network, semi-autonomous buses can be competitive. Conventional buses will eventually fail to serve very high demand since solely adjusting service headways will lead to

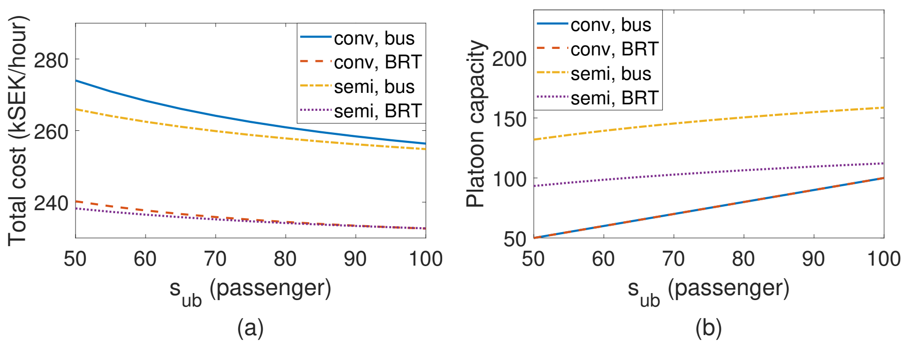

Fig. 2: Results with respect to different upper bound s_{ub}, $q = 4000$ pax/hour.

unachievable short headways and extremely large fleet size, which creates heavy congestion and other externalities.

Acknowledgement

The support from China Scholarship Council is gratefully acknowledged.

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