Real Time Control for Transit Systems with Transfers

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Outline

- Introduction
- State of the art
- Model description
- Demonstration case studies
- Conclusions and future improvements

Introduction

- Objective
  - Improve service quality and reduce passengers delays
    - Increase reliability
    - Schedule adherence
    - Regularity
- Develop control strategies
  - Planning
  - **Operation (Real time)**

Real time control

- **Classification** (Eberlein et al. 1999 and Zolfaghari et al. 2004)
- At Stop
  - Holding
  - Stop skipping
- Inter stop
  - Change speed
  - Signal priority
- Line
  - Deadheading
  - Short turning
  - Short cut
  - Expressing
  - Adding reserve vehicle

Control of single line

- Most common
- Often uses holding strategy
- Rule-based (Fu and Yang 2002, Daganzo 2009, Xuan et al. 2011, Cats et al. 2010, 2011)

e.g. $$h_{actual}^{\min} \geq (0.6 \div 0.8) \cdot H_{planned}$$

- Optimization-based (Eberlein et al. 1999, Fu et al. 2003, Zolfaghari et al. 2004)

$$\min \sum \text{passengers costs}$$

  - Passengers costs: waiting time, in vehicle time, skip time, variance of headway/ schedule

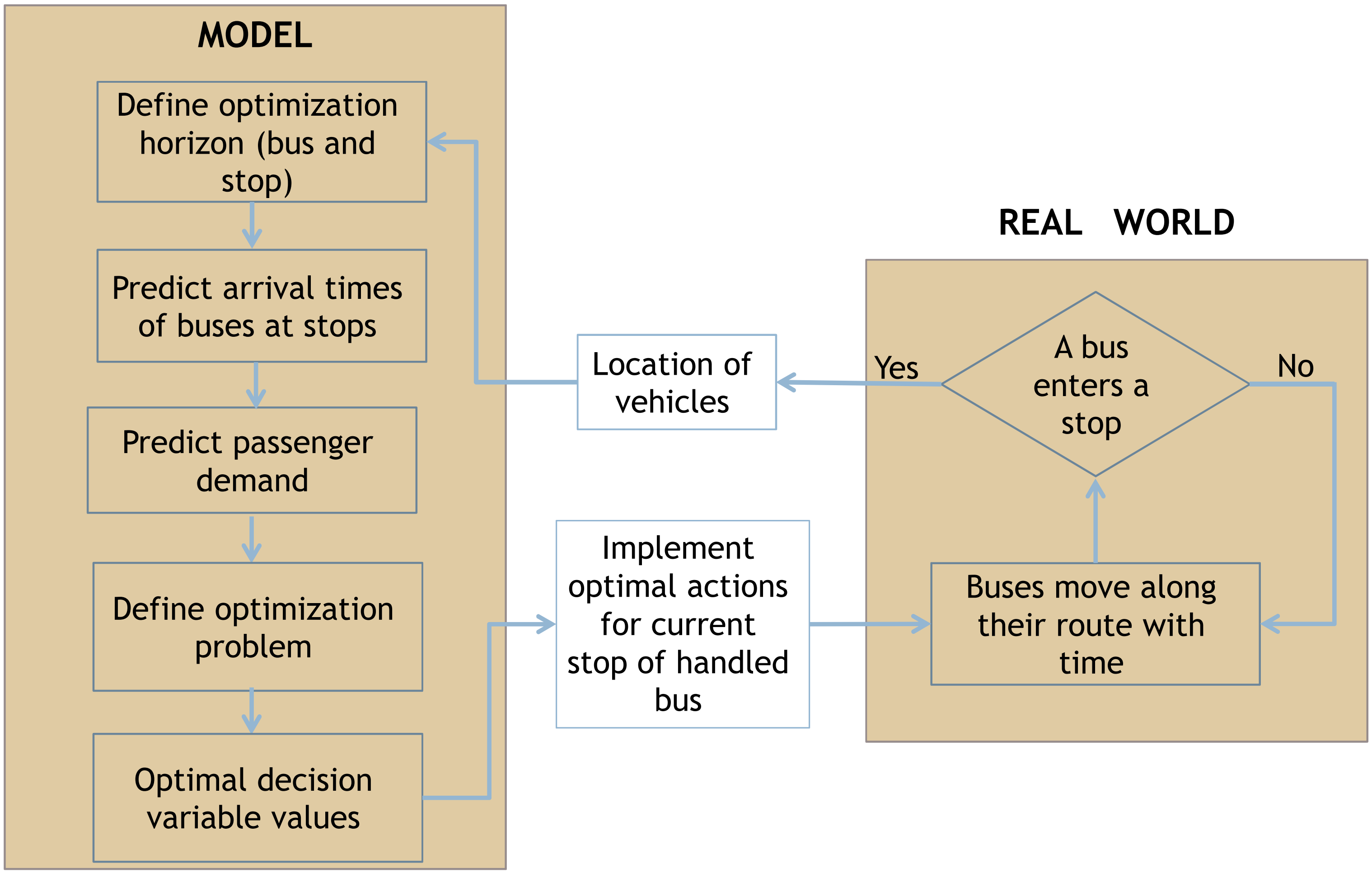
Control of multiple lines

- Integrated PT systems with transfers
- Rule-based
  - Guevara et al. 2014: skip stop, offline and online holding, high demand transfer stops
- Optimization-based
  - Dessouky et al. 1999, 2003: holding at the transfer stop, include delays at the transfer stops and downstream
  - Yu et al. 2012: holding strategy to synchronize vehicles at transfer stops. Consider waiting time at the transfer stop and downstream
  - Hadas and Ceder 2008, 2010, Ceder et al. 2013: optimizing the total travel time. Strategies: holding, skip stop and slowingdown.
  - Khoat et al. 2007: stop skip strategy, minimize waiting time of passengers

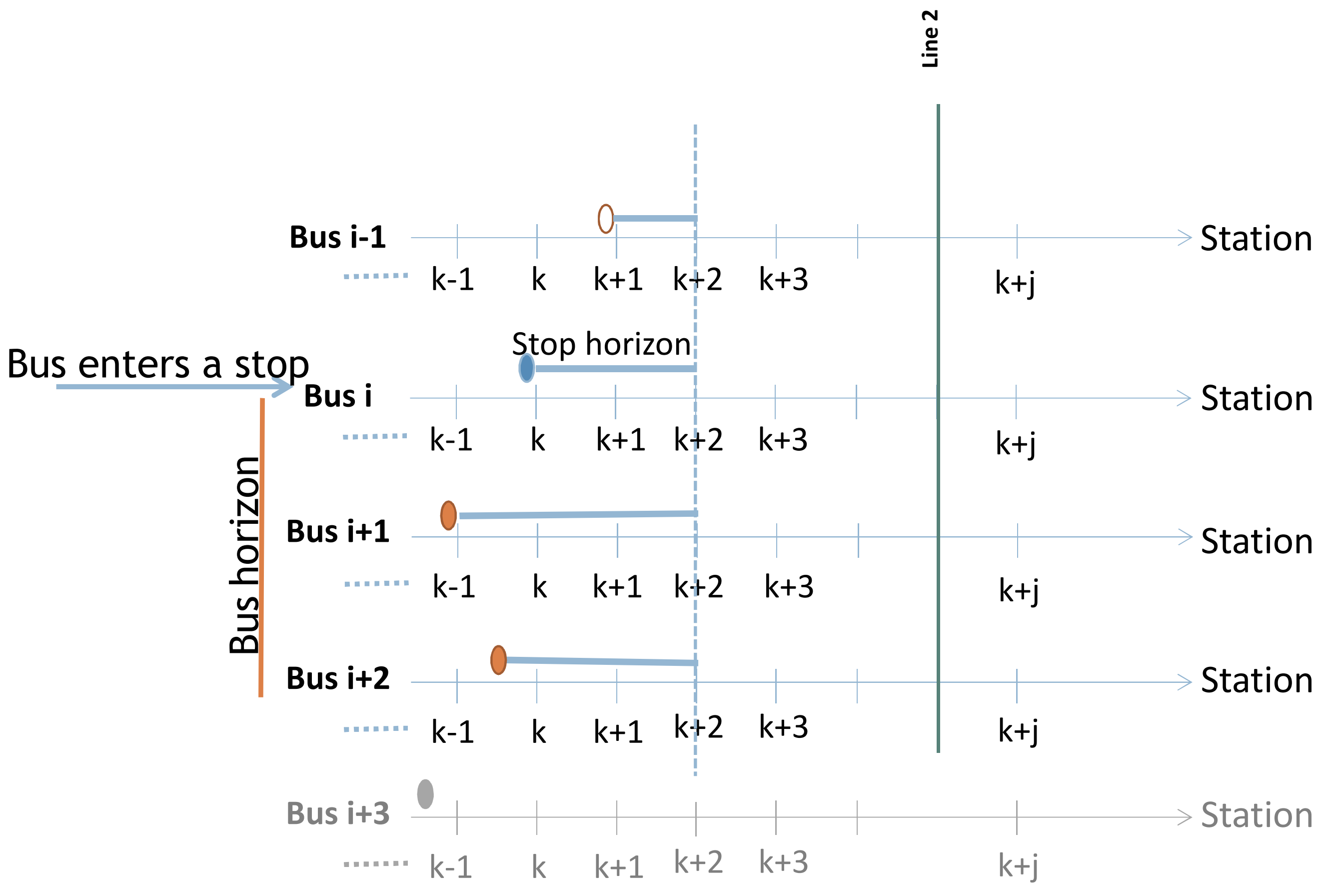
This research

- Develop prediction-based system for operations control
- Minimize total passenger time
  - waiting at stop, travel between stops, dwell time, waiting at the transfer, waiting for skip passengers
- Strategies
  - Holding, change speed, skip stop
- Incorporates
  - Limited capacity, transfer stops

Optimization framework



Rolling horizon implementation



Optimization problem

- Minimum passengers time
- Decision variables
  - Travel time $TT_k^{s,l}$
  - Hold bus $H_k^{s,l}$
  - Skip stop $S_k^{s,l}$

$$Z = \min \sum_{s=1}^{M} \sum_{l=r}^{r+t} \sum_{k=i}^{i+j} \begin{bmatrix} \theta_1 \cdot PDT_k^{s,l} + \theta_2 \cdot PTT_k^{s,l} + \theta_3 \cdot PWT_k^{s,l} + \\ \theta_4 \cdot TPT_k^{s,l} + \theta_5 \cdot SPT_k^{s,l} \end{bmatrix} + \sum_{s=1}^{M} \sum_{l=r}^{r+t} \theta_6 \cdot DTC^{s,l}$$

S.t:

$$TT_{k,\min}^{s,l} \le TT_k^{s,l} \le TT_{k,max}^{s,l}$$

$$0 \le H_k^{s,l} \le H_k^{\max s,l}$$

$$(1 - S_k^{s,l}) \cdot H_k^{s,l} = 0$$

$$S_k^{s,l-1} + S_k^{s,l} \ge 1$$

PDT- Passenger dwell time, PTT- Passenger travel time, PWT- Passenger wait time
TPT- Transfer passengers' time, SPT- Skipped passengers' time

Components of times

k- stop, l- bus, s- line

- Passenger dwell times at stops (PDT)

$$PDT_k^{s,l} = S_k^{s,l} \cdot (np_k^{s,l} - (na_k^{s,l} + ntd_k^{s,l} + nta_k^{s,l} + \sum_{j=k+1}^{J} na_j^{s,l} \cdot \prod_j (1 - S_j^{s,l}))) \cdot \left(st_k^{s,l} + H_k^{s,l} \right)$$

np *Number of passengers on the bus*

na *Number of alight passengers*

ntd *Number of transfer alighting passengers*

nta *Number of alighting passengers to the transfer*

S *Bus stops at stop*

st *Service time at stop*

H *Holding time at stop*

Components of times

- <u>Passenger travel time (PTT)</u>

$$PTT_k^{s,l} = TT_k^{s,l} \cdot np_{k+1}^{s,l}$$

TT *Travel time between stops*

- <u>Passenger wait time (PWT)</u>

$$PWT_k^{s,l} = (nb_k^{s,l} + nto_k^{s,l}) \cdot \left(\frac{dt_k^{s,l} - dt_k^{s,l-1}}{2} \right)$$

nb *Number of passengers that want to board*

nto *Transfer boarding passengers at the origin*

dt *Departure time from stop*

Components of times

- Transfer passengers' time (TPT)

$$TPT_k^{s,l} = ntb_k^{s,l} \cdot \left(dt_k^{s,l} - at_k^{m,n}\right) \cdot S_k^{s,l}$$

at *Arrival time at stop*

- Skipped passengers' time (SPT)

$$SPT_k^{s,l} = (nb_k^{s,l-1} + nto_k^{s,l-1} + ntb_k^{s,l-1} + nsb_k^{s,l} + nsa_k^{s,l}) \cdot (dt_k^{s,l} - dt_k^{s,l-1}) \cdot (1 - S_k^{s,l-1}) \cdot S_k^{s,l} + ndb_k^{s,l-1} \cdot (dt_k^{s,l} - dt_k^{s,l-1}) \cdot S_k^{s,l}$$

nsb *Total passengers that were skipped*

nsa *Passengers on bus that have to alight because of skipping downstream stops*

ndb *Passengers that cannot board the bus because of limited capacity*

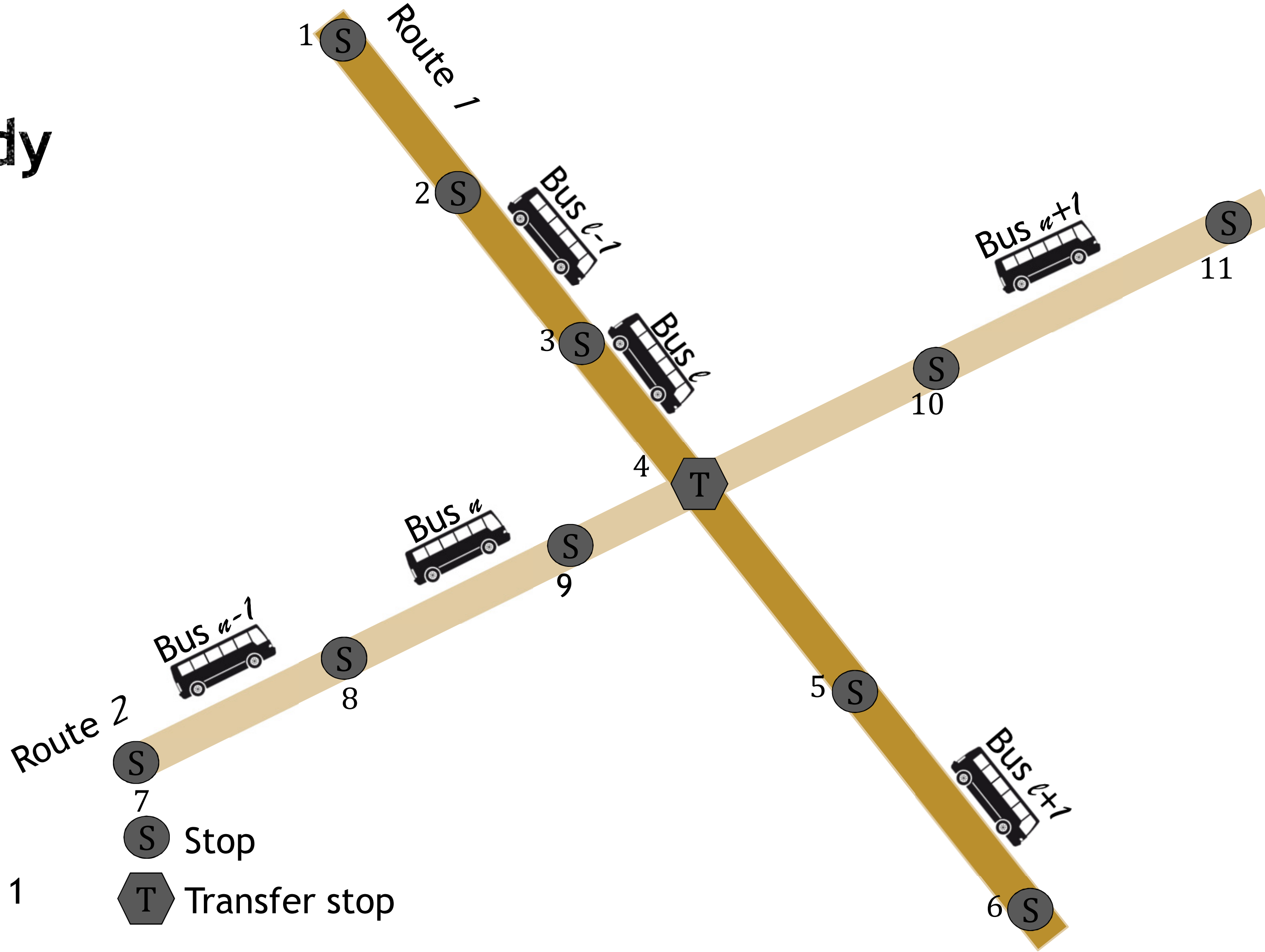
Components of times

- <u>Delay for next trip on chain (DTC)</u>

$$DTC^{s,l} = \frac{\sum_i (nb_i^{s,l} + ntb_i^{m,n} + nto_i^{s,l})}{number\ of\ stations} \cdot (at_{last\ station}^{s,l} - planning\ at_{last\ station}^{s,l} - \beta)$$

β Recovery time

Case study



2 lines, 6 stops each
One transfer stop
Optimize 4 buses on line 1

S Stop
T Transfer stop

Assumptions

- Weight of waiting times double the weight of travel time (FTA, 2005)

$$\theta_1, \theta_3, \theta_4, \theta_5 = 1; \;\; \theta_2 = 0.5$$

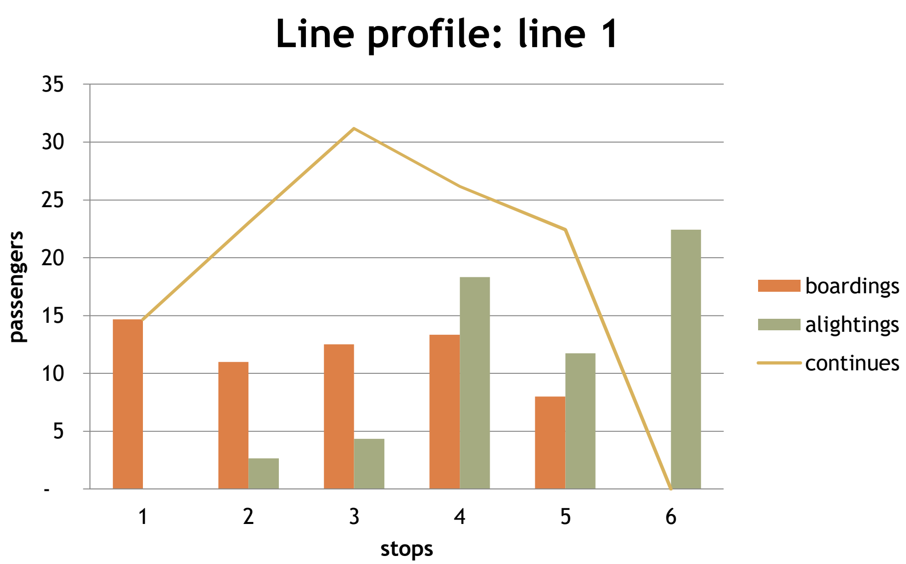
- Weight of delay to the next trip is 0.1
- Boarding/alighting time for passenger is 2.59 seconds
- Maximum speed gain $\Delta V_{max} = 2 \frac{km}{h}$
- Maximum speed loss $\Delta V_{min} = 5 \frac{km}{h}$
- Headway of buses 5 minutes
- Recovery time $\beta = 3$ minutes
- Base horizon 3 stops and 3 buses

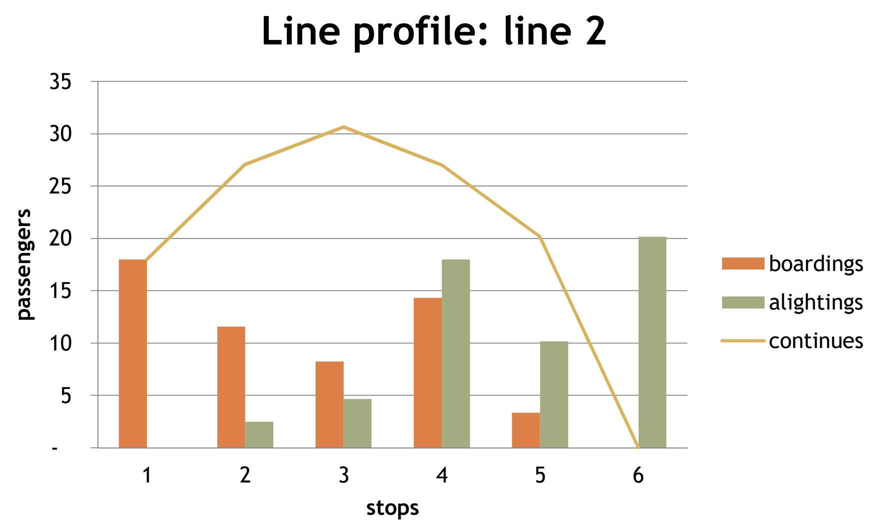
Scenarios

- Scenario 1- Base scenario
- Scenario 2- Bunching on line 1
- Scenario 3- High demand and bunching on line 1
- Scenario 4- High demand and bunching on both lines
- Scenario 5- Extreme demand and bunching on line 1
- Scenario 6- Extreme demand and bunching on both lines

Scenario	1	2	3	4	5	6
Demand	Normal	Normal	High	High	Very high	Very high
transfer	Normal	Normal	High	High	Very high	Very high
Bunching line 1	No	Yes	Yes	Yes	Yes	Yes
Bunching line 2	No	No	No	Yes	No	Yes

Demands


Line profile: line 1
35
30
25
20
15
10
5
-
passengers
1
2
3
4
5
6
stops
boardings
alightings
continues

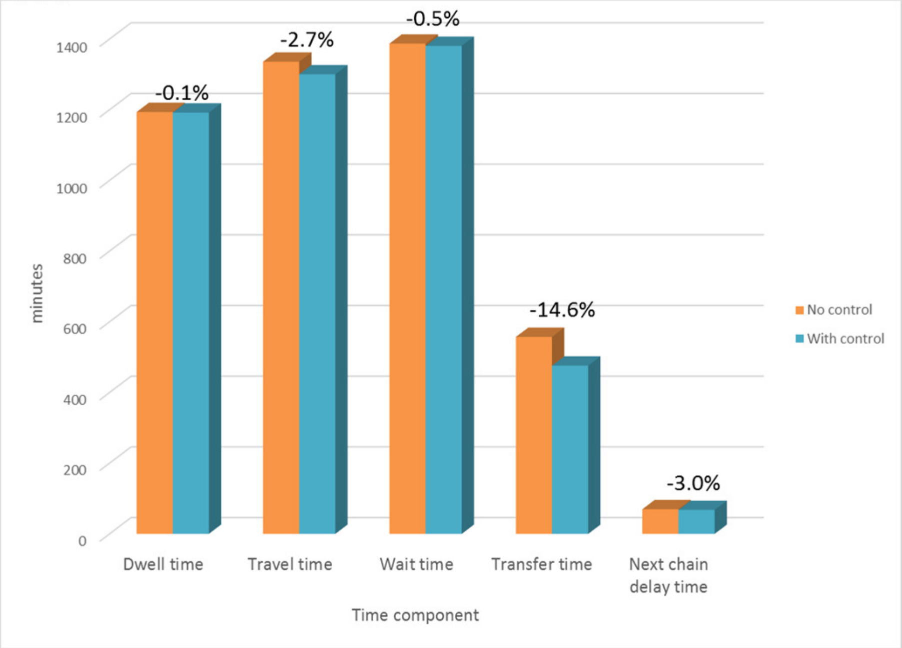

Line profile: line 2
35
30
25
20
15
10
5
-
passengers
1
2
3
4
5
6
stops
boardings
alightings
continues

Scenario 1- Base scenario

- Operation with even headway
- Base demand level
- Optimal control
  - Buses run at the maximum allowed speed, without holding
  - Total passenger time reduction: 127 minutes (3%)

Bus	Stop	△V (km/h)	H (minutes)
1	1	2.0	0.0
	2	2.0	0.0
	3	2.0	0.0
	4	2.0	0.0
	5	2.0	0.0
2	1	2.0	0.0
	2	2.0	0.0
	3	2.0	0.0
	4	2.0	0.0
	5	2.0	0.0

Bus	Stop	△V (km/h)	H (minutes)
3	1	2.0	0.0
	2	2.0	0.0
	3	2.0	0.0
	4	2.0	0.0
	5	2.0	0.0
4	1	2.0	0.0
	2	2.0	0.0
	3	2.0	0.0
	4	2.0	0.0
	5	2.0	0.0



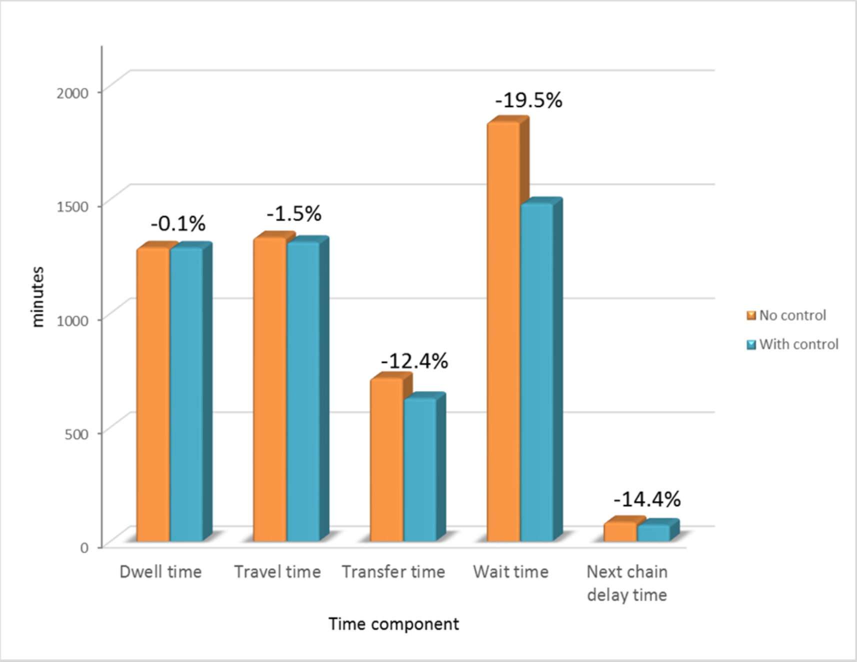
Scenario 2- Bunching on line 1

- Base demand
- Optimal control
  - Hold bus 2 at stop 1 the maximum allowed time (3.5 minutes), and bus 3 at stop 1 and bus 4 at stop 1 for 2.9 minutes
  - Buses run at the maximum allowed speed except bus 4 from stop 1 to 3
  - Total hold time: 8 minutes
- Total passenger time reduction: 481 minutes (9%)

Bus	Arrival time
1	8:05
2	8:06
3	8:15
4	8:16
5	8:25
6	8:30
7	8:35
8	8:40
9	8:45
10	8:50
11	8:55
12	9:00

Bus	Stop	△V (km/h)	H (minutes)
1	1	2.0	0.0
	2	2.0	0.0
	3	2.0	0.0
	4	2.0	0.0
	5	2.0	0.0
2	1	2.0	3.5
	2	2.0	0.0
	3	2.0	0.0
	4	2.0	0.0
	5	2.0	0.0

Bus	Stop	△V (km/h)	H (minutes)
3	1	2.0	0.9
	2	1.8	0.0
	3	2.0	0.0
	4	2.0	0.0
	5	2.0	0.0
4	1	-5.0	2.9
	2	-2.1	0.0
	3	2.0	0.0
	4	2.0	0.0
	5	2.0	0.0



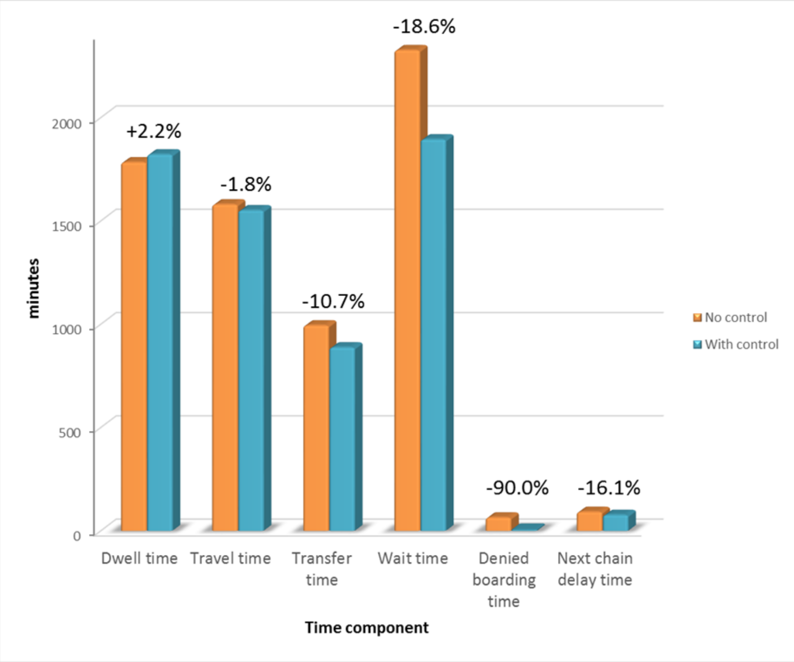
Scenario 3- High demand and bunching on line 1

Bus	Arrival time
1	8:05
2	8:06
3	8:15
4	8:16
5	8:25
6	8:30
7	8:35
8	8:40
9	8:45
10	8:50
11	8:55
12	9:00

- Optimal control:
  - Hold bus 2 at stop 1 for 3.5 minutes, Hold bus 4 at stop 1 for 2.6 minute and at stop 2 for 0.5 minutes
  - Total hold time: 6.6 minutes
  - Bus 2 slows from stop 3 to 4, bus 4 slows from stop 2 to 3
- Total passengers time reduction: 601 minutes (9%)

Bus	Stop	△V (km/h)	H (minutes)
1	1	2.0	0.0
	2	1.7	0.0
	3	2.0	0.0
	4	2.0	0.0
	5	2.0	0.0
2	1	2.0	3.5
	2	2.0	0.0
	3	-4.2	0.0
	4	2.0	0.0
	5	2.0	0.0

Bus	Stop	△V (km/h)	H (minutes)
3	1	1.9	0.0
	2	2.0	0.0
	3	2.0	0.0
	4	2.0	0.0
	5	1.7	0.0
4	1	2.0	2.6
	2	-2.7	0.5
	3	2.0	0.0
	4	1.9	0.0
	5	2.0	0.0



Scenario 3- High demand and bunching on line 1

Departure and arrival time to transfer stop for transfer from line 1

	Without control		With control	
Bus	Departure time of line 2	Arrival time of line 1	Departure time of line 2	Arrival time of line 1
1	08:06	08:12	08:06	08:12
2	08:13	08:14	08:13	08:16
3	08:19	08:23	08:19	08:22
4	08:23	08:25	08:23	08:25
5	08:29	08:33	08:28	08:33
6	08:32	08:37	08:32	08:37
7	08:39	08:42	08:39	08:42
8	08:43	08:47	08:43	08:47
9	08:48	08:52	08:48	08:52
10	08:53	08:57	08:53	08:57
11	08:57	09:02	08:57	09:02
12	09:04	09:07	09:04	09:07

Departure and arrival time to transfer stop for transfer to line 1

	Without control		With control	
Bus	Departure time of line 1	Arrival time of line 2	Departure time of line 1	Arrival time of line 2
1	08:14	08:05	08:14	08:05
2	08:15	08:12	08:17	08:12
3	08:25	08:17	08:24	08:17
4	08:26	08:22	08:26	08:22
5	08:36	08:26	08:35	08:26
6	08:38	08:32	08:38	08:32
7	08:44	08:37	08:44	08:37
8	08:48	08:42	08:48	08:42
9	08:53	08:47	08:53	08:47
10	08:58	08:51	08:58	08:51
11	09:03	08:56	09:03	08:56
12	09:08	09:03	09:08	09:03

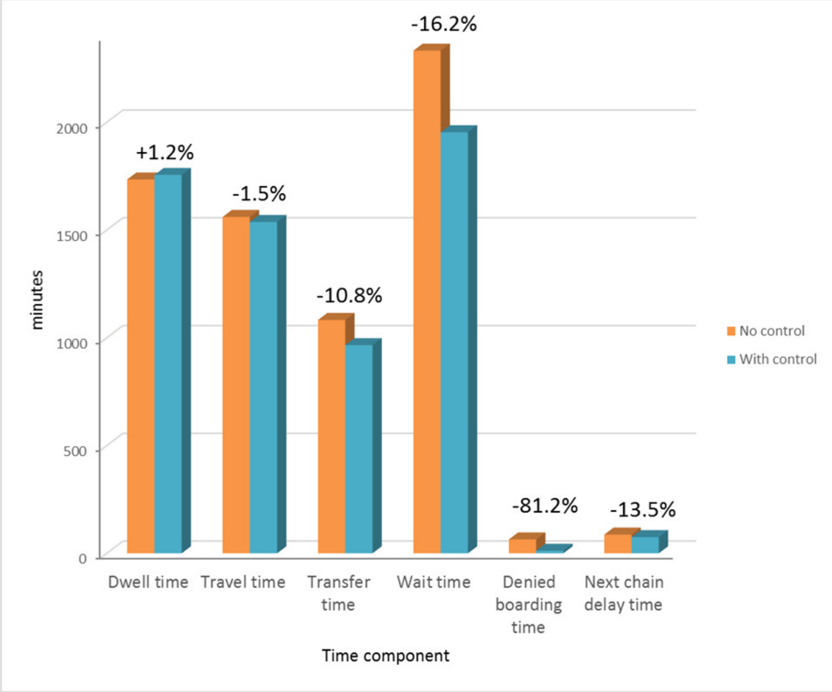
Scenario 4- High demand and bunching on both lines

Bus\Arrival time	Line 1	Line 2
1	8:05	8:00
2	8:06	8:01
3	8:15	8:10
4	8:16	8:11
5	8:25	8:20
6	8:30	8:25
7	8:35	8:30
8	8:40	8:35
9	8:45	8:40
10	8:50	8:45
11	8:55	8:50
12	9:00	8:55

- Optimal control:
  - Hold bus 2 at stop 1 for 3.5 minutes and at stop 2 for 1.2 minutes. Hold bus 3 at stop 1, and bus 4 from stop 1 to 3 for 2.2 minutes.
  - Total hold time: 8.1 minutes
  - Bus 4 slows from stop 1 to stop 3
- Total passengers time reduction: 562 minutes (8%)

Bus	Stop	ΔV (km/h)	H (minutes)
1	1	2.0	0.0
	2	2.0	0.0
	3	2.0	0.0
	4	1.5	0.0
	5	1.5	0.0
2	1	2.0	3.5
	2	1.5	1.2
	3	1.5	0.0
	4	2.0	0.0
	5	2.0	0.0

Bus	Stop	ΔV (km/h)	H (minutes)
3	1	2.0	1.0
	2	1.7	0.0
	3	2.0	0.0
	4	2.0	0.0
	5	2.0	0.0
4	1	-5.0	0.0
	2	-0.2	1.8
	3	1.7	0.1
	4	0.9	0.3
	5	2.0	0.0



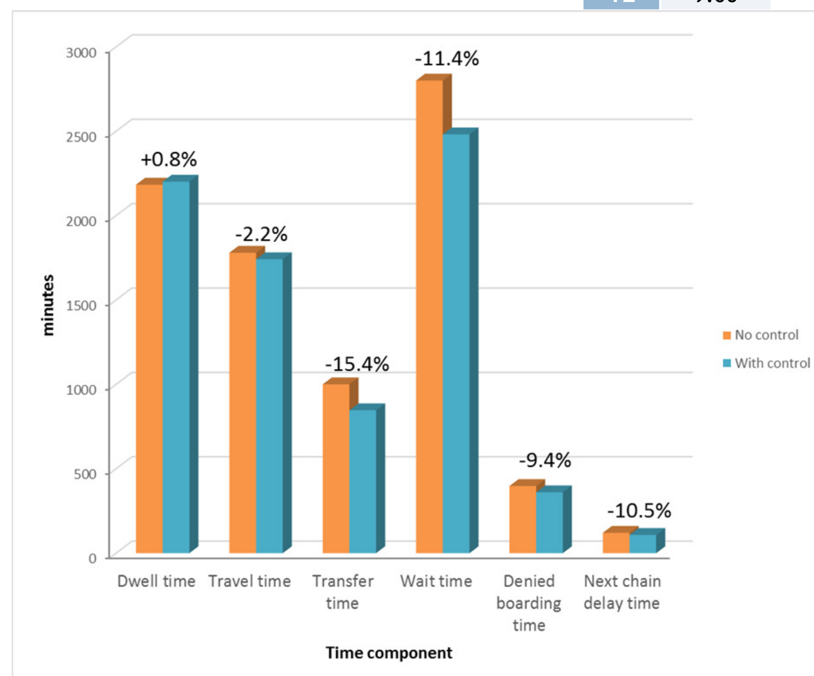
Scenario 5- Extreme demand and bunching on line 1

Bus	Arrival time
1	8:05
2	8:06
3	8:15
4	8:16
5	8:25
6	8:30
7	8:35
8	8:40
9	8:45
10	8:50
11	8:55
12	9:00

- Optimal control:
  - Hold bus 2 at stop 1 ,3 and 5
  - Total hold time: 3.3 minutes
  - Bus 2 slows from stop 1 to 2 and from stop 3 to 4, bus 4 slows from stop 1 to stop 4.
  - Total delay time reduction: 544 minutes (7%)

Bus	Stop	ΔV (km/h)	H (minutes)
1	1	2.0	0.0
	2	2.0	0.0
	3	2.0	0.0
	4	2.0	0.0
	5	2.0	0.0
2	1	-5.0	2.3
	2	2.0	0.0
	3	-5.0	0.2
	4	2.0	0.0
	5	2.0	0.7

Bus	Stop	ΔV (km/h)	H (minutes)
3	1	2.0	0.0
	2	2.0	0.0
	3	2.0	0.0
	4	2.0	0.0
	5	2.0	0.0
4	1	-5.0	0.0
	2	-5.0	0.0
	3	-5.0	0.0
	4	2.0	0.0
	5	2.0	0.0

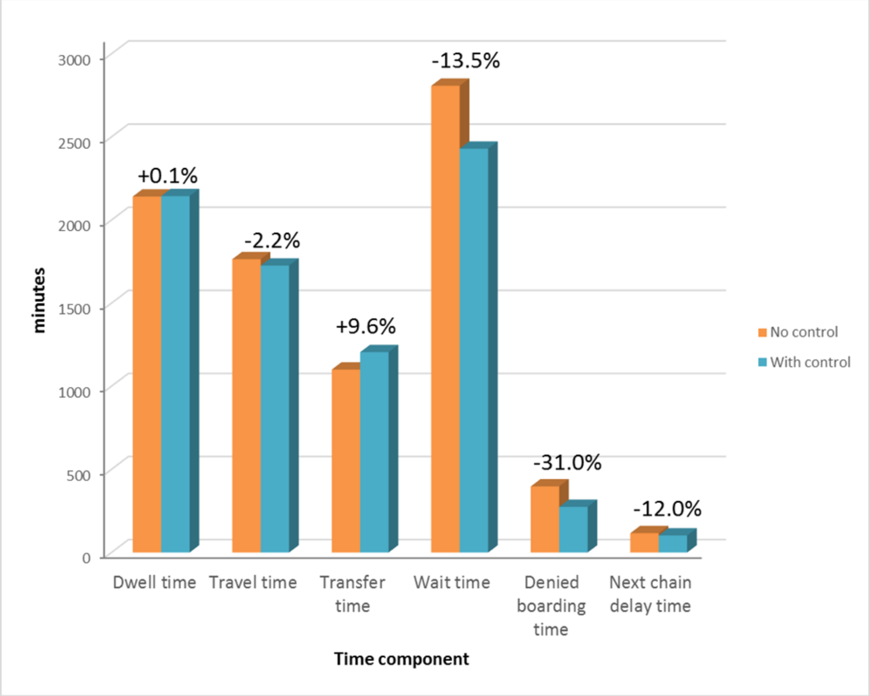


Scenario 6- Extreme demand and bunching on both lines

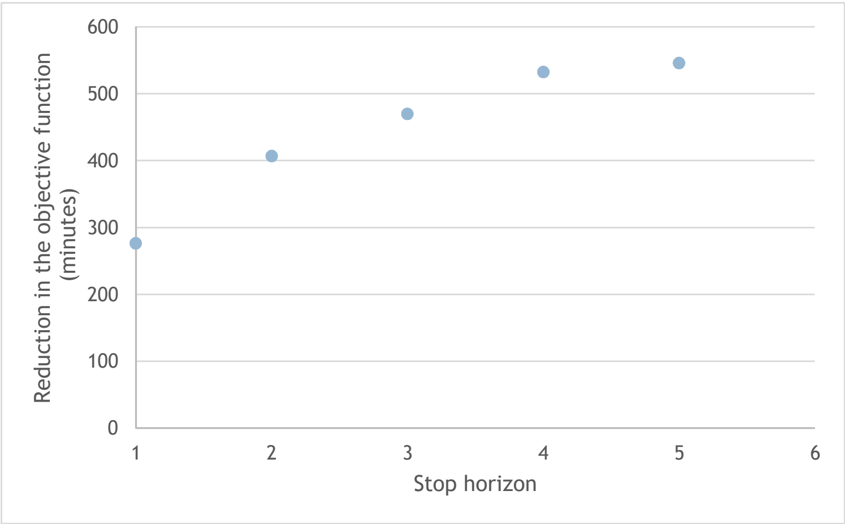
- Optimal control:
  - Hold bus 2 at stops 1 and 4. Hold bus 4 at stops 2 to 4
  - Total hold time: 6.5 minutes
  - Bus 2 slows at stops 1, and bus 4 slows from stops 1 to 3
- Total passengers time reduction: 446 minutes (5%)

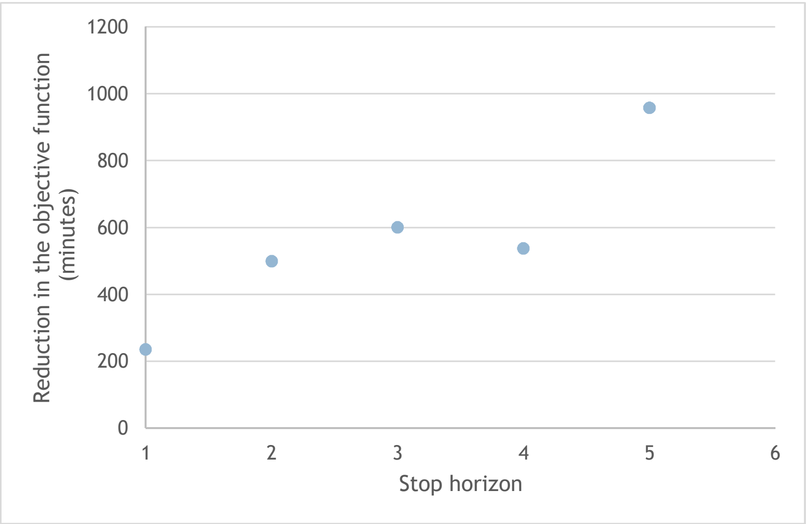
Bus	Stop	△V (km/h)	H (minutes)
1	1	2.0	0.0
	2	2.0	0.0
	3	2.0	0.0
	4	2.0	0.0
	5	2.0	0.0
2	1	-5.0	2.4
	2	1.4	1.7
	3	2.0	0.0
	4	1.6	0.0
	5	2.0	0.0

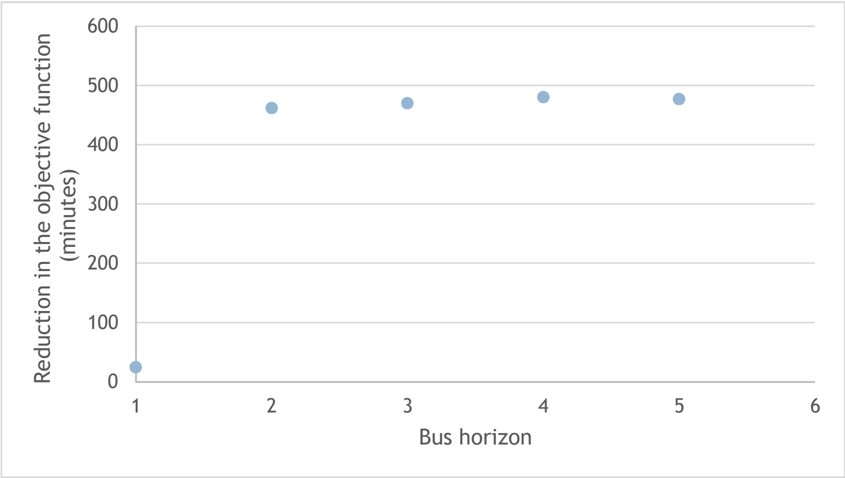
Bus	Stop	△V (km/h)	H (minutes)
3	1	2.0	0.0
	2	2.0	0.0
	3	2.0	0.0
	4	2.0	0.0
	5	1.8	0.0
4	1	-5.0	0.0
	2	-3.4	1.9
	3	2.0	0.4
	4	1.2	0.1
	5	2.0	0.0

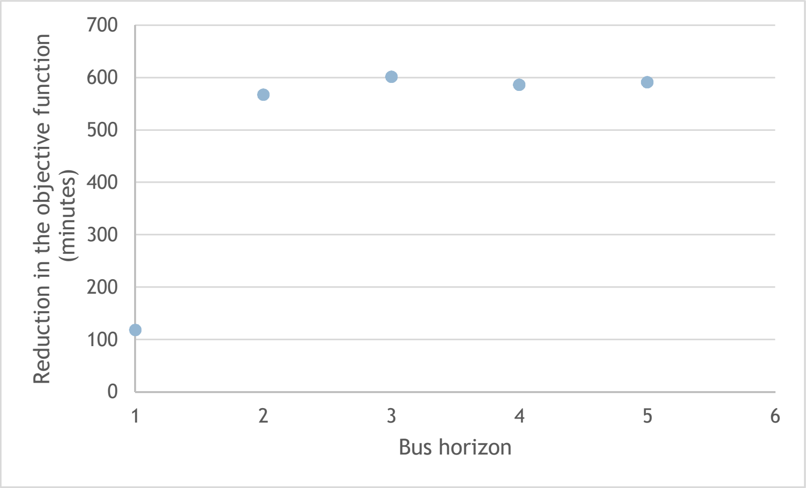


Effect of the horizon



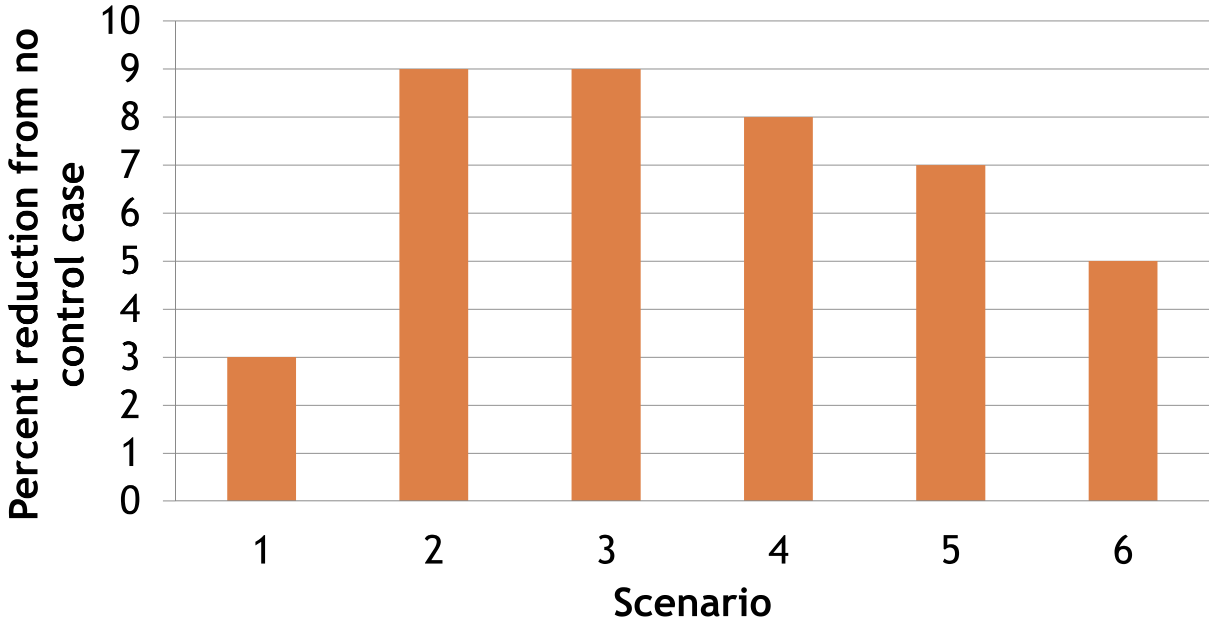






Results

- The operation control found to reduce the total time by up to 9%
  - Larger reduction with high demand and bunching
  - Smaller reduction in extreme load



Ongoing research

- Real world testing
- Model to predict times and demands
- Dealing with shared road segments
- Computational aspects
- Weights for different steps of the horizon

Thank you