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Optimizing the integration of express bus services with micro-mobility: a case study

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Abstract

Considering a bus line, the problem of defining an express bus line consists in determining which stops of the original line will belong to the express line and the frequency of the new line. The objective of the optimization is a trade-off between the advantages of the passengers that benefit from the new service and the disadvantages of the passengers that cannot exploit the improved service. The advantages and disadvantages are measured in terms of total travel and waiting time.

In this work we consider the introduction of micro-mobility, such as shared electric scooters or bikes, to mitigate the disadvantages and to increase the ridership of the express line. The contribution of the paper is twofold. On the one hand, we propose an improved mathematical model for defining an express bus line. The model is based on a longest path problem on an acyclic graph; thus, it is very efficient with respect to the other models in the literature. On the other hand, we consider the real case of two urban bus lines in the city of Milan and present the results computed on real passenger data. The results provide evidence that implementing an express line can improve total travel and waiting time. The time wasted by switching lines is in general higher than the time gained by the passengers. However, this can be compensated by the introduction of micro-mobility means of transportation.

Keywords: Express bus lines; micro-mobility; minimum travel time; longest path model.

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1. Introduction

Bus lines are a flexible and widely used form of public transit in several cities. However, bus services may fail to attract customers due to long in-vehicle travel times caused by frequent stops. To address this issue, express lines are commonly established, by skipping some stations of a line. This way, passengers can take advantage of faster and more efficient service, with reduced delays caused by unnecessary stops. In this paper, we address the problem of optimizing one such express line. To this end, given a line we consider the problem of determining which stops of the original line to skip, and the frequency of the express line, with the objective of minimizing the overall passenger travel time. In addition, we will consider the impact of micro-mobility to mitigate the disadvantage of passengers affected by the stop skipping.

Consider a bus line operating on a set of stops S, ordered from 1 to $|S|$. The line is operated at a constant frequency over a period of T minutes (e.g., AM peak or PM peak). Moreover, we assume that the fleet of buses is homogeneous. The demand of transportation is known and given by p^k, for each pair of stops $k \in K$:

$$K = \{k = (s^k, d^k) \mid s^k, d^k \in S,\ s^k < d^k\}$$

The time saving for skipping the stops between i and j is denoted by c_{ij}. If the two stops i and j are adjacent, that is $j = i + 1$, then $c_{ij} = 0$. We assume that the total number of buses operating the service is constant and given by F.

The decisions concern the set of stops defining the express line (EL), the number of buses devoted to the new line and, therefore, the number of buses that are left for the traditional line (TL). The objective is to maximize the difference between the saved time by the passengers of the EL and the increased waiting time experienced by the passengers. The first operating EL line is attributed to the Chicago Transit Authority (CTA), which implemented the first skip-stop system in 1948, Garfield (2021). Initially the experiment was implemented on a single line, but it was later deployed across the whole system due to its success. This skip-stop mechanism, where some lightly used stops are removed, is the core of modern EL. Usually it combines an EL that operates skip-stop and a full-stop local service. Different solutions have been proposed, which we briefly discuss in the following.

Ulusoy et al. (2010) introduces a model that minimizes the total cost subject to operational constraints. The structure of the system is composed of an all-stop service, a short-turn service and an EL line. Stops allocation and commuters demand are given and eligible turn-back points for short-turn service patterns are assumed to be predetermined by the supplier. The costs take into account the user and the supplier costs, including the wait, transfer, and in-vehicle costs, as well as the product of travel time between stops, vehicle frequency, and hourly operating cost. In this work, the decisions are related to the frequencies of integrated service patterns. The mixed-integer nonlinear total cost function is minimized subject to frequency conservation, capacity, and fleet size constraints. The problem is solved by exhaustive search. The problem's complexity increases with the number of stops and, thus, the computation of the potential patterns has limitations.

The method proposed by Leiva et al. (2010) minimizes the social costs of a bus corridor, related with wait and travel times, as well as the costs facing the operator. The demand matrix is assumed to be given. Passengers arrive at the stop at a given average rate and their assignment to the network reflects the minimum transit itineraries defined by the set of services that minimizes expected travel time for the considered segment. Two types of costs are considered: operator costs, involving fixed costs, variable costs dependent on distance, and variable costs dependent on time; and user costs, involving access time, waiting time, in-vehicle travel time and transfer time. Capacity constraints are included in the model. The problem is formulated as a nonlinear integer model. To simplify it, a routine is designed to select an overcrowded line and to solve the model again after including a constraint on the minimal increment of the frequency.

Chiraphadhanakul and Barnhart (2013) look for an integrated EL service to operate in conjunction with an existing local bus service. The goal is to reassign the buses, as opposed to organizing additional trips to supply the EL service, while avoiding extra costs from the organization and provision of new buses. The system is characterized by trade-offs between the in-vehicle time reduction of the EL users and the out-of-vehicle increased waiting for the traditional line users, caused by the new reduced frequency of the local service. In addition, the work models passengers' behavior in response to the new EL line. Passengers that are served by both services can have different reactions and board either bus in relation to the waiting time and subsequent in-vehicle time. The goal is to develop a tractable optimization

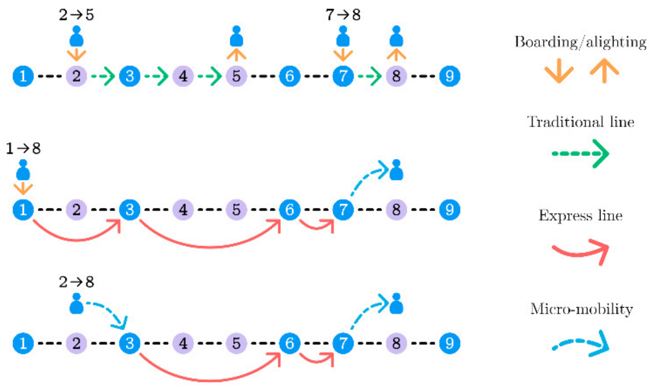


Fig. 1. Example of passenger trajectories using the express line and micro-mobility.

model, whose solution approach can be applied to real-world systems to solve the incremental bus service design problem. This problem was studied in Chiraphadhanakul and Barnhart (2013), where an integer nonlinear programming model and a heuristic are proposed. One of the main outcomes of that work is that a passenger boarding or alighting in a stop not served by the EL has no advantage in connecting with the EL in an intermediate stop, due to the combination of walking or waiting times.

Chen et al. (2015) presents an integer nonlinear model for the EL bus service including capacity constraint and considering stochastic travel time between stops. The problem was solved by means of an artificial bee colony meta-heuristic algorithm combined with a Monte Carlo method.

Zhang et al. (2021) develops an agent-based simulation model for the optimization of a dynamic stop-skipping and a real-time holding scheme, while considering stochastic travel times and passenger arrival rates. This model minimizes passenger travel costs and headway irregularity for stochastic travel times and passenger arrivals. The model is tested under different scenarios, following real-time stop-skipping and holding or real-time stop-skipping strategies. Dong et al. (2020) proposes a model that integrates train stop plans and timetables under time-dependent passenger demand. The problem is modelled as a mixed-integer nonlinear programming problem that optimizes passenger travel efficiency, based on the total waiting time at stops, the delay time for trains due to a train stop, and the minimization of the total train running time. The problem is solved by an extended adaptive large-scale neighborhood search algorithm.

More recently, Sadrani et al. (2023) proposed a mixed-integer nonlinear mathematical model for EL service to minimize user and operator costs, while considering passenger flow, vehicle and passenger travel time, in-vehicle crowding, and the value of passengers' waiting time. This work includes the waiting time of the passengers failing to board and limits the number of non-stop consecutive buses at a stop. A genetic algorithm is designed to solve the problem. Finally, a survey on robustness in public transport can be found in Ge et al. (2022).

Our contribution considers the setting introduced in Chiraphadhanakul and Barnhart (2013) and it includes the possibility for passengers to use micro-mobility (like shared electric scooters or shared bikes) to move between TL stops and EL ones to take advantage of the fast service. We assume that passengers will take advantage of the EL whenever possible, even in the case where the origin or the destination stops of the passenger are not served by the EL. When this is the case, passengers will use available micro-mobility services to make the first and the last leg of their journey. Conversely, in the case where the EL may not be used by the passenger, the passengers will use the regular bus service. Note that this corresponds to the case where less than two express line stops lie between the origin and the destination stops of the passenger.

In Figure 1 we show examples of possible passenger trajectories on a 9-stop line, with an EL serving stops 1, 3, 6, 7, and 9. As we can see, passengers originating from stop 2 and heading to stop 5 will make use of the TL and will therefore board in stop 2 without making use of micro-mobility. Similarly, passengers originating from stop 7 and heading to stop 8 will also make use of the TL. Conversely, passengers originating from stop 1 and heading to stop 8

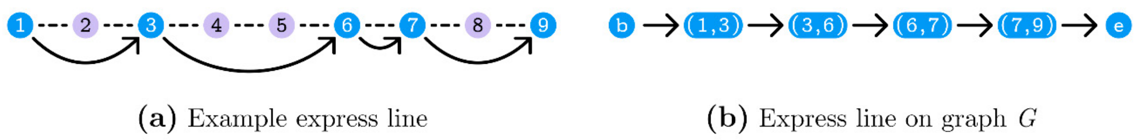


Fig. 2. Example of an express line.

can make use of the EL. Since stop 8 is not an EL stop, the passengers will alight from the EL at stop 7 and then use micro-mobility to head directly to their destination. Lastly, passengers originating from stop 2 and heading to station 8 can use micro-mobility to head to stop 3, where they will onboard the EL until reaching stop 7. From that point on they can head on to stop 8 using micro-mobility again.

The main methodological contribution is the introduction of a new model based on the computation of a longest path on an acyclic graph to solve the problem of selecting the EL bus stops. We apply the model to two urban lines in Milan. The remainder of the paper is organized into three additional sections. Section 2 introduces the longest path problem model that enables the selection of bus stops along a TL. Section 3 presents the results of the computational experiments carried out for two types of bus lines within the city of Milan. Finally, concluding remarks and future research directions are drawn in Section 4.

2. Graph Model

We consider the problem of defining an express bus service operating alongside a TL. Given the characteristics of the TL: travel times, distance between stations, demand, and number of buses, the problem consists of identifying the stops served by the EL and the number of buses allocated to it. We make the following assumptions: the origin-destination demand is given and fixed; the random arrival of the passengers at their starting stops is maintained at a constant rate over the time period under consideration; the buses have no capacity constraints; passengers are always assigned to the limited-stop service if the option is available along their path, if necessary they will use micro-mobility services to complete the missing legs of the journey; passengers cannot transfer between the TL and the EL; the micro-mobility system offers an unlimited number of electrical scooters ready to use at each stop.

Let us consider a bus line S connecting stop 1 to stop $|S|$. Given F buses assigned to line S, the computation of the optimal selection of stops for the EL considers a given number f of buses allocated to the EL and, therefore, $F - f$ buses left to the TL. To determine the selection of EL stops that minimizes the overall travel time, we construct a suitable directed graph $G = (N, A)$. We formulate the problem of defining an express bus service operating alongside a TL as a longest path problem between two particular nodes in graph G.

The nodes in $N' = \{(i,j): i,j \in S \wedge i < j\}$ represent pairs of consecutive stops in the EL. In addition to those nodes, we consider two dummy nodes, b and e, representing the beginning and the end of the line, respectively. Thus,

$$N = N' \cup \{b, e\}.$$

The arc set A contains all possible pairs of nodes $\big((i,j),(q,r)\big)$ such that $j = q$, thus corresponding to all possible triplets of stops $(i,j,r), i < j < r$. Moreover, A also includes the arcs connecting the dummy node b to the pairs $(1,j) \in N'$, as well as the arcs connecting the pairs $(i,|S|) \in N'$ to the dummy node e. Thus,

$$A = \{\big((i,j),(j,r)\big): (i,j),(j,r) \in N'\} \cup \{\big(b,(1,j)\big): (1,j) \in N'\} \cup \{\big((i,|S|),e\big): (i,|S|) \in N'\}.$$

Then, any path from b to e in G corresponds to a possible EL. In Figure 2 we present an example EL on a 9-stops bus line, as well as the corresponding path in G. The TL is represented by the dashed lines, whereas the solid lines show the consecutive stops selected in the EL. In this case the selected stops are 1, 3, 6, 7 and 9.

Given an arc $\big((i,j),(j,r)\big) \in A$, its arc length δ_{ijr} accounts for the contribution to the overall time saving due to the selection of the consecutive stops i, j and r in the EL. To compute this value we consider several terms, to account for the impact of the selected stops on the overall travel time of the passengers, depending on how they relate to stops

i, j and r. Any passenger boarding in i or before and alighting at j or after will benefit from the time saved by EL by skipping the stops between i and j. A similar reasoning is applied to the segment defined by the other two consecutive stops of the triplet j and r. The second term to be accounted for relates to the passengers that will use micro-mobility because of the consecutive stops i, j and r. Specifically, any passenger originating between i and j excluded and heading to r or after will make use of the EL starting from stop j, and therefore will suffer a time-loss due to using micro-mobility to access EL at j. Similarly, originating from stop i or before, and heading to stops between j and r excluded, will suffer a time-loss due to using micro-mobility from stop j to their destination. The third term relates to the waiting time of passengers originating from stops i (included) to j (excluded) to board a bus. Of those passengers, all passengers that are heading to r or after will make use of EL, and therefore will experience an expected waiting time of half of the headway of EL. Similarly, passengers originating at i and heading to j will also make use of EL. All other passengers will make use of TL and will therefore experience an expected waiting time of half of the headway of TL. Note that the waiting time of the other passengers is accounted for by other arcs of G. Formally, the value of δ_{ijr} is given by:

$$\delta_{ijr} = \delta^1_{ijr} - \delta^2_{ijr} - \delta^3_{ijr}$$

where

$$\delta^1_{ijr} = \sum_{k\in K,\, s^k\leq i,\, d^k\geq j} p^k c_{ij} + \sum_{k\in K,\, i<s^k\leq j,\, d^k\geq r} p^k c_{jr}$$

$$\delta^2_{ijr} = \sum_{k\in K,\, i<s^k<j,\, d^k\geq r} p^k \Delta_{s^k j} + \sum_{k\in K,\, s^k\leq i,\, j<d^k<r} p^k \Delta_{jd^k}$$

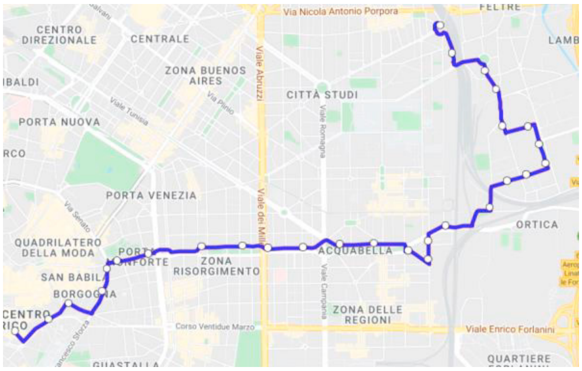
$$\delta^3_{ijr} = \sum_{k\in K,\, i<s^k<j,\, d^k\geq r} p^k \frac{1}{2}\left(\frac{T}{f} - \frac{T}{F}\right) + \sum_{k\in K,\, i<s^k<r\ j<d^k<r} p^k \frac{1}{2}\left(\frac{T}{F-f} - \frac{T}{F}\right)$$

Here Δ_{hl} is the time needed to go from stop h to stop l by micro-mobility means and T is the duration of the TL trip from 1 to S. The first component, δ^1_{ijr}, accounts for the time saving achieved by passengers that make use of EL between stops i and j or between j and r. The second component, δ^2_{ijr}, considers the loss of time due to the use of micro-mobility by passengers that board EL at stop j or by passengers that alight from EL at stop j. Lastly, δ^3_{ijr} considers the average waiting times difference due to the proposed solution. Passengers making use of EL, wait on average $\frac{T}{2f}$, whereas passengers making use of TL wait on average $\frac{T}{2(F-f)}$. Those waiting times are compared with the waiting time of the passengers if no EL were to be used, and thus all buses could be assigned to the TL. In this case, all passengers would wait on average $\frac{T}{2F}$. Note that the computation of δ_{ijr} must be adjusted in case $i = b$ or $j = e$, that is, if the arc is the first or the last triplet of the path. We omit the details due to space limitations.

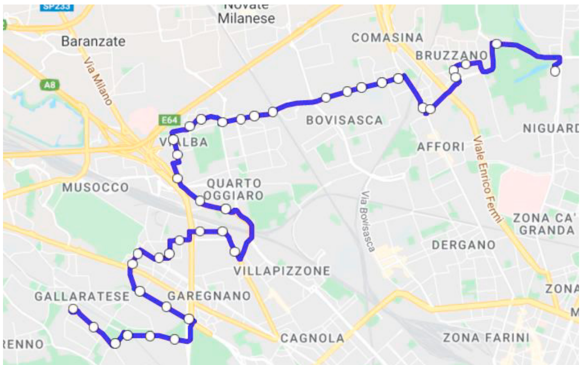
The longest path from b to e in G provides the EL stop selection yielding the maximum time saving. It is worth noting that the graph G is acyclic, therefore the computation of the longest path from b to e requires linear time in the number of arcs, so the EL can be found in time of $O(|S|^3)$.

3. Computational Results

We implemented the proposed model in Python (2020) and used the Python-MIP package Santos and Toffolo (2020) to solve the minimum cost flow problem used in the formulation. The model was tested on instances based on two real-world bus lines from the Milan bus network: one line operating in the city center (line 54), and one line operating in the city suburbs (line 40). Line 54 is characterized by a greater demand flow, with highly concentrated demand, and noticeable differences between peak and off-peak hours. Line 40 is characterized by lower demand, a larger number of stops and higher average distance between stops, and thus, lower overall bus frequency. We report in Figure 3 the maps of the trajectories of these two lines. The line parameters, including travel times, bus frequency and demand data for the two lines, were provided by the mobility agency of Milan (AMAT), based on direct demand measurements and simulation. The demand flow is obtained from real data measurements and a traffic simulator operated by AMAT. The analyzed data refer to the peak hours 7–9 a.m., the simulation is performed partially with the tool OpenStreetMap, available online. The passengers are assigned to a stop by using a probabilistic model which uses information such as population density in a determined public area, categories of the buildings present in the area and number of people related to them. The analysis is performed by layers of a selected zone or per house number. Its accuracy is greater in the center of the city, because of the larger volume of data that can be retrieved, compared to the less populated areas. In Figure 4 we show the histograms of the boarding and alighting distributions across the different stops of the two lines. Travel times for micro-mobility users were computed based on Google maps (2021).

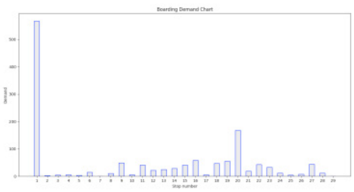


Route of line 54.

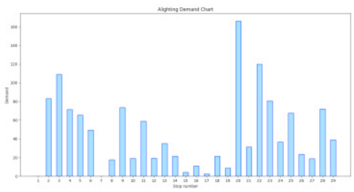


Route of line 40.

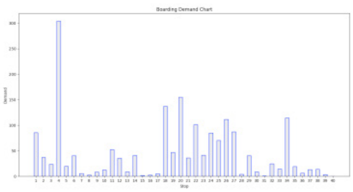
Fig. 3. The two routes retrieved using the "find lines" tool.



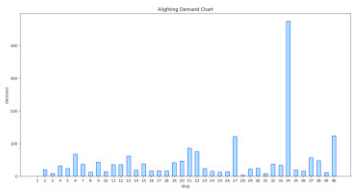
Line 54 boarding demand chart



Line 54 alighting demand chart



Line 40 boarding demand chart



Line 40 alighting demand chart

Fig. 4. The demand flow of the analyzed lines simulated by AMAT (2022).

To evaluate the impact of the proposed EL combined with micro-mobility, we conducted several experiments, varying the number of buses assigned to the express line, f, while keeping the total number of buses operating, F, constant. Table 1 shows the results for line 54, and Table 2 shows the results for line 40. For each evaluated configuration, we report the overall saved time, as well as the average waiting time for the EL passengers and for the TL passengers. The first row refers to the TL without the presence of the EL. We observe that the EL requires a minimum service frequency to provide any benefit to the passengers. Indeed, when the frequency of the EL is too low, the overall waiting time of the passengers increases. At high frequencies, we observe significant reductions in the total passenger waiting time. We note that, when the frequency of the EL is increased, the TL passengers experience a corresponding increase in their average waiting time. This can lead to very high waiting times for TL passengers, therefore, despite a decrease in the average passenger waiting time, maximizing the frequency of the EL is not necessarily desirable.

Table 1. Comparison between TL and EL with micro-mobility system integration and route redefinition (city center line).

Line 54				
Frequency		Average saved time (min)	Average waiting time (min)	
f	$F - f$		EL	TL
0	8	N.A.	N.A.	3.32
1	7	-3.51	11.54	3.87
2	6	-0.44	7.38	4.64
3	5	1.35	5.54	5.80
4	4	2.46	4.46	7.74
5	3	3.44	3.72	11.61
6	2	4.14	3.21	23.22

Table 2. Comparison between TL and EL with micro-mobility system integration and route redefinition (city suburbs line).

Line 40				
Frequency		Average saved time (min)	Average waiting time (min)	
f	$F - f$		EL	TL
0	6	N.A.	N.A.	4.77
1	5	-0.15	12.01	5.96
2	4	1.32	8.01	7.95
3	3	4.31	3.97	11.93
4	2	4.14	3.89	23.85

In Figures 5 and 6 we report a visualization of the stops selected by the express services at various frequencies. We observe that in line 54, where the demand is more evenly distributed throughout the line, the model tends to select evenly spaced stops for the EL. Instead, for line 40, where demand is less homogeneous, the express service skips very large portions of the line. In this case it can be worth introducing explicit constraints that limit the number of consecutive skipped stops. This type of constraint is easily implemented in the graph model, since it is sufficient to avoid the introduction of triplets with large gaps between stops.

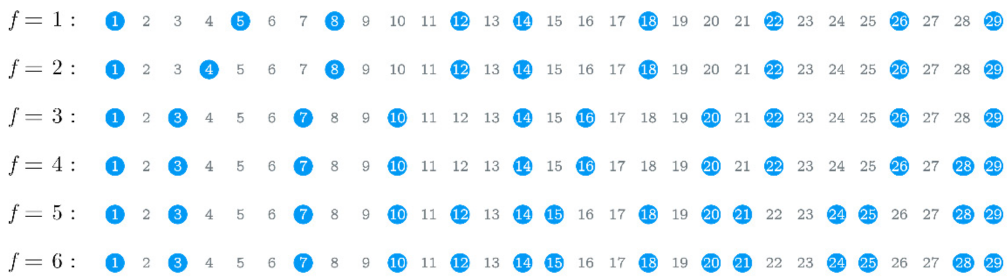


Fig. 5. The stops selected at each frequency of buses assigned to the express line for line 54.

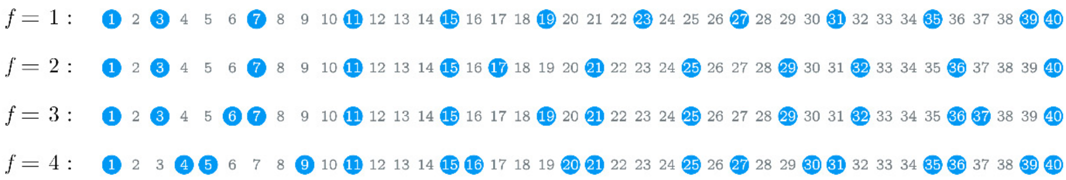


Fig. 6. The stops selected at each frequency of buses assigned to the express line for line 40.

4. Conclusions

In this paper, we formulate the problem of optimizing the stops of an express bus line in conjunction with micro-mobility services with the objective of minimizing the passengers' waiting time. We formulate the problem as a longest path problem on an appropriately constructed graph, which can be easily solved in polynomial time using out-of-the box tools, without the need for specialized heuristics. Through our computational experiments, we observe that the proposed express service can lead to a significant decrease in the average waiting time of the passengers using the line, both in urban and sub-urban lines. In future work, we intend to extend the model presented in the paper to account for multiple bus routes. Additionally, a more detailed modeling of the passenger dynamics and bus capacities could also constitute an interesting future research direction.

Acknowledgements

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