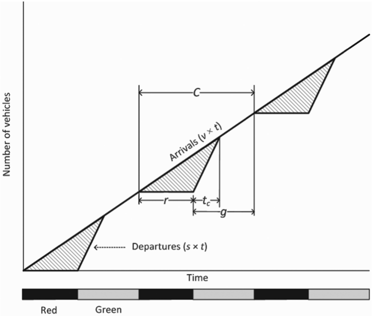
CE 269
Traffic Engineering

Lecture 15

Signalized Corridors and Networks

Previously on Traffic Engineering

Suppose $sg > vC$. Calculate the following quantities:



- The time to clear the queues after the start of the effective green.

$$t_c = \frac{vr}{s - v}$$

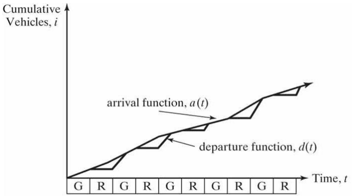
- The proportion of the cycle time with a queue.

$$t_c = \frac{r + t_c}{C}$$

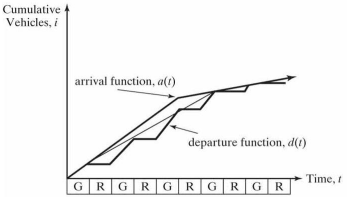
- Total vehicle delay per cycle and average delay per vehicle.

$$D_t = \frac{vr^2}{2(1 - v/s)} \quad D_{avg} = \frac{0.5C(1 - g/C)^2}{1 - (v/c)(g/C)}$$

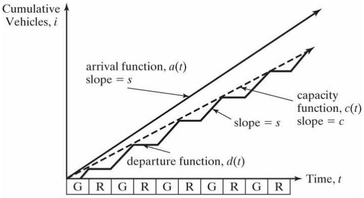
Previously on Traffic Engineering



(a) Stable Flow



(b) Individual Cycle Failures Within a Stable Operation



(c) Demand Exceeds Capacity for a Significant Period

Previously on Traffic Engineering

Based on empirical and simulation studies, the following formula has been proposed in US-HCM for average additional delay per vehicle due to random arrivals and oversaturation.

$$d_2 = 900T\left[(v/c-1)+\sqrt{(v/c-1)^2+\frac{8kI(v/c)}{cT}}\right]$$

- T is set to 0.25 if a 15-min peak hour traffic is considered for analysis.
- k is set to 0.5 for pre-timed controllers and is a function of v/c for actuated signals.
- The metering factor I which accounts for the presence of an upstream signal since it can reduce the randomness at the junction being analyzed. It is set to 1 for isolated intersections.

The total average signal delay is estimated as

$$d = d_1 + d_2 + d_3$$

where d_1 is the uniform delay (same as UD) and d_3 is set to the delay due to initial queues that exist at the start of the analysis period.

Lecture Outline

1. Corridors and Progression
2. Actuated Signals
3. Networks of Signals

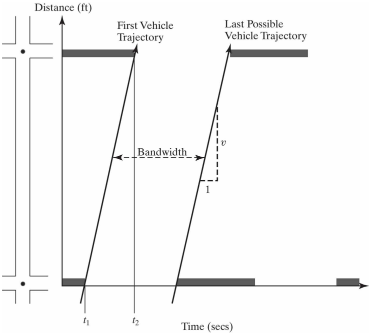
Lecture Outline

Corridors and Progression

Corridors and Progression

Introduction

For corridors with multiple signals which are close to each other, it is prudent to not design them in isolation. These signals typically have the same cycle time but their greens start with an *offset*.



In the above figure, $t_2 - t_1$ is the offset. Ideally this should be set to the distance between junctions divided by the average speed of the vehicle.

Corridors and Progression

Introduction

Bandwidth is another quantity of interest which is the time difference between the first and last vehicle that passes through the junctions without having to stop.

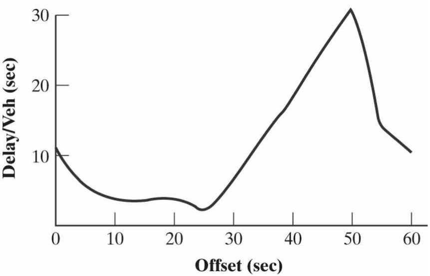
In calculating the offsets, one could also add the start-up delay at the first intersection to t_1 in calculating the offsets.

Since vehicles go through the subsequent intersections without queuing, start-up delays at downstream junctions are not needed.

Corridors and Progression

Effects of Offsets

In the earlier example, the bandwidth is same as the effective green because there are only two intersections and the offsets were carefully chosen.



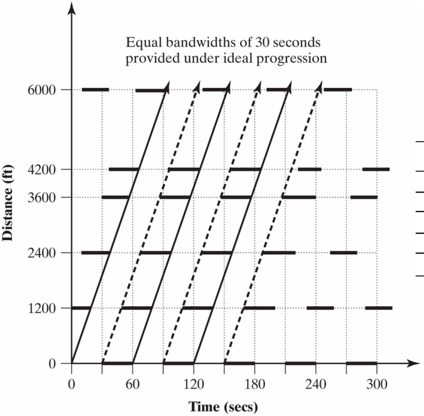
600 ft block
600 vph in two lanes
all through traffic
free speed 24 mph
50-50 split
60 sec. cycle length

When there are more than two intersections and traffic flow in both directions have to be optimized, things can get complicated very quickly.

Corridors and Progression

One-Way Corridors

For more than two junction in a one-way stream, we can still find the offsets as before but by looking at adjacent junctions.



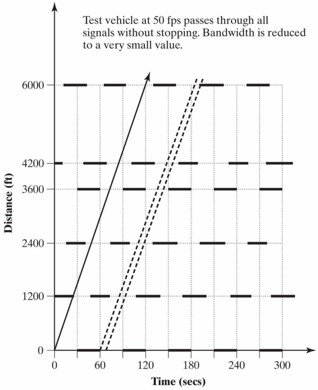
Signal	Relative to Signal	Ideal Offset
6	5	1,800/60 = 30 s
5	4	600/60 = 10 s
4	3	1,200/60 = 20 s
3	2	1,200/60 = 20 s
2	1	1,200/60 = 20 s

The cycle time and green splits are assumed to be pre-calculated and the only decision variable here is the offsets.

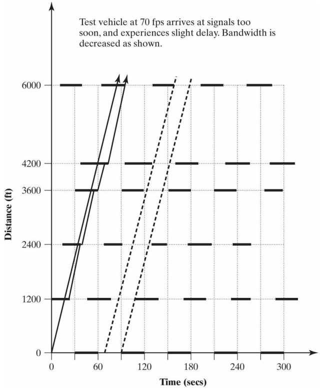
Corridors and Progression

One-Way Corridors

The green wave in the previous example was assumed to be derived for a vehicular speed of 60 ft/s. However, if vehicles travel slower or faster, this can offset the benefits of designing signal progression.



Test vehicle at 50 fps passes through all signals without stopping. Bandwidth is reduced to a very small value.



Test vehicle at 70 fps arrives at signals too soon, and experiences slight delay. Bandwidth is decreased as shown.

Can we ensure that the vehicles adhere to the design speed?

Corridors and Progression

Bandwidth Efficiency and Capacity

The efficiency of a bandwidth is defined as the percentage of the cycle time for which vehicles can pass without having to stop.

$$EFF_B = \frac{100B}{C}$$

where EFF_B is the bandwidth efficiency in percentage, B and C are the bandwidth and the cycle times.

Another measure of efficiency is the capacity of the bandwidth which is the maximum rate at which vehicles can pass through the corridor without stopping.

$$c_{BW} = \frac{3600BN}{Ch}$$

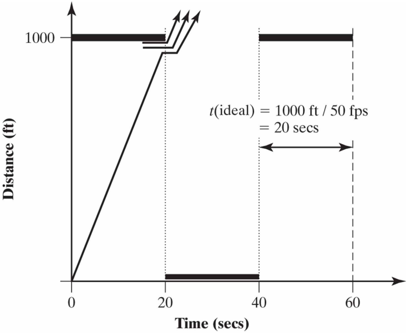
where c_{BW} is the capacity of the bandwidth in vehicles/hr, N is the number of lanes, and h is the saturation headway (in s).

For a corridor with bandwidth of 17 s and cycle time of 60 s, what is the size of the platoon with a saturation headway of 2 s that can successfully go uninterrupted? What is the capacity of the bandwidth?

Corridors and Progression

Queued-Vehicles

Not everything goes according to plan. Sometimes stooped vehicles and internal queues can lead to unexpected results.



What are the source of these queued vehicles? Should the offset in the above example be decreased or increased to improve bandwidth?

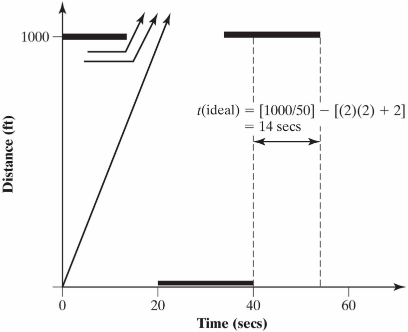
Corridors and Progression

Queued-Vehicles

The adjusted offset is lower and can be computed using

$$t_{adj} = L/S - (Qh + start - uplosttime)$$

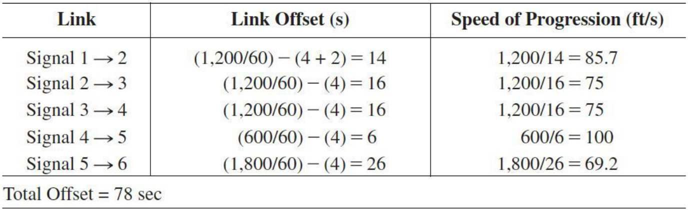
where Q is the average number of vehicles in the queue and h is the discharge headway.



Corridors and Progression

Queued-Vehicles

This exercise can be done at all subsequent intersections. The start-up lost times can however be ignored from Signal 2.



Link	Link Offset (s)	Speed of Progression (ft/s)
Signal 1 → 2	(1,200/60) − (4 + 2) = 14	1,200/14 = 85.7
Signal 2 → 3	(1,200/60) − (4) = 16	1,200/16 = 75
Signal 3 → 4	(1,200/60) − (4) = 16	1,200/16 = 75
Signal 4 → 5	(600/60) − (4) = 6	600/6 = 100
Signal 5 → 6	(1,800/60) − (4) = 26	1,800/26 = 69.2

Total Offset = 78 sec

The speed of progression can be assumed to be the rate at which downstream signals turn green.

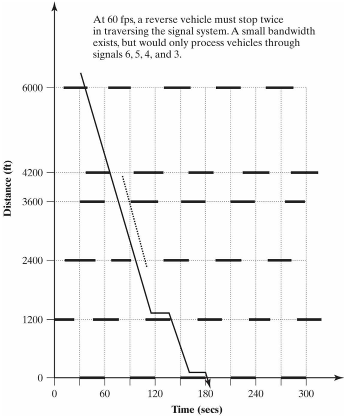
Note that these speeds are greater than the assumed speed of vehicles, i.e., 60 ft/s since the signal should turn green before the platoon arrives to discharge queued vehicles.

Can anything further go wrong after these adjustments are made?

Corridors and Progression

Two-Way Corridors

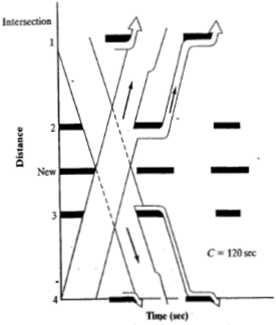
So far we set the offsets based on north-bound traffic. This can, however, lead to no bandwidth in the south-bound direction.



Corridors and Progression

Two-Way Corridors

Setting offsets to cater to traffic in both directions is non-trivial. We may be forced to adjust with different bandwidths.



One could also try to find bandwidths that are proportional to the volume of traffic in both directions.

Corridors and Progression

Two-Way Corridors

Several software automate this process if inputs on average volumes for different turn movements at each junction along a corridor are given.

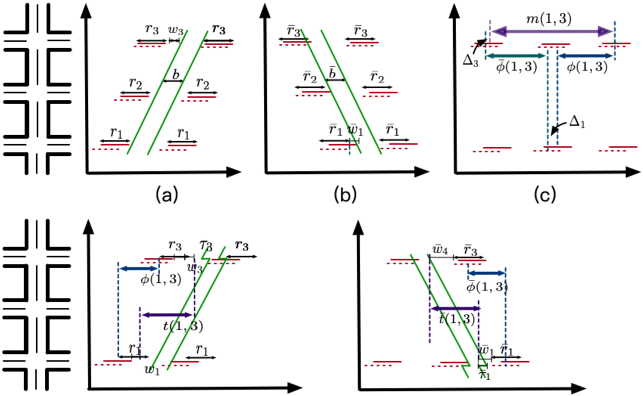
- SYNCRO `https://www.trafficware.com/synchro-studio.html`
- Tru-Traffic `http://www.tsppd.com/`
- TRANSYT-7F `https://mctrans.ce.ufl.edu/hcs/t7f/`
- PTV VISTRO `https://www.ptvgroup.com/en/solutions/products/ptv-vistro/traffic-signal-operations/`

Many of these tools use heuristics such as GA, hill-climbing, and simulated annealing methods for finding the optimal bandwidths.

Corridors and Progression

Two-Way Corridors

Behind these tools, there are optimization models. One such example is the MAXBAND algorithm.



(a) (b) (c)

(d) (e)

Corridors and Progression

Two-Way Corridors

The variables for the SB direction are indicated with similar notation but with a bar.

- b: Bandwidths for the NB direction.
- r_i: Red time at junction i
- $\phi(i, j)$: Offsets between signals at junctions i and j
- $t(i, j)$: Represents the travel times to go from i to j
- τ_i: Queue clearance time at i
- $m(i, j)$: Multiple of the cycle length.

Corridors and Progression

Two-Way Corridors

The objective could be to maximize the bandwidth (if both bandwidths in both directions are made equal) or sum of bandwidths (with additional constraints on minimum bandwidths).

$$
\begin{aligned}
& \max b & & \\
\text{s.t.} \quad & w_i + b \leq 1 - r_i & & \forall\, i \in N \\
& \bar{w}_i + \bar{b} \leq 1 - \bar{r}_i & & \forall\, i \in N \\
& \phi(i,j) + \bar{\phi}(i,j) + \Delta_i - \Delta_j = m(i,j) & & \forall\, i,j \in N \\
& \phi(i,j) + r_j/2 + w_j + \tau_j = r_i/2 + w_i + t(i,j) & & \forall\, i,j \in N \\
& \phi(i,j) + \bar{r}_j/2 + \bar{w}_j = \bar{r}_i/2 + \bar{w}_i + -\bar{\tau}_i + \bar{t}(i,j) & & \forall\, i,j \in N \\
& w_i, \bar{w}_i \geq 0 & & \forall\, i \in N \\
& m_i \in \mathbb{N} & & \forall\, i \in N
\end{aligned}
$$

The constraints represent bandwidth restrictions at each intersection and spatial and temporal constraints between pairs of intersections.

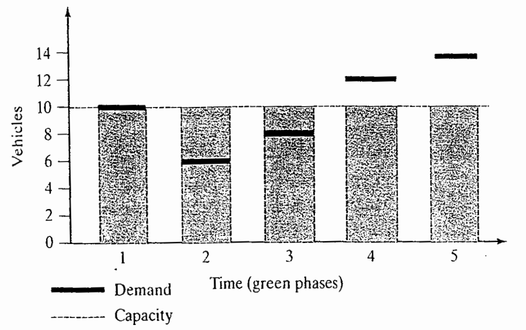
Lecture Outline

Actuated Signals

Actuated Signals

Introduction

The green times provided by fixed-time controllers are not effectively used due to fluctuations in demand.



Actuated controllers use sensors to extend or curtail the green time for an approach.

Actuated Signals

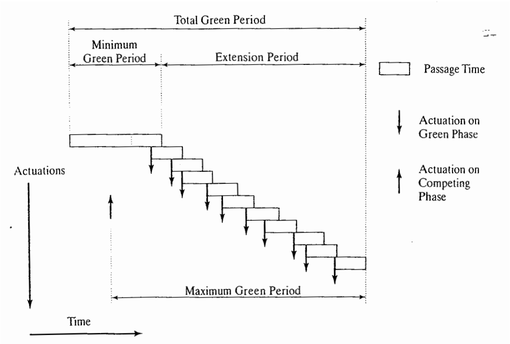
Introduction

Actuated controllers are characterized by the following features:

- **Minimum green time**: If a phase is initiated, a minimum amount of green is provided.
- **Passage time**: If a vehicle is detected by a sensor on an approach, this time is added to the green. Sensors are usually placed away from the stop line. Hence, this time must allow a vehicle detected at a sensor to cross the stop line.
- **Maximum green time**: If demand is high, one may add multiple passage times to the minimum green. This can lead to situations where traffic on minor streets are ignored. Thus, phases are terminated using the maximum green time triggered by *calls* or actuations on a competing phase.

Actuated Signals

Introduction



Lecture Outline

Network of Signals

Network of Signals

Introduction

The methods discussed so far cannot be used to optimize a network of signals since road geometry can be complicated.

The phasing patterns and cycle lengths of different junction may have to be different to avoid queue spillbacks.

Furthermore, demand can be non-isotropic and time-varying which makes a case for using adaptive signals.

Network of Signals

Introduction

The infrastructure required for optimizing a network of signals has matured with more IoT devices, mobile phones, and advances in vision and vehicle (re)identification.

The most challenging part in this multi-agent system is to predict demand (and route choice), determine the ‘optimal’ sequence at each junction, and communicate the actions with each other.

Common objectives include

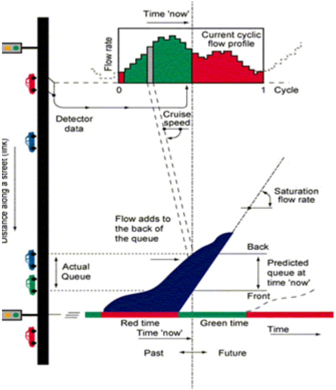
- Average travel time of vehicles
- Queue lengths
- Number of stops
- Throughput

Network of Signals

Classical Approaches

SCOOT is one of the oldest adaptive traffic control method and was developed in UK and it minimizes a weighted sum of delay and stops.

It constructs cyclic flow profiles (CFPs) using detector information.



The size of queues and time required for them to dissipate are used to optimize cycle times, offsets, and green splits.

https://trlsoftware.com/products/traffic-control/scoot/

Network of Signals

Classical Approaches

SCATS (Sydney Coordinated Adaptive Traffic System) uses loop detectors to estimate degree of saturation metrics for each phase. This is calculated by the green time utilized by vehicles/green time provided.

Their algorithms choose from several pre-timed signal plans (which include cycle length, phasing, splits, and offsets).

`https://www.scats.nsw.gov.au/`

RHODES is another approach which makes short-term vehicle arrival and turn-movement predictions using a Bayesian model.

Network of Signals

Classical Approaches

Dynamic programming based methods such as **ALLONS-D** (Adaptive Limited Lookahead Optimization of Network Signals - Decentralized Version) and **OPAC** (Optimized Policies for Adaptive Control) were also developed in the 90s.

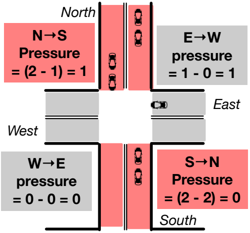
These methods use sensor data and short-term predictions of queue lengths and to minimize the total delay by changing phasing and splits with some constraints on the min and max green for each phase.

Methods to optimize signals in bi-level framework with route-choices captured at the lower level using an equilibrium model also exist.

Network of Signals

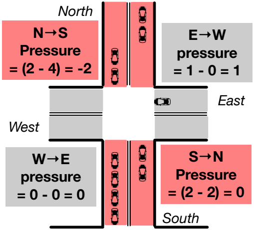
Modern Approaches

Inspired by packet-routing in telecommunications, pressure-based methods have also shown to optimize throughput in transportation networks.



Phase Pressure
Phase (N-S): (2-0)+(2-2) = 2
Phase (W-E): (0-0)+(1-0) = 1

Case A



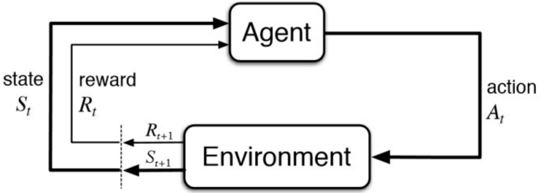
Phase Pressure
Phase (N-S): (2-4)+(2-2) = -2
Phase (W-E): (0-0)+(1-0) = 1

Case B

Network of Signals

Modern Approaches

Several reinforcement-learning based methods have gained prominence in the last decade.

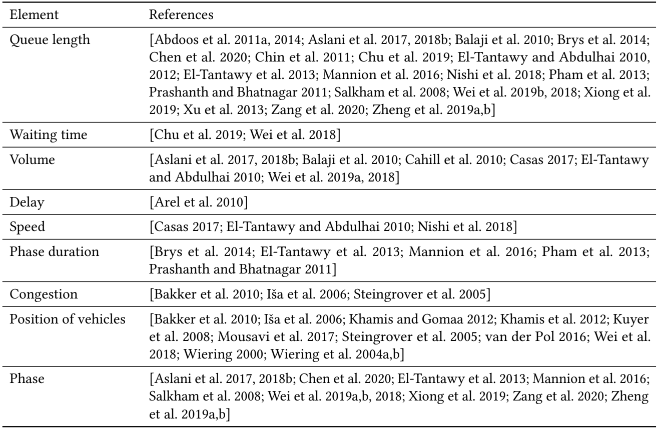


This framework is characterized by states, actions, rewards, and transition functions. The objective is to find policies that optimize the total/average/discounted reward over a time-horizon of interest.

Network of Signals

States

States are inputs to the policy function. There is a trade-off between including more information in the state vector and computational complexity of finding the optimal policy.

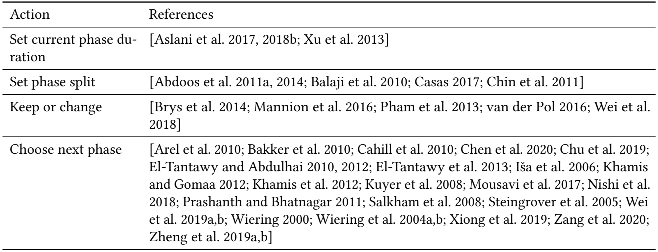


Element	References
Queue length	[Abdoos et al. 2011a, 2014; Aslani et al. 2017, 2018b; Balaji et al. 2010; Brys et al. 2014; Chen et al. 2020; Chin et al. 2011; Chu et al. 2019; El-Tantawy and Abdulhai 2010, 2012; El-Tantawy et al. 2013; Mannion et al. 2016; Nishi et al. 2018; Pham et al. 2013; Prashanth and Bhatnagar 2011; Salkham et al. 2008; Wei et al. 2019b, 2018; Xiong et al. 2019; Xu et al. 2013; Zang et al. 2020; Zheng et al. 2019a,b]
Waiting time	[Chu et al. 2019; Wei et al. 2018]
Volume	[Aslani et al. 2017, 2018b; Balaji et al. 2010; Cahill et al. 2010; Casas 2017; El-Tantawy and Abdulhai 2010; Wei et al. 2019a, 2018]
Delay	[Arel et al. 2010]
Speed	[Casas 2017; El-Tantawy and Abdulhai 2010; Nishi et al. 2018]
Phase duration	[Brys et al. 2014; El-Tantawy et al. 2013; Mannion et al. 2016; Pham et al. 2013; Prashanth and Bhatnagar 2011]
Congestion	[Bakker et al. 2010; Iša et al. 2006; Steingrover et al. 2005]
Position of vehicles	[Bakker et al. 2010; Iša et al. 2006; Khamis and Gomaa 2012; Khamis et al. 2012; Kuyer et al. 2008; Mousavi et al. 2017; Steingrover et al. 2005; van der Pol 2016; Wei et al. 2018; Wiering 2000; Wiering et al. 2004a,b]
Phase	[Aslani et al. 2017, 2018b; Chen et al. 2020; El-Tantawy et al. 2013; Mannion et al. 2016; Salkham et al. 2008; Wei et al. 2019a,b, 2018; Xiong et al. 2019; Zang et al. 2020; Zheng et al. 2019a,b]

Network of Signals

Actions

Actions are outputs of the policy function.

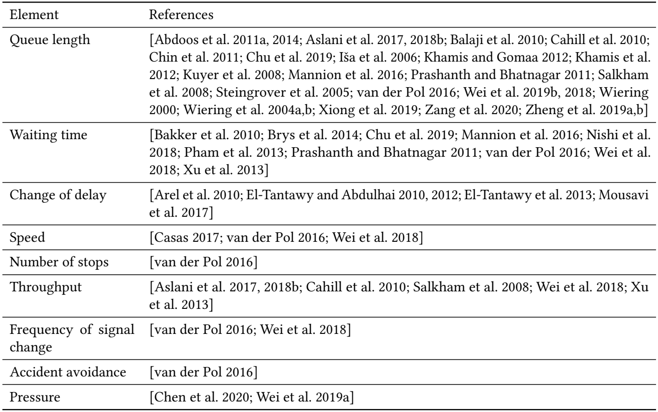


Action	References
Set current phase duration	[Aslani et al. 2017, 2018b; Xu et al. 2013]
Set phase split	[Abdoos et al. 2011a, 2014; Balaji et al. 2010; Casas 2017; Chin et al. 2011]
Keep or change	[Brys et al. 2014; Mannion et al. 2016; Pham et al. 2013; van der Pol 2016; Wei et al. 2018]
Choose next phase	[Arel et al. 2010; Bakker et al. 2010; Cahill et al. 2010; Chen et al. 2020; Chu et al. 2019; El-Tantawy and Abdulhai 2010, 2012; El-Tantawy et al. 2013; Iša et al. 2006; Khamis and Gomaa 2012; Khamis et al. 2012; Kuyer et al. 2008; Mousavi et al. 2017; Nishi et al. 2018; Prashanth and Bhatnagar 2011; Salkham et al. 2008; Steingrover et al. 2005; Wei et al. 2019a,b; Wiering 2000; Wiering et al. 2004a,b; Xiong et al. 2019; Zang et al. 2020; Zheng et al. 2019a,b]

Network of Signals

Rewards

One-step rewards can focus on one performance measure or can be a weighted combination of the following metrics.

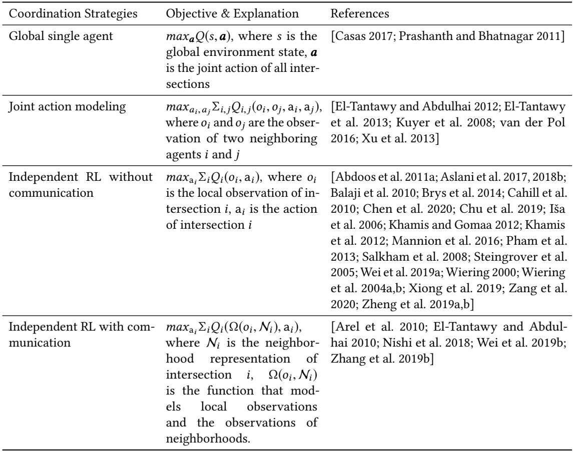


Element	References
Queue length	[Abdoos et al. 2011a, 2014; Aslani et al. 2017, 2018b; Balaji et al. 2010; Cahill et al. 2010; Chin et al. 2011; Chu et al. 2019; Iša et al. 2006; Khamis and Gomaa 2012; Khamis et al. 2012; Kuyer et al. 2008; Mannion et al. 2016; Prashanth and Bhatnagar 2011; Salkham et al. 2008; Steingrover et al. 2005; van der Pol 2016; Wei et al. 2019b, 2018; Wiering 2000; Wiering et al. 2004a,b; Xiong et al. 2019; Zang et al. 2020; Zheng et al. 2019a,b]
Waiting time	[Bakker et al. 2010; Brys et al. 2014; Chu et al. 2019; Mannion et al. 2016; Nishi et al. 2018; Pham et al. 2013; Prashanth and Bhatnagar 2011; van der Pol 2016; Wei et al. 2018; Xu et al. 2013]
Change of delay	[Arel et al. 2010; El-Tantawy and Abdulhai 2010, 2012; El-Tantawy et al. 2013; Mousavi et al. 2017]
Speed	[Casas 2017; van der Pol 2016; Wei et al. 2018]
Number of stops	[van der Pol 2016]
Throughput	[Aslani et al. 2017, 2018b; Cahill et al. 2010; Salkham et al. 2008; Wei et al. 2018; Xu et al. 2013]
Frequency of signal change	[van der Pol 2016; Wei et al. 2018]
Accident avoidance	[van der Pol 2016]
Pressure	[Chen et al. 2020; Wei et al. 2019a]

Network of Signals

Communication Between Agents

To manage a network of intersection, the problem is typically modelled as a multi-agent reinforcement learning (MARL) problem where signals may communicate some state information to its neighbours.



Coordination Strategies	Objective & Explanation	References
Global single agent	$max_{\boldsymbol{a}} Q(s, \boldsymbol{a})$, where s is the global environment state, $\boldsymbol{a}$ is the joint action of all intersections	[Casas 2017; Prashanth and Bhatnagar 2011]
Joint action modeling	$max_{a_i, a_j} \Sigma_{i,j} Q_{i,j}(o_i, o_j, \mathrm{a}_i, \mathrm{a}_j)$, where o_i and o_j are the observation of two neighboring agents i and j	[El-Tantawy and Abdulhai 2012; El-Tantawy et al. 2013; Kuyer et al. 2008; van der Pol 2016; Xu et al. 2013]
Independent RL without communication	$max_{\mathrm{a}_i} \Sigma_i Q_i(o_i, \mathrm{a}_i)$, where o_i is the local observation of intersection i, a_i is the action of intersection i	[Abdoos et al. 2011a; Aslani et al. 2017, 2018b; Balaji et al. 2010; Brys et al. 2014; Cahill et al. 2010; Chen et al. 2020; Chu et al. 2019; Iša et al. 2006; Khamis and Gomaa 2012; Khamis et al. 2012; Mannion et al. 2016; Pham et al. 2013; Salkham et al. 2008; Steingrover et al. 2005; Wei et al. 2019a; Wiering 2000; Wiering et al. 2004a,b; Xiong et al. 2019; Zang et al. 2020; Zheng et al. 2019a,b]
Independent RL with communication	$max_{\mathrm{a}_i} \Sigma_i Q_i(\Omega(o_i, \mathcal{N}_i), \mathrm{a}_i)$, where $\mathcal{N}_i$ is the neighborhood representation of intersection i, $\Omega(o_i, \mathcal{N}_i)$ is the function that models local observations and the observations of neighborhoods.	[Arel et al. 2010; El-Tantawy and Abdulhai 2010; Nishi et al. 2018; Wei et al. 2019b; Zhang et al. 2019b]

Additional Reading

Roess, R. P., Prassas, E. S., & McShane, W. R. (2004). Traffic engineering. Pearson/Prentice Hall.

Little, J. D., Kelson, M. D., & Gartner, N. H. (1981). MAXBAND: A versatile program for setting signals on arteries and triangular networks.

Varaiya, P. (2013). Max pressure control of a network of signalized intersections. Transportation Research Part C: Emerging Technologies, 36, 177-195.

Papageorgiou, M., Diakaki, C., Dinopoulou, V., Kotsialos, A., & Wang, Y. (2003). Review of road traffic control strategies. Proceedings of the IEEE, 91(12), 2043-2067.

Wei, H., Zheng, G., Gayah, V., & Li, Z. (2019). A survey on traffic signal control methods. arXiv preprint arXiv:1904.08117.

Your Moment of Zen

It is becoming impossible to regulate the traffic with just a whistle, sir!