# Principles for setting single line and multiline control based on network characteristics

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## Abstract

Public Transport networks often include one or more sets of common consecutive stops between different lines. In such networks, both single line and multiline control can in principle be applied. In this study, we investigate the effect of both the size of different segments of the network and the characteristics of demand distribution on the performances of single line and multiline control. After introducing the key elements that characterize networks with overlapping segments, two sets of scenarios (a stop set size and a demand based scenario) are conducted on different network configurations, for both control schemes. Results show that the choice between the two control alternatives is more sensitive to demand distribution than to the lines' topology. Passenger groups traversing different stop sets are the most consequential in terms of chosen control strategy's optimality. The results suggest applying multiline shared transit corridor control for corridors given that those stops account for at least 50% of the total number of boarding passengers.

**Keywords:** Public Transport; Holding Strategy; Multi line Control; Networks with shared transit corridor;

## Introduction

Public transport (PT) network design applications primarily aim at minimizing the general passenger cost for the network [1]. However, their consequences for service reliability are often overlooked. The inherent stochasticity of operations requires corrective actions in real time to restore the network's reliability.

Different control strategies can be applied depending on the nature of the transit performance disruptions [2]. A comprehensive literature review on real time transit control has been conducted by Ibarra Rojas et al [3]. Among other strategies, holding has been extensively investigated for single line control. Different holding strategies are developed, based upon either rule based criteria, e.g. to adhere to schedule [4], maintain even spaced headways [5], [6], minimize generalized passenger travel cost [7] and eliminate bunching [8], or optimization problems, to minimize total passenger costs [9]–[12]. Holding strategies may also account for interactions between transit lines via transfer synchronization [13]–[15]. Recently, holding control has been extended beyond single line level for lines with overlapping segments along their routes [16]–[18].

While past studies have focused on where to control on a given line and how many control points to be used for a single line [19] and where to synchronize based on passenger flows [20], there is lack of knowledge on where (and whether) to apply multiline control strategies. This study focuses therefore on identifying under which network characteristics (different number of branch and

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corridor stops, demand profile) an operator should use single or multiline control. Different networks with a shared transit corridor are assessed and initial conclusions are drawn.

## Network Characterization

Stops and stop sets

We define as *Switching Stops,* the stops for which the number of lines operating upstream and downstream changes. The first and the last stop, devised as terminals, are excluded from the analysis. Based on the difference between the number of lines prior and after a switching stop, two categories of switching stops can be defined.

A switching stop where the number of transit lines operating upstream is lower than the number of lines operating between the current and downstream one can be characterized as a *merging stop*¸ denoted by *m*. On the other hand, the switching stops where the number of transit lines that operates upstream is greater than the number of lines operating downstream are characterized as *diverging stops*, denoted by *s*.

Between switching stops, the sets of stops can be characterized as branches and shared transit corridors (or for simplicity corridors).

As *branch*, we characterize a set of stops that is served exclusively by one line. A branch stop set can start with a splitting stop and/or end to a merging stop. Along this stop set, single line control is recommended, as there is no interaction between lines. Coordination actions have been proven effective when multiline control is applied prior to a shared transit corridor.

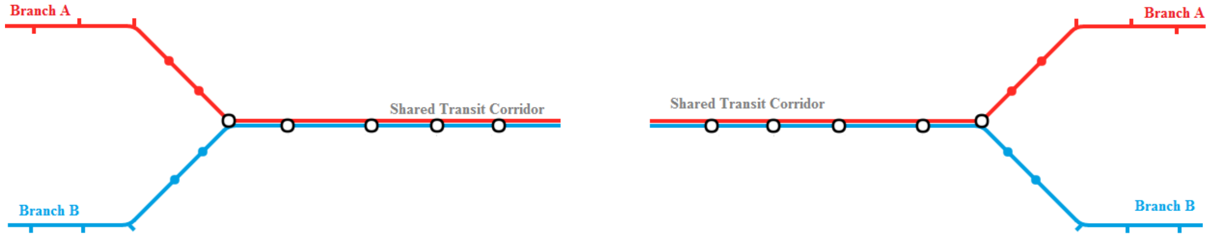
We denominate by *Shared Transit Corridor* a set of consecutive stops that is served by at least two lines. It is important to set a minimum number of consecutive stops, served by multiple lines, that can be characterized as a corridor. A shared transit corridor should also be determined based on the relative size of the overlapping part of the network compared to the overall size of the network and the branch stop sets. Additionally, a corridor can be defined based on the distribution of the demand on the network. If there is a subset of the network where the majority of the demand is generated or attracted, that stop set can be considered a corridor.

## Systematic analysis

### Scenario description

In this study we focus on understanding how the distribution of length between branches and shared corridors, as well as demand, affects the performance of real time cooperative control as opposed to individual line control. Therefore, we test different network configurations, where both schemes can be applied, under different stop set sizes and demand distributions. Based on the test results, considering regularity indicators and total passenger cost as Key Performance Indicators, we define under which conditions a stop set can be characterized as shared transit corridor and is recommended to be treated as one control wise.

We compare two network configurations with overlapping segments. The first network, dubbed *merging fork*, consists of two lines serving different stop sets and then merging to a shared transit corridor. The second network, dubbed *diverging fork*, is the inverse of the first configuration, with the lines first serving the shared stop set and then bifurcating to different branches. Schematic network representations are depicted in Figure 1.



**(a)** **(b)**

**Figure 1 Schematic representation of a merging (a) and a diverging (b) fork network**

### Merging Fork application for different numbers of stops

A first set of scenarios, comprising of different configurations of branch stops and corridor stops, is tested on the Merging Fork network. A toy network is used, composed of two lines with 30 stops each. Both lines have the same demand profile. The scenarios tested on the merging fork network are summarized in Table 1.

**Table 1 Merging Fork Scenarios**

| | **Number of Stops** | | | | |
|---|---|---|---|---|---|
| **Scenario Number** | Branch Stops | Corridor Stops | Network Stops | Share of Branch Stops (%) | Share of Corridor Stops (%) |
| **1** | 27 | 3 | 30 | 90 | 10 |
| **2** | 24 | 6 | 30 | 80 | 20 |
| **3** | 21 | 9 | 30 | 70 | 30 |
| **4** | 18 | 12 | 30 | 60 | 40 |
| **5** | 15 | 15 | 30 | 50 | 50 |
| **6** | 12 | 18 | 30 | 40 | 60 |
| **7** | 9 | 21 | 30 | 30 | 70 |
| **8** | 6 | 24 | 30 | 20 | 80 |
| **9** | 3 | 27 | 30 | 10 | 90 |

### Diverging Fork application on different demand shares between passenger groups

The second scenario set deals with different demand shares between the three passenger groups of a diverging fork network. The three passenger groups to be distinguished in this network configuration are i) the passengers travelling within the shared transit corridor, ii) passengers travelling from the shared transit corridor to a branch and iii) passengers travelling within a branch. The scenarios are tested on a real world Diverging Fork network from the city of Stockholm, Sweden. Lines 176 and 177 consist of 43 and 36 stops respectively. The common stops between lines are 24, and there are 19 remaining branch stops for line 176 and 12 branch stops for line 177. Twenty-five different demand scenarios are tested, as detailed in Table 2. Each row corresponds to a different share of passengers travelling within the branch while each column to different share of passengers travelling from corridor to branch; each cell contains the share of the total demand that travels within the corridor with the scenario ID in parenthesis. Both lines have the same demand segmentation for all scenarios.

**Table 2 Diverging Fork Scenarios**

| | | **Share of Passengers Travelling within Branch (%B)** | | | | |
|---|---|---|---|---|---|---|
| | | 5 | 10 | 15 | 20 | 25 |
| **Share of Passengers Travelling from Corridor to Branch (%CB)** | 5 | (1) 90 | (3) 85 | (6) 80 | (10) 75 | (15) 70 |
| | 10 | (2) 85 | (5) 80 | (9) 75 | (14) 70 | (19) 65 |
| | 15 | (4) 80 | (8) 75 | (13) 70 | (18) 65 | (22) 60 |
| | 20 | (7) 75 | (12) 70 | (17) 65 | (21) 60 | (24) 55 |
| | 25 | (11) 70 | (16) 65 | (20) 60 | (23) 55 | (25) 50 |

The 9 stop setting scenarios and 25 demand distribution scenarios are evaluated using the simulation tool BusMezzo, a mesoscopic transit simulator embedded on the traffic simulator Mezzo [21], [22]. BusMezzo enables the implementation of different control strategies and the evaluation of the performance of a transit network. Additionally, passengers are represented as agents, enabling the analyst to monitor and record the individual, groups-specific and network-wide passenger costs. For each scenario, 50 replications are conducted. The total execution time is about 10minutes per scenario.

## Control Strategies

Two holding based control schemes are used for the experimental scenarios. The first is a single line holding strategy introduced by Cats et al [6], [23] that aims at evening out headways and thus restores regularity by accounting for the headway from the preceding and the succeeding vehicle and limits the maximum allowed holding time to a specific share of the planned headway of the line. The second approach is a multiline holding strategy developed in Laskaris et al [18], [24]. The holding criterion developed therein restores single line headway or joint regularity based on the stop characterization (branch or corridor) and determines the holding time with explicit consideration of the passengers that will experience the control decision. Moreover, it accounts for the coordination between lines when they merge, and the transition from common to single line operation when lines diverge.

## Performance Indicators

The performance of single and multiline control is assessed using both regularity indicators and passenger cost indicators. For regularity, the coefficient of variation (CV) of headway for each line and for the shared transit corridor is given as an index of variability of the headways [25]. The passenger cost of the different passenger groups is also reported at network level. Passenger cost consists of the unweighted sum of waiting time and in-vehicle time.

# Results

## Merging Fork application for different numbers of stops

Regularity Index

The scenario set concerning different distributions for the two stop sets is conducted considering the toy network of Figure 1(a). Table 3 summarizes the results of the CV of headway for each of the lines and of the joint headway for the shared transit corridor. It is clear from the results that single line control outperforms multiline in regulating line headways. Indeed, the variability of individual line headways with multiline control almost doubles and, similarly to previous findings, one line is more penalized due to the coordination actions taken prior to the shared transit corridor [18].

**Table 3 CV of Headway of merging fork scenarios**

| Scenario | CV of Headway | | | | | |
|---|---|---|---|---|---|---|
| | Single Line Control | | | Multiline Control | | |
| | Line 1 | Line 2 | Shared Transit Corridor | Line 1 | Line 2 | Shared Transit Corridor |
| **1** | 0.18 | 0.18 | 0.58 | 0.27 | 0.27 | 0.57 |
| **2** | 0.17 | 0.19 | 0.61 | 0.30 | 0.27 | 0.51 |
| **3** | 0.17 | 0.18 | 0.59 | 0.28 | 0.30 | 0.48 |
| **4** | 0.17 | 0.18 | 0.55 | 0.30 | 0.29 | 0.45 |
| **5** | 0.18 | 0.18 | 0.62 | 0.31 | 0.29 | 0.44 |
| **6** | 0.17 | 0.17 | 0.66 | 0.33 | 0.30 | 0.43 |
| **7** | 0.17 | 0.17 | 0.64 | 0.31 | 0.30 | 0.42 |
| **8** | 0.16 | 0.17 | 0.64 | 0.32 | 0.30 | 0.42 |
| **9** | 0.17 | 0.17 | 0.59 | 0.30 | 0.30 | 0.41 |

On the other hand, multiline control is superior in regulating the joint headway between lines. As depicted in Figure 2, the coefficient of variation of joint headway decreases significantly as the length of shared corridor increases. The overlapping segment can be treated as a shared transit corridor stop set if long enough, so that an operator can aim at regulating the joint headway. In any other case, single line control should be preferred.

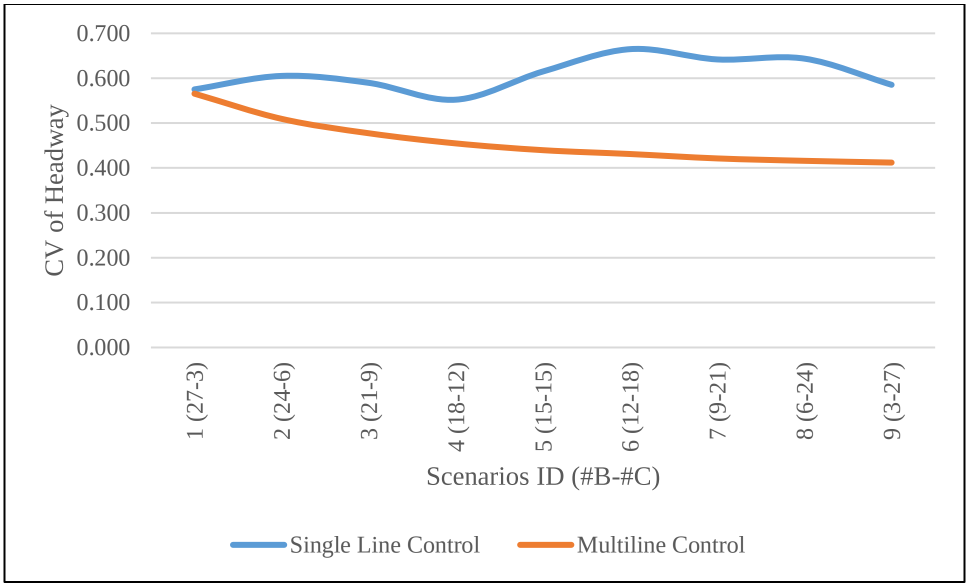


**Figure 2 CV of Joint Headway for the merging fork scenarios**

## Passenger Cost

The passenger costs over the different scenarios clarifies what should be the minimum size of the corridor set. Figure 3 illustrates the difference in passenger costs, compared to no control, at a network level. Both control regimes exhibit similar performances for the scenarios with longer branch stop sets (Scenarios 1-4).

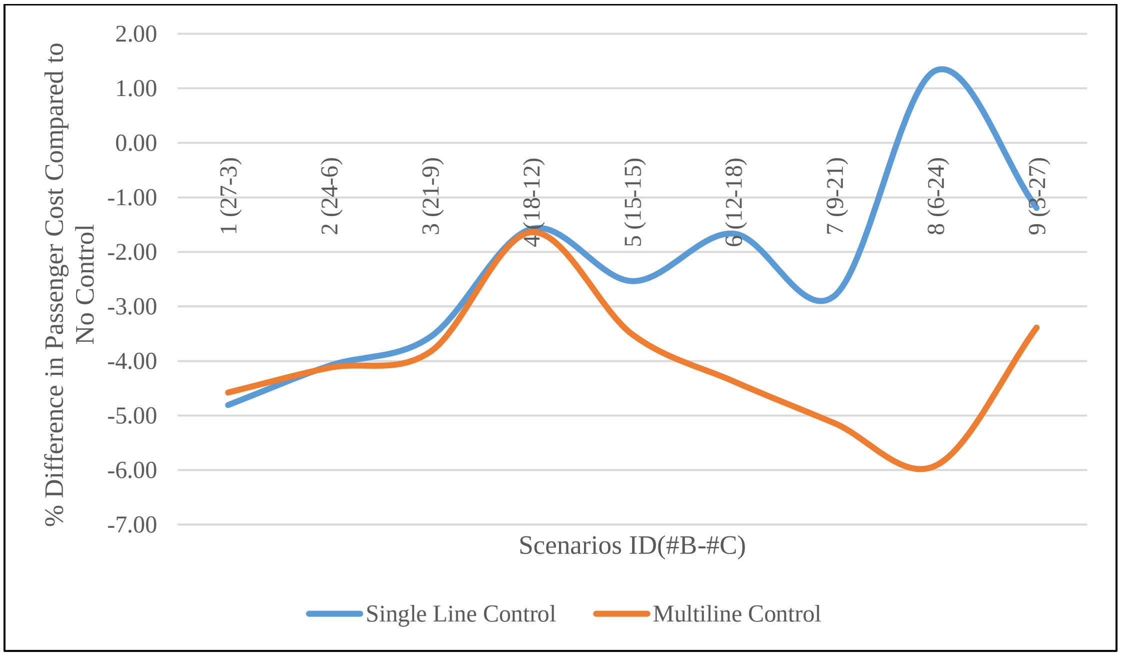


**Figure 3 Difference between Multiline and Single Line Passenger Cost and No Control Scenario**

However, for even sized branch and corridor stop sets (Scenario 5) and longer corridor stops sets (Scenarios 6-9), a significant difference is observed in favor of multiline control.

Combining the results obtained, we can deduce that an overlapping segment should be characterized as shared transit corridor where multiline control can be successfully applied when the number of corridor stops is half or more that of the total stops of the route of each line.

### Diverging Fork application on different demand shares between passenger groups

Regularity Index

The demand scenario results for the coefficient of variation are shown in Table 4.

**Table 4 CV of Headway of diverging fork scenarios**

| Scenario ID (%B-%CB) | CV of Headway | | | | | |
|---|---|---|---|---|---|---|
| | Single Line Control | | | Multiline Control | | |
| | Line 176 | Line 177 | Shared Transit Corridor | Line 176 | Line 177 | Shared Transit Corridor |
| 1 (5%-5%) | 0.162 | 0.194 | 0.457 | 0.180 | 0.214 | 0.362 |
| 2 (5%-10%) | 0.171 | 0.172 | 0.427 | 0.192 | 0.219 | 0.360 |
| 3 (10%-10%) | 0.171 | 0.169 | 0.446 | 0.185 | 0.194 | 0.340 |
| 4 (5%-15%) | 0.168 | 0.178 | 0.436 | 0.212 | 0.229 | 0.389 |
| 5 (10%-10%) | 0.167 | 0.182 | 0.437 | 0.183 | 0.203 | 0.345 |
| 6 (15%-5%) | 0.176 | 0.176 | 0.439 | 0.185 | 0.184 | 0.341 |
| 7 (5%-20%) | 0.173 | 0.186 | 0.435 | 0.230 | 0.241 | 0.398 |
| 8 (10%-15%) | 0.172 | 0.169 | 0.427 | 0.198 | 0.215 | 0.343 |
| 9 (15%-10%) | 0.170 | 0.177 | 0.430 | 0.184 | 0.197 | 0.334 |
| 10 (20%-5%) | 0.190 | 0.161 | 0.390 | 0.186 | 0.188 | 0.318 |
| 11 (5%-25%) | 0.163 | 0.168 | 0.453 | 0.221 | 0.257 | 0.443 |
| 12 (10%-20%) | 0.162 | 0.172 | 0.393 | 0.216 | 0.220 | 0.400 |
| 13 (15%-15%) | 0.160 | 0.183 | 0.429 | 0.208 | 0.217 | 0.378 |
| 14 (20%-10%) | 0.164 | 0.176 | 0.455 | 0.189 | 0.174 | 0.357 |
| 15 (25%-5%) | 0.159 | 0.172 | 0.412 | 0.170 | 0.168 | 0.314 |
| 16 (10%-25%) | 0.165 | 0.168 | 0.411 | 0.216 | 0.235 | 0.397 |
| 17 (15%-20%) | 0.168 | 0.176 | 0.379 | 0.215 | 0.210 | 0.356 |
| 18 (20%-15%) | 0.163 | 0.177 | 0.384 | 0.191 | 0.193 | 0.336 |
| 19 (25%-10%) | 0.170 | 0.167 | 0.362 | 0.185 | 0.163 | 0.304 |
| 20 (15%-25%) | 0.179 | 0.167 | 0.368 | 0.229 | 0.230 | 0.403 |
| 21 (20%-20%) | 0.161 | 0.165 | 0.356 | 0.206 | 0.201 | 0.346 |
| 22 (25%-15%) | 0.164 | 0.172 | 0.386 | 0.204 | 0.185 | 0.328 |
| 23 (20%-25%) | 0.156 | 0.165 | 0.361 | 0.225 | 0.216 | 0.366 |
| 24 (25%-20%) | 0.164 | 0.159 | 0.361 | 0.191 | 0.182 | 0.320 |
| 25 (25%-25%) | 0.158 | 0.160 | 0.323 | 0.207 | 0.216 | 0.377 |

Unlike the Merging Fork scenarios, for these variable demand scenarios on the real world network from Stockholm line and joint performance do vary substantially among different demand segmentations. In scenarios exhibiting low share of passengers travelling from corridor to branch (1,3,6,10 and 15), both strategies show similar performance in line level and multiline control performs better in terms of variability of joint headway at the overlapping segment. In contrast, for scenarios where traversing passengers comprise one fourth of the total demand (11,16,20,23 and 25), multiline control performs poorly compared to single line control.

Passenger Cost

From the comparison of the passenger cost, we can also observe that the demand segment that is the most critical is the passenger group that traverses from the corridor to the branch stop set. Table 5 shows the percental difference in passenger cost for the different control schemes at network level. The passenger cost of multiline control is subtracted by the single line control cost. It is clear that multiline control is more effective when the share of passengers travelling from corridor to branch is lower than 20%. At 20% both strategies exhibit similar performance, while single line control outperforms multiline control for 25% of traversing passengers. For high passenger shares of branch passengers and traversing passengers, more users are experiencing longer travel times because of the transition of common operation towards single line operation.

**Table 5 Passenger Cost comparison between control strategies**

| | | **Share of Passengers Travelling within the Branch %B** | | | | |
|---|---|---|---|---|---|---|
| | | **5** | **10** | **15** | **20** | **25** |
| **Share of Passengers Travelling from Corridor to Branch %CB** | **5** | -0.27 | -0.90 | -0.54 | -0.45 | -0.98 |
| | **10** | -0.31 | -1.20 | -0.25 | -0.61 | -0.86 |
| | **15** | -0.40 | -0.49 | -0.62 | -0.16 | -0.41 |
| | **20** | -0.02 | 0.34 | -0.18 | 0.02 | -0.29 |
| | **25** | 0.04 | 0.29 | 0.26 | 0.36 | -0.02 |

## Conclusions

This study focuses on identifying whether single or multiline control should be applied on a public transport network, based on the network's topological configuration and demand profile. Through experimental results, based on both toy networks and a real-life instance, we show that the decision to apply single or multiline control is more sensitive to the demand profile of the network than on network topology. Results further suggest that a stop set can be treated as a shared transit corridor in terms of control if it has equal or higher number of stops compared to the branches of the network. Furthermore, the size of the group of traversing passengers between stop sets is the most critical factor. The more this share increases, the lower the performance of multiline control is.

Additional results will be presented at the symposium, including networks with branches prior and after the shared transit corridor (double fork) and will include transferring passengers, to assess their effect on control decision (single line control, multiline control, synchronization).

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