Feedback Control of Bus Operations

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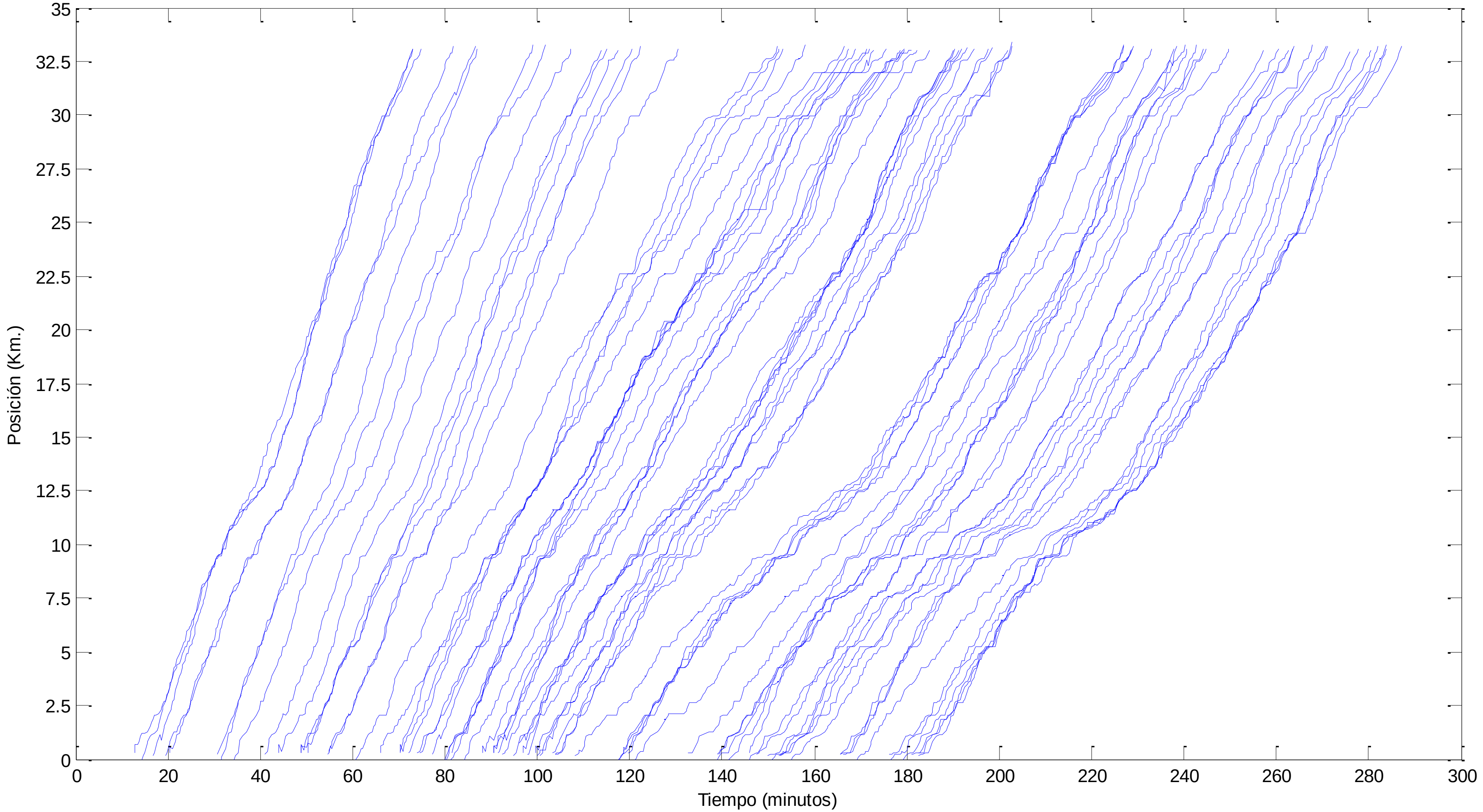
Special Thanks to Prof.Munoz Pontificia Universidad Católica de Chile

Santiago, Chile

Time-space trajectories Line 201, March 25th, 2009

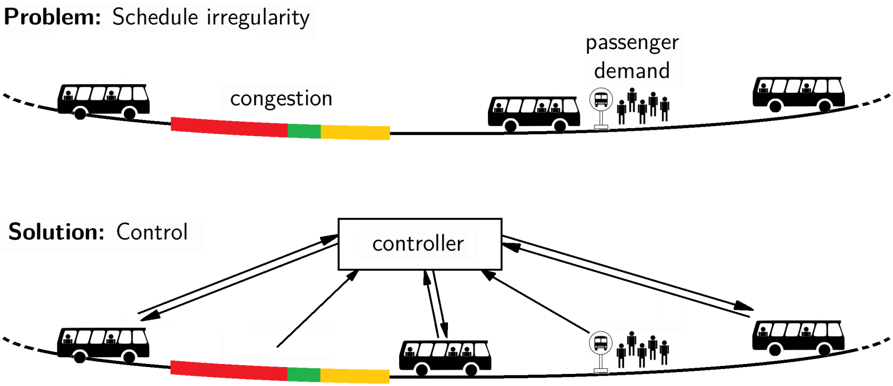


6:30 AM

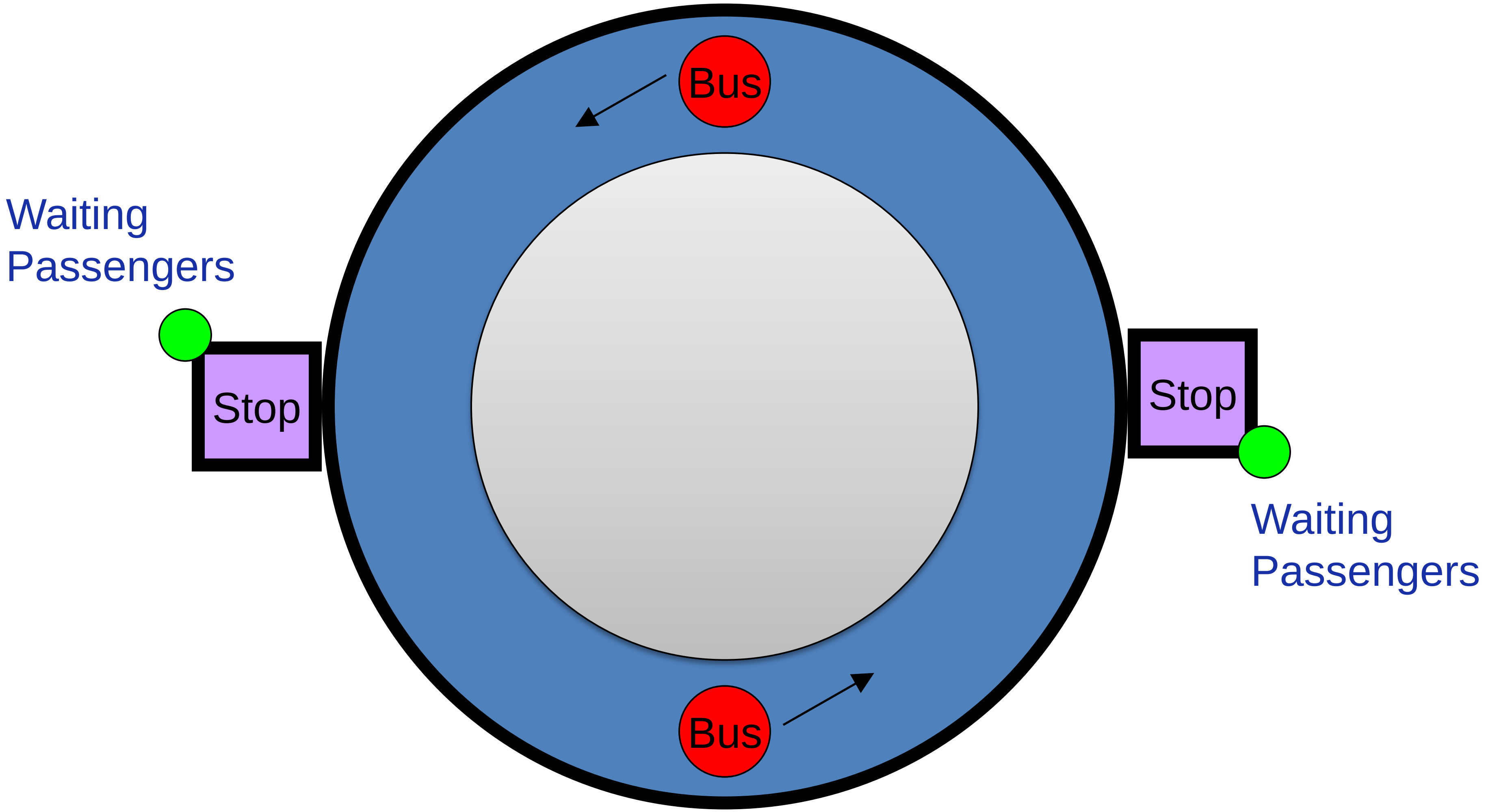
8:30 AM

Boston, MA; line 1 during winter

Motivation - Why do we need control?

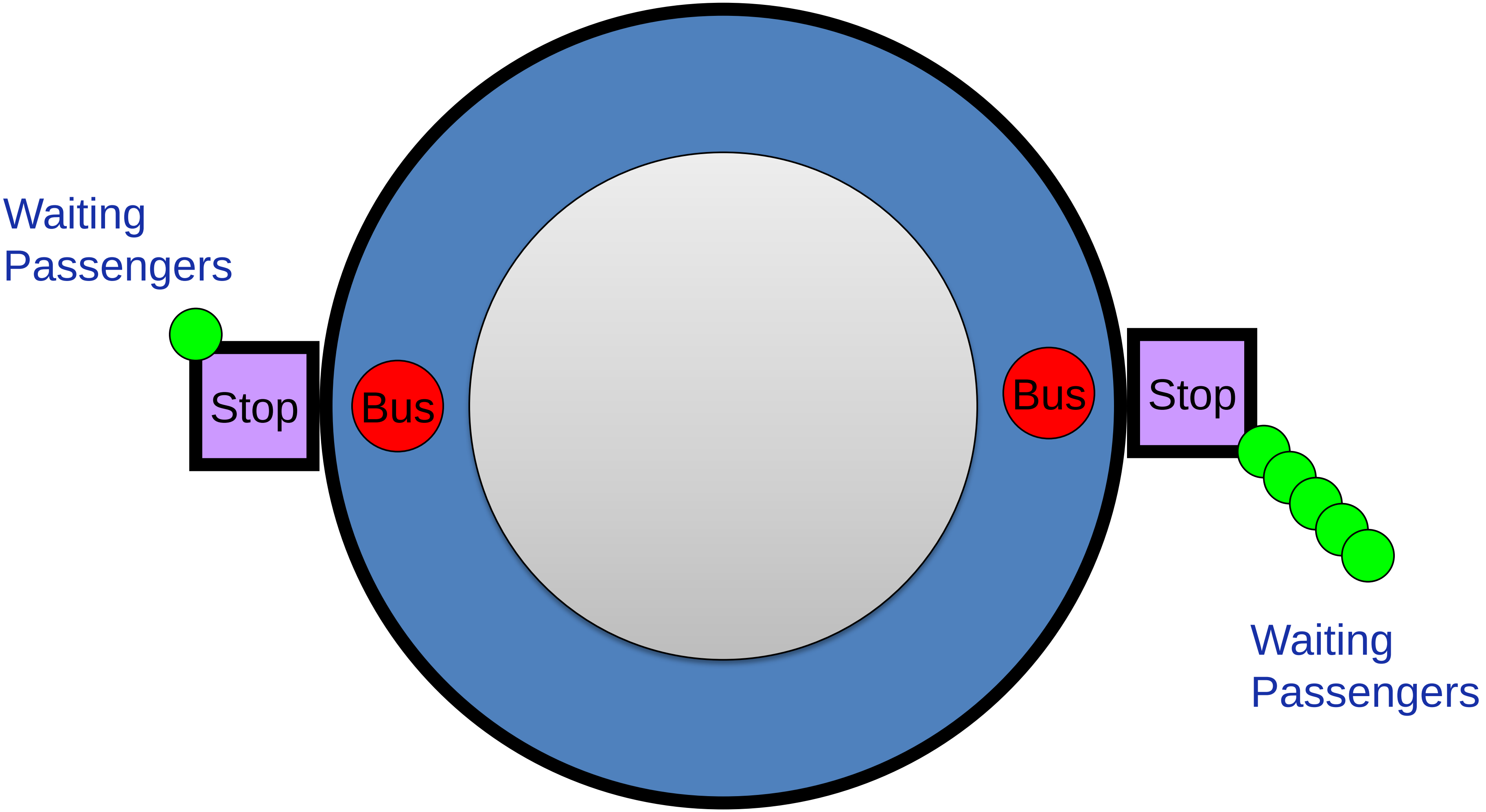


Bus Operations without Control



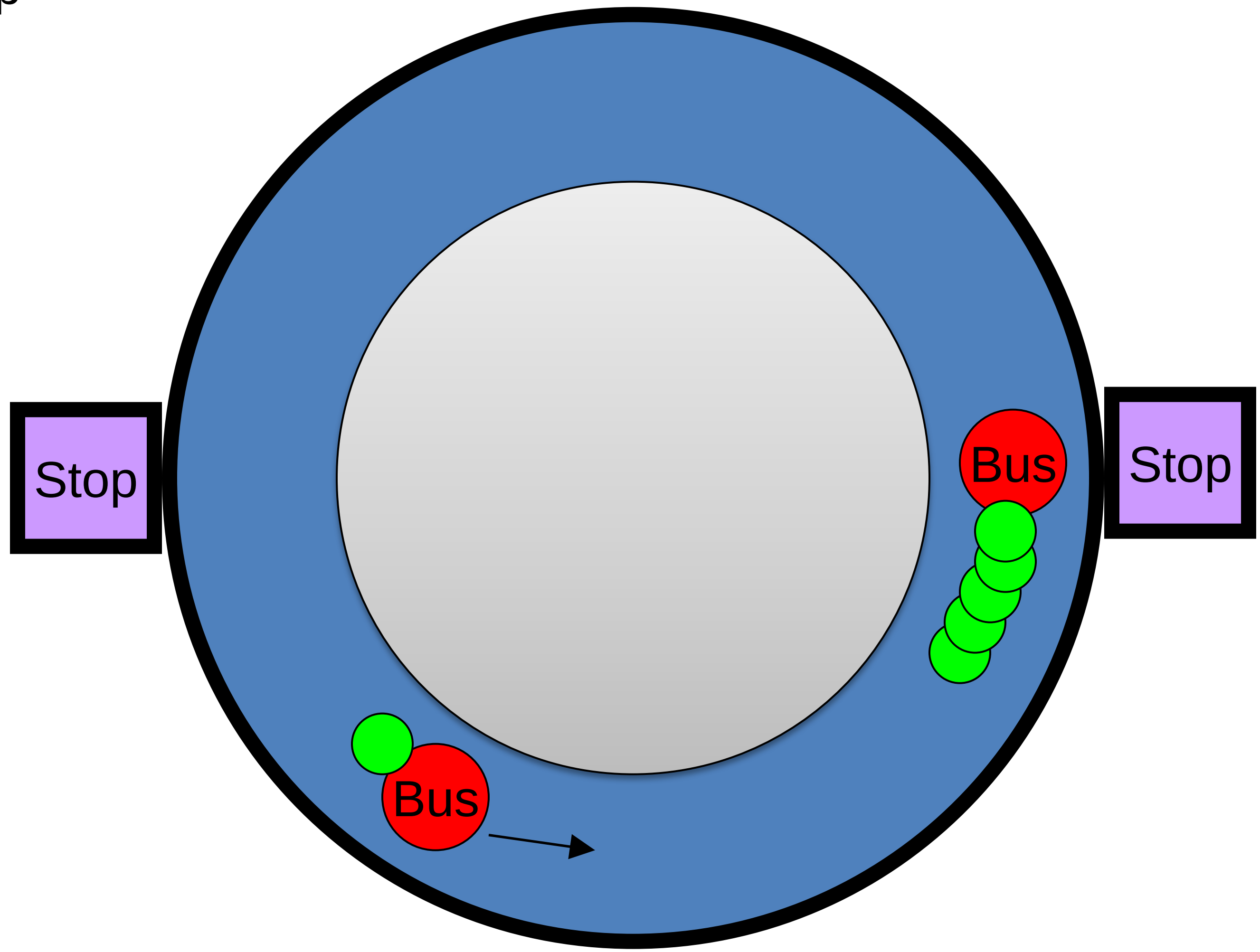
Bus Operations without Control

a small perturbation…

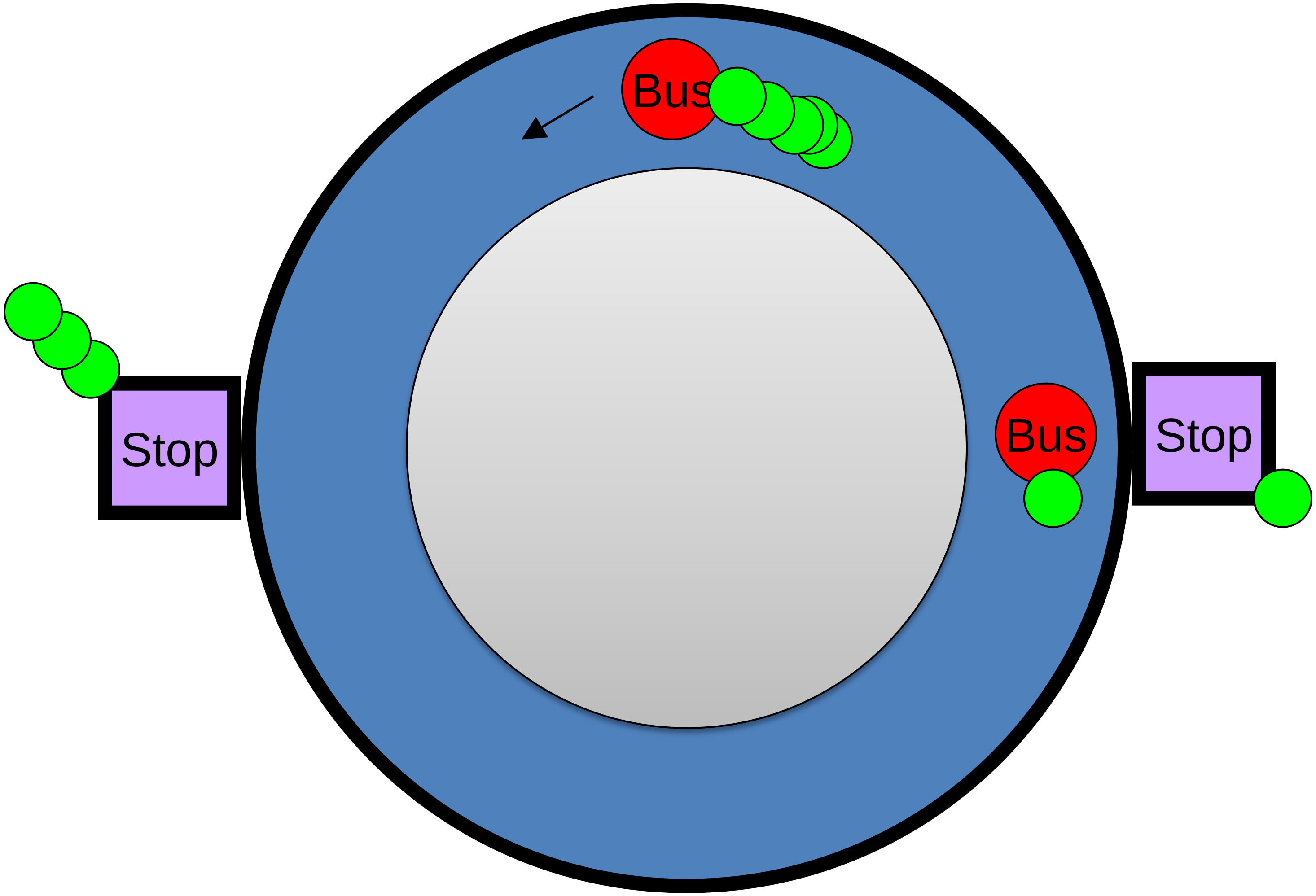


Bus Operations without Control

While one bus is still loading passengers the other bus already left its last stop

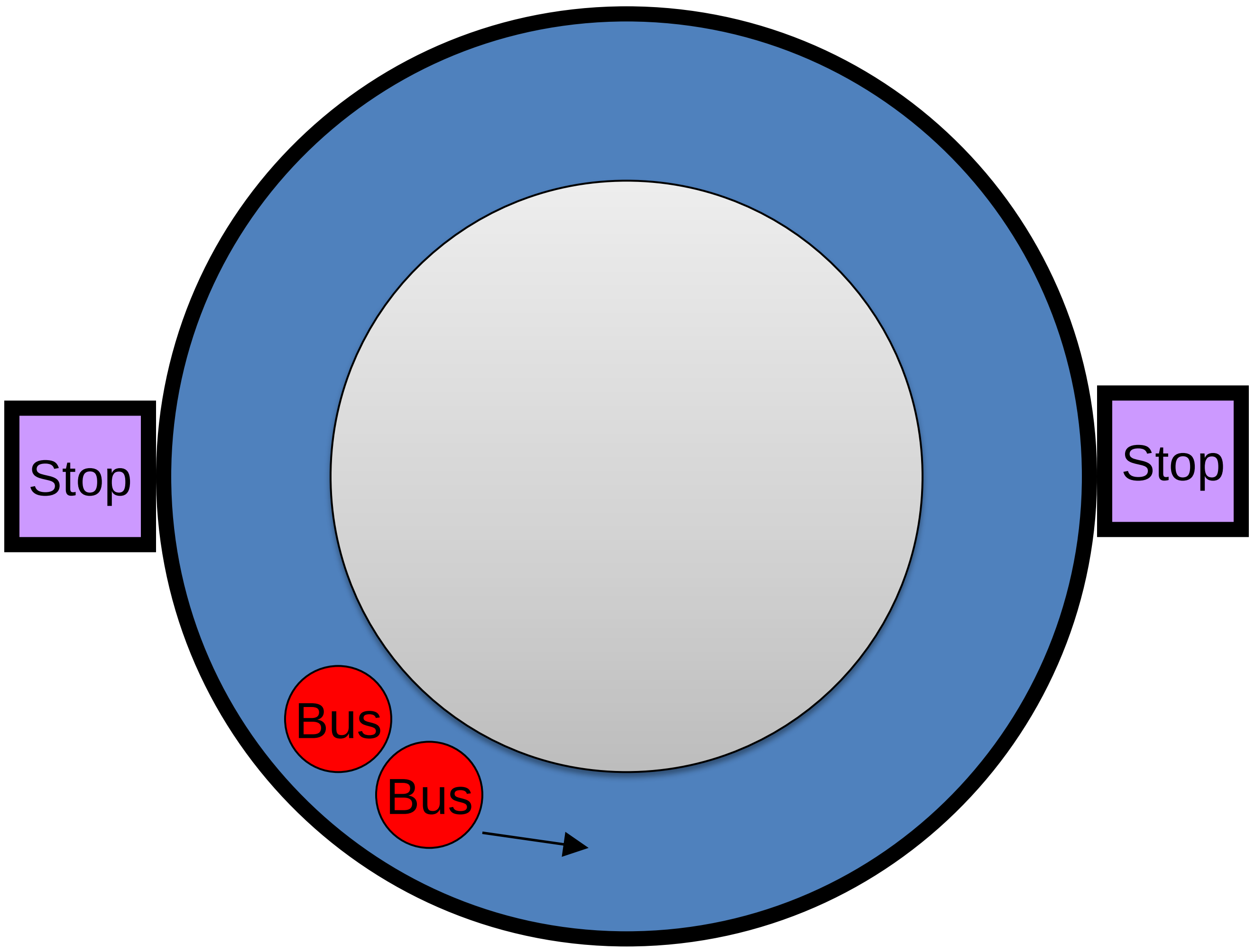


Bus Operations without Control



Bus Operations without Control

Without bus control, bus bunching occurs!!!



Stable versus unstable equilibrium

Stable versus unstable equilibrium

Bus bunching is specially serious, where bus capacity is an active constraint.

Bus bunching

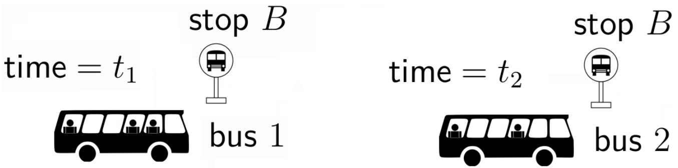
- Severe problem if not controlled
  - Most passengers wait longer than they should for crowded buses
  - Reduces reliability affecting passengers and operators
  - Affects Cycle time and capacity
  - Creates frictions between buses (safety)
  - Put pressure in the authority for more buses

Contribution: Control Mechanism to Avoid Bus Bunching!

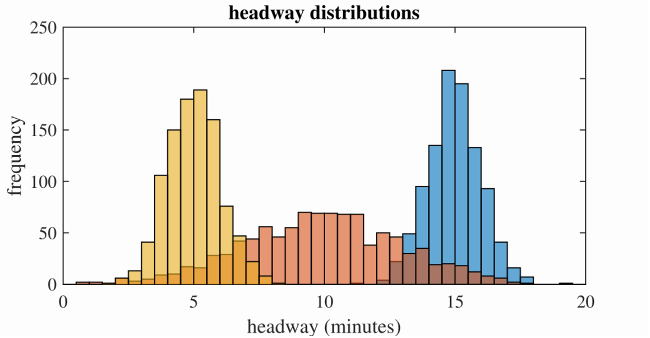
Classification of bus control methods

- **Station control** (only at some stops)
  - Holding
  - Stop-skipping
- **Inter-station control** (while buses are moving)
  - Traffic signal priority
  - Speed control (focus of this lecture)

Problem statement - Headways

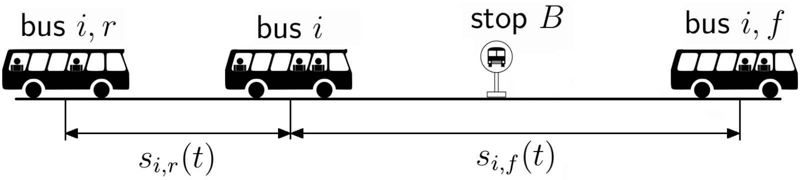


headway $= t_2 - t_1$



Spacings - I-controller

use spacing as a proxy for headway:



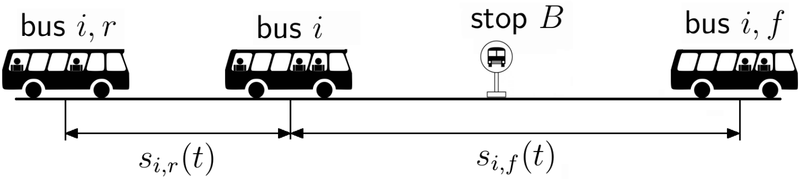
spacing error: $e_i(t) = s_{i,f}(t) - s_{i,r}(t)$

solution with classical control:

$$\text{I-controller: } v_i(t) = v_i(t-1) + K_{\mathsf{I}} \cdot e_i(t)$$

Spacings - PI-controller

use spacing as a proxy for headway:



spacing error: $e_i(t) = s_{i,f}(t) - s_{i,r}(t)$

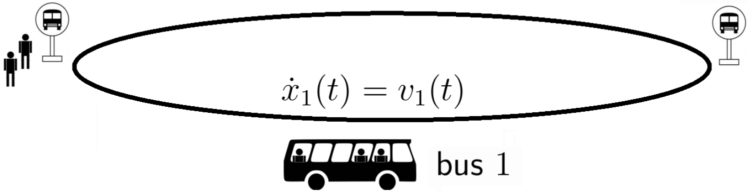
solution with classical control:

PI-controller: $v_i(t) = v_i(t-1) + K_{\mathsf{P}} \cdot (e_i(t) - e_i(t-1)) + K_{\mathsf{I}} \cdot e_i(t)$

Bus and passenger dynamics

simple scenario with 1 bus and 2 stops
(demand only from stop A to stop B)

$$\dot{m}_{A,B}(t) = \beta_{A,B}(t) - q^{\text{in}}_{A,1}(t)$$



$$\dot{x}_1(t) = v_1(t)$$

$$\dot{n}_{1,B}(t) = q^{\text{in}}_{A,1}(t) - q^{\text{out}}_{1,B}(t)$$

Process of a bus waiting at a stop

bus starts waiting at a stop:
a) **IF** it arrives at the stop.

bus can leave the stop:
b) **IF** there are no passengers trying to alight,
AND
  EITHER
    c1) **IF** there are no passengers trying to board,
  OR
    c2) **IF** the bus has no more vacant places.

Hybrid model predictive controller

$$\underset{v_i}{\text{minimize}} \quad \sum_{k=1}^{N} \sum_{i=1}^{K_b} \overbrace{e_i^2(k)}^{\text{spacing error term}} + \sigma \cdot \overbrace{(v_{i,\max}(t,k) - v_i(k))^2}^{\text{speed error term}}$$

subject to initial state

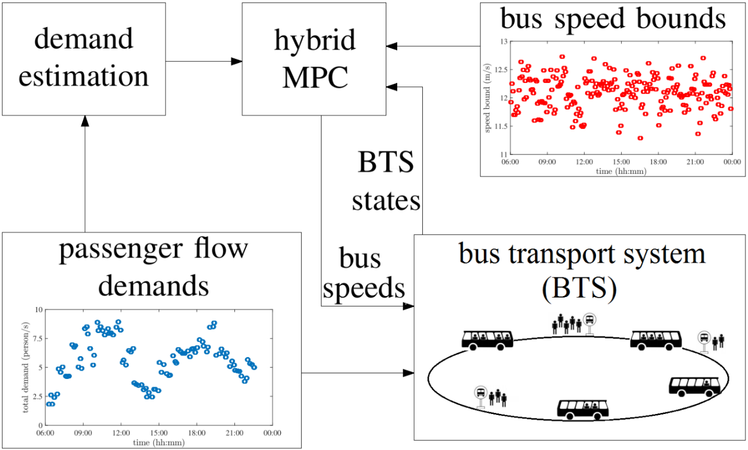
for $k = 1, \ldots, N$:

bus and passenger dynamics

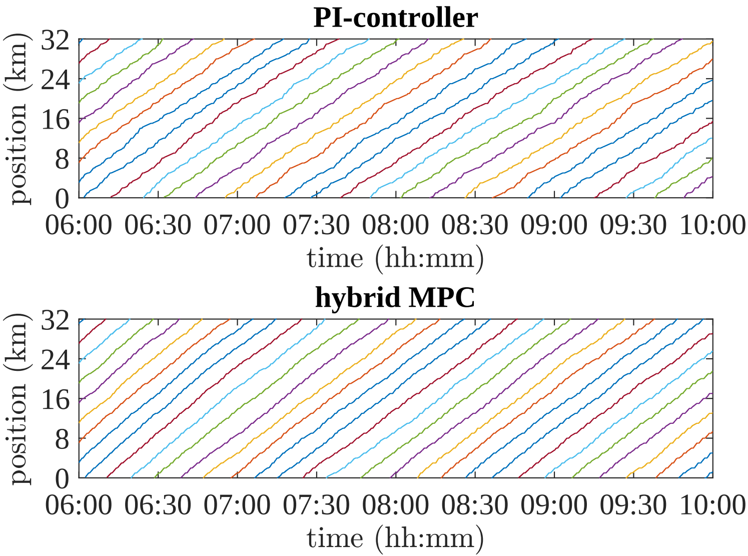
bus speed constraints

passenger flow constraints

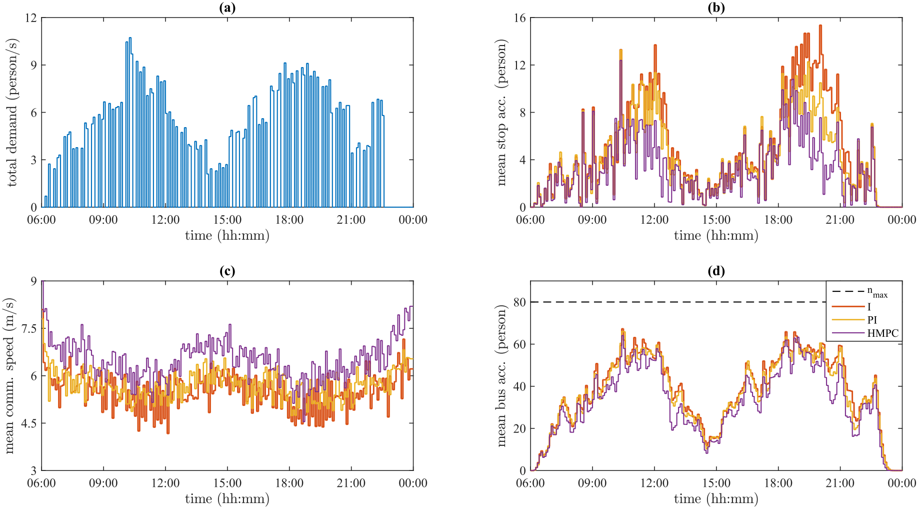
Feedback control structure



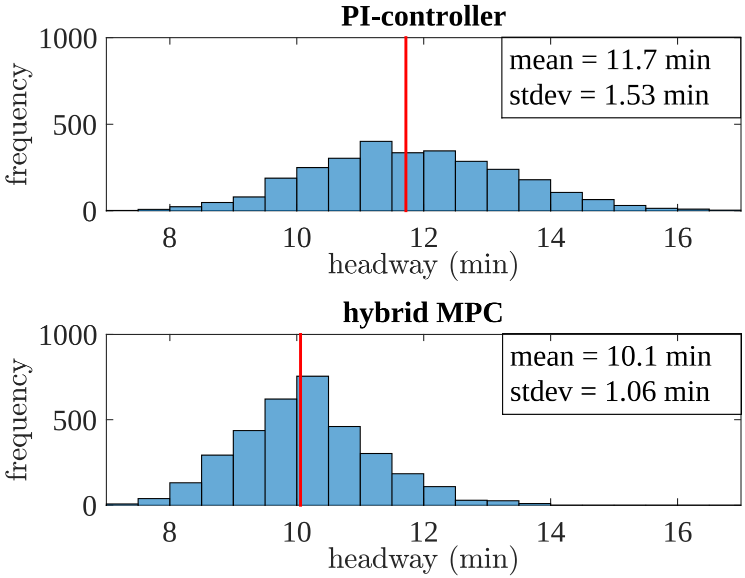
Time-space diagrams



Demand, speed, and accumulations



Headway distributions



Bus Bunching: A holding strategy implemented in Chile

Thanks to Prof.Munoz

Pontificia Universidad Católica de Chile

Objective

- Propose a headway control mechanism for a high frequency & capacity-constrained corridor.
- Consider a single control strategy based on Holding
- Explore its impact in waiting, reliability, capacity and comfort
- Identify scenarios where the control strategy is recommended.

Approach

Based on real-time information (or estimations) about:

Bus position.

Bus loads.

# of Passengers waiting at each stop.

A rolling-horizon optimization model each time a bus reaches a stop or every certain amount of time (e.g. 2 minutes)

The model minimizes:

Time waiting for first bus + time waiting for subsequent buses +
+ time held + penalty for being prevented from boarding

4. Experiment: Control strategies

No control

Spontaneous evolution of the system.

Buses dispatched from terminal as soon as they arrive or until the design headway is reached.

No other control action is taken along the route.

Threshold control

Myopic rule of regularization of headways between buses at every stop.

A bus can be held at every stop to reach a minimum headway with the previous bus.

Holding (HRT)

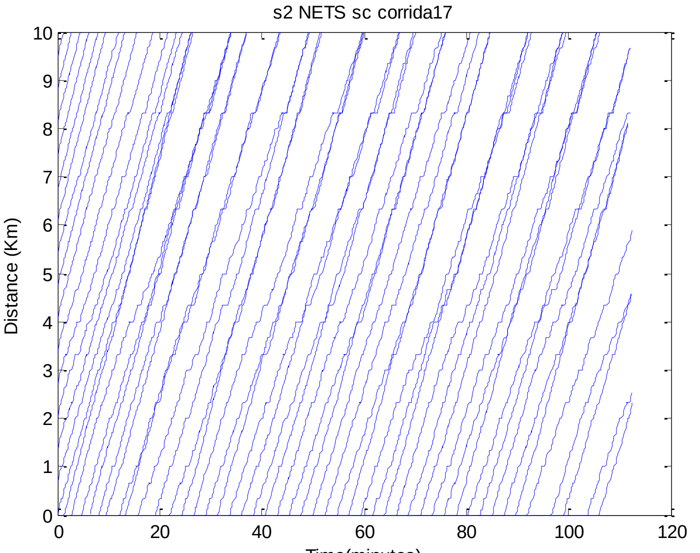
Solve the rolling horizon optimization model not including green extension or boarding limits.

5. Results: Time savings

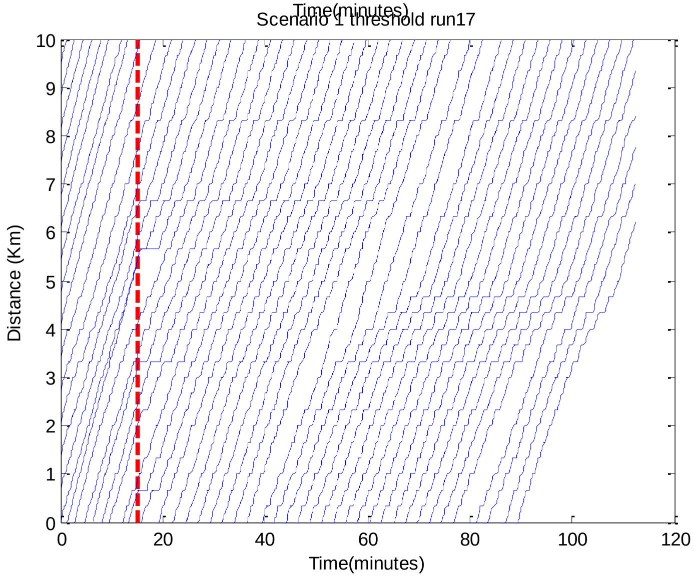
	No control	Threshold control	HRT
Wfirst	4552.10	1220.47	805.33
Std. Dev.	459.78	310.43	187.28
% reduction		-73.19	-82.31
Wextra	1107.37	661.70	97.49
Std. Dev.	577.01	1299.95	122.59
% reduction		-40.25	-91.20
Win-veh	270.57	6541.56	1649.28
Std. Dev.	36.00	868.74	129.56
% reduction		2317.74	509.57
Tot	5930.03	8423.73	2552.10
Std. Dev.	863.80	2377.11	390.01
% reduction		42.05	-56.96

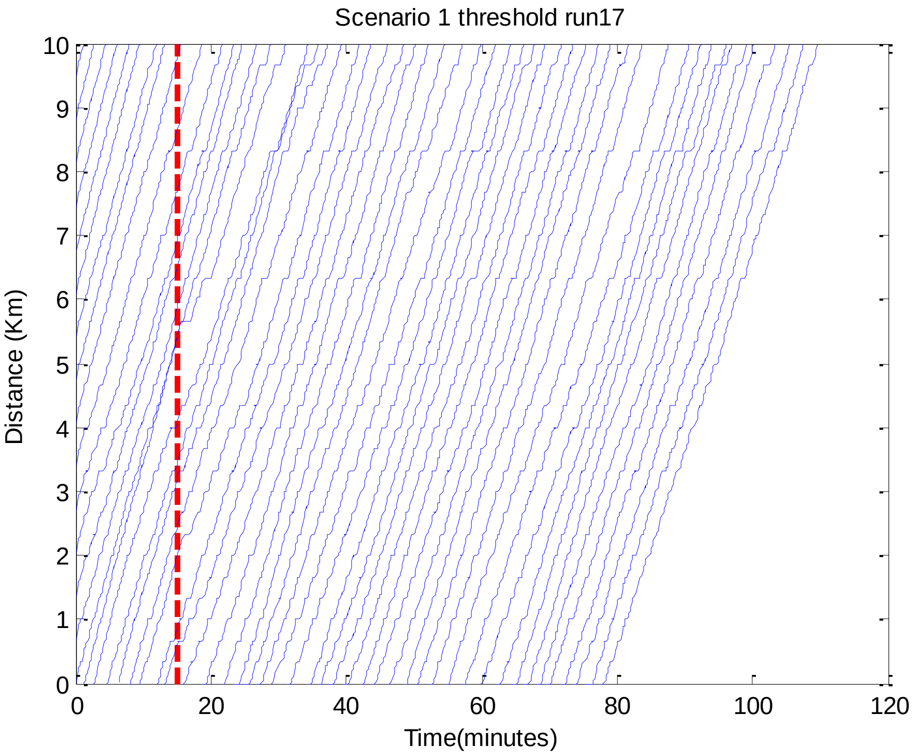
5. Results: Time-space trajectories

No Control



Threshold

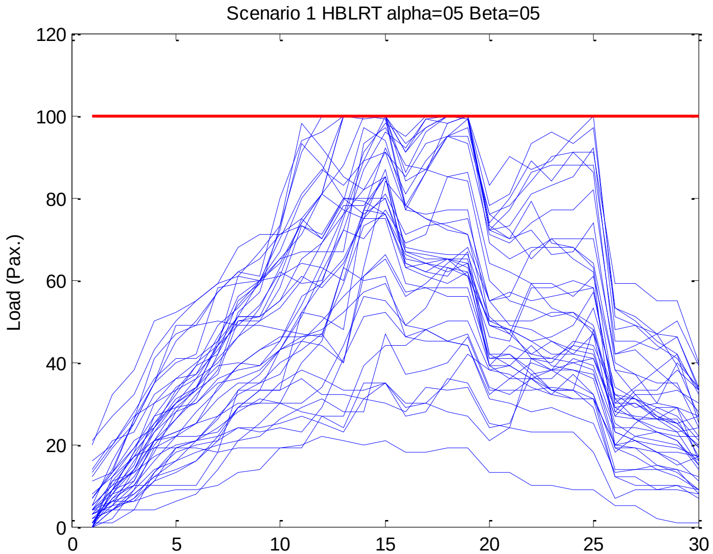




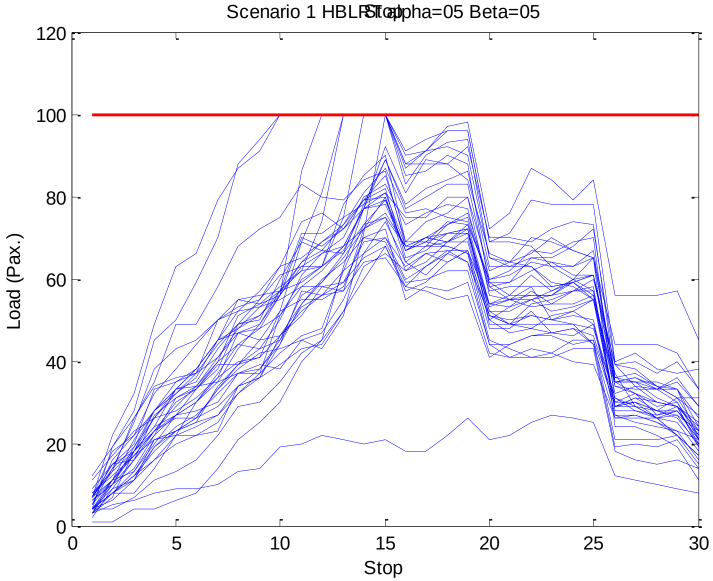
HRT

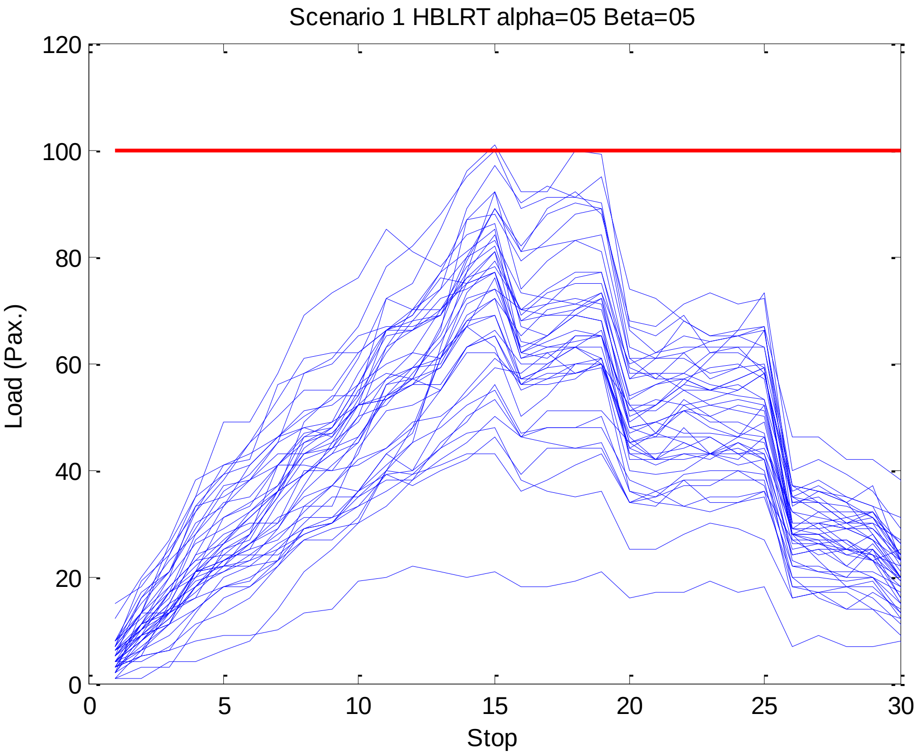
5. Results: Bus Loads

No Control



Threshold

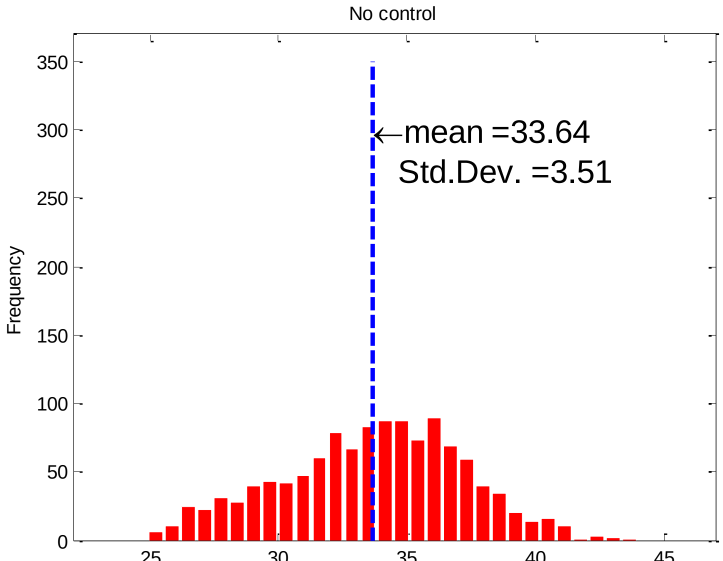




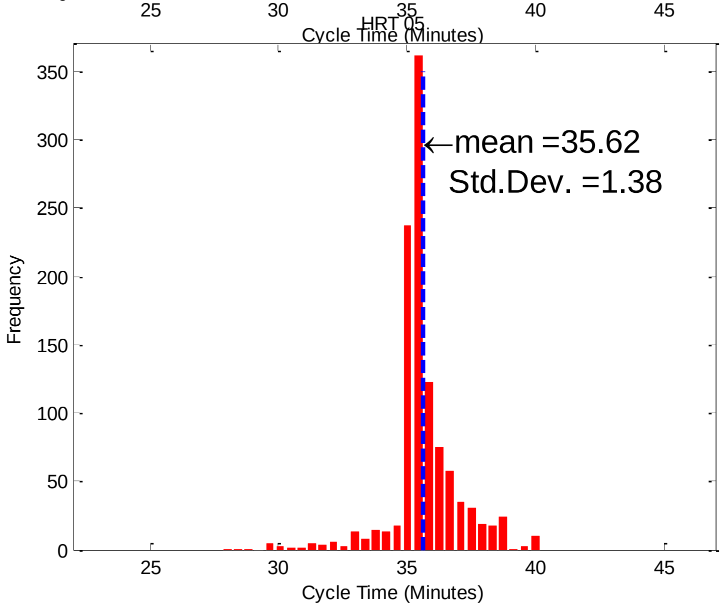
HRT

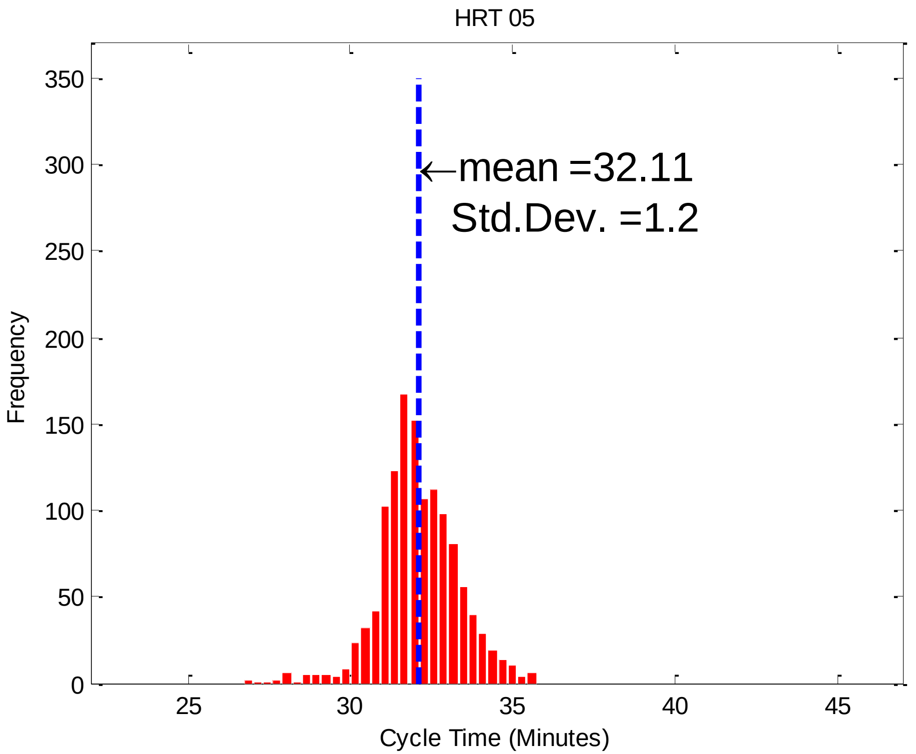
5. Results: Cycle Time

No Control



Threshold





HRT

5. Results: Waiting time Distribution

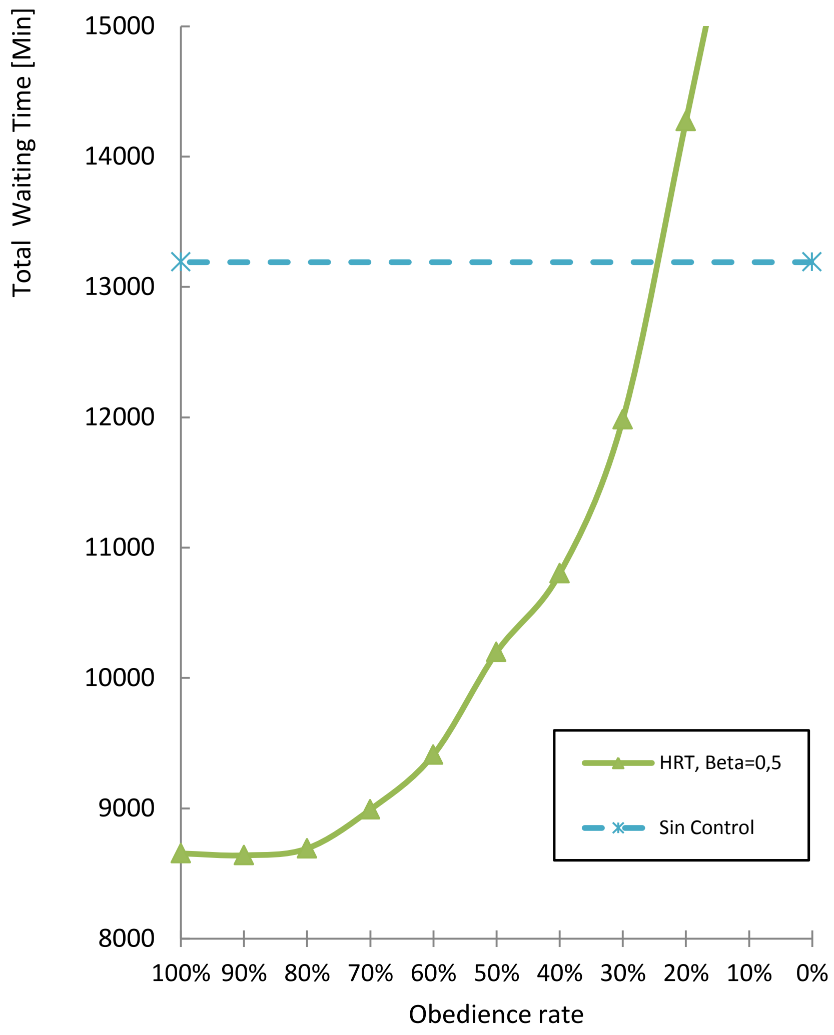
% of passengers that have to wait between:

	Period 15-25			Period 25-120		
	0-2 min	**2-4 min**	**> 4 min**	**0-2 min**	**2-4 min**	**> 4 min**
No Control	57.76	29.60	12.64	63.46	27.68	8.86
Threshold Control	78.15	20.64	1.21	82.52	16.46	1.02
HRT	79.24	20.29	0.47	87.30	12.62	0.08

6. Impact of implementation failures

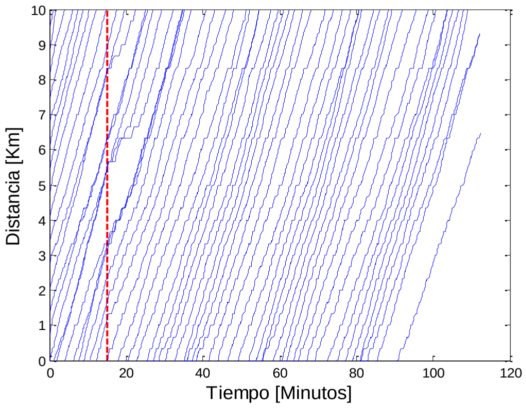
	Disobeying Drivers	Technological Disruption
Homogeneous distribution across buses	Similar disobedience across all drivers	Random signal fail
Concentration in certain buses	A subset of drivers never obey	Failure in the signal receptor equipment
Concentration in certain stops		Signal-less zone

Common disobedience rate across drivers

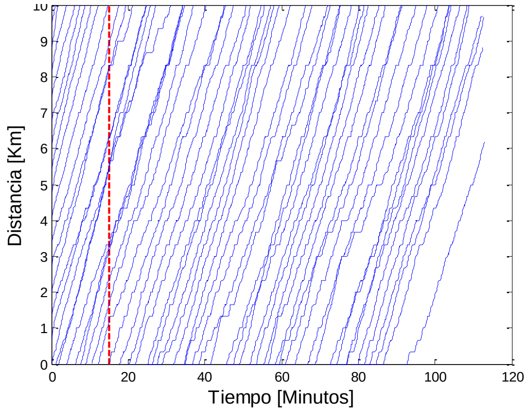


Common disobedience rate across drivers

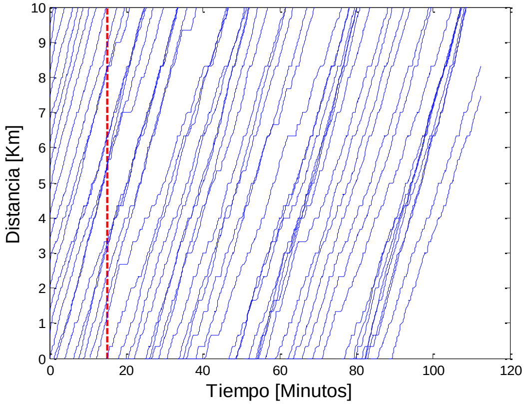
HRT



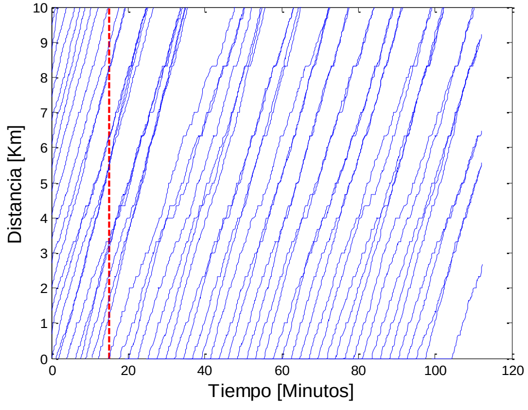
HRT, 50% obedience



HRT, 20% obedience



No Control



7. Implementation

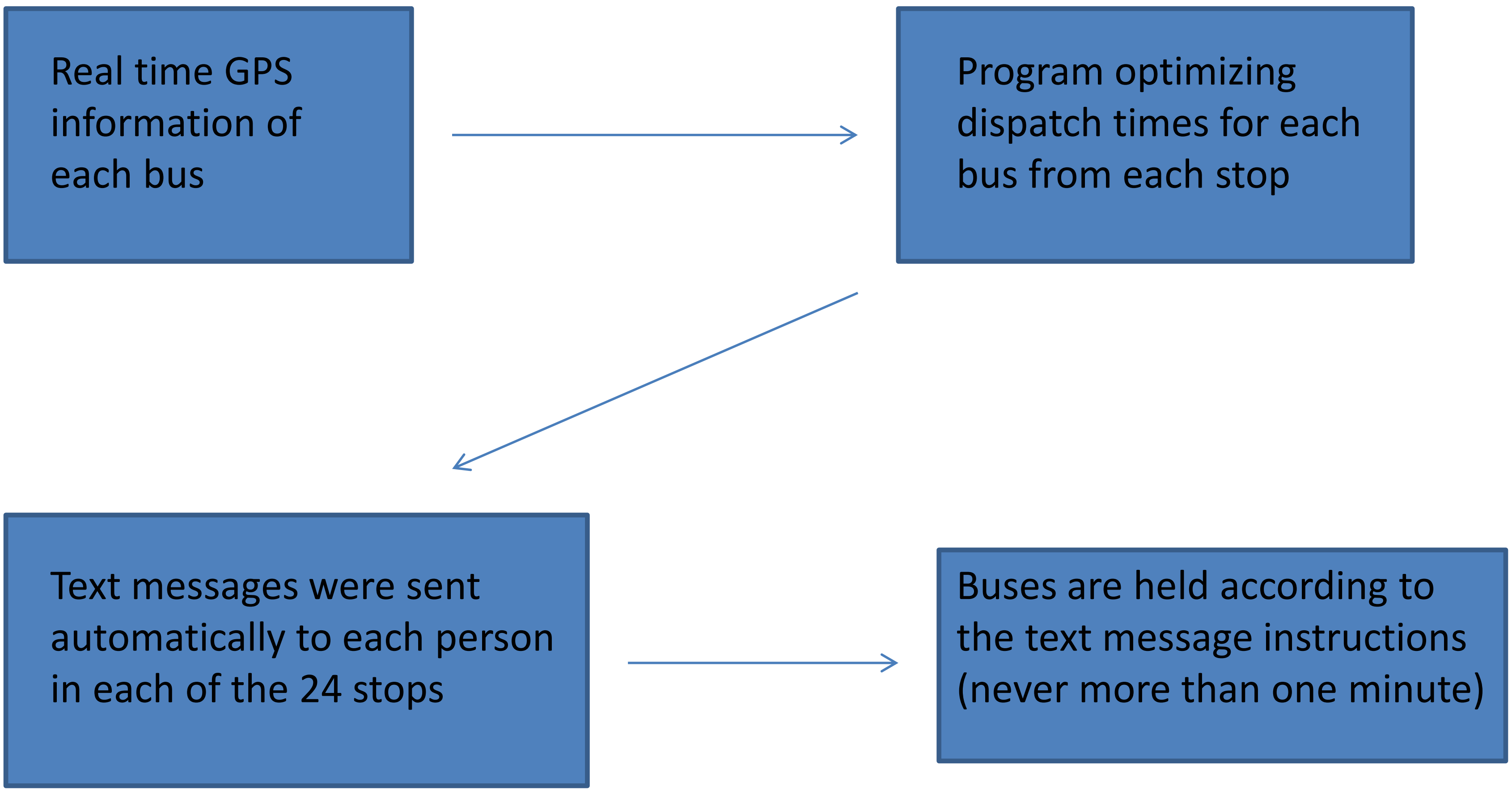
- The first pilot plan consisted in implemnting our holding tool in buses of line 210 of SuBus from Transantiago (Santiago, Chile) along its full path from 7:00 to 9:30 AM.

- We chose 24 out of 130 stops to hold buses

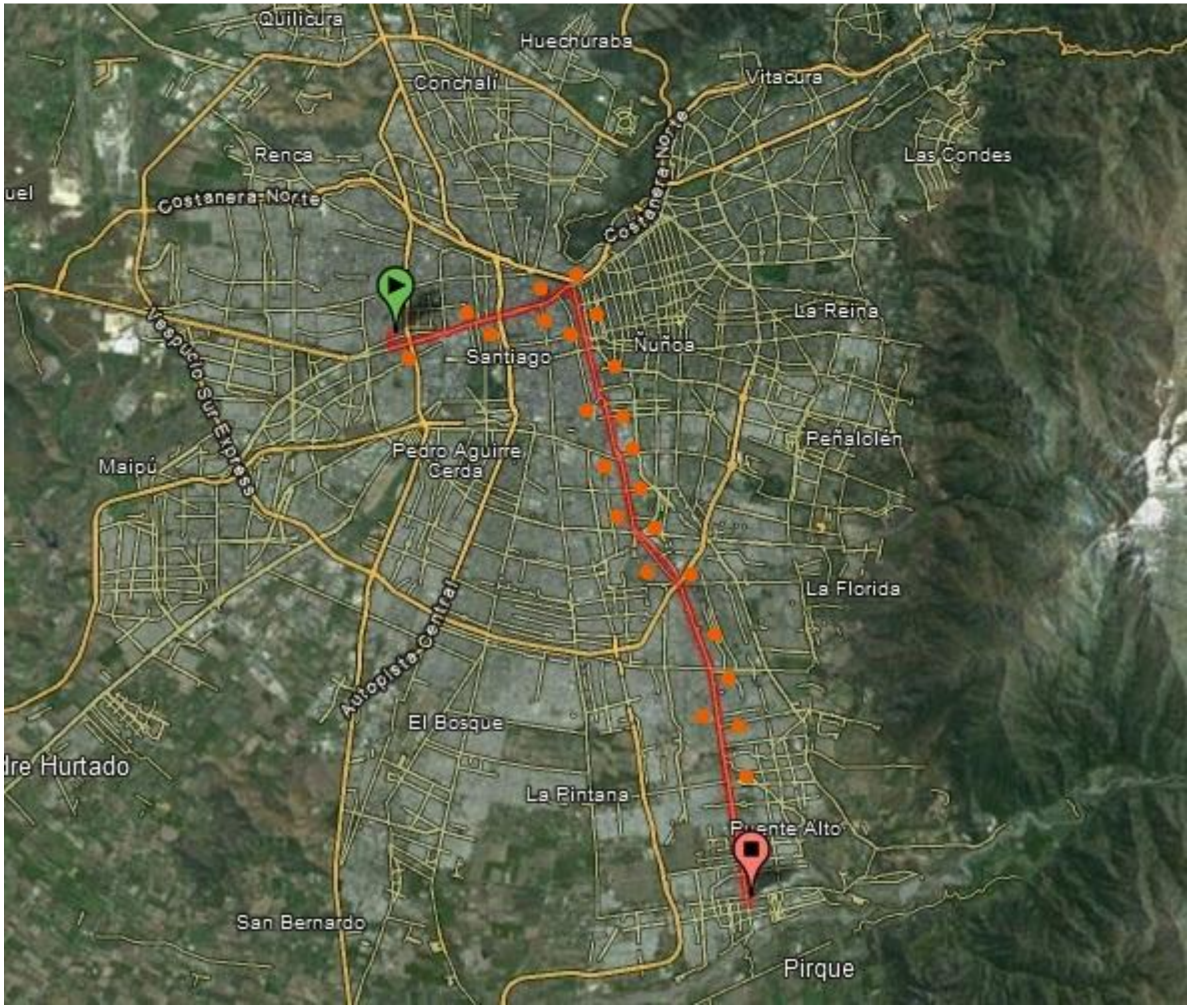
- One person in each of these 24 stops received text messages (from a central computer) into their cell phones indicating when each bus should depart from the stop.

Plan Description

Implementation



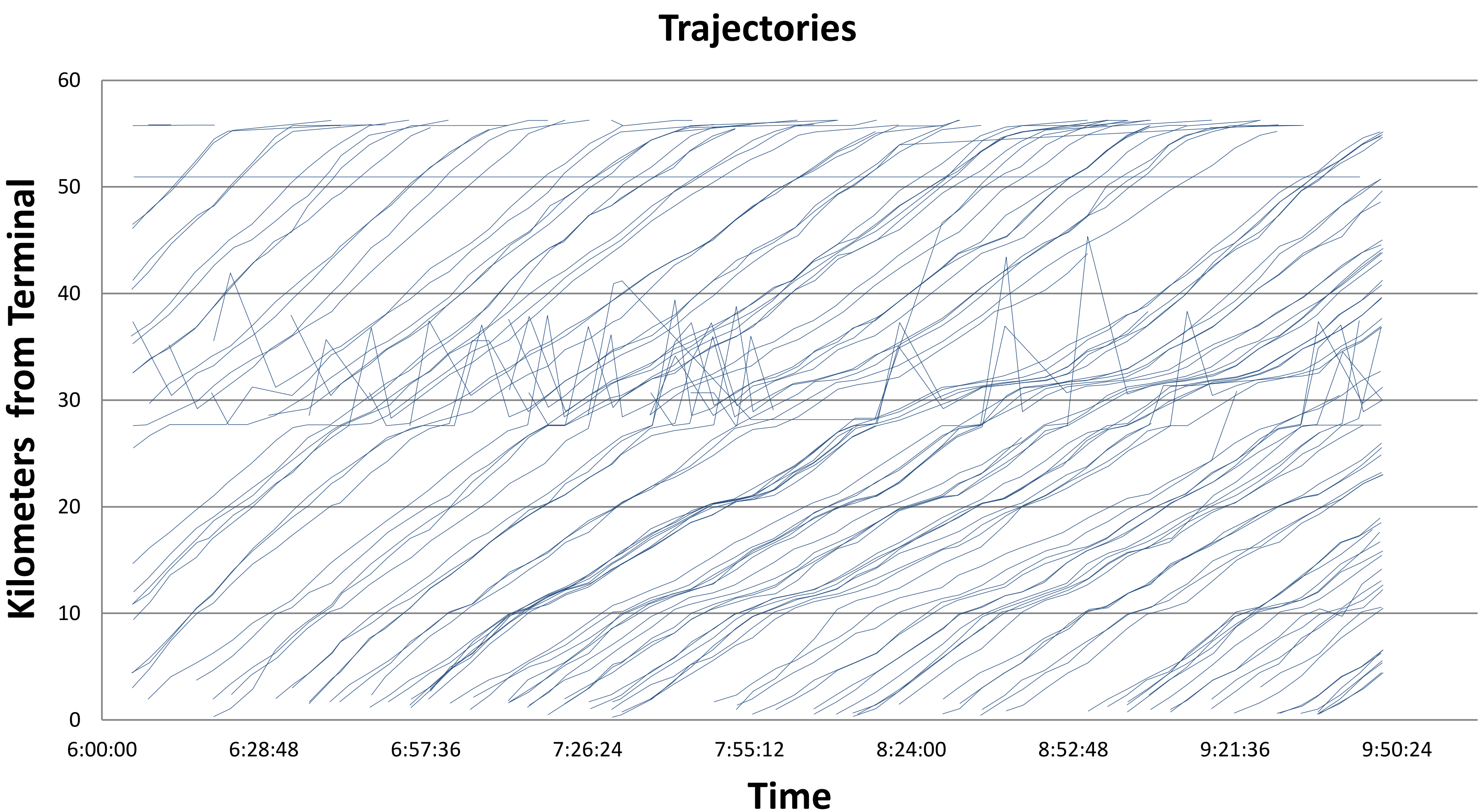
Control Points



The results were very promising even though the conditions were far from ideal

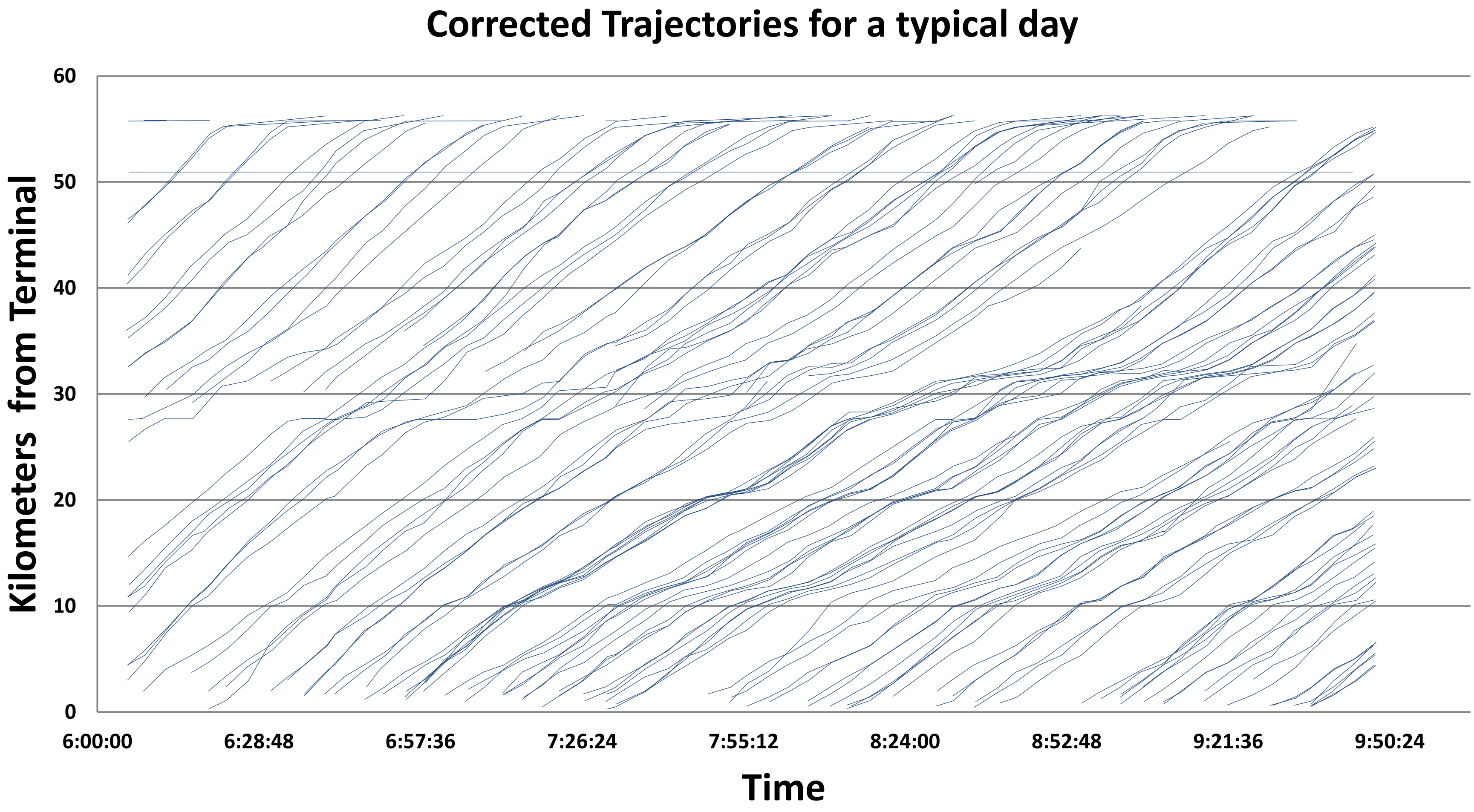
Input Data

- Trajectories of given GPS data (on a regular day)



Input Data

- The trajectiories traveled by buses can be inferred as:



Pilot Analysis

- Trajectories of our experiment