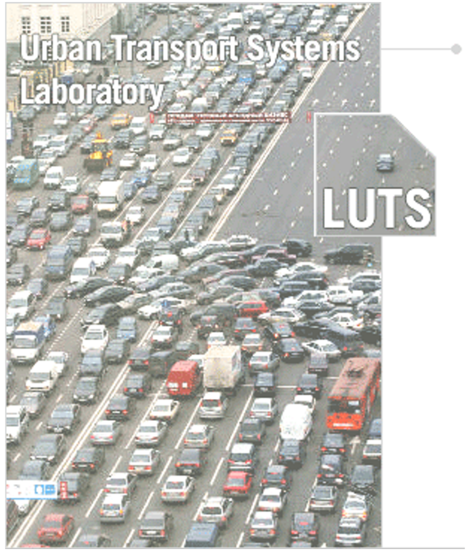
Traffic Engineering
CIVIL-349

Preferential Treatment of Bus systems



Prof. Nikolas Geroliminis

Transit signal priority

Pre-signals

Bus bunching

Transit Signal Priority

Special thanks to Prof. Skabardonis (UC Berkeley)

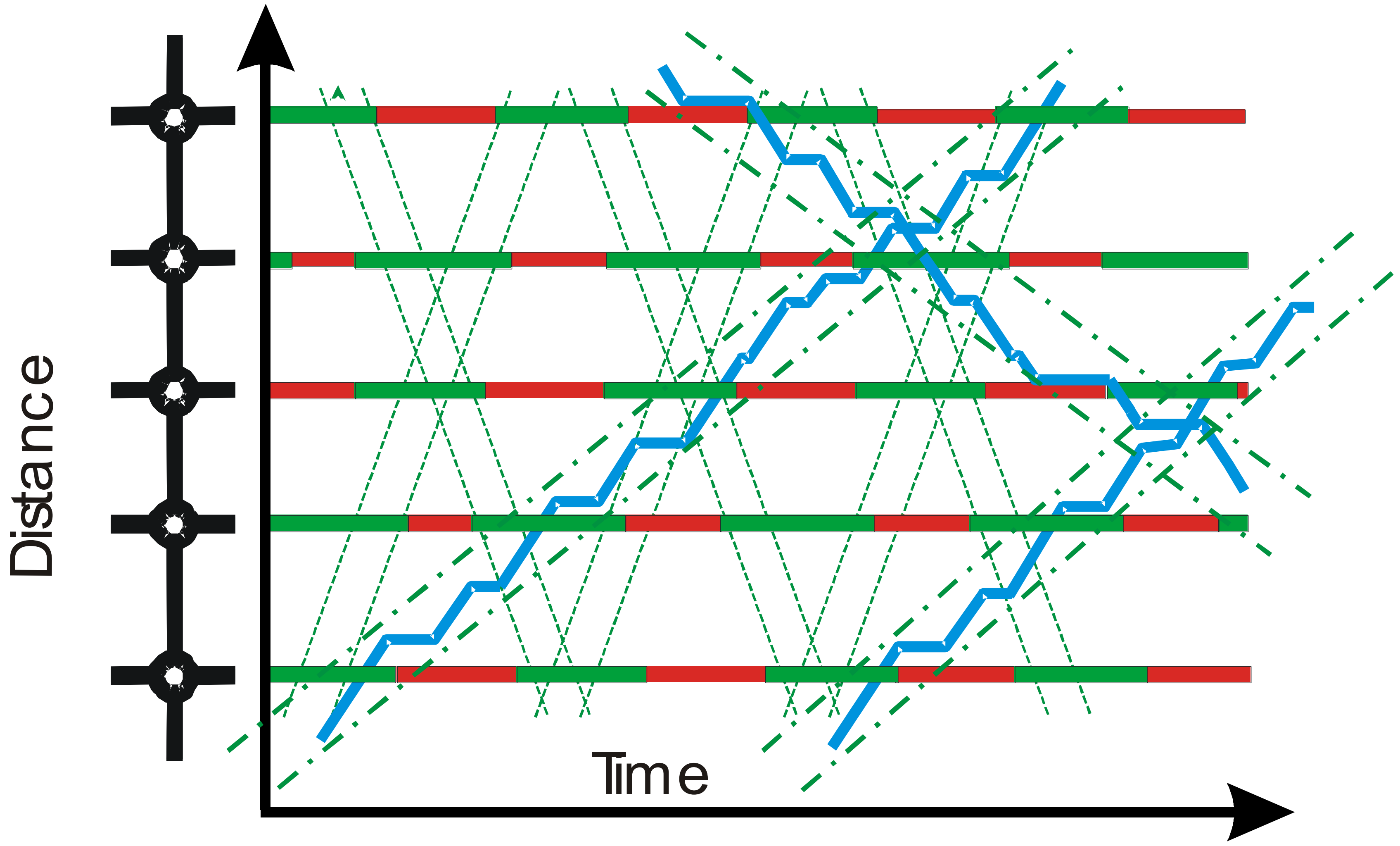
Transit Signal Priority – Examples

- Zurich: nearly zero traffic delay for trams, even with mixed traffic (and punctuality!!)
- Geneva tram: green wave through downtown intersections
- Some US applications: < 3 s savings per intersection , or ...

Overview: Transit Priority Strategies

- Design
  - Bus (HOV/HOT) lanes
  - Queue Jump lanes
- Control (Traffic Signals)
  - Passive
  - Active
- Combination
- Benefits to Transit
  - Travel time (delay) reduction
  - Improved schedule reliability
  - Customer satisfaction/ridership increase

Passive Priority Strategies (1)



Source: L Head, TCRP A-16

Passive Priority Strategies (2)

Signal Timing Plan

Offsets/Splits/Cycle

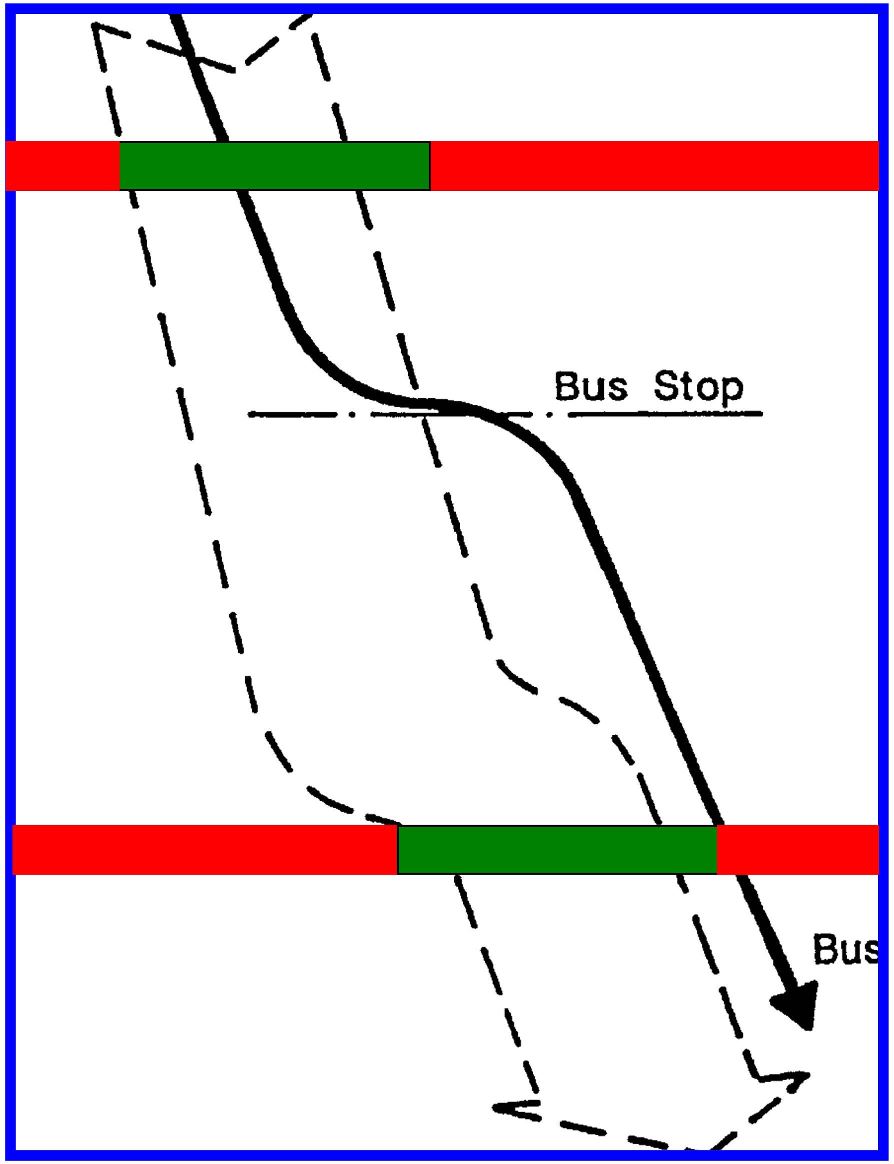
Optimized to provide priority to transit movements

Apply Bus Weighting Factors in optimization

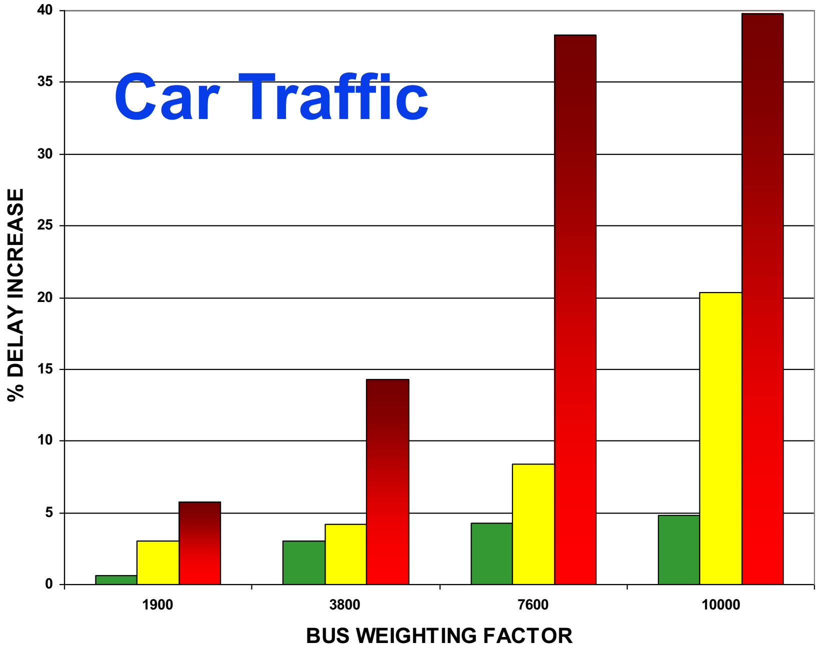
$$PI = \sum_{i=1}^{N} W_{Di} \ D_i + K W_{si} \ S_i$$

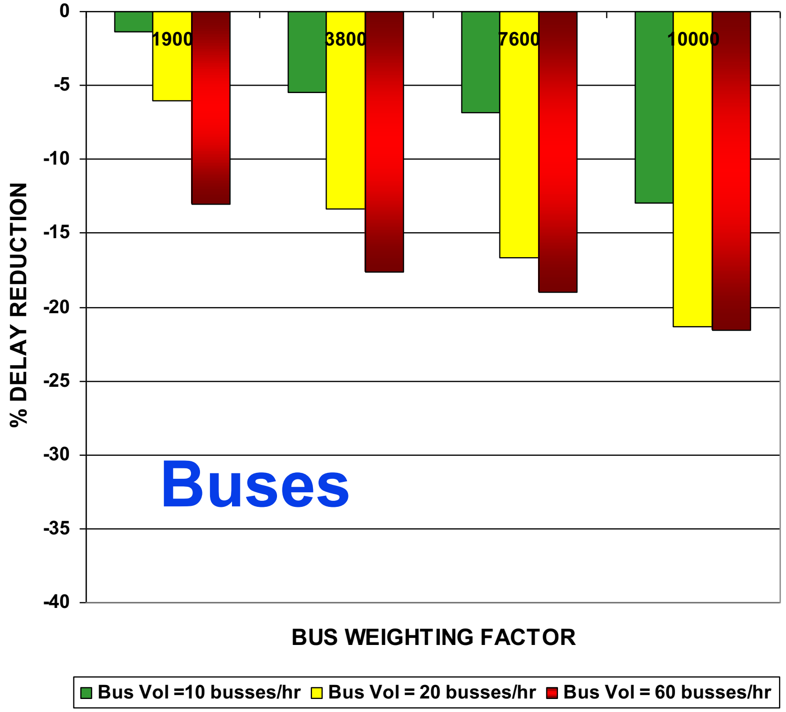
Di: delay for link i.   Si: stops for link i
K: is the stop penalty

For the bus links
additional weighting factors for delays and stops
Dwi, Swi
so the timing will favor the buses.



Impacts of Bus Weighting





Preemption vs. Priority

Preemption: Interrupts normal signal operations

- Request shall be serviced
- Only one request serviced at a time
- All other signal operations temporarily suspended

Priority: Modifies normal signal operations

- **Service not guaranteed**
- **May service simultaneous requests**
- **Minimize delay for special vehicles**
- **Only limited adjustments are made to signal operations**

Active Priority Strategies (1)

Early Green

Green Extension

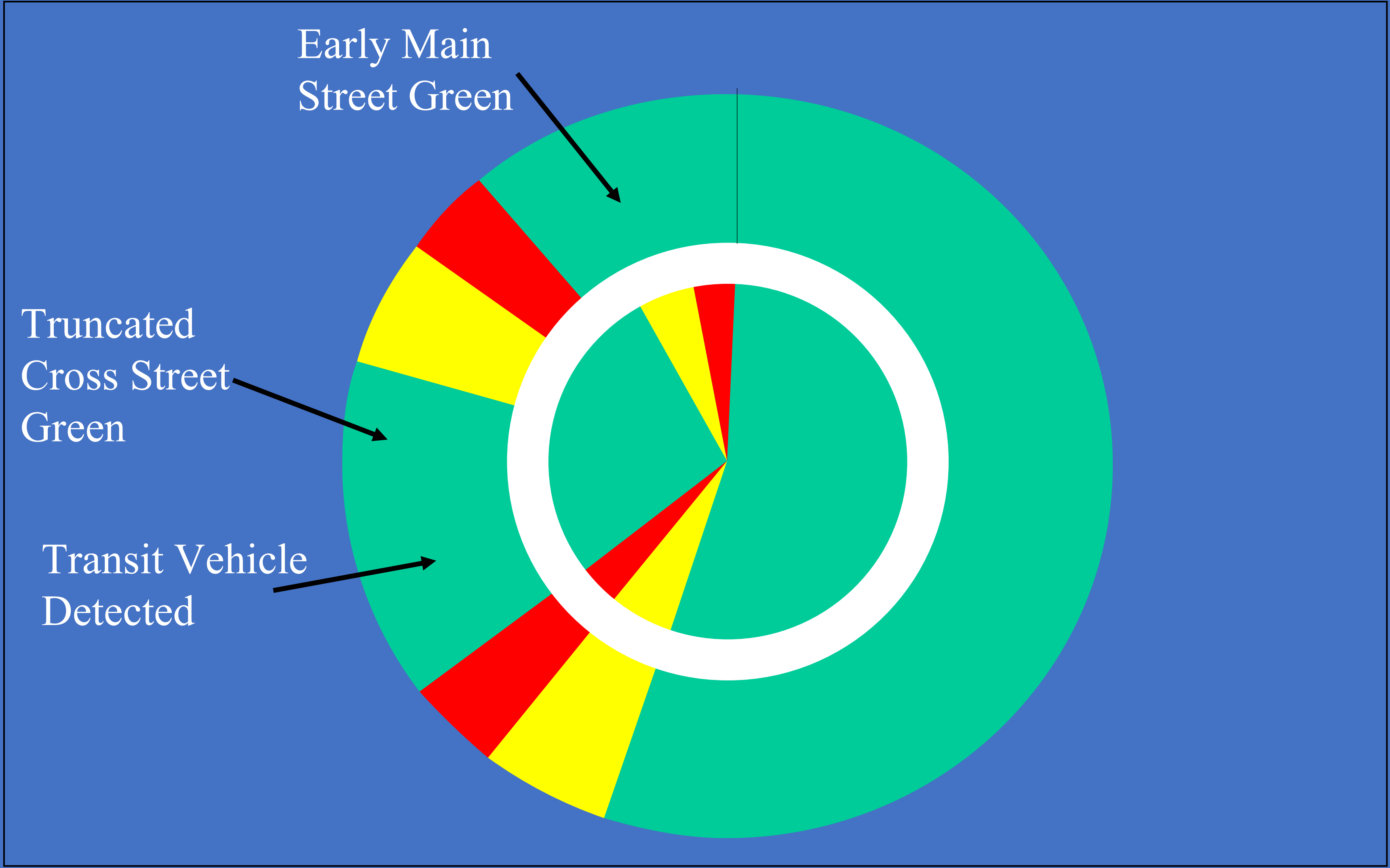
Exclusive Transit Phase

Phase Recall

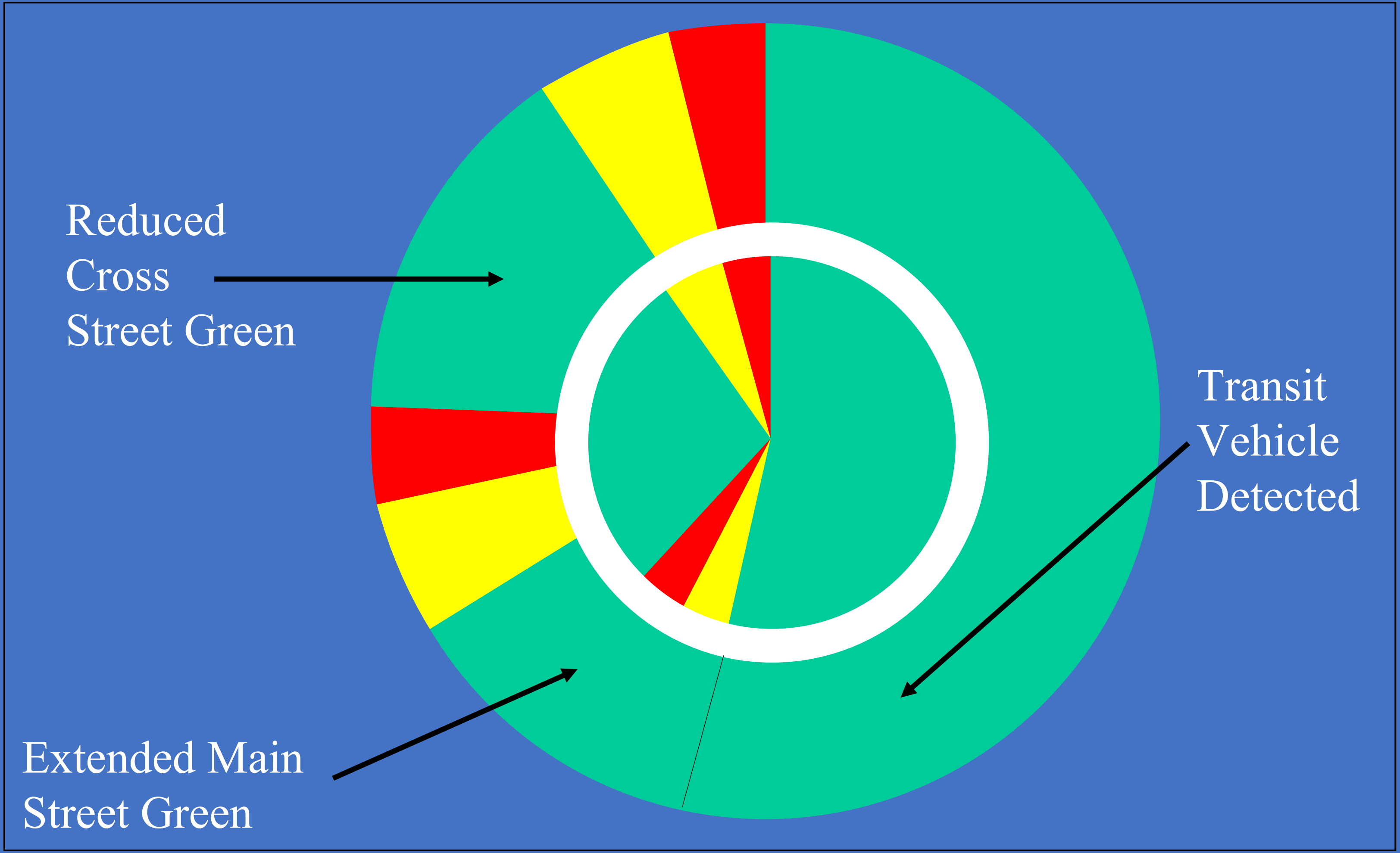
Constraints

- staying in coordination
- not skipping phases
- providing pedestrian clearances
- emergency calls override

Early Green (Red Truncation)



Green Extension



Active Priority Strategies: Issues (1)

Spare Green time in the Signal Cycle

Critical intersections

High pedestrian volumes

Insufficient queue storage

$$G_e = \sum^{N} G_i (1 - X_i)$$

N : number of phases
G_i : green time for phase i
X_i : degree of saturation for the critical link --phase i

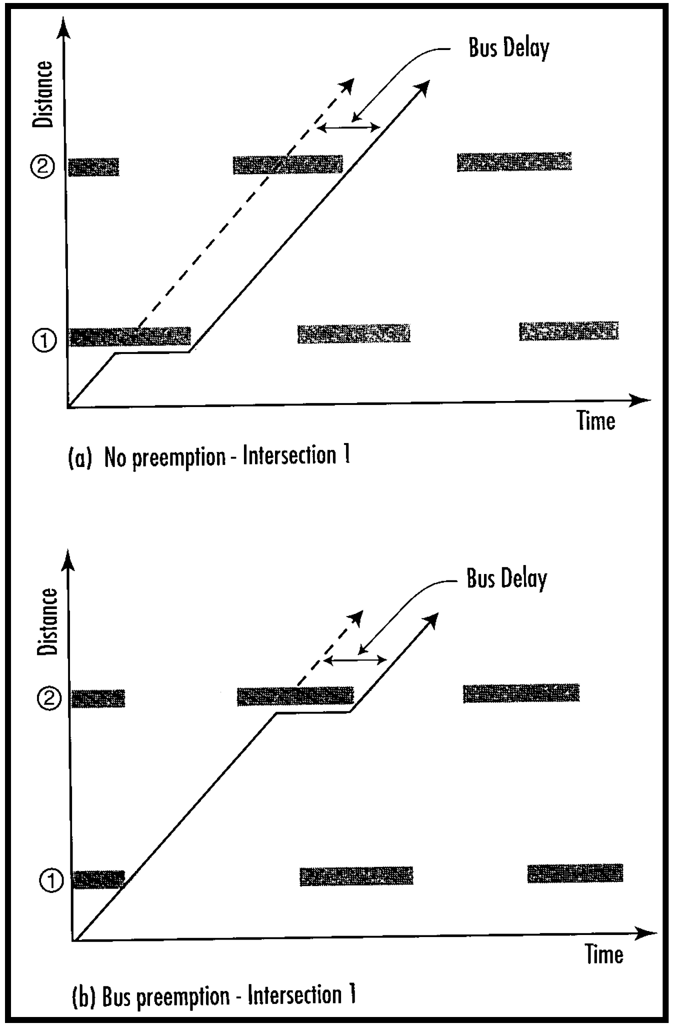
Bus Route Progression

Schedule Adherence

Empty/Out of Service Late Runners?

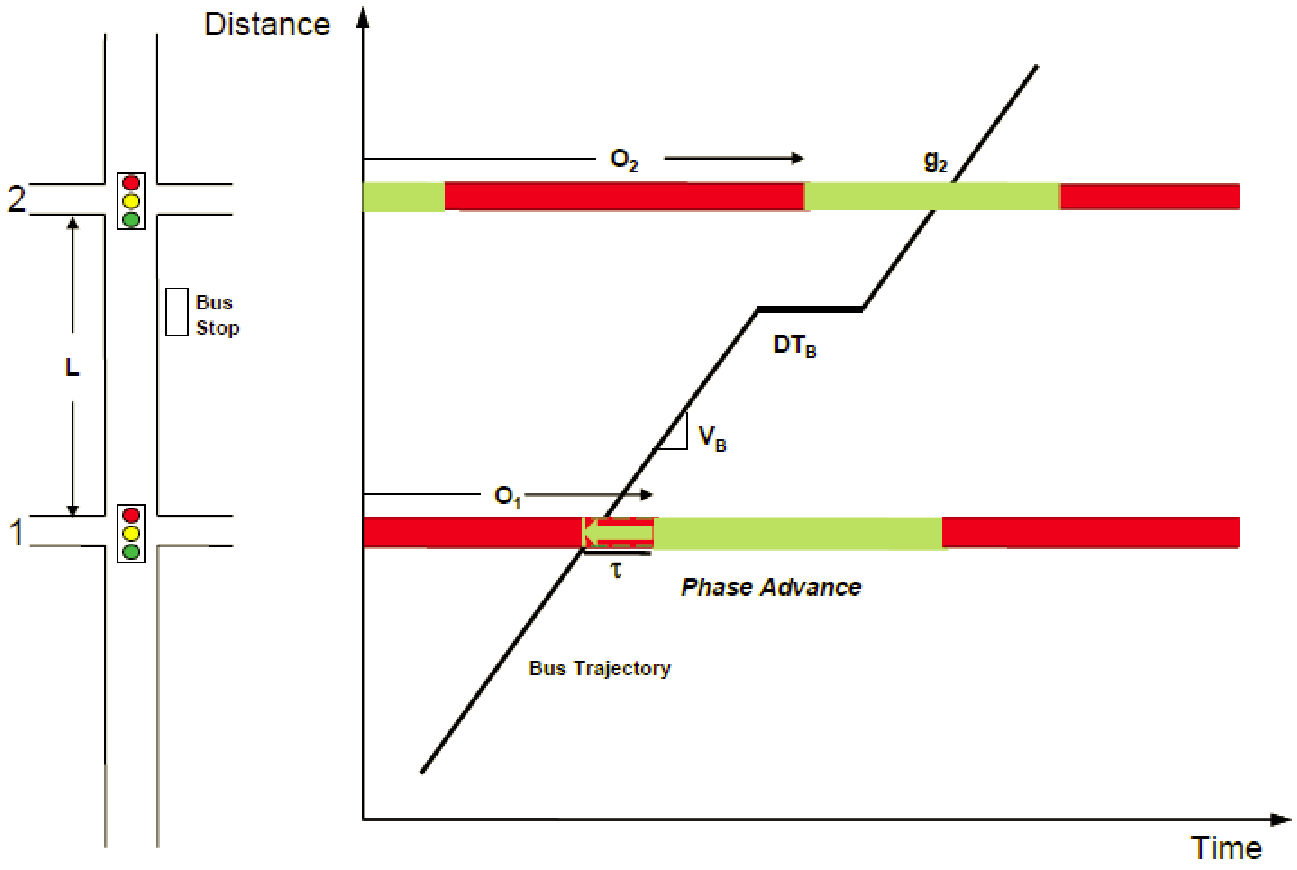
Active Priority Strategies: Issues (2)

"Wasted" Priority Call



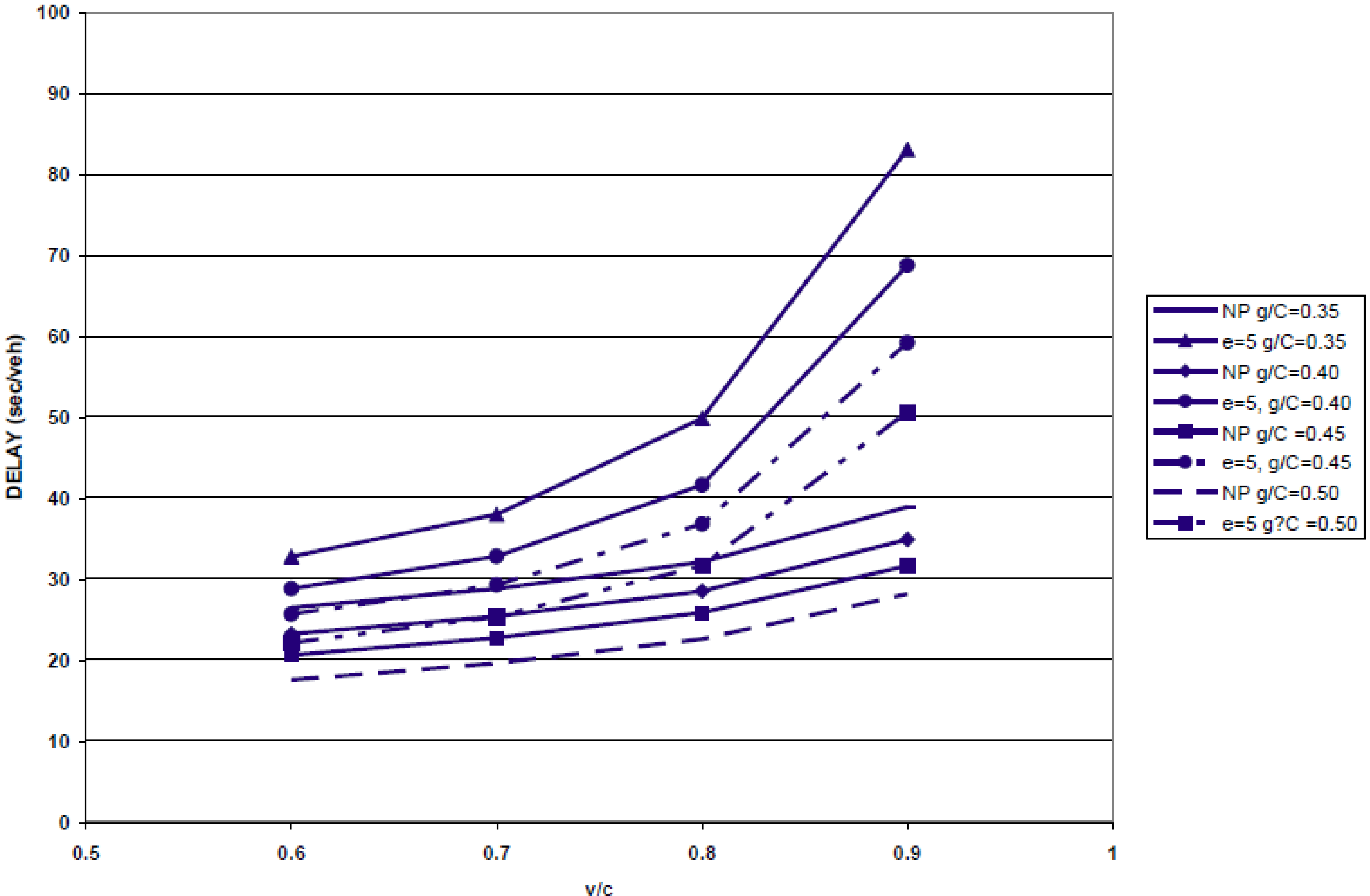
Active Priority Strategies: Issues (3)

$$O_2 \le (O_1 - \tau) + \frac{L}{V_B} + D_B \le O_2 + g_2$$

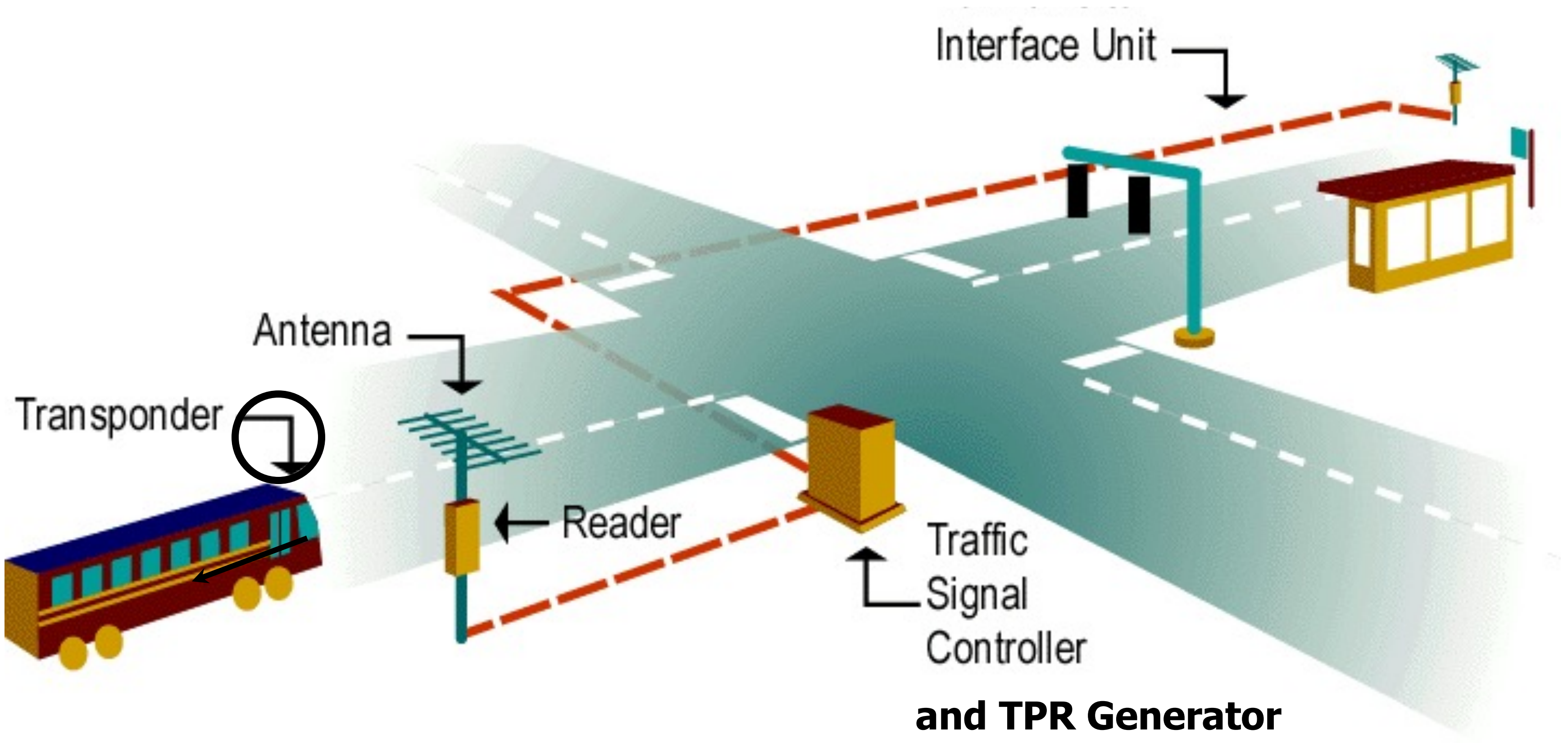


Impacts of Priority – Cross Streets

Cycle Length: 90 sec, extension e: 5 sec



TSP System & Equipment



Stakeholder Discussions..

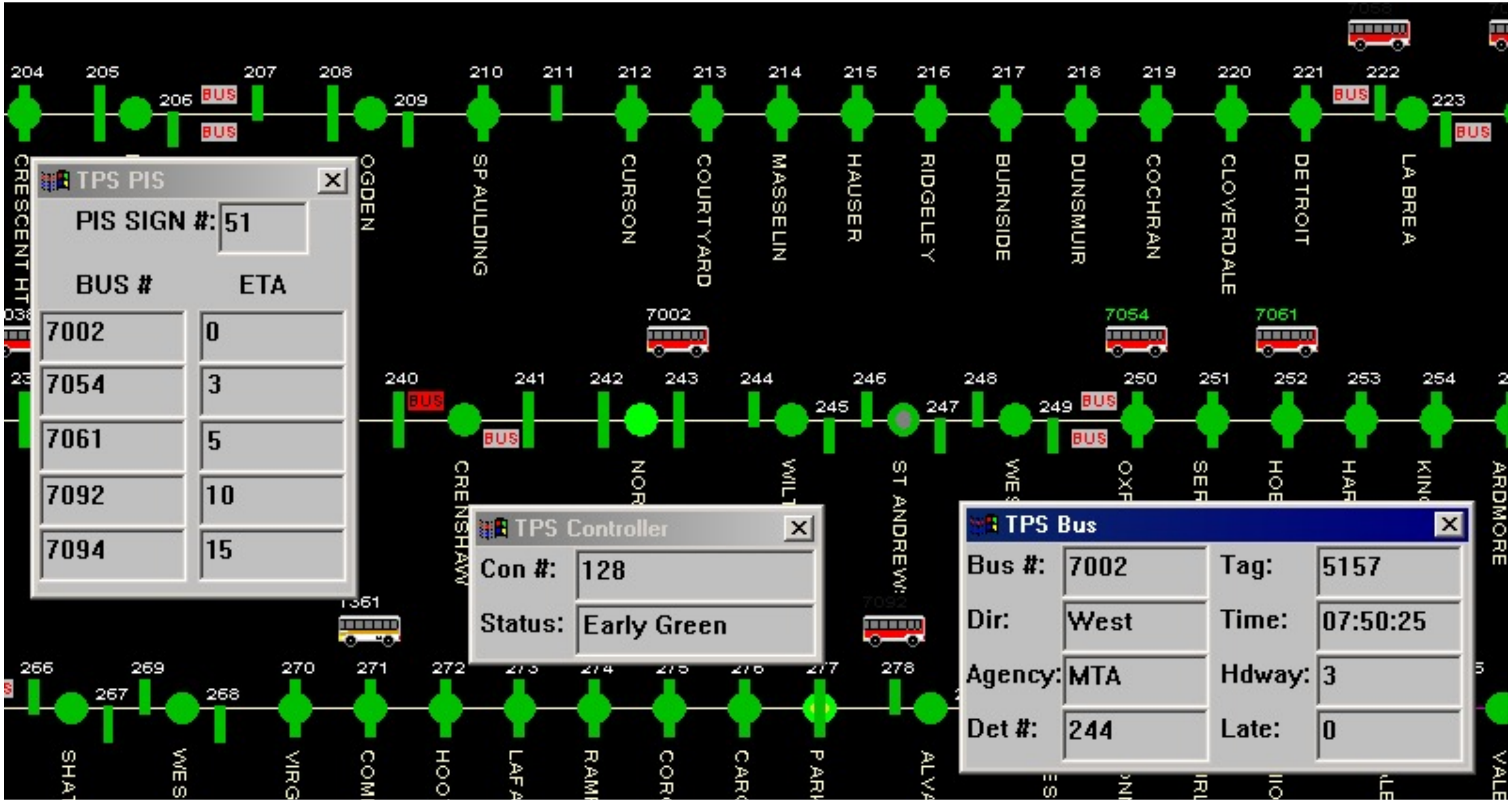
Traffic

Transit

TSP—Los Angeles (1)

- Selected loop-transponder
- Inductive loops placed in the roadway serve as antennas to receive bus transponder ID
- Advance (check-in) detector just past upstream bus stop
- Release (check-out) detector just prior to limit line or within the intersection

TSP—Los Angeles (2)

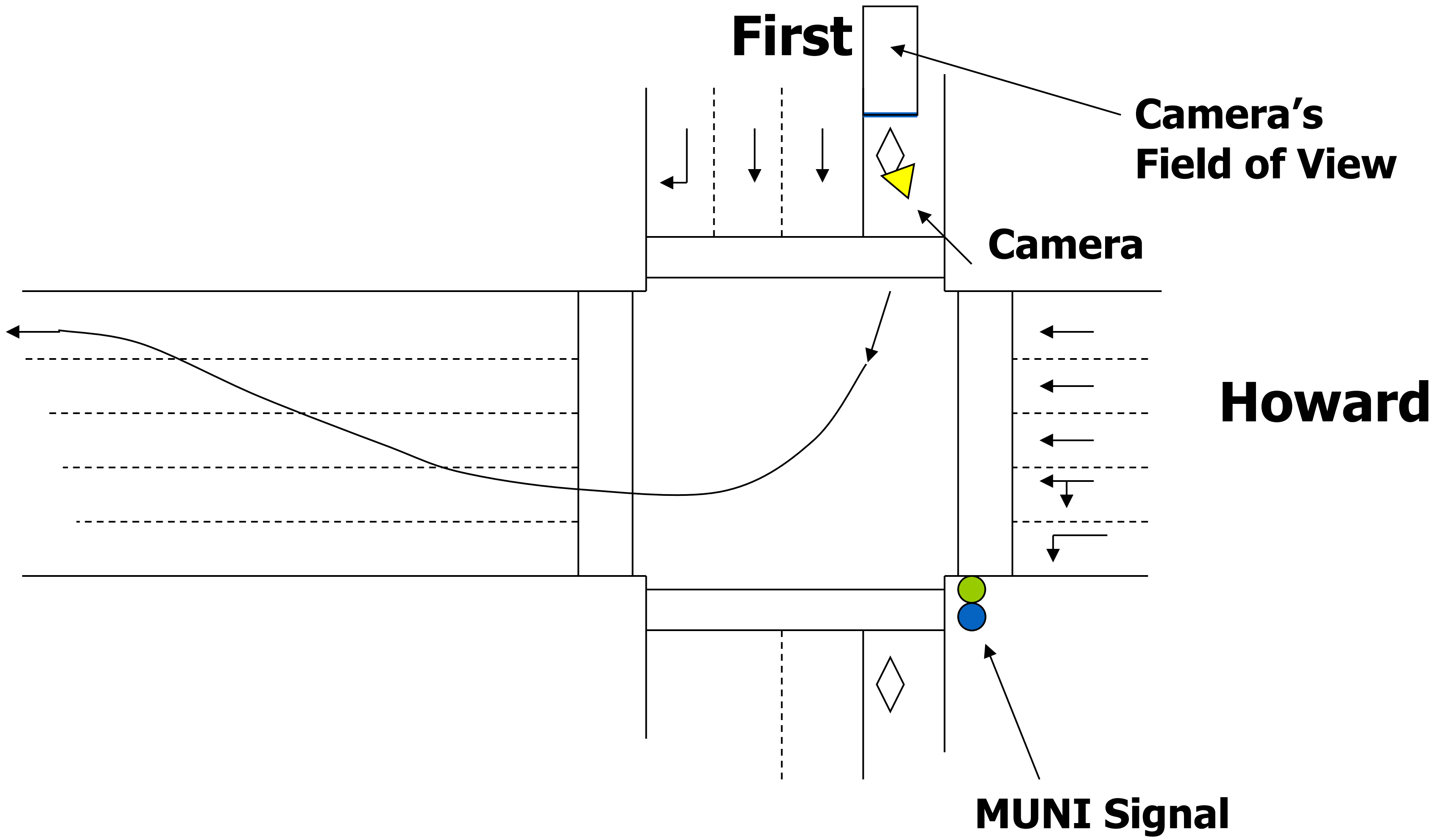


TSP—Los Angeles: Impacts

- The Metro Rapid Buses achieved a 25% reduction in total travel time
- Transit Priority System alone contributed to 30% of the total travel time saving
- Bus delays at signalized intersections were reduced by 33-39%

- Average of 1 second per vehicle per cycle increase in delay to the cross traffic
- The Level of Service did not change as a result of the Transit Priority System
- At some locations timing was changed to provide additional cross street green time

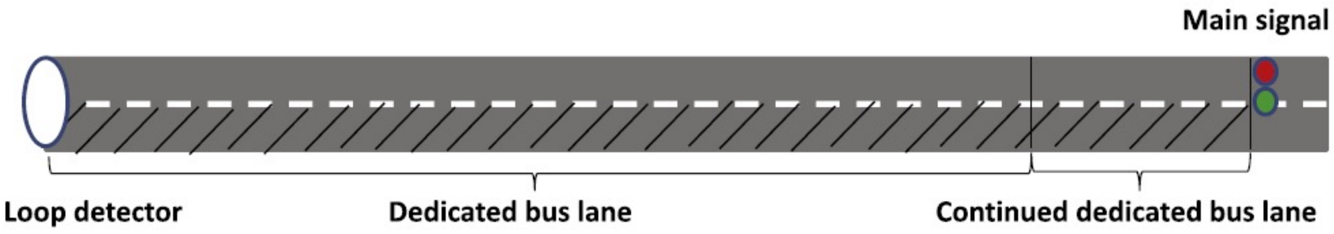
Local TSP--Queue Jump – San Francisco



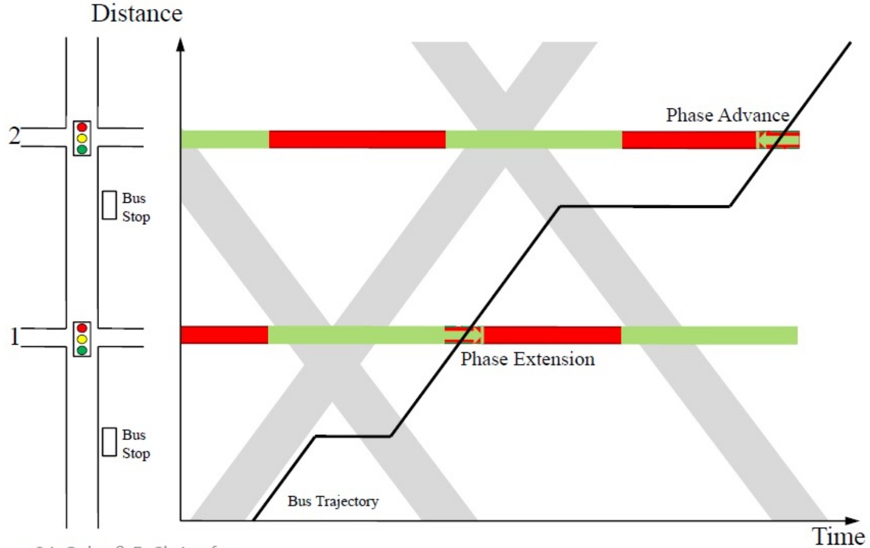
Optimal pre-signal control for buses and cars at isolated signalized intersections

Special thanks to Prof. Haddad (Technion) and Prof. Menendez (NYU AD)

Traditional Strategies to improve bus priority at Signalized Intersections

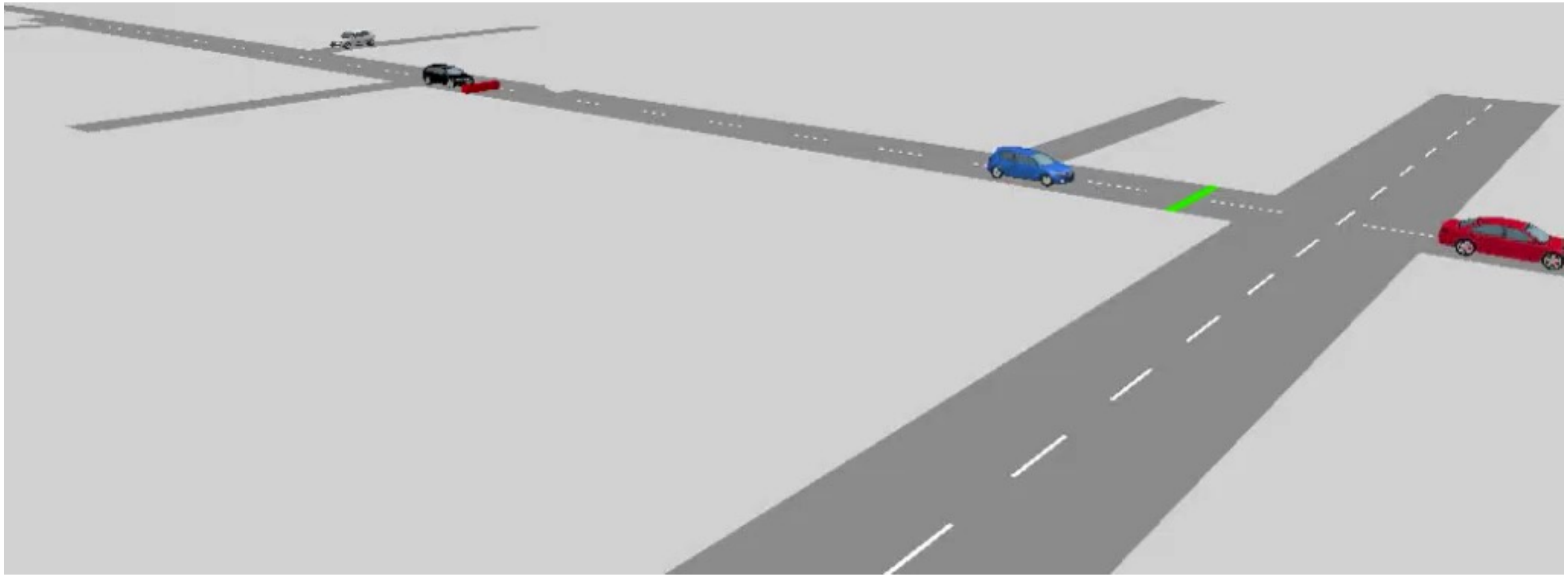


Active TSP: Phase Extension (Green Extension)- Phase Advance (Red Truncation)



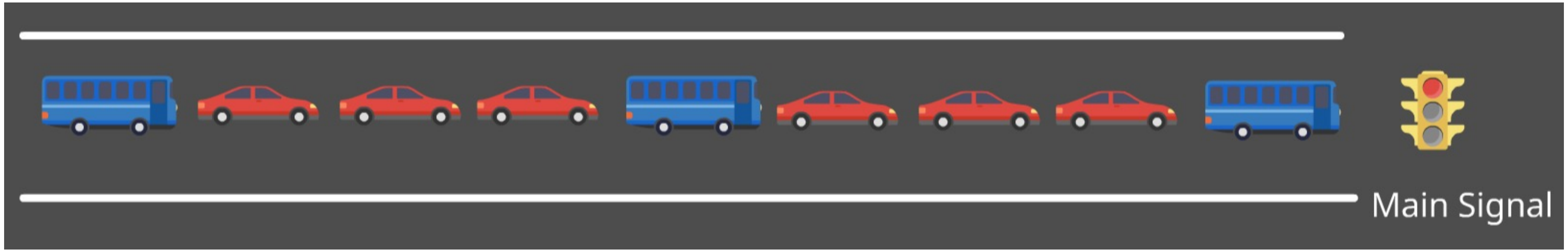
S.I. Guler & E. Christofa

What is a Pre-signal?

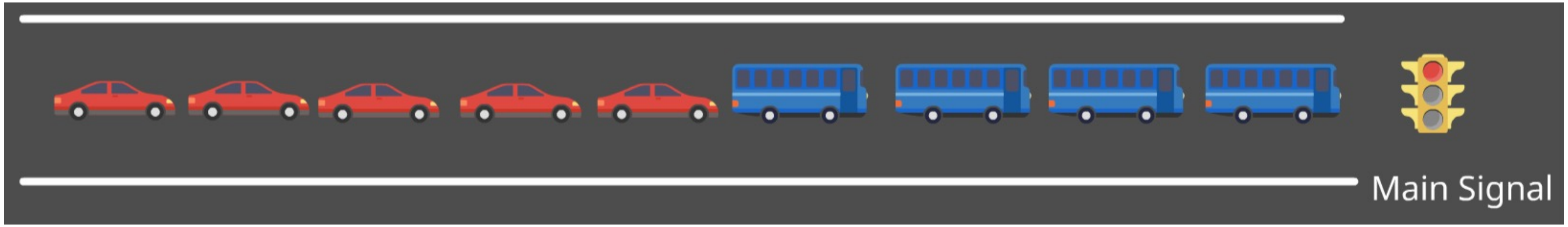


Special thanks to Prof. Menendez (NYU AD)

The concept

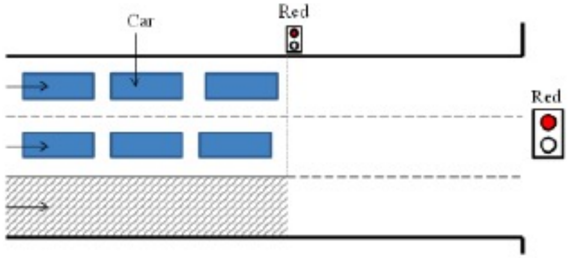


Vehicles location without pre-signal



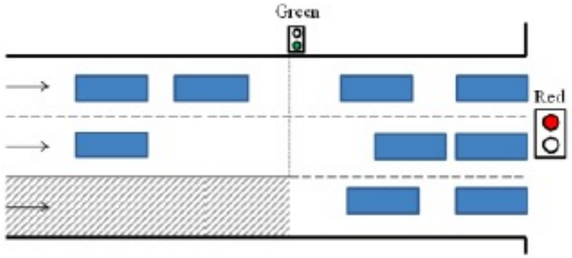
Vehicles location with pre-signal

1. Both signals are red:



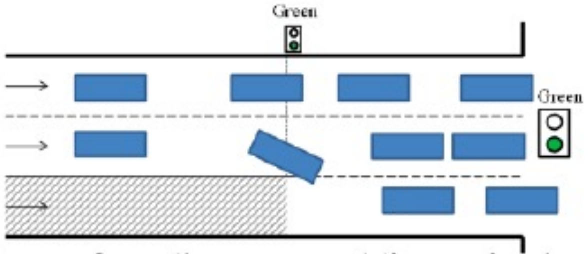
Cars queue at pre-signal

2. Pre-signal turns green:



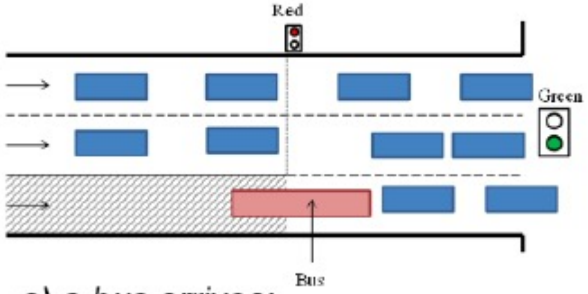
Cars start queuing at main signal

3. Main signal turns green

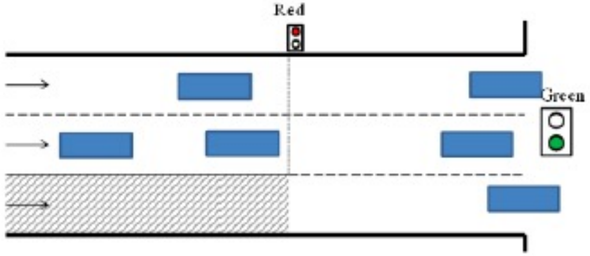


Enough cars can discharge from the queue at the main signal to saturate the green

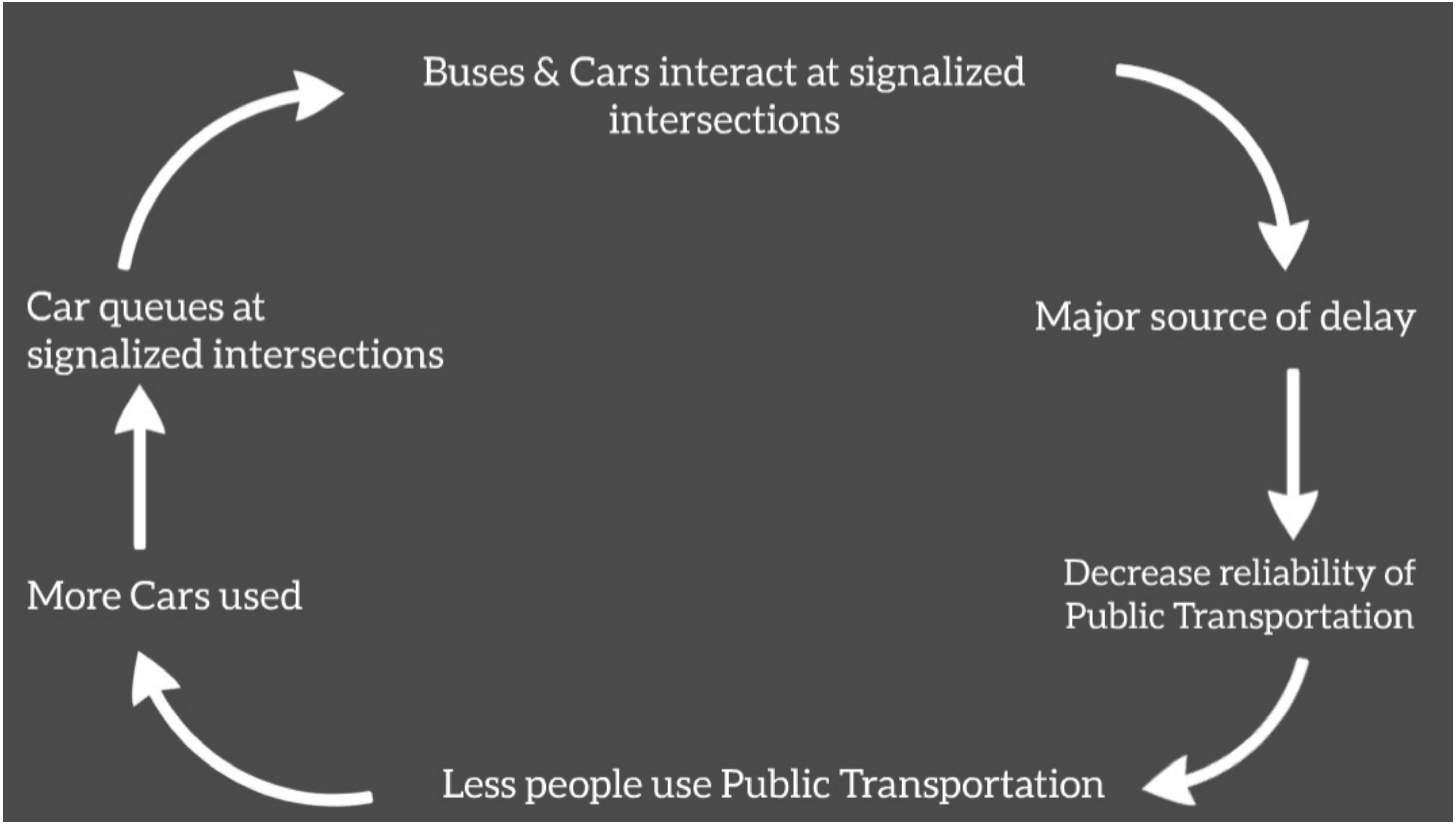
4. Pre-signal turns red if:



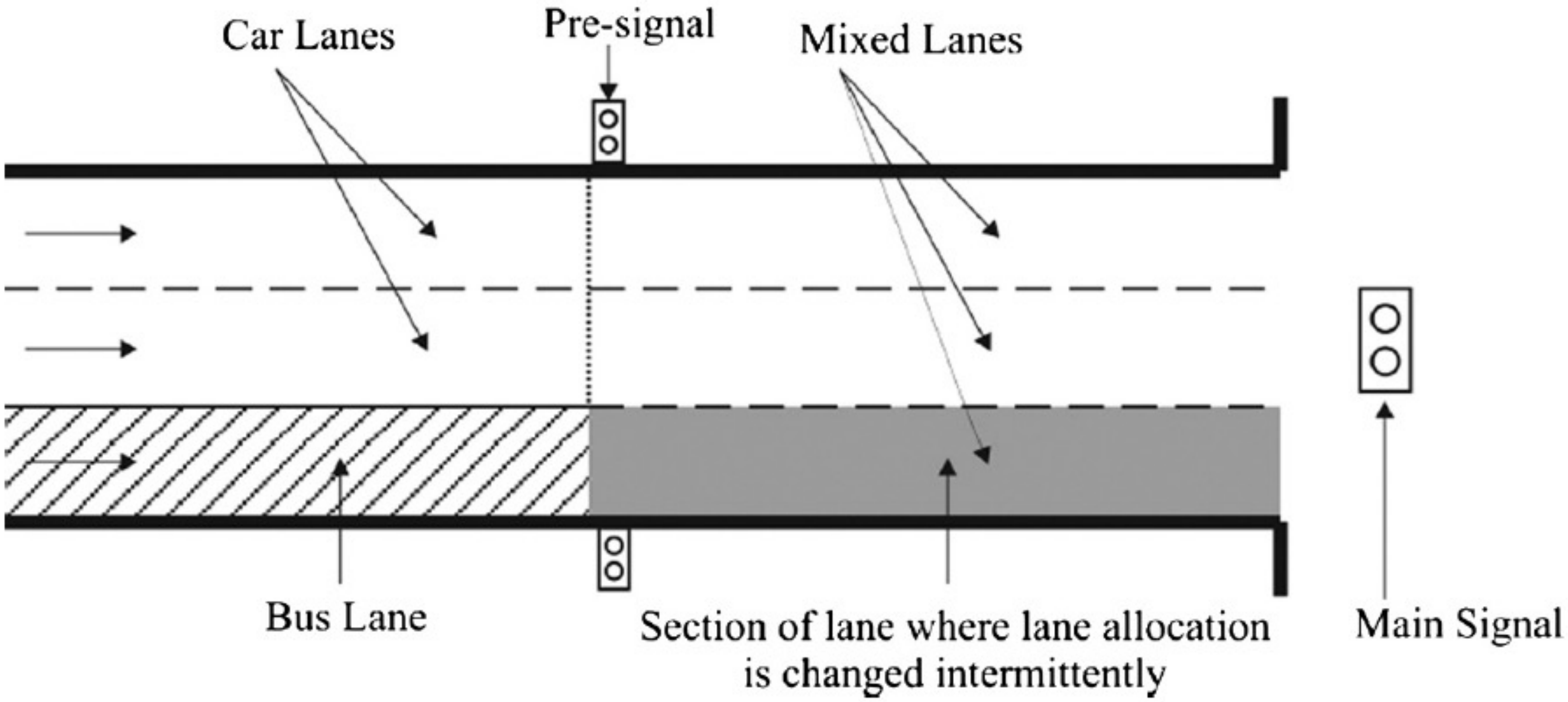
a) a bus arrives;



b) or such that cars only queue at the pre-signal


Buses & Cars interact at signalized intersections
Major source of delay
Decrease reliability of Public Transportation
Less people use Public Transportation
More Cars used
Car queues at signalized intersections

Pre-signal Strategy



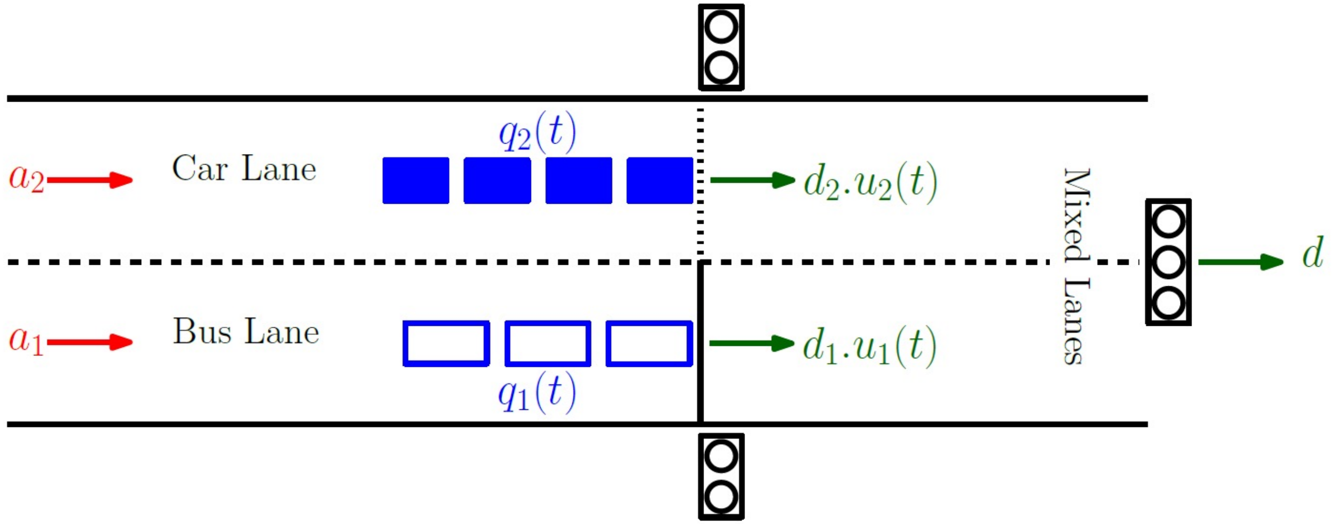
1. **Develop** a continuous-time model

2. **Formulate** an optimal pre-signal control problem (min. total person delay)

Khwais M,Haddad J. Optimal control for buses and cars at isolated signalized intersections. IFAC-PapersOnLine.

1. Develop a continuous-time model

A continuous-time model for controlled intersections with Pre-signal



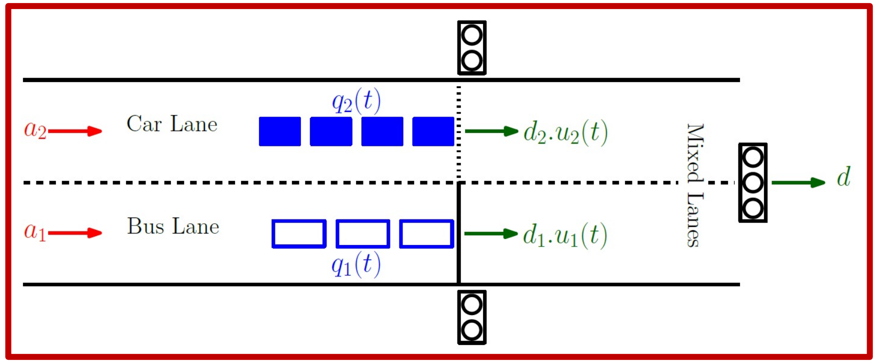
- Traffic terminology:
- q_1[buses], q_2[cars]; number of buses and cars stopping behind the pre-signal stop line
- a_1[bus/s], a_2[car/s]; arrival rates of buses and cars
- d_1[bus/s], d_2[car/s]; departure rates of buses and cars
- d [eq. car/s]; output capacity of a joint lane in terms of equivalent cars
- u_1, u_2 green split times at the pre-signal for buses and cars

2. Formulate an optimal control problem

- Dynamic equations:

The evolution of the queue lengths

$$\frac{\mathrm{d}q_1(t)}{\mathrm{d}t} = a_1(t) - d_1(t)\cdot u_1(t),$$
$$\frac{\mathrm{d}q_2(t)}{\mathrm{d}t} = a_2(t) - d_2(t)\cdot u_2(t),$$



The amount of equivalent cars q(t) [car] after the pre-signal lights

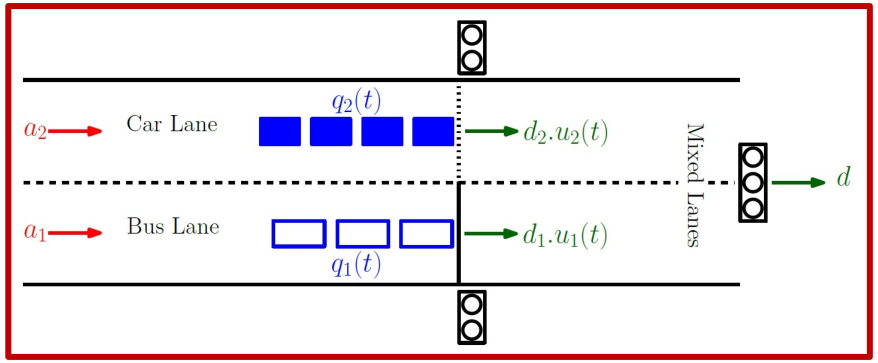
$$\frac{\mathrm{d}q(t)}{\mathrm{d}t} = u_1(t)\cdot d_1(t)\cdot k + u_2(t)\cdot d_2(t) - d(t)$$

where k [equivalent car/bus], $k > 1$ cars : for equivalence of buses and cars in terms of traffic space

- Control constraints: $\underline{u}_1 \leq u_1(t) \leq \overline{u}_1, \qquad \underline{u}_2 \leq u_2(t) \leq \overline{u}_2$

- State constraints: $q(t) \leq \bar{q}$

Optimal Control Problem Definition



- Given:
  - Initial queue lengths: $q_1(0), q_2(0)$
  - Arrival and departure rates: $a_1(t), a_2(t), d_1(t), d_2(t), d(t)$
  - Control constraints: $\underline{u}_1, \underline{u}_2, \overline{u}_1, \overline{u}_2$
  - Mean number of people in the bus and car: B, M
  - Constant k which translates bus into equivalent car in terms of traffic space

Goal:

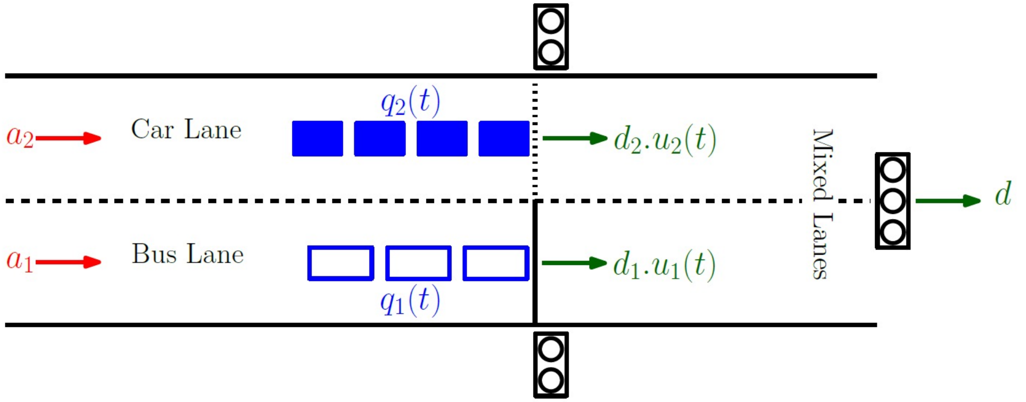
Manipulate $u_1(t)$ and $u_2(t)$ to optimize the minimum total person delay in the system:

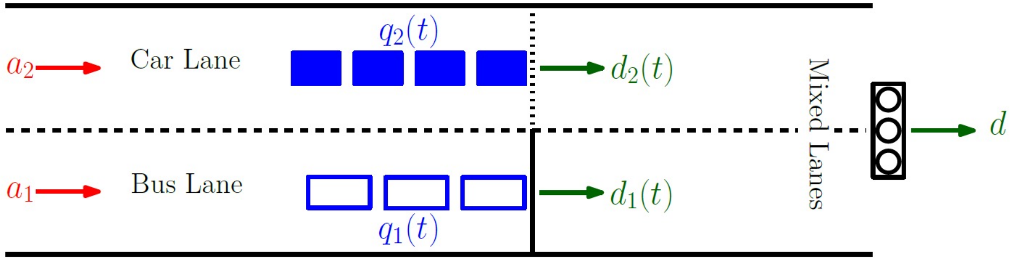
$$\int_0^T [B \cdot k \cdot q_1(t) + M \cdot q_2(t)] \mathrm{d}t \rightarrow \min$$

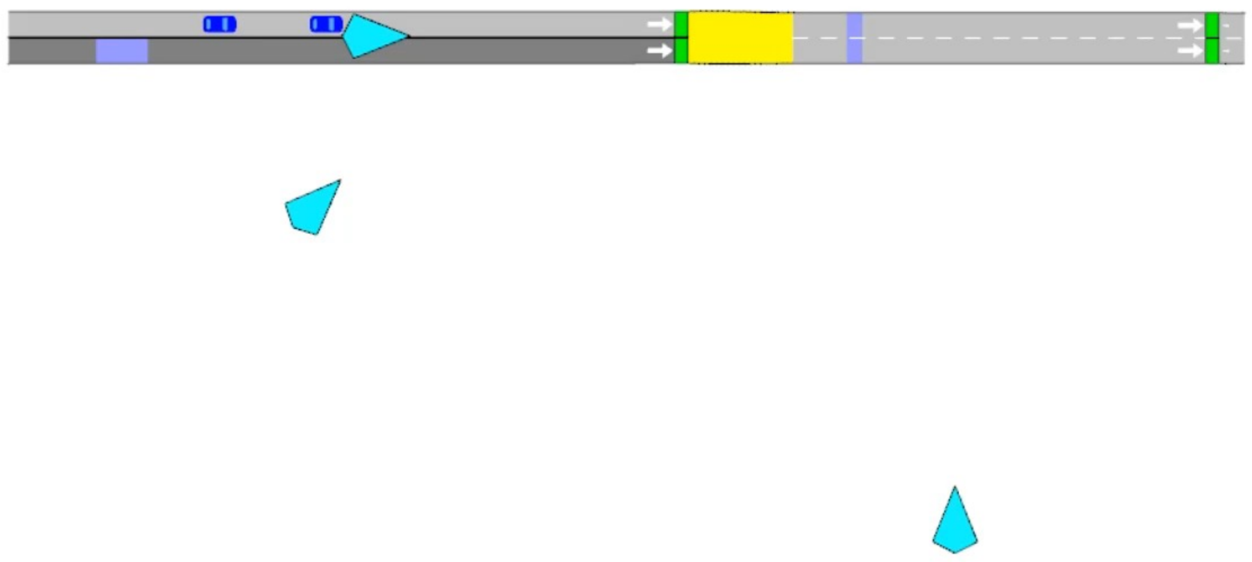
$T(s)$: The final time is fixed

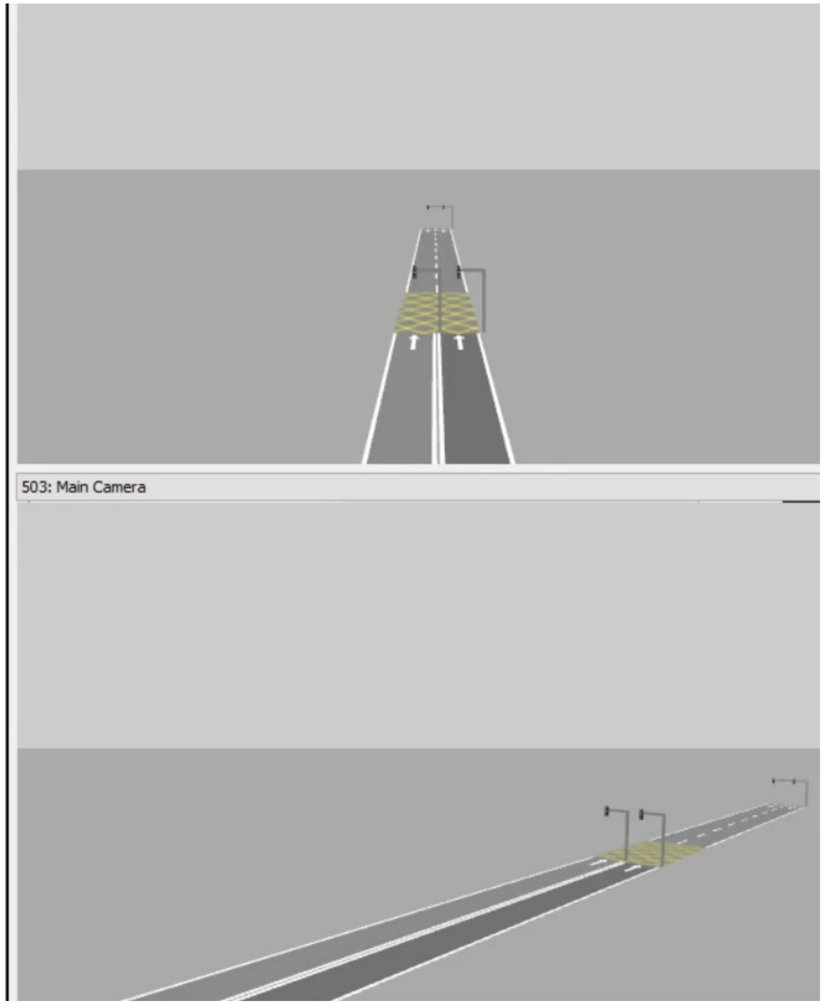
Problem

- The Pre-signal strategy is not useful for cases of high vehicle demand and immoderate bus frequency.

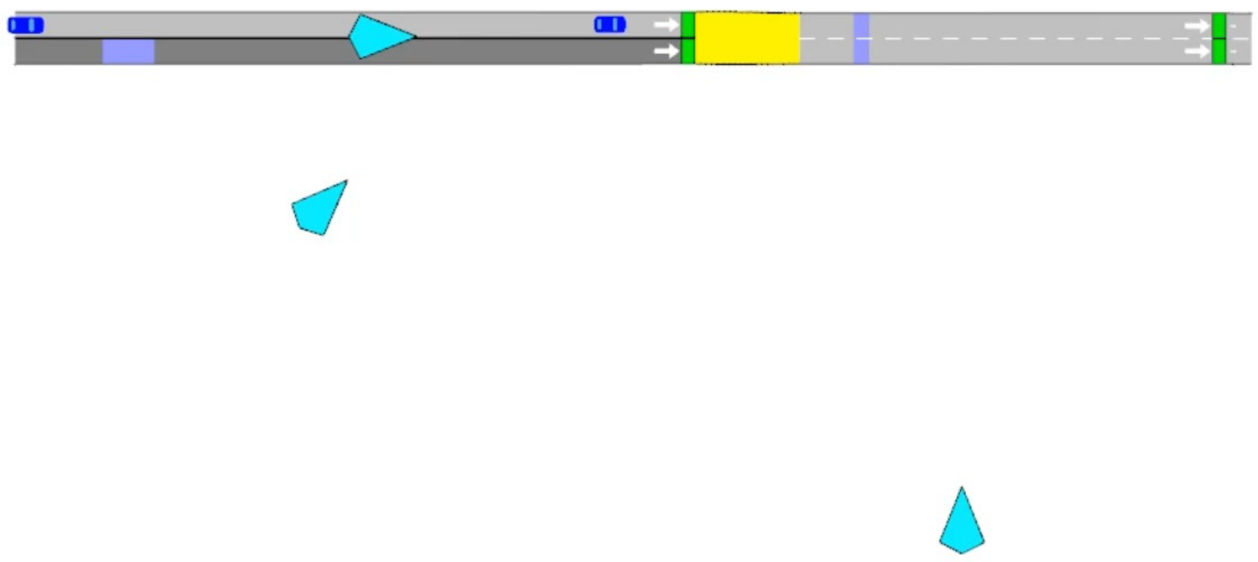


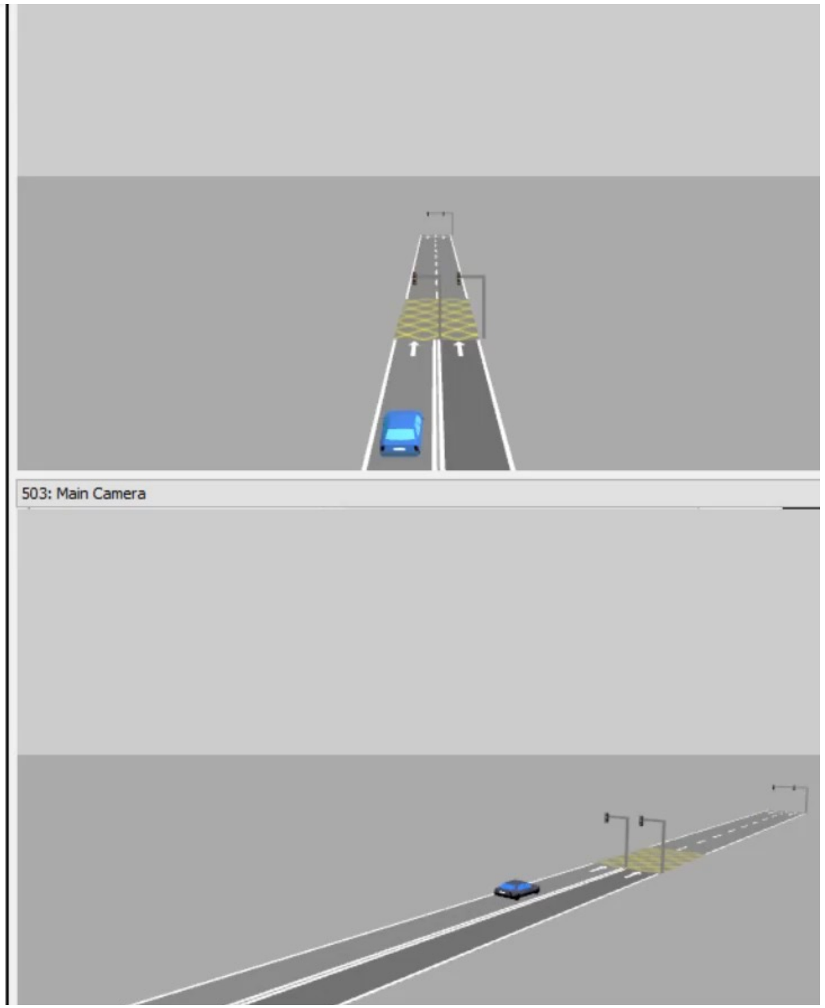




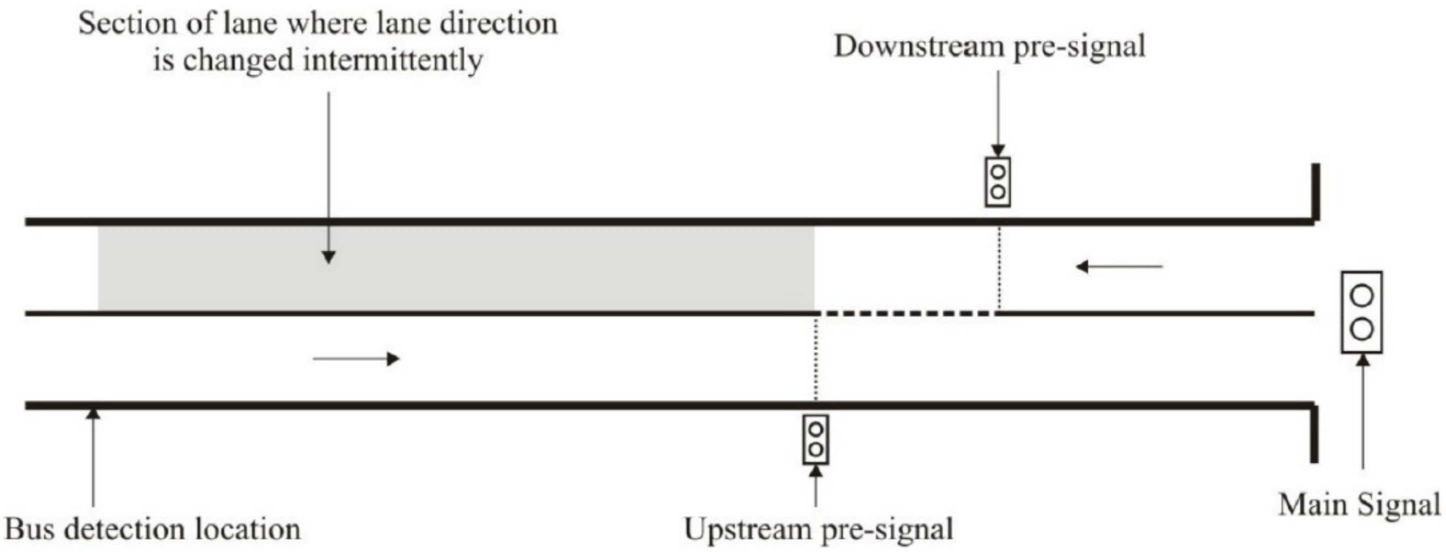


Special thanks to Prof. Haddad (Technion)

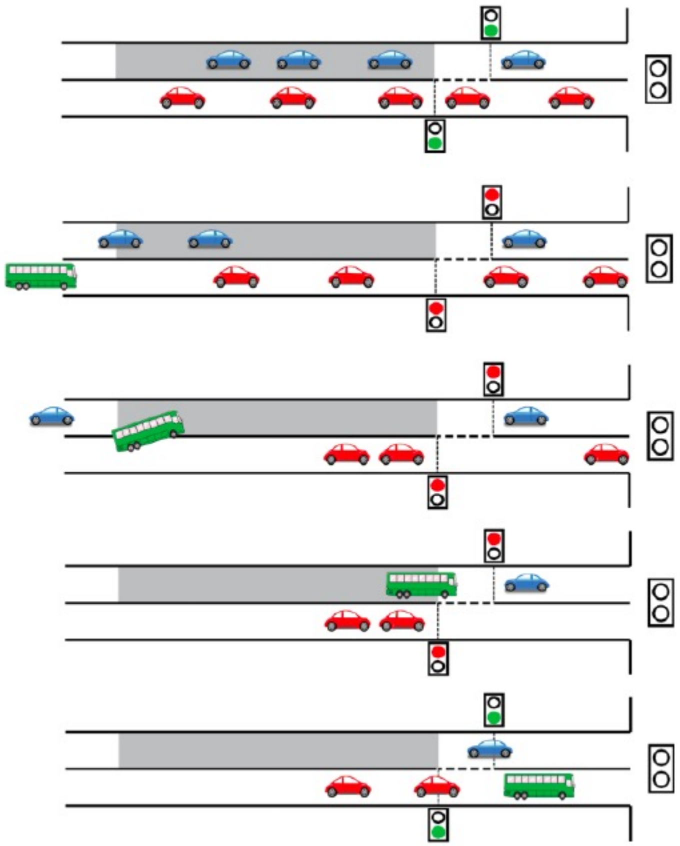



503: Main Camera

A more complex pre-signal (contra flow)



A more complex pre-signal (contra flow)



No bus is present: both pre-signals are green (operation is as if the pre-signals did not exist)

Bus arrives at x_1 – both pre-signals turn red

Bidirectional lane segment clears of cars

Bus travels on the opposite lane

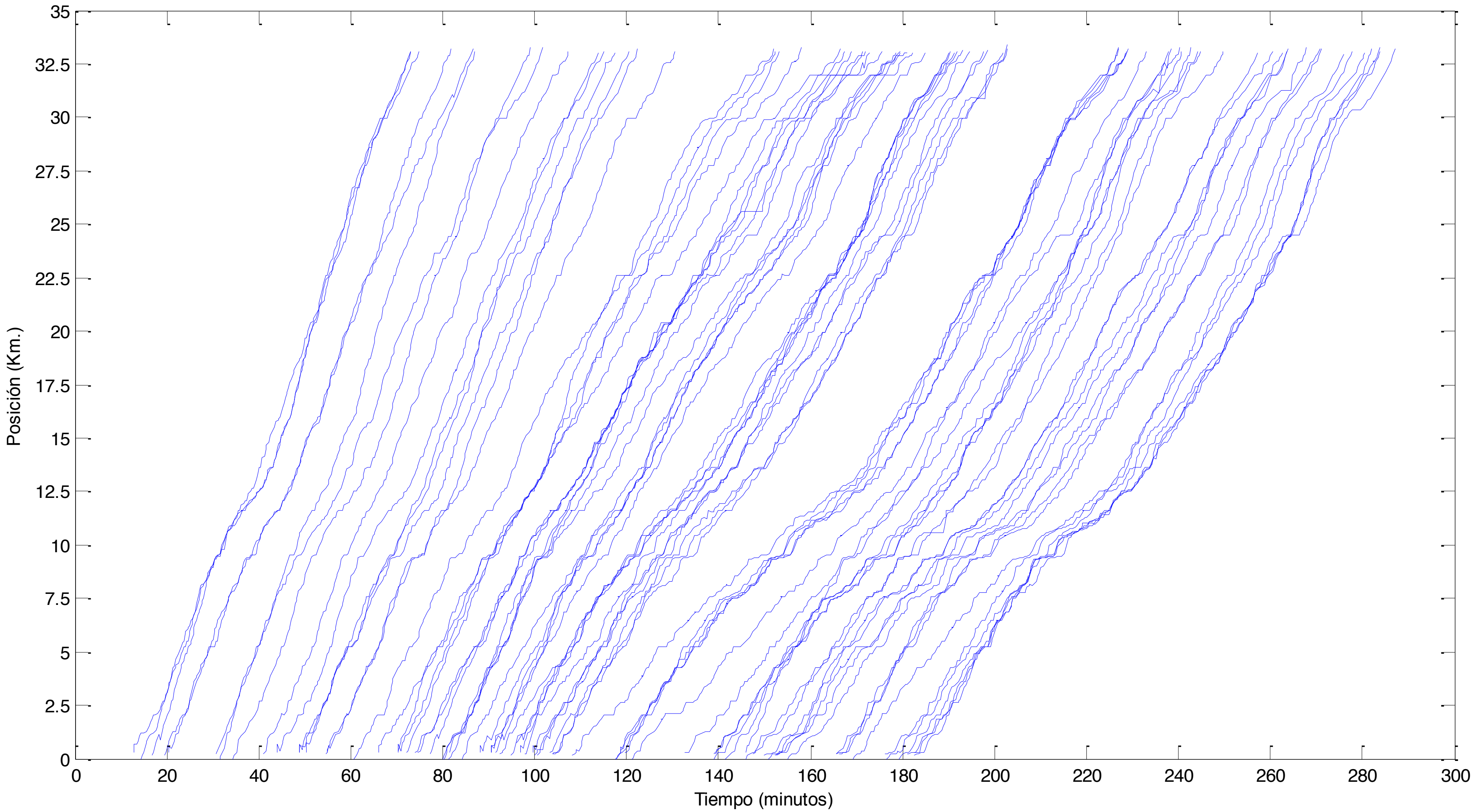
Bus merges back onto its original lane – green phase at both pre-signals is resumed

Bus Bunching

Santiago, Chile

Boston, MA; line 1 during winter

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



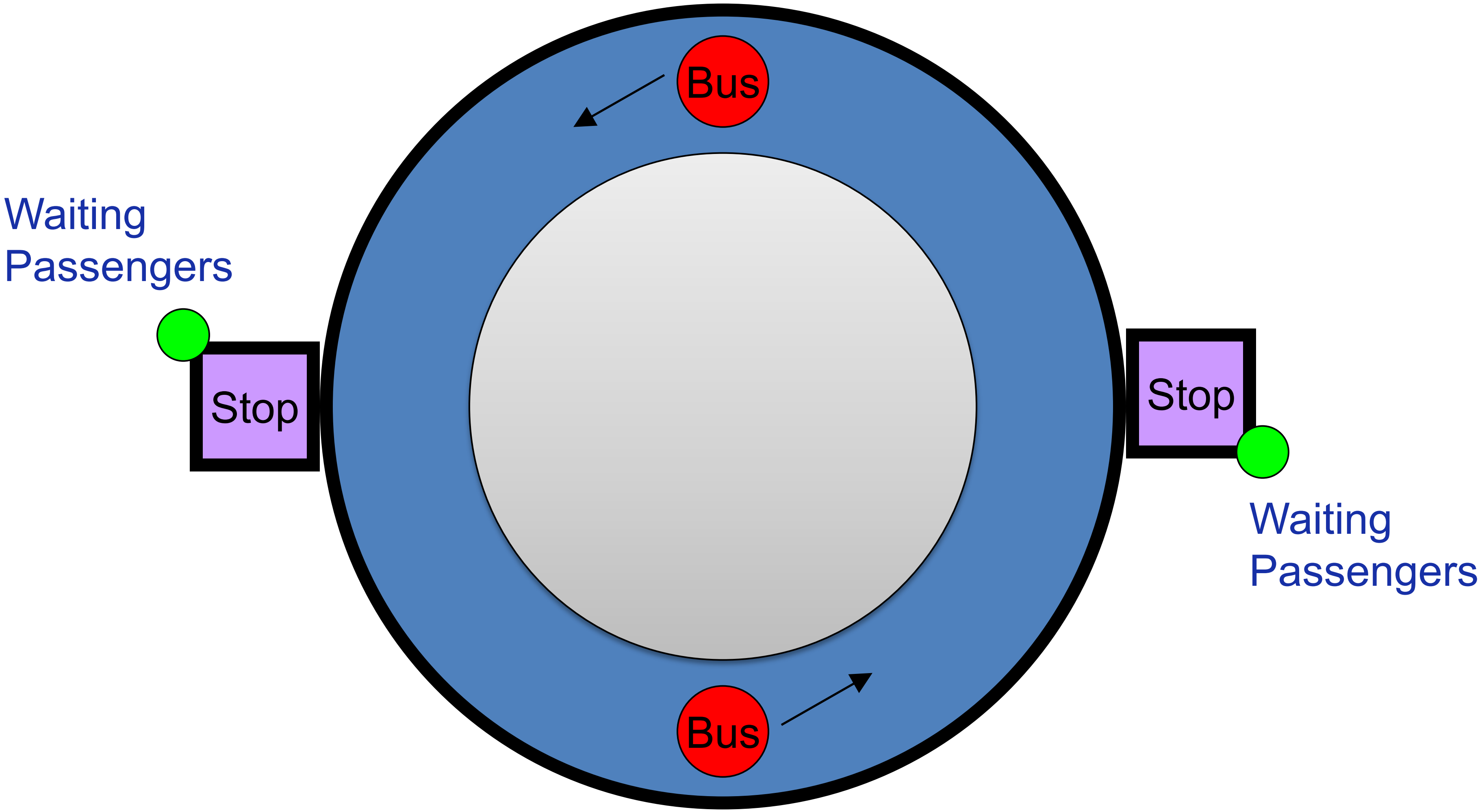
6:30 AM

8:30 AM

Thanks to Prof. Munoz
Pontificia Universidad Católica de Chile

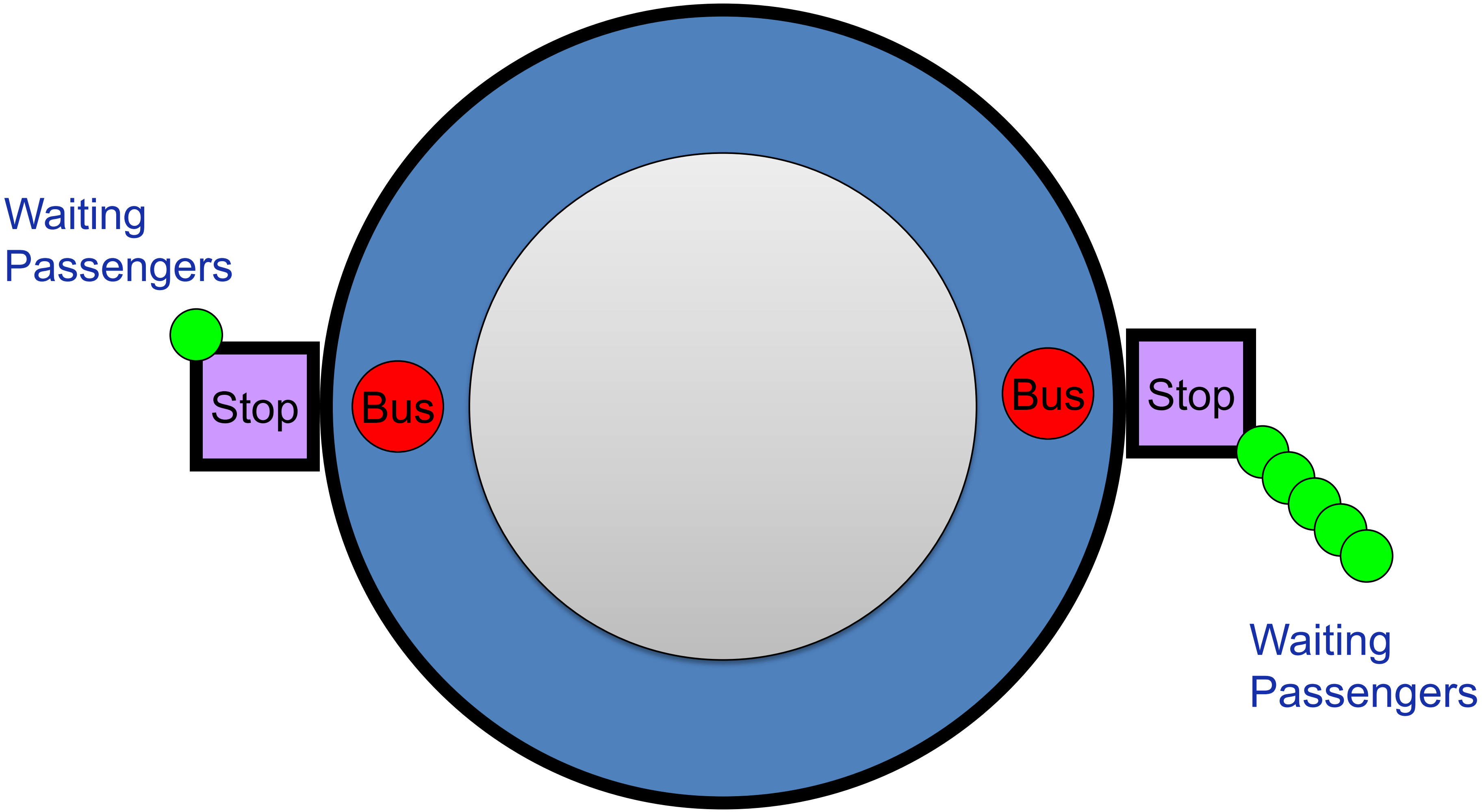
Is keeping regular headways that difficult?

Bus Operations without Control



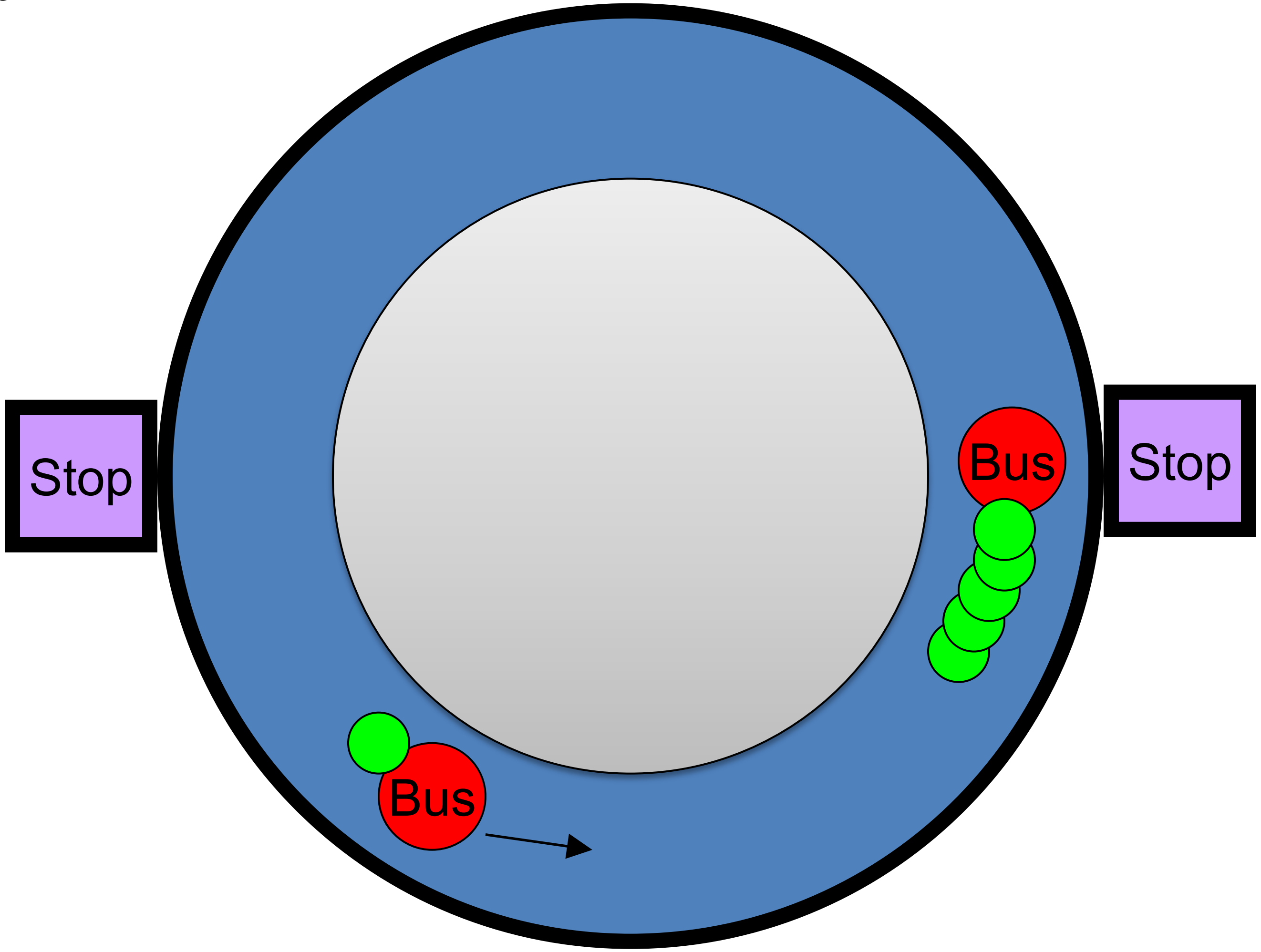
Bus Operations without Control

a small perturbation…

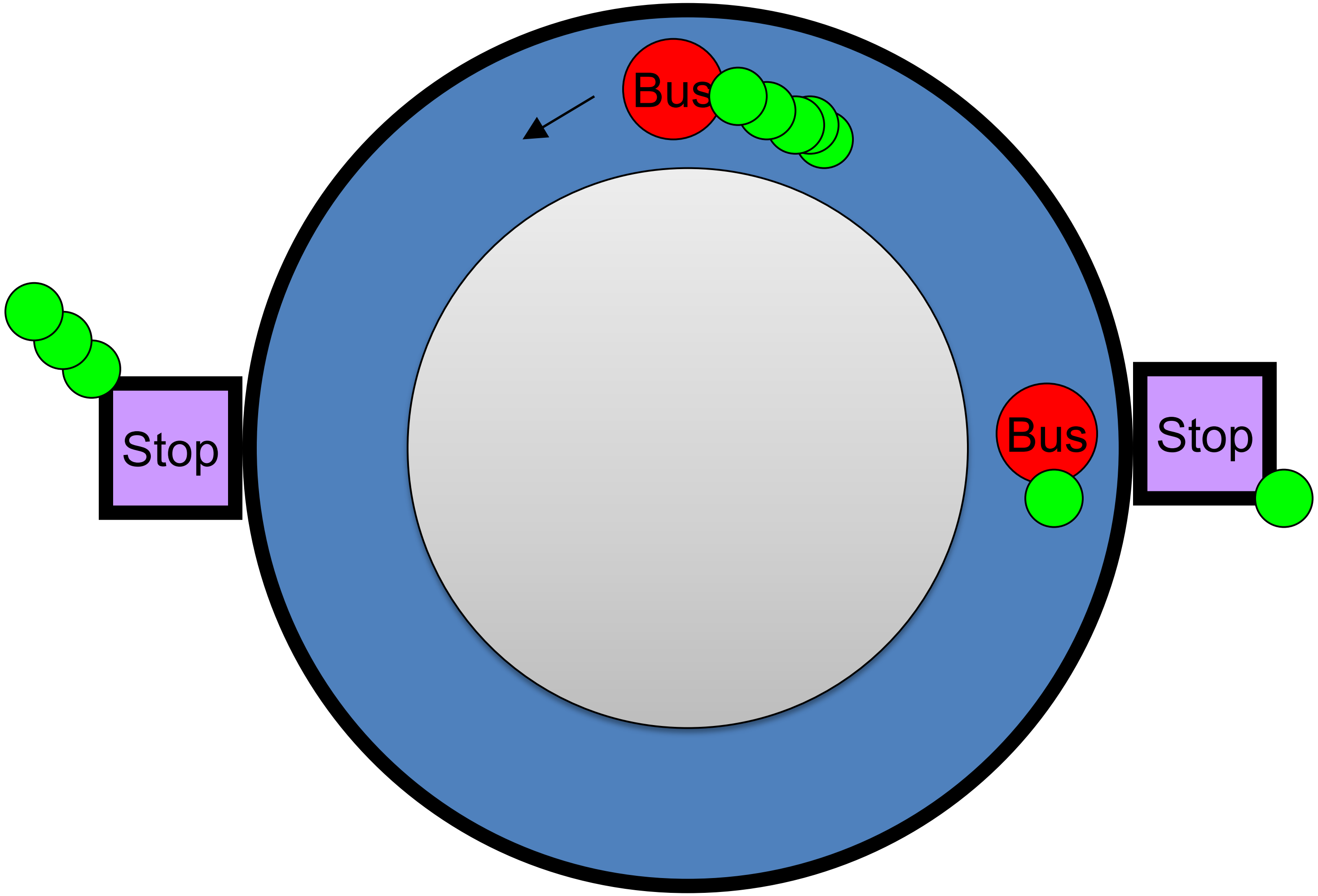


Bus Operations without Control

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

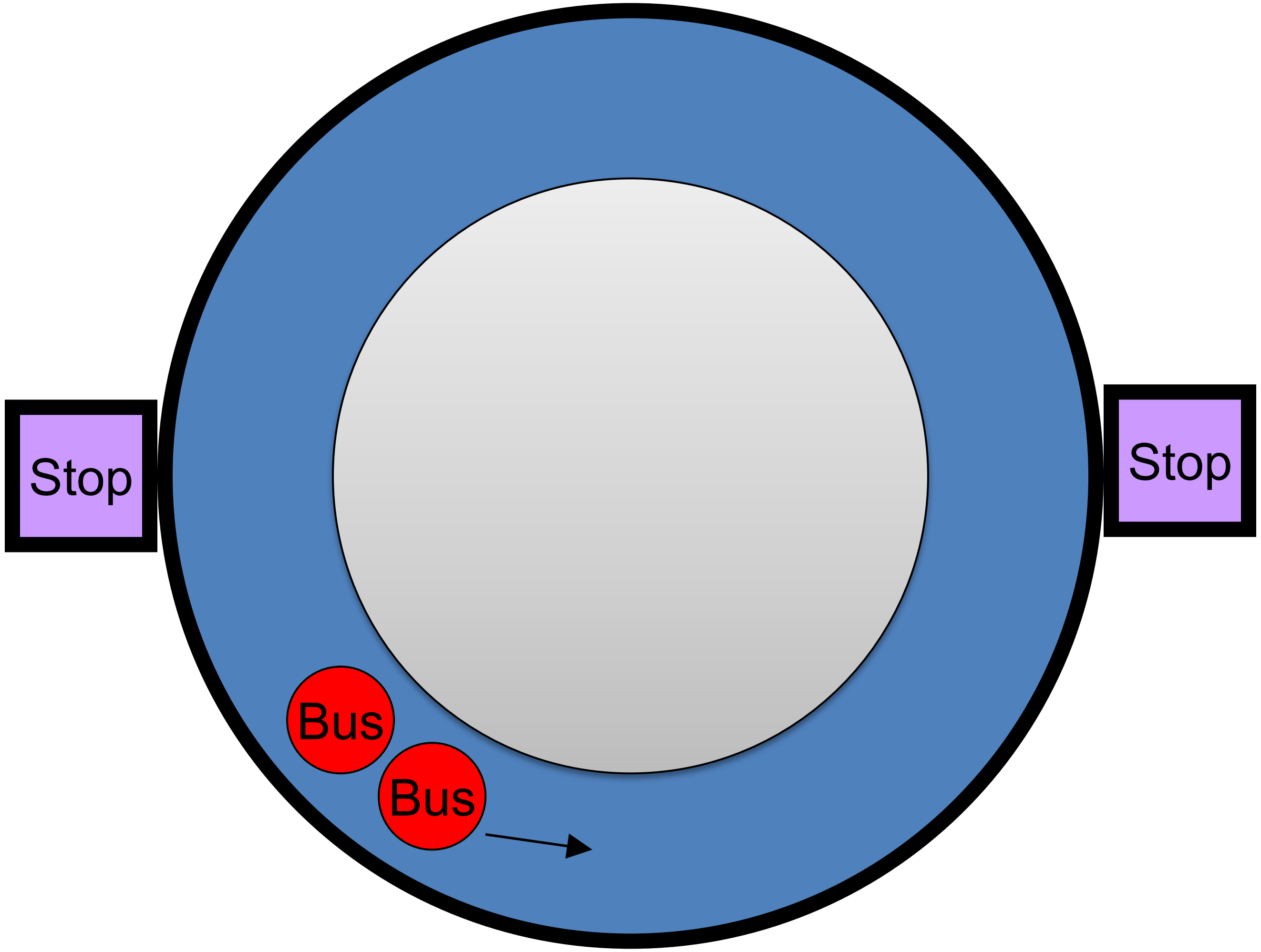


Bus Operations without Control



Bus Operations without Control

Without bus control, bus bunching occurs!!!



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

Control mechanism to avoid bus bunching

Control of bus networks

- Setting:

  Bus line 2 of Fribourg bus network

  9 buses, 44 stops

- Comparison between:

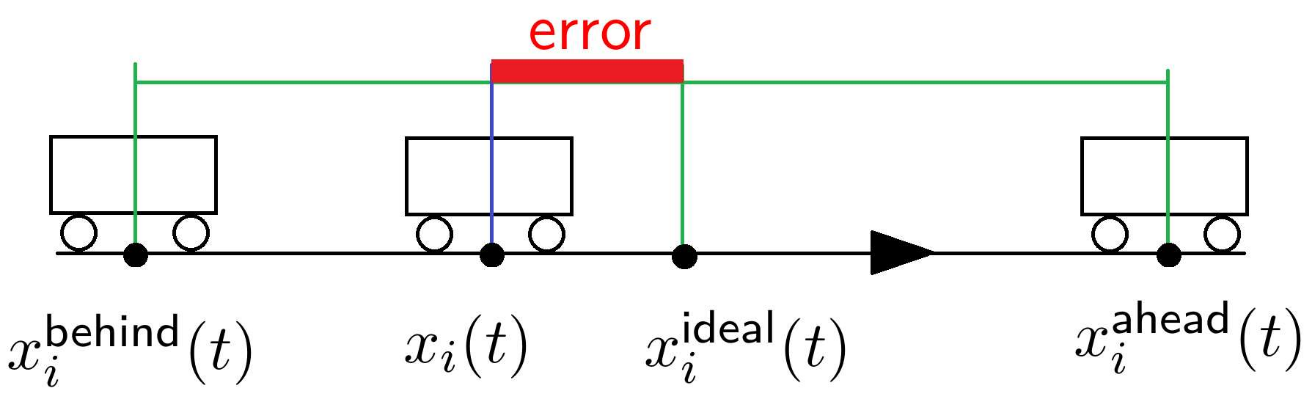
  a) No control, holding inactive

  b) No control, holding active

  c) Double control

  d) Linear model predictive control

Double control



$$x_i^{\text{ideal}}(t) = \frac{x_i^{\text{ahead}}(t) + x_i^{\text{behind}}(t)}{2}$$

error

$$v_i(t+1) = v_i(t) + K_{\text{DC}} \cdot \boxed{(x_i^{\text{ideal}}(t) - x_i(t))}$$

Linear model predictive control (QP)

regularize headways

drive as fast as possible

$$\underset{v_i(t)}{\text{minimize}} \quad \sum_{t=0}^{N} \sum_{i=1}^{K_\mathsf{b}} \left(\boxed{(x_i(t) - x_i^{\mathsf{ideal}}(t))^2} + \sigma \boxed{(v_i(t) - v_{\mathsf{max}})^2} \right)$$

subject to for $i = 1, \ \ldots, \ K_\mathsf{b}$:

$$\boxed{x_i(0) = \hat{x}_i(t_k)}$$

measurement of initial bus positions

for $t = 0, \ \ldots, \ N-1$:

$$\boxed{x_i(t+1) = x_i(t) + T_s v_i(t)}$$

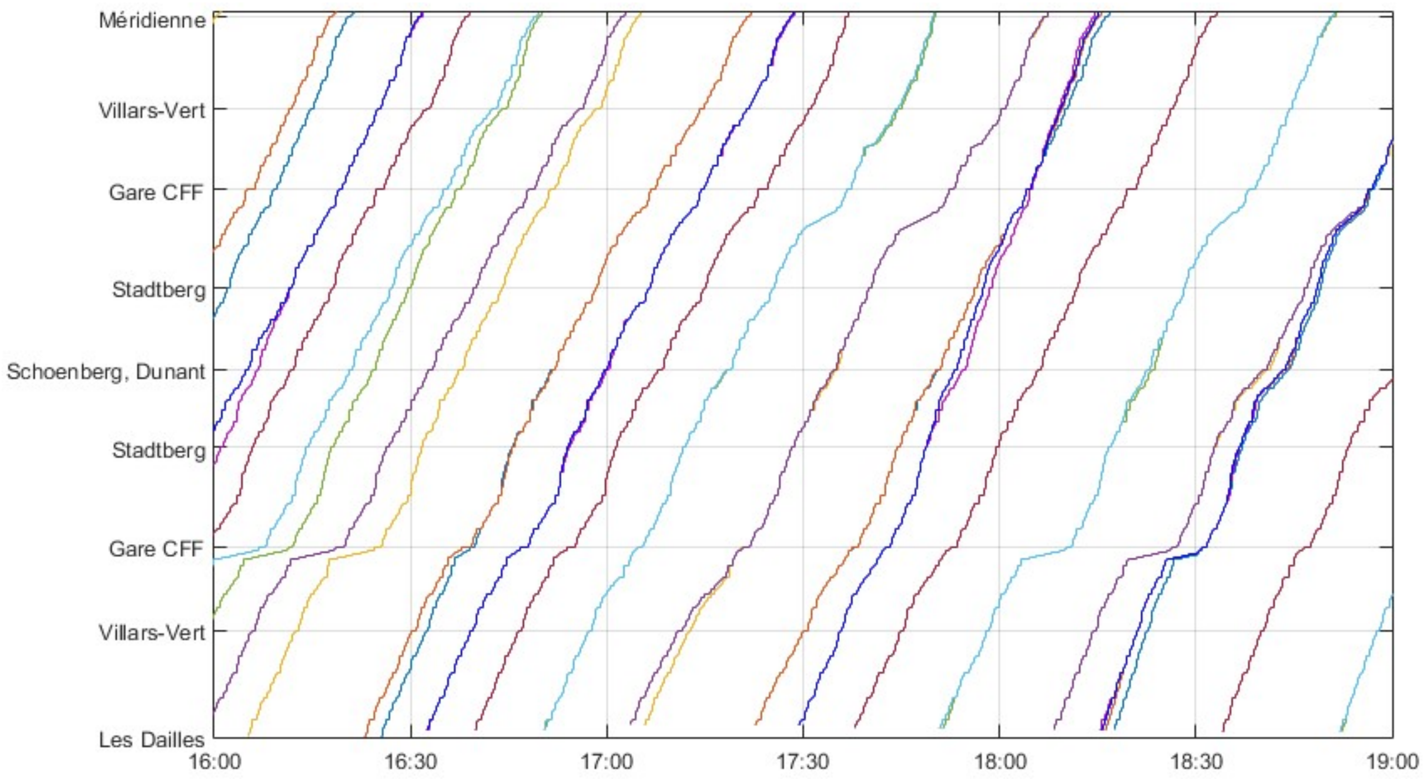
dynamical model of bus motion

$$x_i^{\mathsf{ideal}}(t) = 0.5(x_i^{\mathsf{ahead}}(t) + x_i^{\mathsf{behind}}(t))$$

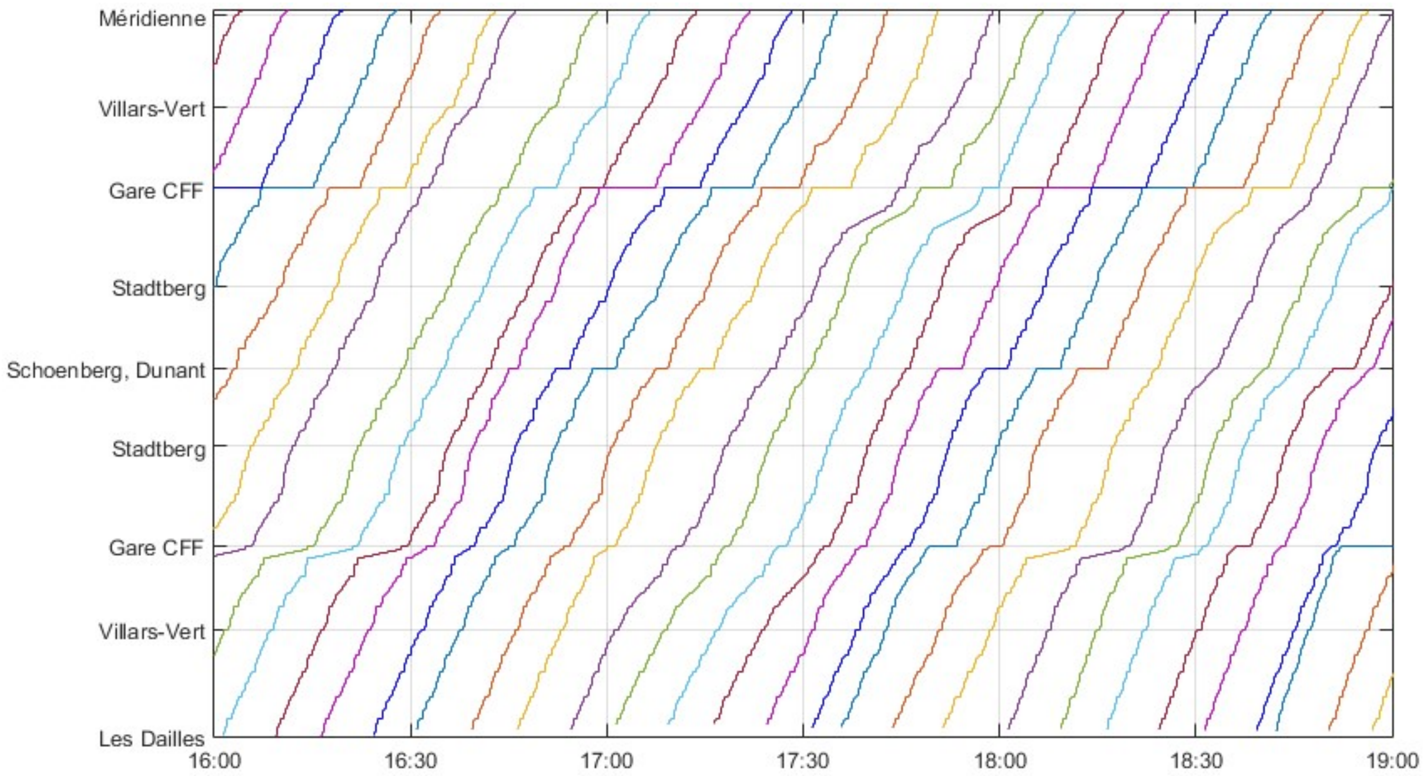
$$\boxed{v_{\mathsf{min}} \leq v_i(t) \leq v_{\mathsf{max}}}$$

bounds on bus speed

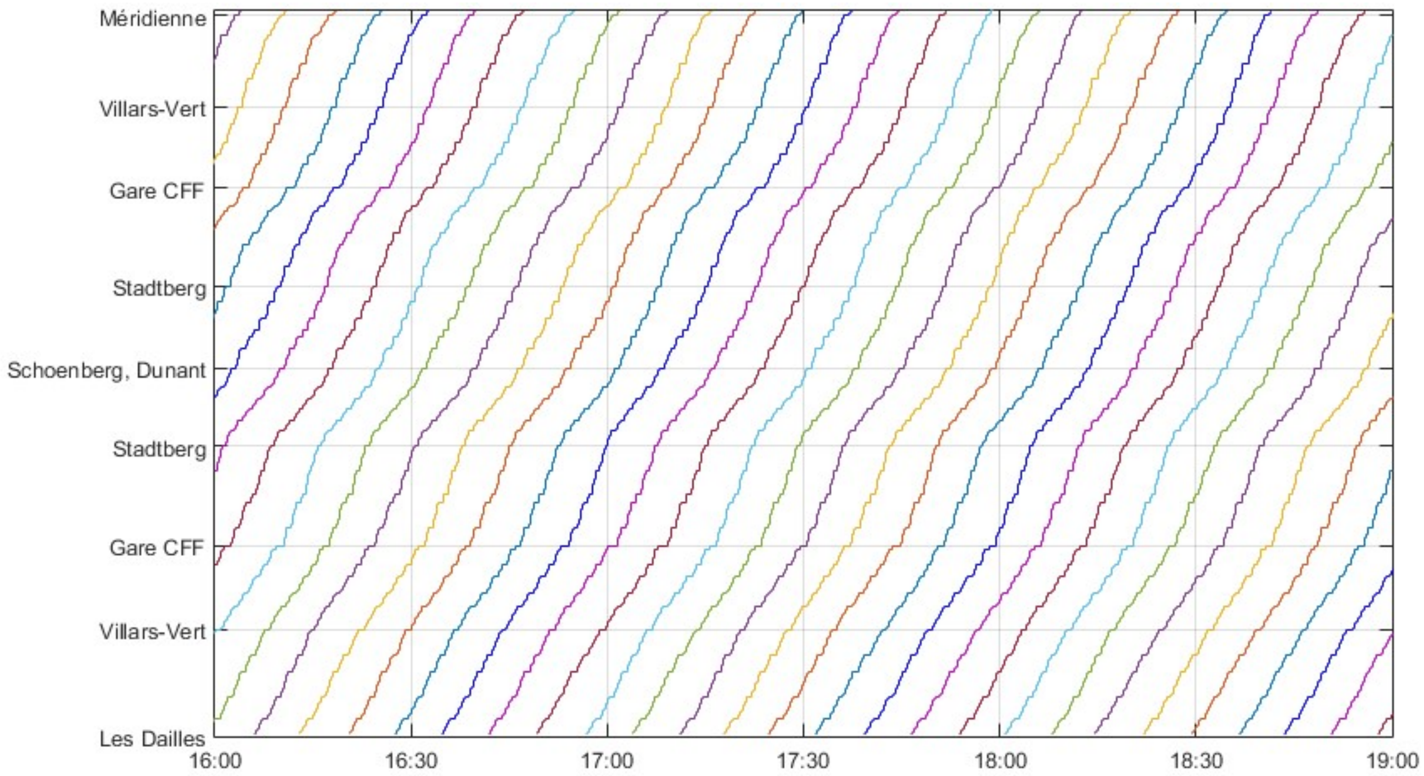
Bus positions (no control, holding inactive)



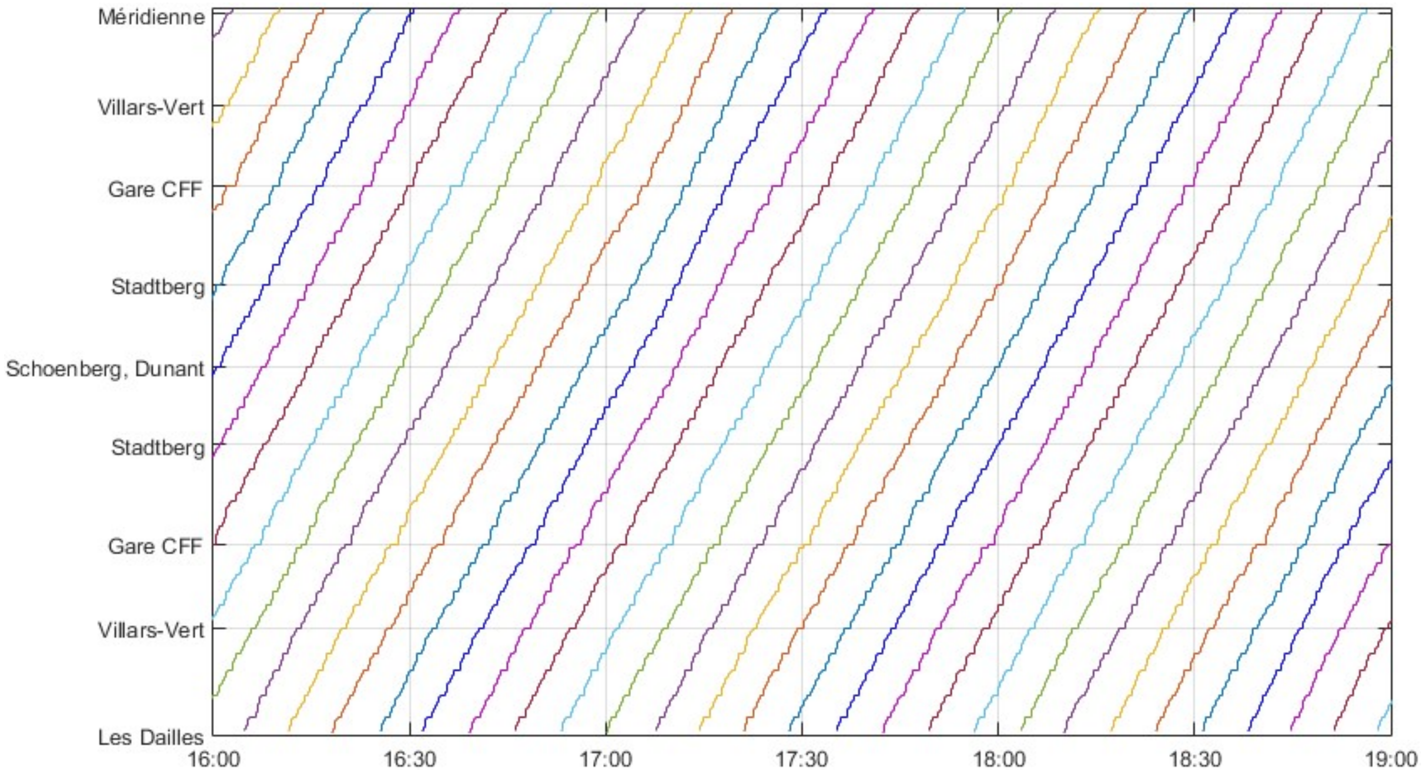
Bus positions (no control, holding active)



Bus positions (double control)



Bus positions (linear model predictive control)



Comparison of headway distributions