Oct. 16th, 2015

Research Update

Bus Speed Control System

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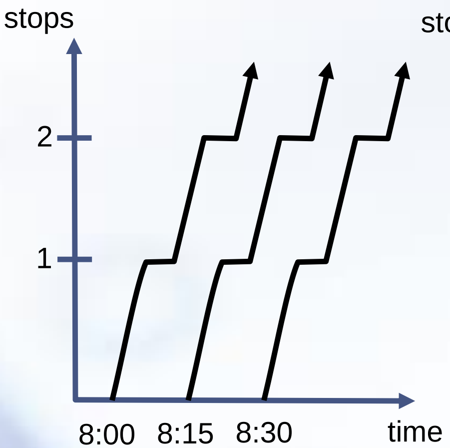
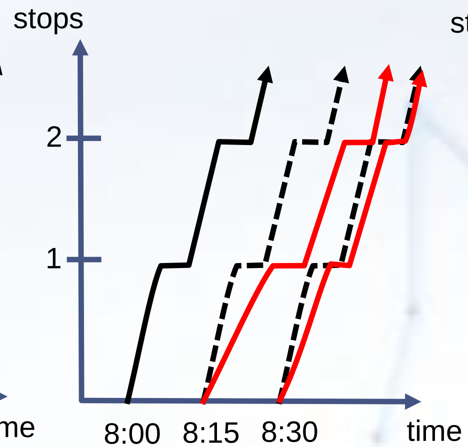
INTRODUCTION

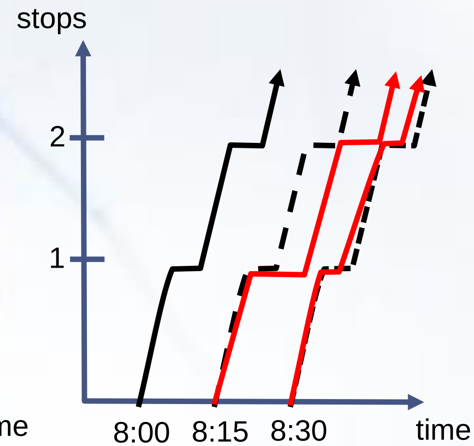
❖ BUS Bunching



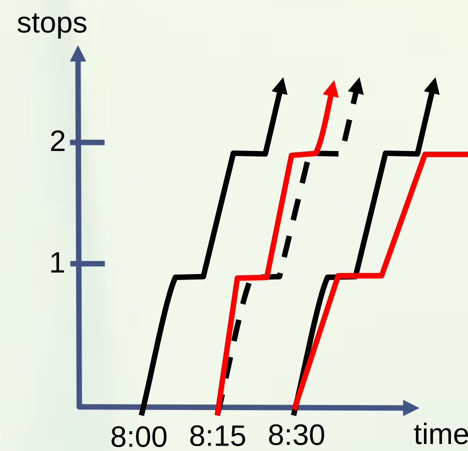
<Scheduled timetable>



<Traffic Delay>



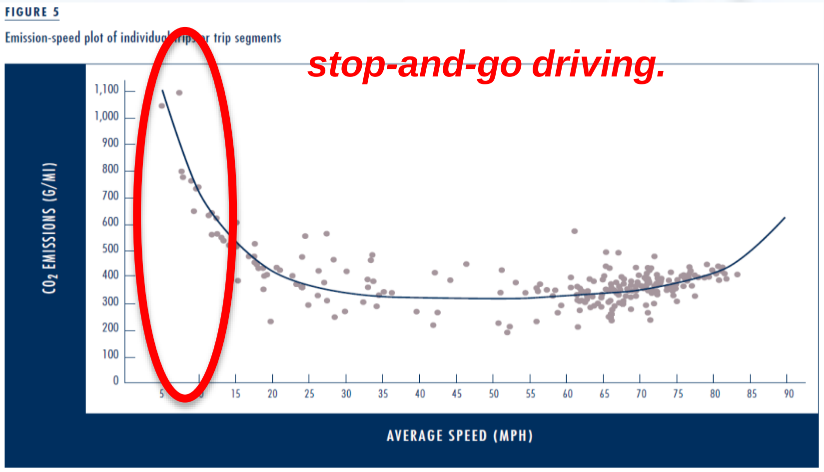
<Unbalanced PAX Demand>



<Traffic Signal Inference>

INTRODUCTION

❖ Stop-and-go Driving



Source: *'Traffic Congestion and Greenhouse Gases' by Matthew Barth and Kanok Boriboonsomsin (Access, number 35, Fall 2009)*

INTRODUCTION

❖ Objective

- Develop a bus speed control system so as to minimize bus headway variance while reducing the fuel consumption

❖ Decision Outcome

- Advisory bus speed to the next traffic signal

Bus Speed Control Environment

- Bus Speed Control Condition:
  - Frequent bus service
  - Far-side bus stops
  - Pre-timed signal control

- Given Information:
  - Individual bus information
  - Traffic information
  - Signal information

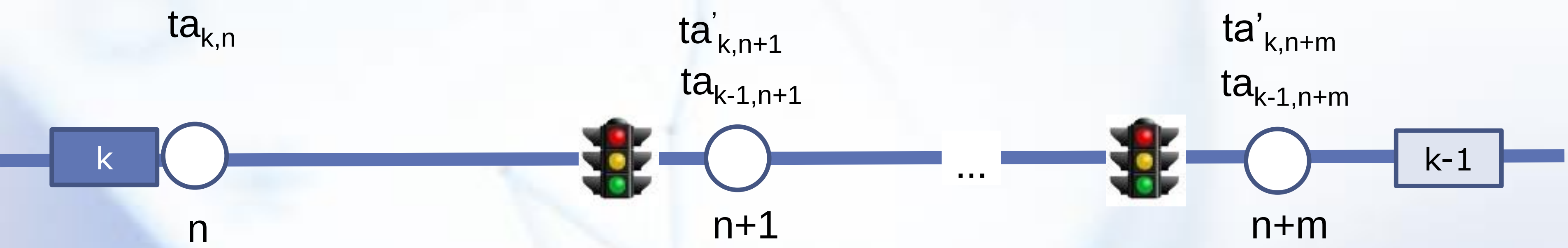
Bus Speed Control Environment

❖ Assumptions

- Travel speeds of general traffic between stops and passenger arrival rates at each stop are assumed known and fixed for the period of interest.
- Signal timing plans for each intersection between stops are pre-timed and fixed for the period of interest.
- Each stop has a dwell time function depending on the number of passengers boarding.
- Buses obey advisory running speed.
- Vehicles at intersections are fully discharged in every cycle.
- Bus stops are located in the far-side.

Rolling Horizon Approach

- Whenever a bus(k) arrives at the bus stop(n), the system provides the adjusted speed to the next stop so as to reduce headway variance *up to the bus stop(n+m) that the preceding bus(k-1) just left* in a way to improve fuel efficiency.



$ta_{k,n}$: Actual arrival time of bus k at stop n
$ta'_{k,n}$: Estimated arrival time of bus k at stop n

Bus stop

Bus

Model Development

❖ Bi-Level bus speed control :

1. Determine how many cycles the bus waits to pass the n^{th} signal so as to reduce headway variance
2. Determine a bus advisory speed to enhance fuel efficiency with the reduced signal stopped delay

Notation

- k: bus index, k=1,…,K
- n: bus stop index, n=1,...,N
- i: driving mode index (i=1:stop, 2: cruise, and 3:accelation)
- e_k: stop immediately upstream from bus k, if bus k is in stop n then e_k =n
- α: weight factor included in the objective function
- ta_{kn}: actual arrival time of bus k at stop n
- ta'_{kn}: estimated arrival time of bus k at stop n
- $\widetilde{ta}_{kn}$: expected arrival time of bus k at stop n
- t_{kn}' : estimated arrival time of bus k at traffic signal between stops n and n+1
- o_n: offset of the signal between stops n and n+1
- m: previous cycle index at the current time (current cycle index: m+1)
- C: cycle length (seconds)
- τ_n: travel time from the signal to stop n+1 (seconds)
- f'_{kn}: estimated dwell time of bus k at stop n (seconds)
- b'_{kn}: estimated number of passengers who board bus k at stop n
- t_b: passenger boarding time (seconds per passenger)
- t_0: door opening/closing time (seconds)
- v_n: traffic speed between stop n and n+1
- λ_n: vehicle arrival rate at the signal between stops n and n+1 (vehicles per hour)
- $P\lambda_n$: passenger arrival rate at stop n(passengers per minute)

Notation

- E: total fuel consumption (liter)
- FR_i: fuel consumption rate (liter per second) of driving mode i
- $TVSP_i$: trip time spend in driving mode i (seconds)
- VSP_i: vehicle specific power in driving mode i (m^2/s^3)
- a: acceleration rate (m/s^2)
- sd_{kn}: signal delay of bus k at the signal between stops n and n+1 (seconds)
- d_n: distance between stops n and n+1 (mile)
- ds_n: distance between stop n and the traffic signal (mile)
- s: saturation flow rate (vehicle per hour)
- tr_{kn}: start time of targeting cycle of bus k at the traffic signal between stops n and n+1
- R_n: red interval of the traffic signal between stops n and n+1
- g_n: green time ratio of nth signal
- ${v_{kn}}^{LB}$: lower bound of bus advisory speed (mile per hour)
- ${v_{kn}}^{UB}$: upper bound of bus advisory speed (mile per hour)
- t0: estimated departure time
- t1: start time of target cycle
- t2: time that all queue is discharged
- t3: end time of target cycle
- u: unit conversion factor
- L: vehicle length (mile)
- v_{kn}: advisory bus speed (mile per hour)

Upper Level

- Determine how many cycles the bus waits to pass the nth signal so as to reduce headway difference

Objective

$$Min \sum_{n=e_k+1}^{e_{k-1}} \alpha * (ta_{k-1n} - ta'_{kn})^2 + (1-\alpha) * (\widetilde{ta}_{kn} - ta'_{kn})^2$$

Estimated arrival time of bus k at stop n+1

$$ta'_{kn+1} = o_n + (m + x_{kn}) * C + \tau_n - \mathrm{g}(*)$$

Bus k passes the n^{th} intersection during target cycle x_{kn}

$$ta'_{kn} + f'_{kn} + \frac{\mathrm{ds_n}}{v_n} \le o_n + (m + x_{kn}) * C$$

$$o_n + (m + x_{kn} + 1) * C \le ta'_{kn} + f'_{kn} + \frac{\mathrm{ds_n}}{v_n}$$

Estimated dwell time of bus k at stop n

$$f'_{kn} = b'_{kn} \cdot t_b + t_0$$

Estimated # of pax boarding bus k at stop n

$$b'_{kn} = P\lambda_n \cdot (\mathrm{ta'_{kn}} - \mathrm{ta}_{k-1n})$$

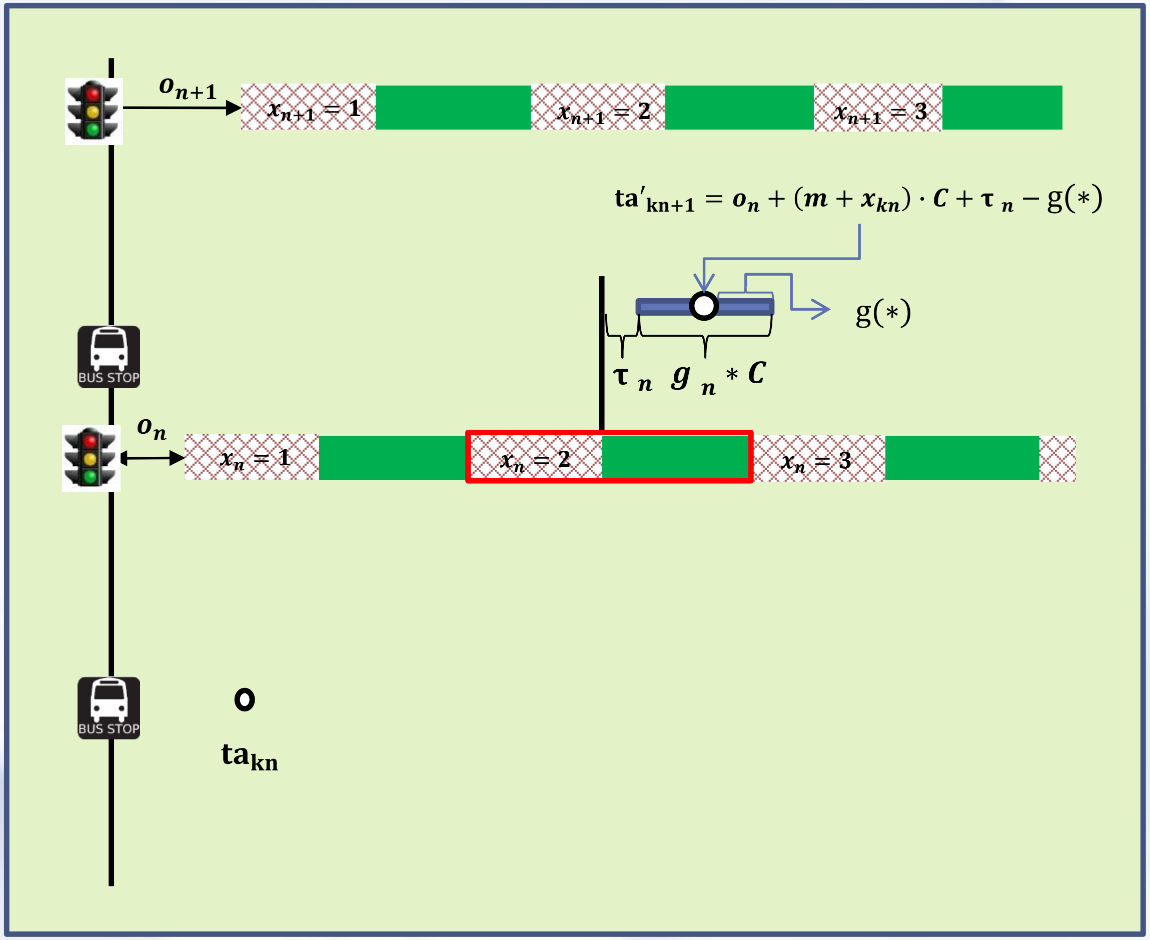
$$1 \le x_{kn} \le M$$

Decision Variable $x_{kn} \ge 0, \quad integer$

How many cycles the bus k waits to pass the nth signal

Upper Level

- Determine how many cycles the bus waits to pass the nth signal so as to reduce headway difference



Lower Level

- Determine the bus desired speed so as to minimize the fuel consumption while satisfying the upper level decision

Objective $Min\ E$

Decision Variable $y_{kn} \geq 0$, integer

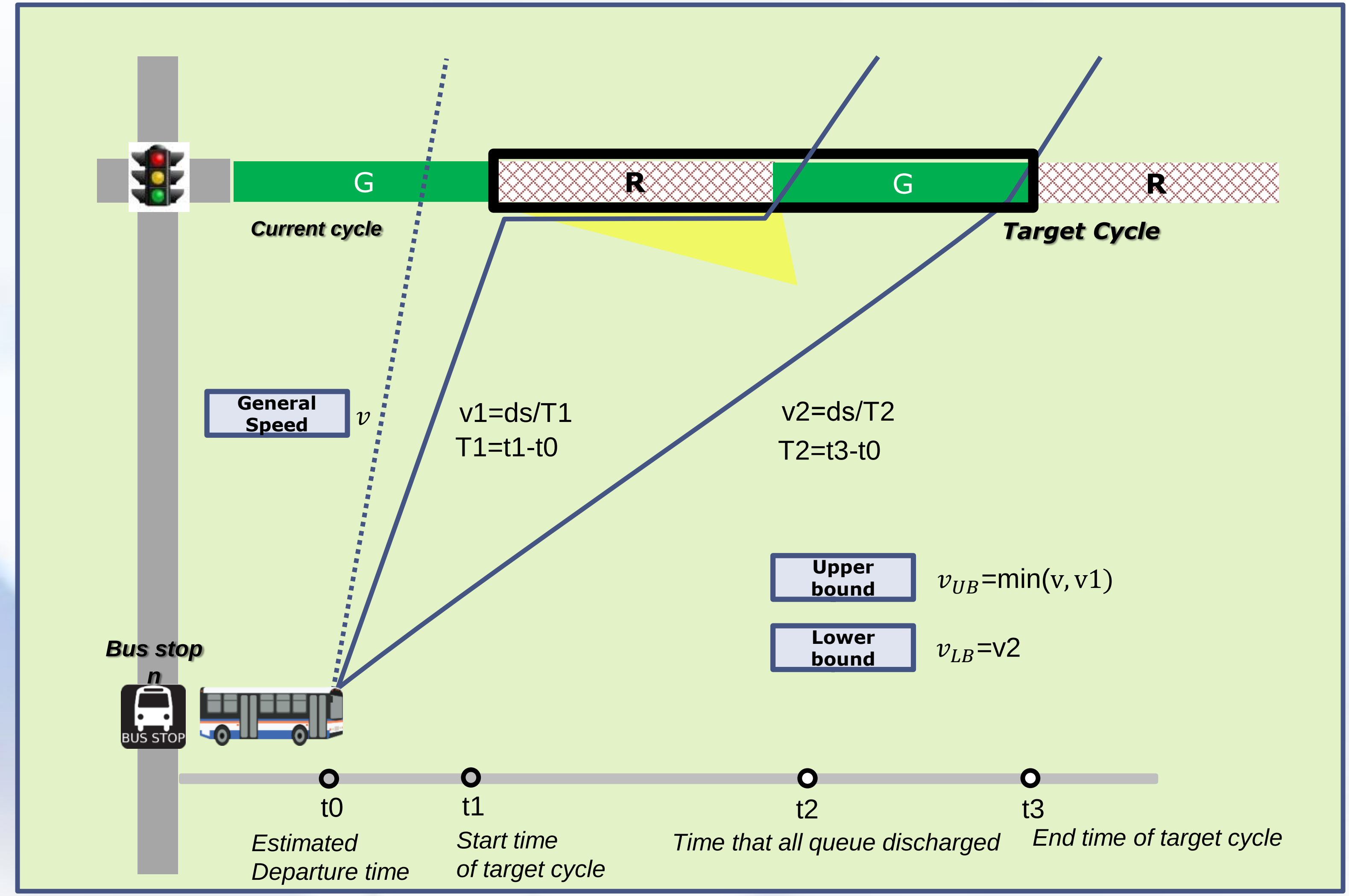
Desired Speed of bus k to the nth intersection $v_{kn} = 5y_{kn}$

Desired Speed range ${v_{kn}}^{LB} \leq v_{kn} \leq {v_{kn}}^{UB}$

$${v_{kn}}^{UB} = \begin{cases} \min\left\{\dfrac{ds_n}{t1 - t0}, v_n\right\} & t1 - t0 > 0 \\ v_n & t1 - t0 \leq 0 \end{cases}$$

$${v_{kn}}^{LB} = \frac{ds_n}{t1 + C - t0}$$

Lower Level



G
R
G
R
Current cycle
Target Cycle
General Speed
v
v1=ds/T1
T1=t1-t0
v2=ds/T2
T2=t3-t0
Upper bound
v_{UB}=min(v, v1)
Lower bound
v_{LB}=v2
Bus stop n
BUS STOP
t0
Estimated Departure time
t1
Start time of target cycle
t2
Time that all queue discharged
t3
End time of target cycle

Lower Level

Fuel consumption rate(l/s) for driving mode i

Total Fuel consumption

$$E = \sum_{i=1}^{3} FR_i \times TVSP_i$$

Trip time spend(s) in driving mode i

For i=1:stop, 2: cruise, and 3:accelation

vsp in driving mode i

$$VSP_i = \begin{cases} 0 & i = 1 \\ (v_{kn} \times u) \times 0.092 + 0.00021 \times (v_{kn} \times u)^3 & i = 2 \\ (v_{kn} \times u) \times (a + 0.092) + 0.00021 \times (v_{kn} \times u)^3 & i = 3 \end{cases}$$

Trip time spend in driving mode i

$$TVSP_i = \begin{cases} sd_{kn} & i = 1 \\ \dfrac{d_n}{v_{kn}} & i = 2 \\ \dfrac{v_{kn}}{a} & i = 3 \end{cases}$$

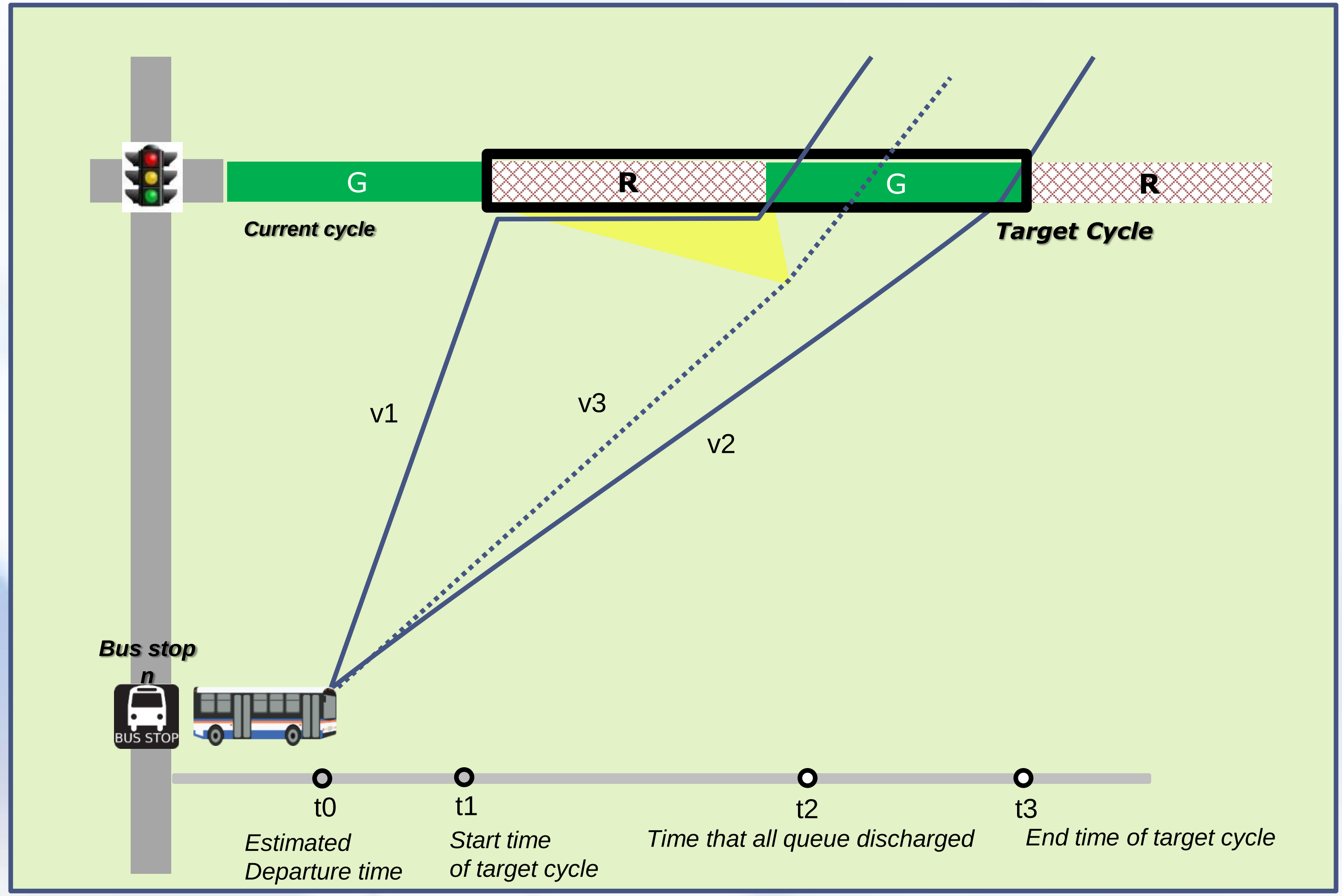
$$\mathrm{VSP} = v \times (a + g \times \sin(\varphi) + 0.092) + 0.00021 \times v^3$$

where VSP is the Vehicle Specific Power (m^2/s^3); v is instantaneous speed at which the vehicle is traveling (m/s); a is instantaneous acceleration of the vehicle (m/s^2); φ is instantaneous road grade (decimal fraction); 0.092 is rolling resistance term coefficient; and 0.00021 is the drag term coefficient.

Definition of Vehicle Specific Power (VSP) modes

VSP mode	VSP range (m^2/s^3)	VSP mode	VSP range (m^2/s^3)
1	$\mathrm{VSP} \leqslant 0$	5	$6 \leqslant \mathrm{VSP} < 8$
2	$0 < \mathrm{VSP} < 2$	6	$8 \leqslant \mathrm{VSP} < 10$
3	$2 \leqslant \mathrm{VSP} < 4$	7	$10 \leqslant \mathrm{VSP} < 13$
4	$4 \leqslant \mathrm{VSP} < 6$	8	$\mathrm{VSP} \geqslant 13$

* H. Christopher Frey at al(2007).Comparing real-world fuel consumption for diesel- and hydrogen-fueled transit buses and implication for emissions, Transportation Research Part D, 12


G
R
G
R
Current cycle
Target Cycle
v1
v3
v2
Bus stop n
BUS STOP
t0
Estimated Departure time
t1
Start time of target cycle
t2
Time that all queue discharged
t3
End time of target cycle

Lower Level

Signal delay

$$sd_{kn} = \begin{cases} 0 & v_{kn} < v3 \\ [tr_{kn} + R_n - t_{kn}'] + \left[(t_{kn}' - tr_{kn}) \cdot \lambda_n \cdot \frac{1}{s}\right] & v_{kn} > v3 \end{cases}$$

Waiting time to GREEN start — **Queue discharging Time**

Distance to the intersection

$$ds_n = \begin{cases} (t_{kn}' - (ta_{kn} + f'_{kn}))/3600 \cdot v_{kn} & v_{kn} < v3 \\ \left(t_{kn}' - \left(ta_{kn} + f'_{kn}\right)\right)/3600 \cdot v_{kn} + (t_{kn}' - tr_{kn})/3600 \cdot \lambda_n \cdot L & v_{kn} > v3 \end{cases}$$

Travel distance of the bus — **Queue length**

Estimated dwell time of bus k at stop n

$$f'_{kn} = b'_{kn} \cdot \tau_b + \tau_0$$

boarding time + door open/close time

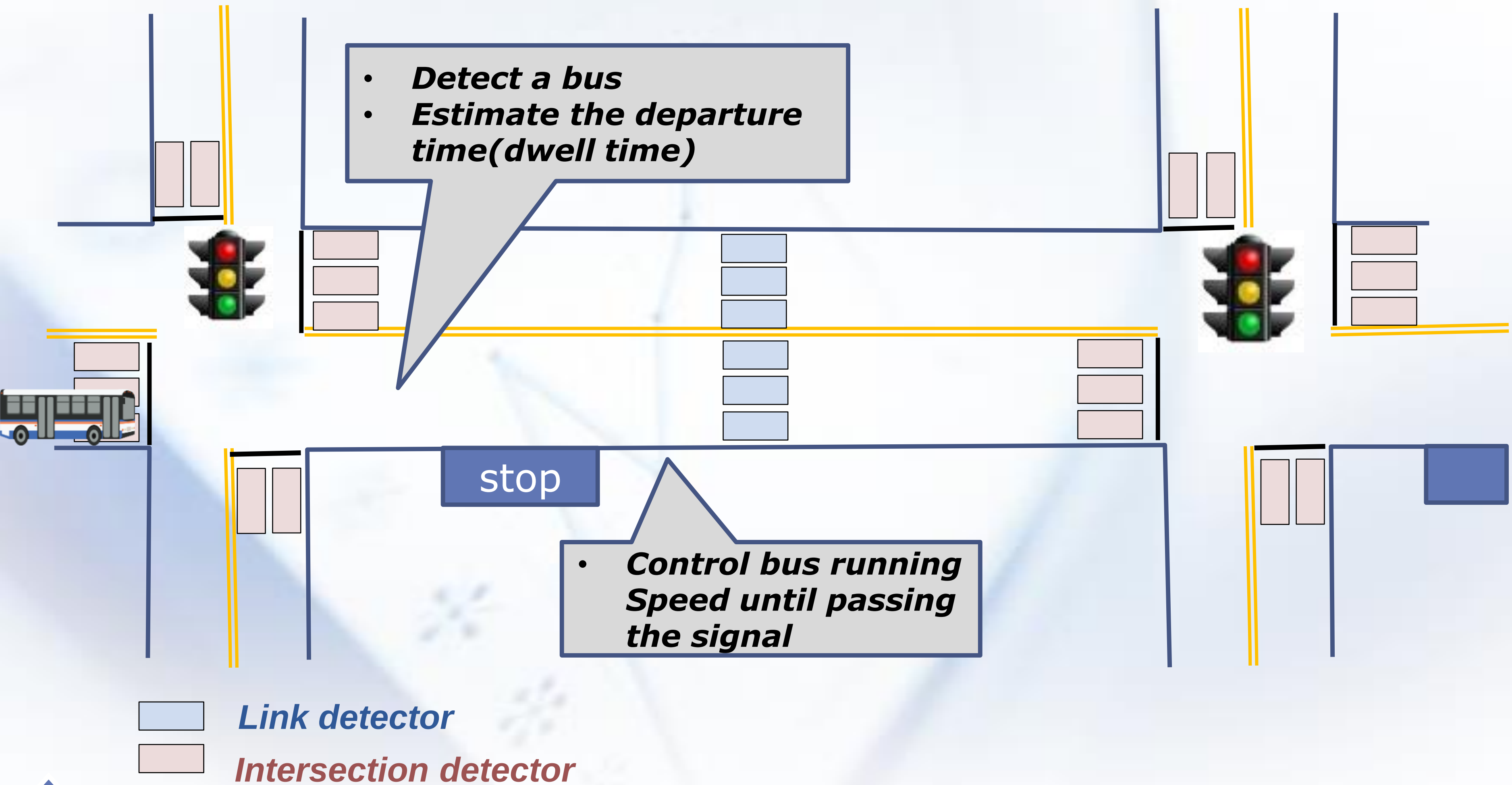
Estimated # of pax boarding bus k at stop n

$$b'_{kn} = P\lambda_n \cdot (ta'_{kn} - ta_{k-1n})$$

PAX arrival rate * bus headway

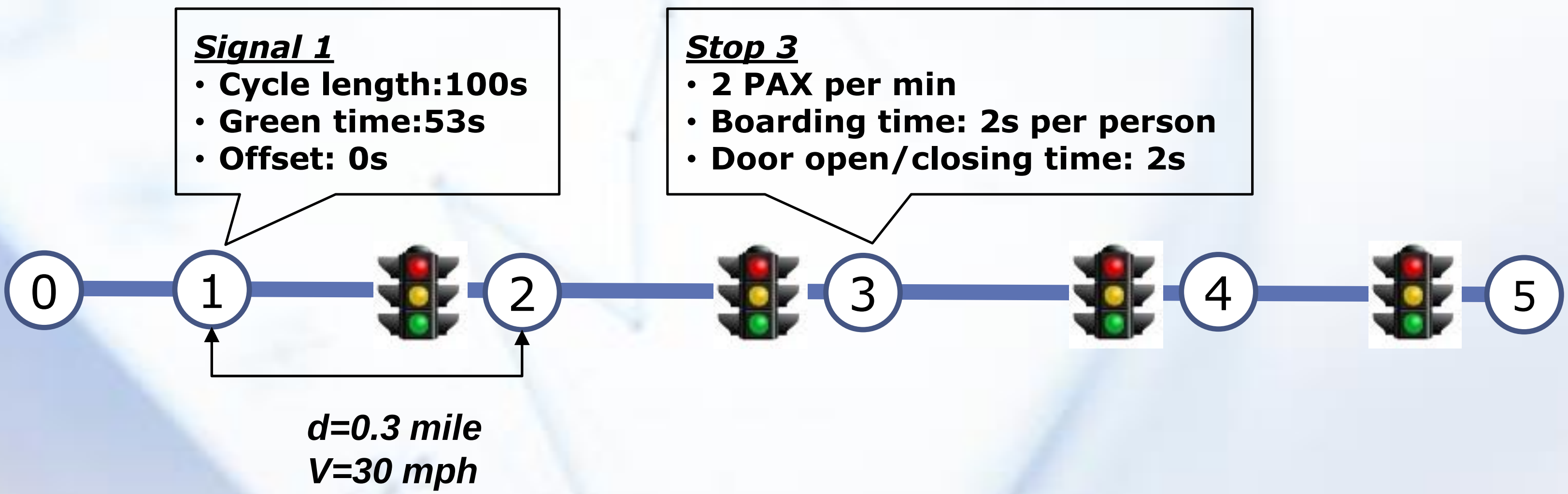
Numerical Example

❖ Bus speed control in VISSIM

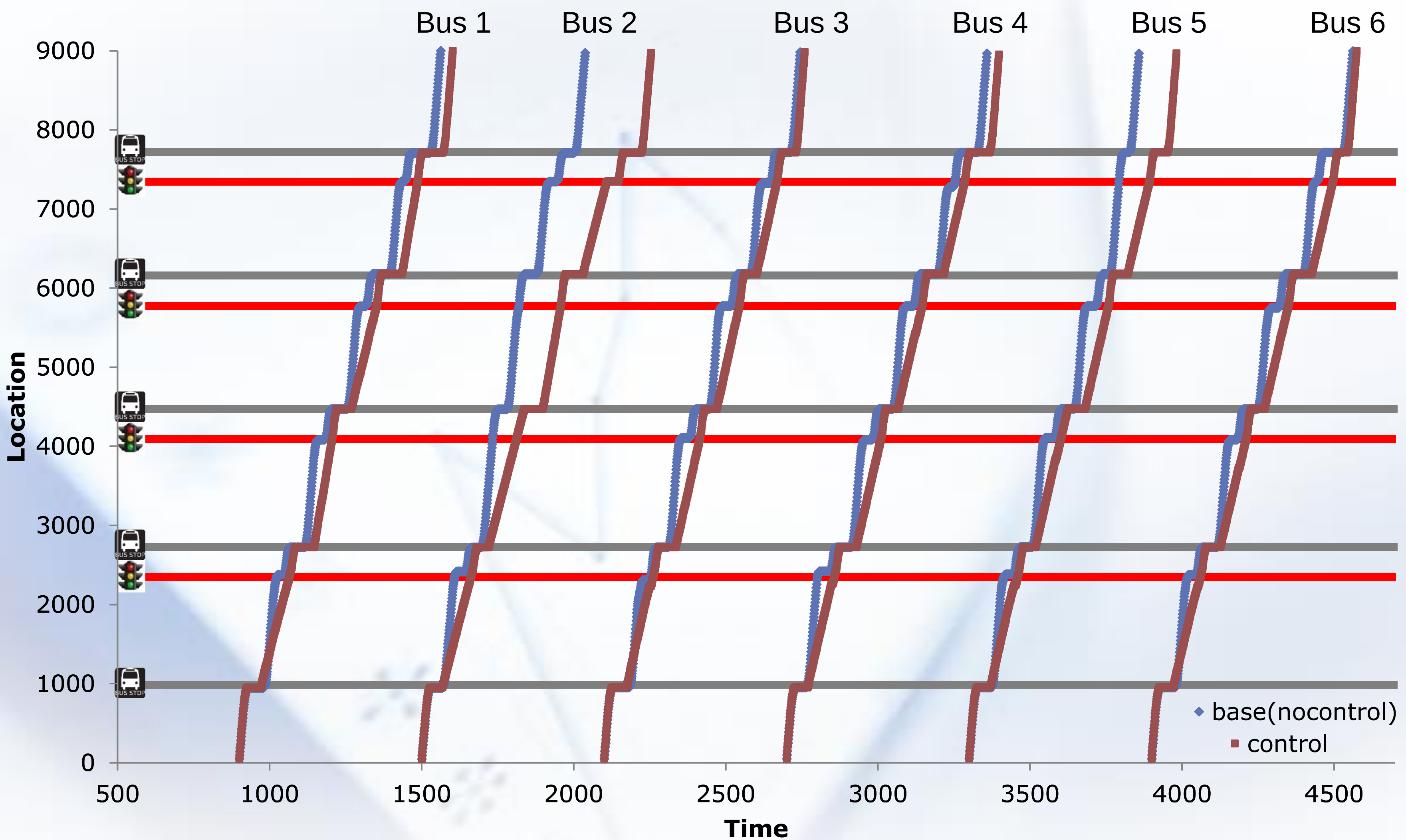


Numerical Example

- 5 Bus stops
- 6 Buses with 10 min headway
- Pre-timed signal control

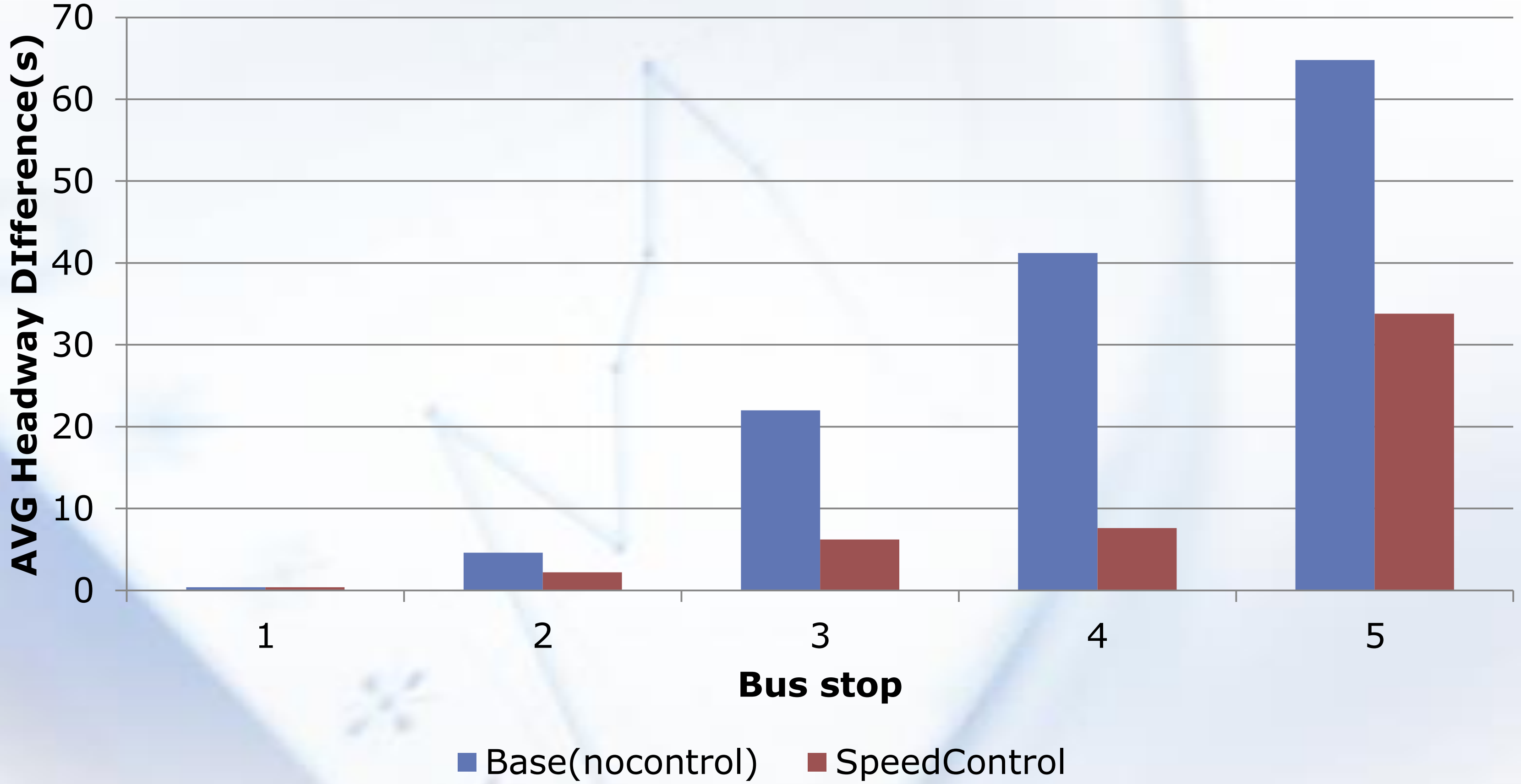


Numerical Example



Numerical Example

❖ **Average Headway Difference of buses**

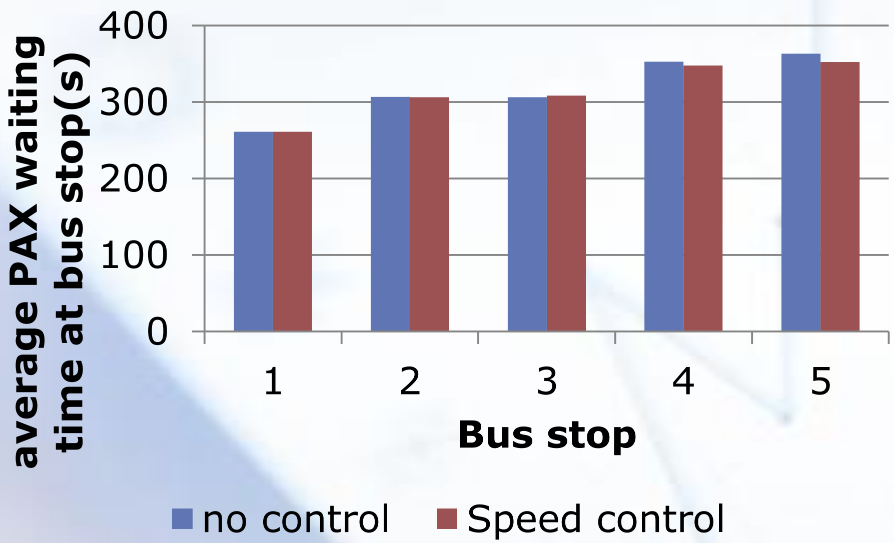


Reliability of bus service is improved

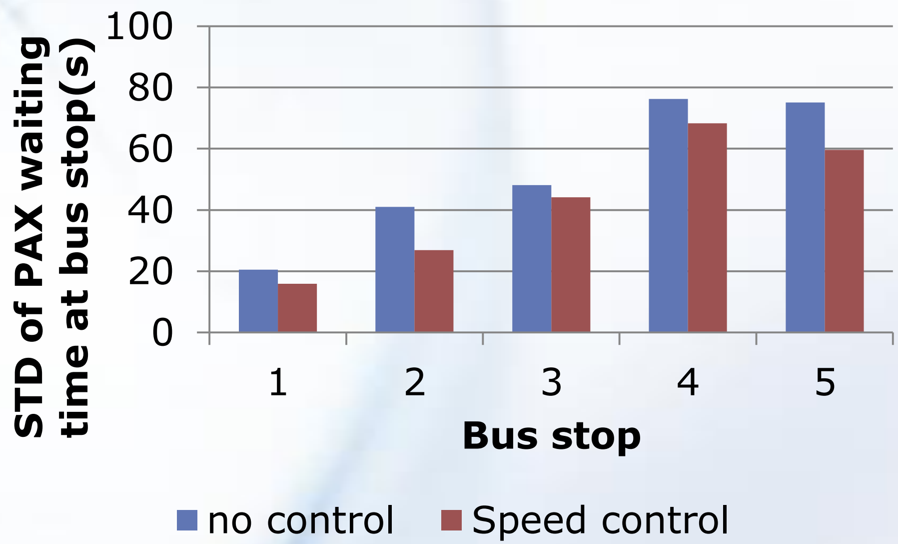
Numerical Example

- **PAX Waiting Time for a bus at each bus stop**

  - Mean(s)



  - Standard Deviation(s)



Reliability of bus service is improved

Numerical Example

- **Operation Time, #of stops, fuel consumption and emission for each bus**

	Travel Time(s)		Stopped Time (s)*		Fuel Con. (ml)**		CO_2(g) ***	
	Wo	W	Wo	W	Wo	W	Wo	W
Bus 1	664	704	345(88)	267(0)	2919	2591	1209.6	1186.730
Bus 2	553	757	247(38)	264(33)	2372	2733	1065.9	1290.900
Bus 3	656	661	334(99)	205(0)	2861	2449	1247.0	1170.067
Bus 4	665	701	342(111)	233(0)	2920	2596	1274.0	1219.175
Bus 5	526	685	237(66)	207(0)	2336	2479	1042.8	1214.864
Bus 6	648	676	331(88)	205(0)	2823	2478	1230.5	1201.234
Total	3712	4184	1836(402)	1381(33)	16231	15326	7069.8	7282.971

* Stopped time is the sum of dwell time at stops and stopped time at signals. The number in parenthesis represents the sum of stopped time at signals.
** H. Christopher Frey at al(2007).*Comparing real-world fuel consumption for diesel- and hydrogen-fueled transit buses and implication for emissions, Transportation Research Part D, 12*
*** United States Environmental protection Agency(2002), Methodology for Developing Modal Emission Rates for EPA's Multi-Scale Motor Vehicle and Equipment Emission System, EPA420-R-02-027

Bus operates in an environmentally-friendly way.

On-going Work

Model Improvement

- Dwell-Time Estimation
- Maximum Queue Estimation

Different Simulation Scenarios

- Bus Service Frequency
- Congestion Level