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Synchronizing Traffic Signals on Grid Networks During a Rush

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Synchronizing Traffic Signals on Grid Networks During a Rush

by

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Professor Michael Cassidy, Chair
Professor Carlos Daganzo
Professor Rhonda Righter

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Abstract

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Professor Michael Cassidy, Chair

A simple strategy is offered for coordinating all traffic signals on street networks arranged as grids. The strategy is based on the finding that signals of symmetric networks can be perfectly synchronized in two orthogonal directions. With this in mind, the strategy synchronizes signals in the directions that point towards the center of gravity of all workplaces in the morning rush, and away from that center during the evening. Although the strategy was initially developed for symmetric networks, it can readily be adapted to accommodate asymmetrical grid arrangements as well. The strategy is also dynamic and adaptive to real-time traffic conditions. Signals are synchronized according to the free flow motion of vehicles in under-saturated traffic, and to backward waves once street links are filled with queues. An algorithm is developed to switch smoothly between the two synchronization modes as conditions change during a rush.

The strategy was tested via simulations of 20 x 20 signalized grids, operating in non-steady-state traffic conditions typical of rush periods, and benchmarked against a fixed zero-offset strategy commonly recommended for congested traffic. In a scenario representing a morning rush with a monocentric distribution of workplaces, the strategy was also benchmarked against the well-known SYNCHRO program. While SYNCHRO reduced the morning commute delays by 7% relative to the fixed zero-offset strategy, the proposed strategy reduced delays by 32% (more than four times that achieved by SYNCHRO). The strategy continued to perform well when workplaces were distributed more broadly over the network, and when workplaces were distributed in a multi-centric pattern. The strategy also performed well when tested for an evening rush, and was adapted to perform well when the grid's original symmetry was distorted to represent a more realistic transportation network.

To my family, for their love and support

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Acknowledgments

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Chapter 1

Introduction

This chapter introduces background information pertaining to the synchronization of traffic signals. It also provides an overview and road map of the dissertation.

1.1 Background

Traffic congestion remains a serious problem in every city in the world. A recent study estimated that United States citizens spent around 8.7 billion hours of delay in traffic in 2019 [40]. The study also showed that this figure has been steadily increasing since 1982 and is expected to continue to increase in the future.

As city traffic is becoming worse, transportation researchers, engineers, and practitioners are actively exploring strategies and solutions to combat congestion. One of many solutions proposed entails developing smarter traffic signal coordination strategies. This solution approach is desirable since a well-coordinated signal plan can significantly reduce travel delay.

Numerous coordination strategies have been proposed in the past few decades. It has long been known that the relationship between the signal timing plans of adjacent intersections along a traffic corridor significantly influence the capacity of the corridor as a whole [7]. As a result, [1] suggested that traffic signals at adjacent intersections with separations of less than 0.5 miles should be coordinated.

Traffic signals at distinct intersections are said to be coordinated if the start of the green phases for a particular movement (say N-S movements) at those intersections are synchronized [3]. Synchronization can be achieved by properly timing a traffic signal parameter called the signal $offset$, defined here as the start of the green phase, for a particular movement, relative to some master clock.

Mountains of literature exist on how best to synchronize traffic signals along one-dimensional arterials. Most recent proposed solutions and strategies found in the literature for coordinating arterials turn out to be effective, often considerably outperforming coordination strategies obtained from state-of-the-practice computer programs [55, 43], which tend to lag behind state-of-the-art and rely on older techniques.

With this in mind, researchers have extended arterial signal coordination schemes to two-dimensional grid networks. The performance of these extended schemes were also benchmarked against state-of-the-practice computer programs. In the case of networks, however, improvements in total travel delay typically ranged between just 1% - 5% [39].

1.2 Dissertation Overview

This dissertation proposes a simple, dynamic strategy for coordinating all signals on a grid network. The strategy is based on the finding that signals of translationally symmetric networks[1] can be synchronized for progression at any speed in two orthogonal directions. With this in mind, the strategy is designed to provide orthogonal coordination in the directions that favor vehicle movements headed toward the focus of all workplaces during the morning commute, and away from that focus during the evening commute. As such, we refer to the strategy as Focused Orthogonal Progression (FOP) during the morning commute, and Dispersed Orthogonal Progression (DOP) during the evening. Note that the strategy is completely independent of turning movement counts at individual intersections, and therefore does not adapt the signals to the routes the drivers want to take (as commonly done in the literature). Instead, the coordination strategy creates efficient routes that consider the distribution of residences and workplaces across the grid, and forces traffic to adapt to these routes.

FOP/DOP was evaluated with simulations in scenarios where homes were uniformly distributed across the grid and workplaces were distributed in various ways. In all scenarios, FOP/DOP was benchmarked against a fixed zero-offset strategy (referred to as the benchmark from now on). In an important scenario representing a severely congested morning rush, however, simulations were also performed using offsets obtained from the state-of-the-practice computer program called SYNHCRO [54]. While SYNCHRO reduced the morning commute delays by 7% relative to the benchmark, FOP reduced delays by 32% (more than four times what was achieved by SYNCHRO). In all the other workplace distributions considered, FOP/DOP continued to perform better than the benchmark, except in the extreme and unrealistic case where workplaces were uniformly distributed across the grid.

Although FOP/DOP was initially developed for translationally symmetric grids, it was adapted to accommodate asymmetric networks that are not perfectly rectangular. Simu-

[1]Translationally symmetric networks are composed of streets that have uneven block lengths but have the same block length as the next street in the orthogonal direction.

lations show that the designed adaptations allow FOP/DOP to perform well even in these more irregular (realistic) networks. In fact, FOP/DOP reduced delays by a double-digit percentage, relative to the benchmark, when tested on a network that resembles downtown Los Angeles (California) in terms of the variations in block lengths and speed limits.

1.3 Dissertation Organization

A summary of related studies and the gaps in these studies is provided in Chapter 2. The proposed strategy is described in Chapter 3. The experimental setup for evaluating the strategy is presented in Chapter 4. Numerical analyses and findings are discussed in Chapter 5. In Chapter 6, a case study on a grid network that roughly resembles downtown Los Angeles is conducted. Conclusions and future research directions are presented in Chapter 7.

Chapter 2

Literature Review

This chapter provides a summary of related studies in the literature. Signal coordination strategies developed for arterial networks are presented in Section 2.1. Extensions applied to these strategies to serve two-dimensional grid networks are described in Section 2.2. Gaps in the literature are discussed in Section 2.3, and contributions made in this dissertation are highlighted in Section 2.4. Section 2.5 presents tools and techniques to model traffic in urban networks. Finally, Section 2.6 presents network performance measures commonly used in the literature and explains why network-wide delay was the measure used to evaluate FOP/DOP.

2.1 Signal Coordination at the Arterial Level

Coordinating signals along a one-directional arterial is an effective strategy to improve network performance, particularly when traffic demand at crossing streets is relatively low [13]. When arterial traffic is under-saturated[1], signals are typically coordinated by synchronizing offsets to the free-flow motion of vehicle platoons. This kind of coordination is known as forward progression and allows the platoons to travel through the intersections without being interrupted, thereby reducing travel times, delays, and number of stops [13].

When arterial traffic is over-saturated, however, forward progression is not as effective [46, 44, 48, 47, 34, 35, 6]. The reason is that when the signal for an arterial approach displays green, vehicle platoons are not able to proceed downstream since downstream links are filled with traffic queues. So, a portion of the green time is wasted for that movement.

Researchers have responded to this issue by synchronizing the signals along an arterial in a backward fashion (i.e., downstream signals display green before upstream signals do)

[1] Under-saturated traffic refers to situations where no traffic queues exist at the end of the green interval (i.e., there is enough green time to clear all vehicles arriving within one cycle).

[46, 44, 48, 47, 34, 35]. Green times in these cases are not initiated for a given movement until the intersection is cleared of any queues immediately downstream. This enables the movement to proceed through the intersection unimpeded during its green. This kind of coordination is known as backward progression.

Things get more complicated and harder to resolve on two-directional arterials. In these cases, the coordination that works for one travel direction may not suit the opposing direction. When the arterial exhibits an unbalanced traffic demand in the opposing directions, common practice entails coordinating signals in the heavier-flow direction [6]. This can increase the rates that vehicles complete trips on the arterial, which reduces delay.

However, when traffic demand is relatively balanced in the opposing direction, researchers have followed approaches that consider the arterial's performance along both travel directions. To this end, mathematical programming models [28, 41, 37, 20, 16, 14, 30, 43, 32, 38, 12] as well as simulation-based models [49, 4, 33, 54] were developed.

While the mathematical programming formulations can provide optimal signal coordination schemes for arterials with relatively balanced traffic demands in opposing directions, they usually assume either steady-state or periodic[2] traffic conditions. These assumptions are made in order to develop simple and accurate link performance functions, which are commonly used in the objective function of the mathematical programs.

Simulation based models are sometimes used as an alternative to the mathematical programming models to determine optimal signal offsets. A few simulation models have been proposed in the literature in the past few decades [49, 4, 33, 54]. Currently, SYNCHRO is one of the most widely used simulation software packages for optimizing signal offsets. It does so by combining macroscopic simulation with non-linear optimization gradient-based search techniques [15].

2.2 Signal Coordination at the Network Level

Coordinating signals on two-dimensional networks can be harder to resolve since now each intersection serves four directions of travel and the best offset might be different for each. This means that coordinating signals for an E-W street in a network might not suit the intersecting N-S streets at all. Researchers have responded to this challenge in a variety of ways.

Perhaps the first algorithm developed for signal coordination in grid networks was the Combination Method [5, 22]. The proposed algorithm starts with a small subnetwork, characterized by a tree structure, for which the set of optimizing offsets are determined using

[2] Periodic traffic conditions refer to situations where vehicle platoons arrive to intersections at intervals.

mathematical programming tools. An iterative process is then followed where at each stage, the subnetwork is extended by one or more intersections. The offsets of the added intersections are optimized while keeping prior determined offsets fixed. However, as noted in [5], the method suffers from computation and memory requirements that grow rapidly with network size.

Later, [42] reformulated the network coordination problem as a mixed-integer program and introduced the network loop constraints. These constraints ensure that the green intervals of intersecting arterials do not overlap in time for all junctions in the network [42, 21]. While the network loop constraints are fundamental, they pose the greatest demand on computation time and require a search procedure of a combinatorial nature [42].

To reduce the computational burden, [23, 24] proposed a network decomposition technique. It works by randomly selecting a tree subnetwork and finding the set of optimizing offsets for that subnetwork. The optimized offsets are then input into the network loop constraints and the offsets of the remaining intersections are determined by solving the general network mixed-integer program. This process is repeated for all possible tree subnetworks and the subnetwork with the most favorable network performance is selected.

Later, [56, 39] developed a more systematic approach in identifying the tree subnetwork. Each arterial in the network was assigned a priority level index. This index is based on the traffic demand and geometry of the arterial, as well as an importance score decided by experts and engineers. The arterial with the highest priority level index is selected as the base subnetwork and the remaining parts of the network are coordinated in a manner similar to earlier work.

These network decomposition techniques along with the mathematical programming formulations result in improved network coordination plans relative to what can be achieved by commercially available computerized models like SYNCHRO. However, these improvements tend to be modest. Reductions in vehicle delay relative to SYNCHRO, for example, typically range from 1-5 % [39].

2.3 Gaps in the Literature

Different strategies for coordinating signals on grids have been proposed in the literature. These strategies generally share two common limiting features: First and foremost, all strategies either assume steady-state or periodic traffic conditions. The assumptions are uncharacteristic of the real world traffic conditions of interest: over-saturated rush hours with temporary queue spillovers. Second, the existing strategies in the literature determine signal offsets based on observed vehicle turning counts at individual intersections. By taking these turning movements as given, the existing literature implicitly assumes that vehicle routes are fixed; i.e. that vehicles do not adapt to traffic conditions. This is unrealistic. Furthermore, by doing so, the strategies adapt the signals to the routes the drivers want to take, and therefore, miss the opportunity to use signals to encourage efficient routing [17]. A signal coordination strategy that addresses these limitations is needed.

2.4 Contributions

This dissertation contributes to the body of literature by introducing FOP/DOP: a simple strategy for coordinating all traffic signals on grid networks. FOP/DOP is dynamic and adaptive to real-time traffic conditions. Offsets are synchronized to the forward motion of vehicle platoons when traffic is undersaturated, and to backward waves when traffic is oversaturated. It proves to be spectacularly effective for the non-steady state conditions that arise during real rush hours. Furthermore, FOP/DOP does not depend on observed vehicle turning movement counts at individual intersections, but is based on the overall distribution of homes and workplaces in the network. Offsets are chosen to favor orthogonal vehicle movements that are headed toward major workplace clusters in the morning rush (FOP), and away from those clusters in the evening (DOP). The idea is akin to favoring heavy-flow directions on arterials, and can be applied in both mono- or multi-centric cities. Although FOP/DOP was developed for translationally symmetric networks, it can be adapted to serve asymmetric networks that are not perfectly rectangular, as commonly occur in real settings.

Since the proposed strategy is reactive to real-time traffic conditions, accurate models that relate traffic conditions to network performance are needed. The next section presents models available in the literature for evaluating traffic in urban networks.

2.5 Modeling Traffic in Urban Networks

Daganzo proposed a framework that relates the rate at which vehicles leave a network (trip completion rate) to the network accumulation [18]. The author showed that this relationship holds for homogenously congested neighborhoods, if traffic conditions change slowly over time [18]. The relationship was later named the Network Exit Function (NEF) by Gonzalez and Daganzo [27]. The NEF assumes that the average trip length should not change over time so that the trip completion rate can be obtained by dividing the total number of trips completed by the (fixed) average trip length [27].

Later, [19] refined the relationship in [18] to develop the Macroscopic Fundamental Diagram (MFD). The MFD is a relationship between network flow, q, and network density, k, such that $q = Q(k)$. Numerous simulations as well as real-world experimental tests followed to prove the existence of a well-defined MFD and to better understand its properties and governing conditions [9, 57, 29, 26, 25, 36, 51]. Researchers have discovered that the MFD is invariant to changes in traffic demand, routes, or origin destination tables, but is rather a function of the network geometry and traffic control parameters [19, 25].

With this in mind, [34, 35] studied how different coordination strategies may affect the MFD of a circular ring network characterized by geometrically homogeneous streets. The authors showed that the forward progression strategy produces higher network flows than the backward progression strategy when the average traffic density in the circular network fell below a certain threshold, k_0. The reverse was observed when the average traffic density in the network exceeded k_0.

These findings are enlightening. MFDs for both the forward and backward progression schemes can now be used to determine the threshold density, k_0. This density can in turn be used to trigger a switch from one scheme to another as traffic conditions change during a rush. The dissertation follows this approach to effectively switch between the two progression schemes. More details on the methodology are provided in Chapter 3.

The next section discusses network performance measures commonly used in the literature and specifies the performance measure that will be used to evaluate FOP/DOP.

2.6 Network Performance Measures

There are two basic performance measures used for optimizing signal timing: overall network delays and the network bandwidth[3] [6]. Although bandwidth maximization schemes are commonly used in the literature [28, 41, 37, 20, 16, 14, 30, 43, 32, 38, 12, 15, 42, 24], they suffer from some limitations [45]. The most apparent limitation is that maximizing the network bandwidth does not necessarily ensure that every approach in the network has a sufficient green interval to accommodate the incoming traffic. So, in that sense, these schemes are only appropriate for under-saturated conditions. The strategy proposed in this dissertation is also based on maximizing the network bandwidth, but is more general than earlier approaches in that it can be viewed as a dynamic version of bandwidth maximization (maximizing the flow of vehicle platoons in under-saturated traffic and the flow of backward green waves in over-saturated traffic).

As noted in [45], however, it is not obvious that the offsets that maximize the bandwidth also minimize delays. For this reason, the dissertation will use the total network delay as the main measure of performance.

[3] The bandwidth of a traffic corridor is defined as the total amount of time per cycle available for vehicles to travel through a corridor of coordinated intersections at the progression speed [3]. The network bandwidth is the sum of bandwidths across all corridors in the network.

Chapter 3

Proposed Strategy

The network in Figure 3.1, with its convenient symmetry, will be used to introduce the FOP strategy for a morning rush.[1] Although the arterial streets in each direction (N-S and E-W) have unequal block lengths, the streets are translationally symmetric in orthogonal directions. We shall also assume that: streets are homogeneous with the same fundamental diagram; all intersections are controlled by pre-timed, two-phase traffic signals with identical phase lengths and cycle time, C; and workplaces are distributed in monocentric fashion. In our present example, the workplaces' center of gravity (CoG) lies in the network's lower left corner, near the intersection labeled 5.[2]

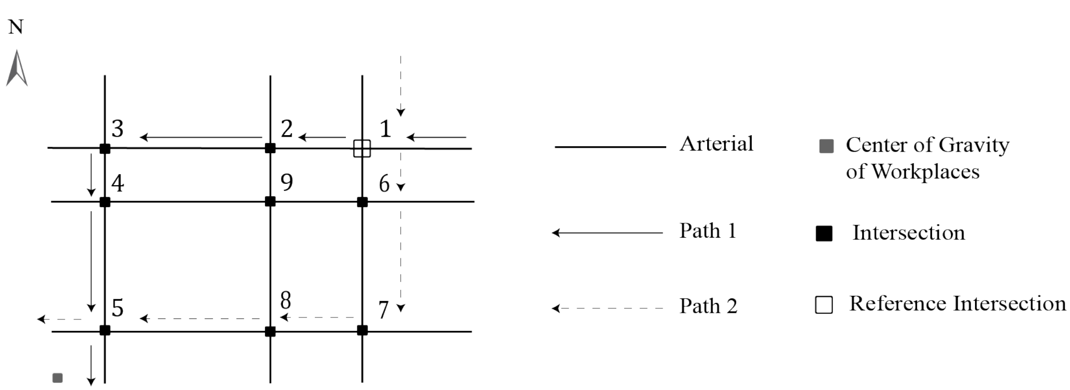


Figure 3.1: 3x3 Example Network

[1] The ideas can be readily adapted to an evening rush (DOP), as will be illustrated in Sec 3.4. Networks of other forms will be used to advance the discussion as needed.

[2] Note that although Figure 3.1 displays the paths of only two trips originating from the same intersection, the coordination strategy and ideas discussed in the following sections apply to all trips that originate from any point in the network and travel towards (away from) the CoG of workplaces during the morning (evening) commute.

Sections 3.1 and 3.2 use Figure 3.1 to discuss how to synchronize offsets when traffic is under-saturated and over-saturated, respectively. Then, Sec 3.3 discusses a method to toggle between the two synchronization modes and Sec 3.4 explains how the method can be modified for the evening commute. Sec 3.5 shows how to handle networks with multiple workplace clusters and, finally, Sec 3.6 explains how to apply the method to geometrically irregular grids.

3.1 Under-saturated Traffic in the Morning Commute

The intersection labeled 1 in Figure 3.1 (the one furthest from the CoG) is designated as a reference intersection. Its offsets are defined as the times, modulo C (% C), when the intersection's E-W and N-S green phases start. They are designated δ^i_{ref}, where superscript i denotes the E-W or N-S phase: $i = 1$ for the E-W phase, and $i = 2$ for the N-S phase. The δ^1_{ref} and δ^2_{ref} differ by an effective red time.

Because traffic is under-saturated, we deploy forward progression in the directions pointing towards the CoG. This means that the green phases at intersection j are started when a free-flowing vehicle released from the reference intersection at the start of the corresponding phase and traveling along the shortest path would arrive at j. If we use v_f for the free-flow vehicle speed, and x_j and y_j for the E-W and N-S distances between the reference intersection and j, then the offset δ^i_j, is:

$$\delta^i_j = (\delta^i_{ref} + \frac{x_j + y_j}{v_f}). \tag{3.1}$$

The time-space diagrams in Figure 3.2 label the δ^1_5 and δ^2_5 as examples.[3]

Since the network is translationally symmetric with rectangular blocks, both the southbound and westbound links pointing to j are on a shortest path from the reference intersection to j. Therefore, according to (1), a vehicle passing the upstream end of one of these links at the beginning of that intersection's green phase will also arrive at j at the beginning of its green phase. And, since this is true for both orthogonal links and for all j, all southbound and westbound links can be traversed without delay by a free-flow vehicle. This observation is not just true of the network in Figure 3.1, but of all networks with the same translational symmetries. This is good news, since many real-world networks have these symmetries, at least approximately.

Although there is perfect forward progression in the southbound and westbound directions, vehicles still must stop soon after performing a turn maneuver; see for example in

[3] The offsets of intersection 5 are shown after applying modulo C. The sum of the intervals depicted by the dashed and solid dimension lines delineate the offsets prior to applying modulo C, which may make it easier to understand the coordination plan.

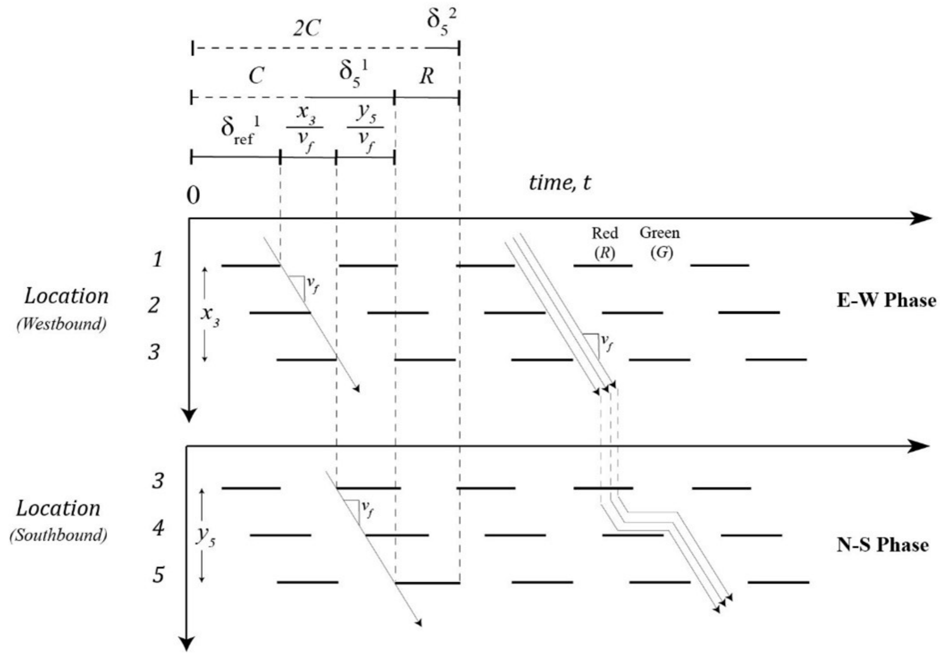


Figure 3.2: Forward Progression Time Space Diagrams

Figure 3.2 how the platoon turning at Intersection 3 must stop at Intersection 4. Therefore, commuters traveling toward a workplace cluster in uncongested conditions may learn to favor paths with only one turn.

3.2 Over-saturated Traffic in the Morning Commute

Backward progression is used when queues spill-over from one street link to the next. To achieve this progression, signals should be coordinated based on a backward wave emanating from the intersection nearest the CoG and traveling to all other intersections. For this reason, offsets are now calculated based on the trip time of a moving observer traveling from j to the reference intersection (Intersection 1 in the present example) at the backward wave speed, -w, and along the shortest path; i.e., using the northbound and eastbound directions.

Offsets at the reference intersection, $\delta^i_{ref}{}'$, again take values between 0 and C, and the prime symbol is used to differentiate the backward progression strategy from the forward one. Offsets at each j^{th} intersection, $\delta^{i\prime}_j$, are set to favor movements focused toward the CoG (FOP). The offset formula is similar to (3.1) but based on the backward wave speed. If the E-W and N-S distances are $x^{\prime}_j$ and $y^{\prime}_j$, respectively, the offset is:

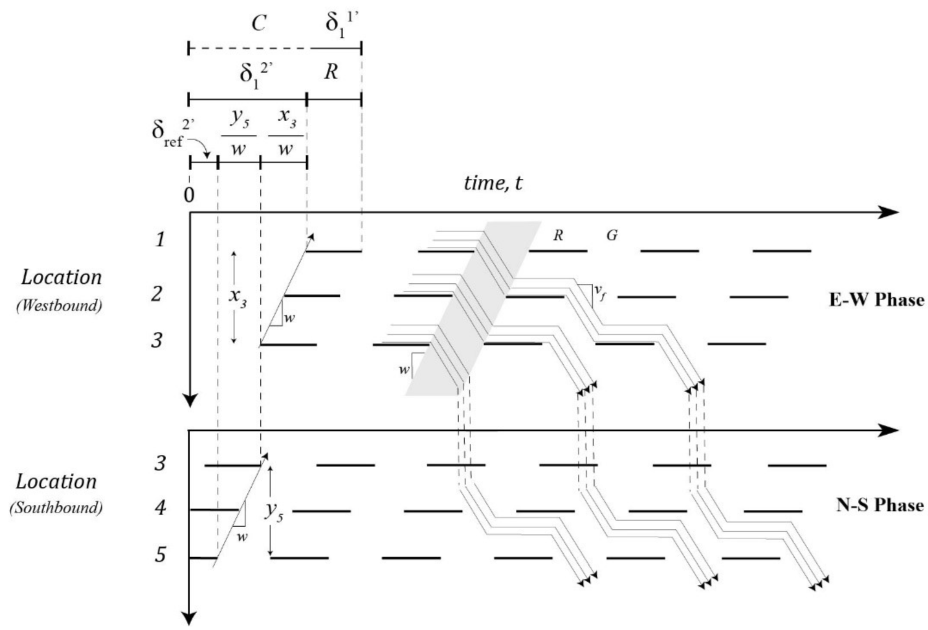


Figure 3.3: Backward Progression Time Space Diagrams

$$\delta_j^{i'} = \delta_{ref}^{i'} - \frac{x_j^{'} + y_j^{'}}{w}. \tag{3.2}$$

The time-space diagrams in Figure 3.3 label the $\delta_5^{1'}$ and $\delta_5^{2'}$ as examples.

As in the previous subsection, backward progression can be achieved for all westbound and southbound links. This is also true of all networks with the symmetries of Figure 3.1.

Inspection of Figure 3.3 also reveals that FOP prevents spill-over queues from impeding vehicle platoons, but can force platoons to stop at red phases as they travel along a single street.[4] Further note how vehicles enter a backward green wave immediately upon turning at Intersection 3, and thus pass through Intersection 4 without stopping. Therefore, in contrast to what happens when traffic is under-saturated, commuters can now shorten their travel times by turning frequently.

[4] The example in Figure 3.3 has platoons stopping at nearly every intersection. More generally, the number of intersections through which platoons can pass without stopping depends upon link lengths, w, and v_f.

3.3 Dynamics of the Morning Rush: Toggling Between Synchronization Modes

FOP can toggle between forward- and backward progression, as street links transition between under- and over-saturated conditions during a rush. To do this, the offsets of all intersections relative to a reference intersection would be simultaneously switched at some decision instant, t_s. An example of this kind of intervention is shown in Figure 3.4(a). It displays phases along an arterial with seven signalized intersections. Periods characterized by forward- and backward progression are labeled “F” and “B”, respectively. The switch is from forward to backward progression. The invariant reference intersection is at Location 1 (upstream). Four of the backward waves are shown by dashed lines. Waves i and ii show the initiations of the green phases.

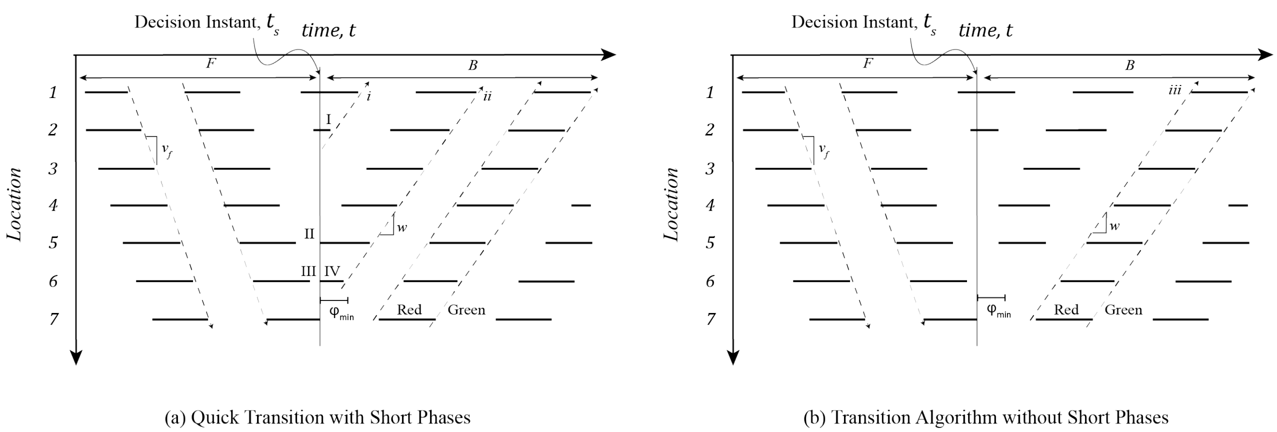


Figure 3.4: Switching Between Coordination Strategies

Note from these waves how the leading edge of a backward-moving wave has reached every intersection within one cycle time of t_s. This is obviously true in general, even if the progression is switched from backward to forward.

Unfortunately, as Figure 3.4(a) shows, the method just described can create phases, such as those labeled I-IV, that fall below a specified minimum, ϕ_{min}.[5]

The algorithm developed in the present work smooths the transitions by ensuring that phases never fall below ϕ_{min} in duration. This is accomplished either by extending the phases that are shorter than ϕ_{min} in duration, or completely eliminating these short phases and joining the bracketing same-color phases into a single long phase. A detailed description of the algorithm's logic is furnished in the appendix. For now, outcomes from the algorithm are

[5] Minimum phase durations are often set to accommodate pedestrian crossings; e.g., see [2].

shown for our seven-signal arterial in Figure 3.4(b). Note that with the transition algorithm, the switch in progression (from forward to backward) is experienced at all intersections no later than $3\phi + \phi_{min}$ from t_s, where ϕ is the original phase duration. Note how all the signals are resynchronized in less than two cycles from t_s. This is highlighted via the backward wave labeled *iii* in the figure.

3.4 The Evening Commute

The ideas presented in Secs 3.1 and 3.2 can be extended to the evening commute by simply reversing coordination directions. Now, coordination is provided in the directions that fan away from the CoG (DOP). Procedurally, this can be achieved by simply changing the signs of the free-flow speed in (3.1) and the backward wave speed in (3.2). The transition algorithm remains the same.

3.5 Generalization for Widely Separated Workplace Clusters

If the workplaces are dispersed into widely separate clusters, it may be of benefit to decompose the network into parts associated with each cluster and treat those parts separately. One way to achieve the decomposition is to simply assign each intersection to the CoG closest to it. The set of intersections assigned to the same CoG will form a simply connected subnetwork with a single cluster of workplaces. All traffic signals within same subnetwork are then coordinated in the manner already described. An illustration will be furnished in Sec 5.3.

3.6 Geometrically Asymmetric Grids

The small grid in Figure 3.5(a) is used to describe how the FOP strategy can be adapted to accommodate geometrically asymmetrical grids. Discussion will assume that all links are under-saturated and progression is forward, but the idea also applies to the over-saturated case. Note from the figure that the center of mono-centric workplaces again resides in the grid's lower left corner. The two E-W (horizontal) street links are of identical length, L_h. In contrast, the curvy N-S link connecting intersections 1 and 3 is longer than its counterpart connecting intersections 2 and 4, i.e., $L_{v1} > L_{v2}$.

Since traveling from Intersection 1 to 4 via Path 1 is of shorter distance than via Path 2, the required starting time of the N-S and E-W green phases at Intersection 4 no longer differ by an effective red time. Hence, it is not possible to synchronize all westbound and southbound links of the grid, as occurred in Secs 3.1 and 3.2. An incompatibility now occurs instead.

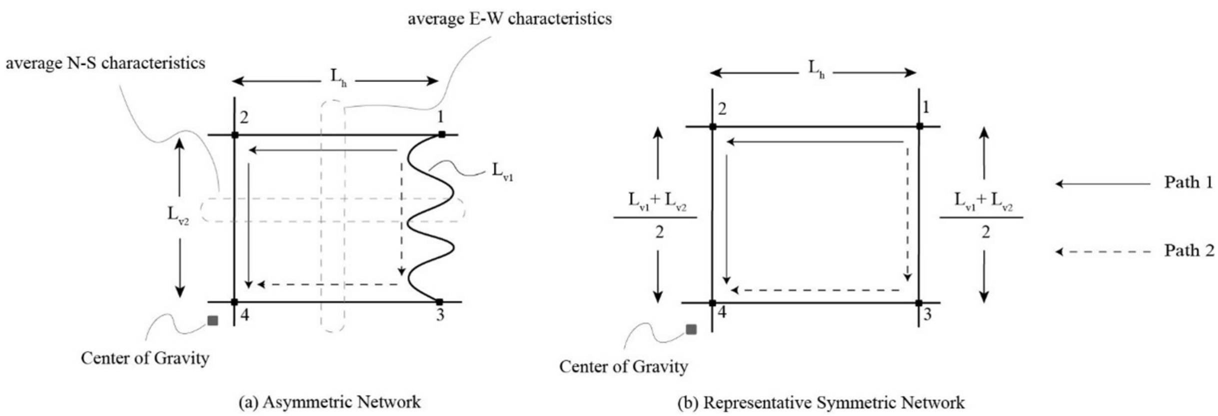


Figure 3.5: Asymmetric and Representative Symmetric Grids

Our coordination plan for these circumstances entails constructing the symmetric version of the grid that most closely resembles the actual, asymmetric one. This construction is achieved by averaging characteristics (i.e., link lengths, free-flow speeds, and backward wave speeds) for all N-S streets along each tier of the network, and for all E-W streets along each network column. The single tier and column for the simple network in Figure 3.5(a) are depicted by the dotted horizontal and vertical swaths, respectively. A grid composed of links that have been averaged in this fashion is used as the homogeneous and symmetric representation of the asymmetric grid, as exemplified in Figure 3.5(b).

Offsets are determined for the symmetric version as described in Sec 3.1 and 3.2, and used for the actual, asymmetric network. The idea will be further explored for a large, distorted grid in sec 5.5.

Chapter 4

Experimental Setup

A description of the grid configuration, traffic demand, and the means used to simulate driver behavior in choosing routes is provided in this chapter.

4.1 Grid Configuration

The strategy was tested using the AIMSUN traffic simulation platform [11]. Simulations were performed for a grid formed by two intersecting sets of 20 parallel, unevenly spaced, streets with two lanes in each travel direction. Link lengths varied randomly from 150m – 250m, commensurate with what is observed in many cities [52]. Intersections were controlled by 2-phase signals, all with a 90s cycle length and 44s of effective green for each phase. The fundamental diagram was the same everywhere with v_f = 50 km/h,[1] w = 18 km/hr, and optimal density, k_0 = 45 veh/km/lane. Figure 4.1 displays the configuration of the grid.

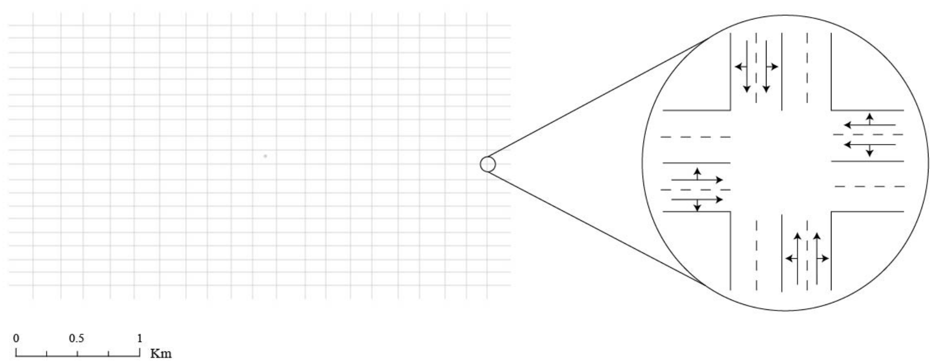


Figure 4.1: 20x20 Grid Network

[1] While all links in the grid had the same speed limit, different vehicles traveled at different speeds as a result of the random acceleration and deceleration characteristics assigned to each vehicle.

4.2 Traffic Demand

Vehicles entered the network at the rates shown by the cumulative vehicle count curve in Figure 4.2. A total of 88,000 vehicles entered the network during a 2-hour rush period, with more than 60% entering during the peak hour. Homes (origins in the morning and destinations in the evening) were uniformly distributed over the entire network. Workplaces were distributed in various ways across distinct experiments.

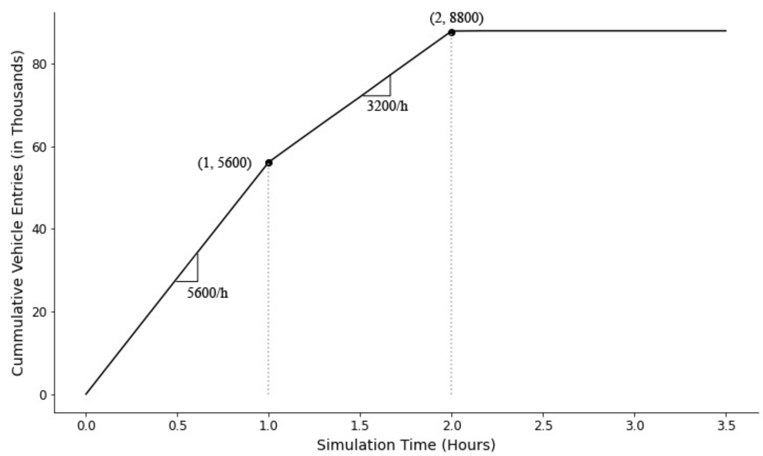


Figure 4.2: Cumulative Vehicle Entries into the Network

4.3 Adaptive Rerouting

Seventy percent of simulated drivers were assigned routes in a static fashion. These drivers faithfully followed the shortest-time paths to their destinations, as determined upon their entries onto the network. The remaining 30% of drivers altered their routes dynamically, based upon travel-time updates that they received every 6 minutes. Update instances were distributed evenly over the population, and updated shortest-time paths were selected from sets of routes obtained as per the model in [53].

Chapter 5

Numerical Analysis

This chapter evaluates the performance of the FOP/DOP strategy under different workplace distributions using the grid and traffic demand presented in Chapter 4. It also tests the performance of the strategy on a geometrically distorted grid.

Section 5.1 studies the morning commute scenario, assuming workplaces are quite concentrated in the center of the grid. For this scenario, three coordination schemes were evaluated: a fixed zero-offset benchmark, a coordination scheme obtained from a state-of-the-practice computer program called SYNCHRO, and the FOP strategy. SYNCHRO turned out to provide modest improvements over the zero-offset benchmark. For this reason, and other difficulties in using it, SYNCHRO is not evaluated in the remaining sections. The remaining sections compare the performance of the FOP/DOP strategy with the zero-offset benchmark. Sections 5.2 and 5.3 report results for dispersed workplace distributions and multi-modal workplace distributions, respectively. Sec 5.4 presents results for the evening commute for our original mono-centric setting of sec 5.1. In Sec 5.5, the performance of FOP is evaluated on a deformed grid. All outcomes to be presented are averages of 10 simulations, each with a distinct random seed.

5.1 Basic Scenario: Morning Commute with Concentrated Workplaces

Workplaces were clustered as a joint Gaussian distribution around the center of the 20x20 translationally symmetric grid. Approximately 40% of the workplaces resided inside the 6x6 sub-network in the grid's center.

FOP was implemented by partitioning the grid into four equally-sized quadrants, as shown in Figure 5.1. All offsets within a quadrant were chosen to favor movements headed toward the CoG at the grid's center. Reference intersections resided at the grid's four corners, one for each quadrant, also as shown in Figure 5.1. Since the centrally-located

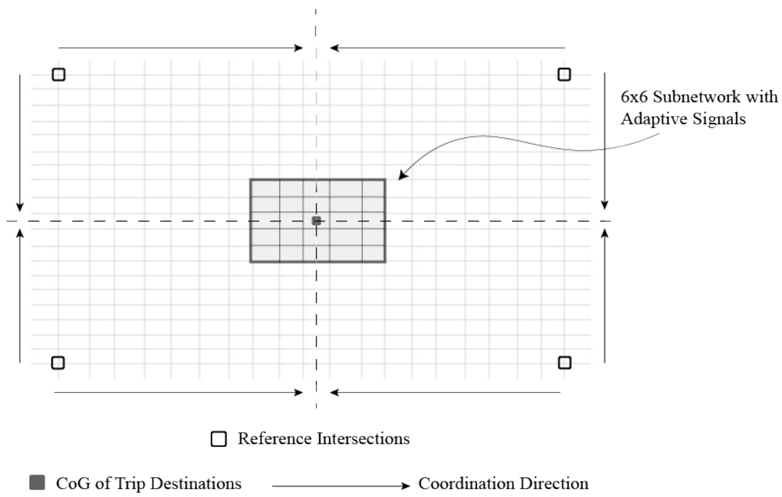


Figure 5.1: Schematic of the Coordination Plan for the 20x20 Grid Network

6x6 sub-network was subject to over-saturation, its signals toggled between forward- and backward progression. Average traffic density in that sub-network was the metric used to determine when toggling was to occur: the threshold was 45 vehicles/km/lane, which is the lowest density yielding capacity flows.[1]

The SYNCHRO-optimized offsets were obtained using a 5-step process diagrammed in Figure 5.2. The process entailed use of the AIMSUN and SYNCHRO computer programs in the following way. (1) Offsets at all intersections were initially set to zero, and resulting vehicle turn counts were obtained via AIMSUN. (2) These turn counts were used as inputs to SYNCRHO, which then varied offsets at all signals iteratively, until vehicle delay was minimized network-wide. (3) These initially-optimized offsets were, in turn, used in AIMSUN to update the turn counts. (4) Updated counts were used in SYNCHRO to re-optimize offsets, which in turn (5) were used in AIMSUN to predict the resulting network performance.

Outcomes are presented in Figure 5.3. The dotted curve presents the grid's time-varying vehicle accumulation resulting from the zero-offset benchmark. Network-wide Vehicle-Hours Traveled (VHT) is the area under the curve: 28,318 (hours). Network-wide Vehicle-Hours of Delay (VHD) due to speeds falling below the free-flow rate, $v_f = 50$ km/h, (not shown in the Figure) was 21,755 hours. Note that the zero-offset benchmark severely congested the grid; average delay per vehicle was around 15 minutes.

[1]This is the average density at which the central district's exit function began to plateau, as observed in AIMSUN simulations. The inspection interval for identifying over-saturated conditions was set at 6 min, an integer multiple of the system's 90s cycle length.

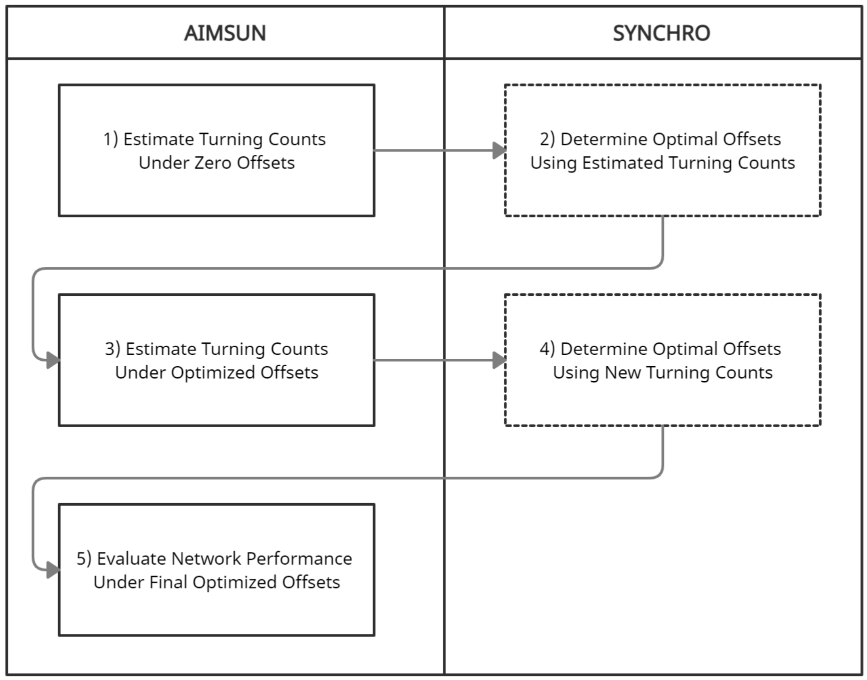


Figure 5.2: Process for Determining Optimal Offsets in SYNCHRO

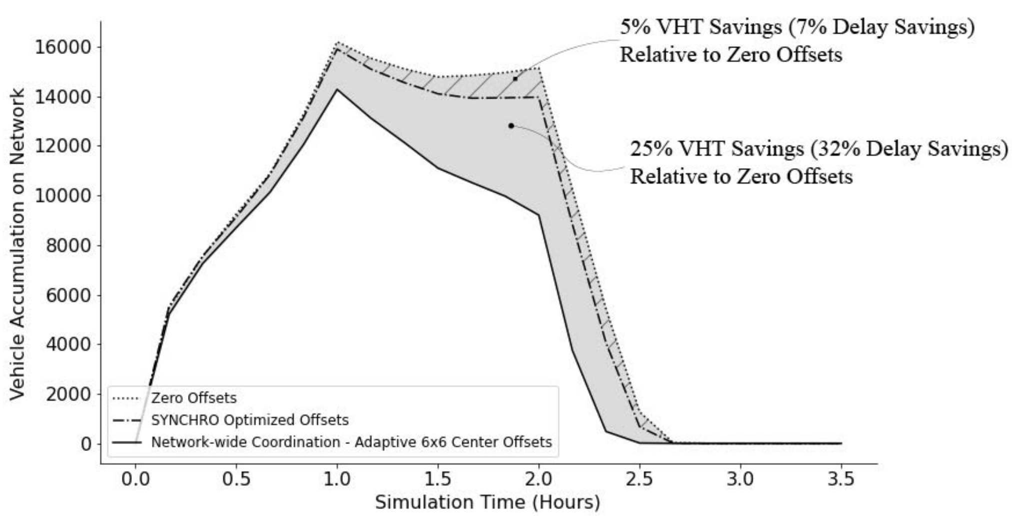


Figure 5.3: Vehicle Accumulation on Network for Different Coordination Strategies

As an interim comparison, the dot-dash curve in Figure 5.3 displays network accumulations under the SYNCHRO-based optimization of offsets. Relative to the zero-offset benchmark, SYNCHRO reduced network-wide VHD by 7%.

The solid curve in Figure 5.3 displays network accumulations when offsets were determined as per the FOP strategy. Note how the strategy is spectacularly effective, reducing VHD by 32% relative to the benchmark (more than 4 times the reductions achieved by SYNCHRO). These reductions are noteworthy since previous proposed strategies outperformed SYNCHRO by only 1% -5% [39].

These outcomes should not be surprising. SYNCHRO and other proposed strategies in the literature optimize offsets based on turning count data at individual intersections, and therefore, adapt the coordination plan to the routes that drivers want to take. By doing so, the strategies miss the opportunity of encouraging efficient routing. In view of this limitation, and other difficulties in using it, SYNCHRO will no longer be used as a benchmark.

5.2 Morning Commute with Dispersed Workplaces

We continue to examine mono-centric cities in the morning rush with the same global demand rates, but now test the strategy in settings where workplaces are more dispersed - with 4 dispersion levels in total. Results are displayed in Figure 5.4.

The figure plots the percent improvement in VHD against the level of dispersion. The leftmost scenario on the horizontal axis corresponds to the base settings described in Sec 5.1. The rightmost scenario corresponds to an unrealistic case where workplaces are uniformly distributed over the entire 20x20 grid.

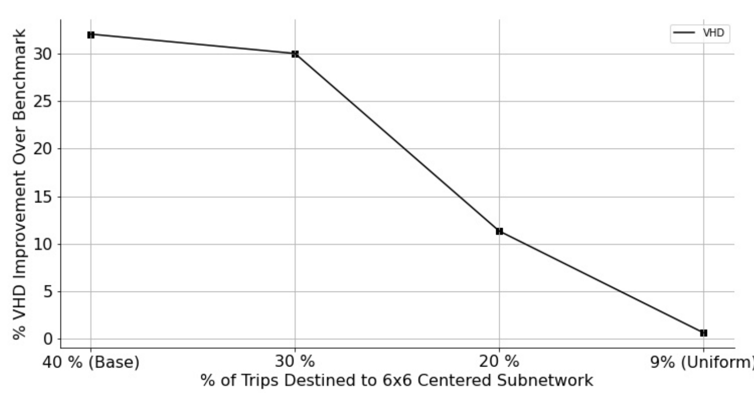


Figure 5.4: VHD Improvement Over Benchmark vs. Dispersion Level

Note how VHD improvements over the benchmark gradually decline as the level of dispersion increases. This is expected and makes sense because as dispersion increases, a smaller number of trips travel towards the CoG of workplaces, and therefore a smaller number of trips benefit from the coordination. Furthermore, higher degrees of dispersion mean less congestion in the center of the network, meaning fewer queue spillovers, and therefore less need for backward progression and the benefits it can bring.

Also, note how the VHD improvement over the benchmark is negligible in the extreme case of uniform workplace distributions. This suggests that the proposed coordination plan works well only when the distribution of workplaces exhibits a certain degree of concentration. Our simulation experiments show that improvements are considerable when more than 20% of workplaces reside in an area covering 10% of the entire grid.

5.3 Morning Commute with Multimodal Clusters of Workplaces

We continue to study the morning commute, with demands as shown in Figure 4.2. Now, however, workplaces are clustered according to the multi-centric pattern shown in Figure 5.5. Note from the figure that the two CoGs separately reside toward the left- and right-hand sides of the network. Each cluster was described by a joint Gaussian distribution. Each node in the figure corresponds to a workplace, and its shading depicts its respective demand; i.e., the rate at which trips end at that node.

As per the description in Sec 3.5, the grid was partitioned into two equally-sized sub-networks, each with its own cluster of workplaces. All signals in a given sub-network were coordinated to favor movements headed toward its cluster's CoG.

For this scenario, simulations were performed using three different coordination schemes: the zero-offset benchmark, the FOP strategy in which the CoG resides at the mean location of all workplaces (i.e., the geometric center of the grid), and the generalized FOP strategy, obtained as per the description in Sec 3.5, with two CoGs. Table 5.1 summarizes the results.

First, note how both FOP strategies dramatically outperform the zero-offset benchmark. Further, note how the FOP strategy with one CoG located in the geometric center of the grid performed as well as – even slightly better than – the FOP strategy with two CoGs. This was not expected, but can be explained by the observation that the multi-modal distribution used for this test congested the center of the grid more than its other parts. This helped the FOP strategy with one CoG work more effectively. The good news is that these results show that the FOP strategy, with one CoG, is robust to the distribution of workplaces. Of course, if the two CoGs of Figure 5.5 were placed further apart, say at opposite corners of the grid, the FOP strategy with two CoGs will likely outperform the FOP strategy with one

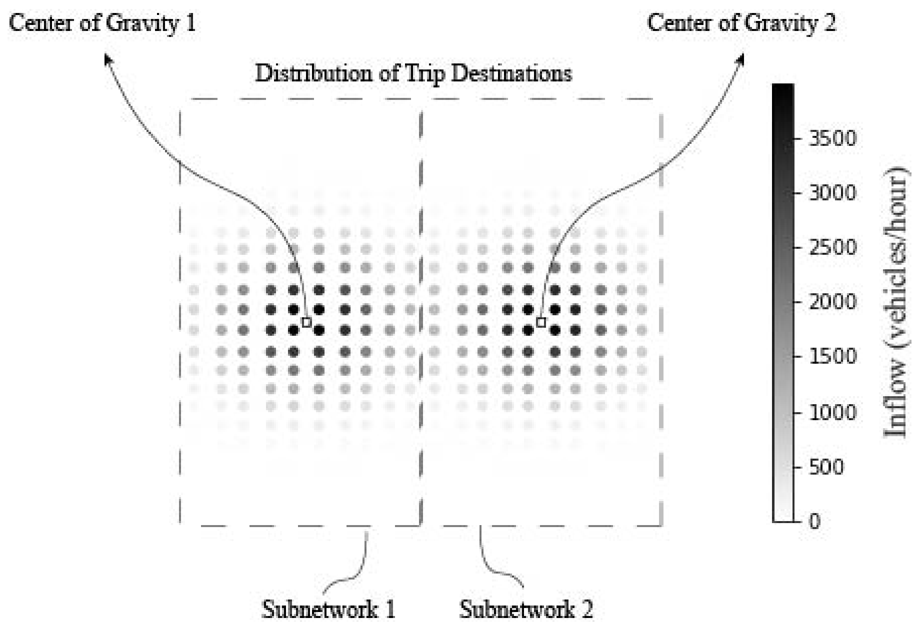


Figure 5.5: Multi-modal Workplace Distribution and Sub-networks

Strategy	VHD	Improvement (%)
Zero Offset	12,964	-
FOP Strategy (one CoG)	9,954	23.22
FOP Strategy (two CoGs)	10,377	19.95

Table 5.1: VHD Improvements Over Benchmark for Morning Commute with Multi-modal Clusters of Workplaces

CoG. To confirm this, we also ran simulations for a scenario where the two CoGs are located at the top left and bottom right corners of the network. In this case, the generalized FOP strategy outperformed the zero offset benchmark by 8%, whereas the FOP strategy with one CoG located at the geometric center of the grid deteriorated network performance by 3% relative to the benchmark. This was expected since the latter strategy synchronizes signals in the directions of lower traffic demand.

5.4 Evening Commute

We now return to the original mono-centric setting of Sec 5.1. We continue to use the demands shown in Figure 4.2, but now reverse the origin-destination pattern to resemble an evening commute. Outbound trips thus originate as per the Gaussian distribution originally used for destinations, and destinations are now uniformly distributed over the entire network. Traffic signals in each quadrant were coordinated to favor movements heading away from the CoG. Signals residing inside the 8x8 sub-network at the grid's center toggled between forward- and backward progression, as its links transitioned between under- and over-saturated conditions. The size of this sub-network (8x8) was optimized using AIMSUN in trial-and-error fashion.

Although the origin-destination pattern of the evening commute produced less congestion than in the morning rush, the DOP strategy still outperformed the zero-offset benchmark, just as well as in the morning rush in percentage terms. This time around, the strategy reduced VHD by 33% relative to the benchmark.

5.5 Geometrically Irregular Grids

We again examine the morning commute for the mono-centric city in Sec 5.1. Now, however, the network geometry was distorted from the ideal as explained below.

The horizontal streets of the grid were slanted at alternating angles of $\pm 0.725°$ from the horizontal. Furthermore, to prevent excessively short vertical street lengths, the average separation between each pair of horizontal streets was increased by 50m. These modifications resulted in a network in which the vertical links on the E and W end of each row differ in length by a large 100m. The complete network is shown to scale in Figure 5.6.

All other features of the network (i.e., number of street lanes, cycle length and green splits) were as before. The time-varying demand in Figure 4.2 was used to load and congest the network.

A symmetric version of this network was obtained by averaging link features, as described in Sec 3.6. Offsets were synchronized to suit this version. Even under the extremely distorted grid presently considered, the strategy reduced VHD by 13% relative to the benchmark.

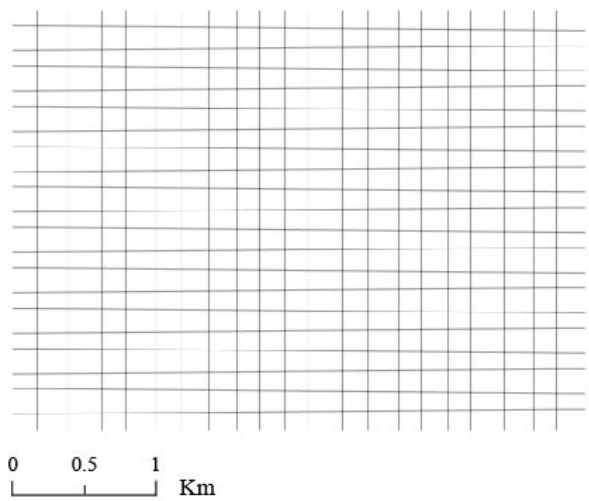


Figure 5.6: Distorted Grid

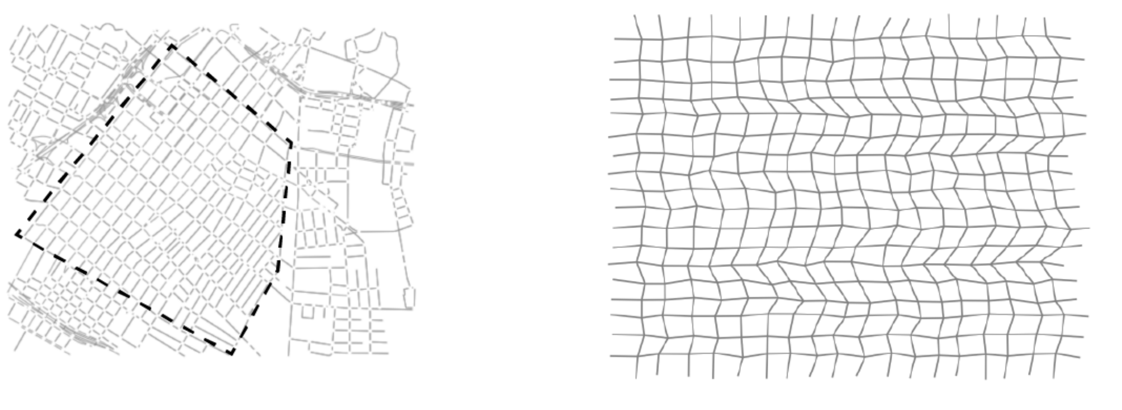
Chapter 6

Case Study: Downtown Los Angeles

This chapter evaluates the performance of the proposed strategy on a grid that roughly resembles downtown Los Angeles (California) in terms of variations in block lengths, speed limits, and traffic congestion levels. In the absence of more detailed information, we assume that residences and workplaces are distributed in an identical fashion to the morning commute scenario presented in Sec 5.1.

6.1 Block Lengths

A digital representation of downtown Los Angeles' grid was obtained via Open Streets Map [8] and is shown in Figure 6.1(a). Also shown in the figure is a sub-grid enclosed by a dashed polygon. This sub-grid was used for analysis in the case study. The standard deviation of the sub-grid's block length was 20 meters.



(a) Sub-grid of Downtown Los Angeles

(b) Distorted Grid Resembling Downtown Los Angeles

Figure 6.1: Block Length Variation in Downtown Los Angeles

To construct a grid with similar variations in block length, each link in the original symmetric grid (used in Secs 5.1 - 5.4) was extended/shortened by a random variable that is uniformly distributed with a mean of zero and a standard deviation of 20 meters. This adjustment resulted in the distorted, Los Angeles-like grid shown in Figure 6.1(b).[1]

6.2 Speed Limits

The digital representation of the sub-grid also contained information pertaining to the speed limit of each of its links. The discrete distribution of speed limits was as follows: roughly 54% of links exhibited a speed limit of 25 mph (40 kph); 11% exhibited a speed limit of 30 mph (48 kph); and 35% exhibited a speed limit of 35 mph (55 kph).

From the above distribution, 40 speed limits were sampled using the discrete inverse transform method (see [50] pp. 639 - 641 for more details). Each generated speed limit was assigned to all the streets of a particular arterial in the Los Angeles-like grid. This allowed different arterials in the grid to exhibit different speed limits, but all the street links along a particular arterial had the same limit.

6.3 Traffic Demand

The time-varying demand in Figure 4.2 was used to load and congest the network. This demand produced a congestion period of around 2 hours, commensurate with what is reported for downtown Los Angeles [31].

6.4 FOP Coordination

A symmetric version of the grid shown in Figure 6.1(b) was obtained by averaging link features as per the procedure described in Sec 3.6. Offsets were synchronized to suit this version, and were then applied to the Los Angeles-like grid in Figure 6.1(b).

At the beginning of every simulation experiment, all signals on the grid were coordinated in a forward fashion in the directions pointing towards the CoG of workplaces (located at the geometric center of the grid), since traffic conditions were initially under-saturated. When traffic conditions became over-saturated, signals residing inside the 6x6 centered sub-network were coordinated in a backward fashion in the directions pointing away from the

[1] Note that the original Los Angeles grid from Open Streets Map could not be directly imported into AIMSUN. So, using the actual grid of downtown Los Angeles would have required us to manually build the grid in AIMSUN, which would have consumed a significant amount of time. To circumvent this issue, we generated a script that allows us to modify block lengths and speed limits of grids that already exist in AIMSUN and then used that script to construct a grid that closely resembles downtown Los Angeles.

CoG. Backward progression was activated in the sub-network whenever its average traffic density exceeded 45 vehs/km/lane.

Close inspection of the experiments revealed that in all 10 distinct simulation runs, backward progression in the 6x6 centered sub-network was activated sometime between 20 - 30 minutes into the simulation and remained active until sometime between 1 hour and 20 minutes - 1 hour and 40 minutes into the simulation. The switch from one synchronization mode to another was thus only triggered twice.

6.5 Outcomes

Outcomes were favorable. The FOP strategy reduced network-wide VHD by 14% relative to the zero-offset benchmark. Note that although this improvement is relatively close to the 13% improvement reported for the severely distorted grid of Sec 5.5, these should not be compared against each other. This is mainly because we introduced variations in speed limits to the Los Angeles-like grid, which made it more difficult to reduce VHD. To illustrate, we also ran simulations for the Los Angeles-like grid but with a uniform speed limit of 50 kph across the entire grid. VHD improvements in this latter case were as high as 22%.

We argue that the 14% improvement in VHD in a realistic setting is quite impressive. Recall from Sec 5.1 that SYNCHRO improved VHD by only 7% relative to the benchmark when tested on an idealized grid with identical demand conditions. This 7% improvement by SYNCHRO would almost surely be smaller if tested on the Los Angeles-like grid. So, we can infer that even under realistic settings, the FOP strategy is likely to outperform SYNCHRO by a wide margin.

These results are enlightening and suggest that the proposed strategy can reduce congestion for many real cities around the world, when these cities exhibit fairly concentrated workplace distributions.

Chapter 7

Conclusion

This chapter highlights the main findings of the dissertation and discusses potential future research avenues.

7.1 Dissertation Findings

It is well known both in the literature and in practice that synchronizing signals on grid networks is a challenging problem. This is mainly because the offsets required to synchronize signals in one-direction of travel often do not suit the opposing or the orthogonal directions.

Although different methods have been proposed in the literature to overcome this challenge and coordinate signals on grid networks, these methods generally (i) adapt the signals to the routes that drivers want to take and (ii) assume steady-state traffic conditions. The FOP/DOP strategy proposed in this dissertation is inherently different. First, it is completely independent of disaggregate (individual intersection) traffic conditions. And, it can be applied to grids characterized by over-saturated traffic with temporary queue spill overs, as commonly occur in real settings.

The FOP/DOP strategy recognizes that signals on symmetric networks can be perfectly synchronized in two orthogonal directions. Hence, the strategy synchronizes every street block of the network in a centripetal direction during the morning rush and in a centrifugal direction in the evening. This way the strategy forces traffic to adapt to the controls, which are set to facilitate smooth flow, rather than adapt the control to traffic (as done in the literature). While the strategy was initially developed for symmetric grids, it was adapted to serve asymmetric grid arrangements as well.

FOP/DOP is also dynamic and suitable for non-steady-state traffic conditions. Signals are synchronized to the free-flow motion of vehicle platoons when traffic is under-saturated, and to backward waves when links are filled with queues. The switch from one synchronization mode to another is done smoothly - thanks to the transition algorithm developed in this dissertation.

The strategy was evaluated via simulations of 20x20 signalized grids operating in non-steady-state traffic conditions, typical of rush periods. The strategy dramatically outperformed the fixed-zero offset strategy commonly recommended for congested networks [10], and the state-of-the-practice computer program SYNCHRO, in a morning commute scenario with a mono-centric distribution of workplaces. In fact, the strategy reduced delays beyond what could be achieved by SYNCHRO by more than 25%. This is to be compared with other strategies in the literature which typically outperform SYNCHRO by 5% or less.

The favorable performance of the strategy over the zero-offset benchmark spanned a range of conditions including: different congestion levels, concentrated, dispersed and poly-clustered workplaces, as well as the traffic patterns of the evening commute. However, the strategy did not improve things when workplaces were uniformly distributed across the grid. This suggests that the strategy should be implemented only when there exists some degree workplace concentration in the grid.

The strategy continued to perform well, with double-digit improvements in VHD, when the grid geometry was severely distorted. It also performed well when tested on a grid that resembles downtown Los Angeles in terms of block length and speed limit variations, and traffic congestion levels.

7.2 Future Work

In this section, we present some future research avenues that may help advance this work by making the strategy more general and more broadly applicable to other roadway networks.

Partially Signalized Grids

The FOP/DOP strategy assumes that all intersections in a grid are signalized, which is uncommon in the real world. The strategy can still be applied to partially signalized grids but some modifications may be needed to account for delays experienced at unsignalized intersections. What should these modifications look like and how will it affect the performance of the FOP/DOP strategy?

Network Structure

In this dissertation, we only considered grid networks with four-legged intersections. Real street networks, however, can have intersections with more than four approaches. Is it feasible to identify an underlying grid by ignoring a few streets and links? Could the strategy be then applied to the underlying grid and by doing so improve overall network performance?

Complex Signal Timings

We also assumed that all signals on the grid have only two phases. Another interesting research avenue might be to explore what modifications are needed when some signals also have one or more protected left-turn phases. How does that impact the performance of the strategy?

Transition Between Synchronization Modes

The switch between the two synchronization modes (forward- and backward progression) was implemented across all signals residing in the central district region based on the average traffic density in that region. One could explore the benefits of switching between the two modes on a link-by-link basis based on localized traffic information. Perhaps this may negate the benefit of creating efficient routes and inducing the drivers to take these routes, as the current strategy seems to do.

Adaptive Rerouting and Field Tests

The results of any network simulation depend on the assumed routing behavior of drivers. Although we tried to be as realistic as possible in our simulations, drivers are idiosyncratic and difficult to model. For this reason, it would be valuable to test the robustness of the strategy against different routing behaviors. Preliminary experiments revealed that when drivers update their routes very frequently (every 2 minutes), activating backward progression in the congested central district may not be beneficial. But then again, we are not confident about how realistic this aggressive driving behavior is. We believe that if the simulation results turn out to be very sensitive to the assumed routing behavior, then the ultimate answer lies with field tests. Perhaps a static version of the strategy can be tested first, since it is simpler to implement in the real world.

Appendix A

Switching Synchronization

We start with our initial approach for switching signals between forward and backward progression, and show by example how this can produce phases of unacceptably short durations. The algorithm for correcting the problem is presented in Sec A.2, and is applied in Sec A.3 using our initial example.

Phases will be numbered in the following simple fashion to aid in our discussion. The two phases that bracket a decision instant, t_s, are numbered 1 and 2. These phases can be non-distinct (i.e., both are either red or green), or distinct (one is red and the other green). Phases 3 and 4 follow in sequence.

A.1 Initial Switch Scheme and Its Problem

As a first iteration, the scheme initiates a green phase at time $t_s + \delta_j^{i'}$, where $\delta_j^{i'}$ is the offset for direction i at intersection j. We assume here, without loss of generality, that progression is switching from forward to backward at t_s.

To see why this simple scheme can produce unacceptably short phases, consider a signal with two phases, each of duration ϕ. Suppose that the phase sequencing for direction i is as shown in Figure A.1. Note the desired time for initiating the green. If $\delta_j^{i\prime} \leq \phi$, the scheme would have initiated a red phase at t_s, which would have continued for duration $\delta_j^{i'}$. Since in Figure A.1 the $\delta_j^{i'} > \phi$, a green phase is initiated at t_s instead, and is continued for duration $\delta_j^{i'}$ - ϕ. This is followed by a red phase of duration ϕ.

The latter outcome is shown in Figure A.2. The duration of phase 2 (displayed immediately after t_s) is denoted ${\tau_{j,2}}^{i\prime}$, and would be:

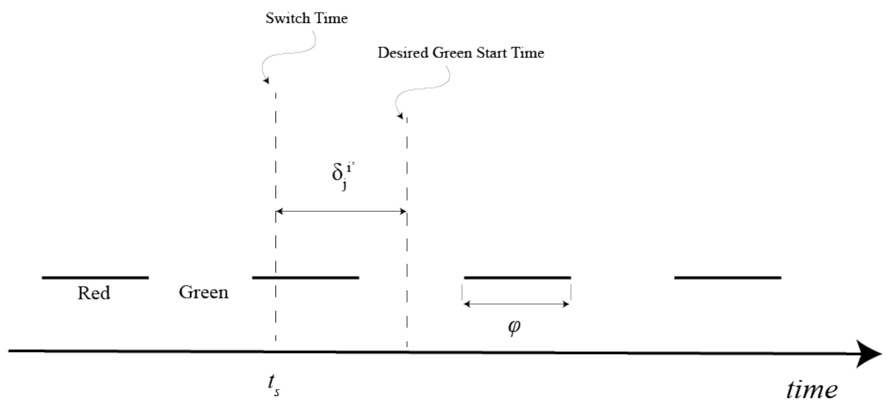


Figure A.1: Intersection j's Ordinary Phase Sequences for Direction i

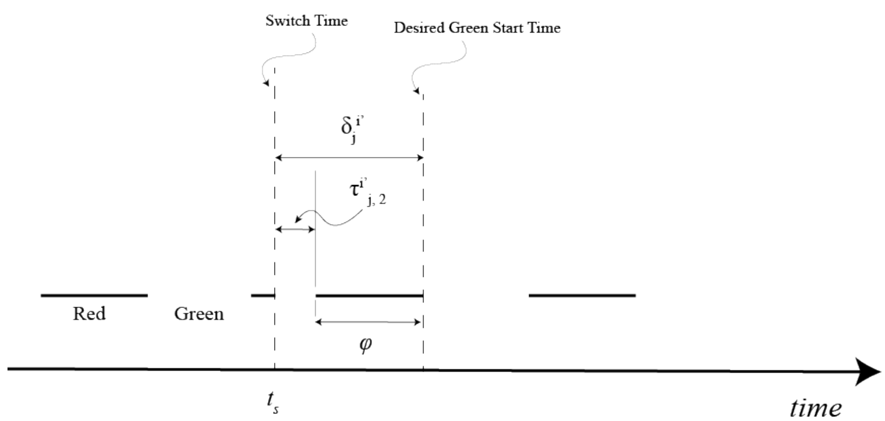


Figure A.2: Intersection j's Ordinary Phase Sequences for Direction i Absent Transition Algorithm

$$\tau_{j,2}^{i'} = \begin{cases} \delta_j^{i'}, & \delta_j^{i'} \leq \phi \\ \delta_j^{i'} - \phi, & \delta_j^{i'} > \phi \end{cases} \quad \text{(A.1)}$$

As a result of (A.1), phases 1 or 2 bracketing t_s may fall below the specified minimum duration, ϕ_{min}. We will assume this to be the case for both phases.

A.2 Transition Algorithm

Our algorithm modifies phases whenever one or both bracketing phases (1 and 2) would otherwise be smaller than ϕ_{min}. It does so to achieve a two-fold objective that: (i) ensures that an intersection's offsets synchronize with its neighbors as soon after t_s as possible; subject to the constraint that (*ii*) all signal phases have durations not less than ϕ_{min}.

As a first attempt, the algorithm appropriates time from phase 3 and reassigns that time to whichever bracketing phase(s) would otherwise be less than ϕ_{min}. If this reapportionment would leave phase 3 with a duration less than ϕ_{min}, the algorithm instead prolongs one or both bracketing phases (and eliminates others) in such ways as to achieve its two-fold objective. As noted in Sec 3.3, an intersection is in this way re-synchronized with the entire network no later than $t_s + \phi_{min} + 3\phi$; i.e., in less than 2 cycle lengths.

Details are shown via the flow chart in Figure A.3. Note how the algorithm first tries to reappropriate either ϕ_{min} or $2\phi_{min}$ from phase 3, depending upon whether one or both of the bracketing phases are less than ϕ_{min}.

If phase 3's duration would fall below ϕ_{min} as a result, the algorithm instead prolongs one or both bracketing phases, depending upon whether those phases are distinct. If they are not, the two phases are prolonged by duration 2ϕ. Phase 3 is eliminated and the prolonged bracketed phases blend together with (non-distinct) phase 4. If the two bracketing phases are distinct, phase 1 is prolonged by ${\tau^i_{j,2}}' + \phi$. Phase 2 is eliminated, such that (non-distinct) phases 1 and 3 are joined together as a single (long) phase.

We now continue with the example introduced in Sec A.1, which will follow the path shown with bold arrows in Figure A.3. Returning to Figure A.2, recall that phase 1 (the short red) and phase 2 (the short green) are distinct. Since we suppose that their durations are each shorter than ϕ_{min}, the algorithm: first appropriates $2\phi_{min}$ from phase 3 and allocates that time equally to the bracketing phases; see Figure A.4. We will suppose that this reapportionment would cause phase 3's duration to fall below ϕ_{min}. For this reason, the algorithm reinstates the condition shown in Figure A-2. It then prolongs phase 1 by ${\tau^i_{j,2}}' + \phi$ and eliminates phase 2; see Figure A-5. The transition is complete, as Fig. A-5 makes clear.

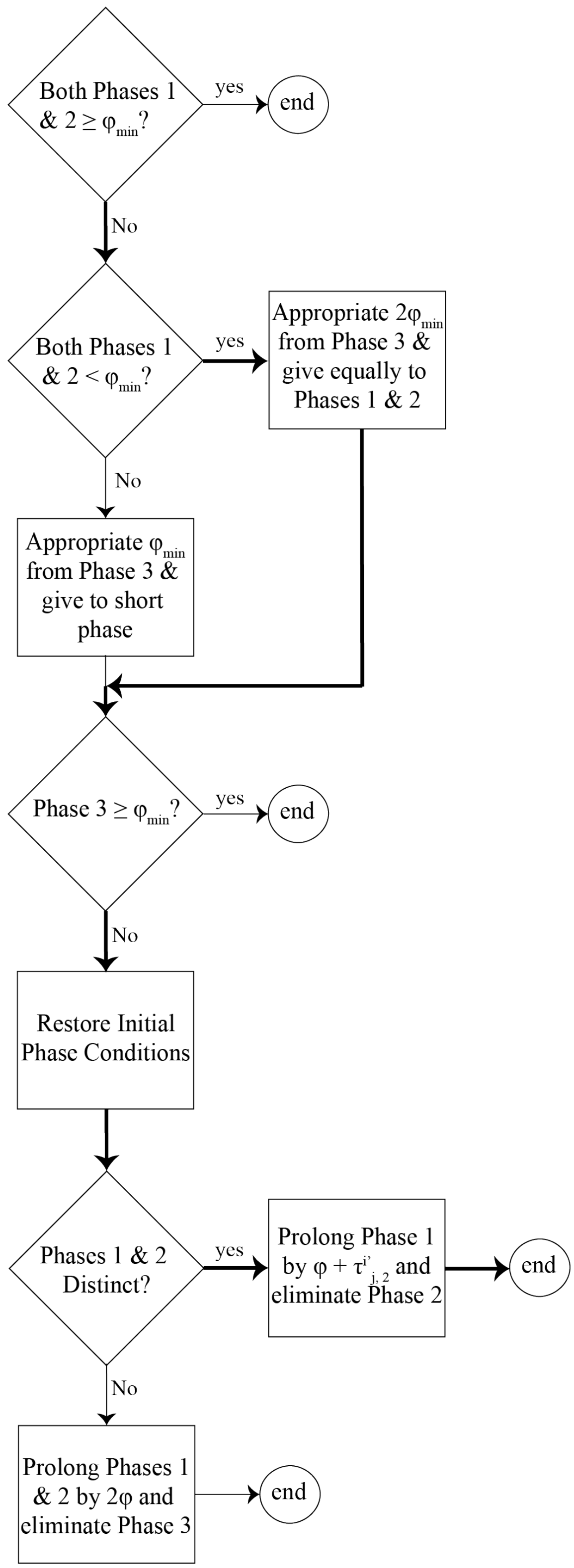


Figure A.3: Flowchart of Algorithm's Logic

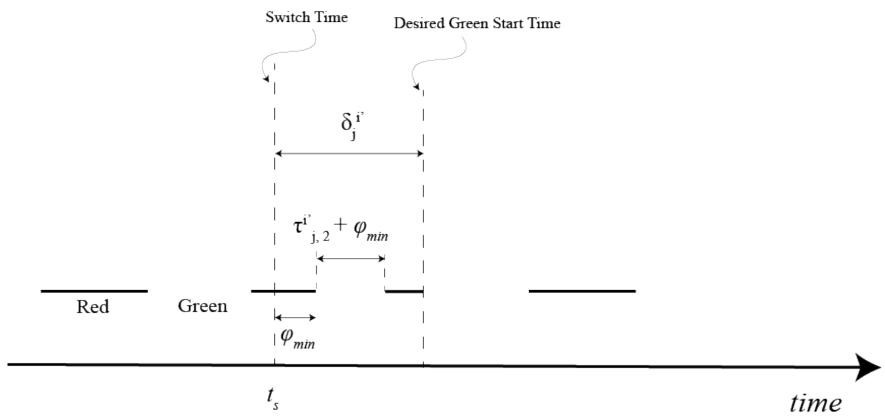


Figure A.4: Intersection j's Ordinary Phase Sequences for Direction i with Transition Algorithm - First Step

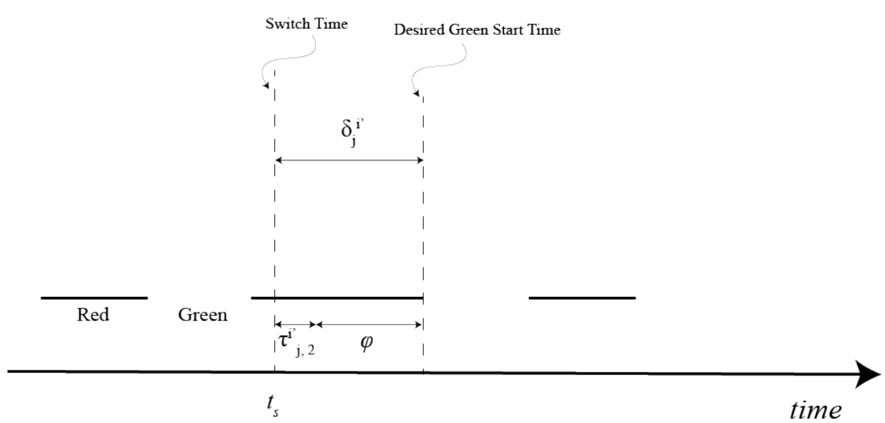


Figure A.5: Intersection j's Ordinary Phase Sequences for Direction i with Transition Algorithm - Second Step

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