Optimization-based operations control for public transport service with transfers

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Abstract
The stochastic nature of travel times and dwell times dictate that transit service cannot follow the planned schedule perfectly. Therefore, in the recent years there has been an interest in operational strategies to react to changing conditions and to reduce waiting times and delays to passengers. However, most studies on control strategies deal with a single line, and the treatment of networks with multiple lines is limited only to the transfer stop itself or to small networks without taking into account all the components of the passengers’ time.

This research aims to develop a real time simulation based control framework to determine strategies in order to minimize passengers' total time. The model attempts to coordinate the public transportation network in real time. This coordination aims both to allow smoother transfers, and to maintain the regularity of the lines. The real time control system predicts the arrival and departure times of buses and the demands at the handled stop and downstream using a prediction horizon and optimize the total passengers’ time by using strategies: holding and speed change. A case study demonstrates the use of this framework and its potential to decrease the total passengers' time was applied based on the Metronit BRT network in Haifa- Israel.

1. Introduction

Efficient public transportation systems (PTS) are essential for the provision of sustainable and high-quality mobility in urban areas. Planning agencies worldwide are investing in the design and operation of these systems. However, even an optimally designed PTS may not perform as expected due to service disruptions, road incidents, fluctuations in demand and other unexpected events. In order to realize the potential benefits of PTS to travelers, operators and the transportation system as a whole, real-time control of PTS is required. Examples of real-time PTS control include holding,
speed change, expressing, stop skipping, short turning and deadheading. All are aimed to maintain regular service and recover from disruptions and unexpected events.

Most early works on real-time PTS control treated a single line (e.g., Fu and Yang, 2002; Xuan et al., 2011; Cats et al., 2010, 2011; Eberlein et al., 1999, 2001; Zolfaghari et al., 2004). The shift toward design and operation of integrated public transportation services, which require transfers between lines, challenged researchers to develop real time control strategies that deal with multiple lines. Guevara et al. (2014) used micro-simulation to study the impacts of stop skipping and offline and online holding on the performance at high demand transfer stops. They developed a rule-based method with the purpose of reducing the variance of bus loads and headways. Dessouky et al. (1999) and Dessouky et al. (2003) developed a simulation system for evaluation of holding strategies. They examined seven different holding strategy combinations on networks that allow transfers. They assumed that passenger demand and bus travel times are deterministic and implemented holding only at transfer stops. Hadas and Ceder (2008, 2010) optimized the total travel time and thereby increased the encounter probability.

The strategies they used were holding, stop skipping and slowing down. However, they did not account for the limited capacity of buses. In addition, their optimization function included only passengers' time on the bus and in transfer stops. Hadas et al. (2013) developed an integer linear programming optimization model that uses holding and stop skipping in order to minimize the total passengers’ travel time and maximize the number of direct transfers. However, they did not consider the delays to passengers that are waiting to board a bus at a skipped stop. In addition, the model is myopic in that it assumes that the next bus would be on time and that passenger demands would not change as a result of the control. Liu et al. (2014) optimized the synchronization of planned transfers using holding and change of speeds. They suggested two different objective functions: minimizing the distance gap between vehicles from the two lines at the transfer stop or the total passengers’ travel time in the system. They also defined two types of transfers: at a single transfer point or along a shared corridor with multiple common stops. However, their formulation did not account for delays due to limited vehicle capacities or passengers’ waiting time until the arrival of the first bus. In summary, most studies on transit control were aimed at a single line. The few studies
that handled multiple lines often assumed a single transfer stop and executed control only at that stop. Vehicle capacity constraints were largely ignored.

This research presents an optimization-based system to control multiple lines. It aims to minimize total passengers’ time including all its components: waiting at stops, travel between stops, dwell times, waiting at transfer stops and additional delays to passengers that are denied boarding. The next sections present the overall framework for the control system and the details of the optimization problem. This is followed by a case study to demonstrate the system. Finally, discussion and conclusions are presented.

2. Overall system framework

The overall framework is shown in Figure 1. The optimization process is run whenever a bus enters a stop along its route. The system searches for a set of optimal control actions: holding times at the current and next stops and the travel speed between them. These decisions are estimated for the current bus and for other buses on the same and intersecting lines. In making these decisions it is assumed that the system has information about the current location of all the relevant vehicles. The system then determines the boundaries of the optimization problem to be solved in terms of the buses and stops that would be accounted for in the objective function. The travel times between the stops within this horizon are predicted and used also to predict the passenger demands and dwell times at these stops. These predictions are based on historic and real-time information that may be available. These are used to define an optimization objective to minimize the total passengers’ time. Once the optimal solution is found, only the immediate control actions for the current bus at the current stop are implemented: holding and speed change to the next stop. Control actions for subsequent stops and other buses will be re-evaluated when the optimization is run again the next time that a bus enters a stop.

The prediction horizon used in the optimization is defined by several stops downstream of the location of the current bus and by a number of buses upstream of it on the same line, as shown in Figure 2. Other buses on the same line that are ahead of the current bus, but are within the stop horizon are also included, and so are buses on other lines that would serve stops within the horizon within the same period of time. The horizon length in the example shown in Figure 2 is three stops and three buses. Bus \( i \) on line 1
enters stop \( k \) and triggers the optimization. The system predicts the arrival time of other buses to that stop. The buses on the same line with the nearest future arrival time to the stop are included in the horizon. Buses that are ahead but still within the prediction horizon (i.e., buses \( i-1 \) and \( i-2 \)) are also included. The optimization objective, and decision variables include these buses at all the stops until the last stop within the horizon. Moreover, if the horizon includes a transfer stop (i.e., stop \( k+1 \)), the system predicts the arrival time of buses on other lines (i.e., line 2) to the transfer stop in order to calculate the waiting time for the transfer passengers, these buses will also be considered in the optimization. Mathematically, the buses and stops in the same line that are included in the horizon are defined by:

\[
I_{b,s} = \begin{cases} 
1 & \{t(b, s) \geq t_0 \cap s \leq k + n \cap b \leq i + m \} \\
0 & \text{otherwise}
\end{cases} 
\]  

(1)

Where, \( I_{b,s} \) is an index that equals to 1 if stop \( s \) of bus \( b \) is included in the horizon and 0 otherwise. \( t_0 \) is the time that bus \( k \) enters stop \( s \), \( t(b, s) \) is the arrival time of bus \( b \) to stop \( s \), \( n \) is the length of the stops horizon, \( m \) is the length of the buses horizon. The stops that are included in the horizon are the stops of the preceding buses that are still within the stop horizon, and the stops of the following buses, within the bus horizon, from their current location to the stop horizon.

The buses and stops on the connecting line that are included in the horizon are defined by:

\[
I_{b',s'} = \begin{cases} 
1 & \{t(b', s') \geq t_0 \cap s' \leq s^* + n' \cap t(b', s^*) \leq t(i + m, s^*) \} \\
0 & \text{otherwise}
\end{cases} 
\]  

(2)

Where, \( I_{b',s'} \) is an index that equals to 1 if stop \( s' \) of bus \( b' \) in the connecting line is included in the horizon and 0 otherwise. \( s^* \) is the transfer stop, \( n' \) is the length of the stops horizon on the connecting line, which may differ from that of the handled line. \( t(i + m, s^*) \) is the time that the last bus within the horizon on the handled line arrives at the transfer stop. Thus, the buses on the connecting line that are included in the horizon
are those that arrive to the transfer stop before the last bus in the handled line arrive there.

After finding the optimal variable values, the system implements the decisions (holding time and travel speed to the next stop) only for the current bus \((i)\) at the current stop \((k)\). This process is repeated each time a bus enters a stop.

![Diagram](image_url)

Figure 1: Overall framework of the optimization system
3. Optimization problem

The objective function for the optimization is to minimize the total travel time of passengers within the bus and stop horizon. This includes dwell time at stops (DT), in-vehicle travel time between stops (IVT), waiting time at the origin (WT), waiting time at transfer stops (TWT) and the additional waiting times for passengers that were denied boarding (DBT):

\[
Z = \min_{H, TT} \sum_l \sum_b \sum_s \delta_{s}^{b,l} \left( \theta_1 DT_s^{b,l} + \theta_2 IVT_s^{b,l} + \theta_3 WT_s^{b,l} + \theta_4 TWT_s^{b,l} + \theta_5 DBT_s^{b,l} \right)
\]

(3)

Where, the indices \( s, b \) and \( l \) signify stops, buses and lines, respectively. \( \delta_{s}^{b,l} \) is an indicator variable that equals to 1 if the specific stop of a specific bus is within the optimization horizon, and 0 otherwise. \( H \) and \( TT \) are the vectors of decision variables of holding and travel time between stops within the optimization horizon, respectively.
\( \theta \) are parameters that allow to assign different weights to different components of the travel time, which has been shown to exist in passengers’ perceptions (Currie, 2005).

The various travel times components within this objective function are calculated using estimates of the numbers of passengers boarding and alighting the buses at the various stops:

Dwell times (DT) are incurred by passengers that are on the bus when it is at a stop boarding and alighting passengers or being held:

\[
DT^{b,l}_s = \left[ np^{b,l}_s - \left( na^{b,l}_s + ntd^{b,l}_s + nta^{b,l}_s \right) \right] \left( st^{b,l}_s + H^{b,l}_s \right)
\]  (4)

Where, \( np^{b,l}_s \) is the number of passengers on the bus when it enters the stop. \( na^{b,l}_s, ntd^{b,l}_s \) and \( nta^{b,l}_s \) are the numbers of alighting passengers: at the destination without and with having made a transfer, and those alighting at the transfer stop, respectively. \( st^{b,l}_s \) is the boarding and alighting service time. \( H^{b,l}_s \) is the holding time at the stop.

In-vehicle travel times (IVT) are between two consecutive stops. They are incurred by all the passengers on the bus:

\[
IVT^{b,l}_s = TT^{b,l}_s np^{b,l}_{s+1}
\]  (5)

Where, \( TT^{b,l}_s \) is the travel time in the section between stops \( s \) and \( s+1 \).

Waiting times (WT) are incurred by passengers at the origin stop from their arrival at the stop to the departure of the first bus on the line they are served by (regardless of wetjer or not they are able to board this bus). Assuming that passengers’ arrival to the stop is random, the waiting time is given by:

\[
WT^{b,l}_s = (nb^{b,l}_s + nto^{b,l}_s) \cdot \left( \frac{dt^{b,l}_s - dt^{b-1,l}_s}{2} \right)
\]  (6)

Where, \( nb^{b,l}_s \) and \( nto^{b,l}_s \) are the number of passengers that want to board the bus at the origin. These are, respectively, those that will only use this line and those that will make
a transfer later. \( d_{s}^{b,l} \) and \( d_{s}^{b-1,l} \) are the departure times from the stop of the current and previous bus on the same line, respectively.

Transfer waiting time (TWT) is the time that passengers wait at the transfer stop from when they alight the bus they transfer from to the arrival of the bus they need to transfer to:

\[
TWT_{s}^{b,l} = ntb_{s}^{b,l} \left( dt_{s}^{b,l} - at_{s}^{m,n} \right)
\] (7)

Where, \( ntb_{s}^{b,l} \) are the number of passengers that want to board the bus at the transfer stop after getting off the first bus on their trip. \( at_{s}^{m,n} \) is the arrival time of the bus the passenger is transferring from to the same stop.

Denied boarding time (DBT) is the additional delay incurred by passengers that cannot board a bus because of crowding.

\[
DBT_{s}^{b,l} = ndb_{s}^{b-1,l} \left( dt_{s}^{b,l} - dt_{s}^{b-1,l} \right)
\] (8)

Where, \( ndb_{s}^{b-1,l} \) is the number of passengers boarding the bus that were unable to board the previous bus on the same line due to limited capacity.

Within the calculation of the delays, the various numbers of passengers need to be estimated. The number of passengers on the bus when it enters a stop is calculated based on the load on the bus when it entered the previous stop and the numbers of boarding and alighting passengers in that stop. It is also constrained by the bus capacity:

\[
np_{s}^{b,l} = \min(np_{s}^{b,l}, C_{\max}^{b,l})
\] (9)

\[
np_{s}^{b,l} = np_{s}^{b-1,l} + \left[ nb_{s}^{b,l} - na_{s}^{b,l} + ntd_{s}^{b,l} - nta_{s}^{b,l} + ntb_{s}^{b,l} - ndb_{s}^{b-1,l} \right]
\] (10)

Where \( np_{s}^{b,l} \) is the number of passengers that would like to be on the bus without considering its capacity, \( C_{\max}^{b,l} \) is the capacity of the bus.

The numbers of boarding and alighting passengers are estimated using the headways between buses and origin-destination matrices of the direct and transfer demands that
are available from historic information. The numbers of passengers waiting to board are given by:

\[ n_{sd}^{b,l} = \mu_{sd}^{b,l} (d_{s}^{b,l} - d_{s}^{b-1,l}) \]  
(11)

\[ nt_{sd}^{b,l,n} = v_{sd}^{b,l,n} (d_{s}^{b,l} - d_{t}^{b,l}) \]  
(12)

Where, \( n_{sd}^{b,l} \) is the demand of passengers that wish to board bus \( b \) at stop \( s \) to destination \( d \) without making transfers. \( nt_{sd}^{b,l,n} \) is the demand of passengers that wish to travel on bus \( b \) from stop \( s \) to destination \( d \) making a transfer at stop \( t \) to line \( n \). \( \mu_{sd}^{b,l} \) and \( v_{sd}^{b,l,n} \) are the corresponding demand rates.

Based on these, the various numbers of passengers are calculated as summation of the relevant passengers’ demands (boarding passengers, alighting passengers, transfer boardings at the origin, transfer alighting at the transfer stop, transfer boarding at the transfer stop and transfer alighting at the destination):

\[ nb_{s}^{b,l} = \sum_{d=s+1}^{S} n_{sd}^{b,l} \]  
(13)

\[ na_{s}^{b,l} = \sum_{j=t+1}^{j-1} n_{js}^{b,l} \]  
(14)

\[ nto_{s}^{b,l,n} = \sum_{n}^{N} \sum_{d}^{D} \sum_{t=s+1}^{T} nt_{sd}^{b,l,n} \]  
(15)

\[ ntd_{s}^{b,l} = \sum_{n}^{N} \sum_{d}^{D} \sum_{j=1}^{J-1} nt_{sd}^{b,l,n} \]  
(16)

\[ ntb_{s}^{b,l} = \sum_{n}^{N} \sum_{m}^{M} \sum_{j=1}^{J} nt_{sd}^{m,n,l} \delta_{s}^{m,n,b,l} \]  
(17)

\[ ntd_{s}^{b,l} = \sum_{n}^{N} \sum_{m}^{M} \sum_{j=1}^{J-1} nt_{js}^{m,n,l} \delta_{s}^{m,n,b,l} \]  
(18)
Where, $\delta^{m,n,b,l}_{s}$ is an indicator variable, which takes the value 1 if bus $b$ is the first bus on line $l$ to serve stop $s$ after bus $m$ on line $n$ serves that stop (i.e. passengers transferring from bus $m$ would use bus $b$), and 0 otherwise.

The number of passengers that are unable to board a bus is the excess demand at the stop considering its capacity and current load:

$$ndb^b_l = np^b_l + \left[ nb^b_l - nta^b_l - nt^b_l + ntb^b_l - nta^{b-1}_l + ndb^{b-1}_l \right] - C^{o,f}_{max} \quad (19)$$

If this value is positive, the numbers of boarding passengers in the current stop are reduced proportionally. The proportionality value is given by:

$$1 - \frac{ndb^b_l}{nb^b_l + nta^b_l + ntb^b_l + ndb^{b-1}_l} \quad (20)$$

As a result, the numbers of alighting and transferring passengers in subsequent stops that were presented above are also adjust to reflect the actual number of boarding passengers.

Finally, the various travel times need to be estimated. The departure time from a stop is calculated by the arrival time to that stop and the time that the bus is delayed there:

$$dt^b_s = at^b_s + (st^b_s + H^b_s) \quad (21)$$

Where, $at^b_s$ is the arrival time of the bus to the stop, which in turn is calculated by the departure time from the previous stop and the travel time between the two stops:

$$at^b_{s+1} = dt^b_s + TT^b_s \quad (22)$$

The service time at a stop is estimated assuming a constant time for each boarding or alighting passenger:

$$st^b_s = \sigma^b_s \left( na^b_s + nta^b_s + ntd^b_s + nb^b_s + ntb^b_s + nta^{b-1}_s + ndb^{b-1}_s \right) \quad (23)$$

Where, $\sigma^b_s$ is the service time for each passenger.
The optimization problem is constrained by bounds on the control variables. The speed change that may be applied is limited (e.g., due to speed limits, traffic conditions). Similarly, the allowed holding time may be bounded. These are captured by the constraints:

\[ TT_{s,\text{min}}^{b,j} \leq TT_{s}^{b,j} \leq TT_{s,\text{max}}^{b,j} \]  \hspace{2cm} (24)

\[ 0 \leq H_{s}^{b,j} \leq H_{s,\text{max}}^{b,j} \]  \hspace{2cm} (25)

Where, \( TT_{s,\text{min}}^{b,j} \) and \( TT_{s,\text{max}}^{b,j} \) are the minimum and maximum travel times between the two stops and \( H_{s,\text{max}}^{b,j} \) is the maximum allowable holding time.

4. Case study

4.1. Network

The Metronit BRT network in Haifa, Israel was used for the case study. The Metronit network, shown in Figure 3, is 60 km long, of which 40 km are on dedicated lanes and roadways. The Metronit includes three lines with a total of 192 stops, and 19 shared stops. In May 2015, the daily ridership on the Metronit was 92,000.

Figure 3: The Metronit case study network
Below is a figure of the southbound profile of the busiest line of the Metronit network. During the AM peak hour (7:00-8:00) the average headway on this line is 4 minutes.

![Demand profile of Line 1](image)

**Figure 4: Demand profile of Line 1**

### 4.2. Scenarios

The performance of the proposed control system is evaluated using BusMezzo (Toledo et al., 2010), a detailed traffic and transit simulation model that generates real-time information that is used within the control systems as well as measures of performance for it. In the case study it was assumed that the information available to the system in real time is only about the current locations of the buses in the Metronit network. Predictions of travel times between stops and passengers’ demands at stops are based solely on averages of historic data. The control system predicts the buses arrival and departure times from stops and the numbers of waiting passengers at these stops. These are used to define the optimization problem to be solved in order to determine holding times and speed changes.

Holding at a stop was constrained to up to 0.1 of the scheduled headway. The speed change was constrained to be between -5 km/hr (slower) and +2 km/hr (faster) compared to the normal running speed in the section between two consecutive stops.

For the optimization objective, a weight of 2 was used for the waiting times (waiting at the origin stop, waiting for transfer and waiting for denied boarding), and 1 for riding...
times and dwell times. Within the optimizations, a horizon of 3 buses and 3 stops were used.

The proposed optimization control (OC) was compared with a base no control strategy (NC) and a headway-based control (HC) for a single line (implemented on each of the lines, separately), which takes into account the headway from both the preceding and the following buses when making holding decisions to a pre-specified minimum headway (Cats et al., 2010):

\[
ET_{ijk} = \max \left\{ \min \left\{ \frac{AT_{ijk} + (AT_{ijk} - AT_{j,k-1}) + (AT_{m,k-1} + SRT_{mj} - AT_{ijk})}{2}, \right. \right. \\
\left. \left. \frac{AT_{ijk} + \alpha H_{ik} - k}{AT_{ijk} + DT_{ijk}} \right\} \right\},
\]

(26)

Where \( ET_{ijk} \) is the departure time for the bus on trip \( k \) of line \( i \) from stop \( j \). \( AT_{ijk} \) is the actual arrival time and \( DT_{ijk} \) is the dwell time. \( m \) is the index of the previous stop that was visited by the bus. \( SRT_{mj} \) is the scheduled travel time between stops \( m \) and \( j \). \( H_{ik}^{k-1,k} \) is the scheduled headway between the two buses. \( \alpha \) is a parameter.

### 4.3. Results

Table 1 shows the total weighted travel times and its components for the three different control cases (none, headway-based, optimization-based). The total headway-based control has the lowest waiting times. This is not surprising since it is designed to reduce passengers’ waiting time. However, this strategy results in much more holding than the other methods. As a result, the total weighted travel time is increased, even compared to the no control case (by 2.1%). The optimization-based control is designed to minimize travel times in the system taking into account all components of the travel time. It is able to reduce the total weighted travel time by 4.0% compared to the no control case. This reduction stems from reductions in all of riding times, dwell times and waiting times, but with much lower holding times compared to the case of headway-based control.

<p>| Table 1: Components of passengers’ times (minutes) |</p>
<table>
<thead>
<tr>
<th>Control</th>
<th>Riding time</th>
<th>Dwell time</th>
<th>Waiting time</th>
<th>Holding time</th>
<th>Total weighted travel time</th>
</tr>
</thead>
<tbody>
<tr>
<td>None (NC)</td>
<td>212,531</td>
<td>41,667</td>
<td>65,844</td>
<td>0</td>
<td>385,887</td>
</tr>
<tr>
<td>Headway (HC)</td>
<td>212,022</td>
<td>39,899</td>
<td>56,798</td>
<td>14,229</td>
<td>393,976</td>
</tr>
<tr>
<td>Optimization (OC)</td>
<td>211,018</td>
<td>40,161</td>
<td>58,547</td>
<td>2,201</td>
<td>370,475</td>
</tr>
</tbody>
</table>

The variability of headways along the southbound of Line 1 are shown in Figure 5. The coefficients of variation demonstrate that both optimization and headway-based strategies are effective in improving regularity but the effect of the proposed strategy is more pronounced in the second half of the route because it explicitly takes the demand on the line into account.

![Figure 5: Coefficient of variation of headways along Line 1](image)

Table 2 shows measures of performance at the system level. The headway-based control perform best in terms of the number of passengers that are unable to board buses that are full to capacity and waiting times at stops. These results represent decreases of 81% and 17% compared to the no control case on these two performance measures, respectively. The comparable reductions for the optimization-based control are 65% and 13%, respectively. In terms of service reliability, the optimization-based control vastly outperformed both the headway-based and no control. Arrivals between one
minute early and three minutes late compared to the scheduled arrival were considered on time.

Table 2: Service measurements of performance

<table>
<thead>
<tr>
<th>Control</th>
<th>Passengers unable to board</th>
<th>Waiting time per passenger (sec)</th>
<th>On-time arrivals (%)</th>
<th>Early arrivals (%)</th>
<th>Late arrivals (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>None (NC)</td>
<td>145</td>
<td>167.9</td>
<td>33%</td>
<td>56%</td>
<td>11%</td>
</tr>
<tr>
<td>Headway (HC)</td>
<td>28</td>
<td>140.1</td>
<td>36%</td>
<td>49%</td>
<td>14%</td>
</tr>
<tr>
<td>Optimization (OC)</td>
<td>51</td>
<td>145.9</td>
<td>97%</td>
<td>2%</td>
<td>1%</td>
</tr>
</tbody>
</table>

The optimization-based control results above used two measures: holding at stops and speed change in sections between stops. The usefulness of each of these measures was evaluated by running optimizations with controls that only implements one of them. Table 3 shows the overall performance of the controls.

The two measures used separately yielded low improvements in the total weighted travel times over the no control case: 0.4% and 1.4% for holding and speed change measures, respectively. This is compared to 4.0% for the optimization with both measures. Moreover, the optimization control implementing both measures yielded lower values in all components of travel time except holding time. It also holds buses less compared to the holding-only strategy. Thus, the results show that the combination of the two measures outperforms using each one of them separately. The speed change measure can compensate for delays caused by holding and so help reduce late arrivals.

Table 3: Components of passengers’ times- one control strategy (minutes)

<table>
<thead>
<tr>
<th>Control</th>
<th>Riding time</th>
<th>Dwell time</th>
<th>Waiting time</th>
<th>Holding time</th>
<th>Total weighted travel time</th>
</tr>
</thead>
<tbody>
<tr>
<td>None (NC)</td>
<td>212,531</td>
<td>41,667</td>
<td>65,844</td>
<td>0</td>
<td>385,887</td>
</tr>
<tr>
<td>Optimization – Speed change (OSC)</td>
<td>211,287</td>
<td>42,287</td>
<td>65,381</td>
<td>0</td>
<td>384,335</td>
</tr>
<tr>
<td>Optimization – Holding (OHC)</td>
<td>213,313</td>
<td>40,786</td>
<td>58,828</td>
<td>4,318</td>
<td>380,392</td>
</tr>
<tr>
<td>Optimization (OC)</td>
<td>211,018</td>
<td>40,161</td>
<td>58,547</td>
<td>2,201</td>
<td>370,475</td>
</tr>
</tbody>
</table>
5. Summary

This study focuses on developing and testing an optimization framework for real time control of transit systems with transfers. The proposed control method uses two measures: holding and speed change in order to minimize total passengers’ travel time that include riding time, dwell time, wait time, transfer time and skip time. The optimization process is implemented in a rolling horizon framework and initiated when a bus enters a stop.

The performance of the proposed model is evaluated with a case study of three BRT lines in Haifa, Israel. The simulation-based evaluation uses BusMezzo, a mesoscopic transit simulation model. The results show that the optimization-based control performs better than headway-based control or no control not only in terms of total passengers’ travel time and its components, but also in terms of service regularity and on-time performance.

Future work may focus on the impact of different levels of information about travel times and passengers’ demand that is available in real time on the performance of the optimization-based control. In addition, the robustness of the method to measurement and prediction errors and in scenarios of service disruptions and surges in demand should be studied.

6. References


