# Chapter 38

# Coordinated Traffic Signal

## 38.1   Overview

This chapter covers basic aspects of traffic signal coordination. Signal coordination is done when they are closely space to enable vehicle in one predominant direction to get continuous green. This will reduce the delay and travel time in one direction and increases throughput. The design principles of signal coordination will be presented in this chapter.

## 38.2   Concepts of signal coordination

For signals that are closely spaced, it is necessary to coordinate the green time so that vehicles may move efficiently through the set of signals. In some cases, two signals are so closely spaced that they should be considered to be one signal. In other cases, the signals are so far apart that they may be considered independently. Vehicles released from a signal often maintain their grouping for well over 335m.

### 38.2.1   Factors affecting coordination

There are four major areas of consideration for signal coordination:

1. Benefits

2. Purpose of signal system

3. Factors lessening benefits

4. Exceptions to the coordinated scheme

The most complex signal plans require that all signals have the same cycle length. Fig. 38:1 illustrates path (trajectory) that a vehicle takes as time passes. At $t = t_1$, the first signal turns
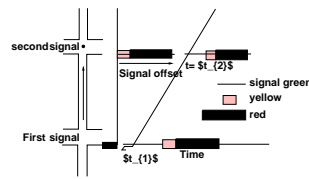
Figure 38:1: Vehicle trajectory

green. After some lag, the vehicle starts and moves down the street. It reaches the second signal at some time $t = t_2$. Depending on the indication of that signal, it either continues or stops. The difference between the two green initiation times is referred to as the signal offset, or simply as the offset. In general, the offset is defined as the difference between green initiation times, measured in terms of the downstream green initiation relative to the upstream green initiation.

## 38.2.2 Benefits

It is common to consider the benefit of a coordination plan in terms of a *cost* or *penalty* function; a weighted combination of stops and delay, and other terms as given here:

$$\text{cost} = A \times (\text{total stops}) + B \times (\text{total delay}) + (\text{other terms}) \tag{38.1}$$

The object is to make this dis-benefit as small as possible. The weights $A$ and $B$ are coefficients to be specified by the engineer or analyst. The values of $A$ and $B$ may be selected so as to reflect the estimated economic cost of each stop and delay. The amounts by which various timing plans reduce the cost, can then be used in a cost-benefit analysis to evaluate alternative plans. The conservation of energy and the preservation of the environment have grown in importance over the years. Given that the vehicles must travel, fuel conservation and minimum air pollution are achieved by keeping vehicles moving as smoothly as possible at efficient speeds. This can be achieved by a good signal-coordination timing plan. Other benefits of signal coordination include, maintenance of a preferred speed, possibility of sending vehicles through successive intersections in moving platoons and avoiding stoppage of large number of vehicles.

## 38.2.3 Purpose of the signal system

The physical layout of the street system and the major traffic flows determine the purpose of the signal system. It is necessary to consider the type of system, whether one-way arterial, two-way arterial, one-way,two-way, or mixed network. the capacities in both directions on some streets, the movements to be progressed, determination of preferential paths
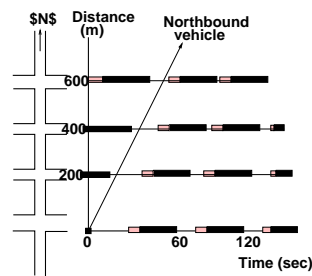
Figure 38:2: Time space diagram

## 38.2.4  Factors lessening benefits

Among the factors limiting benefits of signal coordination are the following:

- inadequate roadway capacity

- existence of substantial side frictions, including parking, loading, double parking, and multiple driveways

- wide variability in traffic speeds

- very short signal spacing

- heavy turn volumes, either into or out of the street

## 38.2.5  Exceptions of the coordinated scheme

All signals cannot be easily coordinated. When an intersection creating problems lies directly in the way of the plan that has to be designed for signal coordination, then two separate systems, one on each side of this troublesome intersection, can be considered. A critical intersection is one that cannot handle the volumes delivered to it at any cycle length.

## 38.2.6  Time-space diagram and ideal offsets

The time-space diagram is simply the plot of signal indications as a function of time for two or more signals. The diagram is scaled with respect to distance, so that one may easily plot vehicle positions as a position of time. Fig. 38:2 is a time-space diagram for two intersections. The standard conventions are used in Fig. 38:2: a green signal indication is shown by a blank or thin line, amber by a shaded line and red by a solid line. For purpose of illustration of trajectory in the time space diagram for intersections, a northbound vehicle going at a constant speed of 40fps is shown. The *ideal offset* is defined as the offset that will cause the specified objective to
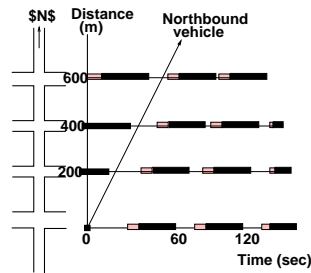
Figure 38:3: Case study:progression on a one way street

be best satisfied. For the objective of minimum delay, it is the offset that will cause minimum delay. In Fig. 38:2, the ideal offset is 25 sec for that case and that objective. If it is assumed that the platoon was moving as it went through the upstream intersection then the ideal offset is given by

$$\text{t(ideal)} = \frac{L}{S} \tag{38.2}$$

where: $t(ideal)$ = ideal offset,sec, $L$ = block length, m, $S$ = vehicle speed, mps.

## 38.3   Signal progression on one-way streets

### 38.3.1   Determining ideal offsets

In Fig. 38:3 a one-way arterial is shown 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. For the purpose of illustration, a platoon speed of 60 fps is assumed. The offsets are determined according to Eqn. 38.2. Next the time-space diagram is constructed according to the following rules:

1. The vertical should be scaled so as to accommodate the dimensions of the arterial, and the horizontal so as to accommodate at least three to four cycle lengths.

2. The beginning intersection should be scaled first, usually with main street green initiation at t=0, followed by periods of green and red.

3. The main street green of the next downstream signal should be located next, relative to t=0 and at the proper distance from t he first intersection. With this point located, the periods of green, yellow and red for this signal are filled in.

4. This procedure is repeated for all other intersections working one at a time.
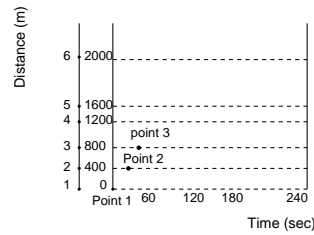
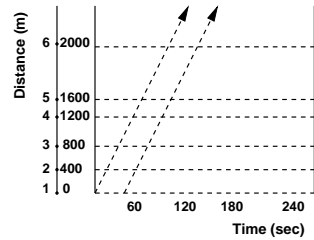Figure 38:4: Time space diagram for case study



Figure 38:5: Vehicle trajectory and green wave in a progressed movement

Fig. 38:4 shows the time-space diagram for the illustration mentioned previously. Fig. 38:5 explores some features of the time-space diagram.

## 38.3.2  Effect of vehicles queued at signals

It sometimes happens that there are vehicles stored in block waiting for a green light. These may be stragglers from the last platoon, vehicles that turned into the block, or vehicles that came out of parking lots or spots. The ideal offset must be adjusted to allow for these vehicles, so as to avoid unnecessary stops. The ideal offset can then be given as:

$$t_{\text{ideal}} = \frac{L}{S} - (Qh + \text{Loss}_1) \tag{38.3}$$

where, $Q$ = number of vehicles queued per lane, veh, $h$= discharge headway of queued vehicle, sec/veh, and $Loss_1$ = loss time associated with vehicles starting from rest at the first downstream signal.

## 38.3.3  A note on queue estimation

If it is known that there exists a queue and its size is known approximately, then the link offset can be set better than by pretending that no queue exists. There can be great cycle-to-cycle variation in the actual queue size, although its average size may be estimated. Even then, queue estimation is a difficult and expensive task and should be viewed with caution.
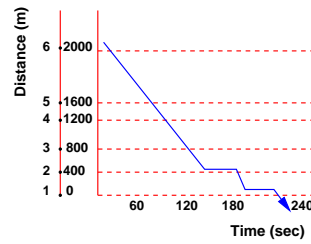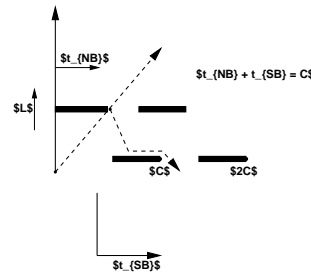
Figure 38:6: Moving southbound



Figure 38:7: Offsets on 2 way arterial are not independent- One cycle length

## 38.4 Signal Progression on two-way streets

Consider that the arterial shown in Fig. 38:3 is not a one-way but rather a two-way street. Fig. 38:6 shows the trajectory of a southbound vehicle on this arterial.

### 38.4.1 Offset determination on a two-way street

If any offset were changed in Fig. 38:6 to accommodate the southbound vehicle(s), then the northbound vehicle or platoon would suffer. The fact that offsets are interrelated presents one of the most fundamental problems of signal optimization. The inspection of a typical cycle (as in Fig. 38:7) yields the conclusion that the offsets in two directions add to one cycle length. For longer lengths (as in Fig. 38:8) the offsets might add to two cycle lengths. When queue clearances are taken into account, the offsets might add to zero lengths. The general expression
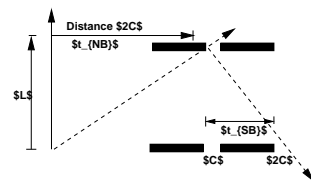


Figure 38:8: Offsets on 2 way arterial are not independent- Two cycle length
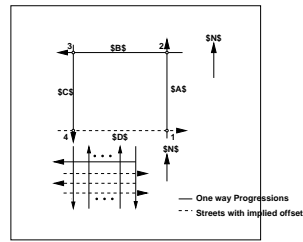
Figure 38:9: Closure effect in grid

for the two offsets in a link on a two-way street can be written as

$$t_{\text{NB},i} + t_{\text{SB},i} = nC \tag{38.4}$$

where the offsets are actual offsets, n is an integer and C is the cycle length. Any actual offset can be expressed as the desired *ideal* offset, plus an *error* or *discrepancy* term:

$$t_{\text{actual}(j,i)} = t_{\text{ideal}(j,i)} + e_{(j,i)} \tag{38.5}$$

where $j$ represents the direction and $i$ represents the link.

## 38.4.2   Offset determination in a grid

A one-way street system has a number of advantages, not the least of which is traffic elimination of left turns against opposing traffic. The total elimination of constraints imposed by the *closure* of loops within the network or grid is not possible. Fig. 38:9 highlights the fact that if the cycle length, splits, and three offsets are specified, the offset in the fourth link is determined and cannot be independently specified. Fig. 38:9 extends this to a grid of one-way streets, in which all of the north-south streets are independently specified. The specification of one east-west street then *locks in* all other east-west offsets. The key feature is that an open tree of one-way links can be completely independently set, and that it is the closing or *closure* of the open tree which presents constraints on some links.

# 38.5   Bandwidth concept

The bandwidth concept is very popular in traffic engineering practice, because

1. the windows of green (through which platoons of vehicles can move) are easy visual images for both working professionals and public presentations

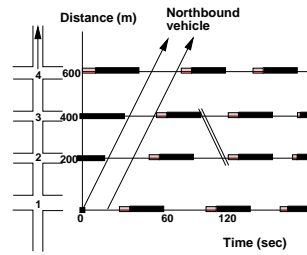2. good solutions can often be obtained manually, by trial and error.

Figure 38:10: Bandwidths on a time space diagram

## 38.5.1  Bandwidth and efficiency of a progression

The efficiency of a bandwidth (measured in seconds) is defined as the ratio of the bandwidth to the cycle length, expressed as a percentage:

$$\text{efficiency} = \frac{\text{bandwidth}}{\text{cycle length}} \times 100\% \tag{38.6}$$

An efficiency of 40% to 50% is considered good. The bandwidth is limited by the minimum green in the direction of interest. Fig. 38:10 illustrates the bandwidths for one signal-timing plan. The northbound efficiency can be estimated as (17/60)100% = 28.4%. There is no bandwidth through the south-bound. The system is badly in need of re-timing at least on the basis of the bandwidth objective. In terms of vehicles that can be put through this system without stopping, note that the northbound bandwidth can carry 17/2.0 = 8.5 vehicles per lane per cycle in a nonstop path through the defined system. The northbound direction can handle

$$\frac{8.5 veh}{\text{cycle}} \times \frac{\text{cycle}}{60 sec} \times \frac{3600 sec}{hr} = 510 \text{vph per lane}$$

very efficiently if they are organized into 8-vehicle platoons when they arrive at this system. If the per lane demand volume is less than $510 vphpl$ and if the flows are so organized, the system will operate well in the northbound direction, even though better timing plans might be obtained. The computation can be formalized into an equation as follows:

$$\text{nonstop volume} = \frac{3600(BW)(L)}{(h)(C)} \text{vph} \tag{38.7}$$

where: $BW$ = measured or computed bandwidth, sec, $L$= number of through lanes in indicated direction, $h$ = headway in moving platoon, sec/veh, and $C$ =cycle length.

## 38.5.2  Trial-and-error approach to find bandwidth

The engineer usually wishes to design for maximum bandwidth in one direction, subject to some relation between the bandwidths in the two directions. There are both trial-and-error
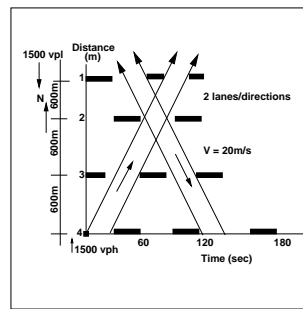
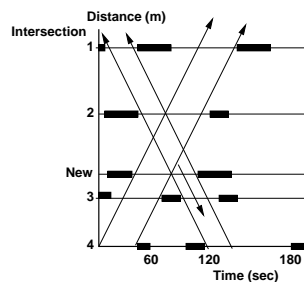Figure 38:11: Case study:Four intersections with good progressions



Figure 38:12: Effect of inserting a new signal into system

and somewhat elaborate manual techniques for establishing maximum bandwidths. Refer to Fig. 38:11, which shows four signals and decent progressions in both the directions. For purpose of illustration, assume it is given that a signal with 50:50 split may be located midway between Intersections 2 and 3. The possible effect as it appears in Fig. 38:12 is that there is no way to include this signal without destroying one or the other through band, or cutting both in half. The offsets must be moved around until a more satisfactory timing plan develops. A change in cycle length may even be required. The changes in offset may be explored by:

- copying the time-space diagram of Fig. 38:12

- cutting the copy horizontally into strips, one strip per intersection

- placing a guideline over the strips, so as to indicate the speed of the platoon(s) by the slope of the guideline

- sliding the strips relative to each other, until some improved offset pattern is identified

There is no need to produce new strips for each cycle length considered: all times can be made relative to an arbitrary cycle length 'C. The only change necessary is to change the slope(s) of the guidelines representing the vehicle speeds. The northbound vehicle takes $3600/60 = 60sec$ to travel from intersection 4 to intersection 2. If the cycle length $C = 120sec$, the vehicle would

have arrived at intersection 2 at $C/2$, or one half of the cycle length. To obtain a good solution through trial-and-error attempt, the following should be kept in consideration:

- If the green initiation at Intersection 1 comes earlier, the southbound platoon is released sooner and gets stopped or disrupted at intersection 2.

- Likewise, intersection 2 cannot be northbound without harming the southbound.

- Nor can intersection 3 help the southbound without harming the northbound.

### 38.5.3   A historical perspective on the use of bandwidth

An elegant mathematical formulation requiring two hours of computation on a supercomputer is some-what irrelevant in most engineering offices. The determination of good progressions on an arterial must be viewed in this context:only 25 years ago, hand held calculators did not exist; 20 years ago, calculators had only the most basic functions. 15 years ago, personal computers were at best a new concept. Previously, engineers used slide rules. Optimization of progressions could not depend on mathematical formulations simply because even one set of computations could take days with t he tools available. Accordingly,graphical methods were developed. The first optimization programs that took queues and other details into account began to appear, leading to later developments that produced the signal-optimization programs in common use in late 1980s. As computers became more accessible and less expensive, the move to computer solutions accelerated in the 1970s. New work on the maximum-bandwidth solution followed with greater computational power encouraging the new formulations.

## 38.6   Forward and reverse progressions

Simple progression is the name given to the progression in which all the signals are set so that a vehicle released from the first intersection will arrive at the downstream intersections just as the signals at those intersections initiate green. As the simple progression results in a green wave that advances with the vehicles, it is often called a forward progression. It may happen that the simple progression is revised two or more times in a day, so as to conform to the direction of the major flow, or to the flow level. In this case, the scheme may be referred to as a flexible progression. Under certain circumstances, the internal queues are sufficiently large that the ideal offset is negative. The downstream signal must turn green before the upstream signal, to allow sufficient time for the queue to start moving before the arrival of the platoon. The visual image of such a pattern is of the green marching upstream, toward the drivers in the platoon. This is referred to as reverse progression.

## 38.6.1   Effective progression on two-way streets

In certain geometries it is possible to obtain very effective progressions in both directions on two-way streets. The existence of these patterns presents the facts that:

- The system cycle length should be specified based primarily on the geometry and platoon speed whenever possible, to enhance progressions.

- The task of good progression in both directions becomes easy if an appropriate combination of cycle length, block length and platoon speed exist.

- Whenever possible the value of these appropriate combinations should be considered explicitly for they can greatly determine the quality of flow for decades.

- In considering the installations of new signals on existing arterial, the same care should be taken to preserve the appropriate combinations and/or to introduce them.

## 38.6.2   Importance of signal phasing and cycle length

The traffic engineer may well be faced with a situation that looks intimidating, but for which the community seek to have smooth flow of traffic along an arterial or in a system. The orderly approach begins with first, appreciating the magnitude of the problem. The splits, offsets, and cycle length might be totally out of date for the existing traffic demand. Even if the plan is not out of date, the settings in the field might be totally out of date, the settings in the field might be totally different than those originally intended and/or set. Thus, a logical first step is simply to ride the system and inspect it. Second, it would be very useful to sketch out how much of the system can be thought of as an *open tree* of one way links. A distinction should be made among

- streets that are one way

- streets that can be treated as one-way, due to the actual or desired flow patterns

- streets that must be treated as two-ways

- larger grids in which streets interact because they form unavoidable *closed trees* and are each important in that they cannot be ignored for the sake of establishing a *master grid* which is an open tree

- smaller grids in which the issue is not coordination but local land access and circulation

Downtown grids might well fall into the last category, at least in some cases. Third, attention should focus on the combination of cycle length, block length and platoon speed and their interaction. Fourth, if the geometry is not suitable, one can adapt and *fix up* the situation to a certain extent. Another issue to address, of course, is whether the objective of progressed movement of traffic should be maintained.

### 38.6.3 Oversaturated traffic

The problem of oversaturation is not just one of degree but of kind - extreme congestion is marked by a new phenomenon: intersection blockage. The overall approach can be stated in a logical set of steps:

- Address the root causes of congestion

- Update the signalization, for poor signalization is frequently the cause of what looks like an incurable problem

- If the problem persists, use novel signalization to minimize the impact and spatial extent of the extreme congestion.

- Provide more space by use of turn bays and parking congestion.

- Develop site specific evaluations where there are conflicting goals.

### 38.6.4 Signal remedies

Signalization can be improved through measures like, reasonably short cycle lengths, proper offsets and proper splits. Sometimes when there is too much traffic then options such as equity offsets(to aid cross flows) and different splits may be called upon. A metering plan involving the three types - internal, external and release - may be applied. Internal metering refers to the use of control strategies within a congested network so as to influence the distribution of vehicles arriving at or departing from a critical location. External metering refers to the control of the major access points to the defined system, so that inflow rates into the system are limited if the system if the system is already too congested. Release metering refers to the cases in which vehicles are stored in such locations as parking garages and lots, from which their release can be in principle controlled.

## 38.7 Summary

The concept of signal coordination is presented in this chapter. Coordination in one way is simple and effective and results in better progression. Two-way coordination is complex and less effective. Bandwidth is an important parameter in evaluating the efficiency of coordination. Further, the concepts of forward and reverse progression are introduced.

## 38.8 References

1. William R McShane, Roger P Roesss, and Elena S Prassas. *Traffic Engineering*. Prentice-Hall, Inc, Upper Saddle River, New Jesery, 1998.