

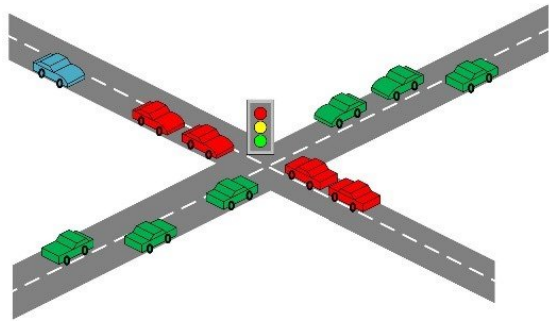
Lecture on
**Signal coordination for
arterials and paired signalized intersections**

Traffic Engineering (CIVIL-349)

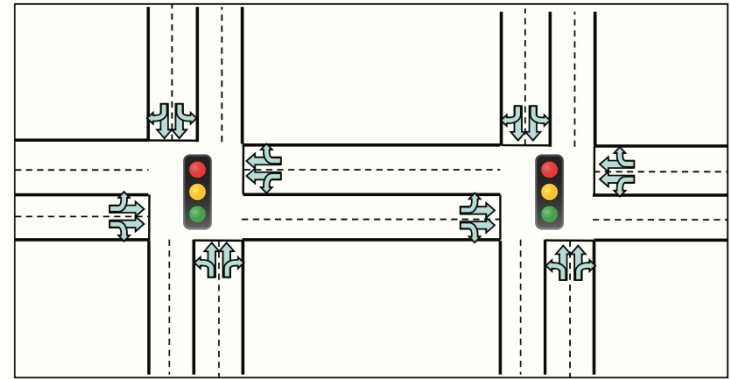
Jack Haddad and Nikolas Geroliminis

Signalized Intersections

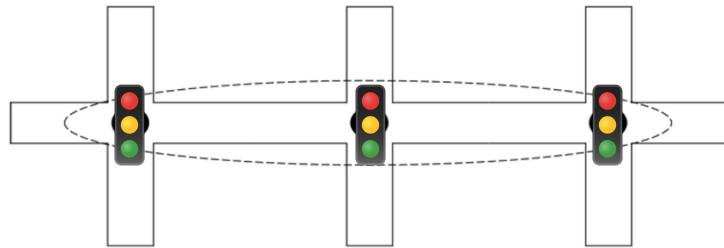
Examples of different types



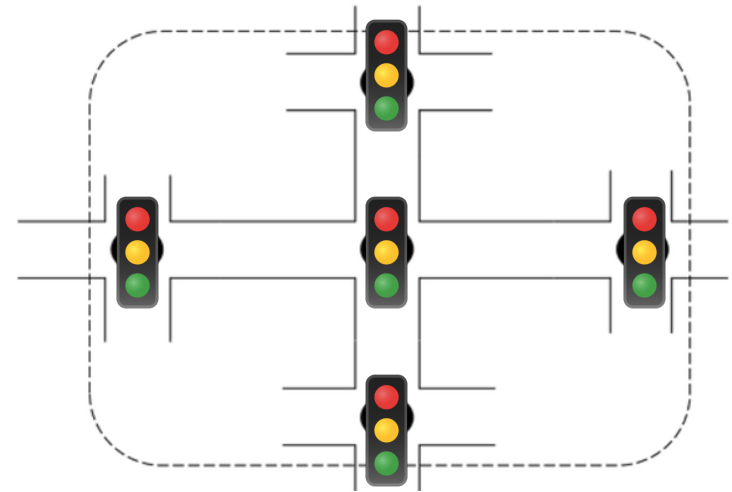
(a) **Isolated** signalized intersection



(b) **Paired** Signalized Intersections

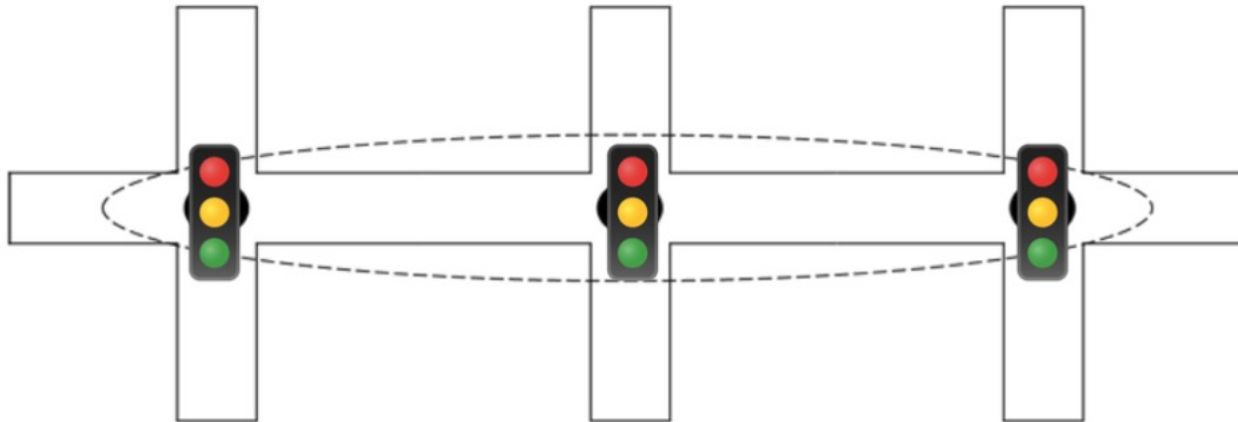


(c) **Arterial**



(d) **Network**

Signal coordination for arterials

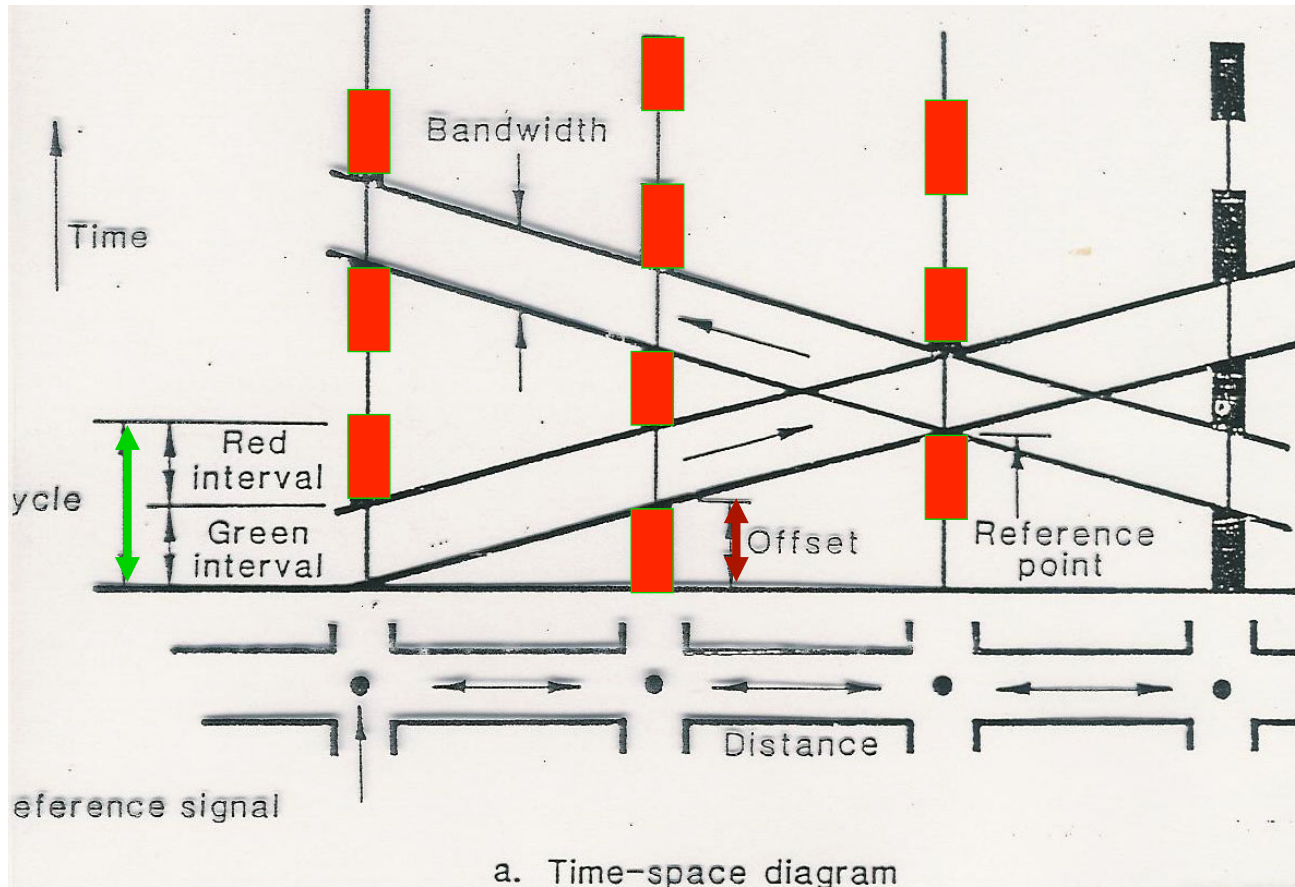


Fixed-Time Traffic Signal Optimization Methods for Arterials

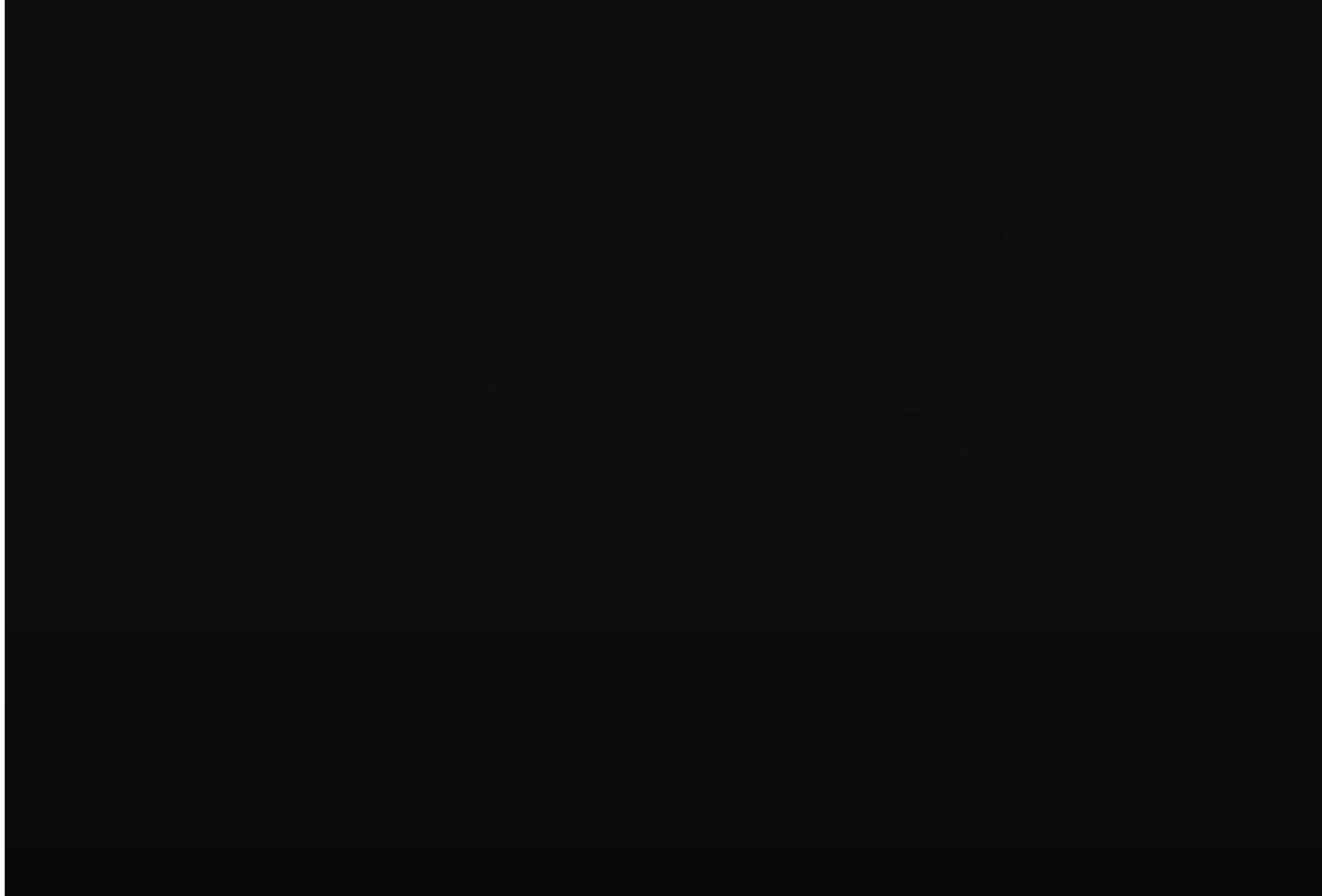
- Progression Methods (to coordinate green times so that vehicles may move efficiently through the set of signals)
 - Bandwidth based
 - Intuitively appealing
 - Simple and Effective
- Direct Performance Methods
 - Minimize delays and stops
 - Require detailed data
 - Computationally demanding

What is Bandwidth?

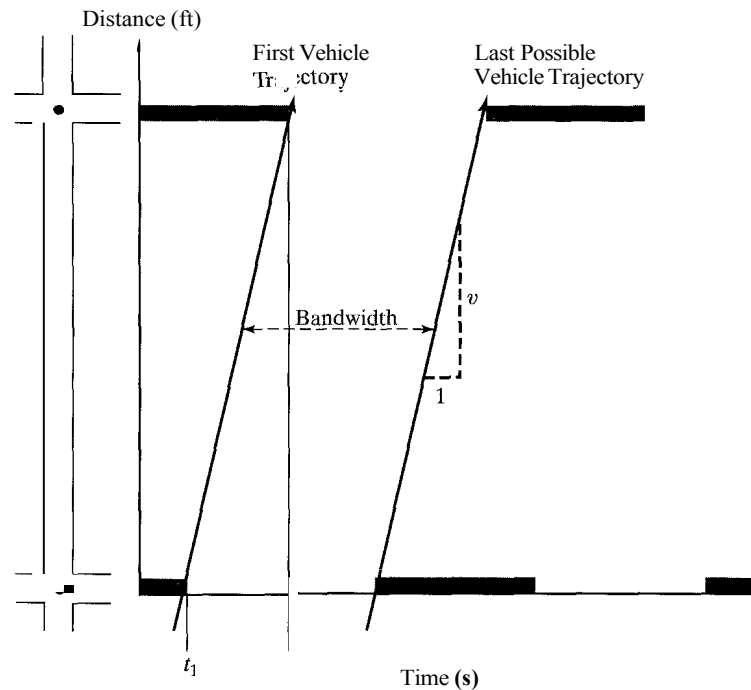
Portion of a signal cycle that provides continuous traffic movement along an arterial street



Video example...



The Time-Space Diagram and Ideal Offsets



- time space diagram for two intersections: green (blank); red (solid).
- **offset**: the difference between the time when the upstream intersection turns green t_1 and the downstream intersection turns green t_2 , i.e. $t_2 - t_1$.

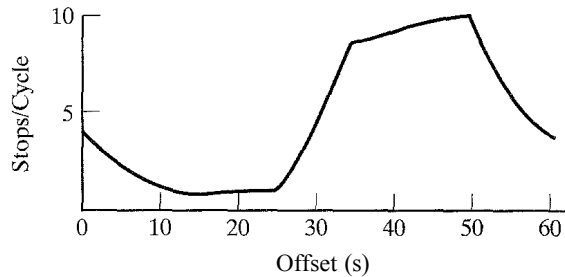
- **ideal offset:** as the first vehicle of a platoon just arrives at the downstream signal, the downstream signal turns green, i.e.

$$t_{\text{ideal}} = \frac{L}{S}$$

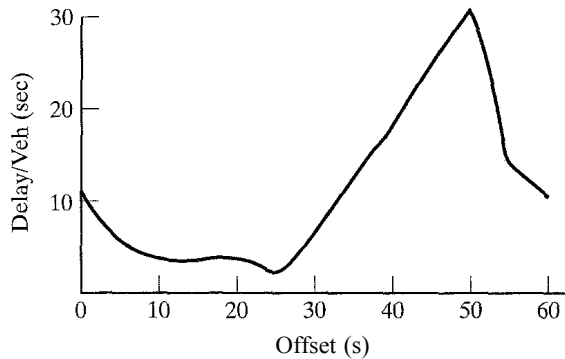
where

- L - distance between signalized intersections
- S - average speed
- **bandwidth:** the amount of green time that can be used by a continuously moving platoon of vehicles through a series of intersections.
- in the figure, the bandwidth is the entire green time at both intersections, because the green times at both intersections are the same.

Effect of offset on stops and delay



(a) Stops



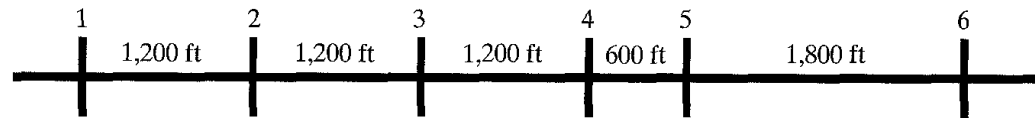
(b) Delay

600-ft block
 600 vph in two lanes
 all through traffic
 free speed 24 mph
 50:50 split
 60 s cycle length

- a 25-s offset is ideal, as it produces the minimum delay and the minimum number of stops.
- Note that the penalty for deviating from the ideal offset is usually not equal in positive and negative deviations.

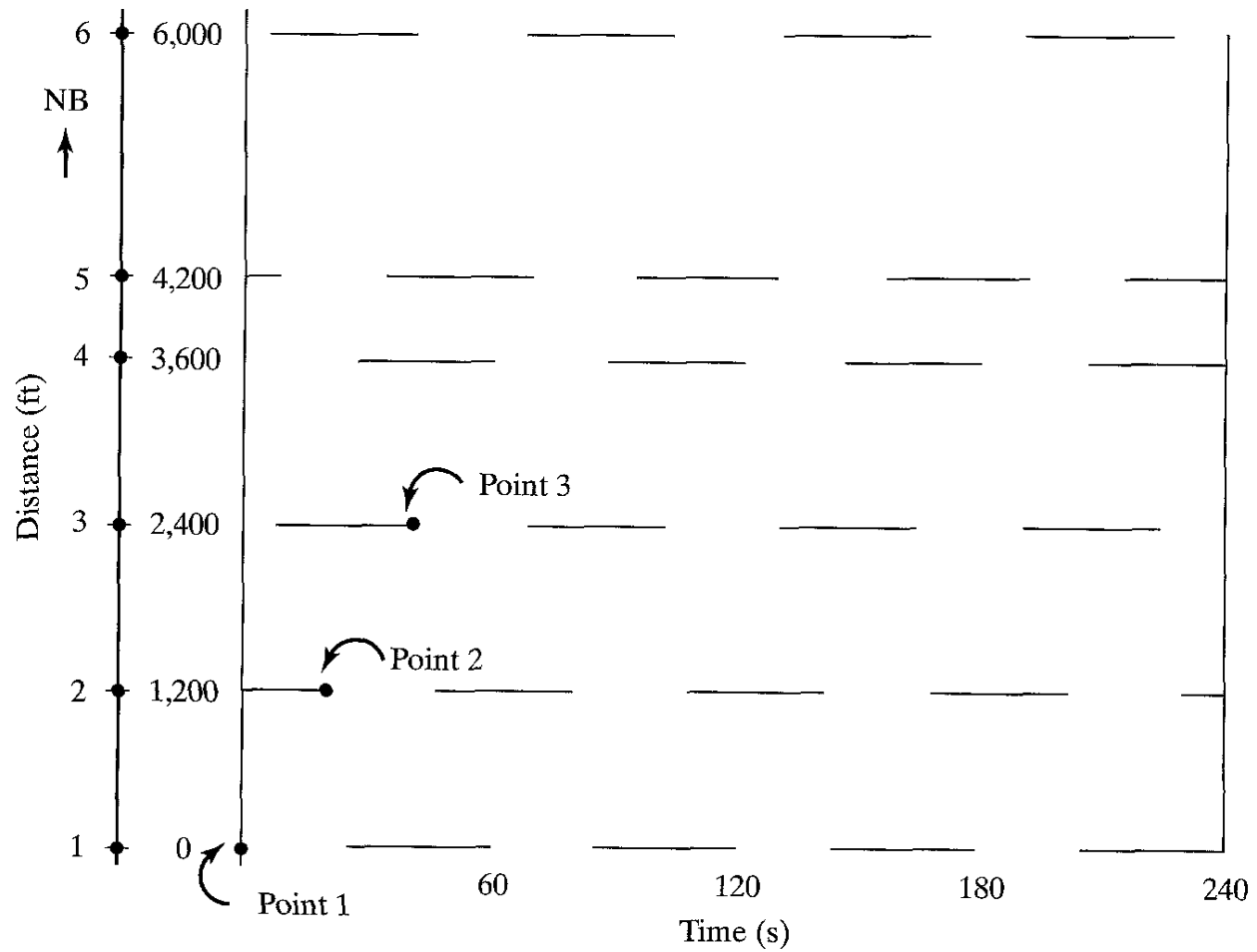
Signal Progression for One-Way Streets

- it is assumed that a cycle length has been chosen and that the green allocation at each signal has been previously determined.
- Consider a one-way arterial with the link lengths indicated.

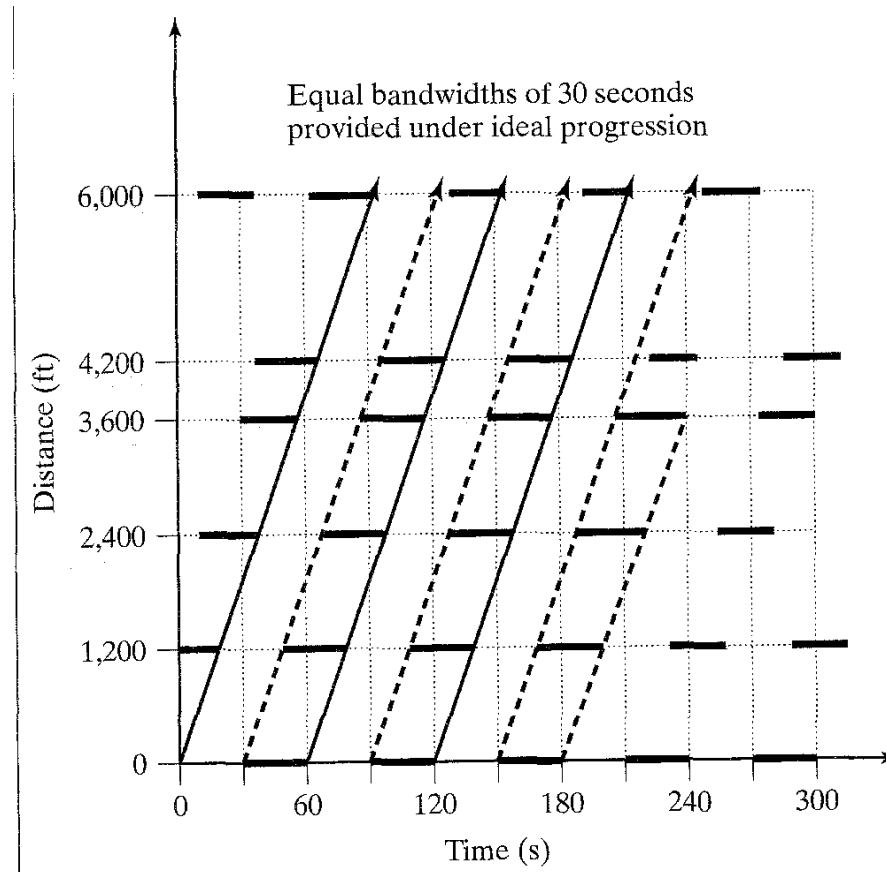


- Assuming no vehicles are queued at the signals, the ideal offsets can be determined if the platoon speed is known (60 ft/s). The cycle length is 60s, and the effective green time at each intersection is 30s.

Signal	Relative to Signal	Ideal Offset
6	5	$1,800/60 = 30 \text{ s}$
5	4	$600/60 = 10 \text{ s}$
4	3	$1,200/60 = 20 \text{ s}$
3	2	$1,200/60 = 20 \text{ s}$
2	1	$1,200/60 = 20 \text{ s}$

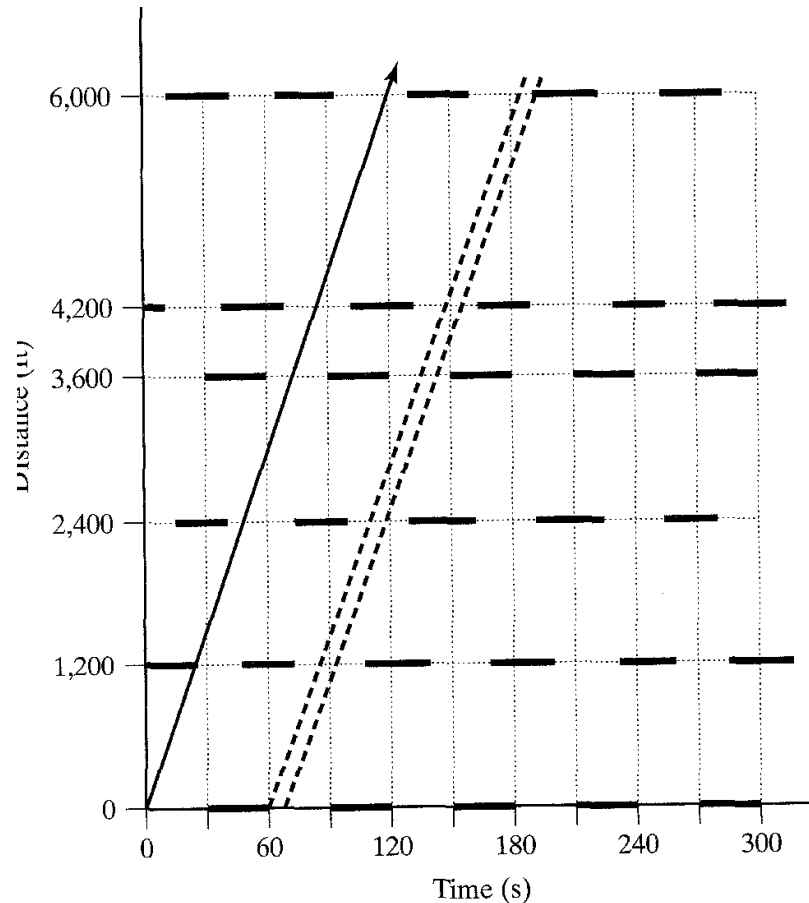


- if a vehicle (or platoon) were to travel at 60 fps...



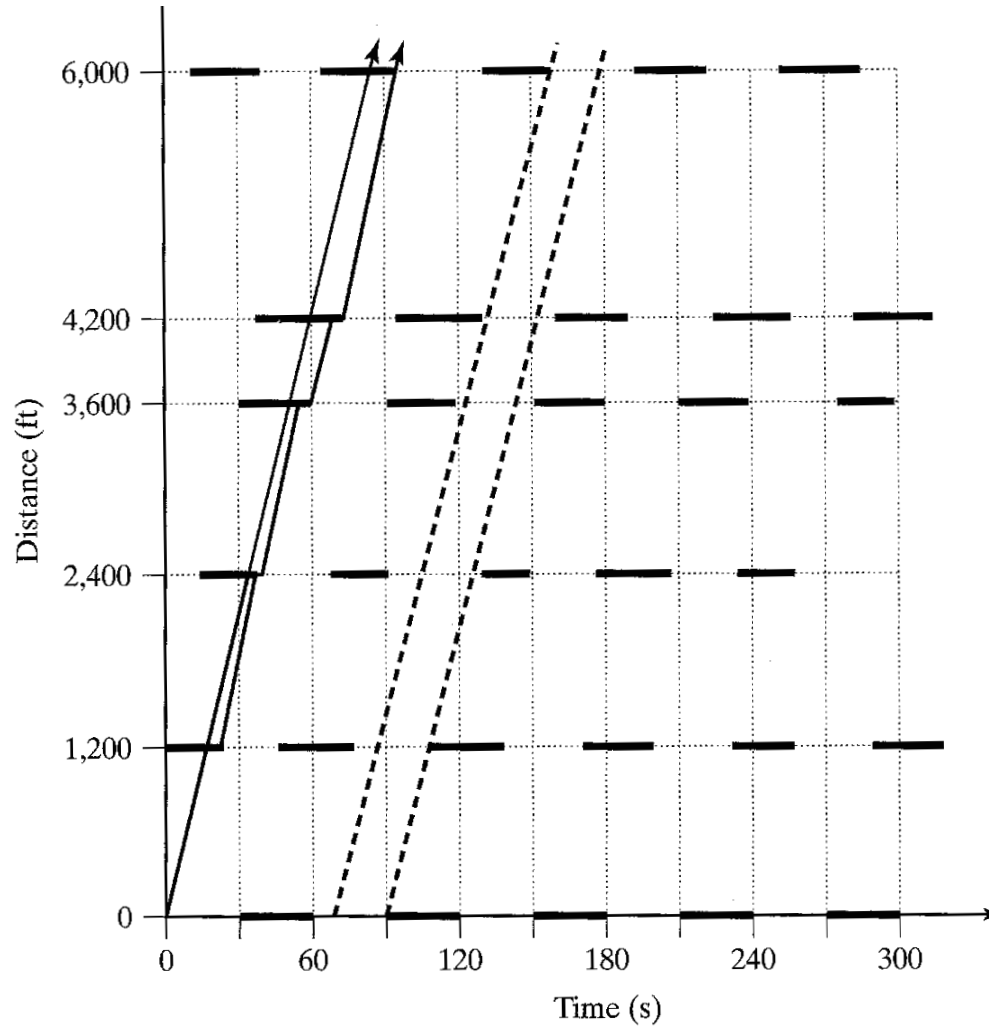
- Recall: bandwidth equals the green time because all signals have the same green time and have ideal offsets.

- if a vehicle (or platoon) were to travel at 50 fps...



- Bandwidth is reduced: only a small window now exists for a platoon of vehicles to continuously flow through all 6 signals without stopping.

- if a vehicle (or platoon) were to travel at 70 fps...



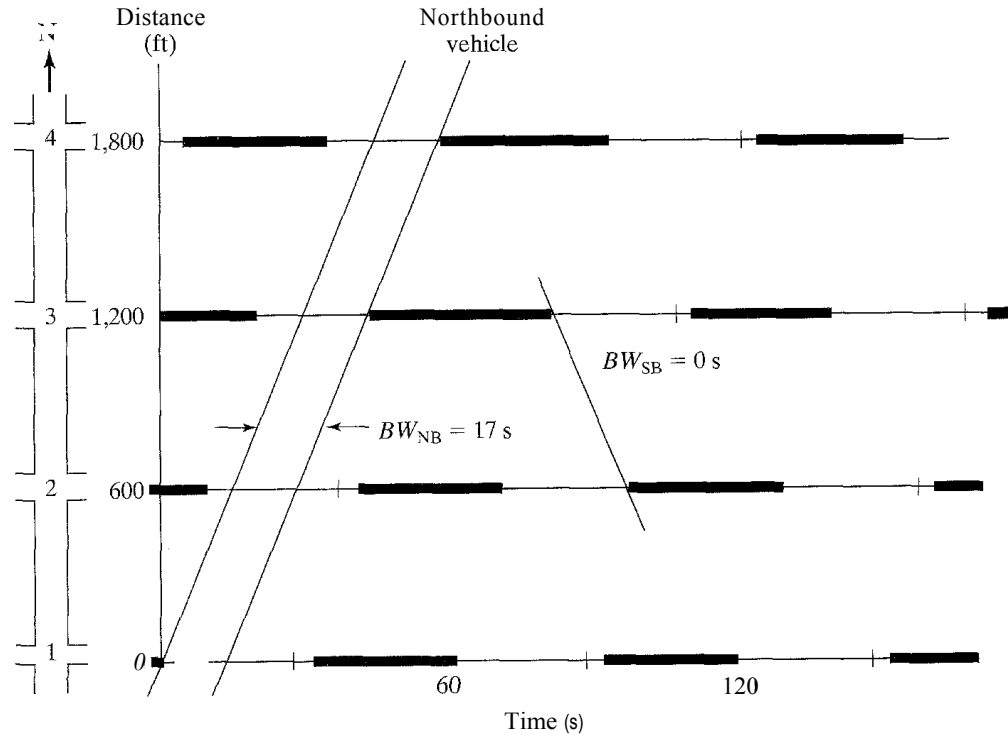
Bandwidth Efficiency

- the efficiency of a bandwidth is defined as the ratio of the bandwidth to the cycle length, i.e.

$$EFF_{BW} = \frac{BW}{C} \cdot 100$$

where EFF_{BW} = bandwidth efficiency [%], BW = bandwidth [s],
 C = cycle length [s].

- a bandwidth efficiency of 40% to 55% is considered good.



- the northbound efficiency can be estimated as $(17/60) * 100\% = 28.3\%$.
- the southbound bandwidth is obviously terrible (possible improvement ?)

Bandwidth Capacity

- the number of vehicles that can pass through a defined series of signals without stopping, i.e.

$$C_{BW} = \frac{3600 \cdot BW \cdot L}{C \cdot h}$$

where C_{BW} = bandwidth capacity [veh/h], BW = bandwidth [s], L = number of through lanes in the indicated direction, C = cycle length [s], h = saturation headway [s]

- In the example, the northbound bandwidth can carry $17/2.0 = 8.5$ vehicles per lane per cycle, with saturation headway is 2.0 s/veh, thus the northbound direction can handle $8.5\text{veh/cycle} * 1\text{cycle}/60\text{ s} * 3,600\text{s/hr} = 510\text{veh/h/ln}$.

The Effect of Queued Vehicles at Signals

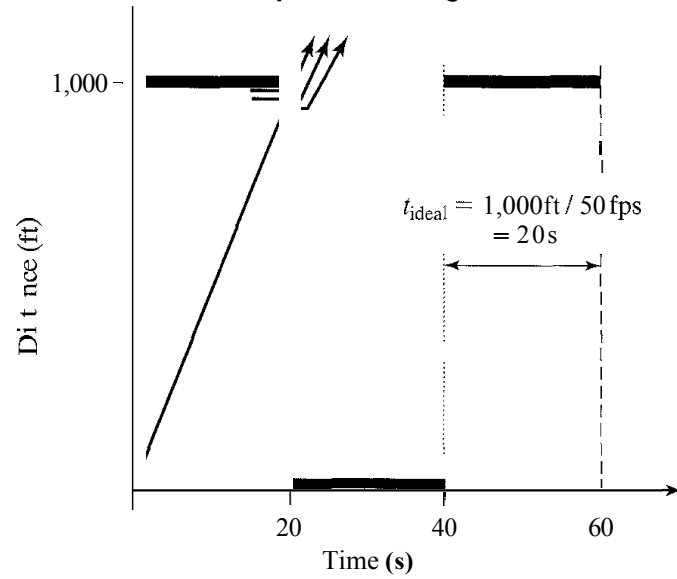
To adjust for the queued vehicles, the ideal offset is adjusted as follows:

$$t_{adj} = \frac{L}{S} - (Qh + l_1)$$

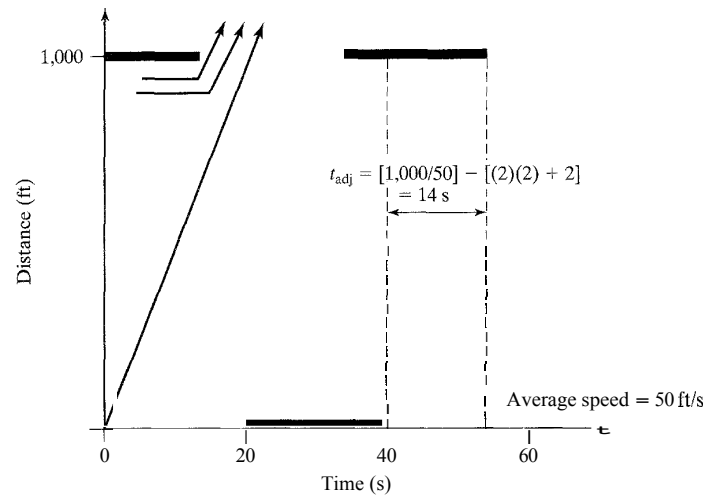
where

- t_{adj} = adjusted ideal offset [s]
- L = distance between signals [ft]
- S = average speed [ft/s]
- Q = number of vehicles queued per lane [veh]
- h = discharge headway of queued vehicles [s/veh]
- l_1 = start-up lost time [s]

without queue adjustment



with queue adjustment

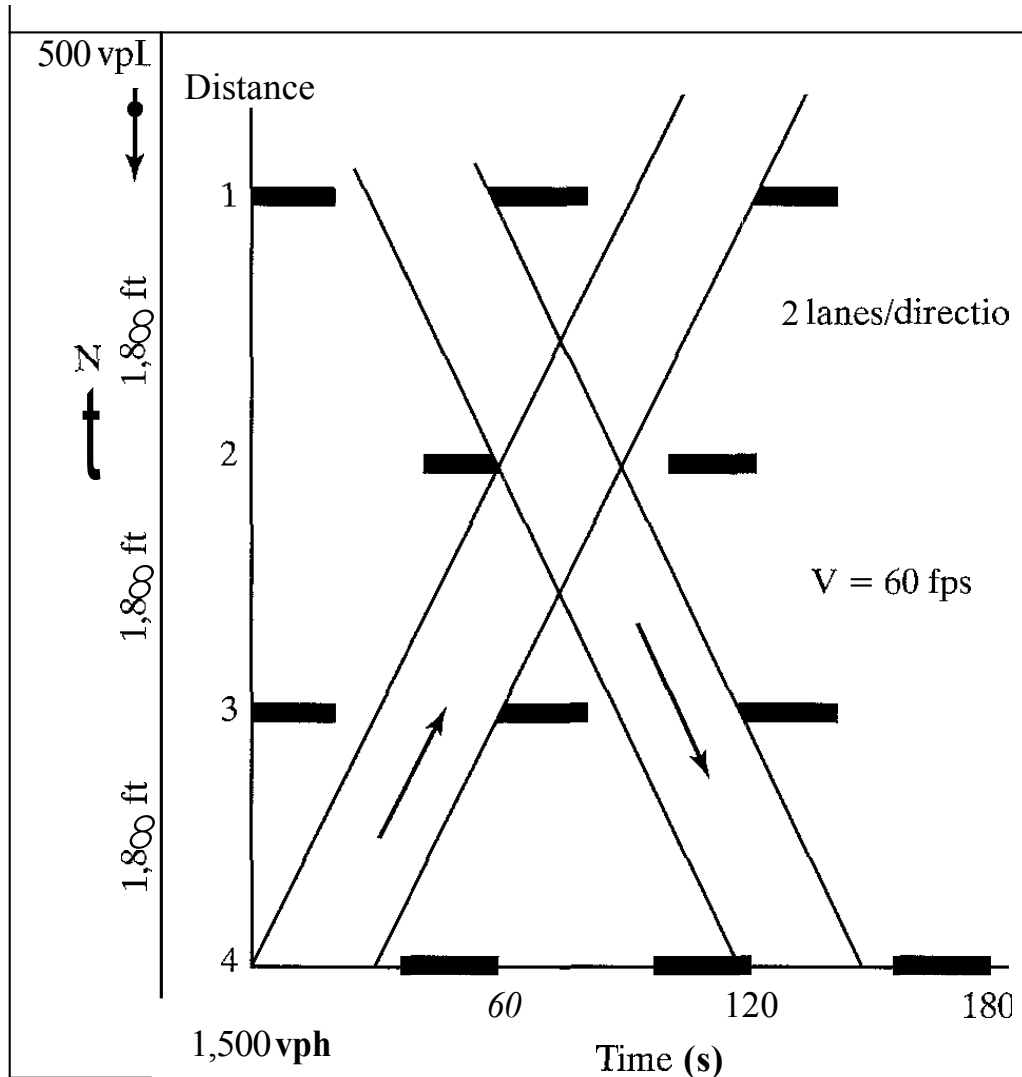


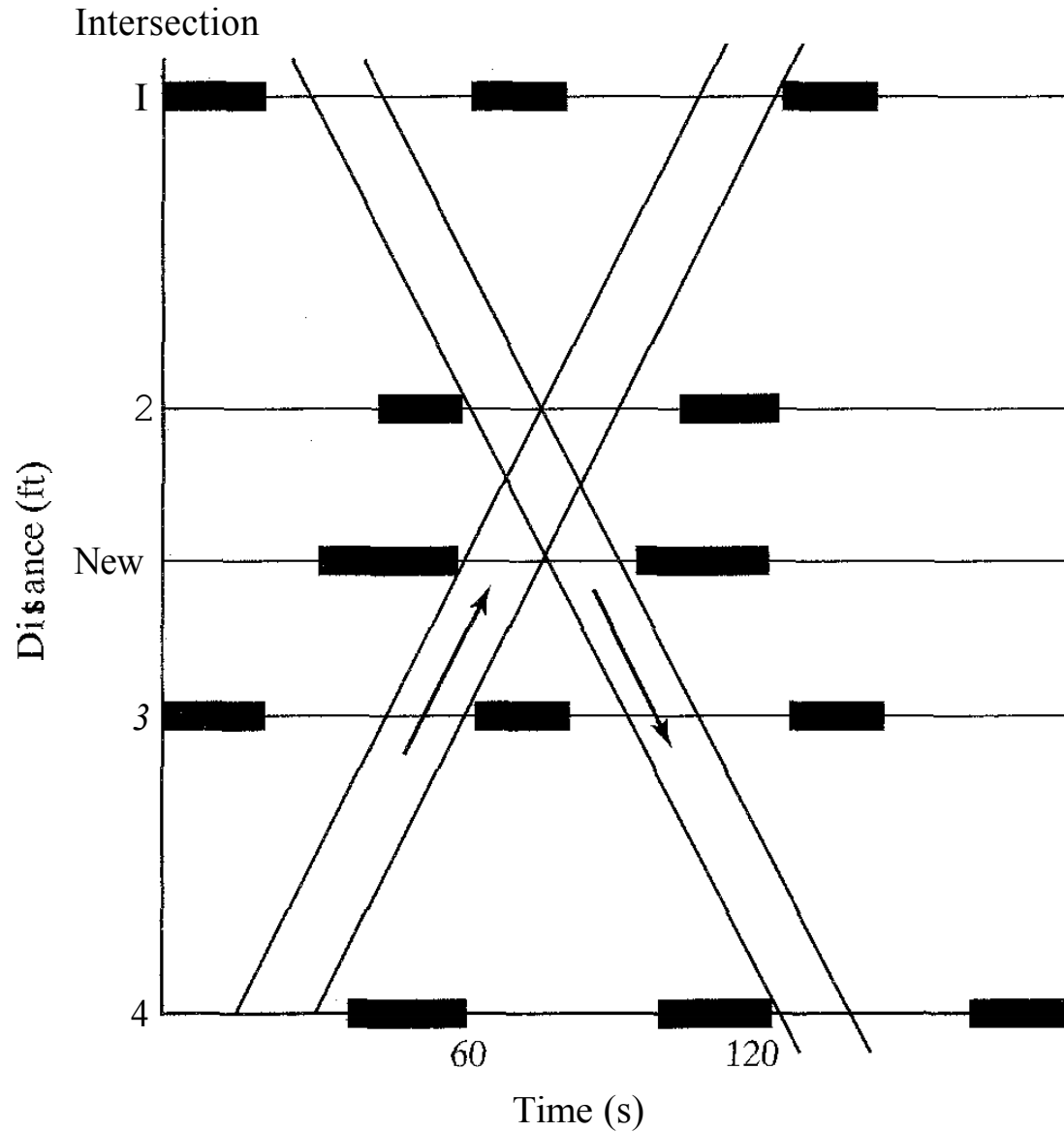
it is assumed that the queue is known at each signal... queue estimation is a difficult and expensive task.

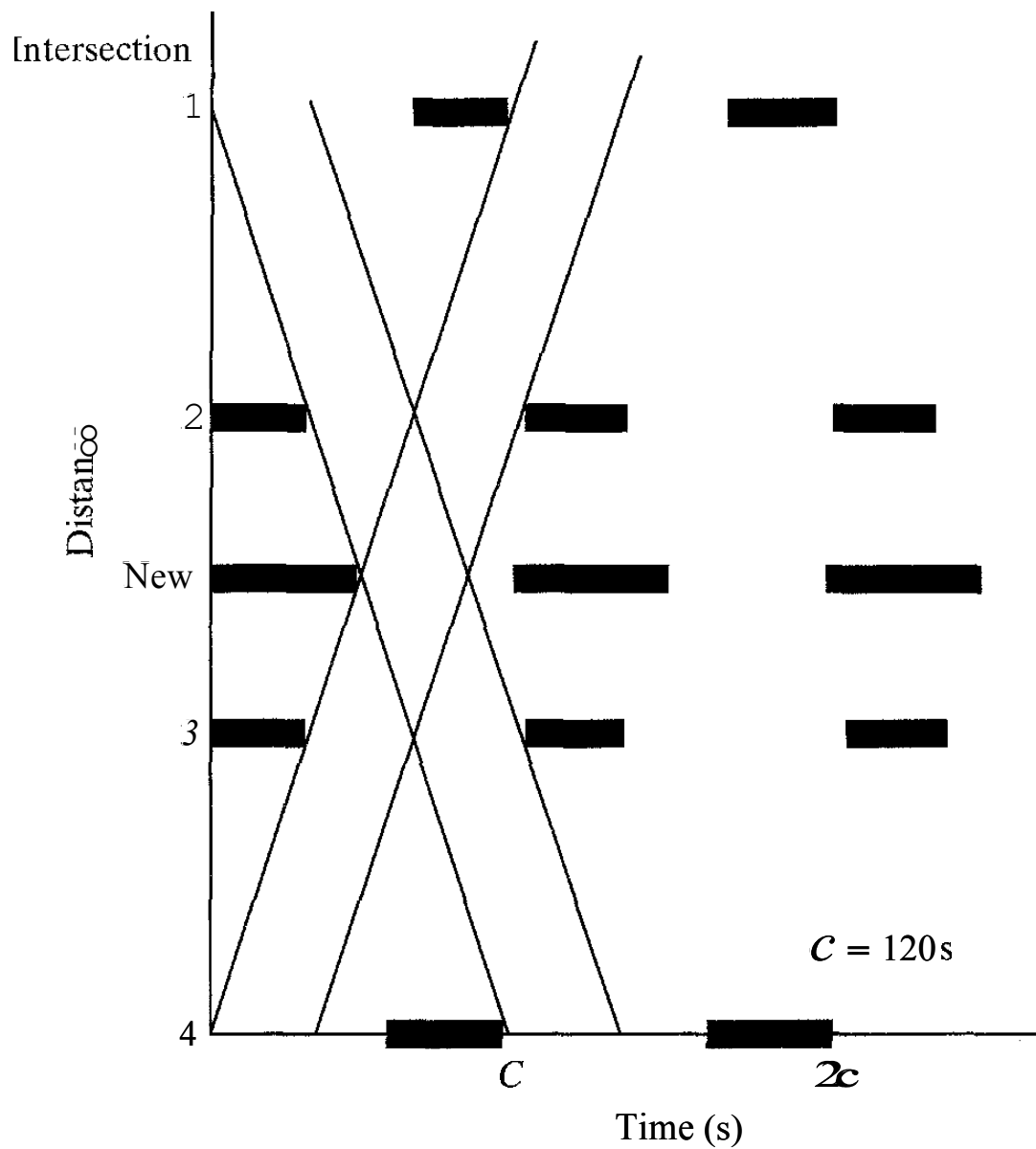
- Vehicles turning in from upstream side streets during their green.
- Vehicles leaving parking garages or spaces.
- Stragglers from previous platoons.

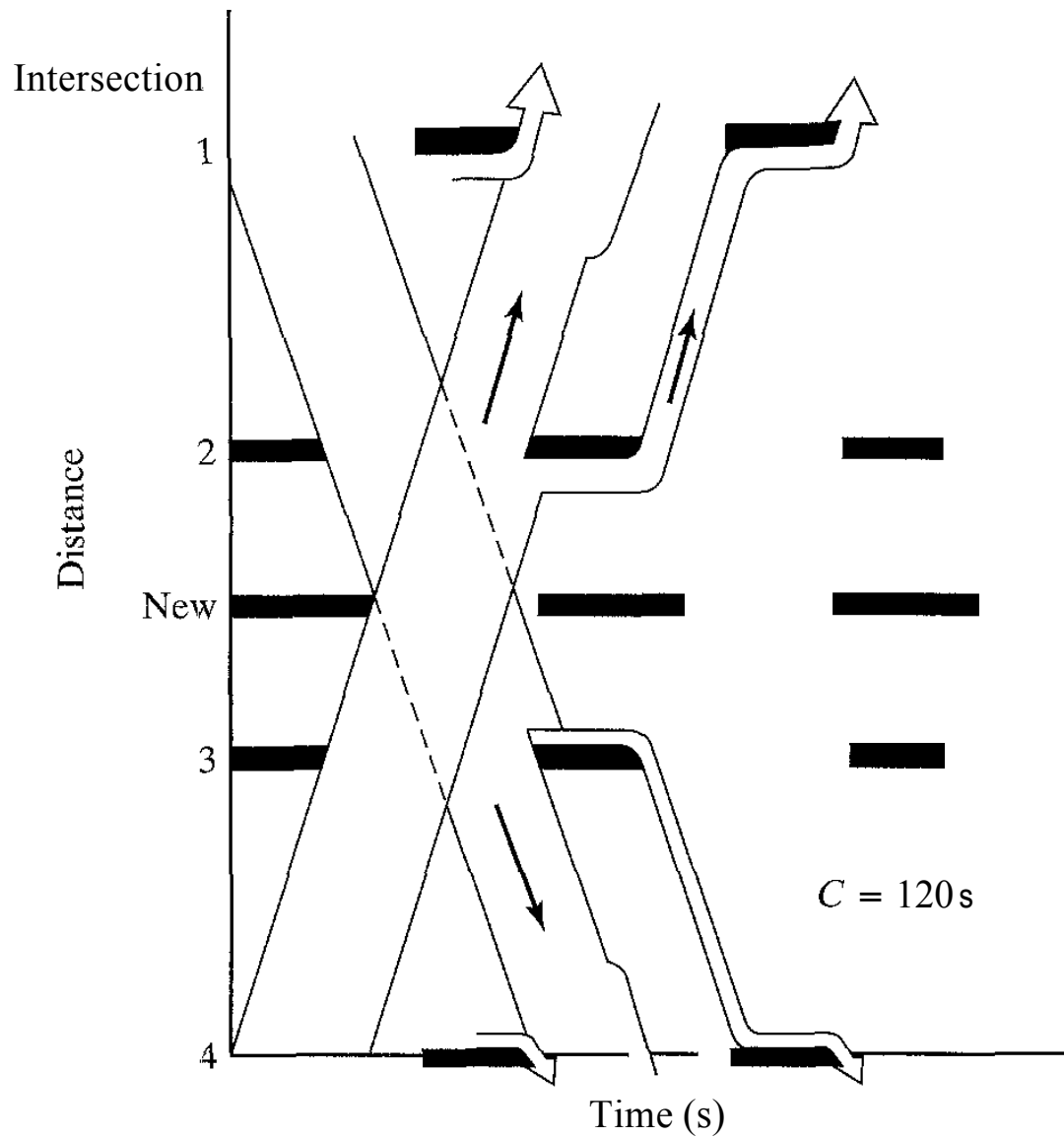
still better than not assuming queues.

Signal Progression for Two-Way Streets

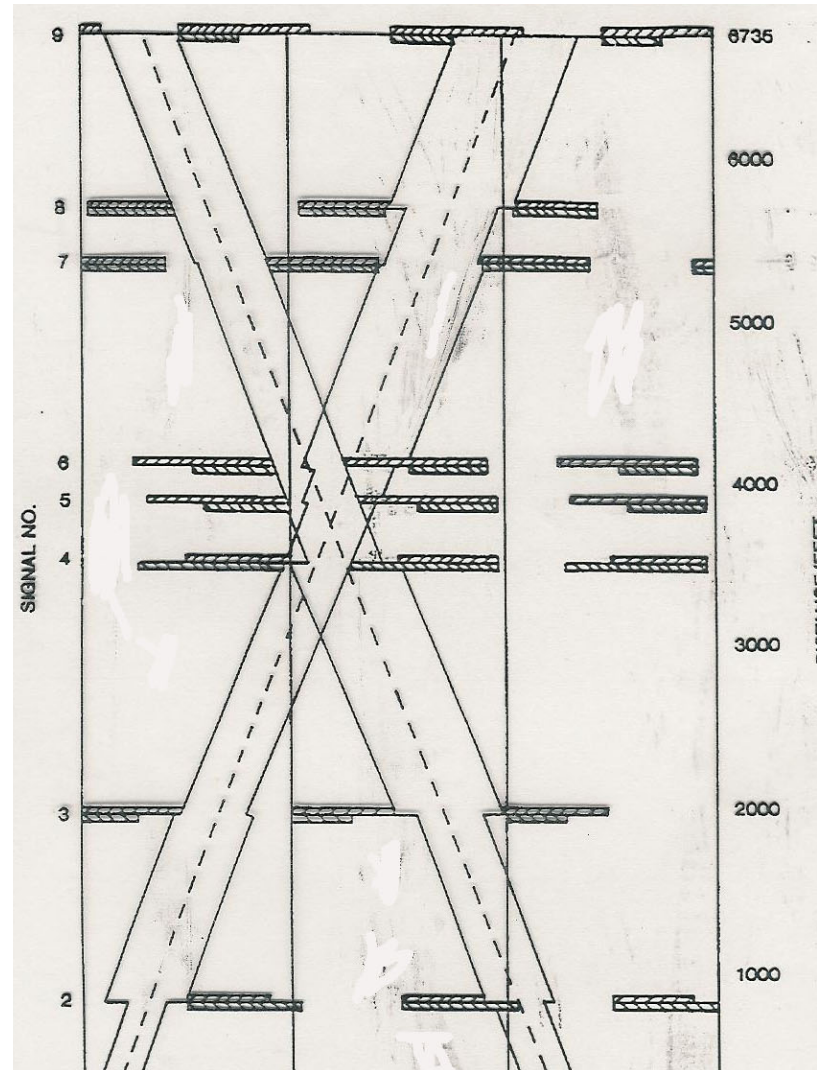




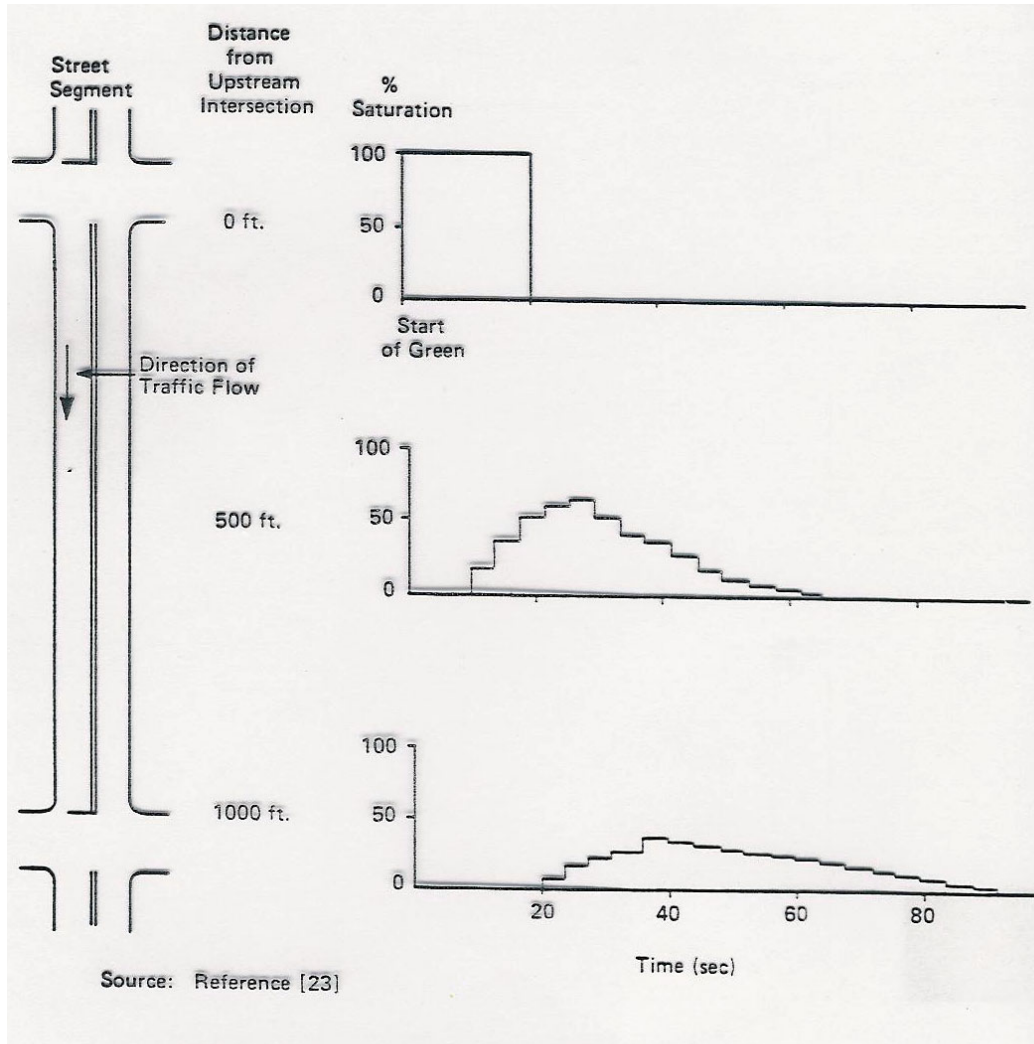


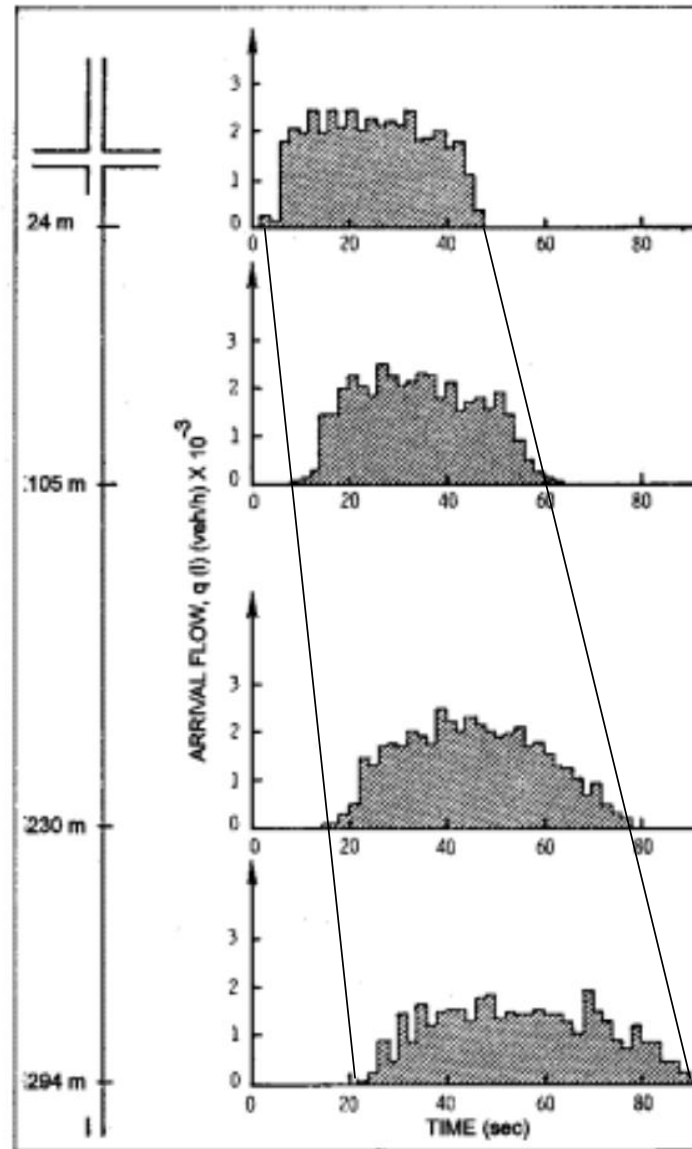


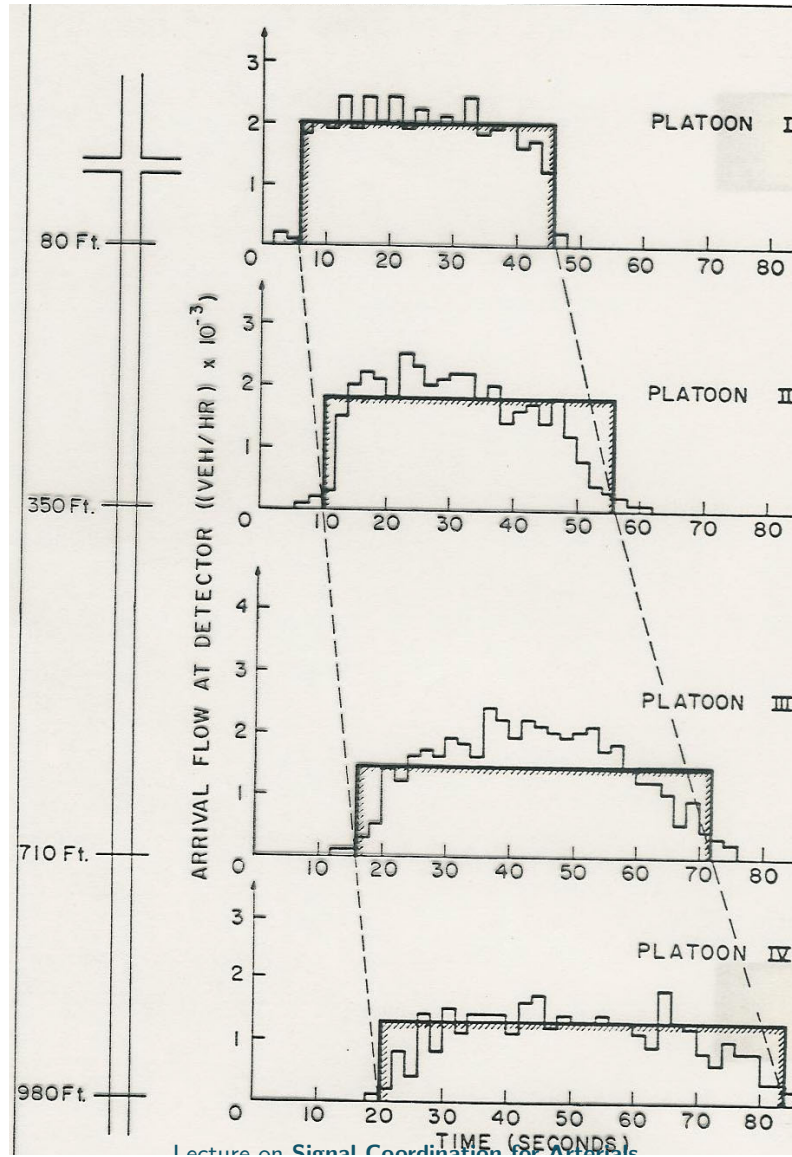
Variable Bandwidth



Effect of Platoon Dispersion

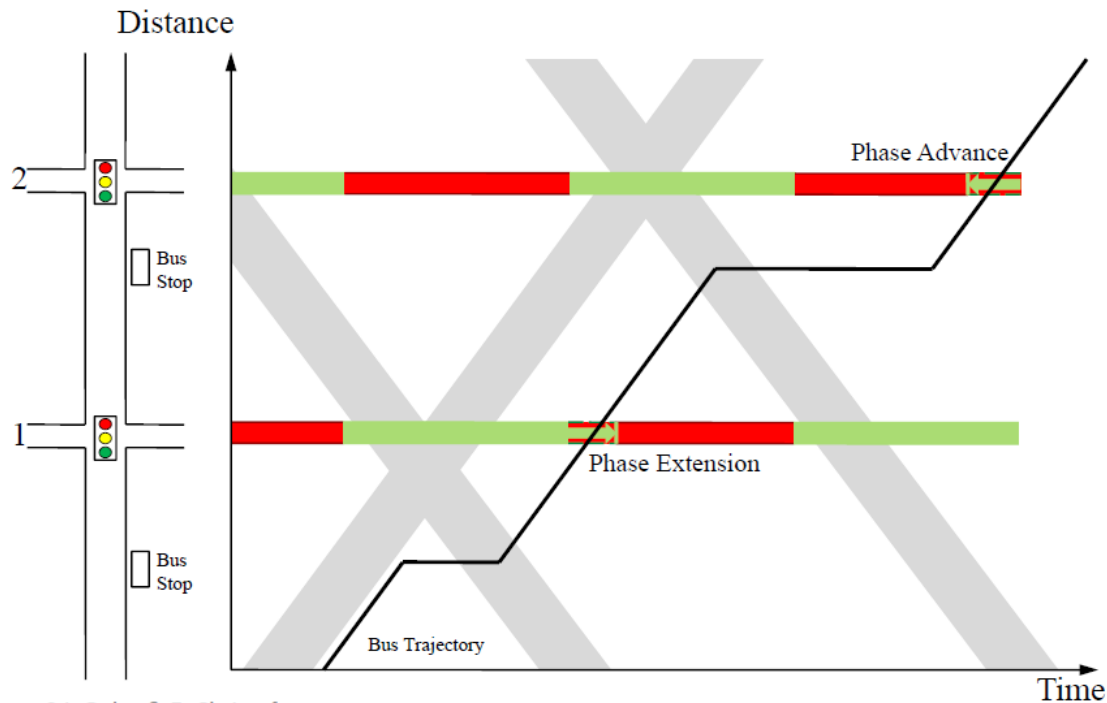




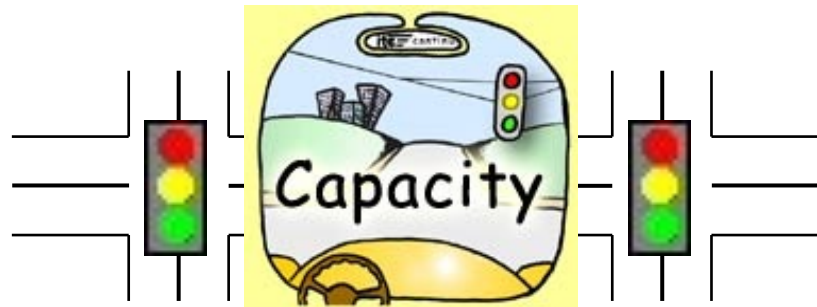


Traditional Strategies to improve bus priority at Signalized Intersections

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

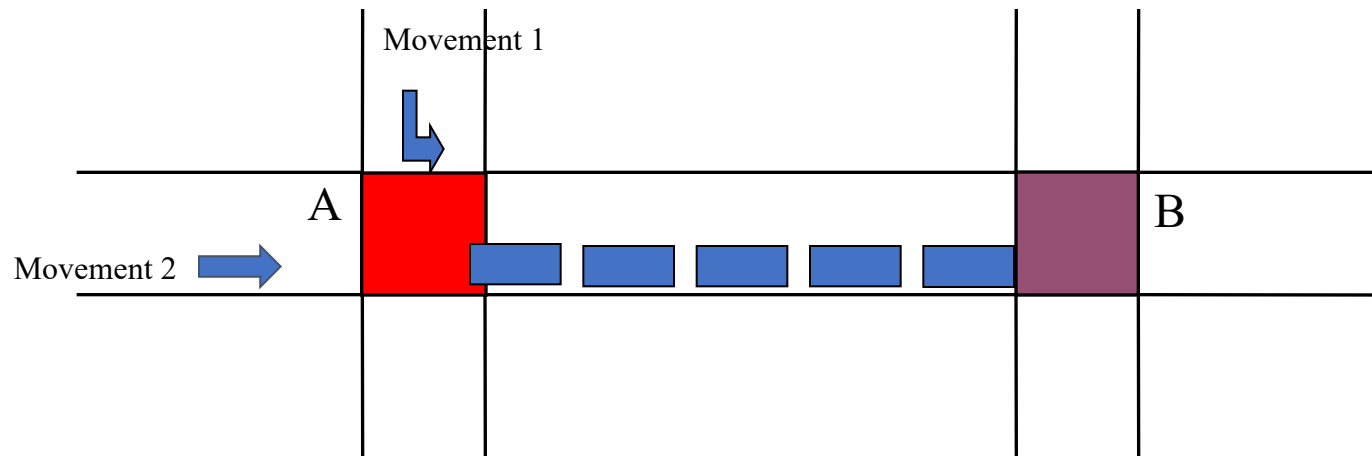


Offset effects on the capacity of paired signalized intersections



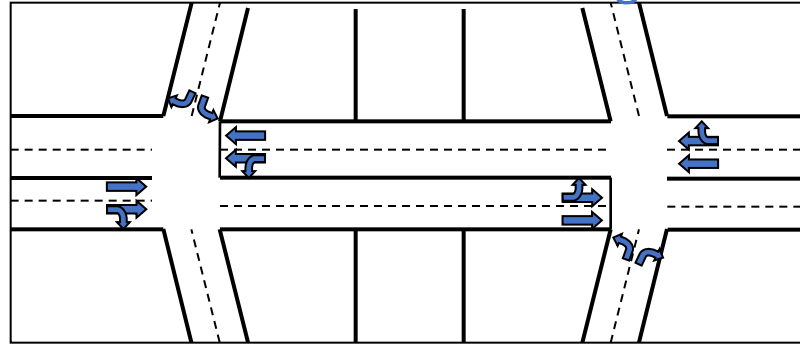
Definition of PSIs

two closely signalized intersections with short distance between them as queue spillbacks and upstream intersection blockages occur.

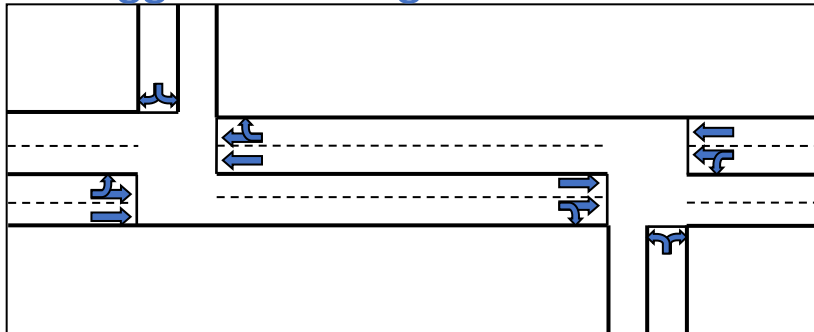


Examples of PSI

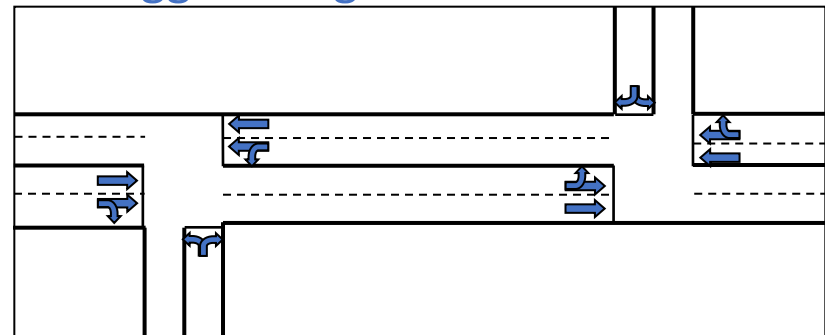
Diamond Interchange



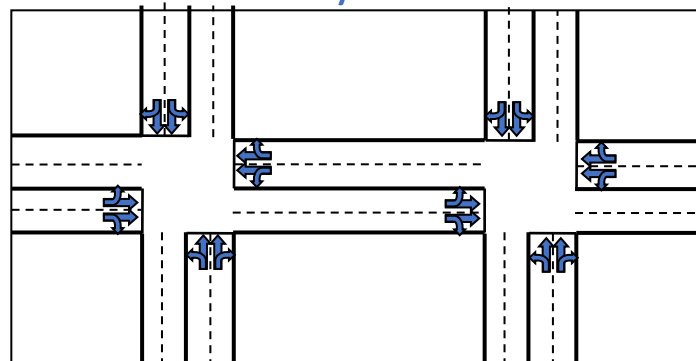
Staggered left-right intersections



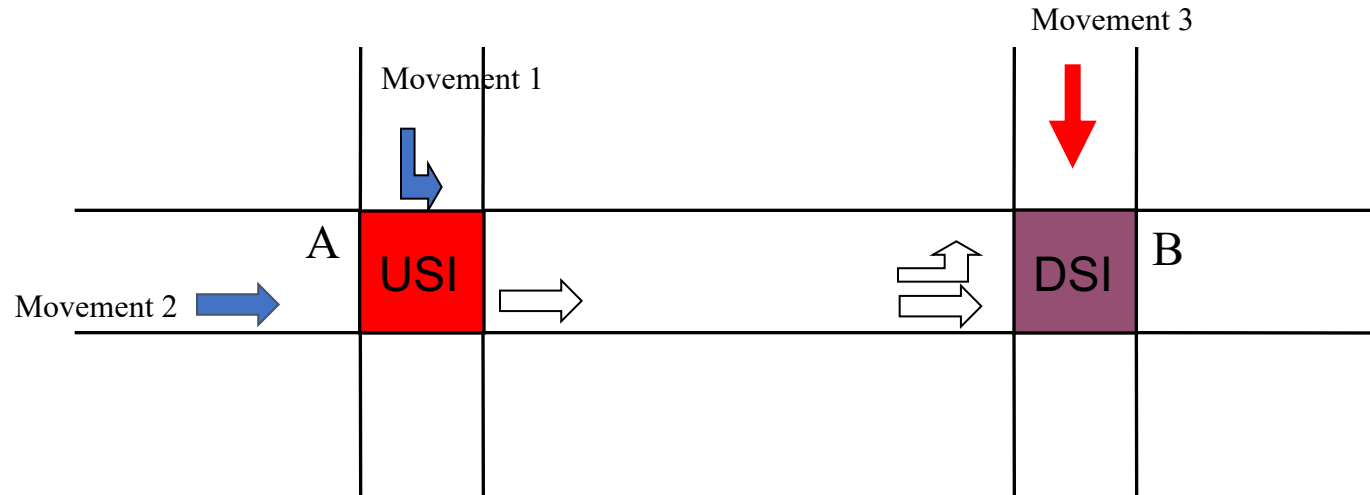
Staggered right-left intersections



Two closely intersections



Movements at PSI



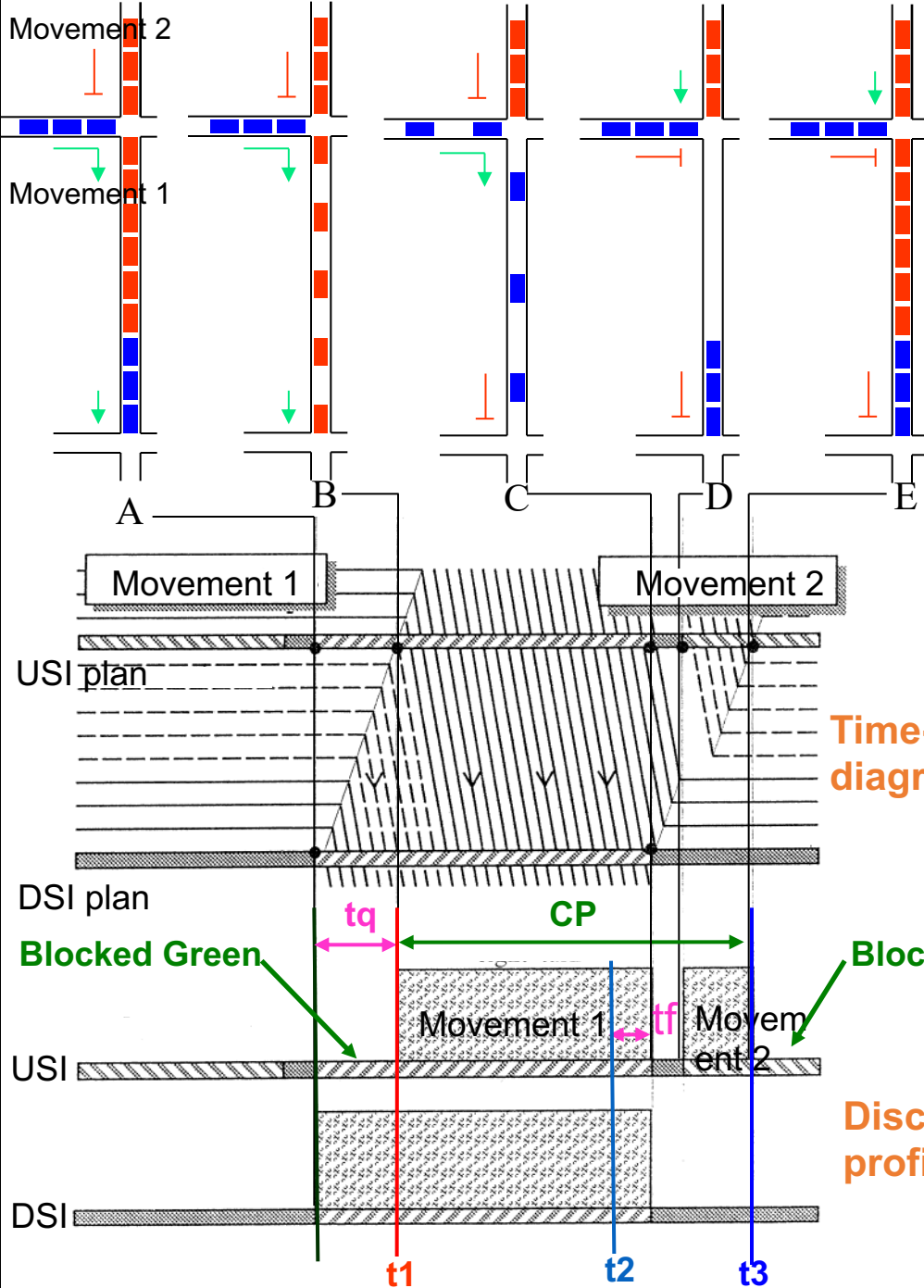
- Some movements pass through the two intersections: **USI** - upstream intersection and **DSI** - downstream intersection
- Other movements pass through only one intersection

Goals

- To examine the traffic flow changes at two adjacent intersections.
- To develop an analytical tool which can test the efficiency of the signal timings plan of PSI.
- The tool allows us to quantitatively compare different traffic light plans and select the most appropriate program.



1. Effect of queue spillbacks at USI



t1
End of spillback, t_q after start of the DSI green

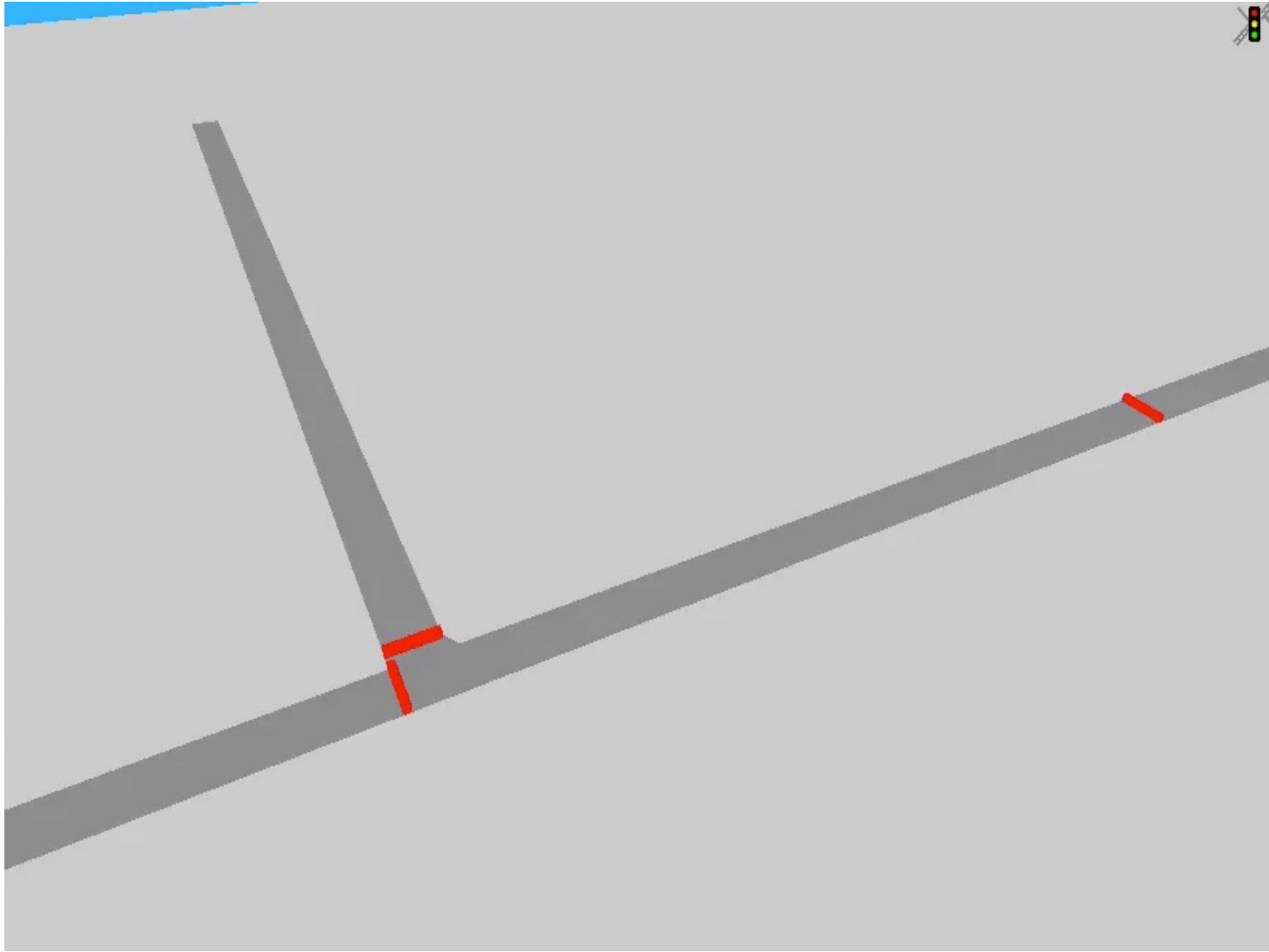
t2
Any vehicle released after t_2 will have to stop after the stop line, when t_2 is t_f seconds before the end of the DSI green light.

t3
Time of spillback occurrence

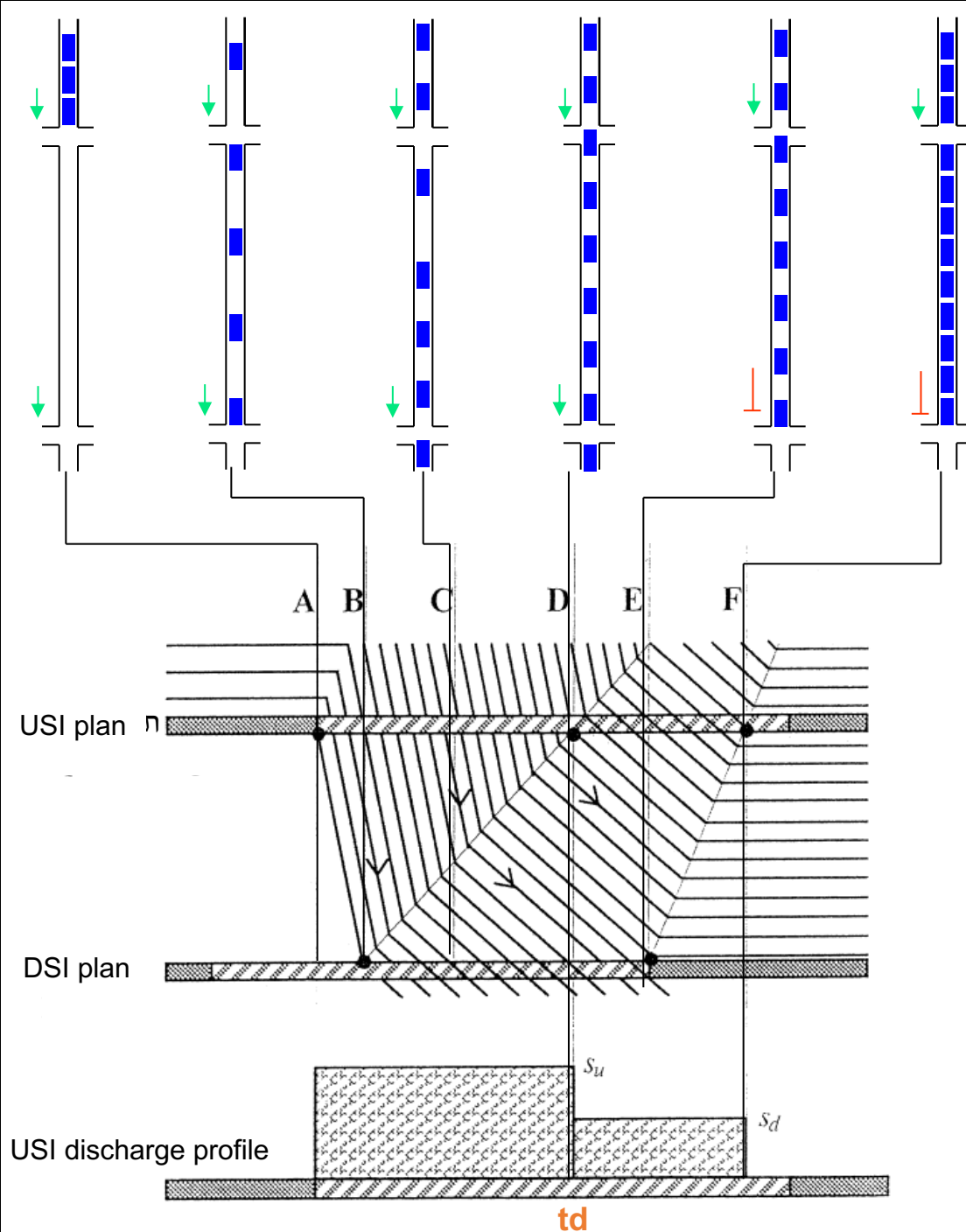
Time-space diagram

CP – Clear Period
The time duration (t_1-t_3) over the cycle when the USI is not blocked

Discharge profiles

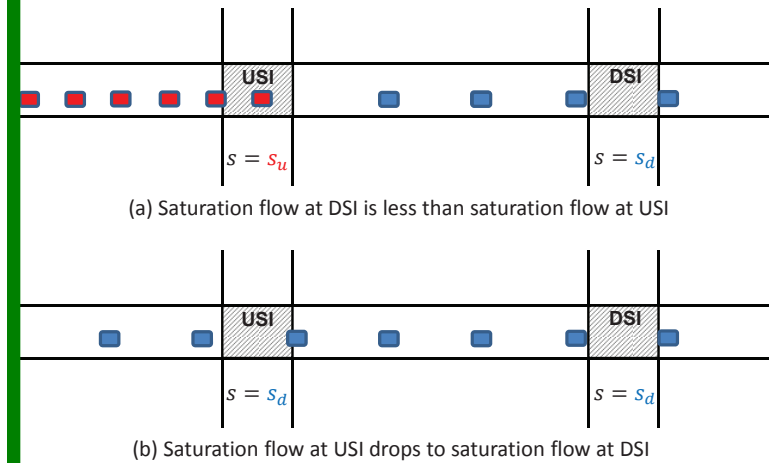


2. Effect of DSI saturation flow

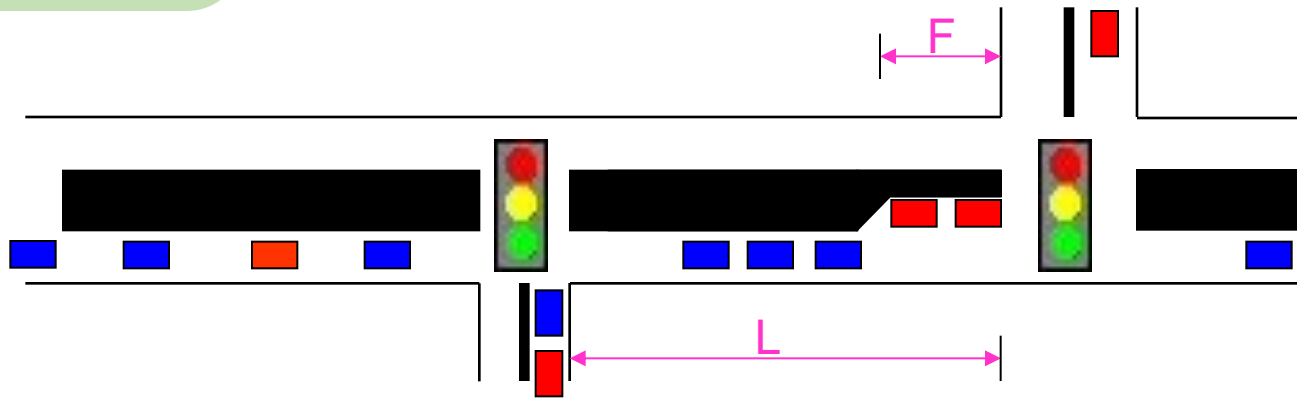
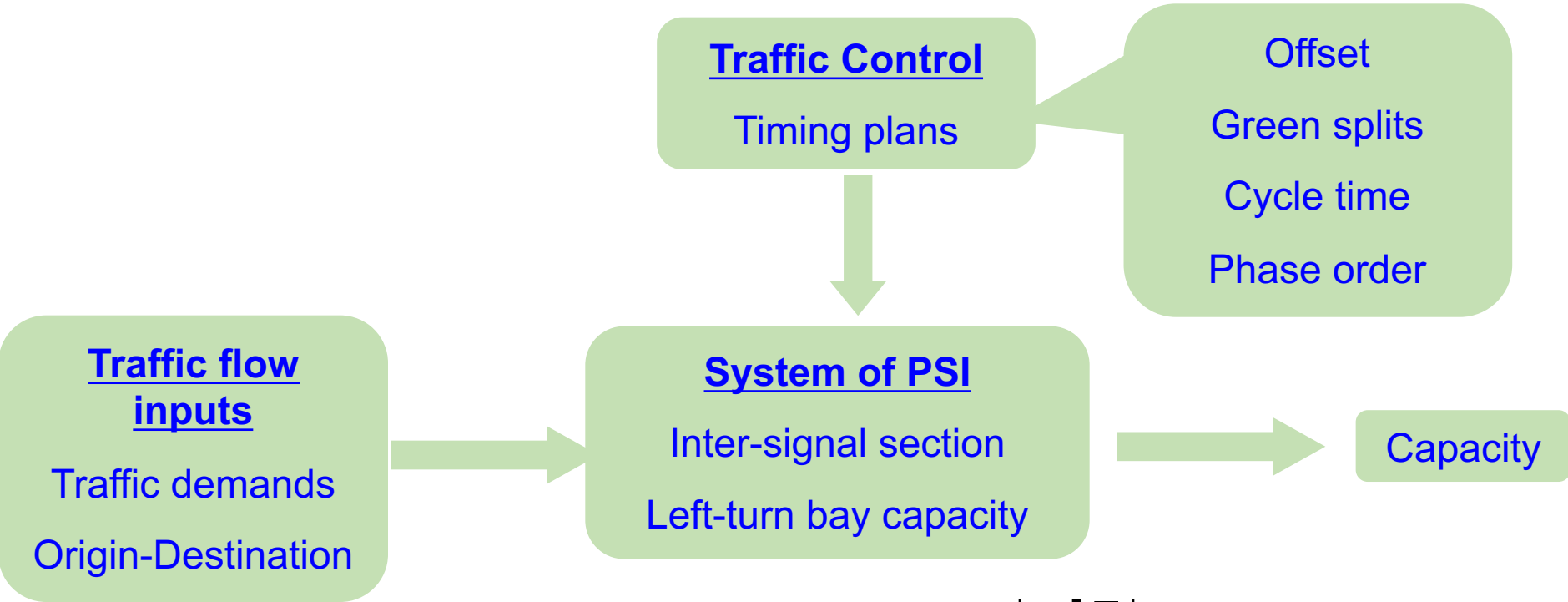


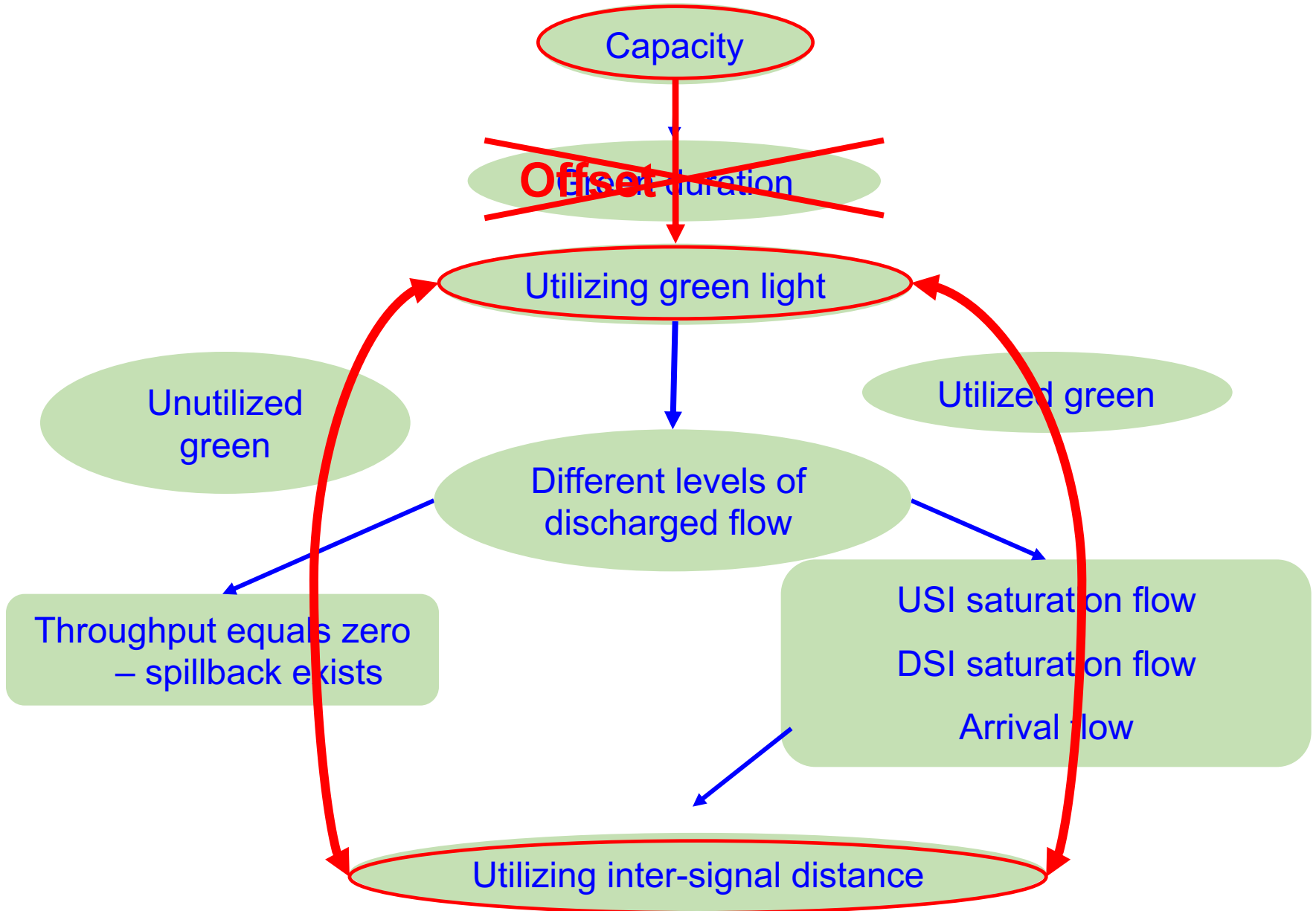
DSI saturation flow is less than USI saturation flow

$$S_d < S_u$$

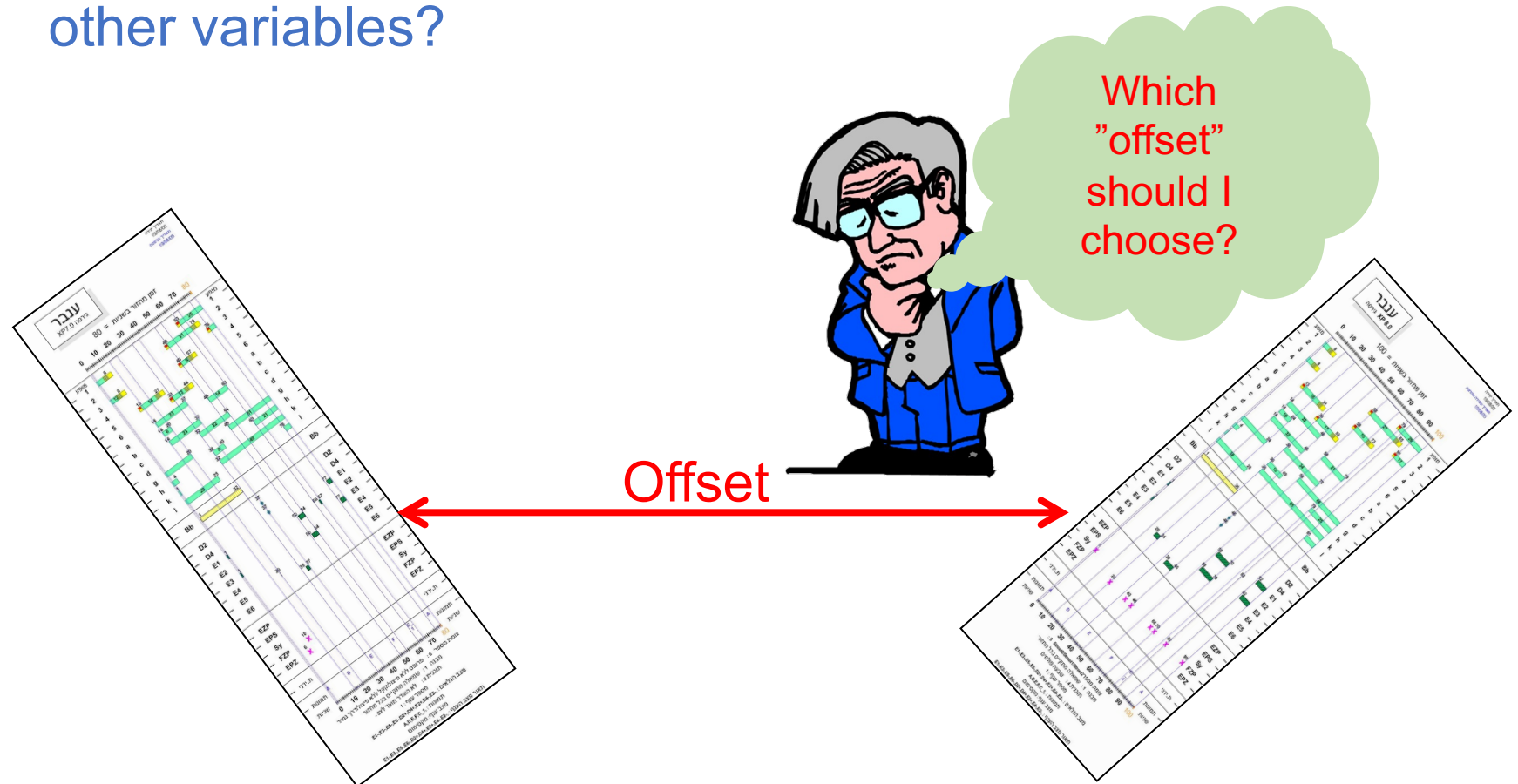


System of Paired Signalized Intersection

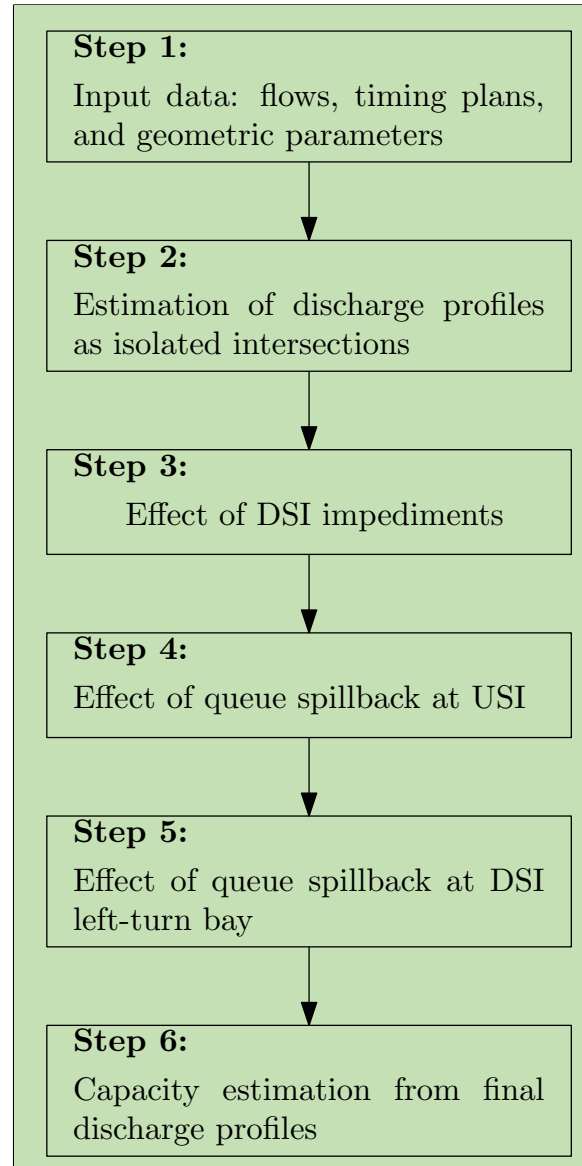




- Determining a suitable offset ? To which movement ?
- How the "offset" can be utilized as decision tool to improve system performance ? When ? How much ?
- What is the relationship between the "offset" and the other variables?

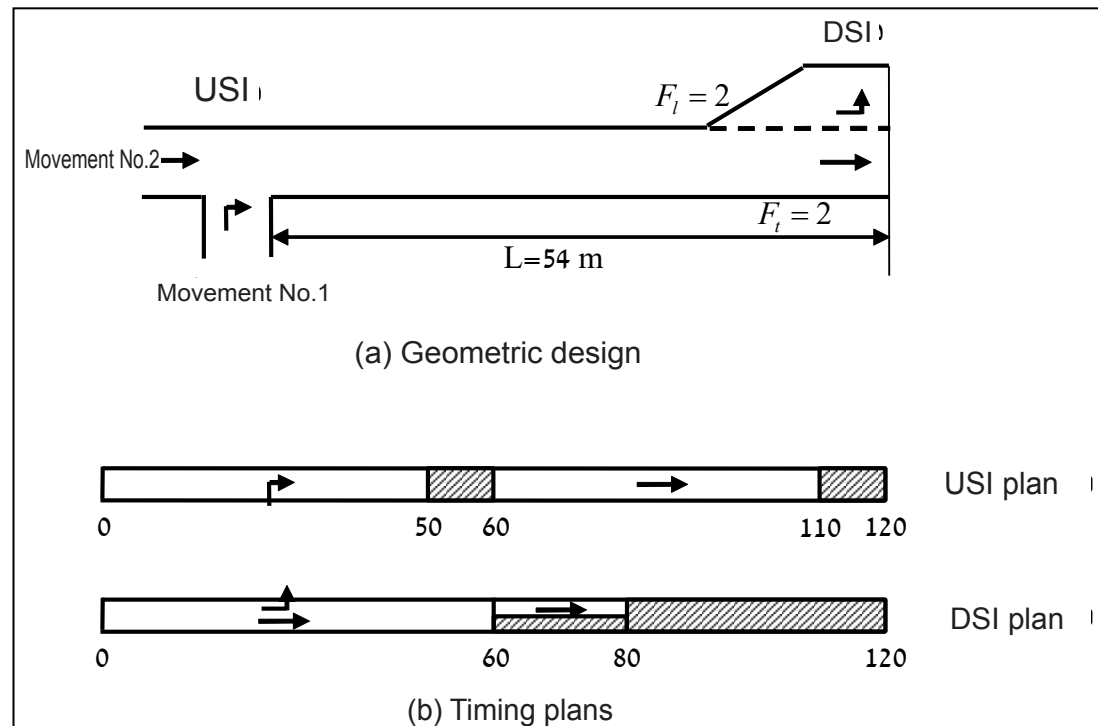


Steps of the model

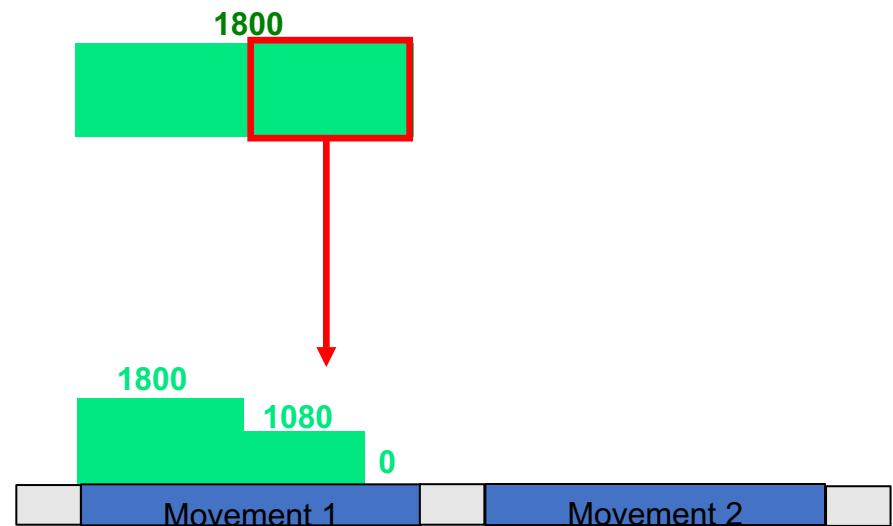


Inputs

- Timing plans at both intersections
- length of the inter-signal section
- Left-turn bay capacity
- Saturation flow values
- Offset
- Inflows (with OD)



- Two isolated signalized intersections
- PSI system



		Movement 1	
Utilized green	Two isolated intersections	50 sec	100%
	PSI system	40 sec	80%
Blocked green		20%	
Capacity (veh/h)	Two isolated intersections	750	100%
	PSI system	498	66.4%

Model 1
One phase at DSI, One lane at section between intersections.

Model 2
Two phases at DSI, Left-turn bay, One lane at section between intersections

Model 3
Two phases at DSI, Left-turn bay, Multiple lanes at section between intersections.

Inter-signal length: 60

Inter-signal length: 70

Inter-signal length
LT bay length

Inter-signal length
LT bay length

Inter-signal length
LT bay length

East Intersection

West Intersection

Enter

Cancel

(a) Geometric parameters

Timing plan
Structure: 3 Plan num.
0 110 Cycle

Test num. 1
Description No Results

Input data

Input data 600 Demand 1600 USI move. Sat. flow headway
 Capacity .16 LT (%) 16

Input data

Input data Demand USI move. Sat. flow headway
 Capacity LT (%) Sat. flow headway

Input data

Input data 700 Demand 1700 USI move. Sat. flow headway
 Capacity .17 LT (%) 17

Input data

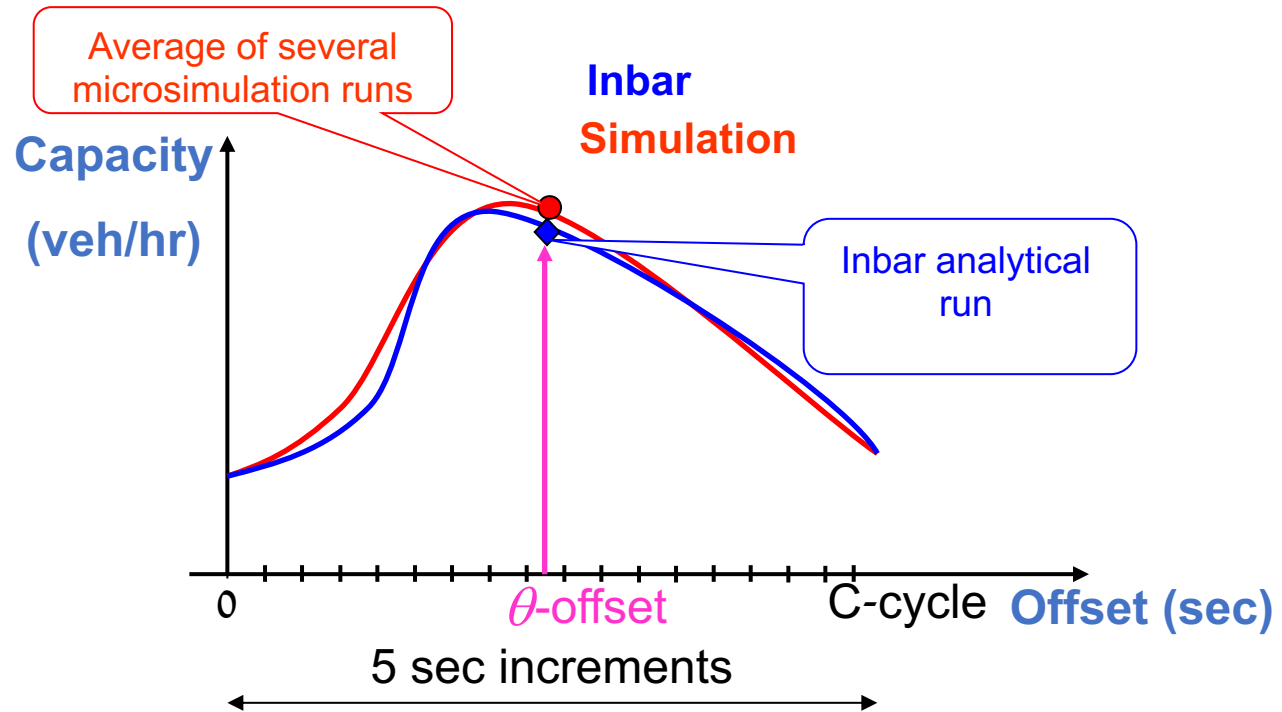
Input data Demand 1700 USI move. Sat. flow headway
 Capacity .17 LT (%) 17

Offset, corresponding to mov. 2
Jam headway 6

Offset, corresponding to mov. 7
Jam headway 7

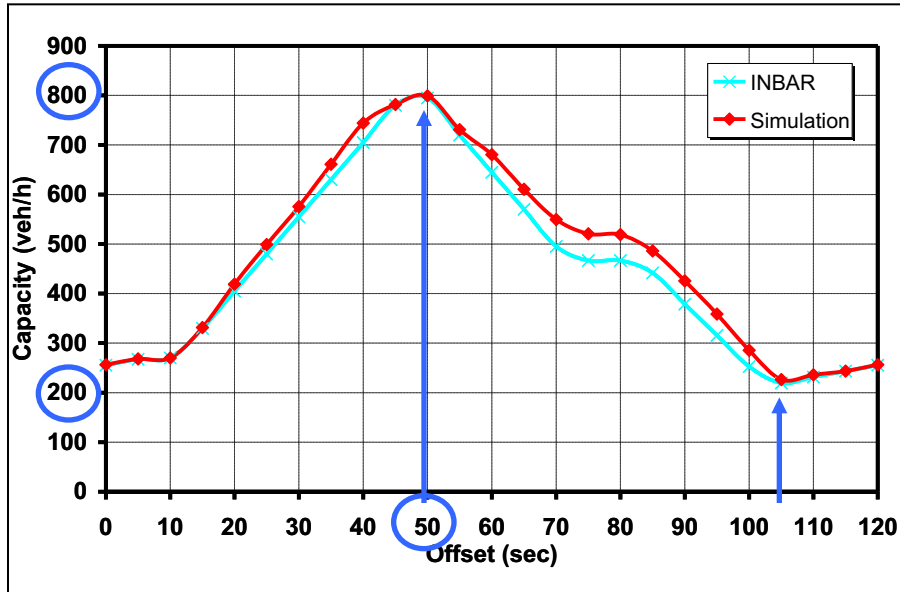
New Test Previous Test Subsequent Test Calculation EnterLeft EnterRight

(b) Traffic flows input

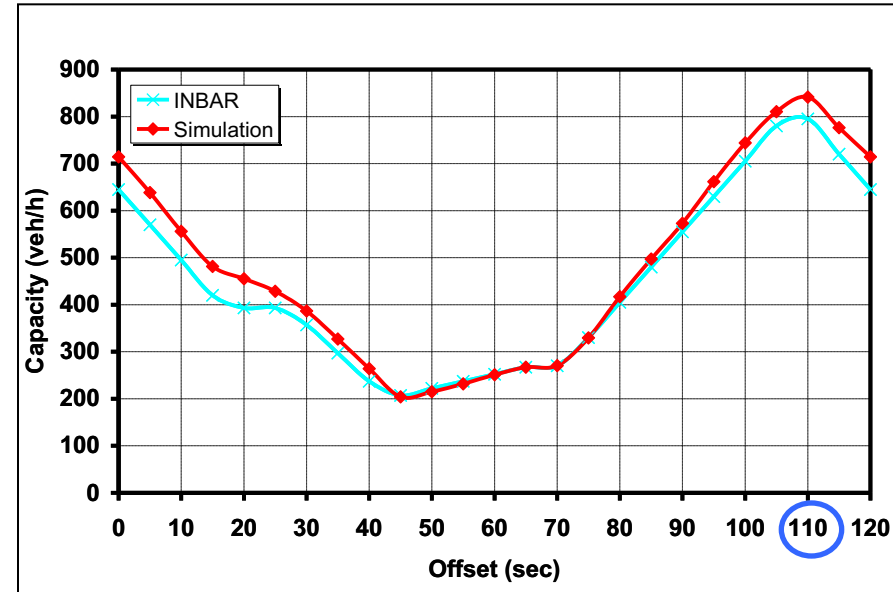


Results

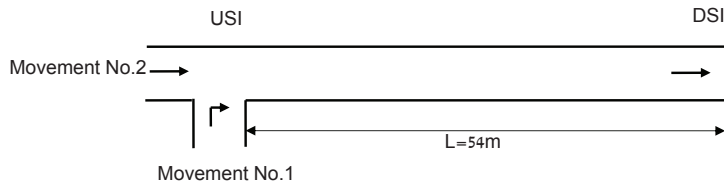
1. Offset effect on movement capacity



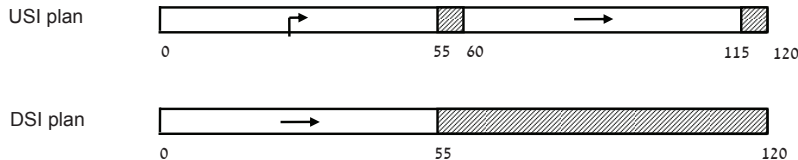
Movement 2



Movement 1



(a) Geometric design



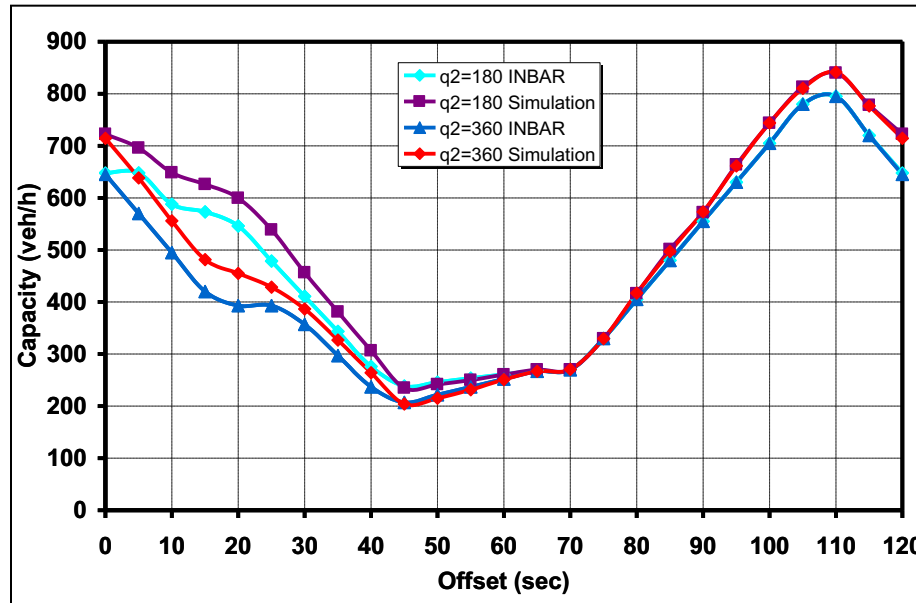
(b) Timing plans

Conclusion 1: Capacity varies in range of offsets. Choosing an appropriate offset may increase the movement capacity.

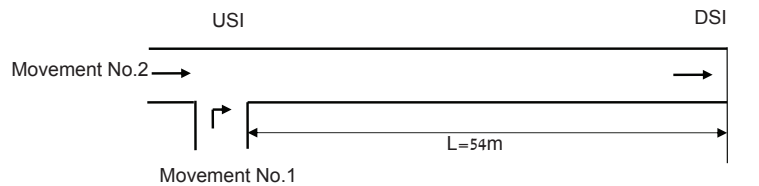
$$IV_{\max} = 9$$

Conclusion 2: Each USI movement has a different offset in which a maximum capacity is obtained.

2. Arrival rate effect on other movement capacity



capacity of movement 1 vs. offset for two arrival rates of movement 2



(a) Geometric design

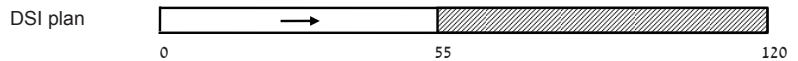
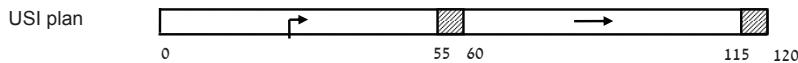
$$s_{u1} = s_{u2} = s_d = 1800 \text{ veh/h (0.5 veh/sec)}$$

$$d_{u1} = d_{u2} = d_d = 18.0 \text{ m}$$

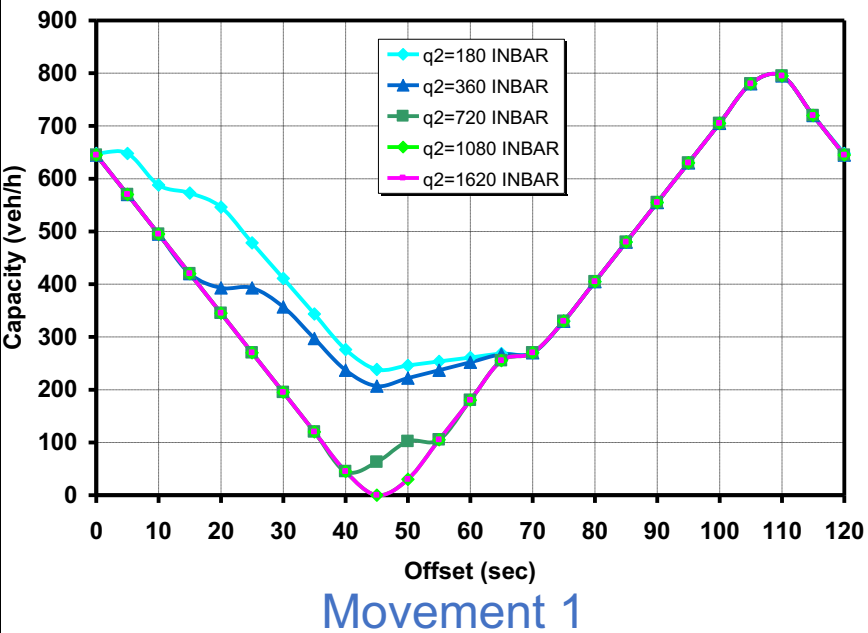
$$q_{u1} = 288 \text{ veh/h (0.08 veh/sec)}$$

$$q_{u2} = 180/360/720/1080/1620 \text{ veh/h (0.05/0.10/0.2/0.3/0.45 veh/sec);}$$

$$N_{\max} = 9$$



(b) Timing plans

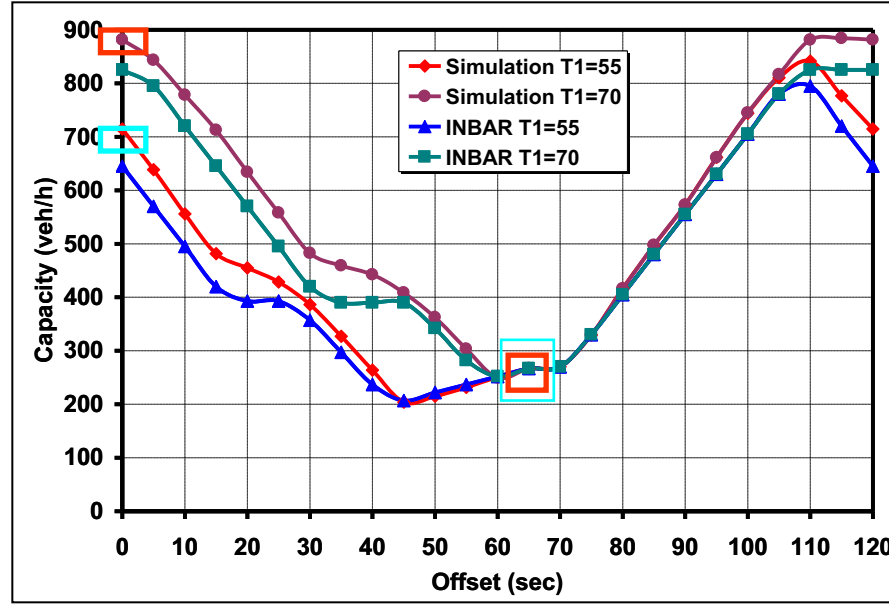


the arrival rate for movement 2 affects the capacity of movement 1 only for certain offsets 0 – 65, while for other offsets 70 – 120 there is no influence on the movement capacity.

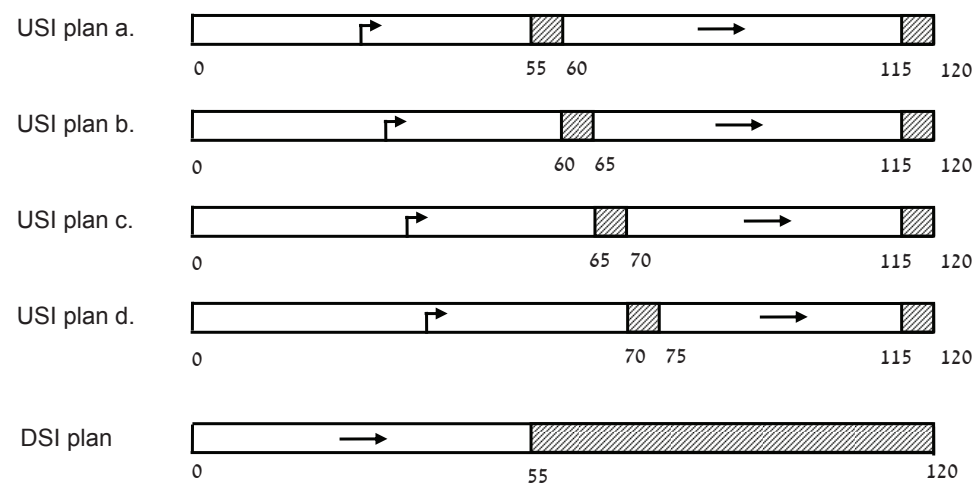
Conclusion 3: Traffic demand affects the (other) movement capacity only for certain offsets.

3. Green duration splits effect on movement capacity

Conclusion 4:
 Increasing green duration for a movement might increase / does not affect traffic capacity - depending on the offset



Movement 1



$$s_{u1} = s_{u2} = s_d = 1800 \text{ veh/h } (0.5 \text{ veh/sec})$$

$$d_{u1} = d_{u2} = d_d = 18.0 \text{ m}$$

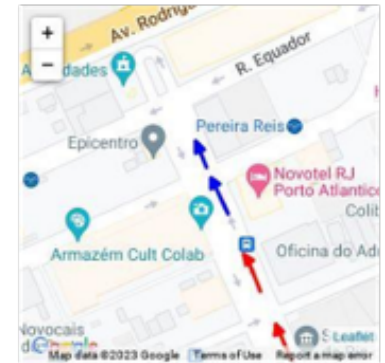
$$q_{u1} = 288 \text{ veh/h } (0.08 \text{ veh/sec})$$

$$q_{u2} = 360 \text{ veh/h } (0.10 \text{ veh/sec})$$

$$N_{\max} = 9$$

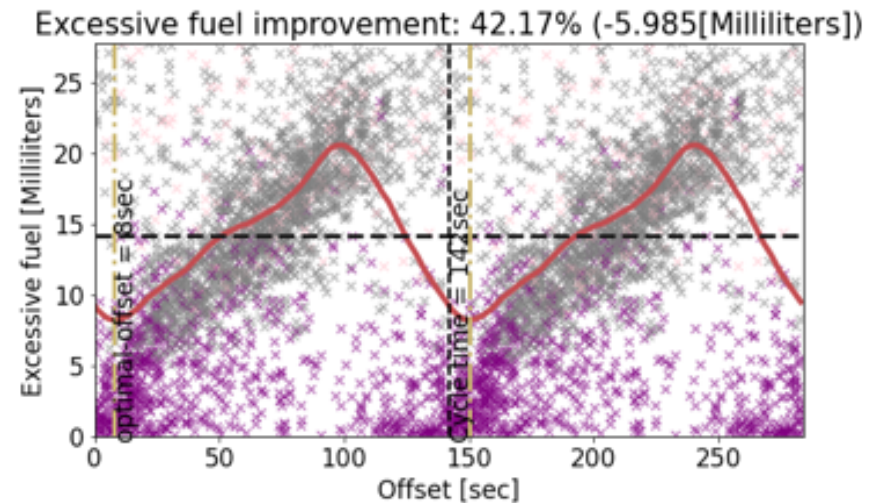
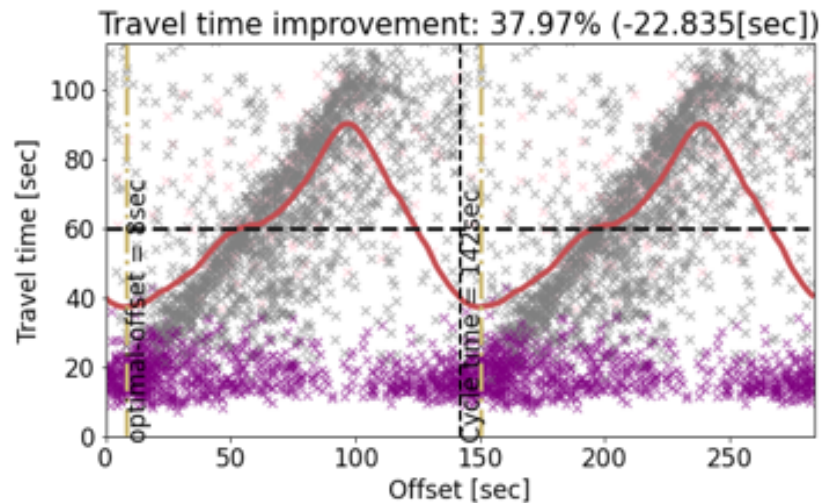
Quantitative approach (probe-data based) for coordination of PSI REAL CASE STUDIES ANALYSIS

- Purple “x” markers: vehicles traveling in free-flow conditions
- grey “x” markers: vehicles that stopped once between the DSI and USI intersections
- pink “x” markers: vehicles that stopped more than once (i.e. experienced split failures)
- Red curve presents the moving average of the metric
- Travel time and excessive fuel improvements are relative to the corresponding total average of the metrics (shown in the horizontal dashed lines)



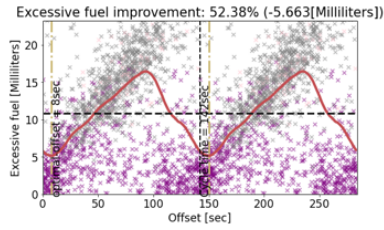
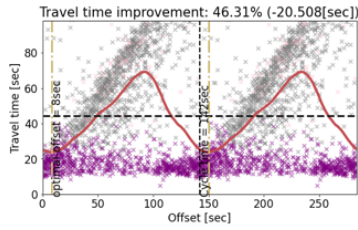
Av. Pereira Reis in Rio de Janeiro

Offset effect

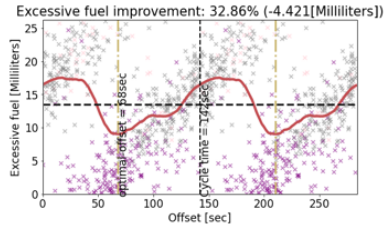
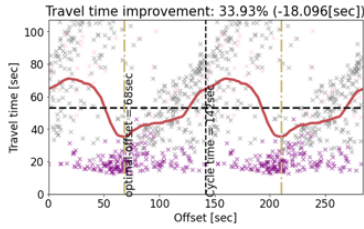


Metric competition among movements

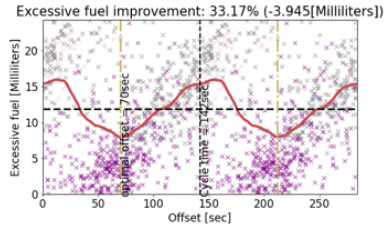
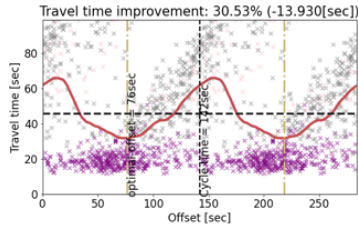
Movement pair 1



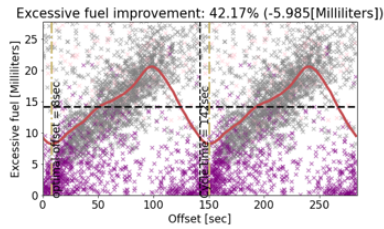
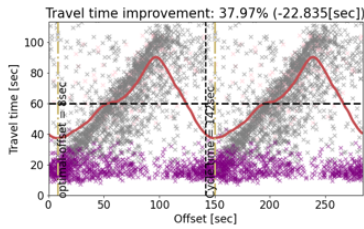
Movement pair 2



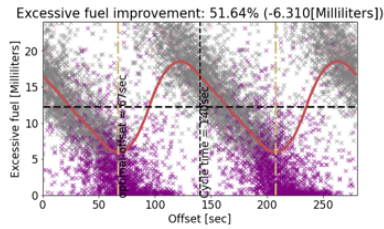
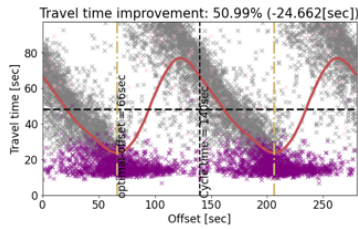
Movement pair 3



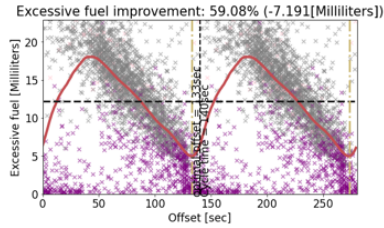
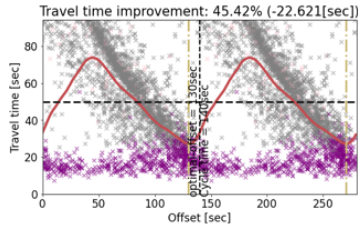
Movement pair 4



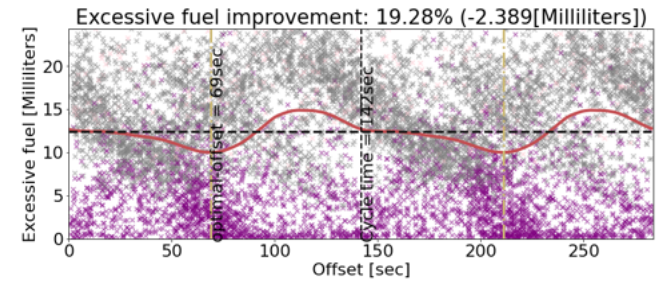
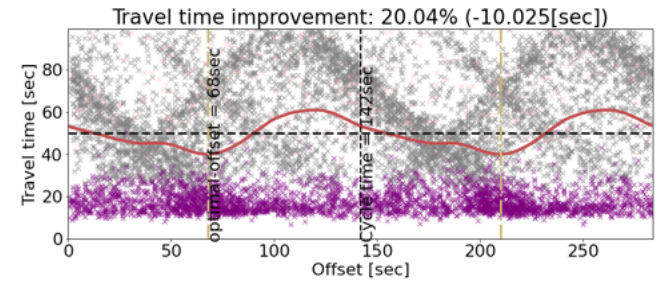
Movement pair 5



Movement pair 6



Weighted (by flow) average travel time and excessive fuel for all six movement pairs



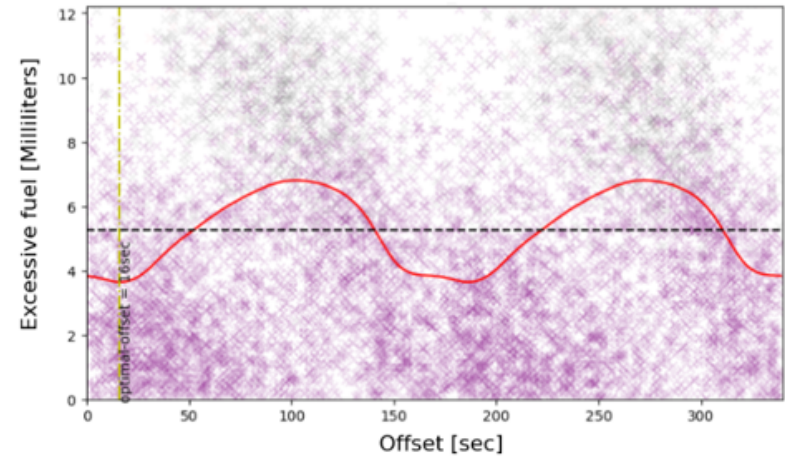
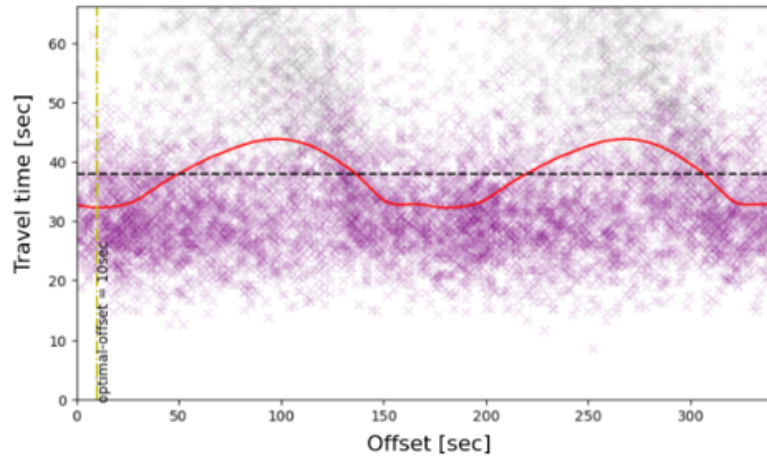
Jakarta



(a)

Travel time improvement: 15% (-5.63[sec])

Excessive fuel improvement: 31% (-1.8 [Milliliters])



**Signalized intersections at Switzerland
(some extra information)**

Statistics on traffic signal control at Switzerland

- Swiss cities and county areas are relatively small: 100 – 150 signalized intersections per city, \approx 500 intersections in a county
- Total intersections that are coordinated for motorized traffic ranges between 10% and 65% within cities
- Software systems in use are: VS-PLUS, FESA, TS2000
- Hardware is mainly provided by the two Swiss companies, VRAG and Bergauer AG, by the German company Siemens, and by the Austrian-German company Swarco.
- Swiss intersections in larger cities tend to be complex, with more than four legs and many individually controlled movements, for cars and public transport, but also for bicycles and pedestrians.

- Zurich has developed all traffic control in-house; other cities might rely on external services and software
- In Switzerland, most signalized intersections are traffic-actuated.
- Oftentimes, the actuation of signal control is driven by public transport, not necessarily by cars.
- On each traffic-actuated controller there must be at least one fixed-time signal plan, called a backup signal plan.

Intersection layout

- Traffic lights are often switched to yellow blinking when the demands are low and the lights are not necessary for traffic safety
- Crossing for pedestrians should always be safe. Pedestrian crossings that span more than three vehicle lanes without a splitter island are usually not accepted.
- A splitter island shall be present between the two driving directions in the case that one of the directions consists of two or more lanes.
- For safety reasons, some cities do not allow two different pedestrian phases (two-step crossing), one for each side of the splitter island.

Multiple intersections

- Many cities in Switzerland (e.g., Zurich) may design green waves primarily for public transport and not for private vehicles
- When coordinating for private vehicles, the number of consecutive coordinated intersections is normally limited to a value between three and five. For a higher number of intersections, capacity might decrease too much due to platoon dispersion.

Signal timing inputs

Transition times

- Transition times are constant for red-yellow before green (1 seconds) or depend on the permitted speed (yellow before red: 3 seconds until 50 km/h, 4 seconds for 60 km/h; 5 seconds for 70 km/h and above).

Cycle length

- cycle times in Switzerland tend to be very short, to easily accommodate pedestrians and bicycles.
- A cycle time between 60 and 90 seconds is generally recommended.
- Cycle times greater than 120 seconds are to be avoided, as they lead to long waiting times for nonmotorized modes, as well as long reds and potentially cyclic spillbacks (as blocks tend to be rather short in many Swiss cities)
- Shorter than 60 seconds cycle times are also used, for example, 45 seconds in Zurich

Signal timing inputs

- These very short cycle lengths are normally used in many Swiss cities to avoid long waiting times for pedestrians.
- If no cycle time is specified, usually a 90-seconds cycle time is assumed.

Further restrictions

- There may be offset restrictions imposed by county or city law, as pedestrian green offsets when green is in parallel to through and turning traffic: pedestrians need to get green before the traffic stream whose turning traffic is unprotected.

Signal timing procedure

- Minimum green times differ from city to city and from canton (state) to canton. Usually, cars have a minimum green time of 4 seconds, while pedestrians get the time required to cross two-thirds of the pedestrian crossing. Pedestrian minimum green times vary frequently by project.
- It is common in Switzerland to develop for each intersection four programs, corresponding to four different time periods: morning peak, evening peak, off-peak, and night.