

MASTER THESIS

Optimization of coordinated traffic signal intersections

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Chapter 1

Background

1.1 Introduction and motivation

The purpose of traffic optimization is to address the task of improving the transportation of each entity in a traffic network from an origin to a destination, based on a set of optimization criteria. Overall the root of any issue has to do with traffic congestions due to demands exceeding the capacity of the traffic network. As of today this presents an increasing problem due to an also increasing number of vehicles, especially motorized ones.

Traffic signals at intersections is one of the most widespread means of controlling traffic. Very large cities may contain hundreds to thousands of intersections requiring traffic signals. Consequently, they are closely grouped together such that the improvement of a single signal may be at the expense of a large neighbourhood of its adjacent signals or even the entire traffic network of the city. Therefore, it is necessary to consider multiple signals simultaneously to allow coordination.

1.2 Terminology

We introduce the technical terms, notions and definitions necessary to the subject of this thesis.

A land based *traffic network* consists of roads on which traffic takes place. Any road consists of a number of traffic lanes. A *traffic lane* is a segment of the road having an appropriately width in order to fit only a single line of vehicles or bicycles, therefore it may serve traffic in a single specific direction only. The most common types of roads, in increasing order of capacity (more lanes and higher speed limits), are *streets*, *collector roads*, *arterial roads* and *free-ways*. A *traffic junction* is any point in the network at which at least two roads meet. Depending on the network topology the roads may meet at different levels of elevation. There are two levels of elevation that characterize the type of junction.

1. An *interchange* is a *grade separated* (over- and undergrade) junction. They involve roads passing below and over each other by means of tunnels and bridges. The exploitation of three-dimensional road networks gives rise to several types of interchanges. A common functionality is to allow an elevated crossover between an arterial road (upper) and free-way (below), where vehicles may switch between both of them using *slip roads*. The *diamond interchange* exactly achieves this. The main purpose is to allow a high speed continuous traffic flow without traffic signals. In large cities complex interchanges may even allow an elevated crossover of between two free-ways. The multi-level stack interchange, Figure 1.1, achieves this by means of several roads splitting and merging together.



FIGURE 1.1: A multi-level stack interchange located in Shanghai, China.

2. An *intersection* is an *at-grade* junction. In most situations two roads meet at a common point forming either a three-way (T junction) or four-way intersection. Naturally the traffic flow of such roads is at conflict and requires traffic signals to avoid collisions. Although interchanges eliminate several needs for traffic signals they are comparatively very expensive in terms of instalment and maintenance with respect to intersections.

A *roundabout* is an alternative means of at-grade junction. The structure imposes a one-way direction, such that one must always give way to traffic approaching from that direction before entering the roundabout. Generally, no traffic signals are required but exceptions may exist. A general downside is the spatial requirements and low speeds (although the latter decreases the risks of severe accidents from occurring).

In summary interchanges and roundabouts are quite similar in various aspects but it is very difficult to alter their functionalities compared to traffic signals that require mostly software regulations only.

A *traffic signal* is a signalized device governing the traffic flow through an intersection by means of assigning the green light to different lanes. An *upstream* (*downstream*) lane leads traffic towards (away from) an intersection, thus a traffic signal must control upstream lanes in terms of vehicles, bicycles and pedestrians¹. The road segment leading towards an intersection is commonly widened to include additional vehicle upstream lanes especially in terms of exclusive left and/or right turns. In addition a reverse procedure is usually adopted for the downstream lanes, i.e., at least two lanes merge together thus narrowing the road correspondingly.

¹Pedestrian lanes are usually two-way directed with both directions obeying the same signal.

Traffic signals utilize different kinds of agreed color codes in order to control each type of upstream lane. The following is a widely used three-color code specifically for vehicle upstream lanes that operates with respect to a well-known four-step cyclic *display sequence*.

1. The red light displayed on its own forbids vehicles to proceed.
2. The red and yellow light displayed simultaneously (pre-green) hint that the signal is about to change to the green light. The step prepares waiting vehicles, in particular the leading one, to accelerate as to minimize any wasted green light.
3. The green light (*right of way*) displayed on its own allows the vehicles to proceed if safe to do so (an elaborated explanation of safe passage is given later on).
4. The yellow light displayed on its own alerts that the signal is about to change to the red light. The general rule suggests drivers to stop before the intersection stop line if safe to do so (in the presence of sufficient brake length and no close-up trailing vehicles), else they may proceed through. The *decision zone* refers to the time interval in which a driver is much unsure whether to proceed or stop which may cause a dangerous situations.

Each display has a duration denoted R, O, G, Y , respectively. A single iteration of every display is referred to as a *cycle*. Therefore, the above durations may be expressed either as a ratio or time interval of a cycle. This type of display sequence usually also handles bicycle upstream lanes. For pedestrians, signals usually switch between displaying either the red or green light on its own in which case the durations of step 1. and 3. are appropriately extended.

Before digging into the terminology of traffic signal optimization it should be noted that a traffic signal is an essential part of a traffic control system.

1.2.1 Traffic control system

A *traffic control system* (TCS) refers to any management tool attempting to improve traffic with respect to one or several optimization criteria of a traffic network. It is comprised of numerous components and considerations that will be described below with respect to traffic signals.

- An *operational environment* is any relevant physical attribute of an intersection. These include the number of intersecting roads (e.g. T or fourway junction), the number of upstream and downstream lanes, the number of (and locations of) available traffic signals and its geometric properties (an uphill intersection may lead to reduced eyesight between opposing movements).
- A *traffic user* is any traffic entity such as passenger cars, transit buses, bicycles and pedestrians that is affected by the outcome of traffic signals. Therefore, it is important to consider various *traffic priorities* under prevailing conditions e.g. some types of entities should receive extended or shortened green light durations than others.
- An *operational objective* is an optimization criteria to be served by the TCS. They may vary depending on the desired outcomes of those that are responsible for the TCS e.g. various municipalities. Some major objectives with respect to traffic signals include vehicle mobility and environmental impact.

- A *performance measure* is a quantification of the degree to which the operational objectives are fulfilled, thus it is what concludes whether or not a TCS is regarded optimal, or produces an approximate solution only. Corresponding examples for vehicle mobility and environmental impacts might be the maximization of vehicle throughput and minimization of vehicle stops, respectively.
- A *control measure* is the physical/digital infrastructure delivering/executing the instructions determined by a control strategy described below. Traffic signals are some of the most common control measures because they are flexible in terms of output, as they need only to know what to display and when.
- A *control strategy* determines the traffic signal instructions based on the following characteristics. The first two describe if the signal operates alone or as part of a system.
 - An *isolated* control strategy decides on the instructions of a single signal. This leads to a local optimization of the traffic network, however, possibly at the expense of any neighbouring traffic, as the instructions may be out of sync to other nearby signals.
 - A *coordinated* control strategy decides on the instructions of several signals as to sync the timing between all signals. The coordination allows to improve on a greater subset of the traffic network.

In addition, the characterization may be based on whether or not the proposed instructions are reconsidered.

- A *fixed-time* control strategy determines the instructions based on traffic data obtained by detectors (e.g. induction loops and cameras) during some time horizon. For instance, given historical data of a month one may examine the distribution of traffic demands and propose corresponding instructions, but it is assumed that the distribution in the future does not change (at least significantly). This is also referred to as a *static* control strategy, i.e., once the optimal instructions have been found they are never re-established on any periodically basis. As a result, any subsequent observations by the traffic detectors are rendered redundant. The major flaw is the lack of considering changing traffic conditions, as the actual optimal instructions may change accordingly. This type of control strategy imposes little to no time constraints to the running time (efficiency) of any devoted optimization algorithm as the instructions are decided a long time in advance prior to be deployed. Therefore, additional attention may be drawn in developing effective algorithms, i.e., they produce the exact intended/expected results.
- A *traffic-responsive* control strategy regularly examines real-time measurements of traffic demands as to adjust the instructions in an adaptive manner destined to serve the current traffic conditions more accurately. This is also known as a *dynamic* control strategy. This type of strategy, compared to the static approach, inherently imposes tighter time constraints on the algorithm running time, as the adjustments usually are required within a short amount of time. Consequently, efficiency is often prioritized in terms of heuristics producing approximately optimal instructions only, however, in a reasonable amount of time. The degree of tighter time constraints depends on how the real-time measurements are to be utilized.

In this sense one may distinguish between applying one of the following two approaches.

- * A *reactive* approach focuses on eliminating problems after they have happened. In the context of a control strategy the instructions should be adjusted almost instantaneously in response to current changing demands. This, however, might only resolve the issues for a very short amount of time, thus to maintain accurate handling of traffic demands a reactive approach must be applied frequently at a high rate with each reactive decision to be determined within an equally short amount of time.
- * A *proactive* approach utilizes predictions to eliminate problems prior to their occurrence. The control strategy assumes that future demands for an extended period of time can be accurately predicted based on historical and current demands, and the instructions need to be determined for that entire period also. Although this is a computationally intensive task, it may successfully prevent certain traffic issues from happening, that would have appeared otherwise in a reactive approach.

These four control strategies work in pairs resulting in four different types of control strategies. In general, a coordinated traffic-responsive strategy is superior in terms of flexibility and potential improvements at the expense of high complexity, whereas the opposite holds for an isolated fixed-time strategy. Nonetheless, an isolated fixed-time strategy often proves sufficient thus encouraging the consideration of traffic-responsive strategies only, if the possibilities of less complicated approaches have been fully explored.

- An *evaluation strategy* carries out the assessment of the TCS by determining the performance measures that determine the degree of optimality of the TCS with respect to the operational objectives. Ideally, the performance measures are derived analytically given a complete knowledge of traffic conditions and traffic signal instructions at any point in time. In reality, this may be feasible for simple cases, i.e., a single traffic signal in conjunction with assumed simplified constant traffic conditions, however, the complexity significantly increases in dealing with coordinated signals such that the performance measures must be estimated by means of traffic simulations. There are two main approaches to traffic simulation.
 1. A *microscopic* simulation considers each traffic entity individually by examining microscopic properties like its position and velocity. This allows accurate estimation of a variety of quantitative measurements such as the number of vehicle stops or time spent in the network.
 2. A *macroscopic* simulation considers traffic as a single entity in terms of a fluid stream, which is characterized by macroscopic properties such as average speed or density. This makes it easier to estimate measurements such as the throughput of vehicles by a single number, however, less accurate than the microscopic model due to the reliance on averages only.

In both methodologies the key point is to derive/estimate similar performance measures with respect to a non-optimized equivalent scenario for comparison, in order to quantify the degree of optimality. If the improvements turn out significant then one should consider implementing the solution in real life.

1.2.2 Traffic signal optimization

first definitions and then describe what to think about when determining these defined terms

maybe use alternatively itemized for the second above part
in phase specification we are determining the composition of phases
remove yellow trap description in footnote

We present the definitions necessary for the optimization of traffic signals.

- A *movement* is the smallest set of upstream lanes that is distinguishable by a set of similar physical signals, such that each upstream lane obey the exact same display sequence of those signals. Therefore the number of movements does not necessarily equal the number of upstream lanes.
- A *phase* is any non-empty subset of movements such that the signals of each movement cycles through a joint display sequence.
- The *split* is the green duration, G , of a cycle but one may also include in the split the yellow duration, Y .
- The *cycle length*, c , is the time span of a cycle. Note that $c = R + O + G + Y$.
- An *offset* is the relative timings among the display sequences of coordinated intersections. It is defined only when dealing with a coordinated control strategy.

There are several considerations that need be taken into account regarding the above definitions.

- A *phase specification* is the set of decided compositions of phases, given a set of movements, that must be served at an intersection. The phase specification must be at least a minimum set cover of the set of movements.

An apparent issue is that the movements composing a phase may conflict with each other if the trajectories inside the intersection followed by the users of those movements intersect. Figure 1.2 [7] illustrates all possible conflict points in a four-way intersection among all traffic users. Note that some conflict points could be avoided in the presence of multiple downstream lanes, for instance the south-north and east-north vehicle movements would not conflict if the northbound downstream road contained two separate lanes to collect traffic for each movements.

Two movements within a phase are mutually *protected* if their intersection trajectories do not intersect at a conflict point, otherwise one of them has to give way to the other such that the former is referred to as a *permitted* movement. A commonly agreed order of priorities suggests that vehicles must give way to bicycles and pedestrians, and bicycles must give way to pedestrians. In addition, given two conflicting movements between equivalent traffic users the ones making a turn should always give way to those proceeding straight forward. Clearly, there are instances in which both movements have equal priority and therefore should not appear in a common phase. Protected movements generally prioritize safety but typically require more phases in order to serve all movements which increases the lost time required when transitioning from phase to phase. The opposite implications apply to permitted movements.

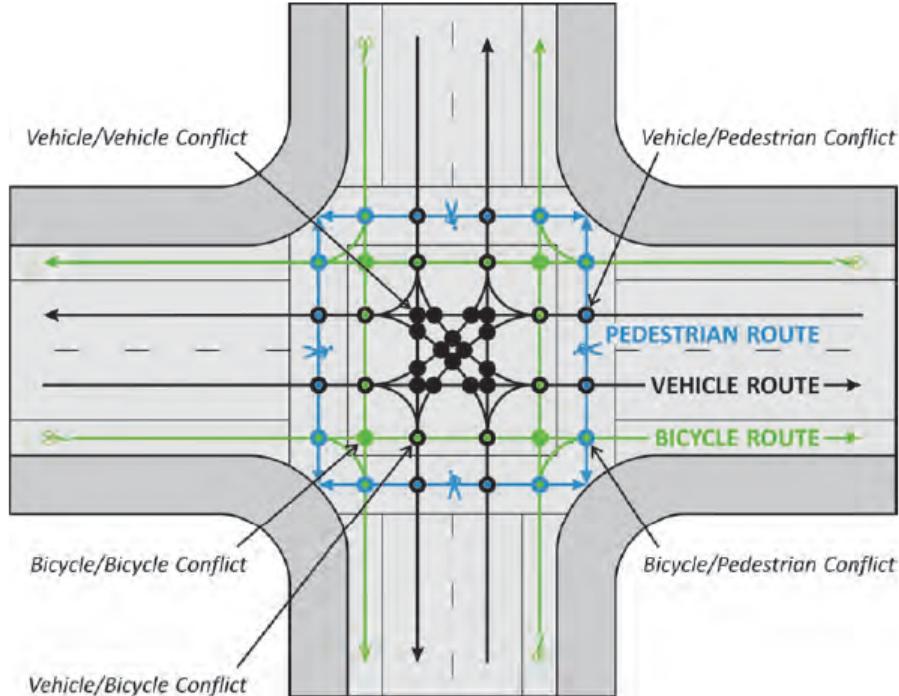


FIGURE 1.2: Illustration of every possible conflict point in a four-way intersection with the specified physical attributes.

An useful alternative description of the above cases is as follows. A pair of movements within a phase may be *compatible* - they are mutually protected), *semi-compatible* - there exists an obvious order of priority such that one movement is protected and the other permitted) or *incompatible* - there exists no such order).

It should be emphasized that the exact jurisdictions of an order of priorities may vary depending on the circumstances of the intersection, i.e., rules dictated by a municipality (or whoever being responsible for the traffic signal). For instance a traffic engineer may adopt a phase specification that signifies certain risks in terms of safety in the favour of other objectives, while other may strive to always maximize safety.

- A *phase schedule* is a set of start and stop times for the split of each phase within a phase specification relative to some reference time-stamp. This is also known as a *stage*. In scheduling the splits one must consider the compatibilities among phases with respect to overlapping splits. These are as follows (an extension of the definition for movements)
 - Two phases are *compatible* if the union of their movements are mutually protected, thus their splits may overlap at any given time.
 - Two phases are *semi-compatible* if there exists an agreed order of priority between each pair of movements from the union of the phases such that one movement is protected and the other permitted. In this case the splits of the phases may overlap, however, potentially subjected to additional constraints.

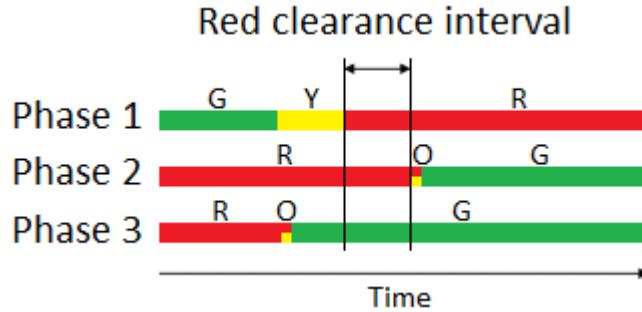


FIGURE 1.3: The red clearance interval is required for the safe transition between two incompatible phases P1 and P2. A third phase P3 is shown to clarify, that the red clearance interval is not necessarily a red period for all phases since P3 is compatible with both P1 and P2.

- Two phases are incompatible if there exists at least one pair of movements from the union of the phases for which there exists no agreed order of priority, thus the split of these phases must not overlap. Incompatible phases impose most restrictions on the phase scheduling. In order to safely transit between two incompatible phases, $\Phi_1 \rightarrow \Phi_2$ one considers the following two intervals.
 - * The *yellow change interval* is the yellow display duration, Y , whose function is to warn that the current phase is about to end.
 - * The *red clearance interval* is a joint short period associated with R for Φ_1 (in the beginning of R) and Φ_2 (at the end of R), see Figure 1.3. The purpose is to provide enough time to clear any traffic in the intersection resulting from Φ_1 that would interfere at the conflict point with Φ_2 . This is to resolve the issue of drivers unable to safely stop during Y .
- The split of a phase must be maximized in order to accommodate the demand for each movement composing the phase. The *minimum green time (maximum green time)* is the minimum (maximum) split that can be assigned to a phase. **these terms have significantly altering meanings if one talks about fixed time or traffic-responsive control strategies.**
- The optimal cycle length was estimated by Webster [11] with respect to n phases given by

$$c_{opt} = \frac{1.5 \sum \ell_{rci}^i + 5}{1 - \sum q_i/s_i} \quad (1.1)$$

where q is the arrival rate and s the saturation flow rate, both explained below.

It is often useful to treat R, O, G and Y as ratios relative to c in which case $c = 1$. In the context of traffic-responsive control strategies the cycle length is of minor importance since phases may be prioritized randomly in response to randomly changing demands.

- The offset must be determined to allow green waves such that vehicles may pass consecutive intersections without the need to stop. Coordination may be either one - or two-way along arterial roads. One-way coordination may be

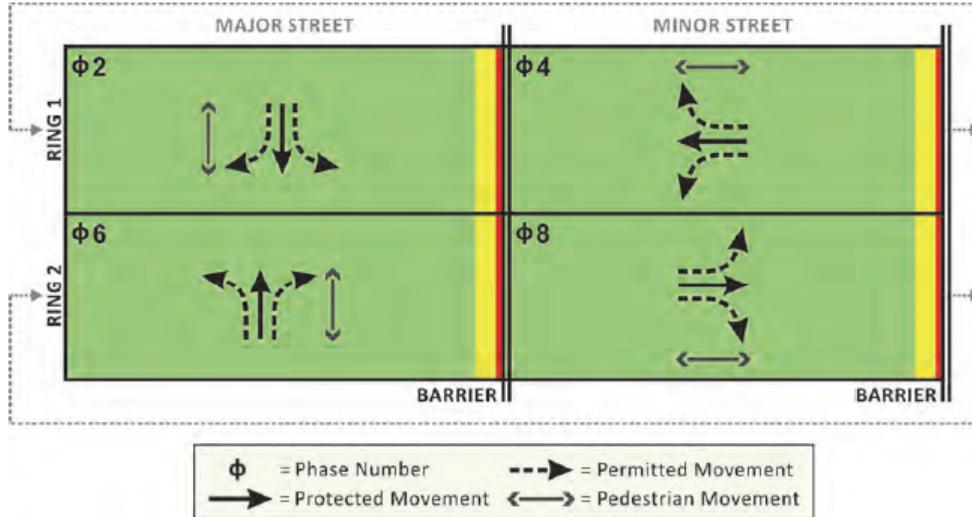


FIGURE 1.4: ADD CAPTION

easily configured given fixed stages for each intersection as one must only take into account the expected travel time between intersections.

Two-way coordination inherently is more difficult

- The intersections in question must have a joint cycle length with respect to long term coordination.
- Consider two intersections for which a two-way coordination is desired. The offset is given by

$$\frac{L}{v} = n \frac{c}{2} \quad (1.2)$$

with

- * L is the distance between the intersections,
- * v is the average velocity of the vehicle platoons in both directions,
- * and $n \in \mathbb{N}$ is the integer multiple between cycles.

Note, the main issue is the fact that the speed limits in each direction must be equal².

- A *stage-specification* essentially encapsulates all of the above considerations, but its specification process depends on assumptions regarding predetermined traffic signals parameters.

The *ring-and-barrier concept* is a helpful means of illustrating the organization of phase orderings with respect to splits. Several examples with respect to a four-way intersection are found in [7]. Figure 1.4 [7] illustrates the most simple example. A *ring* is a sequence of incompatible phases with respect to some order of priorities. A *barrier* divides the rings in such a way that any phase in ring 1 between two barriers may time with any phase in ring 2 (compatible or semi-compatible) between the same two barriers and vice versa. These possibilities are more evident from the example in Figure 1.5 [7] which also illustrates how one may vary the splits of the phases. For instance, Φ_1 may give more time to Φ_2 , and/or Φ_8 should be skipped

²We believe this certainly is true everywhere in the world.

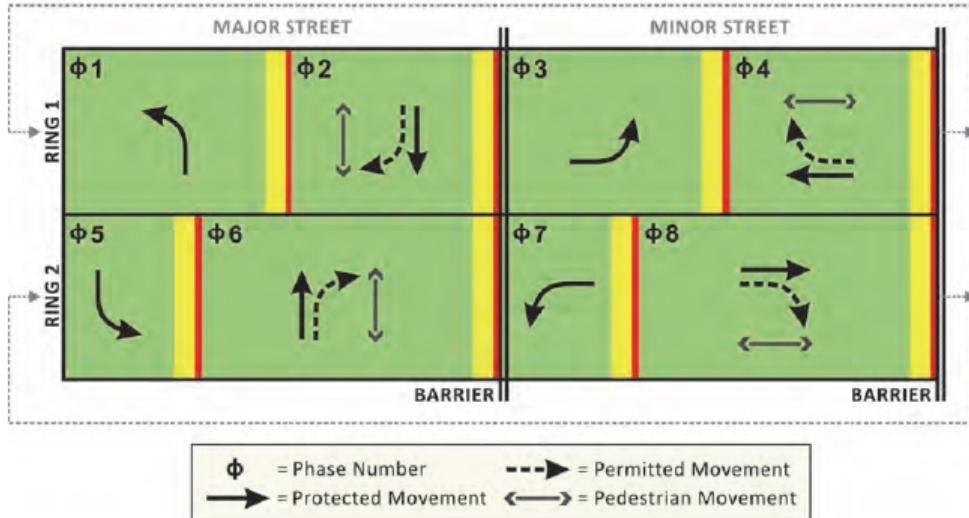


FIGURE 1.5: ADD CAPTION

entirely in favour of phase $\Phi 7$ (assuming a minimum green time equal to 0). In addition, a barrier also marks the point in time at which the phases in both rings must end simultaneously. In the examples, these markings divide the rings with respect to the major and minor street, commonly the arterial road and small streets, respectively. Lastly, the entire ring-and-barrier amounts to a single cycle.

A *time-space diagram* is another helpful means of visualization, in the context of coordinated traffic signals. Basically, one considers an arterial road along consecutive intersections, see Figure 1.6. The objective is to minimize the number of vehicle stops by the coordination of "green waves". The *vehicle trajectory bandwidth* is the horizontal distance between the first and last vehicle trajectory that should be maximized in order to grant the green wave to as many vehicles as possible. This is the key idea of the method *MAXBAND* to be explained in the next chapter.

1.2.3 Other terms

Headway is a central term when describing traffic flow. There are various definitions depending on the situation in question. Mostly, it refers to the distance (tip to tip, or tip to tail) between consecutive vehicles or the time taken for the trailing vehicle to cover that distance. Large headways, especially on freeways, increase vehicle safety - a rule of thumb is to maintain a distance behind the leading car being greater than the distance covered during the average reaction time in case of an emergency braking of the leading vehicle, but at the expense of poorly utilized road capacity. The exact opposite holds for low headways. In *transit* traffic the term has different meanings and heavily relates to the delay of transit vehicles. A set of buses serving a common route, each one punctual on time-schedule, implies an optimal headway, whereas a bus behind its schedule may render the trailing one redundant. This is a serious flaw in resource allocations: a late bus may serve a stop station, leaving the trailing one empty.

A *platoon* is a line of vehicles having in between very small headways, that are accomplished by means of electronic (possibly mechanical) coupling. The line of vehicles then acts as a single unit controlled by the leading vehicle. Some advantages include simultaneous acceleration and braking, thus nullifying the downsides of human reaction time, and reduced air resistance (thus less fuel consumption) due to

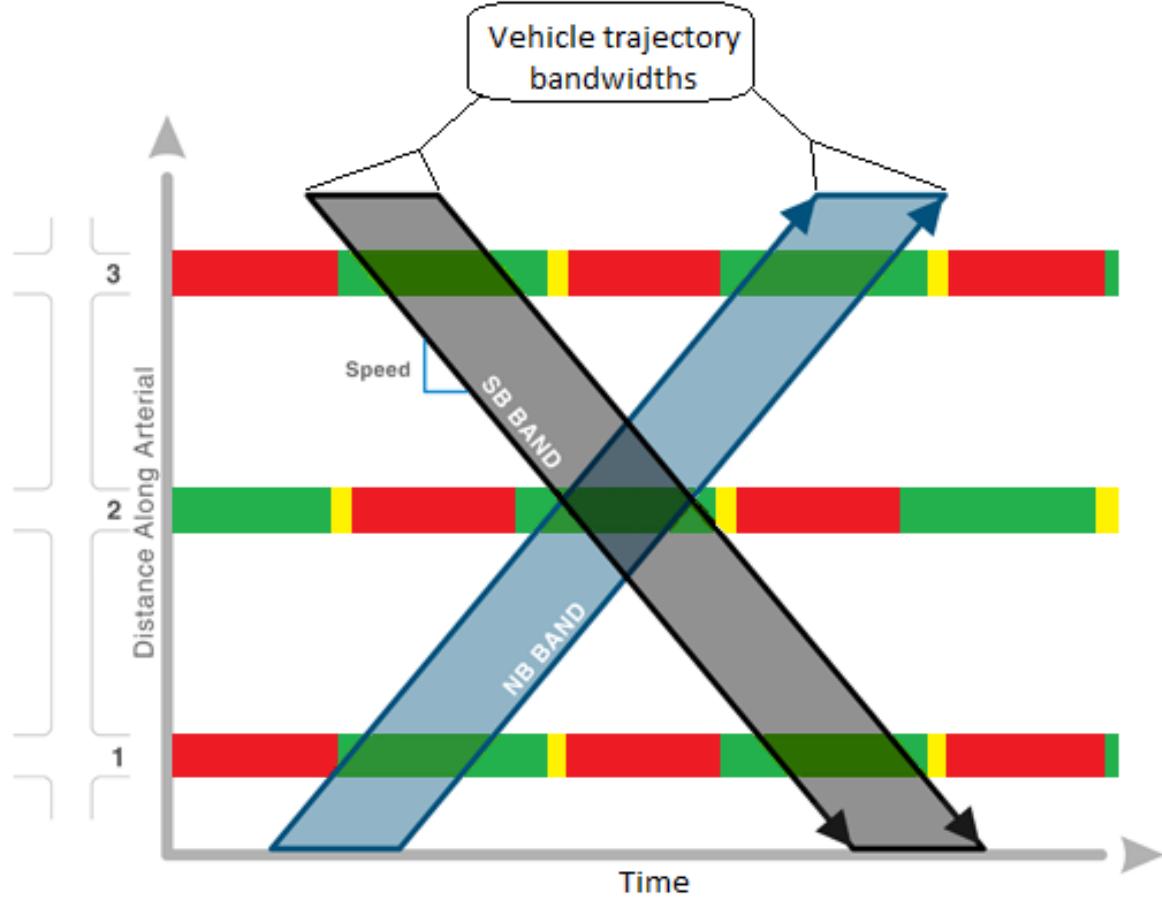


FIGURE 1.6: Time-space diagram for coordination of three consecutive intersections. The south and north bound bands consists of several vehicle trajectories.

drafting. The concept may be regarded as intending to increase the capacity of roads by means of bus imitations. As of today it remains mostly a proposed improvement of traffic flow only, as actual realizations experience several challenges, in particular maximizing the reliability of autonomous vehicle systems. Of course, platoons may still occur spontaneously, although with significantly larger headways due to human reaction time. They are essential when determining if the coordination of traffic signal intersections would be beneficial [7], i.e., if large platoons approaching a series of consecutive intersections should be prioritized as to minimize the number of vehicle stops.

A *passenger car unit* (pcu) is a metric used in quantifying the load or stress that any traffic entity has on traffic in general compared to a single passenger car. An *equivalence factor* is assigned to each entity. For instance, a truck may have a factor of 3 due to poor acceleration and spatial requirements, meaning that it is equivalent to three pcus. In addition, the factor of a bicycle may be as small as 0.2 meaning it imposes 1/5 the load or stress of a single pcu. Note, a bus, although having similar drawbacks as the above truck, may contain a large amount of people relative to its size meaning that the traffic is relieved by an equally large amount of pcus, thus considerably decreasing its equivalence factor. Alternatively, the bus is empty, thus posing a huge load on the traffic. The point is that the equivalence factor for a vehicle may vary with time.

A more accurate metric, especially in the context of traffic signal intersections,

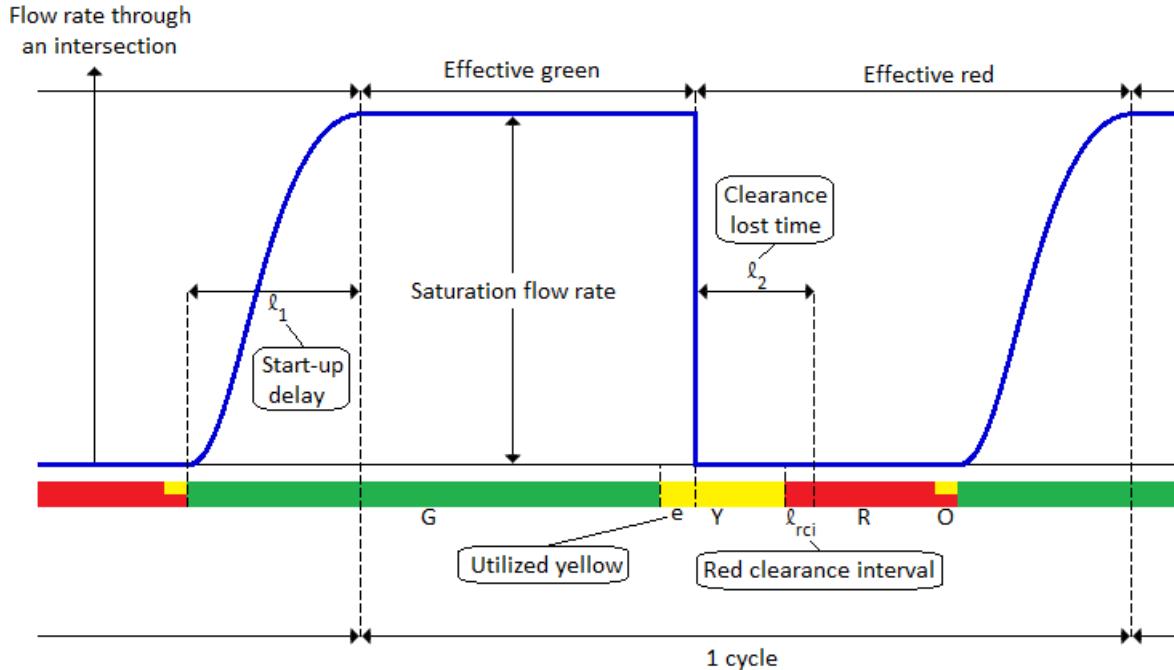


FIGURE 1.7: Intersection flow rate of some phase as a function of its durations in a display sequence.

is the *through car unit* (tcu) that builds upon the assumptions for a pcu. The metric takes into account that pcus proceeding straight forward imposes more throughput compared to turning pcus as the latter require lower speeds to perform a turn.

The following technical terms are associated with an intersection movement.

- The *saturation headway* is the minimum time elapsed between the tip of two consecutive pcus passing a common point. Clearly, this implies that the pcus maintain the corresponding physical minimum safe tip-tail headway.
- The *saturation flow rate* (pcus per hour of green) of an intersection movement is the maximum number of pcus in an infinite platoon that may enter the intersection given one hour of green. It is computed by $\frac{3600}{h}$ where h is the saturation headway.
- A *standing queue* is the queue of stationary pcus that is present as signal turns green. It does not account for pcus arriving at the back of the queue after the signal has turned green.
- To define the remaining terms we first need to consider the various characteristic periods within a display sequence, see Figure 1.7.
 - The *effective green* g (seconds) is the portion of $G + Y$ where pcus enter the intersection in a stable moving platoon at the saturation flow rate. One may also express g in terms of a portion of a cycle, g/c , known as the *effective green ratio*.
 - The *start-up delay* ℓ_1 is equal to the sum of headway delays Δi compared to the saturation headway, see Figure 1.8 [3]. A standing queue receiving the green light is discharging pcus at the saturation flow rate when a vehicle crosses the stop line at the speed limit because the following vehicles will

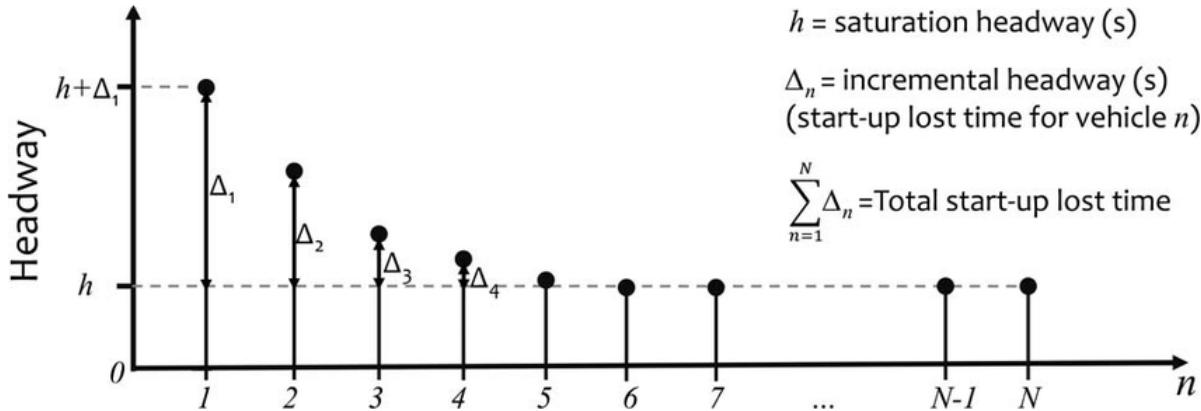


FIGURE 1.8: The x-axis shows the vehicle index in a standing queue containing N vehicles. The y-axis shows the time headway

also be at the speed limit and they will maintain the saturation headway. As a rule of thumb this is achieved by the 4th or 5th vehicle.

The *clearance lost time* ℓ_2 is equal to the red clearance interval plus the portion of Y in which no pcus enters the intersection as they are able to stop safely (the opposite holds for the remainder of Y , often denoted e).

The *lost time* ℓ (seconds) is the time duration in which the intersection is not effectively utilized to serve pcus at the saturation flow rate due to a change between conflicting phases. It is equal to the sum of start-up delay and clearance lost time. In Figure 1.7 it is important to note that the start-up delay is not equal to the portion of G as specified, rather it indicates the time interval of G in which the pcus are not entering the intersection at the saturation flow rate.

- The *effective red* r (seconds) is the portion of the cycle in which pcus do not enter the intersection in a stable moving platoon at the saturation flow rate, however, in the majority of the interval pcus are stationary.

When deciding how much green time to allocate for a phase it is the effective green, not G , being of interest. Formally, given g , the above concepts are related to one another as follows.

$$\ell = \ell_1 + \ell_2 = G + Y - g + \ell_{rci} \quad (1.3)$$

$$c = r + g \quad (1.4)$$

$$c = R + O + G + Y \quad (1.5)$$

- The *capacity* (pcus per cycle) is defined by the product of the effective green ratio and the saturation flow rate.
- The *arrival rate* (pcus per hour) is the number of pcus intending to cross the intersection using the movement during one hour.
- The *demand* (pcus per cycle) is given by the product of the arrival rate and the cycle time.
- The *degree of saturation* is the ratio between demand and capacity.

- Traffic *volume* (pcus per cycle) is the actual number of pcus that are able to cross the intersection in a cycle.
- A movement suffers from (*oversaturation*) if being unable to fully discharge all pcus in its standing queue during a cycle. Demand and volume are proportional until the capacity of the movement is exceeded in which case the volume remains constant but the demand may still increase, thus leading to long term queue build ups.
- A *phase failure* is the occurrence of at least one pcu in a standing queue being unable to cross the intersection during a cycle, thus leading to long term queue build ups.
- *Free flow...*

1.3 Literature review

As already mentioned control strategies are characterized roughly by four operating scenarios. Important methodologies for each of them with respect to traffic signals are highlighted in [8]. We will describe each methodology with respect to the terminology given in this chapter.

- Isolated fixed-time: The methods *SIGSET* and *SIGCAP* assume predetermined phase-specifications in order to find the optimal splits and cycle length. The phase orderings do not affect the main objectives as the phases are mutually incompatible, i.e., they must be served sequentially. Nonetheless, the methods may be stated to determine the stage specification problem. Given n phases the methods specify the splits $\lambda_1, \dots, \lambda_n \in [0, 1]$ as ratios of the cycle length c such that

$$\lambda_0 + \lambda_1 + \dots + \lambda_n = 1 \quad (1.6)$$

where $\lambda_0 = \frac{\sum_{i=1}^n \ell_{rci}}{c}$ from which the insignificance of the phase orderings becomes apparent.

The method presented in [4] solves a similar problem, with the addition of determining the optimal phase orderings as the phases may not be mutually incompatible. The model rises a binary-mixed-integer-linear (MILP) programming problem, which is solved through a branch and bound method utilizing the Simplex algorithm. In the following chapter we explore the method in details with several proposed improvements.

- Coordinated fixed-time: *MAXBAND* attempts to maximize the number of green waves to reduce vehicles stops. In other words it determines appropriate offsets. The concept is similar to the *time-space diagram* described in [7]. The method requires a binary-mixed-integer-programming problem to be solved.

TRANSYT employs a local search heuristic. Given input decision variables (splits, offsets and cycle time) the algorithm introduces small local neighbourhood changes in order to improve the operational objective, until a local minimum has been found.

- Isolated traffic-responsive: The *vehicle interval method* is a two-phase based method. Its basic principle is to determine, for each interval, whether the current phase should end in favour of the other. This is achieved by means of loop inductors located some distance away from the intersection.

Sameh Samra et al. [9] considers a problem referred to as the *traffic control problem*. It assumes a set \mathcal{K} of phase specifications with the phases mutually incompatible as with *SIGSET* and *SIGCAP*. Formally, it asks to determine a timing plan $\Omega = \langle (K_0, t_0), \dots, (K_i, t_i) \rangle$ where $K_i \in \mathcal{K}$ and $t_i < T$, i.e., a sequence of phases, each assigned a split within a time horizon T . Note that T is *not* a cycle length to be enforced since traffic-responsive strategies do not strictly cycle through a specified stage. The authors present a new linear time and space algorithm to solve the problem. It improves upon an existing one having complexity $O(T^3)$ in time and $O(T^2)$ in space. It utilizes a dynamic programming formulation of the problem that heavily relies on predictions of demands, therefore being proactive. Simulation studies were conducted in confirming the superiority of the algorithm compared to other modern methodologies including reinforcement learning, genetic programming and neural networks. The accuracy of the predictions of the demands given to the algorithm, however, were assumed to be perfect.

- Coordinated traffic-responsive: The method *SCOOT* basically applies the same methodology as *TRANSYT*, with respect to real-time measurement, however.

Model-Based Optimization Methods like *OPAC*, *PRODYN*, *CRONOS*, and *RHODES* solve in real time a dynamic optimization problem based on a sampling time of 2-5 seconds of real-time traffic measurements. Generally the problems presented require exponential computation time, thus leaving the problem infeasible for more than a single intersection.

The title of this thesis itself is a broad area of research largely depending on the operational objectives in question. For instance the convenience of and demands for private cars and the feeling of independence may be challenged by introducing transit vehicle priorities by increasing the likelihood of time-schedule punctualities. As a matter of fact a single bus has the potential in replacing 15-20 cars. A comprehensive review of transit priority at traffic signal intersections is given in [5].

Chapter 2

Modeling

In the previous chapter we defined the following optimization tasks with regards to traffic signals: 1) phase-specification, 2) splits, 3) phase-ordering, 4) cycle length and 5) offsets, where the stage-specification problem may encompass several tasks. A method may determine a single or multiple tasks based on the pre-specification of none to several others. In the following we describe currently existing methods with respect to each characteristics of a control strategy. **present this part already as your contribution, a revisit of current models and expansions thereof**

2.1 Fixed-time isolated signal

2.1.1 A naive time signal plan

Consider a predetermined phase specification of n mutually incompatible phases such that they must be served sequentially within a cycle.**brug den danske artikel til at forklare naiv fremgangsmåde** A straight forward approach is to assume equal demand to each phase such that they must have equal splits, G . In addition, it is assumed that the phases share joint values for R, O, Y and ℓ_{rci} . To derive the required durations G and R it must hold that

$$n(G + Y + O + \ell_{rci}) = c \quad (2.1)$$

from which it can be derived that

$$G = c/n - Y - O - \ell_{rci} \quad (2.2)$$

$$R = c - Y - O - G \quad (2.3)$$

Let the beginning of R be a common reference time stamp to which each phase must be shifted, given by $c\frac{i-1}{n}$ for $i = 1..n$ which determines the phase scheduling. As an example, consider four phases with joint values (in seconds) $c = 60, Y = 2, O = 1$ and $\ell_{rci} = 1$, such that $G = 10$ and $R = 46$, by 2.2,2.3). Figure 2.1 illustrates the complete traffic signal plan in terms of the alignment of the display sequence for each phase.

2.1.2 SIGSET and SIGCAP

SIGSET [2] and SIGCAP [1] both determine a stage specification based on a predetermined phase specification. Interestingly, however, both methods are dominated by G. Imrota et al. [4] (GI) of which we present an extended version.

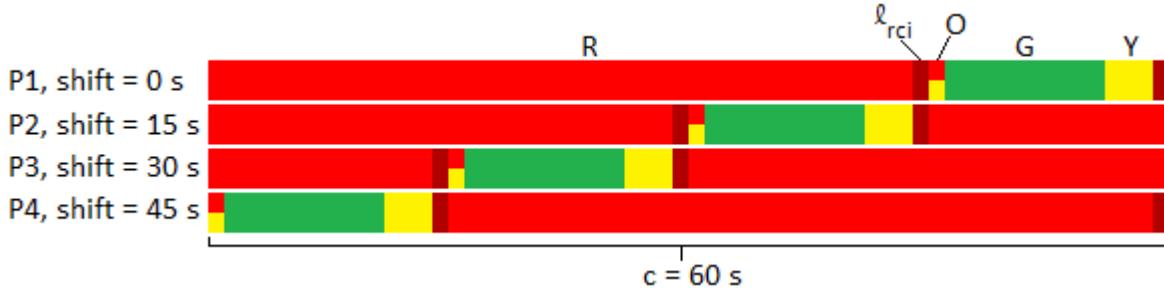


FIGURE 2.1: Recall that the red clearance interval is a joint sub-duration of the R durations of two phases.

2.1.3 An extended version, (GIv2), of (GI)

The model to be presented includes various extensions differently from (GI) that are briefly summarized in the following and explained in details in subsequent sections.

- The model (GI) considers as main input a predetermined phase-specification. Each phase has a critical movement that is the movement having the largest demand to capacity ratio that ultimately restricts the required effective green for the phase in question. In (GIv2) we take into account potential reduced capacities of movements given they have to give way to conflicting priority movements before proceeding.
- The model (GI) is non-linear with respect to two variables: the cycle length and intersection capacity, that each must be optimized. The issue can be naively resolved in fixing one of the variables, however it is suggested to eliminate the cycle length by re-expressing relevant quantities in terms of ratios of a single cycle, which is to be considered in (GIv2). Interestingly, we will see that the elimination of the cycle length renders the overlap constraints presented in (GI) linear, thus simplifying the description of those constraints.

Input parameters

- Let $H = \{h_1, \dots, h_m\}$ be the set of movements of the intersection in question.
- Define a partial order (order of priority) on H such that $h_1, h_2 \in H$
 - are semi-compatible in the sense that $h_1 \prec h_2$ if h_2 is the priority movement, i.e., h_1 must give way to h_2 ,
 - are incompatible in the sense that $h_1 \equiv h_2$ if h_1 and h_2 have equivalent priority.
- Let $\mathcal{K} = \{K_1, \dots, K_n\}$ be a predetermined phase-specification. The set \mathcal{K} is a partition of H , i.e.

$$\bigcup_{\forall K_i \in \mathcal{K}} K_i = H \quad \bigcap_{\forall K_i \in \mathcal{K}} K_i = \emptyset$$

implying that each movement appears in exactly one phase, thus having a single split during a cycle.

- Define a partial order (order of priority) on \mathcal{K} with respect to the partial order defined on H . In this sense, recall from chapter 1 the definition that two phases, $K_i, K_j \in \mathcal{K}$, are incompatible, $K_i \equiv K_j$, if $\exists (h_1, h_2) \in K_i \cup K_j \mid h_1 \equiv h_2$.

- Define the set $I = \{(i, j) \in \{1..n\} \times \{1..n\} \mid K_i, K_j \in \mathcal{K} \mid K_i \equiv K_j\}$.
- Let \underline{c}, \bar{c} (seconds) be the lower and upper bound on the cycle length c (to be defined).
- Let $q_h, s_h \geq 0$ (both pcus/h) with $q_h \leq s_h$ be the arrival rate and saturation flow rate, respectively, for some movement $h \in H$.
- Let $\ell_{rci}^{ij} \geq 0$ (seconds) be the red clearance interval for $(i, j) \in I$ when transitioning from K_i to K_j . Note that we may have $\ell_{rci}^{ij} \neq \ell_{rci}^{ji}$.
- For each movement $h \in H$ we define (all in seconds)
 - Let \underline{r}_h be its minimum and \bar{r}_h its maximum effective red.
 - Let \underline{g}_h be its minimum and \bar{g}_h its maximum effective green.
 - Let ℓ_h be its total lost time, i.e., the sum of start-up delay and clearance lost time. Note, in contrast to the definition in chapter 1 the ℓ_h in this model does *not* include the red clearance interval being specified independently (see above).
- For each phase $K_i \in \mathcal{K}$ we define
 - Let $\underline{r}'_i = \max\{\underline{r}_h, \forall h \in K_i\}$ be its minimum and $\bar{r}'_i = \min\{\bar{r}_h, \forall h \in K_i\}$ be its maximum effective red.
 - Let $\underline{g}'_i = \max\{\underline{g}_h, \forall h \in K_i\}$ be its minimum and $\bar{g}'_i = \min\{\bar{g}_h, \forall h \in K_i\}$ be its maximum effective green.
 - Let $\ell_i = \max\{\ell_h, \forall h \in K_i\}$ be its lost time.
- Finally, the model (GI) defines the critical movement flow ratio for each phase $K_i \in \mathcal{K}$ given by

$$\zeta_i = \max\{q_h/s_h, \forall h \in K_i\} \quad (2.4)$$

Differently from (GI) we take into account that a phase may contain pairwise semi-compatible movements such that the saturation flow rate of the non-priority movement is reduced. Let $h_a, h_b \in K_i$ be two semi-compatible movements in some phase $K_i \in \mathcal{K}$ such that $h_a \prec h_b$. The flow of h_b affects that of h_a in two distinct ways.

- **Free flow:** During free flow in h_b we assume a linear reduction of the saturation flow rate given by

$$s'_{h_a} = s_{h_a} p_{h_b} \quad (2.5)$$

where $p_{h_b} = 1 - \frac{q_{h_b}}{s_{h_b}}$ is the probability that the flow in h_b has an available gap to let pcus from h_a pass. In general, given $h_a \in K_i$ and $K'_i = \{h_b \in K_i \setminus \{h_a\} \mid h_a \prec h_b\}$ then the adjusted saturation flow rate is given by

$$s'_{h_a} = s_{h_a} \prod_{\forall h_b \in K'_i} p_{h_b} \quad (2.6)$$

since the p_{h_b} s are independent events.

- **Conflicting standing queues:** During the red indication standing queues are build up. As the signal turns green the queues are discharged at the saturation flow rate during which there will be no available gaps for the pccus of h_a to pass. After every standing queue has been cleared free flow will be present for which the conditions described in previous item apply. Therefore, h_a must account for the required green time to clear the standing queue in each of the movements $h_b \in K'_i$ for which only the one with the largest demand to capacity ratio is relevant

$$Q_{h_a} = \max\{q_{h_b}/s_{h_b}, \forall h_b \in K'_i\} \quad (2.7)$$

Combining (2.45,2.47,2.48) the critical movement is given by

$$\begin{aligned} \zeta_i &= \max\{Q_{h_a} + q_{h_a}/s'_{h_a}, \forall h_a \in K_i\} & \forall K_i \in \mathcal{K} \\ s'_{h_a} &= s_{h_a} \prod_{\forall h_b \in K'_i} (1 - q_{h_b}/s_{h_b}) \\ Q_{h_a} &= \max\{q_{h_b}/s_{h_b}, \forall h_b \in K'_i\} \end{aligned} \quad (2.8)$$

Decision variables

- For each phase $K_i \in \mathcal{K}$ we define
 - Let g_i be the effective green ratio.
 - Let u_i be the starting time of G and v_i the ending time of Y such that $v_i - u_i$ is the split ratio of K_i that accounts for both g_i and ℓ_i .
- Let $f \geq 0$ be the *intersection capacity factor*. This is a maximum common multiple factor with respect to all phases.
- Let z be the reciprocal cycle length $\frac{1}{c}$ such that $\frac{1}{\bar{c}} \leq z \leq \frac{1}{\underline{c}}$.
- Let $w_{ij} \in \{0, 1\}$ be a binary variable defined for each $(i, j) \in I$ such that $w_{ij} = 0$ if the split of K_i precedes that of K_j , and $w_{ij} = 1$ otherwise, i.e., the split K_j precedes that of K_i .

Constraint formulations

Recall from 1.4 that $c = g + r$, hence

$$\left. \begin{array}{l} z\underline{r}_i \leq 1 - g_i \leq z\bar{r}_i \\ z\underline{g}_i \leq g_i \leq z\bar{g}_i \end{array} \right\} \forall K_i \in \mathcal{K} \quad (2.9)$$

Since $v_i - u_i = G + Y$, assuming G, Y are ratios also, it follows from (1.3) that

$$v_i - u_i = g_i + z\ell_i \quad \forall K_i \in \mathcal{K} \quad (2.10)$$

note, however, the absence of the red clearance interval which is specified independently.

Each phase $K_i \in \mathcal{K}$ must have sufficient effective green in order to the demand in each of its movements. This is constrained with respect to its critical movement.

$$g_i \geq f\zeta_i \quad \forall K_i \in \mathcal{K} \quad (2.11)$$

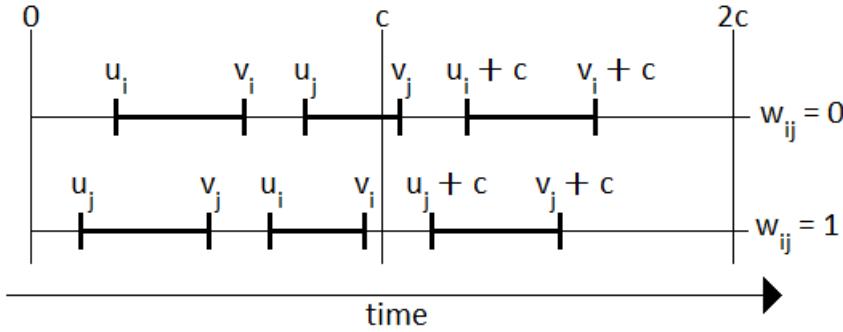


FIGURE 2.2: Time horizon for two cycles which amounts to a time span of two cycle lengths.

Here, f must be maximized since a high value indicates a sufficient utilization of the intersection capacity. If $f = 1$ then g_i in theory suffices for all phases assuming that pccus arrive uniformly, however, as this is unlikely to happen in real life the case of $f \geq 1$ is always desired. In contrast, it may not be possible to allocate a sufficient g_i due to a high value of ζ_i in which case we must have $f < 1$ in order to satisfy the constraint for the movement in question and the overall feasibility of the model. In addition, given $f < 1$ is much likely to cause oversaturation due to queue build ups resulting from phase failures.

A complete traffic signal plan (stage), when implemented in physical signals, may be initiated starting from an arbitrary point in the plan due its cyclic nature. For simplicity we assume

$$u_i \geq 0 \quad \forall K_i \in \mathcal{K} \quad (2.12)$$

such that the resulting plan of this model should be initiated at $t = 0$. In addition, if $u_i \geq 1$ then u_i can be shifted 1 units backwards (1 cycle) along the time axis due to the cyclic nature, thus

$$u_i \leq 1 \quad \forall K_i \in \mathcal{K} \quad (2.13)$$

The following constraints ensure that the split of incompatible phases do not overlap, see Figure 2.4. Let $(i, j) \in I$. If the split of K_i precedes that of K_j , i.e., $w_{ij} = 0$ then

$$z\ell_{rci}^{ij} + v_i \leq u_j \quad (2.14)$$

$$z\ell_{rci}^{ji} + v_j \leq u_i + 1 \quad (2.15)$$

and vice versa

$$z\ell_{rci}^{ij} + v_i \leq u_j + 1 \quad (2.16)$$

$$z\ell_{rci}^{ji} + v_j \leq u_i \quad (2.17)$$

Constraints (2.55-2.57) and (2.56-2.58) can be combined, respectively, as follows

$$\left. \begin{aligned} z\ell_{rci}^{ij} + v_i &\leq w_{ij} + u_j \\ z\ell_{rci}^{ji} + v_j &\leq (1 - w_{ij}) + u_i \end{aligned} \right\} \forall (i, j) \in I \quad (2.18)$$

Finally, substituting $u_i = v_i - g_i - z\ell_i$ from (2.10) into all relevant constraints the

position of the split is determined solely by v_i . From (2.13,2.12) the bounds on v_i become apparent

$$v_i \geq g_i + z\ell_i \quad (2.19)$$

$$v_i \leq 1 + g_i + z\ell_i \quad (2.20)$$

Constraint summary

Model 2.1.1: Model (GIv2)

On from this point we refer to the following constraints by \mathcal{X} .

$$\begin{aligned} & 1 \leq z\bar{c} \\ & 1 \geq z\underline{c} \\ & \left. \begin{array}{l} zr_i \leq 1 - g_i \\ z\bar{r}_i \geq 1 - g_i \\ zg_i \leq g_i \\ z\bar{g}_i \geq g_i \\ g_i \geq f\zeta_i \\ v_i \geq g_i + z\ell_i \\ v_i \leq 1 + g_i + z\ell_i \end{array} \right\} \forall K_i \in \mathcal{K} \\ & \left. \begin{array}{l} z\ell_{rci}^{ij} + v_i - (v_j - g_j - z\ell_j) \leq w_{ij} \\ z\ell_{rci}^{ji} + v_j - (v_i - g_i - z\ell_i) \leq (1 - w_{ij}) \end{array} \right\} \forall (i, j) \in I \end{aligned} \quad (2.21)$$

Objective function

The model (GI) is concerned with the following objectives.

- Maximization of the intersection capacity factor f .
- Minimization of the average travel time. Webster's formula [11] describes the average travel time for a movement $h \in K_i$ in some phase $K_i \in \mathcal{K}$ given by

$$0.9 \cdot (d_h(g_i, c) = \frac{s(c - g_i)^2}{2c(s_h - q_h)} + \frac{3600b^2}{2q_h(1 - b)}) \quad (2.22)$$

where $b = \frac{q_h c}{s_h g_i}$ is the degree of saturation. The first term is due to standing queue build ups during the red indication. The second term is the contribution due to random poisson arrivals investigated by Webster. Finally, Webster considered a third term meant to decrease the travel time, but was simplified by a multiple factor of 0.9. Alternatively, one may instead maximize the sum of effective green ratios.

- Minimization of the cycle length, i.e., for (GIv2) one would maximize z .

to maximize the intersection capacity factor f being the primary objective and the maximization of the sum of effective greens $\sum_{\forall K_i \in \mathcal{K}} g_i$ being the secondary objective.

Therefore we consider a joint objective function such that an optimal value of the latter is accepted only if it does not degrade the value of the former.

2.1.4 An extended version, (GIv3), of (GIv2)

Once again, the details of the extensions are highlighted in the model description.

- The model (GIv3) includes a significant change of view of the problem formulation allowing the joint determination of the phase-specification and stage-specification. This is achieved by considering only the set of movements, essentially, such that each movement is considered a single phase, though they are referred to as movements. In scheduling the splits of the movements separately one may examine from solution of the model if two or more splits align, hence revealing the phase specifications a posteriori. Clearly, since the starting and ending points of the splits are real valued one must consider a threshold with respect to the difference between the starting and ending points.
- Due to the above item the critical movement within each phase clearly is the movement itself.
- In scheduling the phases (GIv3) considers additional constraints with respect to semi-compatible overlapping splits in the sense of reduced saturation flow rates. This is somewhat similar to the idea of (GIv2), however the difference being that the reduced saturation flow rates were fixed due to fixed phases, whereas they may vary in (GIv3) due to the phase schedules being variables.

Input parameters

- Let $H = \{h_1, \dots, h_n\}$ be the set of movements of the intersection in question.
- Define a partial order (order of priority) on H such that
 - $h_i, h_j \in H$ are semi-compatible in the sense that $h_i \prec h_j$ if h_j is the priority movement, i.e., h_i must give way to h_j ,
 - $h_i, h_j \in H$ are incompatible in the sense that $h_i \equiv h_j$ if h_i and h_j have equivalent priority.
- Define the sets $S = \{(h_i, h_j) \in H \times H \mid h_i \succ h_j\}$ and $I = \{(h_i, h_j) \in H \times H \mid h_i \equiv h_j\}$.
- Let \underline{c}, \bar{c} (seconds) be the lower and upper bound on the cycle length c .
- Let $q_i, s_i \geq 0$ (both $pcus/h$) with $q_i \leq s_i$ be the arrival rate and saturation flow rate, respectively, for some movement $h_i \in H$.
- Let s_{min} ($pcus/h$) be the minimum number of pcus that every non-priority movement is able to serve regardless of the saturation of a conflicting priority movement. It is equal to the number of vehicles that are able to move beyond the stop line to enter the intersection. The pcus in j tend to enter the intersection as they await for available gaps. Consequently, depending on the intersection size j always serves a minimum number of pcus regardless of the flow ratio q_i/s_i which is reflected by C with 2 being a reasonable value. **need reformulation!!!!!!**
- Let $\ell_{rci}^{ij} \geq 0$ (seconds) be the red clearance interval for $(h_i, h_j) \in I$ when transitioning from h_i to h_j . Note that we may have $\ell_{rci}^{ij} \neq \ell_{rci}^{ji}$.
- For each movement $h_i \in H$ we define (all in seconds)

- Let \underline{r}_i be its minimum and \bar{r}_i its maximum effective red.
- Let \underline{g}_i be its minimum and \bar{g}_i its maximum effective green.
- Let ℓ_i be its total lost time, i.e., the sum of start-up delay and clearance lost time. Note, in contrast to the definition in chapter 1 the ℓ_i in this model does *not* include the red clearance interval being specified independently (see above).

Decision variables

- For each movement $h_i \in H$ we define
 - Let g_i be the effective green.
 - Let u_i, v_i be the starting time of G and ending time of Y such that $v_i - u_i$ is the split ratio of h_i which accounts for both g_i and ℓ_i .
- Let $f \geq 0$ be the intersection capacity factor. This is a maximum common multiple factor with respect to all movements.
- Let z be the reciprocal cycle length $\frac{1}{c}$ such that $\frac{1}{\bar{c}} \leq z \leq \frac{1}{\underline{c}}$.
- Let $w_{ij} \in \{0, 1\}$ be a binary variable defined for each $(h_i, h_j) \in I$ such that $w_{ij} = 0$ if the split of h_i precedes that of h_j and $w_{ij} = 1$ otherwise, i.e., the split of h_j precedes that of h_i .
- Let $x_{ij} \in \{0, 1\}$ be a binary variable defined for each $(h_i, h_j) \in S$ such that $x_{ij} = 0$ if the splits of h_i and h_j overlap and $x_{ij} = 1$ otherwise.
- Let $y_{ij} \in \{0, 1\}$ be a binary variable defined for each $(h_i, h_j) \in S$ with $x_{ij} = 0$ such that $y_{ij} = 0$ if the split of h_i precedes that of h_j and $y_{ij} = 1$ otherwise, i.e., the split of h_j precedes that of h_i .

Constraints formulations

Recall from 1.4 that $c = g + r$, hence

$$\left. \begin{array}{l} z\underline{r}_i \leq 1 - g_i \leq z\bar{r}_i \\ z\underline{g}_i \leq g_i \leq z\bar{g}_i \end{array} \right\} \forall h_i \in H \quad (2.23)$$

Since $v_i - u_i = G + Y$, assuming G, Y are ratios also, it follows from (1.3) that

$$v_i - u_i = g_i + z\ell_i \quad \forall h_i \in H \quad (2.24)$$

note, however, the absence of the red clearance interval which is specified independently.

Each movement $h_i \in H$ must have sufficient effective green in order to the demand in each of its movements. This is constrained with respect to its flow ratio

$$g_i \geq f \frac{q_i}{s_i} \quad \forall h_i \in H \quad (2.25)$$

Here, f must be maximized since a high value indicates a sufficient utilization of the intersection capacity. If $f = 1$ then g_i in theory suffices for all movements assuming that pcus arrive uniformly, however, as this is unlikely to happen in real life the case of $f \geq 1$ is always desired. In contrast, it may not be possible to allocate a sufficient

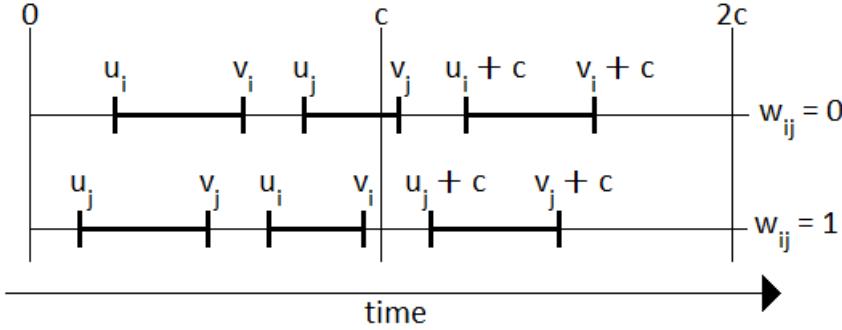


FIGURE 2.3: Time horizon for two cycles.

g_i due to a high value of $\frac{q_i}{s_i}$ in which case we must have $f < 1$ in order to satisfy the constraint for the movement in question and the overall feasibility of the model. In addition, given $f < 1$ is much likely to cause oversaturation due to queue build ups resulting from phase failures.

A complete traffic signal plan (stage), when implemented in physical signals, may be initiated starting from an arbitrary point in the plan due its cyclic nature. For simplicity we assume

$$u_i \geq 0 \quad \forall h_i \in H \quad (2.26)$$

such that the resulting plan of this model should be initiated at $t = 0$. In addition, if $u_i \geq 1$ then u_i can be shifted 1 units backwards (1 cycle) along the time axis due to the cyclic nature, thus

$$u_i \leq 1 \quad \forall h_i \in H \quad (2.27)$$

where the "equal to" is included simply to avoid a strict inequality.

The following constraints ensure that the split of incompatible phases do not overlap, see Figure 2.3. Let $(h_i, h_j) \in I$. If the split of h_i precedes that of h_j , i.e., $w_{ij} = 0$ then

$$z\ell_{rci}^{ij} + v_i \leq u_j \quad (2.28)$$

$$z\varrho_{rci}^{ji} + v_j \leq u_i + 1 \quad (2.29)$$

and vice versa

$$z\ell_{rci}^{ij} + v_i \leq u_j + 1 \quad (2.30)$$

$$z\varrho_{rci}^{ji} + v_j \leq u_i \quad (2.31)$$

Constraints (2.28-2.30) and (2.29-2.31) can be combined, respectively, as follows

$$\left. \begin{array}{l} z\ell_{rci}^{ij} + v_i \leq w_{ij} + u_j \\ z\varrho_{rci}^{ji} + v_j \leq (1 - w_{ij}) + u_i \end{array} \right\} \forall (h_i, h_j) \in I \quad (2.32)$$

The splits $[u_i, v_i]$ and $[u_j, v_j]$ of a pair of semi-compatible movements $(i, j) \in S$ are permitted to overlap *but it is not required*. The splits overlap if

$$u_i < v_j \wedge u_j < v_i \quad (2.33)$$

otherwise we can impose constraints functionally similar to (2.32) but without the red clearance interval, which is only relevant to incompatible movements. We write

$$\left. \begin{array}{l} u_i - v_j + \epsilon \leq 2x_{ij} \\ u_j - v_i + \epsilon \leq 2x_{ij} \\ z\ell_{rci}^{ij} + v_i \leq (1 - x_{ij}) + y_{ij} + u_j \\ z\ell_{rci}^{ji} + v_j \leq (1 - x_{ij}) + (1 - y_{ij}) + u_i \end{array} \right\} \forall (i, j) \in S \quad (2.34)$$

where $\epsilon > 0$ is introduced to handle the apparent strict inequalities. Next, given $x_{ij} = 0$ one must decide on additional constraints with respect to the characteristic of the overlap of the splits. We propose that it must hold that

$$u_i = u_j \wedge v_j = v_i \quad (2.35)$$

that translates into

$$\left. \begin{array}{l} u_i - u_j + \epsilon \leq x_{ij} \\ v_j - v_i + \epsilon \leq x_{ij} \end{array} \right\} \forall (i, j) \in S \quad (2.36)$$

which holds since the starting or ending points of two splits can be at most 1 cycle apart. Note that (2.63) dominates the first two constraints in (2.61). As in model (GIv2) we consider two movements $h_i, h_j \in H$ with $h_i \prec h_j$ such that the flow ratio $\frac{q_j}{s_j}$ is assumed to impose a linear reduction on the saturation flow rate s_i . We write

$$s'_i = s_i(1 - q_j/s_j) \quad (2.37)$$

If $\frac{q_j}{s_j} \geq 1$ then the pcus of h_j maintain the saturation headway which is insufficient in providing any available gaps that allow the pcus of h_i to pass. In fact having $\frac{q_j}{s_j} \geq 1$ leads to oversaturation which this model can not handle. The parameter s'_i is incorporated by introducing an additional constraint similar to (2.25) by replacing s_i with s'_i . Since $s'_i \leq s_i$ we have $\frac{q_j}{s'_i} \geq \frac{q_j}{s_i}$, thus the new constraint restricts g_i to be larger and therefore dominates the original constraint. In addition the split of h_i must also account for the effective green ratio required to clear the standing queue in h_j (also discussed in (GIv2)). In summary we must have

$$f \cdot \left(\frac{q_j}{s_j} + \frac{q_i}{s_i(1 - q_j/s_j) + s_{\min}} \right) - g_i \leq x_{ij} \quad \forall (i, j) \in S \quad (2.38)$$

Alternatively, one may relax the second condition of (2.63), i.e., the non-priority movement j may maintain its split after the one for i has finished such that the adjusted saturation flow rate s'_j is given by the weighted average

$$s'_j = s_j(1 - q_i/s_i)b_{ij} + s_j(1 - b_{ij}) \quad (2.39)$$

$$b_{ij} = \begin{cases} \frac{v_i - u_j}{v_j - u_j} \in [0, 1) & \text{if } v_i < v_j \\ 1 & \text{otherwise} \end{cases} \quad (2.40)$$

where b_{ij} is the portion of the split of j that overlaps with the split of i , and they overlap partially only if $v_i < v_j$ as stated. An apparent difficulty with this approach is apparent due to its non-linearity.

Finally, substituting $u_i = v_i - g_i - z\ell_i$ from (2.24) into all relevant constraints the position of the split is determined solely by v_i . From (2.27,2.26) the bounds on v_i become apparent

$$v_i \geq g_i + z\ell_i \quad (2.41)$$

$$v_i \leq 1 + g_i + z\ell_i \quad (2.42)$$

Model summary

Model 2.1.2: Model (GIv3)

$$\begin{aligned} & 1 \leq z\bar{c} \\ & 1 \geq z\underline{c} \\ & \left. \begin{array}{l} z\underline{r}_i \leq 1 - g_i \\ z\bar{r}_i \geq 1 - g_i \\ z\underline{g}_i \leq g_i \\ z\bar{g}_i \geq g_i \\ g_i \geq f \frac{q_i}{s_i} \\ v_i \geq g_h + z\ell_i \\ v_i \leq 1 + g_h + z\ell_i \end{array} \right\} \forall h_i \in H \\ & \left. \begin{array}{l} z\ell_{rci}^{ij} + v_i - (v_j - g_j - z\ell_j) \leq w_{ij} \\ z\ell_{rci}^{ji} + v_j - (v_i - g_i - z\ell_i) \leq (1 - w_{ij}) \end{array} \right\} \forall (i, j) \in I \\ & \left. \begin{array}{l} (v_i - g_i - z\ell_i) - (v_j - g_j - z\ell_j) + \epsilon \leq x_{ij} \\ v_j - v_i + \epsilon \leq x_{ij} \\ z\ell_{rci}^{ij} + v_i - (v_j - g_j - z\ell_j) \leq (1 - x_{ij}) + y_{ij} \\ z\ell_{rci}^{ji} + v_j - (v_i - g_i - z\ell_i) \leq (1 - x_{ij}) + (1 - y_{ij}) \\ f \cdot \left(\frac{q_j}{s_j} + \frac{q_i}{s_i(1 - q_j/s_j) + s_{\min}} \right) - g_i \leq x_{ij} \end{array} \right\} \forall (i, j) \in S \end{aligned} \quad (2.43)$$

2.1.5 Combining (GIv2) and (GIv3), (GIv23)

The model to be presented includes various extensions differently from (GI) that are briefly summarized in the following and explained in details in subsequent sections.

- The model (GI) considers as main input a predetermined phase-specification. Each phase has a critical movement that is the movement having the largest demand to capacity ratio that ultimately restricts the required effective green for the phase in question. In (GIv23) we take into account potential reduced capacities due to pairs of semi-compatible movements within the phase that potentially may change the critical movement as opposed to (GI).
- In scheduling the phases (GIv23) considers reduced capacities due to overlapping splits of semi-compatible phases. This is almost equivalent to the idea of

previous item, however the difference being that those capacities were fixed due to fixed phases, whereas they may vary in (GIv23) when trying to find the optimal phase scheduling.

- The model (GI) is non-linear with respect to two variables: the cycle length and intersection capacity, that each must be optimized. The issue can be naively resolved in fixing one of the variables, however it is suggested to eliminate the cycle length by re-expressing relevant quantities in terms of ratios of a single cycle, which is to be considered in (GIv23). Interestingly, we will see that the elimination of the cycle length renders the overlap constraints presented in (GI) linear, thus simplifying the description of those constraints.

Input parameters

- Let $H = \{h_1, \dots, h_m\}$ be the set of movements of the intersection in question.
- Define a partial order (order of priority) on H such that $h_1, h_2 \in H$
 - are incompatible, $h_1 \equiv h_2$, in the sense that h_1 and h_2 have equivalent priority,
 - are semi-compatible, $h_1 \prec h_2$, in the sense that h_2 is the priority movement and h_1 must give way to h_2 . Note, a compatible pair of movements is not relevant to the partial order and the overall model.
- Let $\mathcal{K} = \{K_1, \dots, K_n\}$ be a predetermined phase-specification. The set \mathcal{K} is a partition of H , i.e.

$$\bigcup_{\forall K_i \in \mathcal{K}} K_i = H \quad \bigcap_{\forall K_i \in \mathcal{K}} K_i = \emptyset$$

implying that each movement appears in exactly one phase, thus having a single split during a cycle.

- Define a partial order (order of priority) on \mathcal{K} with respect to the partial order defined on H such that $K_i, K_j \in \mathcal{K}$ (recall the definition in chapter 1)
 - are incompatible, $K_i \equiv K_j$, if

$$\exists(h_1, h_2) \in K_i \cup K_j \mid h_1 \equiv h_2$$

- are semi-compatible, $K_i \bowtie K_j$, if

$$(h_1 \prec h_2 \vee h_1 \succ h_2) \forall (h_1, h_2) \in K_i \times K_j \quad (2.44)$$

where the introduced notation within the partial order for semi-compatible phases is due to the fact that both phases may contain an equal number of priority movements. For instance, consider $K_i = \{h_{i1}, h_{i2}\}$ and $K_j = \{h_{j1}, h_{j2}\}$ such that $h_{i1} \prec h_{j1}$ and $h_{i2} \succ h_{j2}$, with the two remaining pairs of movements being compatible, then neither $K_i \prec K_j$ or $K_i \succ K_j$ yield feasible orderings.

- Define the sets

$$I = \{(i, j) \in \{1..n\} \times \{1..n\} \mid K_i, K_j \in \mathcal{K} \mid K_i \equiv K_j\}$$

$$S = \{(i, j) \in \{1..n\} \times \{1..n\} \mid K_i, K_j \in \mathcal{K} \mid K_i \bowtie K_j\}$$

- Let \underline{c}, \bar{c} (seconds) be the lower and upper bound on the cycle length c (to be defined).
- Let $q_h, s_h \geq 0$ (both $pcus/h$) with $q_h \leq s_h$ be the arrival rate and saturation flow rate, respectively, for some movement $h \in H$.
- Let $\ell_{rci}^{ij} \geq 0$ (seconds) be the red clearance interval for $(i, j) \in I$ when transitioning from K_i to K_j . Note that we may have $\ell_{rci}^{ij} \neq \ell_{rci}^{ji}$.
- For each movement $h \in H$ we define (all in seconds)
 - Let \underline{r}_h be its minimum and \bar{r}_h its maximum effective red.
 - Let \underline{g}_h be its minimum and \bar{g}_h its maximum effective green.
 - Let ℓ_h be its total lost time, i.e., the sum of start-up delay and clearance lost time. Note, in contrast to the definition in chapter 1 the ℓ_h in this model does *not* include the red clearance interval being specified independently (see above).
- For each phase $K_i \in \mathcal{K}$ we define
 - Let $\underline{r}'_i = \max\{\underline{r}_h, \forall h \in K_i\}$ be its minimum and $\bar{r}'_i = \min\{\bar{r}_h, \forall h \in K_i\}$ be its maximum effective red.
 - Let $\underline{g}'_i = \max\{\underline{g}_h, \forall h \in K_i\}$ be its minimum and $\bar{g}'_i = \min\{\bar{g}_h, \forall h \in K_i\}$ be its maximum effective green.
 - Let $\ell_i = \max\{\ell_h, \forall h \in K_i\}$ be its lost time.
- Finally, the model (GI) defines the critical movement based on its flow ratio for each phase $K_i \in \mathcal{K}$ given by

$$\zeta_i = \max\{q_h/s_h, \forall h \in K_i\} \quad (2.45)$$

Differently from (GI) we take into account that a phase may contain pairwise semi-compatible movements such that the saturation flow rate of the non-priority movement is reduced. Let $h_a, h_b \in K_i$ be two semi-compatible movements in some phase $K_i \in \mathcal{K}$ such that $h_a \prec h_b$. During the green indication of K_i the flow of h_b affects that of h_a in two distinct ways.

- **Free flow:** During free flow in h_b we assume a linear reduction of the saturation flow rate given by

$$s'_{h_a} = s_{h_a} p_{h_b} \quad (2.46)$$

where $p_{h_b} = 1 - \frac{q_{h_b}}{s_{h_b}}$ is the probability that the flow in h_b has an available gap to let pcus from h_a pass. If $\frac{q_{h_b}}{s_{h_b}} \geq 1$ then the pcus of h_{h_b} maintain the saturation headway which is insufficient in providing any available gaps that allow the pcus of h_{h_a} to pass. In fact having $\frac{q_{h_b}}{s_{h_b}} \geq 1$ leads to oversaturation which this model can not handle. In general, given $h_a \in K_i$ and $K'_i = \{h_b \in K_i \setminus \{h_a\} \mid h_a \prec h_b\}$ then the adjusted saturation flow rate is given by

$$s'_{h_a} = s_{h_a} \prod_{\forall h_b \in K'_i} p_{h_b} \quad (2.47)$$

since the p_{h_b} s are independent events.

- **Conflicting standing queues:** During the red indication standing queues are build up. As the signal turns green the queues are discharged at the saturation flow rate during which there will be no available gaps for the pcus of h_a to pass. After every standing queue has been cleared free flow will be present for which the conditions described in previous item apply. Therefore, h_a must account for the required green time to clear the standing queue in each of the movements $h_b \in K'_i$ for which only the one with the largest demand to capacity ratio is relevant

$$Q_{h_a} = \max\{q_{h_b}/s_{h_b}, \forall h_b \in K'_i\} \quad (2.48)$$

Combining (2.45,2.47,2.48) the critical movement flow ratio is given by

$$\begin{aligned} \zeta_i &= \max\{Q_{h_a} + q_{h_a}/s'_{h_a}, \forall h_a \in K_i\} & \forall K_i \in \mathcal{K} \\ s'_{h_a} &= s_{h_a} \prod_{\forall h_b \in K'_i} (1 - q_{h_b}/s_{h_b}) \\ Q_{h_a} &= \max\{q_{h_b}/s_{h_b}, \forall h_b \in K'_i\} \end{aligned} \quad (2.49)$$

Decision variables

- For each phase $K_i \in \mathcal{K}$ we define
 - Let g_i be the effective green.
 - Let u_i, v_i be the starting time of G and ending time of Y such that $v_i - u_i$ is the split ratio of K_i which accounts for both g_i and ℓ_i .
- Let $f \geq 0$ be the intersection capacity factor. This is a maximum common multiple factor with respect to all movements.
- Let z be the reciprocal cycle length $\frac{1}{c}$ such that $\frac{1}{\bar{c}} \leq z \leq \frac{1}{c}$.
- Let $w_{ij} \in \{0, 1\}$ be a binary variable defined for each $(K_i, K_j) \in I$ such that $w_{ij} = 0$ if the split of K_i precedes that of K_j and $w_{ij} = 1$ otherwise, i.e., the split of K_j precedes that of K_i .
- Let $x_{ij} \in \{0, 1\}$ be a binary variable defined for each $(K_i, K_j) \in S$ such that $x_{ij} = 0$ if the splits of K_i and K_j overlap and $x_{ij} = 1$ otherwise.
- Let $y_{ij} \in \{0, 1\}$ be a binary variable defined for each $(K_i, K_j) \in S$ with $x_{ij} = 0$ such that $y_{ij} = 0$ if the split of K_i precedes that of K_j and $y_{ij} = 1$ otherwise, i.e., the split of K_j precedes that of K_i .

Constraint formulations

Recall from 1.4 that $c = g + r$, hence

$$\left. \begin{array}{l} z\underline{r}_i \leq 1 - g_i \leq z\bar{r}_i \\ z\underline{g}_i \leq g_i \leq z\bar{g}_i \end{array} \right\} \forall K_i \in \mathcal{K} \quad (2.50)$$

Since $v_i - u_i = G + Y$, assuming G, Y are ratios also, it follows from (1.3) that

$$v_i - u_i = g_i + z\ell_i \quad \forall K_i \in \mathcal{K} \quad (2.51)$$

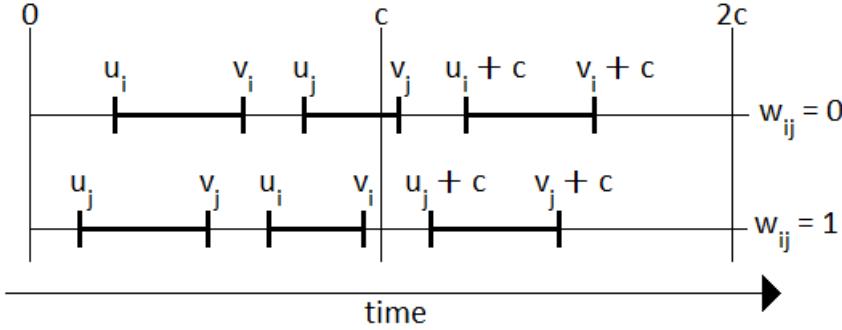


FIGURE 2.4: Time horizon for two cycles which amounts to a time span of two cycle lengths.

note, however, the absence of the red clearance interval which is specified independently.

Each phase $K_i \in \mathcal{K}$ must have sufficient effective green in order to the demand in each of its movements. This is constrained with respect to its critical movement.

$$g_i \geq f\zeta_i \quad \forall K_i \in \mathcal{K} \quad (2.52)$$

Here, f must be maximized since a high value indicates a sufficient utilization of the intersection capacity. If $f = 1$ then g_i in theory suffices for all phases assuming that pcus arrive uniformly, however, as this is unlikely to happen in real life the case of $f \geq 1$ is always desired. In contrast, it may not be possible to allocate a sufficient g_i due to a high value of ζ_i in which case we must have $f < 1$ in order to satisfy the constraint for the movement in question and the overall feasibility of the model. In addition, given $f < 1$ is much likely to cause oversaturation due to queue build ups resulting from phase failures.

A complete traffic signal plan (stage), when implemented in physical signals, may be initiated starting from an arbitrary point in the plan due its cyclic nature. For simplicity we assume

$$u_i \geq 0 \quad \forall K_i \in \mathcal{K} \quad (2.53)$$

such that the resulting plan of this model should be initiated at $t = 0$. In addition, if $u_i \geq 1$ then u_i can be shifted 1 units backwards (1 cycle) along the time axis due to the cyclic nature, thus

$$u_i \leq 1 \quad \forall K_i \in \mathcal{K} \quad (2.54)$$

The following constraints ensure that the split of incompatible phases do not overlap, see Figure 2.4. Let $(i, j) \in I$. If the split of K_i precedes that of K_j , i.e., $w_{ij} = 0$ then

$$z\ell_{rci}^{ij} + v_i \leq u_j \quad (2.55)$$

$$z\ell_{rci}^{ii} + v_j \leq u_i + 1 \quad (2.56)$$

and vice versa

$$z\ell_{rci}^{ij} + v_i \leq u_j + 1 \quad (2.57)$$

$$z\ell_{rci}^{ii} + v_j \leq u_i \quad (2.58)$$

Constraints (2.55-2.57) and (2.56-2.58) can be combined, respectively, as follows

$$\left. \begin{array}{l} z\ell_{rci}^{ij} + v_i \leq w_{ij} + u_j \\ z\ell_{rci}^{ji} + v_j \leq (1 - w_{ij}) + u_i \end{array} \right\} \forall (i, j) \in I \quad (2.59)$$

The splits $[u_i, v_i]$ and $[u_j, v_j]$ of a pair of semi-compatible phases $(K_i, K_j) \in \mathcal{K}$ are permitted to overlap *but it is not required*. The splits overlap if

$$u_i < v_j \wedge u_j < v_i \quad (2.60)$$

otherwise we can impose constraints functionally similar to (2.59) but without the red clearance interval, which is only relevant to incompatible phases. We write

$$\left. \begin{array}{l} u_i - v_j + \epsilon \leq 2x_{ij} \\ u_j - v_i + \epsilon \leq 2x_{ij} \\ z\ell_{rci}^{ij} + v_i \leq (1 - x_{ij}) + y_{ij} + u_j \\ z\ell_{rci}^{ji} + v_j \leq (1 - x_{ij}) + (1 - y_{ij}) + u_i \end{array} \right\} \forall (i, j) \in S \quad (2.61)$$

where $\epsilon > 0$ is introduced to handle the apparent strict inequalities. Next, given $x_{ij} = 0$ one must decide on additional constraints with respect to the characteristic of the overlap of the splits. We propose it must hold that

$$u_i = u_j \wedge v_j = v_i \quad (2.62)$$

such that we can apply the same ideas with regards to reduced saturation flow rates as for the critical movement flow ratio analysis discussed in the parameter section. Constraints (2.62) can be written

$$\left. \begin{array}{l} u_i - u_j + \epsilon \leq x_{ij} \\ v_j - v_i + \epsilon \leq x_{ij} \end{array} \right\} \forall (i, j) \in S \quad (2.63)$$

which holds since the starting or ending points of two splits can be at most 1 cycle apart. Note that (2.63) dominates the first two constraints in (2.61). In the following we generalize the notion of (2.49) with respect to the critical movement in the presence of overlapping splits of two semi-compatible phases. Given $K_i, K_j \in \mathcal{K}$ we consider

$$\begin{aligned} K'_i &= \{h_b \in K_i \cup K_j \setminus \{h_a\} \mid h_a \in K_i \mid h_a \prec h_b\} \\ K'_j &= \{h_b \in K_i \cup K_j \setminus \{h_a\} \mid h_a \in K_j \mid h_a \prec h_b\} \end{aligned}$$

from which we introduce two sets of constraints similar to (2.49)

$$\left. \begin{array}{l} f\zeta'_i - g_i \leq Mx_{ij} \\ f\zeta'_j - g_j \leq Mx_{ij} \end{array} \right\} \forall (i, j) \in S \quad (2.64)$$

where

$$\zeta'_i = \max\{Q_{h_a} + q_{h_a}/s'_{h_a}, \forall h_a \in K_i\} \quad (2.65)$$

$$s'_{h_a} = s_{h_a} \prod_{\forall h_b \in K'_i} (1 - q_{h_b}/s_{h_b}) \quad (2.66)$$

$$Q_{h_a} = \max\{q_{h_b}/s_{h_b}, \forall h_b \in K'_i\} \quad (2.67)$$

$$\zeta'_j = \max\{Q_{h_a} + q_{h_a}/s'_{h_a}, \forall h_a \in K_j\} \quad (2.68)$$

$$s'_{h_a} = s_{h_a} \prod_{\forall h_b \in K'_j} (1 - q_{h_b}/s_{h_b}) \quad (2.69)$$

$$Q_{h_a} = \max\{q_{h_b}/s_{h_b}, \forall h_b \in K'_j\} \quad (2.70)$$

and M is a constant that should be greater than a reasonable maximum achievable value of f . Note that $\zeta'_i, \zeta'_j \geq \zeta_i$ ¹, thus (2.64) restricts the effective green ratios to be larger and therefore dominates (2.49). Note also that one should compute the set of values for ζ'_i and ζ'_j prior to solving the model.

Finally, substituting $u_i = v_i - g_i - z\ell_i$ from (2.51) into all relevant constraints the position of the split is determined solely by v_i . From (2.54,2.53) the bounds on v_i become apparent

$$v_i \geq g_i + z\ell_i \quad (2.71)$$

$$v_i \leq 1 + g_i + z\ell_i \quad (2.72)$$

¹Recall that ζ_i is the critical movement for an arbitrary phase $K_i \in \mathcal{K}$ in the absence of overlaps.

Model summary

Model 2.1.3: Model (GIV23)

$$\begin{aligned}
 & \left. \begin{aligned}
 z\underline{r}_i &\leq 1 - g_i \\
 z\bar{r}_i &\geq 1 - g_i \\
 z\underline{g}_i &\leq g_i \\
 z\bar{g}_i &\geq g_i \\
 g_i &\geq f\zeta_i \\
 v_i &\geq g_i + z\ell_i \\
 v_i &\leq 1 + g_i + z\ell_i
 \end{aligned} \right\} \forall K_i \in \mathcal{K} \\
 & \left. \begin{aligned}
 z\ell_{rci}^{ij} + v_i - (v_j - g_j - z\ell_j) &\leq w_{ij} \\
 z\ell_{rci}^{ji} + v_j - (v_i - g_i - z\ell_i) &\leq (1 - w_{ij})
 \end{aligned} \right\} \forall (i, j) \in I \\
 & \left. \begin{aligned}
 (v_i - g_i - z\ell_i) - (v_j - g_j - z\ell_j) + \epsilon &\leq x_{ij} \\
 v_j - v_i + \epsilon &\leq x_{ij} \\
 z\ell_{rci}^{ij} + v_i - (v_j - g_j - z\ell_j) &\leq (1 - x_{ij}) + y_{ij} \\
 z\ell_{rci}^{ji} + v_j - (v_i - g_i - z\ell_i) &\leq (1 - x_{ij}) + (1 - y_{ij}) \\
 f\zeta'_i - g_i &\leq Mx_{ij} \\
 f\zeta'_j - g_j &\leq Mx_{ij}
 \end{aligned} \right\} \forall (i, j) \in S
 \end{aligned}$$

Objective function

We investigate the following objectives.

1. Maximization of the intersection capacity factor.
2. Maximization of the sum of effective green ratios.
3. Minimization of the cycle length (maximization of z).
4. Minimization of the average travel time. Webster's formula [11] describes the average travel time for a movement $h \in K_i$ in some phase $K_i \in \mathcal{K}$ given by

$$d_h(g_i, c) = 0.9 \cdot \left(\frac{s(c - g_i)^2}{2c(s_h - q_h)} + \frac{3600b^2}{2q_h(1 - b)} \right) \quad \text{seconds} \quad (2.73)$$

where $b = \frac{q_h c}{s_h g_i}$ is the degree of saturation. The first term is due to standing queue build ups during the red indication. The second term is the contribution due to random poisson arrivals investigated by Webster, the main idea being that the random arrivals nearer the saturation level contribute further delay. Finally, Webster considered a third term meant to decrease the travel time, but was simplified by a multiple factor of 0.9. Note that maximizing g_i and minimizing c would minimize the average delay.

Objectives 1) and 2) are positively correlated, however not strictly speaking as it may be possible only to increase the green of a single phase whilst f must remain unchanged due to some other phase whose green can not be increased.

The *critical* cycle length is the required cycle length such that $f = 1$.

Given a set O of objectives there are two ways to handle multi-objectives

- one defines a lexicographical, or priority, order on O , say $o_1 < o_2 < \dots < o_n$, such that the optimal value of o_i is accepted only if it does not degrade the values of $o_{j=1..i} | j < i$.
- one assigns to each objective $o_i \in O$ a weight $w_i \in \mathbb{R}$ from which a single objective is derived by the linear combination $f(O) = \max \sum w_i o_i$.

Intuitively speaking, one expects the best solution if each movement is considered individual phases.

- Is it any beneficial to have semi-compatible phases?
- Pure optimization vs real life considerations, e.g. in real life, phase-specifications may exist to prioritize safety over the sum of green durations.
- The trade-off between semi-compatible phases with reduced capacities but shorter cycle length (less lost time and fewer red clearance intervals), or incompatible phases with constant capacities but longer cycle length (more lost time and more red clearance intervals).

2.1.6 An extended version, (GIv4), of (GIv3)

Once again, the details of the extensions are highlighted in the model description.

- Given a set of movements H the model (GIv4) considers the set of all phases $\mathcal{K} = \mathcal{P}(H) \setminus \emptyset$. At first sight each phase $K \in \mathcal{K}$ is unconditional in the sense that two movements $h_a, h_b \in K$ may be incompatible, but as pointed out in chapter 1 such a phase is infeasible due to the lack of a priority order. Thus, let $\mathcal{K}_{con} \subseteq \mathcal{K}$ be the set of conditional phases such that no phase contains a pair of incompatible movements. Note that \mathcal{K}_{con} is *not* the phase-specification meaning that each phase is not required to be a part of the final phase-specification. Similar to (GIv2) we constrain

$$\bigcup_{\forall K \in \mathcal{K}_{con}} K = H \quad \text{but not} \quad \bigcap_{\forall K \in \mathcal{K}_{con}} K = \emptyset$$

thus final phase-specification may contain multiple phases sharing a common movement. Consequently, depending on the phase scheduling a movement may receive more than one green interval in a cycle. The main task of this model is then to maximize the number of phases and their split durations such that each movement appears in at least one phase while ensuring a feasible phase scheduling.

Input parameters

- Let $H = \{1, \dots, m\}$ be the set of unique movements of the intersection in question.

- Let $\mathcal{K}_{con} = \{K_1, \dots, K_n\}$ be an ordered set of phases such that $K_i \subseteq H$ for $i = 1..n$ and

$$\bigcup_{\forall K \in \mathcal{K}_{con}} K = H$$

- Define the sets $S = \{(I, J) \in \mathcal{K}_{con} \times \mathcal{K}_{con} \text{ s.t. } I, J \text{ are semi-compatible}\}$ and $P = \{(I, J) \in \mathcal{K}_{con} \times \mathcal{K}_{con} \text{ s.t. } I < J \wedge I, J \text{ are incompatible}\}$.
- Let $c \geq 0$ be the cycle length.
- Let q_h, s_h be the arrival rate and saturation flow rate, respectively, for some movement $h \in H$.
- Let ℓ_{IJ}^{rci} be the red clearance interval for incompatible phases $I, J \in \mathcal{K}_{con}$ when transitioning from I to J . Note that we may have $\ell_{IJ}^{rci} \neq \ell_{JI}^{rci}$.
- Given a movement $h \in H$ the following parameters hold.
 - Let $r_{h,\min}, r_{h,\max}$ be its minimum and maximum effective red.
 - Let $g_{h,\min}, g_{h,\max}$ be its minimum and maximum effective green.
 - Let ℓ_h be its lost time, i.e., the sum of the start-up delay and clearance lost time.

- Given a phase $K \in \mathcal{K}$ the following parameters hold.

- Let $r_{K,\min} = \max\{r_{h,\min}, \forall h \in K\}$ be its minimum and $r_{K,\max} = \min\{r_{h,\max}, \forall h \in K\}$ be its maximum effective red, respectively.
- Let $g_{K,\min} = \max\{g_{h,\min}, \forall h \in K\}$ be its minimum and $g_{K,\max} = \min\{g_{h,\max}, \forall h \in K\}$ be its maximum effective green, respectively.
- Let $\ell_K = \max\{\ell_h, \forall h \in K\}$ be its lost time.
- Let (as derived in version 1)

$$\zeta_K = \max\{q_i/s'_i, \forall i \in K\} \quad (2.74)$$

$$s'_i = s_i \prod_{\forall j \in K_i} (1 - q_j/s_j) \quad (2.75)$$

be its critical movement flow ratio.

Decision variables

- Let $\mathcal{K}'_{con} \subseteq \mathcal{K}_{con}$ be the set of phase specifications.
- Let $p_K \in \{0, 1\}$ be a binary variable defined for each phase $K \in \mathcal{K}_{con}$ such that $p_K = 0$ if $K \in \mathcal{K}'_{con}$ and $p_K = 1$ otherwise.
- Let $f \geq 0$ be the *intersection capacity factor*. This is a maximum common multiple factor with respect to all phases.
- Let $w_{IJ} \in \{0, 1\}$ be a binary variable defined for each $(I, J) \in P$ such that $w_{IJ} = 0$ if I precedes J , and $w_{IJ} = 1$ otherwise, i.e., J precedes I .
- Let $x_{IJ} \in \{0, 1\}$ be a binary variable defined for each $(I, J) \in S$ such that $x_{IJ} = 0$ if the splits of I and J overlap and $x_{IJ} = 1$ otherwise.

- Let $y_{IJ} \in \{0, 1\}$ be a binary variable defined for each $(I, J) \in S$ given $x_{IJ} = 0$ such that $y_{IJ} = 0$ if the split of I precedes that of J and $y_{IJ} = 1$ otherwise.
- Given a phase $K \in \mathcal{K}_{con}$ the following variables hold.
 - Let u_K, v_K be the starting time of G and ending time of Y , respectively, such that $v_K - u_K$ is the split of K .
 - Let g_K be the effective green.

Constraint formulations

All constraints from model version 1 carry over to this model, but additional constraints must be considered.

We must have

$$\bigcup_{\forall K \in \mathcal{K}'_{con}} K = H \quad (2.76)$$

$$(2.77)$$

Each movement $h \in H$ must appear in at least one of the phases in \mathcal{K}'_{con}

$$??? \quad (2.78)$$

The splits $[u_I, v_I]$ and $[u_J, v_J]$ of a pair of semi-compatible phases $(I, J) \in S$ are permitted to overlap *but it is not required*. The splits overlap if

$$u_I < v_J \wedge u_J < v_I \quad (2.79)$$

otherwise we can impose constraints functionally similar to (??) but without the red clearance interval, which is only relevant to incompatible phases. We write

$$\left. \begin{array}{l} u_I - v_J + \epsilon \leq Mx_{IJ} \\ u_J - v_I + \epsilon \leq Mx_{IJ} \\ v_I - u_J \leq M(1 - x_{IJ}) + My_{IJ} \\ v_J - u_I \leq M(1 - x_{IJ}) + c + My_{IJ} \\ v_J - u_I \leq M(1 - x_{IJ}) + M(1 - y_{IJ}) \\ v_I - u_J \leq M(1 - x_{IJ}) + c + M(1 - y_{IJ}) \end{array} \right\} \forall (I, J) \in S \quad (2.80)$$

where M is a large constant and $\epsilon > 0$ is introduced to handle the apparent strict inequalities. In model version 2 we constrained the split of a non-priority movement to be included in that of the priority one. However, given two phases $I, J \in \mathcal{K}_{con}$, I may contain a priority movement with respect to some movement in J and/or vice versa. Therefore, we must constrain the splits of I and J be equal and overlap if $x_{IJ} = 0$

$$u_I = u_J \wedge v_I = v_J \quad (2.81)$$

that translates into

$$??? \quad (2.82)$$

Finally, we need to consider the semi-compatibilities among $I \times J$ for $I, J \in \mathcal{K}_{con}$ with respect to reduced saturation flow rates.

Objective function

The objective function remains almost unchanged with respect to the one in version 1 (and version 2). We must consider the maximization of the number of phases in the phase specification

$$\max \sum_{\forall K \in \mathcal{K}_{con}} p_K \quad (2.83)$$

Remark

Given a large number of movements the set \mathcal{K}_{con} may render the model computationally infeasible. Alternatively, one may introduce the set $\mathcal{K}_{fea} \subseteq \mathcal{K}_{con}$ of phases chosen for the sake of computational feasibility.

Model summary

Model 2.1.4: Model (GIV4)

2.1.7 Implementation details

For any intersection it is sufficient specifying only the compatibilities between each pair of movements, as one may then derive necessary relationships among movements composing individual phases (with respect to phase specifications), and among each pair of phases (with respect to phase orderings).

2.1.8 Examples

We consider a four-way intersection with exclusive left and right turn lanes and pedestrian lane for each approach whose movements are numbered as shown in Figure 2.5. The cycle length is a parameter, set to $c = 60$. The example is solved by means of the above model versions 1 and 2.

- Version 1 - we apply the set of phase specifications from Figure 2.6 (non-singleton).
- Version 2 - we consider each movement as a single phase (singleton).

Figure 2.7 and 2.8 illustrate the solutions.

Model version 2 is superior to version 1 in terms of both objectives.

2.2 Fixed-time coordinated signals

2.2.1 MAXBAND

Given a set of pre-optimized fixed time isolated signals they must share a common cycle length in order to be coordinated.

Consider the above nameless method being applied individually to n consecutive intersections S_1, \dots, S_n . The MAXBAND method [6] determines the optimal

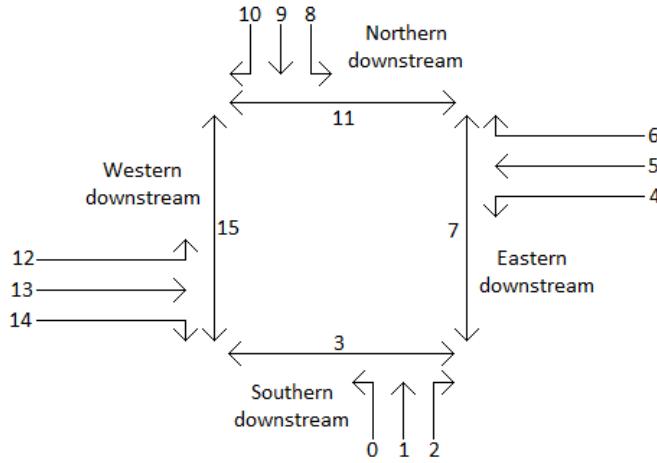


FIGURE 2.5: Movement numbering in a four-way intersection with exclusive left and right turn lanes. Note, each downstream is a single lane e.g. the northern downstream collects incoming traffic from movement 1, 6 and 12. In this example we assume an unique traffic signal assigned to each movement, i.e., the number of lanes equal the number of movements.

offsets based on the determined parameters for each S_i , however, it assumes a common cycle time among all intersections that is unlikely to happen due to each intersection being treated separately. A proposed solution is to apply the nameless method to each intersection followed by another application in which the cycle time is constrained to be equal to the maximum cycle time found among all intersections during the initial application. This is reasonable since an increased cycle time has more effective green time available for allocation among the phases.

2.3 Traffic-responsive isolated signal

The *vehicle-interval method* [8] utilizes real-time measurements from induction loops. It is applicable to an intersection whose movements may be served using only two phases, possibly a three-way (T-shaped) intersection. As the name suggests it does not consider pedestrian and bicycle movements. Each upstream induction loop is located some distance behind the intersection. Minimum green durations (possibly different) are assigned to both phases. Consider the beginning of one of the two phases at an arbitrary point in time. The method asks whether a vehicle passed the induction loop during the minimum green duration. If so, the r.o.w. is extended to a degree that allows the vehicle to pass the intersection based on the speed limit. In the extended r.o.w. the method keeps asking if additional vehicles pass the induction loop, whose presence similarly extends the r.o.w. The process goes on until some maximum green time has been reached, at which the other phase is employed. The method may be deemed a reactive strategy, as it constantly requires yes/no answers only.

2.4 Traffic-responsive coordinated signals

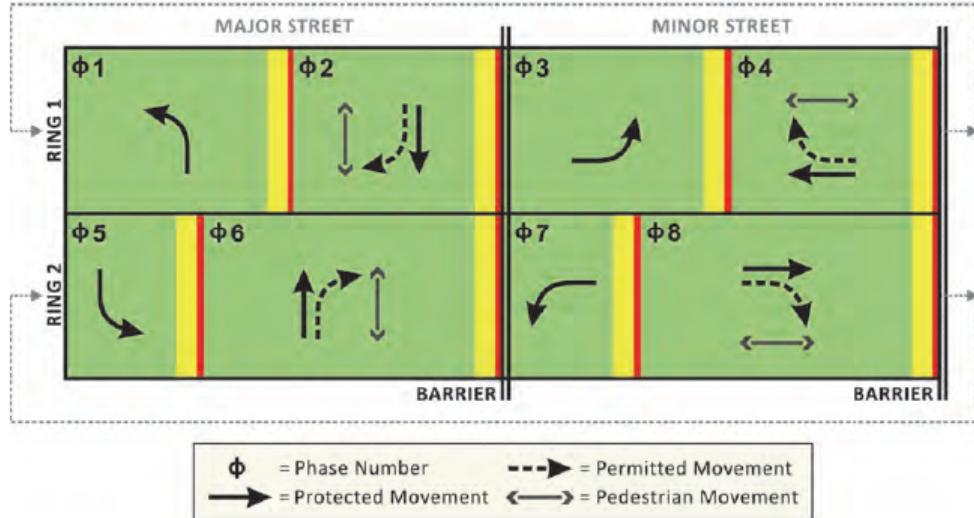


FIGURE 2.6: ADD CAPTION

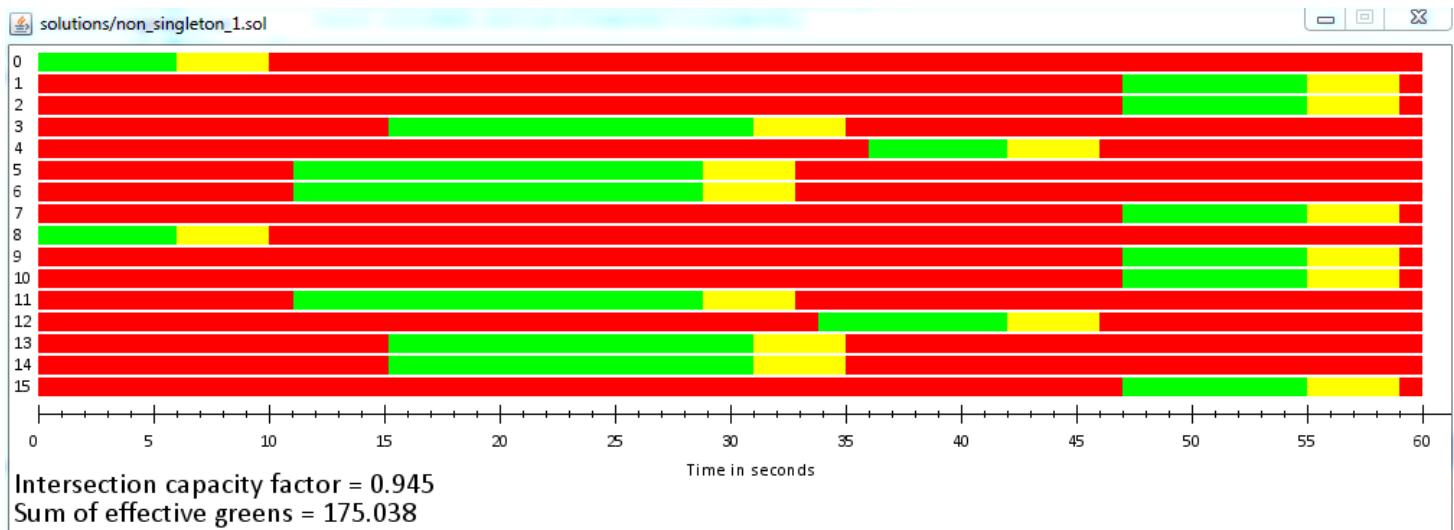


FIGURE 2.7: Time signal plan using predetermined phase specifications. Note, the plot illustrates the display sequence for each individual movement although several movements compose a common phase.

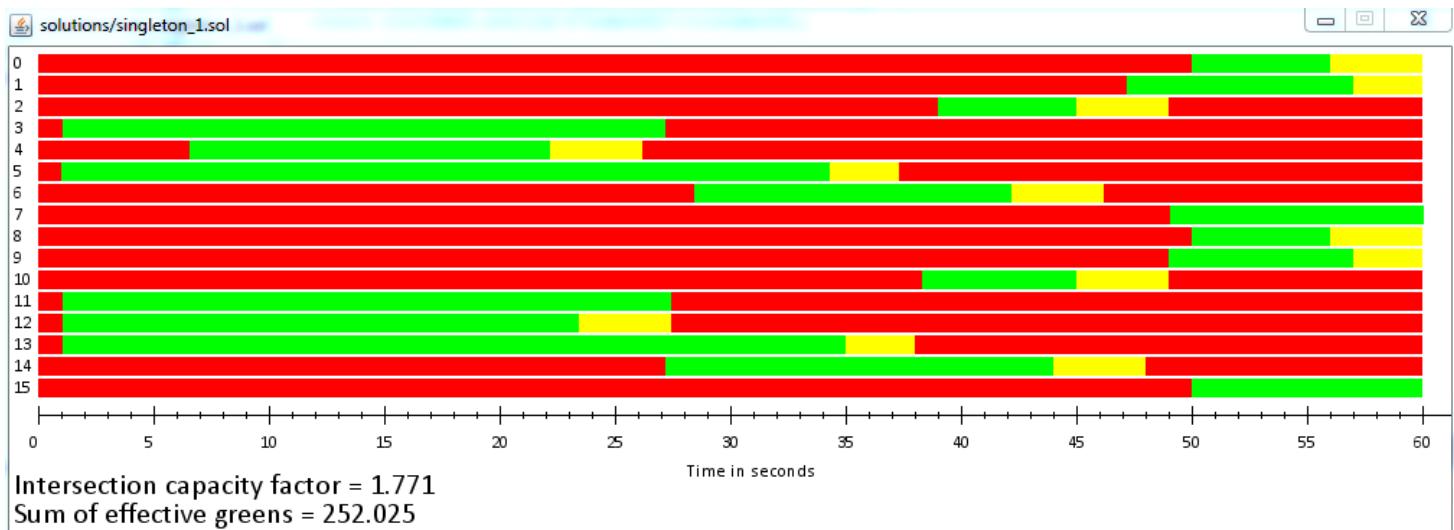


FIGURE 2.8: ADD CAPTION

Chapter 3

Traffic signal simulation

3.1 Motivation

The evaluation strategy of a traffic control system, as described in chapter 1, concerns the task of estimating performance measures based on simulation studies. In particular, this chapter addresses the usage of microscopic simulations.

The general concept of a microscopic traffic signal simulation is that each traffic user is treated individually as separate entities that interact and behave accordingly to its surroundings. A common application is by means of *car-following models* in which each vehicle adjusts its velocity and acceleration with respect to the one in front of it.

3.2 Review of car-following models

3.3 A microscopic traffic signal simulation

We present and discuss a simple microscopic traffic signal simulation. It is made in the Java programming language.

3.3.1 The simulation loop

In general, a simulation loop controls the overall flow of any computer/video game and/or simulation.

- A *tick* refers to a single action in which the logic is updated once with respect to some time step, in particular the position, velocity and acceleration of each vehicle.
- The *rendering* refers to the drawing of every object (vehicles, traffic signals, roads etc.) onto the screen.

A common game loop example design of highest simplicity employing the above concepts is given in **Algorithm 1**.

Algorithm 1

```

1: procedure RUNSIMULATION
2:   while isRunning do
3:     update game logic (tick)
4:     draw to screen (render)
5:   end while
6: end procedure

```

A crucial task in developing a game loop is to ensure a smooth real time simulation flow independent of the hardware of the device on which it is being run. In fact, the game loop 1 exhibits certain flaws as it does not keep track of nor does it measure the time passed, therefore a fast computer would run through the loop at a much greater rate than what would be a conceivable simulation. As already explained the ticks control the game logic, thus they are the ones on which to impose time constraints in order to force a specific number of ticks per second (TPS). In contrast, the rendering frequency, also known as the number of frames per second (FPS), may be as high as possible only limited by the capabilities of the computer. One may argue, however, that rendering a frame should take place only between two ticks to avoid unnecessary utilization of computing resources as the logic of the simulation effectively does not change otherwise.

The above concepts are implemented in Java as follows.

```

1 nspt = 1_000_000_000.0 / tps;
2 delta = 0;
3 lastTime = System.nanoTime();
4 while (true) {
5     now = System.nanoTime();
6     delta += (now - lastTime) / nspt;
7     lastTime = now;
8     while (delta >= 1) {
9         tick();
10        delta--;
11    }
12    render();
13 }
```

The parameters are as follows.

- TICKS1 is the number of ticks per second.
- nspt is the time interval between two consecutive ticks.
- delta accumulates the current time taken as a fraction of npts.
- lastTime and now are timestamps that are used in order to measure the real time simulation advancement.

Figure 1 illustrates the game loop flow details starting at the `while` initialization and onwards 1 second. During the first nspt period there is no tick. This is reasonable as the initial game logic should be rendered prior to any tick updates. The following nspt periods then always first carries out a tick followed by as many renderings as manageable for the computer during the remainder of nspt.

DESCRIBE THE DIFFERENCE BETWEEN SIMULATION TIME AND REAL TIME.
The execution time of the simulation is what we can speed up, the simulation time IS the same as the real time.

In addition to TICKS1 there are two crucial parameters, however not apparent in the game loop, associated with ensuring a smooth real time simulation. In addition, they also ensure a 1:1 scale compared to the real world.

- TICKS2 is the simulation time advancement per tick expressed as a fraction of 1 second. For instance, if TICKS1 = TICKS2 = 1 then the simulation runs in real time since we are executing 1 tick per second and each tick is updating the game logic during a time interval of 1/1 of a second, however, the resulting

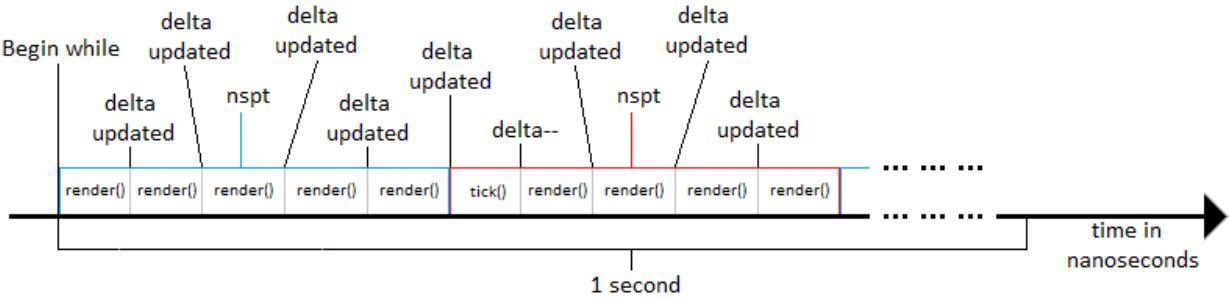


FIGURE 3.1: The game loop flow between ticks and rendering for $\text{TICKS1} = \text{TICKS2} = 60$. Each time interval nspt contains a single tick and 4 renderings (in practice it may vary from 3 to 5). Each tick and render block has a duration of $(\text{now} - \text{lastTime}) / \text{nspt}$

simulation is very jumpy. Similarly, if $\text{TICKS1} = \text{TICKS2} = 60$ then the simulation also runs in real time since we are executing 60 ticks per second and each tick is updating the game logic during a time interval of $1/60$ of a second. In the latter case, the simulation runs much smoother.

- $\text{PPM} \in \mathbb{R}$ (pixels per meter) describes the equivalent distance of 1 meter in terms of screen pixels. It serves as a zooming parameter. Given $\text{PPM} = 2$ and $\text{TAPT} = \frac{1}{60}$ then the conversion from velocity $13.88 \frac{\text{m}}{\text{s}} (\approx 50 \frac{\text{km}}{\text{h}})$ to unit $\frac{\text{pixels}}{\text{tick}}$ is given by

$$13.88 \frac{\text{m}}{\text{s}} \cdot 2 \frac{\text{pixels}}{\text{m}} \cdot \frac{1}{60} \frac{\text{s}}{\text{tick}} \approx 0.463 \frac{\text{pixels}}{\text{tick}} \quad (3.1)$$

thus it becomes evident that moving 0.463 pixels 60 times during 1 second gives rise to smooth movements as stated above, compared to the jumpy situation in which one would move $13.88 \frac{\text{m}}{\text{s}} \cdot 2 \frac{\text{pixels}}{\text{m}} \cdot 1 \frac{\text{s}}{\text{tick}} = 27.76 \frac{\text{pixels}}{\text{tick}}$. Consequently, one should fix $\text{TAPT} = \frac{1}{60}$ ¹.

The most useful relationship between tps and TAPT is the opportunity to speed up the simulation in-time with respect to real time. For instance, to speed up by a factor of 10 one would set $\text{tps} = 600$.

The game loop does not impose any explicit restrictions on the FPS other than that the specified TPS is prioritized, i.e., if TPS is very large then the FPS considerably drops. However, it is worth mentioning that for small values of TICKS1 one may replace

<pre> 1 while ($\text{delta} \geq 1$) { 2 $\text{tick}();$ 3 $\text{ticks}++;$ 4 $\text{delta}--;$ 5 } 6 $\text{render}();$ 7 $\text{frames}++;$ </pre>	if ($\text{delta} \geq 1$) { $\text{tick}();$ $\text{ticks}++;$ $\text{render}();$ $\text{frames}++;$ $\text{delta}--;$ }
--	--

in order to force $\text{TPS} = \text{FPS}$ as to minimize unnecessary rendering.

¹At present day, the majority of movies and video games are captured at 24 FPS, however, they generally aim towards achieving 60 FPS at which most people perceive smoother movements.

The following is the rendering method. The Java programming language offers the class `BufferStrategy` from which one creates a buffer strategy. Essentially, the buffer strategy preloads rendered images in advance prior to be displayed. This ensures that the next image need not be created when requested. The integer argument (in this case 3, also known as triple buffering) determines the number of preloaded images.

```

1  private void render() {
2      BufferStrategy bs = this.getBufferStrategy();
3      if (bs == null) {
4          this.createBufferStrategy(3);
5          return;
6      }
7      Graphics g = null;
8      try {
9          g = bs.getDrawGraphics();
10
11         //////////////// Do all rendering ///////////
12         //////////////// Do all rendering ///////////
13         //////////////// Do all rendering ///////////
14
15     }
16     finally {
17         g.dispose();
18     }
19     bs.show();
20 }
```

The simulation may run freely without any restrictions on the number of ticks per second. In addition the rendering may be ignored enabling a large number of ticks per seconds. This is helpful especially when assessing a traffic signal schedule and one needs to simulate the scenario spanning, say, 24 hours over multiple iterations (due to randomness and we then take the average).

3.3.2 Dynamic vehicle interactions

The behaviour of a trailing vehicle depends on the characteristic parameters of itself and those of the leading vehicle. A vehicle has the following parameters

- `maxAccel` is the maximum acceleration in any given situation,
- `brakePace` is the desired deceleration upon braking given prevailing conditions,
- `maxBrake` is the maximum brake capability in any given situation,
- `reactionTime` is the elapsed time between the point in time at which the leading vehicle decides to accelerate or brake, and the point in time at which this vehicle responds accordingly,
- `length` is the physical length,
- `leftTurningSpeed` (`rightTurningSpeed`) is the safe velocity at which the vehicle performs a left (right) turn. Reasonable values of the former (latter) are near 60% (40%) of the speed limit,
- `minHW` is the minimum tip-to-tail headway

Real life drivers mostly are clueless about the characteristics of the leading vehicle that may cause collisions due to misjudged appropriate tip-to-tail distances. This model is meant to describe accident-free flows as collisions are almost always caused by abnormal driver behaviours that we do not consider [10].

We consider a type of intelligent driver model in which each vehicle always strives to maintain some *minimum safety headway* (MSH) based on the above parameters.

Definition 1. Let d be the reaction time of the trailing vehicle. Consider the following two points in time.

- At $t = 0$ the leading vehicle starts to brake at its desired brake pace.
- At $t = d$ the trailing vehicle responds accordingly and starts to brake at its desired brake pace, assuming its acceleration during the interval $t = [0, d]$ is constant due to its reaction time.

The MSH is the required tip-to-tail distance at $t = 0$ such that at $t = d$ the corresponding tip-to-tail distance allows the trailing vehicle to come to a full stop w.r.t. its desired brake pace.

The MSH can be derived as follows. Consider two vehicles. At $t = d$ the positions of the tip of the trailing vehicle and the tail of the leading one are given by, respectively

$$s_{trail}(t = d) = \frac{a_{trail}d^2}{2} + v_{trail}(t = 0)d + s_{trail}(t = 0) \quad (3.2)$$

$$s_{lead}(t = d) = \frac{b_{lead}d^2}{2} + v_{lead}(t = 0)d + s_{lead}(t = 0) \quad (3.3)$$

The tip-to-tail distance at $t = d$ is given by

$$s_{lead}(t = d) - s_{trail}(t = d) \quad (3.4)$$

which, according to Definition 1, must be the exact distance required such that the trailing vehicle may come to a full stop w.r.t. its desired brake pace. This brake distance is given by

$$\frac{v_{lead}(t = d)^2 - v_{trail}(t = d)^2}{2b_{trail}} \quad (3.5)$$

where

$$v_{lead}(t = d) = b_{lead}d + v_{lead}(t = 0) \quad (3.6)$$

$$v_{trail}(t = d) = a_{trail}d + v_{trail}(t = 0) \quad (3.7)$$

Therefore we must have

$$b_{trail} = \frac{v_{lead}(t = d)^2 - v_{trail}(t = d)^2}{2(s_{lead}(t = d) - s_{trail}(t = d))} \quad (3.8)$$

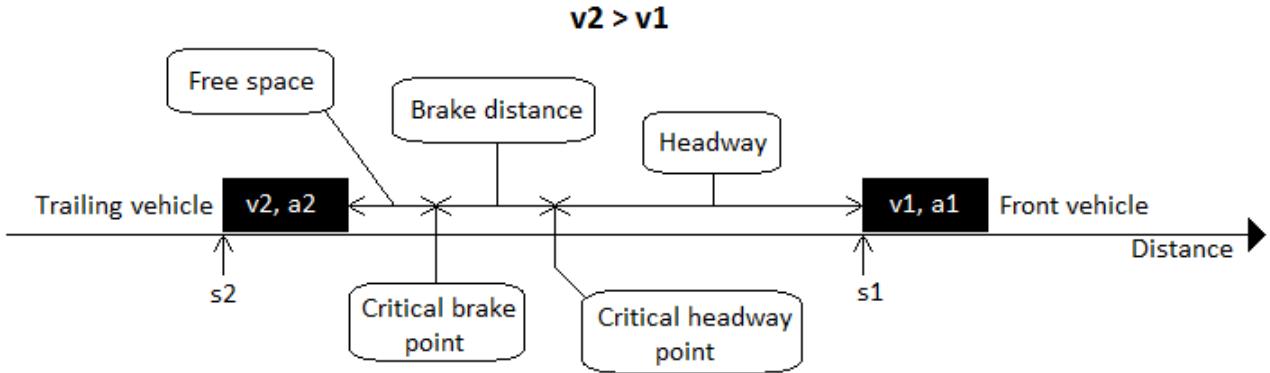


FIGURE 3.2: The interval between each pair of vehicles is divided into three regions.

Finally, we substitute (3.2,3.3) into (3.8) and isolate $s_{lead}(t = 0) - s_{trail}(t = 0)$ that corresponds to the MSH

$$MSH = \frac{(b_{lead}d + v_{lead})^2 - (a_{trail}d + v_{trail})^2}{2b_{trail}} + \left(\frac{a_{trail}d^2}{2} + v_{trail}d \right) - \left(\frac{b_{lead}d^2}{2} + v_{lead}d \right) \quad (3.9)$$

Let h denote the actual tip-to-tail headway. Setting $MSH = h$ we can solve for a_{trail} that is the acceleration function of the trailing vehicle.

$$a_{trail} = \left(b_{trail}d - 2v_{trail} + \sqrt{\sum \alpha_i} \right) (2d)^{-1} \quad (3.10)$$

$$\alpha_1 = 4d^2(b_{lead} - b_{trail}/2)^2 \quad (3.11)$$

$$\alpha_2 = d((4v_{trail} - 8v_{lead})b_{trail} + 8v_{lead}b_{lead}) \quad (3.12)$$

$$\alpha_3 = -8b_{trail}h \quad (3.13)$$

$$\alpha_4 = 4v_{lead}^2 \quad (3.14)$$

If $h > MSH$ then $a_{trail} > 0$ but the velocity is constrained by some speed limit and we must have $a_{trail} \leq \text{maxAccel}$. In contrast, the situation in which $a_{trail} < 0$ is limited by maxBrake .

The simulation considers three regions encapsulated between two critical points and the tip and tail of the trailing and leading vehicle, respectively. This is illustrated in Figure 3.2. Figure 3.2 illustrates The headway region is always greater than 0 due to a forced minimum headway. The brake region is present only given a difference in velocity. The free space region may occur whether or not the brake region is present.

Upon braking the deceleration is recomputed every tick. This makes vehicles brake at non constant deceleration.

- Low reaction time and low brake pace: cautious drivers. Requires large headway.
- High reaction time and high brake pace: aggressive drivers. Requires small headway.
- The last two options 1) low reaction time and high brake pace, 2) high reaction time and low brake pace, require medium headways.

The *minimum safe headway*

3.3.3 Stability analysis

- Explain the role of EPS...
- The value of TAPT imposes restrictions on EPS.
- The value of `maxAccel` must not exceed a certain value (to be explained) in order to ensure stability.

3.3.4 Vehicle spawning

Spawning formula

At each tick it is determined if a vehicle may spawn with respect to the arrival rate. There are $3600 \cdot \frac{1}{TAPT}$ ticks per hour, thus we expect $\frac{q \cdot TAPT}{3600}$ spawning pcus per tick. Therefore the arrival rate is respected if, for every tick, we consider

$$p \leq \frac{q \cdot TAPT}{3600} \quad p \in [0..1] \quad (3.15)$$

As an example, consider $q = 3600 \frac{\text{pcus}}{h}$ and $TAPT = \frac{1}{60} \frac{s}{\text{tick}}$ then $p \leq \frac{1}{60} \frac{\text{pcus}}{t}$. Assuming 60 ticks per second (real time due to $TAPT = \frac{1}{60} \frac{s}{\text{tick}}$) we expect 1 pcu per second which is equivalent to q . Alternatively, assuming, say 180 ticks per second, we expect 3 pcus per second, however, the simulation runs 3 times faster than real time, thus the arrival rate is scaled up correspondingly.

Spawning variable specification

We assume $a_{trail} = 0$ of a spawning vehicle. Let h be the actual tip-to-tail distance, then the safe spawning velocity is given by

$$v_{trail} = db_{trail} + \sqrt{d^2 b_{trail}^2 + (-d^2 b_{lead} - 2v_{lead}d - 2h)b_{trail} + (b_{lead}d + v_{lead})^2} \quad (3.16)$$

3.3.5 Handling oversaturation

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- Vehicle trajectory bandwidth, 10
- Volume, 14
- Yellow change interval, 8