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Cooperative Self-Organizing System for low Carbon Mobility at low Penetration Rates

COLOMBO: Deliverable 2.2

Policy Definition and dynamic Policy Selection Algorithms

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1 Introduction

This deliverable contains the results of the two Tasks of WP2, namely Task 2.1 on Control System Requirements and Task 2.2 on Policy Definition and Implementation.

The first task is aimed defining the control system requirements concerning the policies currently implemented in traffic-lights control systems and their potential adaptation to the self-organizing structure of the developed system have been collected by all partners.

In parallel, national traffic signal guidelines (e.g. German RiLSA-2010, Austrian RVS, British TSRGD-2002 and COLOMBO partnering countries as Italy, Belgium and France) have been collected by TUG and analysed. Relevant legal constraints on inter greens between conflicting movements, phasing and minimum/maximum green and cycle times will be checked by TUG.

The second task instead is devoted to the policy definition and implementation**.** Every policy pursues its own local goals to reach the best overall traffic performance, i.e. to give the single driver the most comfortable experience (highest average speed, lowest wait time at an intersection, etc.) and to help the environment with a sensible decrease in air pollution. Each policy is defined as a set of rules that should be triggered in a given traffic condition. As stated before, different traffic densities need different approaches: policies for low, medium, heavy/congested traffic conditions will be defined by UNIBO.

Therefore this deliverable is divided into two parts: in the first we present a thorough overview of existing control methods and policies, while the second part presents the policies implemented in COLOMBO and the policy selection algorithm that will combine the single policies according to different traffic scenarios.

1.1 Motivation

"*A traffic light or traffic signal is a signalling device positioned at a road intersection, pedestrian crossing, or other location in order to indicate when it is safe to drive, ride, walk, using a universal colour code*". This explanation could be used for every country in the world, but the universal colour code is not the same everywhere.

Despite light signal plants are almost used all over the world, there is no identical handling, appearance, arrangement, usage, calculation method,… concerning light signals. Also within the continent Europe there are no unique guidelines for light signal plants, nor complete agreement on the terms used to identify the same concepts.

Similarly, different countries implement different methods for junction control, following guidelines that may be normative or not.

A general understanding of the problem of traffic control is prerequisite to understanding the different approaches to signal control method, a possible classifications and the new approaches and policies presented in the second part of the document.

1.2 Objectives

Within this work, a lot of guidelines were studied, including the Austrian StVO and RVS, the German StVO, RiLSA and HBS, the MUTCD, TAL, TSRGD and Road Traffic Act of the United Kingdom and others from different countries. The goal was to identify any relevant differences that may impact the design and control of junctions and traffic light. The countries to address were chosen based on the familiarity of COLOMBO partners with the respective guidelines. Additionally, guidelines from all countries COLOMBO partners are located in were chosen, assuming that the respective familiarity with the language would allow to take these guidelines into account as well.

Another important point was to identify a common and non-ambiguous glossary, because among European countries there are different terms with the same meaning and, which is more confusing, sometimes the same term can be used with different meanings.

One emphasis lies on the calculation of intergreen time, where terms such as stages, signal groups, clearance/entrance speed and distance, green periods and green splits, cycle length…are explained, using a simple example.

Generally, the first part of this document should give non traffic engineers a sufficient insight into light signal control and all that goes with it for a clear understanding of the coherences and significances.

The second part of the document should help understand how swarm-intelligence derived concepts have been applied to traffic control, how control methods defined using this approach fall into a more general classification and how they perform in simulation.

1.3 Structure

Chapters 2 to 7 make the first part of the document, related to Task 2.1:

In chapter 2, a literature research points out a lot of differences regarding to light signals, between Austria, Belgium, France, Germany, Italy, Netherlands, and United Kingdom. Normally the street user can handle the different light signals in a safe way, but when planning light signals certain differences could be recognised. In this chapter, a common and unambiguous glossary is defined, highlighting the concepts that will be used in the rest of the document.

In chapter 3, a general overview of signal control methods and a classification after Fixed Time (time dependent) Signal Control, Actuated (traffic dependent) Signal Control and Adaptive Signal Control is presented.

In chapter 4, time-dependent, fixed time signal control methods are presented, and a thorough explanation of the prerequisites for designing this kind of control methods is shown

In chapter 5, the coordination of arterials and networks is properly explained. While this is a special case of time-dependent control, it deserved a full chapter because coordination is very important when controlling arterial streets, mostly in urban areas.

In chapter 6, traffic dependent signal control methods are presented, with a peculiar emphasis on fully traffic dependent, actuated signal control.

Chapter 7 introduces adaptive signal control systems, providing also some historical background on their development and adoption in Europe. The different approaches and results of several methods used all over the world are presented.

Chapter 8 constitutes the second part of the document, the one related to task 2.2. It presents the traffic control method designed for the COLOMBO project, how it is split into a macroscopic level adaptive control system and into several microscopic level policies. Preliminary results on the usage of these policies compared to other policies already implemented into the simulation environment are reported.

Finally, the conclusions are given in Chapter 9.

2 General Information

In this chapter the basics terms of traffic, needed for understanding the content of this document are explained. Therefore, some definitions of terms are included. A glossary of the used traffic terms is given in Section 2.2. Moreover different types of signal heads and signal light sequences for certain countries are shown.

2.1 Signal Group and Stage

The interface between a road user and a traffic signal are the signal heads mounted on poles. Typically a number of identical signal heads are mounted which is important in case of failures. In traffic control language we talk about signal groups. A signal group is the smallest entity of signal heads which indicates exactly the same aspect at each time. Unfortunately the term “signal group” is not used in British English. In the UK the term phase is used instead. In German speaking countries as well as in Italy and the USA, the term phase means a set of compatible signal groups which may have GREEN at the same periods but the timings of Green begin and Green end may not be identical. In the UK the phase as in the USA is called stage. In order not to be misunderstood we are using the terms Signal group and stage which is actually a mixture of US and British English.

Table 2.1: Different Terms in Austria, Germany, Italy, UK and USA

AUSTRIA	GERMANY	France	Italy	United Kingdom	USA
Signalgruppe	Signalgruppe	Signaux lumineux d’intersection	Gruppo di segnali	Phase	**Signal group**
Phase	Phase	Période	Fase	**Stage**	phase

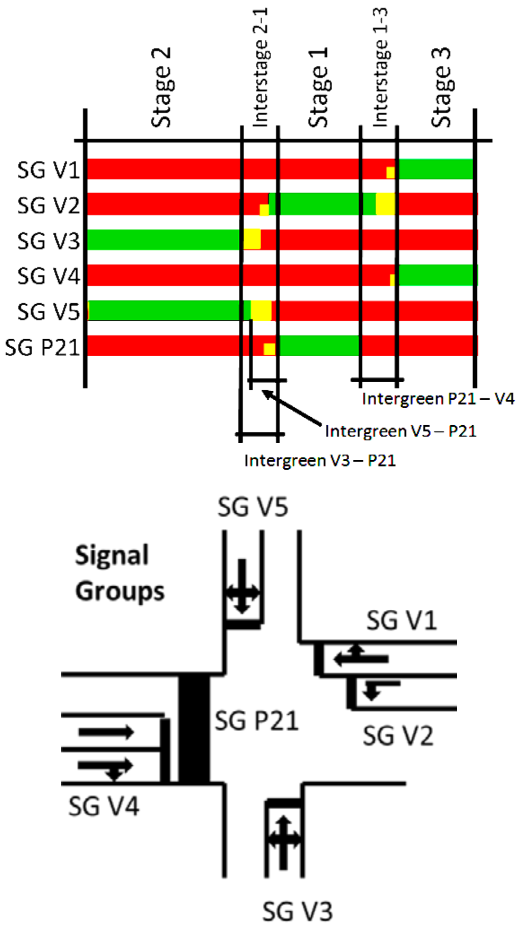


Figure 2.1: Signal Timing Plan (on top) and Signal Groups (on the bottom) for a Junction

Consequently in this report the stage is the part of a signal program, during which a certain ground state of signalisation stays unchanged, but the green periods must not start or end at the same point of time.

At the stage classification there are not conflicting, conflicting and partially conflicting streams.

Compatible (non-conflicting) streams have no joint conflict area.

Partially conflicting streams (semi-compatible movement) are unblocked turning streams that have to give priority to other at the same time unblocked streams. They do have joint conflict areas, the by law given level of priority must be considered. Not conflicting and partially conflicting streams can be signalised together in one stage.

Conflicting streams must be switched separately. Conflicting streams are traffic streams that do have joint conflict areas and that cannot be signalised together.

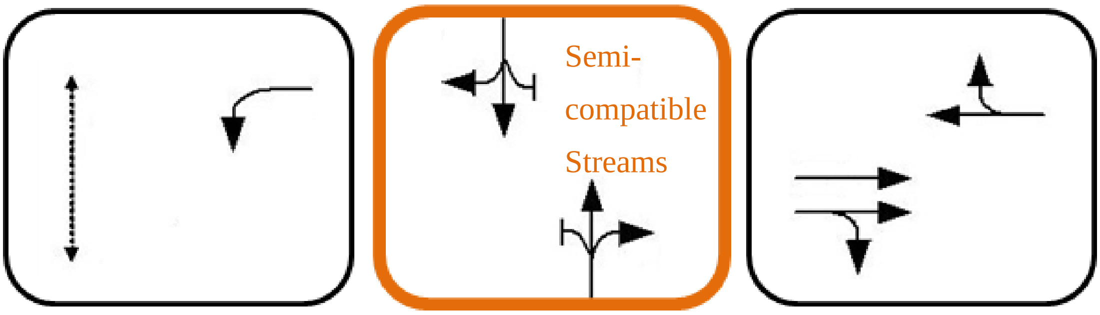


Figure 2.2: Three-Stage-System, with semi-compatible Streams in stage 2

2.2 Glossary

Table 2.2: Glossary

Actuated Signal Control	a control method that allows a variable sequence and variable duration of signal displays depending on vehicle and pedestrian traffic demands, stage time is based on detection data
Actuation	an output from the detector system to the controller unit of any type of detector indicating the presence of a vehicle or pedestrian
All Red	a term referring to an interval during which all signal heads at an intersection display red lights, the red lights are displayed on all signal displays of the junction
Adaptive Signal Control	a signal control concept where vehicular traffic is detected at a point upstream and/or downstream and an algorithm is used to predict when and where traffic will be and to make signal adjustments at downstream intersections based on those predictions
Amber (Yellow)Time	Duration of the amber display for a stage or a movement/stream
Approach (Access)	a set of lanes at an intersection that accommodates left-turn, through and right-turn movements (at least one of it) for a given direction; all lanes of traffic that enter the intersection from the same direction
Arterial	a signalised street that primarily serves through traffic and that secondarily provides access to abutting properties, with signal spacing with ~3 km (~2 miles) or less
Capacity	the highest expected rate at which vehicles can pass through the intersection under prevailing conditions, it is also the ratio of time during which vehicles may enter the intersection
Central reservation	any land between the carriageways of a road comprising two carriageways or any permanent work (other than traffic island) in the carriageway of a road, which separates the carriageway or, as the case may be, the part of the carriageway which is to be used by

	traffic moving in one direction from the carriageway or part of carriageway which is to be used by traffic moving in the other direction
Clearance Interval	is the period which is needed for vehicles of an ending stage to exit the last point of conflict they have with the beginning stage. The longest period is decisive.
Coordination	where traffic signals are closely spaced ~1 km (~1/2 mile or less) it is recommended that they be operated in a way to move large volumes or “platoons” of traffic in one movement along the corridor; in order to accomplish this, communication between each junction within coordination is necessary. Coordination is the ability to synchronize multiple intersections to enhance the operation of one or more directional movements in a system.
Cost (Operating Cost)	a measure that includes the direct vehicle operating cost as well as the time cost of vehicle occupants
Critical Intersection	the intersection in a coordinated signal system that operates with the highest overall degree of saturation during a given period
Critical Lane	a lane in a lane group or approach that has the highest degree of saturation and places the highest demand on green time
Critical Movement	a set of movements that determine the capacity and timing requirements of a signalised intersection
Concurrent Streams (non-conflicting)	two or more movements that are able to operate together without conflicting movements; no conflict point between these movements exists.
Conflicting Streams	two or more movements which cannot operate concurrently without causing interfering traffic movements
Cycle	a complete sequence of signal stages; from green being of a certain stage until the green of that stage would start the next time
Cycle Length (Cycle Time)	Time required for one complete sequence of signal displays (sum green and intergreen times); for a given movement, cycle time is the sum of the durations of red, amber, and green signal displays, or sum of Effective Green and Red Times during one cycle
Cycling lane	a part of carriageway of a road which is used by bicycles and is separated from the rest of the carriageway
Cycling path	a from the lane separated path, where bicycle are separated from vehicle lane by structural measurements
Degree of Saturation	the ratio of arrival (demand) flow rate to capacity during a given flow period; also known as the volume to capacity ratio [-]
Delay	the additional travel time experienced by a vehicle or pedestrian with reference to a base travel time (free-flow travel time)
Demand	the request for service, e.g. one or more vehicles desiring to use a given segment of road during a specified period of time
Density	the number of vehicles per unit distance along a road segment as measured at an instant in time [veh/km]
Detector	a device by which vehicle or pedestrian traffic registers its presence (demand)
Downstream	in the direction of the movement of traffic
Effective Green and Red Times	the green and red times of a movement for capacity and performance analysis purposes, which are determined by adjusting the displayed green and red times for start loss and end gain effects

Effective Intersection Capacity	an aggregate measure of intersection capacity determined as the ratio of total intersection demand flow to the intersection degree of saturation, where the intersection degree of saturation is the largest lane degree of saturation considering all lanes of the intersection
End Gain	Duration of the interval between the end of the displayed green period and the end of the effective green period for a movement; this is used in signal timing and performance analysis to allow additional departures after the end of green period.
Exclusive Pedestrian Stage	a stage at an intersection during which all pedestrian displays are green and all vehicle displays are red, allowing all pedestrian movements to operate simultaneously while all vehicle movements are stopped (all red for vehicles)
Exclusive Lane	A lane (or length of lane) allocated for use only by a particular movement or a type of vehicle, e.g. left-turn lane, through lane, right turn lane, bus lane.
Flow Rate	Number of vehicles or pedestrians per unit time passing (arriving/departing) a given reference point [veh/h]
Fixed-Time Control	A signal control method that allows only a fixed sequence and fixed duration of displays; a present time is given to each movement every cycle regardless of changes in traffic conditions.
Gap	Time, in seconds, for the front bumper of the second of two successive vehicles to reach the starting point of the front bumper of the first; also explained as the interval between the end of one vehicle detector actuation and the end of the following one. At lower speed the difference between front and rear bumper can be significant (e.g. 0.5 s).
Geometric Delay	Delay due to physical and basic traffic control factors as experienced by a vehicle negotiating the intersection in the absence of any other vehicles (deceleration from the approach cruise speed down to an approach negotiation speed, travel at that speed, and acceleration to an exit negotiation speed, and then acceleration to the exit cruise speed)
Green Period/Time	Duration of the green display for a stage or a movement
Hardware	Devices that physically operate the signal timing controls, including the controller, detectors, signal heads, and conflict monitor
Intergreen time	Interval between the end of one green time of a signal group and the start of the green time of the next signal group
Interstage	Change from green period to blocking time and from blocking time to green period.
Isolated Intersection	Junction at least 1.5 km (~1 mile) away from the nearest upstream signalised intersection.
Junction/intersection	a road junction
Km/h	kilometres per hour = 0,621 miles per hour (mph)
Lane group	a set of lanes with one or two shared lanes or a set of exclusive turn lanes
Level of Service	an index of the operational performance of traffic on a given traffic lane, roadway or intersection, based on service measures such as delay, degree of saturation, density and speed during a given flow period
Major road	the road at a junction into which vehicular traffic emerges from a minor road
Mph	miles per hour = 1,609 kilometres per hour
Maximum Green	longest duration that a stage can be green
Minimum Green	There are two different kinds of argumentations of minimum green. One is implemented because of safety reasons; normally a period is given by law/guideline which should not be undercut. There are differences concerning different countries. The other one is the

	preferred green by the road operators. In the context minimum green is used due to safety reasons.
Movement	a term used to describe the user type (vehicle, pedestrian) and action (turning, straight ahead) taken at an intersection; two different types of movements include those that have the right of way and those that must yield consistent with the rules of the road
Non-primary road	is a route, not being a primary route or a motorway or part of a primary route or of a motorway.
Occupancy	Percentage of time that a detector indicates a vehicle is present over a total time period
Occupancy Time	Time that starts when the front of a vehicle enters the detection zone and finishes when the back of it exits the detection zone, i.e. the duration of the period when the detection zone is occupied by a vehicle
Off-Peak Period	Period that have low demand volumes of traffic during the day.
Offset	The difference between the start or end times of green periods at adjacent (upstream and downstream) signals or also described as the time relationship, expressed in seconds of cycle length, determined by the difference between a defined point in the coordinated green and a system reference point, also explained as the time relationship between coordinated stages defined reference point and a defined master reference (master clock or sync pulse)
Pedestrian	an individual traveling on foot
Priority	Traffic signal priority (TSP) is an operational strategy communicated between transit vehicles and traffic signals to alter signal timing for the benefit or priority of transit vehicle.
Progression	Time-relationship, between adjacent traffic signals, which allows vehicles to be given a green signal as they pass through the sequence of intersections
Passenger vehicle	a vehicle constructed or adapted for the carriage of passengers and their effects
Peak Period	Period that has highest demand volume of traffic during the day (peak hour, peak)
Pedestrian Crossing	a transverse strip of roadway marked for the use of pedestrians crossing the road (midblock or at intersections) at a place with a pedestrian crossing sign; in Austria and Germany always a Zebra Crossing is marked (also if signalised)
Primary signals	light signals erected on or near the carriageway of a road and where a stop line is placed in conjunction with the signals, sited beyond that line and near one end or both ends of the line; or where there is no stop line, sited at either edge or both edges of the carriageway or part of the carriageway which is in use by traffic approaching and controlled by the signals
Queue	a line of vehicles or pedestrians waiting to proceed through an intersection; slowly moving vehicles or pedestrians joining the back of the queue are usually considered part as of the queue; the internal queue dynamics can involve starts and stops; a faster-moving line of vehicles is often referred to as a moving queue or a platoon
Red Time (Blocked Period)	Duration of the red signal display for a stage or a movement
Saturation Flow Rate	the highest expected departure (queue discharge) flow rate achieved by vehicles departing from the queue during the green period at traffic signals
Road marking / ground marking	a traffic sign consisting of a line or mark or legend on a road
Secondary signals	light signals erected on or near the carriageway facing traffic approaching from the

	direction of the primary signals but sited beyond those signals as viewed from the direction of travel of such traffic
Signal display/	it indicates a signal colour with a certain meaning; information gets transferred to the road users
Signal group	a set of one or more lanes that receive always the same signal indication
Signal head/ Signal transmitter	Hardware to display right of way with different aspects
Signal program	it defines the signal timings of a traffic signal system regarding duration and assignment of movements
Signal sequence / Signal switching	the order of stages that will be applied in a complete cycle; in fixed time control this will be determined according to minimum value of the sum of intergreen times
Signal Staging	sequential arrangement of separately controlled groups of movements within a signal cycle to allow all vehicles/pedestrians to proceed
Signal timing plan	the geographical display of the signal settings
Speed	Distance travelled per unit time [km/h] or [m/s]
Speed limit	a maximum or minimum limit of speed for the driving of vehicles on a road
Stage	a set of signal groups that do have partially conflicting or non-conflicting streams and can be served in the same time interval
Stage sequence	the order of stages in a signal cycle
Stage split	Duration of each stage (Green Time and Intergreen Time) within a signal cycle; normally expressed as a percentage of cycle length (the percentage of a cycle length allocated to each of the various stages in a signal cycle)
Stage transition/ Transit time	the period from the first green end of the ending stage and the latest green start of the beginning stage
Traffic lane	in relation to a road, a part of the carriageway having, a boundary which separates it from another such part
Traffic Signal [Plant]	Devices to warn, control, or direct at least one traffic movement at an intersection
Traffic Volume	Number of vehicles or pedestrians passing a given point on a lane during a specified period of time [veh/h]
Uninterrupted Flow	A condition in which vehicles travelling in a traffic stream do not have to stop or slow down for reasons other than those caused by the presence of other vehicles in that stream
Unopposed Turn	a left or right-turn movement at a signalised intersection that is made with no opposing or conflicting vehicular or pedestrian flow allowed
Upstream	in the direction opposite to the movement of traffic

2.3 Signal Transmitters/Signal Heads

2.3.1 Aspects and Sequences

Signal transmitters are installations that give optical information to the road users for a certain behaviour, through by law determined light signals. Signal heads are the hardware to display the light signals. They show three different colours. GREEN – AMBER (YELLOW) – RED

			
Green	Amber(yellow)	Red	Red + amber(yellow)

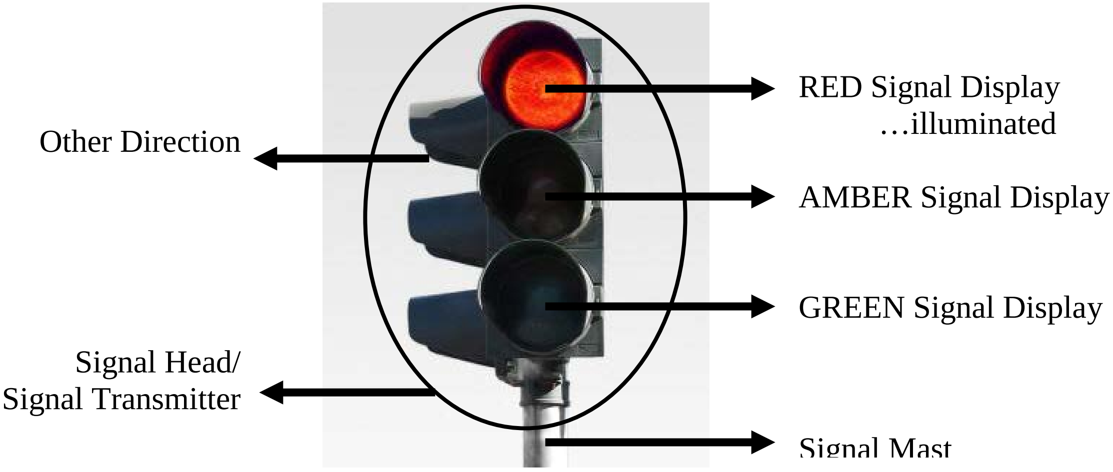


Figure 2.3: Signal Transmitter and Signal Displays

In German speaking countries and also in Italy the mid-level light is called yellow light in the UK the same light is called amber light, in Belgium it is called yellow-orange, in the Netherlands it is called orange, although professionals in the field prefer to use yellow. Further on within this document always the term amber will be used. The different colours have different meanings and give or ban right of way.

[BR Deutschland, BMVIT, The Secretary of State for Transport]

GREEN	go, gives right of way
RED	stop, moving on is prohibited
AMBER	the transition from green to red (interstage)
RED + AMBER	the transition from red to green (interstage), not used in Italy, Belgium, France or Netherlands)
GREEN flashing	only in AUSTRIA: 4 times flashing green lights, ½ second illuminated and ½ second dark (4 times each), as part of the green period showing that amber will start in 4 seconds
AMBER FLASHING	a single amber flashing light or two amber lights flashing alternately, shall mean that drivers may proceed but shall do so with particular care. Also red flashing lights can depict attention. The flashing amber is usually a safety fall-back to warn drivers that the traffic light controller is switched off.
RED FLASHING	It is used to signalize warning/caution, in France a single or two red flashing lights can alternately belong to the Stop signal types. As a Stop signal red flashing light shall mean a temporary total restriction on a road, e.g. to allow emergency vehicles to cross the street.

2.3.2 Different Types of Signal Heads

In Austria, Germany, the UK, France the Netherlands, Belgium and Italy the guidelines and regulations give different specifications of signal transmitters. The regulations and guidelines are summed up in the following.

Vehicular Signal Heads

AUSTRIA:

Normally they have three illuminated fields with the colours red, amber and green. The red light is on top, the amber in between and the green below (same to Germany and the UK). For separate signalisation of singular traffic streams, signal heads with arrows at the illuminated fields (at red and green field) as direction symbol are used. The number of necessary signal heads follows the number of separately signalised traffic streams and the existing cross section of lanes. [FSV]

GERMANY:

At special cases also two-fielded and one-fielded signal heads are used. If a motor vehicle signal is valid just for one certain direction, it must show the direction arrow at all corresponding single transmitters (also for combination arrows). Illuminated arrows at black background have a higher contour-effect, but a lower light intensity than symbols with black direction arrows. Because of that reason at the amber and red light-fields black direction arrows need to be used, for the green field always green illuminated arrows at black background are used. Black arrows are implemented at the red and amber display; green arrows are given at a black background. [FGSV]

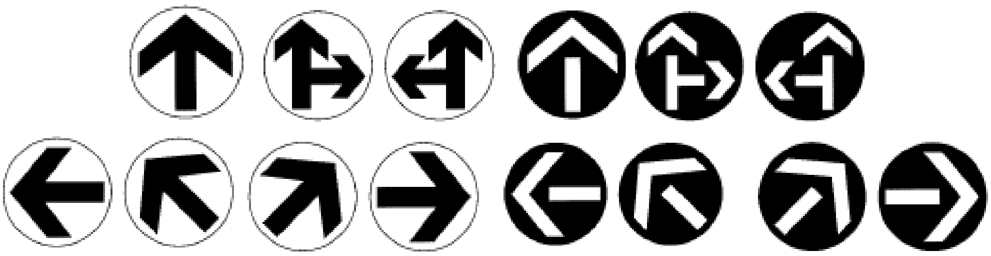


Figure 2.4: German Arrows (RiLSA)

UNITED KINGDOM:

Light signals for the control of vehicular traffic (other than tramcars) shall be of the size, colour and type shown in the figure below.

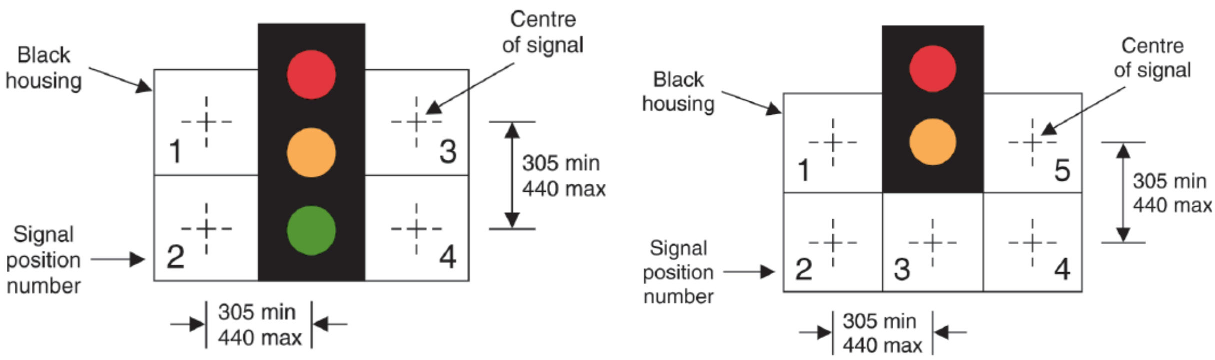


Figure 2.5: Three fielded and two fields Signal Head [TSRGD]

Green arrow light signal transmitters for the control of vehicular traffic

The direction of the arrow shown in indication B may be varied so that the head of the arrow points to any position lying between indication A and indication E.

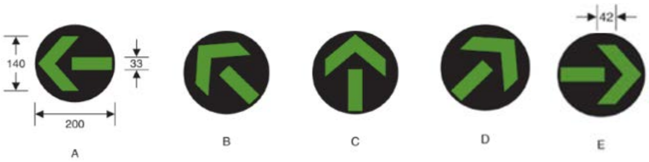


Figure 2.6: UK Arrows [TSRGD]

NETHERLANDS:

There is no uniform requirement of how a traffic light should look exactly. In general the same system as in the UK is used, but the direction markers on the road surface are leading. A lane that is only for turning left uses picture A from Figure 6, and only turning right uses the arrow with the letter E. The arrows of letter B and D are rarely used, but sometimes they can be seen on intersection that have more than four legs or when a through lane becomes a turning direction on the next intersection that is very nearby.

Arrow C is sometimes used when a single lane permits more movements, e.g. through and left, then a circular light is always used. In that case drivers should be attentive of partially conflicting streams, while with separate lanes only for left/trough/right, this is never the case.

ITALY:

For vehicular traffic other than public transport, a signal head with three vertical lights is used, just as in the other countries. If the traffic signal is incorporated in other written signalisation placed above the road, the lights are placed horizontally from left to right. [RENCS 159.2]

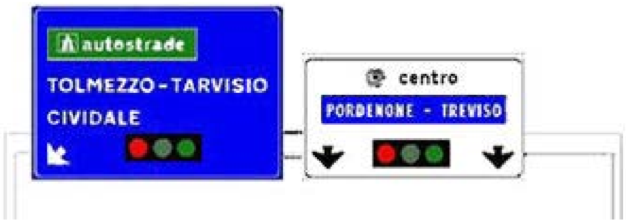


Figure 2.7: horizontally traffic lights in Italy [RENCS]

For roads with alternated traffic, a second red light can be placed on top of the first one, it is done due to safety reasons, to ensure the signalisation of the red light even if one lamp is out of order. [RENCS 159.3]

At crossing where the right turn is always permitted, a single directional green light is placed right to the green signal. When the permitted lane directions belong to different stages, the normal traffic light is replaced by a directional traffic light, where each light, red, amber and green, is an illuminated arrow on black background. Arrows can have any inclination/direction, according to the permitted direction.

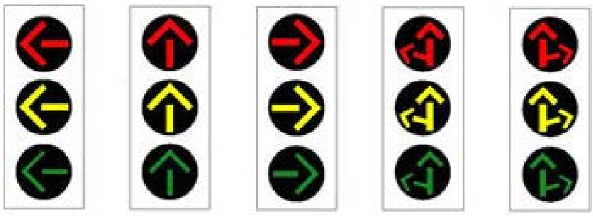


Figure 2.8: directional traffic lights in Italy [RENCS]

A single amber traffic light, usually flashing, can be used above a non-regulated intersection to indicate a possible danger, so that the drivers will take special care when approaching that intersection.

FRANCE:

The full signal of France is similar to that in other European countries. Directional signals have some restrictions in comparison to other countries. They may only indicate strict left/right turns or straight and right, or straight and left turns. If a left turn shall be indicated with a straight and right turn, an additional traffic sign shall be added or a full circular signal can be used instead, Directional lights look the same than the ones of Italy. (Figure: directional traffic lights in Italy).

France has widely deployed conditional signals that may sometimes be hard to interpret. If there is a side directional signal, flashing in amber used, this indicates the direction which is allowed to move on, also if a full circular red signal is given. For example in the figure below, the signal on the left side indicates that only a right turn is forbidden, drivers may proceed for straight or left turns.

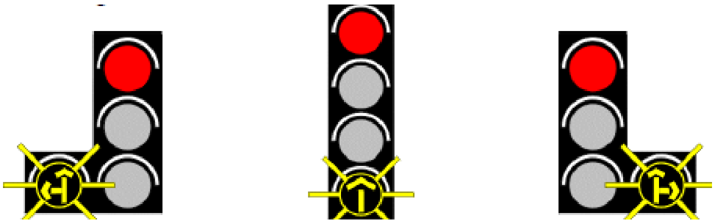


Figure 2.9: Conditional Directional Signals in France

Conditional Signals may also be used for multimodal transportations. The conditional flashing amber signal is either for public transport or for bicycles. The meaning is that drivers must follow the full circular signal in red and fully stop, while the in amber given vehicles may proceed.

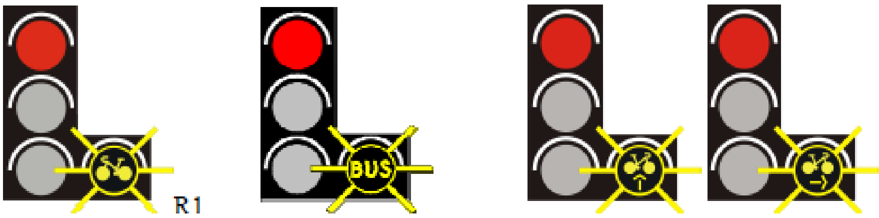


Figure 2.10: France: Conditional Modal signals and Conditional Directional Modal signals

In France a conditional modal signal may also be directional. The side signal can also indicate the go through a particular direction for a particular mode of transportation.

BELGIUM:

The full signal of Belgium is similar to that in other European countries. Full signals may be repeated using smaller lights at the height of the driver. Directional signals may replace the full signals and the may indicate either of they have some restrictions in comparison to other countries. They may only indicate strict left/right turns or straight and right, or straight and left turns. If a left turn shall be indicated with a straight and right turn, an additional traffic sign shall be added or a full circular signal can be used instead. Directional lights look the same than the ones of Italy (directional traffic lights in Italy).

Pedestrian Signal Heads

Normally pedestrian signal heads are just two fielded, this is valid for Austria, Germany and as well for the UK, but there are a lot of exceptions. The exceptions are not given in details. Some are shown at the pictures below.

AUSTRIA and BELGIUM:

Normally they are two fielded and the red field shows a standing/waiting, the green field a walking pedestrian. [FSV]

GERMANY:

Signal transmitters for pedestrians are two- or three- fielded (two times red for visually disabled people). The green field is placed at the bottom. At the red field the sign of a standing, at the green field the sign of a walking pedestrian must be shown. There is a unification treaty where the allowed signs are given. [FGSV]

Figure 2.11: Standing and walking illuminated Pedestrian Sign at black Background [RiLSA]

					
Germany	**Zwickau/ Dresden Germany**	**Oranienburg Germany**	**Hamburg Germany**	**Düsseldorf Germany**	**Vienna Austria**
http://fudder.de/artikel/2006/08/31/ein-rundgang-durch-das-ddr-museum/	http://de.academic.ru/dic.nsf/dewiki/69468	http://www.qype.com/place/2571989-Fussgaengerampel-am-Schlossplatz-Oranienburg	http://www.chrizblog.de/ampel-mit-countdown/	http://kinkerly.blogspot.co.at/2009/06/dusseldorfer-ampeln.html	http://wien.orf.at/radio/stories/2528048/
It is possible that they are three fielded, especially if there is a demand button. The signal can give a “R” which shows the clearance time – time for leaving the driving road (i.e. in Vienna) There are also facilities which show “SIGNAL KOMMT”(= signal will come) at the lowest, highest or at the medium level (dependent on the city) and it is also possible that pedestrian signal heads give a green stage duration or a “countdown”					

Figure 2.12: Pedestrian Signal Heads - Special Cases of Austria and Germany

UNITED KINGDOM:

A sign for conveying to pedestrian traffic warning and information shall be of size, colour and type shown in the following diagram.

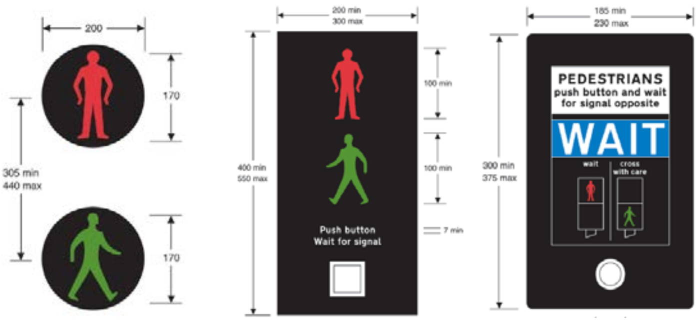


Figure 2.13: Pedestrian Facilities - UK [TSRGD]

ITALY:

Pedestrian traffic lights in Italy have three fielded signal heads, with the symbol of a man. There are three-signals, with the same illumination as the vehicular traffic lights.

Figure 2.14: Pedestrian traffic light in Italy [RENCS]

FRANCE:

Signal transmitters for pedestrians are two-fielded and the red field shows a standing, the green field a walking pedestrian. Compared to other countries, pedestrian signals are primarily horizontal, where the red field is on the left side and the green field on the right side. While acoustic signals could assist hearing impaired persons with the state of the signal, timer indicating the remaining time before the signal will change does not exist.

Figure 2.15: Standing and Walking illuminated Pedestrian Signals in France[1]

Bicycle Signal Transmitters

AUSTRIA:

If the bicycle traffic is signalised separately from the vehicular or pedestrian traffic, bicycle signal transmitters must be placed. The signal head has two or three fields. At the three field signal head, the colours green, amber and red exists, the bicycle symbol must be shown in addition (inside the illuminated area – or above the signal head). At a two fielded signal head just green and red exists, also with the bicycle sign (within illumination). [FSV]

[1] http://de.academic.ru/dic.nsf/dewiki/484538 and http://www.meinstromfresser.de/foto/?id=49568

GERMANY:

At every field at standard-size, the symbol of a bike (illuminated on dark background) must be shown. The red field is on top, the amber one in the middle and the green one at the bottom. If the signal head is just valid for a certain direction, at all three fields an illuminated direction arrow must be shown. If a smaller version is used the bike-sign can be shown as a white illuminated sign on dark background or as an additional signboard. The coloured light fields then have no signs, but if necessary direction arrows (also possible vice versa). [FGSV]

					
Frankfurt Germany			Berlin, München Germany	Münster Germany	Germany
http://www.bild.de/regional/frankfurt/ampel/bild-erklaert-die-neue-fahrrad-ampel-25150148.bild.html	http://foter.com/f/photo/4585300088/9122207665/	http://www.mtb-news.de/forum/showthread.php?t=359218	http://www.reclaimyourcity.net/content/fahrradampel http://www.bund.net/themen_und_projekte/nachhaltigkeit/konsum/konsum_in_kommunen/	http://www.muenstersche-zeitung.de/lokales/muenster/Teil-11-Das-Geheimnis-des-schraegen-gruenen-Pfeils;art993,994530	http://www.fotocommunity.de/pc/pc/display/12506913

Figure 2.16: Bicycle Signal Heads, Special Cases of Austria and Germany

Figure 2.17: Bicycle Facilities - Austria and Germany

UNITED KINGDOM:

Light signals for the control of vehicular traffic consisting solely of pedal cycles shall be of the size, colour and type given in the diagram below.

Figure 2.18: Bicycle Facilities - UK [TSRGD]

NETHERLANDS:

Bicycle lights are always 3-fielded and usually have a bike symbol in it, although simple round lights are often seen as well. Very common are also double signal heads for bikes, one mounted at approximately four meters altitude that is easy to see when approaching from distance, and one smaller "sub signal head" that is mounted at an altitude of around 1 metre. It is easier to watch while standing still at the traffic light. An example is shown in Figure 13. It can also be seen that this problem is solved for the pedestrians by mounting the light on the other side of the crossing.

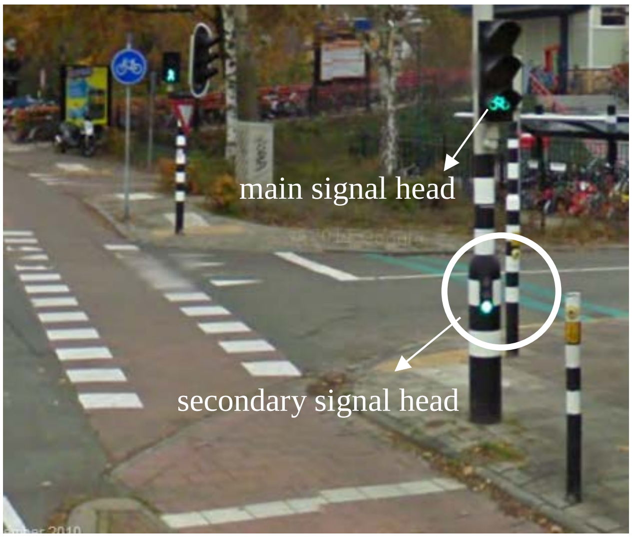


Figure 2.19: Double Signal Heads for Bicycles in the Netherlands

ITALY:

Bicycle signals look the same as pedestrian signals, but they use a symbol of a bike. They must be used only on reserved bike lanes. Otherwise the normal traffic light signals apply.

FRANCE:

Bicycle signals are represented by the symbol of a bike. The colour indication of standard traffic signals is used. As mentioned before bicycle signals may also indicate a direction in which case the arrow indicating the direction is below the standard signal. (Conditional directional modal signal)

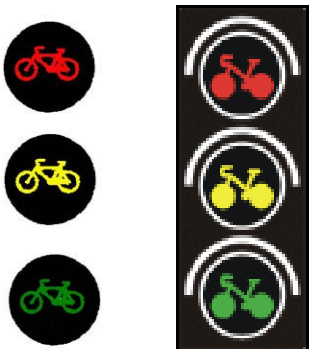


Figure 2.20: Bicycle traffic light in Italy [RENCS] on the left and France on the right side

BELGIUM:

Bicycle signals contain the symbol of a bike. Bicycle lights are 3-fielded as in the Netherlands. Bicycle signals are reserved to appropriately specific bicycle routes. Bicycle signals can also be placed on the altitude of the cyclists.

AUSTRIA:

A two fielded signal head is used. It shows a bicycle, but mostly a combined symbol. [FSV]

GERMANY:

The combined symbols need to be shown at the illuminating fields, like in the diagram below. [FGSV]

Figure 2.21: Joint Bicycle and Pedestrian Signal Transmitters - Austria and Germany

UNITED KINGDOM:

The signal head shall be of the size, colour and type shown in the figure below on the left.

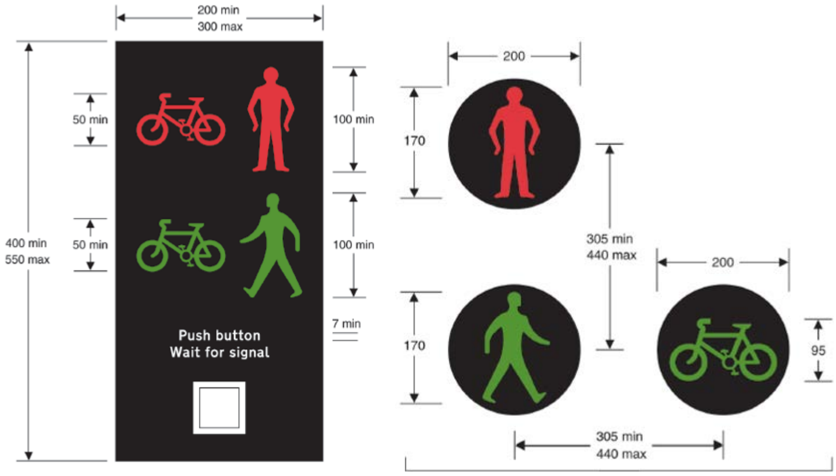


Figure 2.22: Joint Bicycle and Pedestrian Signal Transmitters – UK [TSRGS]

It consists of either a single unit of the size, colour and type shown on the right, or of two units, one comprising the upper and the other the lower part of that unit placed close together. [The Secretary of State for Transport]

FRANCE:

Signals may not be grouped, such as vehicle and pedestrians or bicycle and pedestrians. In the case a signal should indicate multiple modal transportation means, multiple adjacent signals would be used.

Table 2.3: Pedestrian and Cyclists Crossings

Signal	AUSTRIA	GERMANY	UNITED KINGDOM	NETHERLANDS	ITALY	FRANCE / BELGIUM
Green	Cross	Cross	Cross with caution	Cross	Cross	Cross
Flashing green	Continue to cross, prepare that crossing possibility will be over soon.	-	Continue to cross if already in the intersection, but do not start to cross	Pedestrians only: finish crossing, but do not start crossing		-
Flashing amber	Caution	Cross with caution Used when out of order	Caution	Cross with caution Used when out of order	Cross with caution Used when out of order	-
Red	Do not cross	Do not cross	Do not cross	Do not cross	Do not cross	Do not cross
Red and amber	Do not cross prepare for green (only used for bicycles)	Do not cross prepare for green	Do not cross	-	-	-
Amber	-	-	-	Bicycles only: Light will soon turn red, stop if possible.	Continue to cross if already in the intersection, but do not start to cross	Belgium: Bicycles only: light will soon turn red, stop if possible

Signal Heads for Public Transport

AUSTRIA:

It is possible to use signal heads with beam-symbols, light points as well as help signals with letters, arrows and numbers. Due to reasons of uniqueness it is possible to use own signal heads for each driving direction. [FSV]

GERMANY:

The signal heads need to be implemented like BOStrab. Normally, due to reasons of definiteness, due to signal-securing and because of different intergreen periods which needs to be considered, for every driving direction an own signal transmitter is used. For light signal plants accelerating public transport, for better understanding by driving personnel an additional information signals should be shown. This signal shows the driver if he has logged on at the particular plant. The lettering can also be replaced by other information. [FGSV]

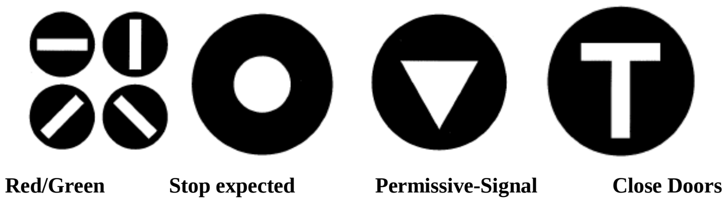


Figure 2.23: Public Transport Signals – Germany [RiLSA]

UNITED KINGDOM:

Light signals for the control of tramcars shall be of the size, colour and type shown in the following diagram:

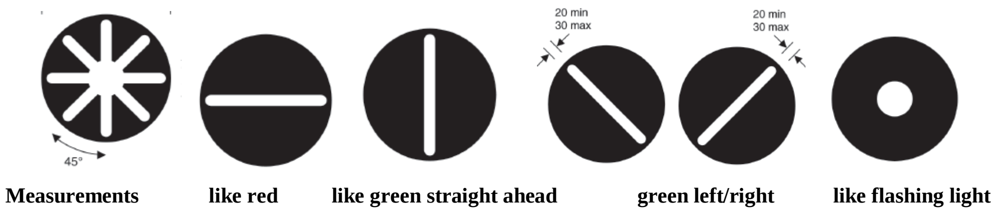


Figure 2.24: Public Transport Signals - UK [TSRGD]

NETHERLANDS:

Public transport lights in the Netherlands are quite different from the rest of Europe, they are shown in Figure 2.25. The meaning of the pictures from left to right is as follows: through only can pass, left only, right only, all directions, stop if possible, stop.

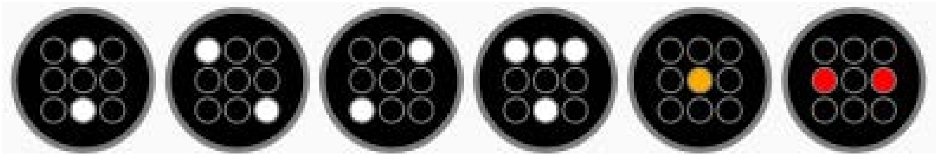


Figure 2.25: Public Transport Signals – Netherlands

ITALY:

Different traffic lights are used to regulate public transportation, only in cases where the use of normal traffic lights could generate confusion, like when some lanes are exclusive for public transportation and when the stages for the same direction of the private transportation are different. The red light is replaced by a horizontal bar, the amber light by a triangle and the green light by a vertical or inclined bar. Although not shown in the picture from the RENCS, the green-left and green-right inclined bars, as used in Germany.

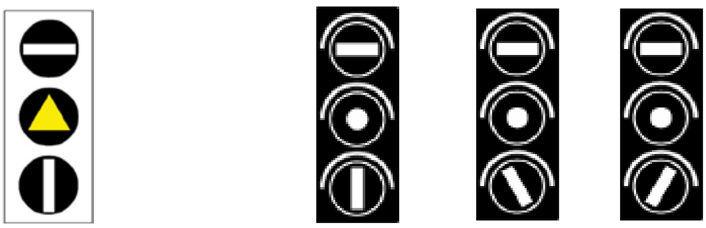


Figure 2.26: Public Transportation Signals in Italy [RENCS] on the left, and Franc on the right

FRANCE:

Signal head for public transport depends whether it is a regular, mostly tram-like service line or a general public transport or irregular line. In the former, black/white signals used as illustrated in the Figure below, a horizontal bar means RED, a vertical bar means GREEN in straight direction, while diagonal bars mean GREEN right/left for public transportation having that direction as destination. A dot means AMBER.

BELGIUM:

Signals for public transport are generally white on black ground. A horizontal bar corresponds to a red light, a white circle and a white triangle correspond to green in usual car traffic lights. A bar that is straight indicates permission to only go straight, while a bar inclined 45° left or right indicates permission to only go in the indicated direction.

Help Signal Transmitters

AUSTRIA:

They are one fielded signal heads which ensure, facilitate or accelerate traffic flow in cooperation with the vehicle signal heads. Signal heads with green direction arrow for singular traffic streams supplement the signal picture. Amber flashing help signals with or without symbols are used for warning/caution. [FSV]

GERMANY:

For danger-warning one-fielded signal transmitters with amber flashing light (with or without symbol) are used. Help signals should be used sparingly. A special form of a help signal is the two-fielded springing light (crossing of tracks) Two, one above/beneath the other arranged signal transmitters with the same symbol are installed. During operation they are flashing in turns. The warning effect is better than with one flashing light. For help signal transmitters only black signs at amber background are allowed. The signal transmitters need to be flashy attached. [FGSV]

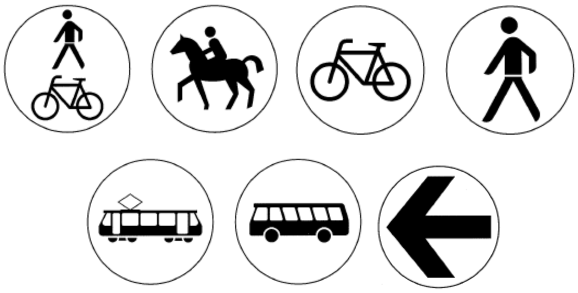


Figure 2.27: Help Signals (amber-illumination) used in Austria and Germany [RiLSA]

NETHERLANDS:

Amber flashing help signals, warning for partially conflicting streams are rarely used, but they do exist.

Speed Signal Transmitters

AUSTRIA:

They show the recommended speed for coordination. There are up to three speed levels. Signal judges are a special case of speed signalisation; they show the speed which, if fulfilled, makes driving without stop possible so that the next light signal plant will show a green signal. [FSV]

GERMANY:

The recommended speed is shown through one or more fielded signal transmitters with white illuminating numbers or through raster-signal transmitters.

Such speed-signal-transmitter can also be used for public transport vehicles. To avoid confusion with speed signal transmitters of the motor vehicle traffic, public transport signs just give one tenth of the desired value. (Number 3 for the recommended speed of 30 km/h) [FGSV]

NETHERLANDS:

The recommended speed for green waves is shown on a matrix display which can usually show speeds with 5 km/h increments. There is also a special symbol to indicate when the green wave is possible or not. Some example signs are shown in the figure below, but cities are free to use other designs.

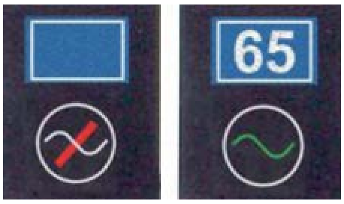


Figure 2.28: Speed Advisory Signs for Green Waves in the Netherlands

Pedestrian Signal Heads for blind and visually disabled People

AUSTRIA:

These additional signal heads give acoustic and or tactile free-signals. For the guiding of visually disabled people towards the additional signal heads, special acoustic orienting signals can be given, these must be clearly different from the free signals. [FSV]

GERMANY:

Additional facilities for blind or visually handicapped people should be installed due to harmonisation with the organisation of affected people and the proper authorities.

Acoustic signal transmitters are differentiated between the orienting and green-signal. The orienting signal helps for finding the ford/signal mast; the green-signal makes the existing green period understandable.

Tactile signal transmitters are normally combined with demand buttons. The walking direction is given with a tactile arrow. Through tactile additional symbols also other information can be given. [FGSV]

ITALY:

For blind or visually impaired people, acoustic signals can help the crossing. Art. 41, par 5 of the road regulation indicates three stages:

- an intermittent sound with 60 impulses per minute indicates the green light;
- an intermittent sound with 120 impulses per minute indicates that the crossing can be terminated but not initiated,
- and is synchronized with the amber light; no sound emission, synchronizes with the red light.

The acoustic signalisation can be continuous, at each traffic light cycle, or only on demand where a tactile request button is placed on the traffic light pole. In this case, the acoustic signalisation is emitted only for the first cycle after the request.

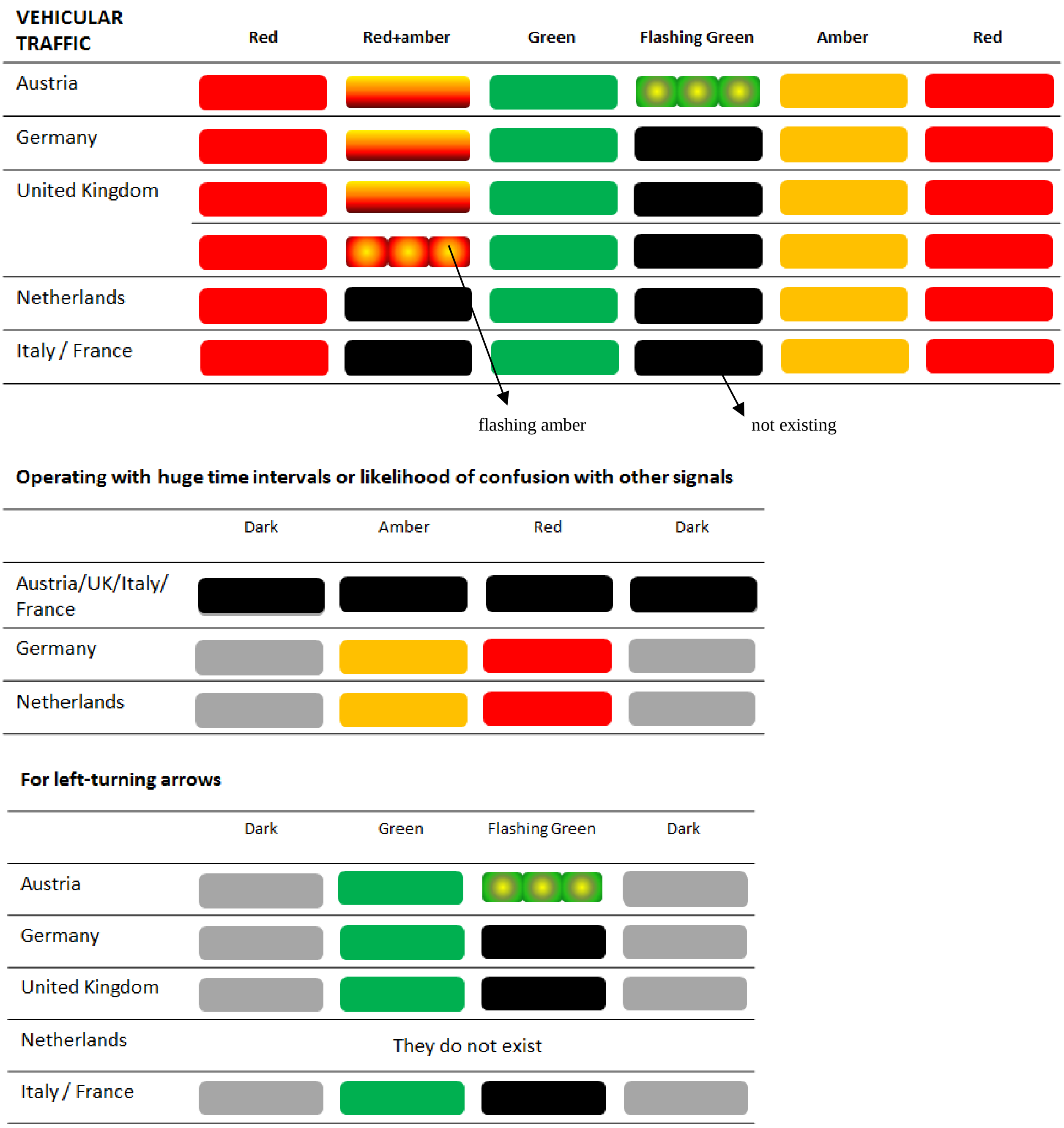
FRANCE:

Additional signal heads give acoustic and tactile free-signals. Acoustic signals for the RED stage must all start by an acoustic sentence said in French: “Red for Pedestrians”. No other signal, voice or code is allowed for the RED stage. For the green stage, a coded signal must be emitted for the whole duration of it. Optionally, a secondary coded acoustic signal may be emitted right at the beginning of the green stage, to indicate it.

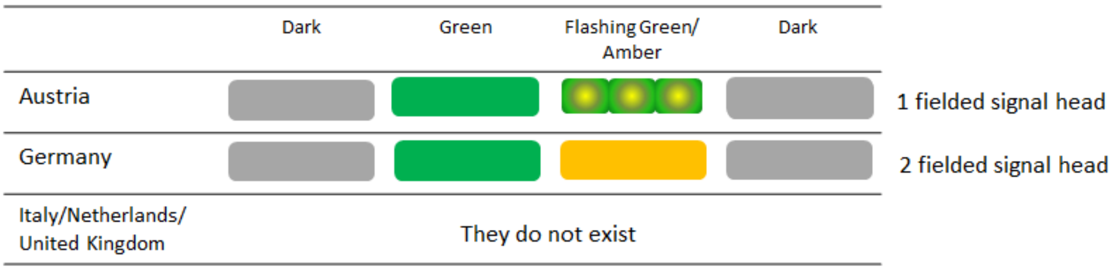
2.4 Signal Sequences

The Signal Sequence fixes the order of one after the other following light(s). The order is not always the same considering different countries, different road user types, different movements and different signal heads. According to the operation type different signal sequences are allowed. The following table shows differences given at guidelines from Austria, Germany, Italy, Netherlands and the UK.

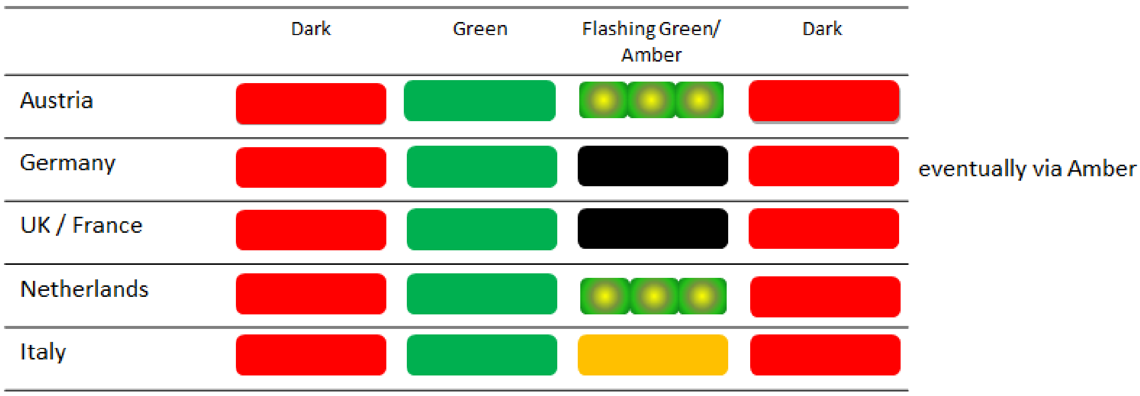
Table 2.4: Signal Sequences



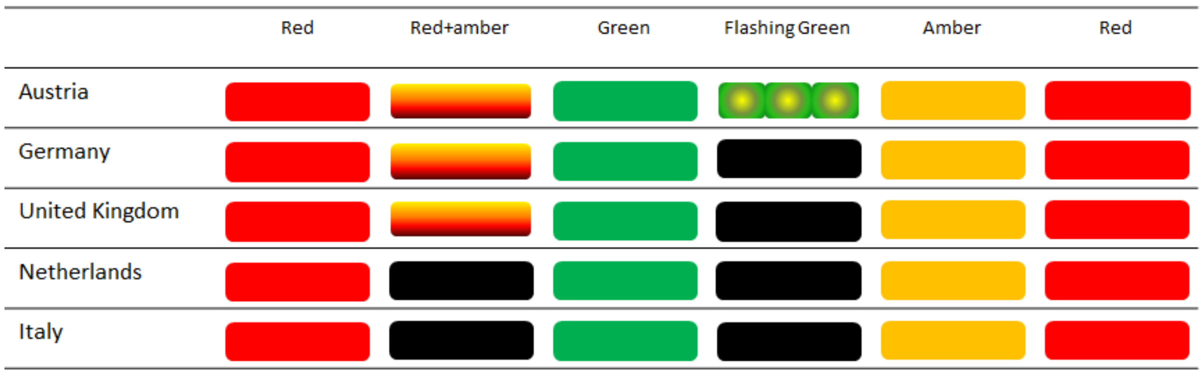
Additive free-time for right turning (with arrow symbol)



Pedestrian crossing

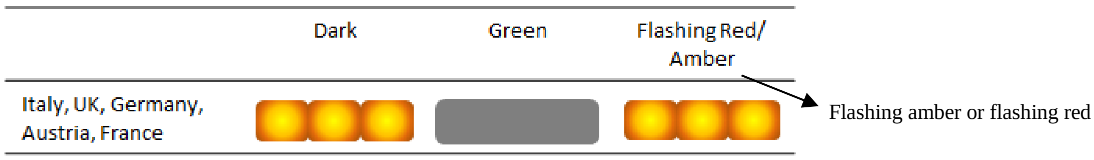


Bicyclists (3-fielded signal heads)



In France they can look like the sequence from Italy, but it is also possible to use additional flashing amber Signals as conditional Signals.

Warning / Caution

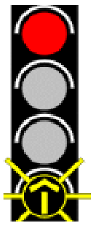


Warning/caution light signals can also be shown in red (additional signal). Much more common is the amber light. The amber light is also used at three fielded signal heads, when there is a break-off.

2.5 Signal Displays

Concerning the guidelines of different countries there are some different meanings, usages and signal switching of the given signal displays and symbols. The table below summarises the given explanations at the individual guidelines and includes also the most important differences.

Table 2.5: Signal Displays

Vienna Convention of Road signs and signals	AUSTRIAN road traffic regulations (StVO 1960)	GERMAN road traffic regulations (StVO)	FRANCE IISR	UK RTA 1988 and TSRGD 2002
Green Light				
***Remark**: The green light always means "go", in Austria there is a specification. They use flashing green light to show that the green period is ending very soon.*				
A green light shall mean that traffic may proceed; however, a green light for controlling traffic at an intersection shall not authorise drivers to proceed if traffic is so congested in the direction in which they are about to proceed that if they entered the intersection they would probably not have cleared it by the next change of stage.	This means "go ahead", the green light must be ended with four times green flashing light. The illuminated and dark times must last ½ second by turns. Green flashing light means that the "go ahead" sign will close very soon. When the green sign is given, vehicles can move but they must not endanger or disturb vehicles, pedestrians and bicyclists who cross their lane at the same time. By turning left they must give priority to oncoming straight ahead and right turning vehicles. Vehicles from the main lanes have priority against vehicles from side lanes.	This means that traffic is given free.	This means that traffic is free. For full circular signals, this means ALL directions, yielding on opposite traffic in case of left turn. For directional signals, this indicate FREE in the given direction.	It indicates that vehicular traffic can proceed beyond the stop line and proceed straight on or to the left or to the right.
Red Light				
***Remark**: The red light means "stop". In Germany there are exceptions given through sign boards*				
A red light shall mean that traffic may not proceed; vehicles shall not pass the stop line or, if there is no stop line, shall not pass beyond the level of the signal or, if the signal is placed in the middle or on the opposite side of an intersection, shall not enter the intersection or move on to a pedestrian crossing at the intersection	This means "stop". The driver must stop the vehicle. 	This means "stop" in front of the intersection. After stopping turning right is allowed if right beneath the light signal red, there is a signboard with a green arrow at black background. Turning from the right lane is possible, no disturbance or endangering of road users is allowed. A black arrow at red background orders a stop. A black arrow at amber background orders waiting for the given direction. A single fielded green arrow shows that at red for the straight ahead direction it is allowed to turn right (picture on the left).	Unless a conditional side signal (flashing amber) indicates it otherwise, this means STOP. 	It conveys the prohibition that vehicular traffic shall not proceed beyond the stop line
Amber Light				
***Remark**: Vehicles must stop/wait in front of the intersection, if this is possible in a safe way.*				
It shall mean that no vehicle may pass the stop line or beyond the level of the signal unless it is so close to the stop line or signal when the light appears that it cannot safely be stopped before passing the stop line or beyond the level of the signal. Where the signal is placed in the middle or on the opposite side of an intersection the appearance of the amber light shall mean that no vehicle may enter the intersection or move on to a pedestrian crossing at the intersection unless it is so close to the crossing or the intersection when the light appears that it cannot be safely stopped before entering the intersection or moving on to the pedestrian crossing.	It means stop, approaching road users must stop, if they are not inside the junction. If they are inside the junction they must leave the junction. Vehicles which cannot stop in a safe way are allowed to pass. Turning left, vehicles must give priority to the oncoming straight ahead and right turning vehicles. Traffic from main lanes has priority against the side-lanes.	It means that vehicles must wait in front of the intersection until the next sign is given.	Used to give right of way to vehicles – when used for conditional signals. (Flashing amber)	When shown alone, it conveys the same prohibition as the red signal, except that any vehicle too close to the stop line to stop safely, it shall convey the same indication as the green signal or green arrow signal.
Vienna Convention of Road signs and signals	AUSTRIAN road traffic regulations (StVO 1960)	GERMAN road traffic regulations (StVO)	FRANCE IISR	UK RTA 1988 and TSRGD 2002
Red + Amber Light				
***Remark**: It means stop and announces the immediately following green period.*				

It shall mean that the signal is about to change, but shall not affect the prohibition of passing indicated by the red light.	This means "stop" like the red light and announces that the green "go ahead" sign follows immediately.	-		It denotes an impending change to green or a green arrow. It also conveys the same prohibition as the red signal.
Flashing Lights				
Flashing lights are warning signs. They give attention/caution.				
A single amber flashing light or two amber lights flashing alternately shall mean that drivers may proceed but shall do so with particular care. It can also mean that a light signal plant is out of order	Flashing amber light means "attention/caution" It can also mean that a signal plant is out of order.	Amber flashing light warns of danger. Light signal plant out of order, partly only at the directions which need to give way.	For any other signals than the conditional signals, this means attention/caution.	An intermitted amber or blue light shall convey the warning that drivers of vehicles should take special care.
Arrows				
Remark*: *A green arrow in Austria does not give way to this direction; there may be partially conflicting streams.				
	Illuminated green arrows are valid as "go ahead" sign like the green signal. A black arrow at the amber (not flashing) light is a sign for "stop", like the amber signal, if safe stopping is not possible, the vehicle must leave the intersection as soon as possible without breaking the law. A black arrow at the red light is a sign for "stop" like the red signal The arrow head always shows the direction for which the signs must be considered.	Green arrow: Traffic given free only in arrow-direction A green left-arrow behind the junction signalises that the opposing traffic is blocked by a red light and left turning vehicles can pass the intersection without any disabilities. There is no other traffic stream which has a shared conflict area, which has green at that time. Also pedestrians cannot have priority		A green arrow indicates that vehicular traffic may, notwithstanding any other indication given by signals, proceed beyond the stop line only in the direction given from the arrow head. When more than one green arrow is affixed to light signals, vehicular traffic may proceed beyond the stop line only in the given direction. Vehicular traffic proceeding beyond a stop line shall proceed with due regard to the safety of other road users, but having priority at the indicated direction.

[Economic Commission for Europe, Inland Transport Committee; BMVIT; BR Deutschland; Government of the United Kingdom; The Secretary of State for Transport]

The Netherlands follow the same guidelines as stated in the column of "Vienna Convention of Road Signs and Signals". Also for Italy the same column can be used. Also Italy and the Netherlands do not have red+amber lights.

2.6 Geometrical Design

2.6.1 Signal Layout Map

The signal layout map illustrates the singular components of a light signal plant at intersections in scale of 1:200 or 1:500. Beneath the signal masts with the mounted signal heads also traffic signs and ground marking are depicted. For the planning of light signals, the draft of the signal layout map is a very important step. With the help of the signal layout map the intergreen times can be calculated. Normally the numbers starts with one and goes round in one direction. The direction is not fixed and differs from town to town also inside the same country. Normally the numbering starts at one arm and goes clockwise ore anti-clockwise. For vehicle, pedestrian and bicycle signals other indications are used. At the example below the letter "V" is used for vehicle signals and "P" is used for pedestrian signals.

The numbering starts at the right hand-side and goes round clockwise. Signals shown for the same traffic stream(s) are numbered with the same index receiving a letter which makes clear the position and is used to avoid misunderstanding for example at maintenance. [FGSV]

The signal layout map includes:

- Road space, (buildings), arms, lanes, traffic islands
- Lane markings, islands ,(location of traffic signs)
- Location of signal heads
- Signal heads of one signal group classified by a, b, ...
- (gradient)
- (speed limits)
- (detector locations, switching cupboards, inductive loops, logging on/off facilities)
- Scale (1:200, 1:500)
- (contrast blind, signal for blind/visually impaired people)

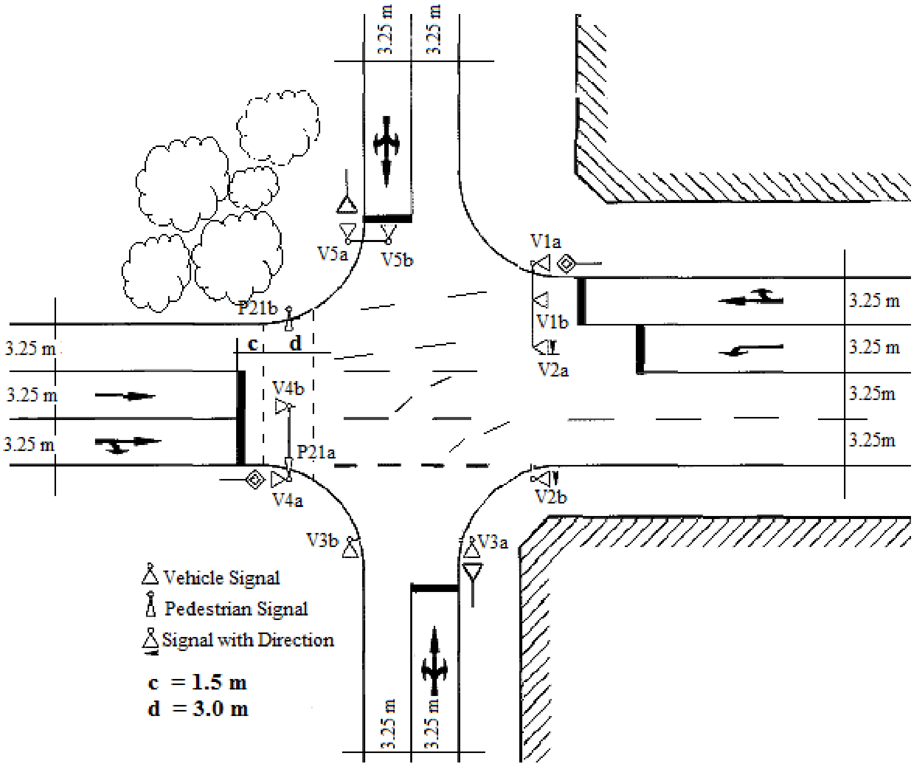


Figure 2.29: Signal Layout Map

2.6.2 Lane Allocation

The number and the allocation of traffic lanes at the intersection are based on traffic volume, the wanted quality of traffic flow for all road user groups, traffic safety and the area-availability. Lanes can also be used dynamically. This requires compelling signal-technical actions and traffic dependent control methods for organising the temporal one-after-another of the multi usage.

Continuous Traffic Lanes

The number of continuous lanes should be the same at the intersection as well as on the connecting section of the road. Especially within cultivated areas it can be necessary to widen the number of continuous lanes at the intersection access to be able to control the capacity. The minimum length [l] by a stable number of continuing lanes at the intersection-exit in Germany can be set to:

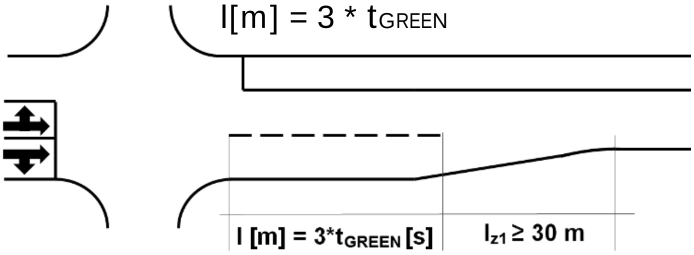


Figure 2.30: Lane Allocation

As green period [t_{GREEN}], the necessary green period during the peak hour is chosen. It is required that for a decrease of the number of lanes a sufficient capacity at the continuing section of the road exists. The distortion [l_{Z1}] of the lane should be symmetric and as long as possible (minimum l_{Z1} = 30 m). Because of that a good traffic flow is most likely possible. If a continuous traffic lane must lead into a turning lane, the marking and signposting must be placed early enough, that not unexpected or disturbingly late lane-changes are probable.

If roads have a levelled or special track, it can be necessary to let the vehicles use the track at the intersection, to enlarge the congestion area and to increase capacity. This is just possible if public transport and motor vehicles are unblocked at the same time when a public transport vehicle is closing up the emptying of the track must be guaranteed.

Dynamically used continuous lanes in the sector of public transport lane can be emptied by a forward planning of motor vehicles, so public transport vehicles can use the same green period without any delay. [FSV, FGSV]

Left-turning-Lane

If a left turning movement is separately signalised a left turning lane is needed. The length of the left turning lane should be chosen in a way that the bordering lanes do not become congested. It is sufficient, when the length of the left turning lane is longer than the critical 95% congestion length at the left turning lane or at the bordering lane (after HBS). The 95% congestion length is the congestion length which is not exceeded in 95% of the cycles. [FGSV 2009, FGSV, FSV]

Also if there is no intention of an own left turning stage, left turning lanes or setting-spaces should only be left out, if the left turning vehicles can flow off or can set themselves at the nearby zone of the intersection in one cycle. If the arrangement of a left turning lane or setting-space is not possible at an intersection access, but left turning cannot be forbidden, the whole intersection access should be unblocked in an own stage. If there are confine conditions, it is appropriate to undercut the regular measure than to relinquish it. The delineation of left turning lanes towards continuous lanes through a lane marking is not permissible if the width of the intersection access measures less than 5.50 m. Narrow setting zones between 4.25 and 5.5 m can be marked with an arrow. [FGSV, FSV]

Right-turning-Lane and right-turning-Road

If there is an own right turning stage, a right turning road must be available. The length results analogy to the left turning vehicles from the 95% congestion length (HBS). At crossings with public transport it is possible to set red just to the right turning vehicles, therefore no right turning road is needed, it is possible to build tight setting spaces with arrow marking. Right turning roads beneath triangular islands for the free guiding of right turning vehicles are a priority help for enlarging the capacity, they are just considered within cultivated areas, if the bicycle and pedestrian traffic is not disturbed. Possibly crossings need to be signalised via right turning roads, which leads to long total-crossing-times (danger of disregarding the signalisation).

At small triangular islands the arrangement of signal heads for pedestrians need a clear allocation. At not signalised right turning roads, the priority conditions should be cleared up through not heightened bicycle crossings at start and end of the right-turning-road as well as through pedestrian-crossings at the middle area of the right-turning-road. As a special exception the ford can be realised without pedestrian crossing. Therefore it is needed to have no marked pedestrian crossing. As alternative the two direction-cycling paths or smaller triangular island in the middle of the right turning road, also a through priority arranged signposting of prioritised bicycle crossings beneath the pedestrian crossing can be considered. [FGSV]

Partial Public Transport Lanes at Intersection Accesses

Partial public transport lanes at single level intersections serve the congestion circumventing and therefore the accelerating of public transport vehicles with design-technical measures. The possible additional action for direction-conform allocation of vehicle streams for controlling public transport vehicles at the peak of the vehicle-crowd and for loss-free regulation of entering and departing at stations and ending public transport lanes are the signal- and control-technical priorities.

Also an until stop line reaching public transport stop bay at the right side of lane or a public transport stop island in the middle can be considered as (partial) public transport lanes. [FGSV]

The direction conform allocation of vehicle streams at signalised intersections are an important requirement for minimising the number of stages and avoiding unused public transport stages at low ride sequence, fixed time control and for guaranteeing as high as possible total traffic volume.

Direction-conformity can be established through:

- driving-direction-based public transport lanes at intersection accesses (structural action)
- divert congestion with controlled addition of public transport vehicles and motor vehicle traffic into the direction conform sorting area (operational action)
- public transport locks (operational action)

The merging or turning of public transport busses from bays of stations and bus lanes in right side position can be provided through a heading time, a permissive signal or (less limited area-availability) a bus-lock. If a bus lock is arranged the motor vehicle traffic is hold back by an additional signal in distance of at least 30 m before the signal transmitter of the intersection approach. The green period of line busses is given in Germany through signal heads of BOStrab.

Change/U-turn Lane

Change lanes should be offered at main roads with not crossable central reserves, especially tracks and bus lanes in middle position. Because u-turning vehicles at intersections represent a loss in safety, capacity and quality of the traffic flow, change lanes should be offered somewhere at sections of the line. Change lanes can also serve for replacement-lanes for left out of left turning. If despite U-turn-need no change lane exists, the signal program structure should be chosen in a way where U-turns do not disturb other traffic movement.

Convenient are change lanes if the through signalisation at neighbouring intersections created gaps in the opposing traffic can be used for U-turns. [FGSV]

Signals for changing (U-turn) traffic are necessary if:

- the opposing traffic is too strong for free changing/turning
- especially tracks or bus lanes must be crossed at middle position

- at the setting space before the change lane or at a broken middle-lane is not enough congestion area for the changing traffic
- the sight at the opposing traffic is not sufficient

2.6.3 Bicycle Lanes

Direct guiding: If bicyclists drive at the following section of the junction directly at the road, they can be signalised together with motor vehicles and can turn left directly. At intersection approaches with more than one lane for direct left turning bicyclists a bicycle path should be offered. If the bicyclists at the junction following road-sections are guided at bicycle paths or lanes with strong left turning bicycle traffic and more than one continuous lane or speedy alignment, it is recommended to erect bicycle locks.

The guidance of left turning bicyclists is an option if at the following road-section of line has bicycle paths or lanes installed. In a lot of cases it makes sense to mark a setting space beneath the bicycle crossing. That special guidance of cyclists should be displayed by a sign. Cyclists who have crossed the street and wait at the setting space for turning left should be signalised separately or together with the pedestrians of the wanted direction. [FGSV]

The joint signalisation assumes that:

- the pedestrian crossing is hardy heightened
- the unblocking of the pedestrian crossing has enough time lead against the at the same stage unblocked partially conflicting turning streams
- with an existing central reserve both pedestrian crossings need to be given free at the same time

2.6.4 Stop Lines

For the motor traffic the stop line should be in 3 m distance of the signal head and at minimum 2.50 m. The distance from the side of a pedestrian crossing needs to be at a minimum 1.00 m away. For a good sight between the approaching bicyclists and vehicle-drivers, especially the heavy-duty-vehicle drivers, the stop lines for the cyclists should be brought 3.00 m forward, in front of the stop line of motor vehicles. If there is strong bicycle traffic, the forward bringing can be set to 4.00 up to 5.00 m. [FGSV] For the crossing- and stop line marking the RiLSA shares the following diagram.

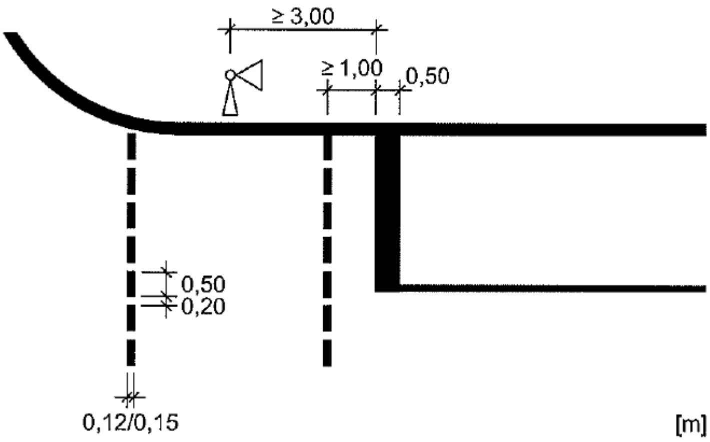


Figure 2.31: Stop Line and Crossing/Ford Marking

Distancing the stop line is necessary at limited area availability or at sharply entering right turning traffic which uses the same intersection approach as the opposing traffic. The two most important standard design vehicles are:

- the biggest after StVO (Germany) permissible vehicle, that is decisive,
- three-wheeled waste vehicle, which represents in common also trucks and fire engines.

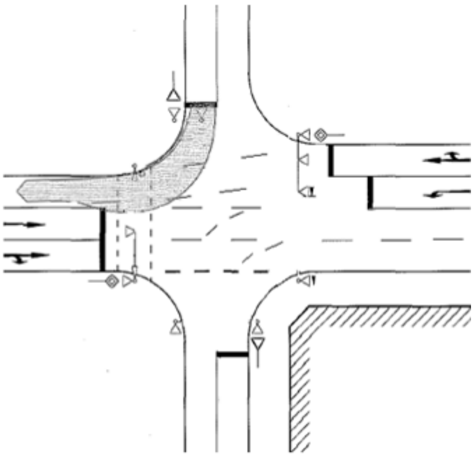


Figure 2.32: Stop Line Allocation and Swept Path

Other special cases can be considered with the help of guidelines for vehicle swept paths. It is suggested to stagger the stop lines. The stop line allocation is also dependent to the vehicle with the largest swept path. An example is shown in the figure. If the stop line would be set nearer to the intersection center, it would not be possible for the given swept path to pass the intersection without endangering for green waiting vehicles. To make planning easier the RiLSA [FGSV] depicts tables for the roughly stop line allocation

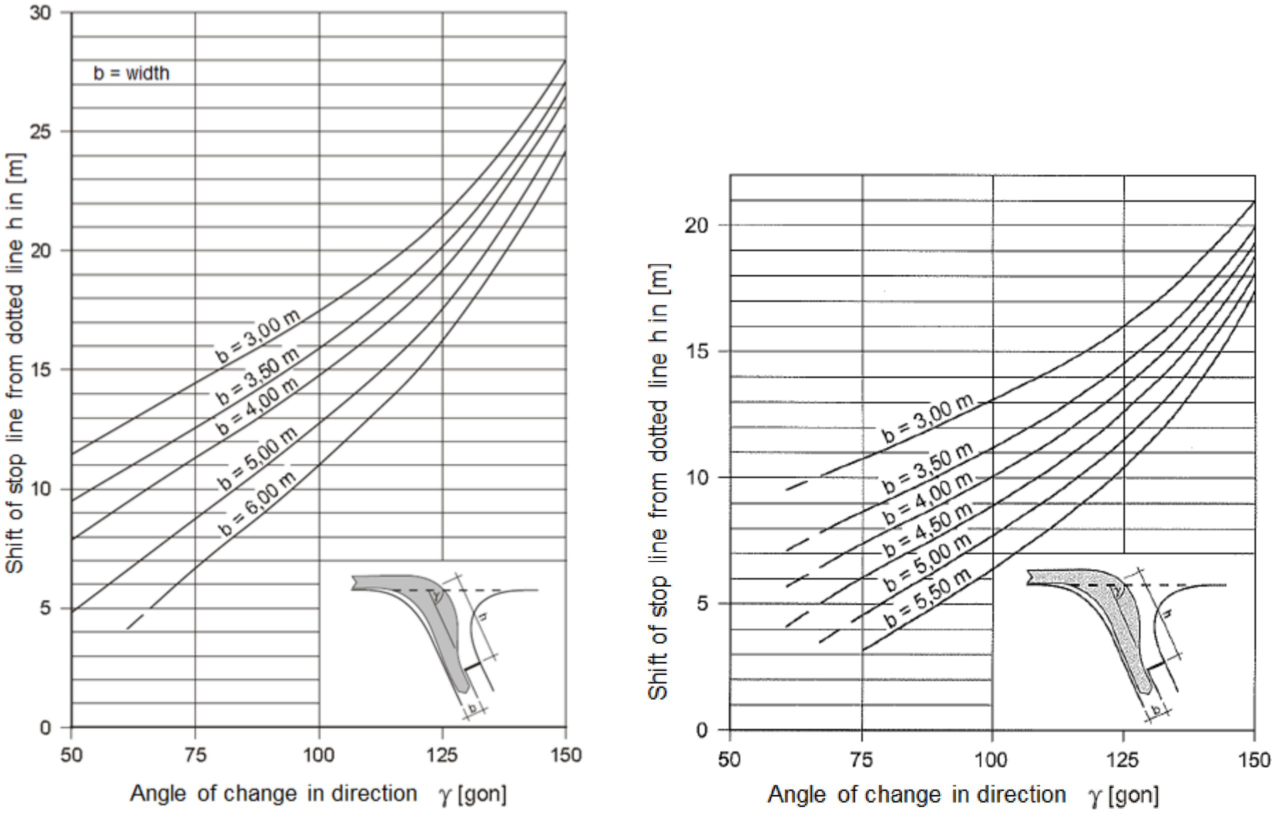


Figure 2.33: Stop Line Allocation [RiLSA]

2.6.5 Ground Marking

With the help of lane marking (ground marking) the clarity and a clear leading can be guaranteed. For the guidance of left turning vehicles in the inner intersection area, lane marking or a line of 1.0 metre length at the point of intersection of the marked crossing lane is practicable.

At meagre determined setting spaces within the intersection area, it is sufficient, as a rule, to lead the left turning vehicles through an outer lane marking. It is important to mark the position, until which the left turners can drive up, without touching the lane of the simultaneous unblocked opposing straight ahead driving traffic. Better than the basically possible marking of a waiting line is the marking of the left limiting of the continuous lane of the oncoming carriageway. [FGSV]

2.6.6 Signposting

The following principles are valid:

- Positive and negative priority-signs are generously to arrange and are always mounted at the signal mast, so that also in case of failing or turned off light-signal-plant a regulation of traffic is available. Normally a left sided repeat is essential.
- If not all directions are allowed at an intersection, the allowed directions need to be stipulated by a sign. The lane-based signposting for supporting the through direction-arrows or light signals given driving direction is not permissible. At intersection accesses with more than two lanes the signs must be repeated at the left side.
- In closed villages/towns, if the light signal-plant is not visible from sufficient distance and because of that stopping without problems is not possible, a special sign should be mounted.
- Outside closed villages/towns the permissible top speed in front of light signal pants must be set to a maximum of 70 km/h. A step by step adaption to this level of speed can normally be left out. [FGSV]

2.6.7 Crossings / Fords

Cyclists and pedestrian fords should be as little as possible distant from the side of the parallel running street. When straight ahead and right turning traffic is led together at one lane, parallel guided cycle or pedestrian fords can be distanced up to 5 m into the side road, to create a setting area for the turning motor vehicles. The priority of cyclists and pedestrians from turning vehicles must be clearly noticeable.

Because of important cycling traffic connections the bicycle ford should not be distanced if because of that strong screwing is necessary. The change from cycle path to cycle lane at the intersection access and at the tighter intersection area should perform well. The pedestrian ford regulation width is 4 m, the minimal width 3 m. The bicycle fords should be at minimum that wide as the bicycle path. At ford widths larger than 8 m there should be a second signal transmitter per direction. Near the location of pedestrian fords sufficient large waiting areas should be located at the side of the road, so that during red times arriving pedestrians can be stored. (Density about $2P/m^2$ or $1bicy/1.5m^2$) [FGSV]

2.6.8 Stations / Stops

By arranging and developing stations the matters of passenger, operation and local matters need to be weight up. The position of stations within the intersection area needs to be set in tight connection to the signal control. The position in front of the intersection has the advantage that time loss because of signal-condition can be used for passenger change and the public transport vehicles can be brought to the peak of following vehicles. Disadvantage could be that during passenger changes, if the crossing traffic cannot be unblocked, towards running passengers are affected. If only straight ahead or right turning buses must be considered, their station can be positioned directly in front of the intersection or at a slightly occupied right turning lane.

The position behind the intersection hast the advantage that the green period of public transport vehicles can be requested and changed in a reliable way, because of sufficient incubation period. Moreover the crossing traffic can be freed exactly after the logging off and therefore during the station-residential-time. If the station of left turning buses cannot be positioned after the intersection exit, a station in connection to a bus lock makes sense (station at least 30 m before the intersection access). Alternative the switching of a demand-stage for left turning line buses of an until intersection area lengthened bus-stop-bay is possible. Beneath the structural measurements also signal-technical and operation-technical measurements need to be included. [FGSV]

Station-islands are common if other vehicle traffic should go on during the stopping process. The signal and control technical requirements are low, because such a solving is structural independent from public transport guiding. If the accesses to the station-island are designed as fords, it is preferable and relevant due to safety to switch the green period dependent to the public transport lane. Waiting passengers should reach the stopping bus from the side in a safe way.

Dynamic stations are common if other traffic can wait during the stopping process and a waiting area for passengers at side can be offered. The passenger change is safe. Signal- and operation-technical requirements for dynamic stations can be important, especially when the station is placed after the intersection-exit and the inflow of turning, crossing traffic needs to be coordinated with the stopping process of the public transport. The signal head shows dark-amber-red-dark, only at request. [FGSV]

2.6.9 Surface Street Control

The main applications of traffic-signal systems use surface street control systems.

Techniques/Strategies

For implementing traffic lights there are different types of Architectures possible. The centralized architecture, distributed architecture with local masters and distributed architecture without local masters.

A centralized architecture is representative of the central control system where a single central computer configures directly the control of duration of every controller stage. The computer transmits commands which are used for break-off of the existing stage to the controller. The transition rate is normally at once-per-second.

The distributed architecture with local masters is representative of most closed-loop systems where second-by-second commands are given from local masters to the intersection controllers. The masters communicate with the central processor just when failure occurs or a command of the central processor exists. The link between the local controllers and masters is normally realized via dedicated twisted-pair cable, with it, minimizing the cost between remote groups of intersections and a central site is possible.

Distributed architecture without a local master is similar the centralized architecture, but the communication capacity requirements are lower. This offers the ability to connect more than 100 intersections to one voice grad facility. It is practical to use a variety of alternative communications media like radio or cable television. The architecture is based on the local controller communications interface devices providing the local timing. [RITA]

3 Overview of Control Methods

A control method describes the process of a signal program, the type and scope and the interaction of changeable control parameters and signal program elements. There are macroscopic and microscopic control level methods.

Macroscopic

Reacting to macroscopic key figures

Mean congestion length, mean traffic density, issuing limiting value

Serving the consideration of long term loading changes of traffic networks, intersections…

Time table dependent (A1) or traffic dependent (A2) signal programs for longer duration

Normally no changes at short notice

Microscopic

Method including changes at short notice, considering the changes at traffic flow

Changes can be noticed/ considered during one cycle time → three different kinds

- fixed time signal programs (B1)
- method of signal program adaption (B2-5)
- method of signal program development (B6)

All versions of the microscopic methods use offline calculated signal programs or a least signal program parts. [FGSV]

Table 3.1: Overview of Control Methods [RiLSA]

<table>
<tr><th rowspan="2"></th><th colspan="2">Control methods</th><th rowspan="2">number</th><th colspan="2">activating</th><th colspan="5">Traffic dependent changeable elements of signal programs</th></tr>
<tr><th>Generic term</th><th>Main feature of changeability of signal programs</th><th>Time table dependent</th><th>Traffic dependend</th><th>Cycle time</th><th>Stage sequence</th><th>Number of stages</th><th>Green period</th><th>Offset time</th></tr>
<tr><td rowspan="3">A:Macroscopic control level</td><td rowspan="2">Signal program choice</td><td>Time table dependent choice</td><td>A1</td><td>X</td><td></td><td colspan="5" rowspan="3">In combination with one control strategies of group B, changeable elements of signal program</td></tr>
<tr><td>Traffic dependent choice</td><td>A2</td><td></td><td>X</td></tr>
<tr><td>Development of the frame signal program</td><td>Traffic dependent development</td><td>A3</td><td></td><td>X</td></tr>
<tr><td rowspan="6">B: microscopic control level</td><td>Fixed time signal program</td><td></td><td>B1</td><td colspan="2" rowspan="6">Activating in accordance with the control strategies of group A</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="4">Signal program adaption</td><td>Green period adaption</td><td>B2</td><td></td><td></td><td></td><td>X</td><td></td></tr>
<tr><td>Stage change</td><td>B3</td><td></td><td>X</td><td></td><td></td><td></td></tr>
<tr><td>Stage request</td><td>B4</td><td></td><td></td><td>X</td><td>X</td><td></td></tr>
<tr><td>Offset time-adaption</td><td>B5</td><td></td><td></td><td></td><td></td><td>X</td></tr>
<tr><td>Signal program development</td><td>Free variability</td><td>B6</td><td>X</td><td>X</td><td>X</td><td>X</td><td>X</td></tr>
</table>

At **fixed time signal programs** there is no change of signal program elements.

At the **signal program adaption** with fixed cycle time, the singular elements can be changed dependent to traffic.

> At the green period adaption the duration or length of green period can be adapted due to the traffic situation. Therefore a fixed cycle time is given and delay which defines the start of green period during the cycle time of a fluctuating duration of free period adaption is allowed (**B2**).
>
> At the stage change the stage sequence gets changed (**B3**).
>
> With the stage request it is possible to insert a demand stages into the given stage sequence at one or more locations of the signal program, through temporary shortening the green periods of other stages (**B4**).
>
> For the offset time adaption the relative start of green periods during a cycle time can be varied (**B5**).

The strategies B2 to B5 are often combined with each other.

For the **signal program development** the changeable elements of signal program can be built up traffic dependent (**B6**).

At the different daytimes different methods of macroscopic and microscopic control-level can be used. For using a signal-group-oriented control, the word stage can be replaced with signal group, because the reference unit at this control is not the stage it is the signal group. The different control systems can be realised rule-based or model-based, which will be explained in chapter 5. [FGSV]

The **macroscopic** control level includes:

Timetable dependent Choice of Signal Programs

> At the timetable dependent signal program choice a program is chosen out of a number of given signals programs, based on calendar day and time. This is enough if the traffic conditions are temporally stable and predictable, that means returning at same week-days and day-times. The establishing and analyses of key figures, the calculation of control values and signal programs as well as the setting of switching times are realised offline.

Traffic dependent Choice of Signal Programs

> At the traffic dependent signal program choice a program is chosen out of a number of given signal programs, based onto actual detected traffic data. The edited and normally smoothened key figures of the actual traffic flow can be connected to equations of condition and threshold values for choosing the control logic of signal programs. The key figures can also serve as entry values for a model-based realisation of control methods. [FGSV]

Traffic Control Systems of the **microscopic** level can be divided into three categories:

Fixed Time Signal Control

All signal program elements are stable and cannot be changed.

Partially Traffic dependent Signal Control

It is also called signal program adaption. Singular signal program elements can be changed due to traffic conditions

Traffic dependent Signal Control

It is also called Signal Program Development. Here all signal program elements are changeable. A frame program with fixed cycle time as at the partially traffic dependent control does not exist. [FGSV]

If the green allowance periods are compared, the difference between the tree methods of microscopic level can be shown clearly in the diagram below.

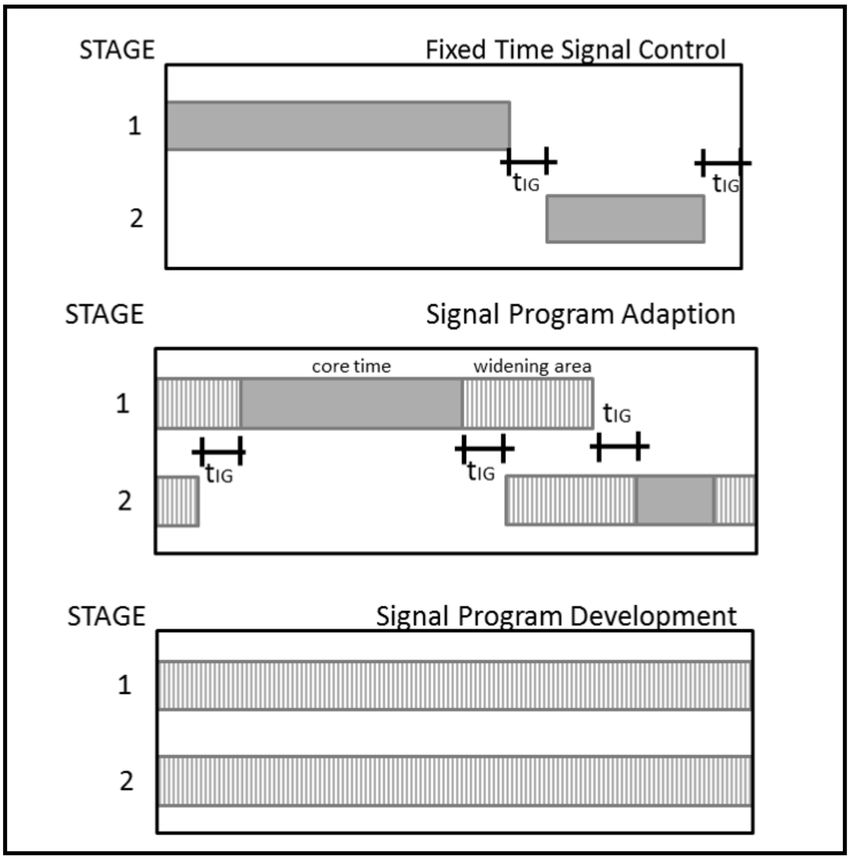


Figure 3.1: Methods of Signal Control

The used green periods cannot overlap in reality. Between the signal group of the ending stage and the one of the beginning stage must always exist an intergreen time. [Bosserhoff] At the signal program development green is allowed at any time if all conditions are satisfied. That means every stage can be unblocked at every time if necessary for the traffic flow. It must be considered, that there are conflicting movements, which cannot have green at the same time.

Because the microscopic arrangement depicted before is very theoretical, in the following chapters the following words are used:

- time dependent control/fixed time control
- traffic dependent control (partly and fully traffic dependent)

4 Time-dependent Control (Fixed Time Signal Control)

The oldest and most widely used traffic signal control method is the fixed time control. Control parameters such as cycle length, green splits and offsets are pre-determined and can only be changed manually or pre-defined by a point of time. A well-designed fixed time signal timing plan can work well enough as long as the pre-measured or pre-determined traffic situation is not changed.

Major advantages of this control method are the simple design, the robustness in operation and the low construction and operation costs (no detectors needed). In addition, fixed time controlled junctions on an arterial can be well coordinated without any software support. The easy way of controlling it on site as well as the possibility of easy revisions are further advantages.

The missing flexibility at changes of traffic load has a negative impact. Because of the advantages of fixed time signal control (same processes, easy control, low costs at revision) the fixed time control is the standard method, provided that the missing flexibility at fluctuations has no negative effect. [FSV]

The different methods of traffic control will be explained by using a simple 4-leg junction. As shown clearly in the Figure below, our model has six different traffic lights, five for traffic control and one for pedestrian crossing. Each traffic light, as mentioned also at the signal layout map, has an individual identity for identification. Each vehicle signal head has three modes, red, amber and green, the pedestrian signal needs just a two fielded signal transmitter.

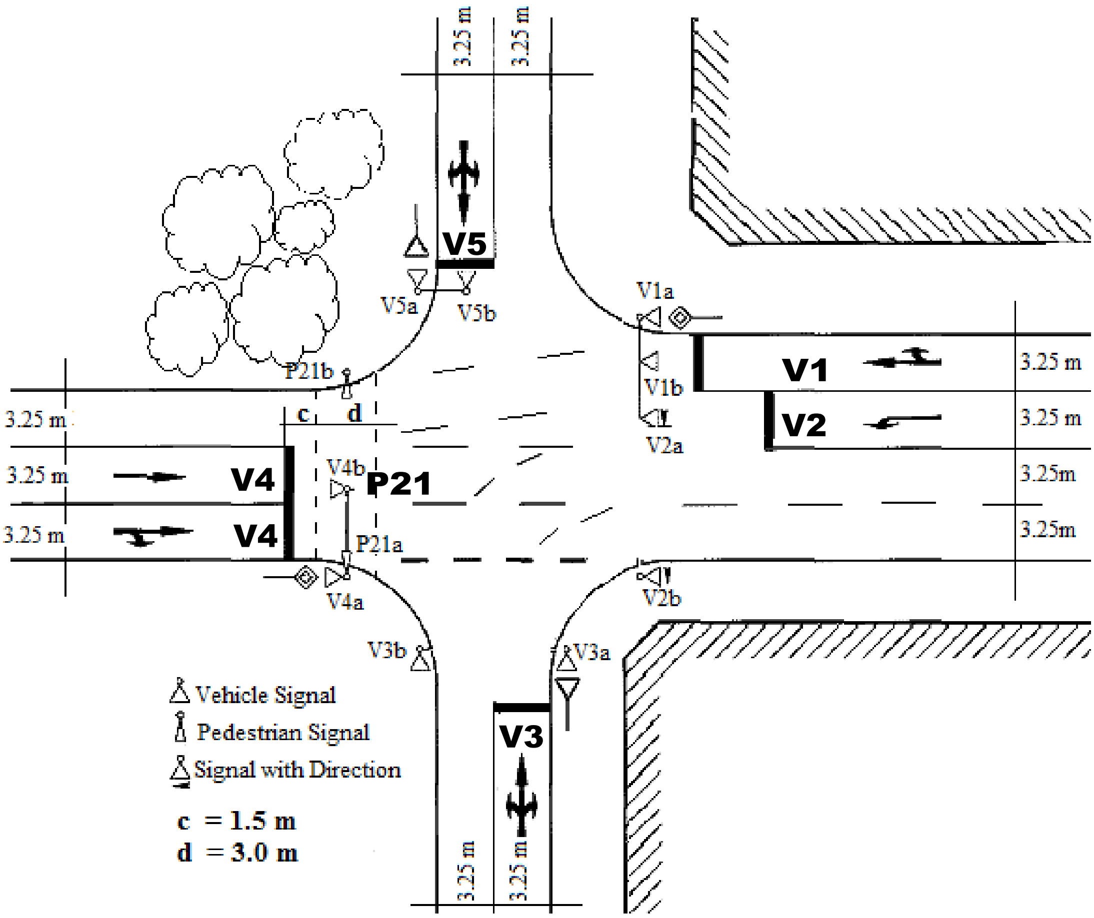
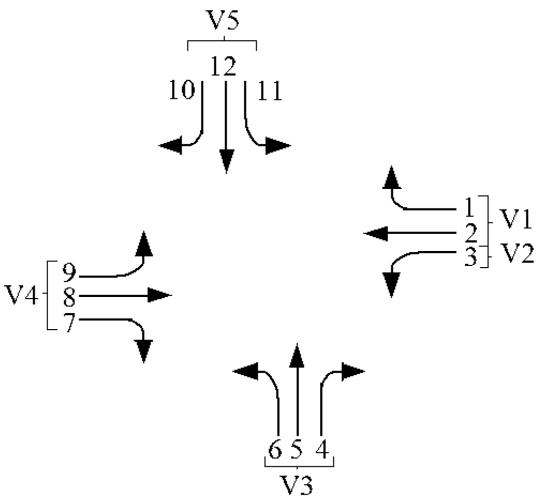


Figure 4.1: 4-Leg Junction with 5 Vehicle- and 1 Pedestrian-Movement

Table 4.1: Traffic Volume at the Junction

Stream	**1**	**2**	**3**	**4**	**5**	**6**
pcu	100	160	320	180	100	140
	260		320	420		
Stream	**7**	**8**	**9**	**10**	**11**	**12**
pcu	100	240	0	250	195	100
	340		0	545		



Fixed time controlled signal programs includes solid green periods for all traffic streams. The duration of green periods is determined offline. Fixed time Signal Programs can fulfil the necessities according to the local and traffic conditions. Due to the loading of motor vehicles for sizing and the interests of other traffic participants the fixing of the cycle time has a special significance. Because there is no change of signal program elements, fixed time signal programs should be preferred used, if it is predictable, that the stage of loading stays the same over longer periods. [FGSV]

If a fixed time control is used, the cycle time should be set in a way, where the waiting times for the motor vehicle traffic stay at a minimum. Therefore the cycle time should not be higher than 300s. The cycle time can be fixed through diagrams or through calculation. [FGSV]

Calculation after RiLSA (Germany):

$$t_{cycle} = \frac{1.3 * T_{IG} + 4}{1 - (\frac{q_1}{qs_1} + \frac{q_1}{qs_1})} \qquad t_{GREENi} = \frac{\frac{q_i}{qs_i}}{\frac{q_1}{qs_1} + \frac{q_1}{qs_1}} * (t_{cycle} - T_{IG})$$

T_{IG}	= sum of the interim periods of both directions TZ = tZ1 + tZ2
q_1 or q_2	= traffic volume [vehicles/h] for the concerning direction
q_{S1} or q_{S2}	= saturation flow [vehicles/h] for the concerning direction

$$q_1 / q_{s1} + q_2 / q_{s2} < 1$$

Because of the local circumstances (lane-condition, traffic-composition), the saturation flow assessment must be estimated. A saturation flow from approximately 1500 veh//h/lane can be taken.

Calculation at Bottlenecks:

As evidence of quality of traffic flow at bottlenecks, the middle waiting time of a vehicle at fixed time control, can be calculated. The connection between length of bottleneck and size of cycle time results from:

$$s_r = V_r * [0.017 * t_{cycle} * (1 - \frac{q_1}{q_{s1}} - \frac{q_2}{q_{s2}}) - 1.54]$$

s_r	= Length of bottleneck [m]
V_r	= middle clearing speed [km/h]
t_{cycle}	= minimum cycle time [s]

If a certain (maximum) cycle time is desired, the length of bottleneck can be calculated from it. At a fixed time control more signal programs should be used, due to the day-time-swaying. [FSV]

4.1 Requirement for Traffic Counts

For the fixed time signal program calculation it is necessary to have certain key figures. The traffic design volumes given in passenger car units, the geometrical design of the junction, the traffic streams are important for calculating the intergreen times. Out of that calculation the intergreen matrix follows. The intergreen time calculation will be given in detail in chapter 4.3 for an example.

4.1.1 Traffic Design Volumes

In Austria, Germany and the United Kingdom the vehicles are counted per lane, movement and vehicle type. Normally for the calculation passenger car units (pcu's) are used. Generally a peak of 15 minutes is taken for the calculation; the used unit are pcu (rolling horizon). If there is no pcu calculation possible the peak can be multiplied by 1 to 1.2.

Remark: turning volumes from transport demand models (e.g. VISUM assignment) are critical, because of common lack of calibration. There is a difference by calculating the pcu. For more detailed information take a look at the table underneath.

Table 4.2: Passenger Car Units [pcu]

		AUSTRIA (A)	
pcu	Passenger car Units	bicycle	… 0,3 pcu
		motor bike	… 0,5 pcu
		motor car	… 1,0 pcu
		truck/bus/tractor	… 2,0 pcu
		bendy bus/ juggernaut	… 3,0 pcu
		truck/tractor + trailer	… 4,0 pcu

		GERMANY (D)	
pcu	Passenger car Units	Pedal cycle	… 0,2 pcu
		Motor cycle	… 0,5 pcu
		passenger car	… 1,0 pcu
		Medium light goods vehicle	… 2,0 pcu
		HGV is unknown → multiply counted vehicles by 1,1	
		Busses and coaches	… 2,0 pcu

		UNITED KINGDOM (UK)	
pcu	Passenger car Units	Pedal cycle	… 0,2 pcu
		Motor cycle	… 0,4 pcu
		Car or light goods vehicle	… 1,0 pcu
		Medium light goods	… 1,5 pcu
		HGV(heavy goods vehicle)	…2,3 pcu
		Busses and coaches	… 2,0 pcu

		ITALY (IT)	
pcu	Passenger car Units	Pedal cycle	… 0,2 pcu
		Motor cycle	… 0,5 pcu
		Car or light goods vehicle	… 1,0 pcu
		HGV(heavy goods vehicle)	…2,0 pcu

[FSV; FGSV; Kimber, MITRS]

4.2 Intergreen Calculation and Intergreen Matrix

Intergreen time

- Intergreen time is the time between the end of green of the ending signal group and the green begin of the beginning signal group, both signal groups are conflicting.
- During intergreen time vehicles of the ending signal can clear [in Austria it is also possible that new vehicles may enter but the mutual conflicting point (area) will not be reached at the same time]
- Departure length = stop line until conflict point s_0 plus vehicle length l_{veh}
- Entering length s_e = stop line until conflict point
- It is better to take the most pessimistic conflict point of a conflict area (safety reason)

Intergreen matrix

- Intergreen times are given in full seconds and presented in a 2-dimensional intergreen matrix
- Clearing cars to entering cars need about 4-6 seconds intergreen time
- Clearing pedestrians and entering (nearside) cars need about 10 to 15 s intergreen (early red for pedestrians)

Table 4.3: Key figure calculation for cars

Key figures		AUSTRIA (A) 	GERMANY (D) 	UNITED KINGDOM (GB) 
t_{IG}	Intergreen period [s]	$t_{IG} = t_t + t_{cl} - t_e$ [s]	$t_{IG} = t_t + t_{cl} - t_e$ [s]	Distance x [m] → intergreen [s]
		It is the duration between the end of the green period of a traffic stream and the start of the green period of another traffic stream, which will cross the way of the first traffic stream or enters into it. It is shown with an amber signal.	It is the duration between the end of the green period of one traffic stream and the start of the green period of a following released conflicting or partially conflicting traffic stream.	
x	Distance [m]			To calculate the clearance time, measure the extra distance travelled to the probable collision points by vehicles losing right compared with those gaining right of way… the longest distance = x
t_i	Interstage [s]	3s …→ 60 km/h 4s … → 70 km/h } $t_{t,amber}$ 2 s … $t_{red/amber}$	3 s … ≥ 50 km/h 4 s … ≥ 60 km/h 5 s … ≥ 70 km/h } $t_{t,amber}$ 1 s… $t_{red/amber}$	normal minimum = 5 s 3 s amber after, 2 s amber before
		The change from green period to blocking time and from blocking time to green period. The transition period red/amber has duration of 2 s, the duration period amber, follows the permissible speed at the access.	the change from green period to red times is symbolised through the transition signal amber before red → transition signal amber The transition signal red/amber is shown before green.	
t_t	Transit Time [s]	3s …→ 60 km/h 4s … → 70 km/h	*T_{IG} + t_{cl} ≥ tG +1* *Straight ahead … 3 s* *Turning … 2 s* *Pedestrians … 0 s*	-

		Duration between the end of the green period and the point of time where the stop line was overran by the last clearing vehicle	The duration between the end of the green period and the beginning of the clearing time	
s_{cl}	Clearance distance [m]	$s_{cl,A}$	$s_{cl0} = s_{cl,A}$ $s_{cl,D} = s_{cl0} + l_{veh}$	The UK calculates with X – Distance x
		The length of the clearance distance is normally calculated by using the axis of the particular lanes as distance between the stop line and the decisive conflict point. The clearance distance for pedestrians must be calculated for the total crossing. If an enough wide traffic island exists, the clearance distance can also be calculated just to the traffic island.	The clearance distance is the distance between the stop line and conflict point /area of the clearing car or the distance between the beginning of the ford and the conflict point /area. The reference line is the central line of lane or foot-path.	
t_{cl}	Clearance time [s]	$\frac{s_{cl,A} + l_{veh}}{v_{cl}}$ for cars $t_{cl} = \sqrt{2 * \frac{s_{cl} + l_{veh}}{b}}$ for tramcar b = 0,8 to 1,0 m/s² (acceleration)	$\frac{s_{cl,D}}{v_{cl}}$	-
		The duration for passing the clearance distance ü vehicle length with a clearing speed.	It is the duration for emptying the clearance distance + vehicle length with clearing speed	
v_{cl}	Clearance speed	**cars** 10 m/s → radius smaller and 20 m 7 m/s → radius smaller and 10 m **Bicycle** 5m/s bicycle with separate signalisation speed is reduced to 4m/s **Pedestrians**: 1,0 up to 1,5 m/s	**cars** 10 m/s → straight ahead 7 m/s → turning 5 m/s → turning radius smaller 10m **Bicycle** 4,0 m/s **Pedestrian** 1,0 – 1,5 m/s → 1,2 m/s **Tramcar and line buses** acceleration = 0,7 – 1,5 m/s² (tram) acceleration = 1,0 – 1,5 m/s² (bus)	-
l_{veh}	Length of vehicle	Bicycles … 2m Motor vehicles … 6m Tramway … 15m	Bicycles … 0m Motor vehicles … 6m Tramway … 15m	-
t_e	Entrance time [s]	$\frac{s_e}{v_e}$ for motor vehicles for bicyclists = 0 or 1 s for pedestrians = 0 or 1 s $t_e = \sqrt{2 * \frac{s_e}{a}}$ … for tramways	$\frac{3,6 * s_e}{40}$ for motor vehicles $t_e = \sqrt{2 * \frac{s_e}{a}}$ for tramways acceleration out of standstill $t_e \leq v_{max}/(3.6 * a)$ Bicycles normally =0 s Pedestrians = 0 s	-

		The duration for the passing of the entering distance with an entering speed.	The duration for the passing of the entering distance. For motor vehicles it is understood that the first vehicle passes the stop line at the beginning of the green period, independent of the permissible top speed and driving direction with an entrance speed of 40 km/h. ***	
s_e	Entrance distance	The length of entrance distance is normally calculated by using the axis of the particular lanes as distance between the stop line and the decisive conflict point.	The reference line is the central line of lane or foot-path. The entrance distance is the distance between the stop line and conflict point of the entering car or the stop line and the conflict area of the ford or the beginning of the ford and the conflict point.	The UK calculates with X – Distance x
v_e	Entrance speed [m/s]	**Cars** 12 m/s → general 10 m/s → radius ≤ 20 m 7 m/s → radius ≤ 10 m At green period start of help signals (green direction arrow) the entrance time is raised by 1 second **Bicycles and Pedestrians** Normally no entrance processes are considered – for special cases a entering time of 1 second can be observed **Tramcar and line-buses** If entering from station = on-going out of standstill a = 0,8 to 1,0 m/s² If tramcars can enter without stop, a flying start must be calculated	**Cars** For calculation = 40 km/h 10 m/s → straight ahead 7 m/s → turning 5 m/s → radius < 10 m **Bicyclists** 5 m/s → bicyclists **Pedestrians** Normally the entrance processes for pedestrians and bicyclists are not decisive – not considered.	
$t_{gr,min}$	Minimum green	8 s…vehicle, cycle, pedestrian 5 s… public transport 15 s main stream recommendation	Minimum green 5 s (Normally 10 s for vehicle streams and 15 s for main approaches)	Minimum green = 7 s Pedestrians = 3 s
$t_{red,min}$	Minimum red	-	1 s	-

[FSV, FGSV, FGSV 2009, Department for Transport, Scottish Executive, Welsh Assembly Government]

In the **Netherlands** the rules are comparable to Germany with a few exceptions. The entrance time is calculated under the assumption that vehicles accelerate from standstill at the instant the light turns green, with a rate of 2.5 m/s². Amber times are generally following the same numbers as in Germany, but cities can have their own policies on this. In the Netherlands they use only the amber transition period (not the red/amber one). Minimum green is 4 seconds, but most cities have also their own policy of extending this minimum. The minimum red is 2 seconds. Here the minimum red is the time for one signal group before it can be turned to green again.

In **Italy** the rules are basically the same as for Germany, with no notable exception in numbers.

In **France** the rules are comparable to Germany, with some noticeable exceptions and differences. The Minimum Green or Flashing Amber duration is 6 seconds. The minimum duration of a full Amber is either 3s or 5s, where the 3 seconds is for urban areas and the 5s for higher class road intersections.

For Pedestrians, the Minimum Green is 6 seconds. For the conditional signals, the operation of the flashing amber follows the scheme of the main signal: it remains dark during the associated Green stage and starts flashing with the associated Red.

A Red-clearance time duration is computed on a case-by-case basis. A Red clearance stage is an extra time between Red on one direction and the beginning of Green on a conflicting direction. This Red clearance phase duration should leave enough time for a vehicle, which entered the conflicting area at the last instant of the fixed Amber to clear this zone before the other signal turns to a green signal. The estimated speed to clear a conflict area is 10 m/s for motor vehicles and 1m/s for pedestrians. Particular circumstances may have lower values (trucks, bicycles…). Finally, time/flow controlled signals have an extra requirement: The maximum Red duration for time controlled signals is 120 seconds.

In **Belgium** the rules are similar to those in the other countries. The minimum duration for the amber duration depend on the expected speed or cars and range between 5 to 7 seconds. However, the specific times depend also on the regions. There are different durations used. (Flemish, Brussels or Wallonie)

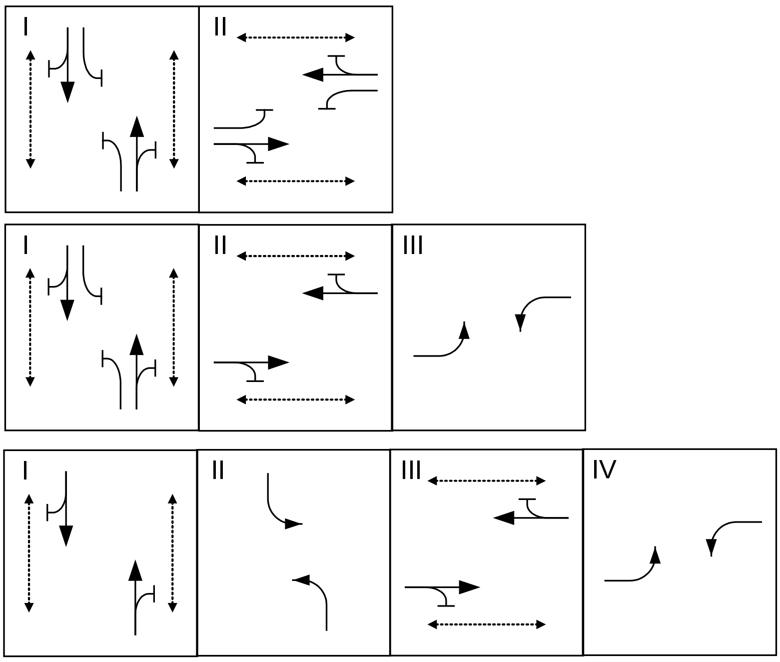
4.3 Stage Definition, Stage Sequence

Stage definition is classified by

- Non-conflicting movements (protected left turn)
- Partially conflicting movements (permitted left turn)
- conflicting movements

Potential safety problems

- Stage only contains compatible and semi-compatible movements
- Adding singular signal groups to an existing stage
- Critical: adding parallel pedestrians, if right/left-turning car movements have already GREEN
- Returning to previous stage
- Early start for left turning movements
- Parallel pedestrians or bicyclist have right-of-way against permitted turns; for safety vulnerable movements should enter the conflict area first [Fellendorf]
-



2-stage system; maximum capacity; left-turns may dissipate during transition period. This situation is very rare, it only occurs for very quiet arms on an intersection.

3-stage system; improves left turn for major movement (E-W)

4-stage system; maximum safety; If n-stages, then (n-1)! stage sequences

Figure 4.2: Different Stage Systems

4.3.1 Stage Definition for the Example

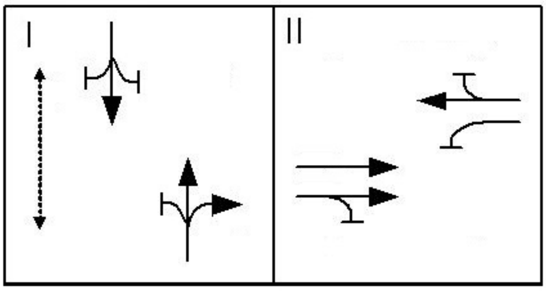
Left turning vehicles can flow off during the transition period (interstage).

Possible and useful stage systems for the given example are:

2-Stage-System:

Highest expected capacity

Table 4.4: Two Stage System

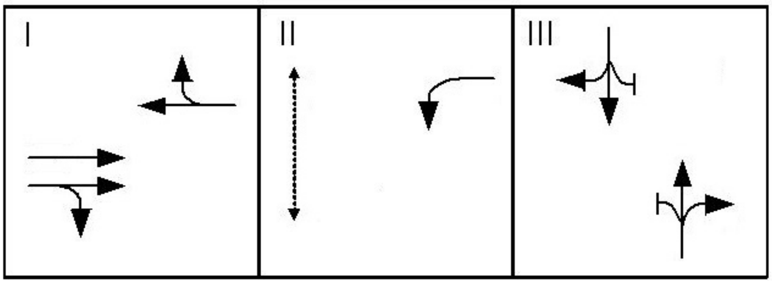


partially conflicting   partially conflicting

3-Stage-System:

Secure guided left turning vehicles

Table 4.5: Three Stage System



secured guiding   secured guiding   partially conflicting

For the 3-stage-system a signal program for the example is calculated with the use of the three different guidelines of Austria, Germany and the UK, to show the methodology.

4.3.2 Clearance and Entrance Distances

AUSTRIA and GERMANY [FSV, FGSV, FGSV 2009]

$S_{cl,Germany} = S_{cl0} + l_{veh}$

Se….entrance distance $S_{cl,Austria}$ = Scl0,Germany…..clearance distance l_{veh}….. Length of vehicle

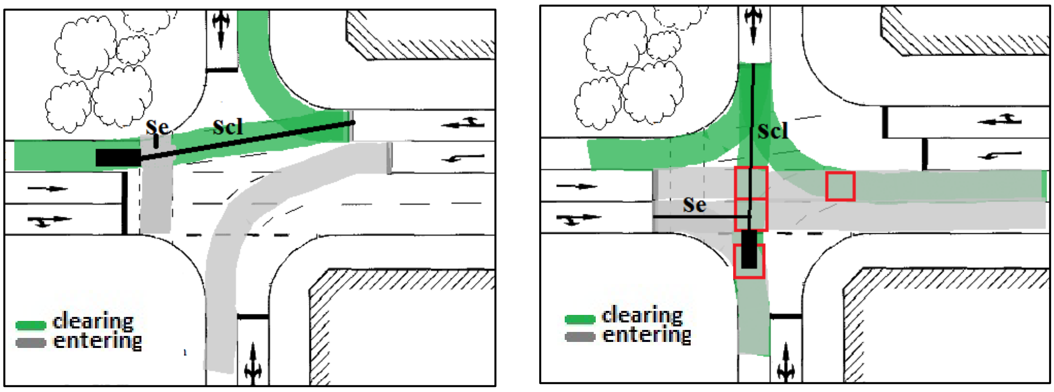


Figure 4.3: Conflict Area between entering P21- clearing V1 and entering V4 - clearing V5

NETHERLANDS:

The Netherlands are following the same rules as Austria and Germany they work with conflict areas considering the whole car (not narrow paths). The clearance distance includes the vehicle length.

UNITED KINGDOM: [Department for Transport, Scottish Executive, Welsh Assembly Government]

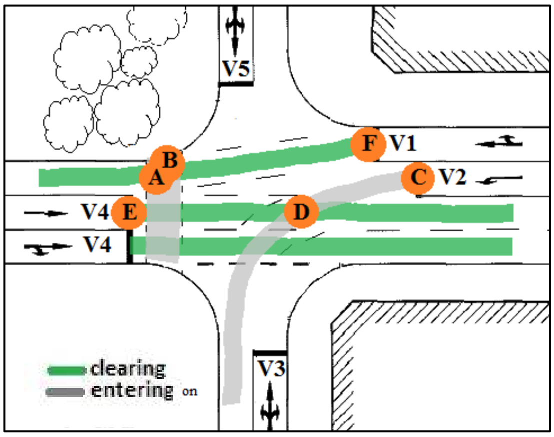


Figure 4.4.4: Distance "x" Calculation-Graphic (UK)

The collision points of concern, for the depicted movements are shown in red. To calculate the clearance periods, measure the extra distance travelled to the probable collision points by vehicle losing right of way, compared with those gaining right of way – the longest distance is needed and it is called distance “x”.

Table 4.6: Distance "x" - Intergreen – UK

Distance x [m]	**9**	**10-18**	**19-27**	**28-37**	**38-46**	**47-55**	**56-64**	**65-73**
Intergreen [s]	5	6	7	8	9	10	11	12

For example: FA – BA = 18.6 – 1.0 m = 17.6 m

ED – CD = 10.2 – 12.9 m = - 2.7 → x = 17,6m → Intergreen = 6s

If x is up to 9 m the minimum intergreen period should be satisfactory – if it is higher, the table underneath should be used.

Table 4.7: Clearance/Entrance Distances (Example)

		beginning					
	stage	V1	V2	V3	V4	V5	P21
ending	V1	x	x	17,6 / 5,0	x	10,6 / 9,4	18,6 / 1,0
	V2	x	x	14,4 / 5,5	15,1 / 8,0	21,1 / 7,0	x
	V3	7,2 / 15,4	7,7 / 12,2	x	9,0 / 16,9	19,7 / 8,5	28,6 / 1,0
	V4	x	10,2 / 12,9	19,1 / 6,8	x	15,1 / 9,8	7,4 / 1,0
	V5	11,6 / 8,4	9,2 / 18,9	10,7 / 17,5	12,0 / 12,9	x	20,5 / 1,0
	P21	10,4 / 14,6	x	10,4 / 23,6	10,4 / 2,4	10, 4 / 15,5	x

The formula for calculating the clearance and entrance distance can be measured from the signal layout map. Therefore the driven line must be known. Because movement V1 and V2 do not have any conflict, there exists no clearance or entrance distance. Also the movement V1 and V4, as well as V2 and P21 do not have conflicts. The movements depicted underneath are non-conflict movements which could be included into one secured guided stage. With the clearance and entrance distances the intergreen matrix for Austria, Germany and the UK are calculated, by using the predefined calculation rules. The calculation sheet for Austria, Germany and the UK is given at Figure 33 Intergreen Matrix Calculation of Austria, Germany and the UK.

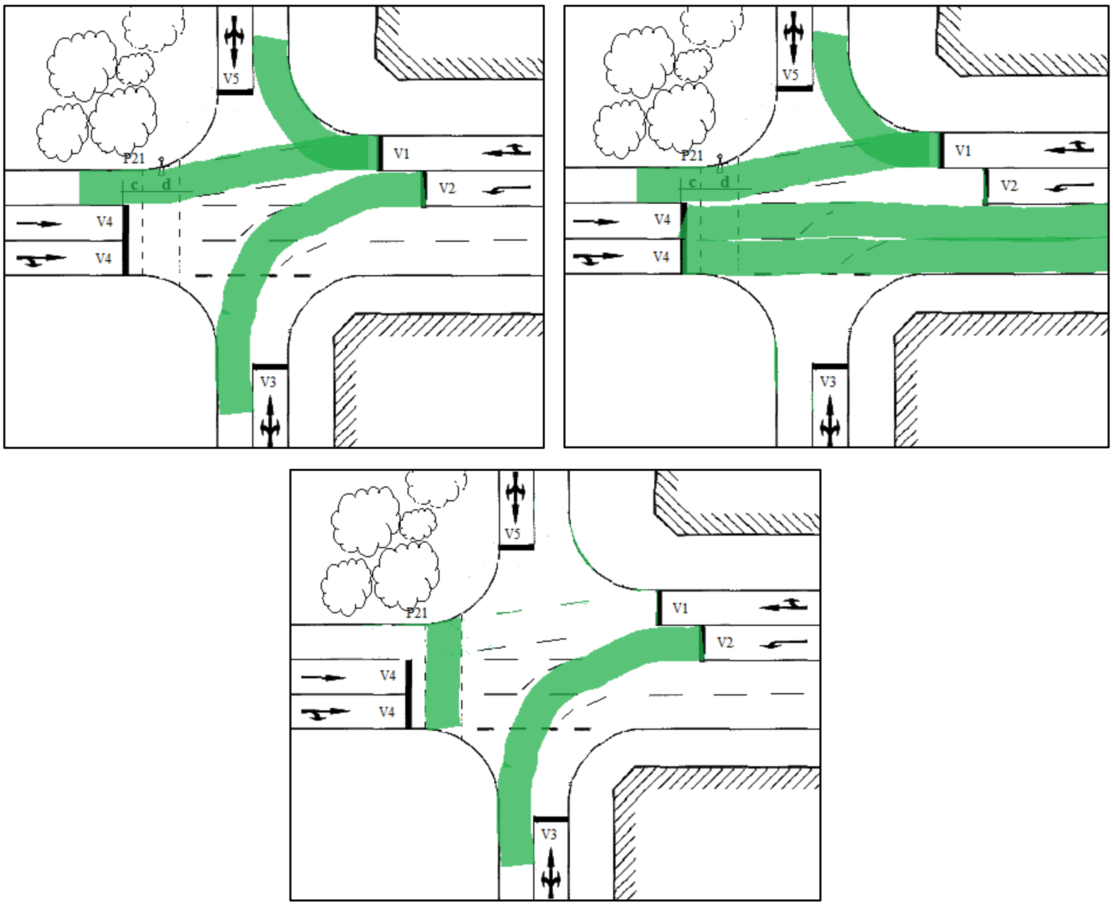


Figure 4.5: Movements without Conflict

	Starting Signal Group					
	AUSTRIA					
Ending Signal Group	V1	V2	V3	V4	V5	P21
V1			5		5	6
V2			6	5	6	
V3	3	4		4	6	5
V4		4	7		5	7
V5	5	4	4	5		7
P21	9		8	10	8	

	Starting Signal Group					
	GERMANY					
Ending Signal Group	V1	V2	V3	V4	V5	P21
V1			5		6	6
V2			7	7	8	
V3	3	4		4	6	5
V4		4	8		5	7
V5	5	4	4	5		7
P21	9		8	10	9	

	Starting Signal Group					
	UK					
Ending Signal Group	V1	V2	V3	V4	V5	P21
V1			6		5	6
V2			5	5	6	
V3	5	5		5	6	5
V4		5	6		5	7
V5	5	5	5	5		7
P21	5		5	5	5	

Figure 4.6: Intergreen Matrix Austria, Germany and UK

AUSTRIA

Tig = tt + tcl - te			V1-3	V1-5	V1-P21	V2-3	V2-4	V2-5	V3-1	V3-2	V3-4	V3-5	V3-P21	V4-2	V4-3	V4-5	V4-P21	V5-1	V5-2	V5-3	V5-4	V5-P21	P21-V1	P21-V3	P21 - V4	P21 - V5
	scl,A	Clearance distance in m	17,6	10,6	18,6	14,4	15,1	21,1	7,2	7,7	9	19,7	7,4	10,2	19,1	15,1	28,6	11,6	9,2	10,7	12	20,5	10,4	10,4	10,4	10,4
tt Transit time [s]	lvh	length of vehicle in m	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	0	0	0	0
= 3s	vcl	clearance speed in m/s	10	7	10	7	7	7	10	10	7	7	7	10	7	10	10	7	7	7	7	7	1,5	1,5	1,5	1,5
tcl Clearance time [s]		Clearance time	2,36	2,37	2,46	2,91	3,01	3,87	1,32	1,37	2,14	3,67	1,91	1,62	3,59	2,11	3,46	2,51	2,17	2,39	2,57	3,79	6,93	6,93	6,93	6,93
(scl,A + lvh) / vcl =		Transit Time:	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	se	enterance distance in m	5	9,4	1	5,5	8	7	15,4	12,2	16,9	8,5	1	12,9	6,8	9,8	2,4	8,4	18,9	17,5	12,9	1	14,6	23,6	2,4	15,5
te entrance time [s]	ve	entrance speed in m/s	12	12	12	7	7	7	12	12	12	12	10	12	12	12	12	12	10	12	12	7	12	10	12	7
(se/ve) =			V1-3	V1-5	V1-P21	V2-3	V2-4	V2-5	V3-1	V3-2	V3-4	V3-5	V3-P21	V4-2	V4-3	V4-5	V4-P21	V5-1	V5-2	V5-3	V5-4	V5-P21				
		Entrance time	0,42	0,78	0,00	0,79	1,14	0,00	1,28	1,02	1,41	0,71	0,00	1,08	0,57	0,82	0,00	0,70	1,89	1,46	1,08	0,00	1,22	2,36	0,20	2,21
tig intergreen time			V1-3	V1-5	V1-P21	V2-3	V2-4	V2-5	V3-1	V3-2	V3-4	V3-5	V3-P21	V4-2	V4-3	V4-5	V4-P21	V5-1	V5-2	V5-3	V5-4	V5-P21	P21-V1	P21-V3	P21 - V4	P21 - V5
tt + tcl - te		Intergreen time	4,94	4,59	5,46	5,13	4,87	6,87	3,04	3,35	3,73	5,96	4,91	3,55	6,02	4,29	6,46	4,81	3,28	3,93	4,50	6,79	8,72	7,57	9,73	7,72
		rounded	5	5	6	6	5	7	3	4	4	6	5	4	7	5	7	5	4	4	5	7	9	8	10	8

GERMANY

Tig = tt + tcl - te			V1-3	V1-5	V1-P21	V2-3	V2-4	V2-5	V3-1	V3-2	V3-4	V3-5	V3-P21	V4-2	V4-3	V4-5	V4-P21	V5-1	V5-2	V5-3	V5-4	V5-P21	P21-V1	P21-V3	P21 - V4	P21 - V5
	scl,A	Clearance distance in m	17,6	10,6	18,6	14,4	15,1	21,1	7,2	7,7	9	19,7	7,4	10,2	19,1	15,1	28,6	11,6	9,2	10,7	12	20,5	10,4	10,4	10,4	10,4
tt Transit time [s]	lvh	length of vehicle in m	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	0	0	0	0
straight 3s, turning 2s	vcl	clearance speed in m/s	10	5	10	5	5	5	10	10	7	7	7	10	5	10	10	7	7	7	7	7	1,5	1,5	1,5	1,5
tcl Clearance time [s]		Clearance time	2,36	3,32	2,46	4,08	4,22	5,42	1,32	1,37	2,14	3,67	1,91	1,62	5,02	2,11	3,46	2,51	2,17	2,39	2,57	3,79	6,93	6,93	6,93	6,93
(scl,0 + lvh) / vcl =		Transit Time:	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	se	enterance distance in m	5	9,4	1	5,5	8	7	15,4	12,2	16,9	8,5	1	12,9	6,8	9,8	2,4	8,4	18,9	17,5	12,9	1	14,6	23,6	2,4	15,5
te entrance time [s]	ve	entrance speed in km/h	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40
(3,6*se)/40 =			V1-3	V1-5	V1-P21	V2-3	V2-4	V2-5	V3-1	V3-2	V3-4	V3-5	V3-P21	V4-2	V4-3	V4-5	V4-P21	V5-1	V5-2	V5-3	V5-4	V5-P21	P21-V1	P21-V3	P21 - V4	P21 - V5
		Entrance time	0,45	0,85	0,00	0,50	0,72	0,63	1,39	1,10	1,52	0,77	0,00	1,16	0,61	0,88	0,00	0,76	1,70	1,58	1,16	0,00	1,31	2,12	0,22	1,40
tig intergreen time			V1-3	V1-5	V1-P21	V2-3	V2-4	V2-5	V3-1	V3-2	V3-4	V3-5	V3-P21	V4-2	V4-3	V4-5	V4-P21	V5-1	V5-2	V5-3	V5-4	V5-P21	P21-V1	P21-V3	P21 - V4	P21 - V5
tt + tcl - te		Intergreen time	4,91	5,47	5,46	6,59	6,50	7,79	2,93	3,27	3,62	5,91	4,91	3,46	7,41	4,23	6,46	4,76	3,47	3,81	4,41	6,79	8,62	7,81	9,72	8,54
		rounded	5	6	6	7	7	8	3	4	4	6	5	4	8	5	7	5	4	4	5	7	9	8	10	9

UNITED KINGDOM

x Distance in m		V1-3	V1-5	V1-P21	V2-3	V2-4	V2-5	V3-1	V3-2	V3-4	V3-5	V3-P21	V4-2	V4-3	V4-5	V4-P21	V5-1	V5-2	V5-3	V5-4	V5-P21	P21-V1	P21-V3	P21 - V4	P21 - V5
the Intergreen can be read	Distance x	12,6	1,2	17,6	8,9	7,1	14,1	-8,2	-4,5	-7,9	11,2	6,4	-2,7	12,3	5,3	26,2	3,2	-9,7	-6,8	-0,9	19,5	-4,2	-13,2	8	-5,1
from the table	Intergreen [s]	6	5	6	5	5	6	5	5	5	6	5	5	6	5	7	5	5	5	5	7	5	5	5	5

Figure 4.7: Intergreen Matrix Calculation Austria, Germany and UK

ITALY:

The entrance distance is the distance between the stop line at the traffic light and the closest conflict point, for pedestrians it is usually 0. The entrance time is calculated considering an average speed of 40 Km/h for vehicles, 5 m/s for bicycles in reserved bike lanes and 1,5 m/s for pedestrians if the entrance distance is non-zero. For trams and busses, if there is no bus stop close to the intersection, a speed of 20 Km/h is considered, while acceleration and maximum vehicle speed are considered it there is a bus stop.

The clearance distance (l_c) is between the stop line and the farthest conflict point. In calculating the clearance period (t_c), the vehicle length (l_v)is added to the clearance distance, and an exit time is added. The exit time (t_e) is the time between the end of green and when the clearance period starts, and is due to the vehicle's speed and the deceleration characteristics. The total clearance time is then:

$$t_{tc} = t_e + t_c = t_e + (l_v + l_c)/v_m$$

The values for the vehicle length are

- Bikes 0m
- Cars and other vehicles 6m
- Tramway 15 m

The following table contains the values to be used for t_e and v_m

Table 4.8: Italy, Values for entrance time

Outgoing traffic flow	Speed (m/s)	t_e
Vehicles going straight	10	3
Vehicles turning (radius >= 10 m)	7	2
Vehicles turning (radius < 10 m)	5	2
Trams or busses with no stop before the intersection	<= 8 <= 14 <= 19	3 5 7
Trams or busses with stop before the intersection	V_{max}	0
Bikes	4	1
Pedestrians	1 - 1,5	0

If a tram or bus has a stop before the intersection, the clearance time is calculated considering the acceleration and the maximum speed attainable. For trams acceleration can vary between 0,7 m/s^2 and 1,2 m/s^2, for busses between 1,0 $m/s^2$and 1,5 m/s^2.[RENCS]

4.4 Signal Program

A signal program gives all needed details for a light signal plant. The more complex the signal control, the bigger the signal program. The easiest way for developing a signal program is the fixed time signal program, because therefore no detectors and fewer algorithms are needed.

In the Netherlands there exist no specific guidelines for the signal program (except saturation flow calculation), because almost all controllers are either adaptive or vehicle actuated.

4.4.1 Saturation Flow and Discharge Rate

The discharge rate and from it deriving saturation flow are very important for dimensioning intersections. The saturation flow is one of the main variables of cycle length calculations and capacity. It is the number of vehicles per hour that can pass within one green hour from a signal approach. The base value of saturation flow can vary from one country/city to another. This depends on different traffic rules and regulations, geometric standards and driving behaviour.

It is the maximum flow, expressed in vehicles or pc (passenger cars) that can be discharged from a traffic lane when there is a continuous green indication and a continuous queue on the approach. The saturation flow is independent of traffic and control factors.

The saturation flow is not exactly determined, neither at guidelines from Austrian, nor at the ones of German. Different saturation flow ranges are defined, but these values cannot be used off-handed because there are different influences that reduce or heighten these values.

In Germany the given saturation flow is declared between 2000 and 3000, but it must be reduced to a permissible saturation flow which includes also the load factor (x). There is also a correlation with the green period and some local boundary conditions which changes the saturation flow (i.e. gradient, HGV, turning radius…). In Austria using the formula $t_B = 3600 / q_s$, with a t_B of 2.0 or 1.8 (turning or straight ahead) the range of the saturation flow of 1800 to 2000 emerges.

Mark Wenzel found out in his Bachelor Thesis, by proving the German calculation of saturation flow through measuring, a relatively well fitting saturation flow for straight ahead going vehicles results, but the used factors cannot reduce the saturation flow in a satisfying way for turning vehicles.

In Austria the calculation of the saturation flow is most vague. At the United Kingdom a very detailed calculation of saturation flow is realised. For calculating the saturation flow also the cycle time is important. Therefore first the cycle time must be estimated by the use of not calculated rudiments of saturation flow. Afterwards also the radii, gradients, proportions of turning vehicles, lane position, lane width and number of lanes are considered at the calculation. A detailed calculation is given after estimating the cycle time. [FSV, FGSV, Kimber, Department for Transport, Scottish Executive, Welsh Assembly Government]

Table 4.9: Different Saturation Flows

	Chosen Saturation Flow for the Signal Group…				
Country	V1	V2	V3	V4	V5
AUSTRIA	**1800**	**1800**	**1800**	2000+1800= **3800**	**1800**
GERMANY	2040*1.08*0.85 **1983**	2040*1.08*0.85 **1983**	2040*1.08*0.85 **1983**	2040*0.92 + 2040*0.92*0.85 **3676**	2040*0.92*0.85 **1689**
UNITED KINGDOM **1-Assessment**	1810	1934.9	1977.2	3233.6	1883.4
2-Assessment	**1885**	**1935**	**1507**	**3885**	**1759**

The detailed calculation is given in the following pages. The United Kingdom calculates the saturation flow much more precise than Austria and Germany, but the intergreen matrix calculation much more imprecise.

GERMANY:

The maximum saturation flow [q_s] after HBS is calculated. The maximum saturation flow is reduced via the load factor x to a permissible saturation flow $q_{s,zul}$

$$q_{s,\,perm} = x * q_s$$

2400 * 0.9 = 2160

For the load factor x a value between 0.80 and 0.90 can be chosen (details look at HBS).

In Germany, the saturation flow q_s depends on the expected green time. At short green times the base saturation flow q_{s0} will be higher as queued vehicles can clear during the transition period (effective green).

$t_{green} > 10$ s → $q_{s0} = 2000$

$t_{green} = 10$ s → $q_{s0} = 2400$

$t_{green} = 6$ s → $q_{s0} = 3000$

Interpolating for values between 6 and 10 s.

The base saturation flow rate q_{s0} is effected by geometrical and traffic related factors; only the two most effective factors (f_1, f_2) will be considered

$$q_{s,\,zul} = q_{s0} * f_1 * _{u2}$$

Table 4.10: Impact factor - Adjustment value (f)

Impact factor		Adjustment value (f)
Rate of HGV's	HGV < 2% HGV = 2 …15% HGV > 15%	1.0 1-0.0083 e 1/(1+0.0015 * HGV)
Lane width	2.60 m 2.75 m 3.00 m and higher	0.85 0,90 1.00
Turning radius	R < = 10m R < = 15 m R > 15 m	0.85 0.90 1.00
Gradient	+ 5% +3% 0% -3% -5%	0.85 0.90 1.00 1.10 1.15
Parallel pedestrian movement for semi compatible movement	Strong Medium Weak	0.80 0.90 1.00

V1) 2040 * 1.08 * 0.85 = 1982.88

V2) 2040 * 1.08*0.85 = 1982.88

V3) 2040 * 1.08 * 0.85 = 1982.88

V4) 2040 * 0.92 + 2000 * 0.92 * 0.85 = 3676.32

V5) 2000 * 0.92 * 0.85 = 1689.12 [FGSV, FGSV 2009]

UNITED KINGDOM:

First Assessment

$$S_1 = \frac{(S_0 - 140\, d_n)}{(1 + 1.5\, \frac{f}{r})} \quad \cdots pcu/h$$

where:

$$S_0 = 2080 - 42\, d_g \times G + 100\,(w - 3.25)$$

- d_n = 1 for nearside lanes or = 0 for non-nearside lanes
- f = proportion of turning vehicles in a lane
- r = radius of curvature (m)
- d_g = 1 for uphill or = 0 for downhill
- G = gradient in %
- w = lane width

V1)

S_{01} = 2080 – 42 * 0 * 2.5 + 100 * (3.25 – 3.25) = 2080

= 2080 + 0 + 0 = 2080 pcu/h

$S_{1,1}$ = (2080 – 140 *1) / (1 + 1.5 * (0.385/8)) = 1940/1.029 = 1810.1 pcu/h

---

V2)

S_{02} = 2080 – 42 * 0 * 2.5 + 100 * (3.25 – 3.25) = 2080

$S_{1,2}$ = (2080 – 140 *0) / (1 + 1.5 * (1/20)) = 2080/1.075 = 1934.9 pcu/h

---

V3)

S_{03} = 2080 – 42 * 0 * 2.5 + 100 * (3.25 – 3.25) = 2080

$S_{1,3a}$ = (2080 – 140 * 0)/(1+1.5*0.429/8) = 1925.1

$S_{1,3b}$ = (2080 – 140 * 0)/(1+1.5*0.333/20) = 2029.3

$S_{1,3}$ = ($S_{1,3a}$ + $S_{1,3b}$)/2 = 1977.2 pcu/h

V4a)

S_{02} = 2080 – 42 * 1 * 2.5 + 100 * (3.25 – 3.25) =

= 2080 – 105 + 0 = 1975 pcu/h

$S_{1,2}$ = (2080 – 140 *1) / (1 + 1.5 * (0/8)) = 2080/1.075 = 1835.0 pcu/h

---

V4b)

S_{04b} = 2080 – 42 * 1 * 2.5 + 100 * (3,25 – 3,25) =

= 2080 – 105 + 0 = 1975 pcu/h

$S_{1,4b}$ = (1975 – 140*0) / (1 + 1.5 * (0.455/8)) =1975/1.034 = 1398.6 pcu/h

---

V4)

= V4a + V4b = 3233.6 pcu/h

V5)

S_{05} = 2080 – 42 * 1 * 2.5 + 100 * (3.25 – 3.25) = 1975 pcu/h

$S_{1,5a}$ = (1975 – 140 * 0)/(1+1.5*0.459/8) = 1818.5

$S_{1,5b}$ = (1975 – 140 * 0)/(1+1.5*0.183/20) = 1948.3

$S_{1,5}$ = ($S_{1,3a}$ + $S_{1,3b}$)/2 = 1883.4 pcu/h

Because there is no cycle time known at that moment, the calculation is done without the factors t1 and t2 for turning vehicle streams.

[Kimber, Department for Transport, Scottish Executive, Welsh Assembly Government]

AUSTRIA:

The Saturation flow is the maximum traffic volume of a movement, which can discharge during one hour of Green period. It is given in q_s [veh/h]

The discharge rate is the average total headway between two vehicles at a saturated approach measured while passing the stop line. It is given as t_B

$$t_B = \frac{3600}{q_s} \qquad q_{s,\,right} = 1800[veh/h] \qquad t_{B,\,right} = 2.0[s/veh]$$
$$q_{s,\,through} = 2000[veh/h] \qquad t_{B,\,through} = 1.8[s/veh]$$

The Traffic Volume q of a movement i at a single lane [q_i] is calculated by total volume divided by the number of lanes n of this movement i (when no lanes for multiple movements).

Traffic volume of a movement i will be distributed accordingly and multiplied with individual discharge rates (with existing lanes for multiple movements).

V1) 1800

V2) 1800

V3) 1800

V4) 2000 + 1800 =3800

V5) 1800 [FSV]

NETHERLANDS:

No mandatory guidelines exist. In general 1800 veh/h/lane is used with sometimes correction factors for narrow roads, turning directions or other special cases. A major difference with the German system is that at the first 6 seconds the saturation flow is actually lower than 1800 veh/h/lane, due to acceleration loss and reaction time. Detailed advisory guidelines can be found in [CROW]. An alternative method is to use effective green time. In this case 2 seconds are subtracted from the total green time to compensate for acceleration loss and reaction time. A user defined amount of seconds can be added to the effective green for usage of the amber phase. This varies per city and sometimes even per intersection as driver behaviour is not the same. In some cases even a part of the clearance time is still exploited by road users, especially when the intergreen time formula would result in a negative all-red time. This is because all-red is minimally zero and it is not allowed to turn a conflicting signal group to green while the previous group is still in amber. However, drivers that follow the same route every day see that the margin is too big and start violating the beginning of the red phase regularly.

ITALY:

In Italy the saturation flow depends on the width of the incoming lane (w):

S = 165*w + 45 for a 15 minute interval.

For a 3m wide lane, for an hour, the saturation flow is therefore: **(165*3 + 45) * 4 = 2160 veh/h**

This value can be reduced multiplying by a factor between 0 and 1 which derives from observations and measurements of the intersection. [C.N.R]

4.4.2 Green Period

GERMANY

$$t_{GREEN,nec,i} = \frac{q_{lane,dec,i} * t_{cycle}}{x * q_{S,i}}$$

The calculation for cycle time dependent green periods for the individual motor traffic used in Germany is given above. For the case, that there are reserves within the cycle, they can be shared out according to the individual planning goals. A total sharing of the possible green periods in relation to traffic volume can be reached with the formula below. This formula shares the green periods in a way, that for the decisive streams of all stages the same load factor can be reached. Requirement for the usage is a cycle time t_{cycle}, which equals at least the necessary cycle time $t_{cycle,nec}$. If beside the cycle time dependent green periods there are also fixed green periods as decisive green periods of a stage, they need to be, similar to the cycle time, added to the sum of interim periods.

$$t_{GREEN,i} \geq \frac{t_{cycle,cho} - \sum t_{IG,nec}}{\sum \frac{q_{dec,j}}{q_{S,j}}} \cdot \frac{q_{dec,i}}{q_{S,i}}$$

$t_{,GREEN,nec}$ = required green of a movement [s]

q = volume [veh/h]

q_s = saturation flow [veh/h]

t_{cycle} = cycle time [s]

The decisive or critical movement of a stage is that movement, which requires the longest green time. Each stage has a decisive movement.

4.4.3 Minimum and Optimal Cycle Length

A signal cycle follows the sum of the necessary green periods for the decisive signal groups of the singular stages and the intergreen periods which lies in-between. The cycle is the complete rotation through all indications. The cycle time is the time of one full cycle. Cycle time is one of the significant parameter affecting quality of traffic flow.

- Long enough that each approach can be served in one cycle
- Too long cycle time should be avoided because the average waiting time gets higher and the acceptance of pedestrians decreases.

To find the optimum cycle time it should be aimed, to minimize the average vehicle delay.

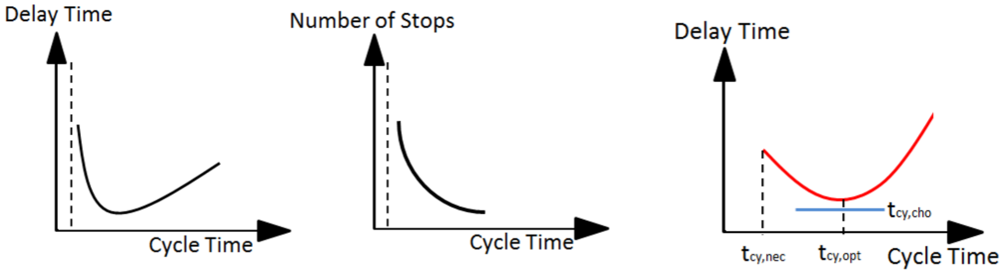


Figure 4.8: Cycle Time

Table 4.11: Cycle time

		AUSTRIA (AT)	GERMANY (D)
t_{cycle}	Cycle time [s]	50 – 100 s …normal 120 s … maximum 150 s … special case	30 s … minimum 90 (120) s … maximum

		UNITED KINGDOM (UK)	ITALY(IT)
t_{cycle}	Cycle time [s]	max 120 s recommended	30 s minimum 50 - 75 s normal 120 s maximum

4.4.4 Green Split per Signal Group

The green period is the time interval in which vehicles are allowed to pass the intersection. A required green time for each approach is calculated as shown in the following [Germany]

The selected/chosen cycle length has to be higher than the necessary length → $t_{cy,cho} > t_{cy,nec}$

The green split time $t_{Gs,i}$ of the signal group should be:

$$t_{Gs,i} = \frac{t_{cycle,cho} - \sum t_{cycle,nec}}{\sum \frac{q_{dec,j}}{q_{s,j}}} * \frac{q_{dec,i}}{q_{s,i}}$$

$t_{Gs,I}$	…green split cycle time [s]
$t_{cycle,cho}$	…selected/chosen cycle duration
$t_{cycle,nec}$	…necessary/required cycle length
$q_{dec,I}$	…decisive lane specific volume of critical movement within stage I [veh/h]
$q_{s,I}$	…associated saturation flow rate [veh/h]

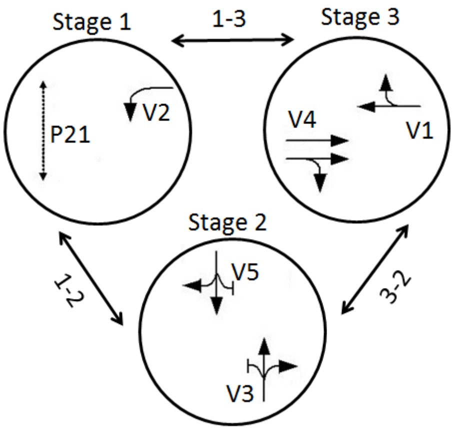
According to RiLSA the minimum green time for vehicle traffic flow should be 10s and generally 15 seconds green time for the main approaches. At intersections with very low traffic volume minimum green time can be reduced to 5 seconds. In Austria 8 seconds green period for vehicle, pedestrian and bicycle traffic should not be undercut.

4.4.5 Calculation of Cycle Time and Green Split

AUSTRIA:

Table 4.12: Intergreen Settings – Austria

Intergreen			**Used Settings**	AUSTRIA
Stage 1-2	17 s		Minimum Green	8s
Stage 1-3	19 s		Minimum Red	1s
Stage 2-1	16 s			
Stage 2-3	14 s		**Guideline determined Settings**	
Stage 3-1	16 s		t_{amber}	3s (speed 50km/h)
Stage 3-2	16 s		$t_{red/amber}$	2s
Stage sequence: 1 – 2 – 3 …. 47 s 1 – 3 – 2 …. 51 s				



Performance / Effectiveness

$P_i = t_{GREEN,i}/t_{cycle} * M_{s,i}$

$t_{GREEN,i}$ = green duration for a lane [s]

t_{cycle} = used cycle time [s]

$M_{s,i}$ = Saturation Traffic volume of a lane [pcu/h]

P = Performance [pcu/h]

$P_{V1} = P_{V2} = P_{V3} = P_{V5} = 8/47*1800 = 306.38$ (→ not always satisfying)

P_{V4} $= 8/47*1800 = 646.38$ (2 lanes, one just straight ahead (1800 + 2000))

Necessary pcu/h: P1…260 P2…320 P3…420 P4…544 P5…545

The cycle time of 47 seconds is not sufficient because the necessary performance cannot be reached. Because the necessary pcu/h and lane are known, the formula can be adapted, to get a sufficient cycle time and green period split.

$P = t_{GREEN,i}/t_{cycle} * M_{s,i} \rightarrow P_i/M_{s,i} * t_{cycle} = t_{GREEN}$

Through this adaption an approximation can be done.

Because of the chosen 3-stage-system some vehicle streams are connected and because of that, they get the same amount of green duration.

With a chosen **cycle time of 69** seconds the following performance can be reached:

11s …Pv1 = 11 / 69 * 1800 = 286.96 [260]

13s …Pv2 = 13 / 69 * 1800 = 339.13 [320]

22s …Pv3 = 22 / 69 * 1800 = 573.91 [420]

11s …Pv4 = 11 / 69 * 3800 = 605.80 [544]

22s …Pv5 = 22 / 69 * 1800 = 573.91 [545]

2379.71 2089

Stage 1) = 13s

Stage 2) = 22s

Stage 3) = 11s

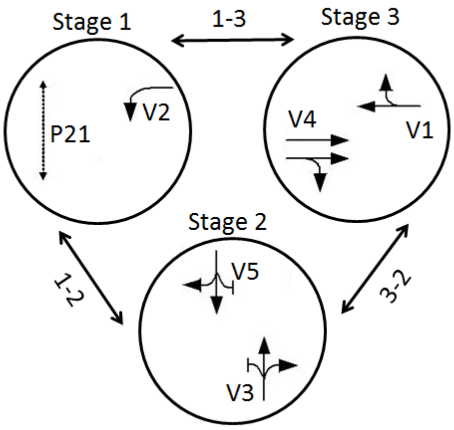
Green Split: 1) 28.26% 2) 47.83% 3) 23.91%

[FSV]

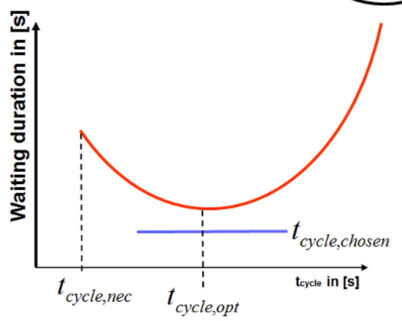
GERMANY:

Table 4.13: Intergreen Settings – Germany

Intergreen			**Used Settings**	GERMANY
Stage 1-2	17 s		Minimum Green	8s
Stage 1-3	18 s		Minimum Red	1s
Stage 2-1	15 s			
Stage 2-3	13 s		**Guideline determined Settings**	
Stage 3-1	15 s		t_{amber}	3s (speed 50km/h)
Stage 3-2	15 s		$t_{red/amber}$	1s
Stage sequence: 1 – 2 – 3 …. 45 s 1 – 3 – 2 …. 48 s				



$$t_{cycle,nec} = \sum_{i=1}^{p} t_{F,dec,i} + \sum_{i=1}^{p} t_{IG,nec,i}$$



$$t_{cycle,nec} = \frac{\sum_{i=1}^{p} t_{IG,nec,i}}{1 - \sum_{i=1}^{p} \frac{q_{dec,i}}{q_{S,i}}}$$

$t_{cycle,nec}$ necessary cycle time [s]

t_{cycle} waiting period optimal cycle time [s]

p number of stages

$q_{dec,I}$ decisive lane-traffic volume of stage i [veh/h]

$q_{S,I}$ related saturation traffic volume [veh/h]

$t_{IG,nec.i}$ decisive intergreen time for stage-change i [s]

$$t_{cycle} = \frac{1{,}5 \cdot \sum_{i=1}^{p} t_{IG,nec,i} + 5}{1 - \sum_{i=1}^{p} \frac{q_{dec,i}}{q_{S,i}}}$$

q_{dec1} = 320 q_{s1} = 1983

q_{dec2} = 545 q_{s2} = 1689

q_{dec3} = 260 q_{s3} = 1983

$$\sum_{i=1}^{p} t_{IG,nec,i}$$

= 45s – (3x8s) = 21 s

= 17-8 + 13-8 + 15-8 = 9 + 5 + 7 = 21s

$$\sum_{i=1}^{p} \frac{q_{maßg,i}}{q_{S,i}}$$

= 320/1983 + 545/1689 + 260/1983 = 0.615

$$t_{cycle,nec} = \frac{\sum_{i=1}^{p} t_{IG,nec,i}}{1 - \sum_{i=1}^{p} \frac{q_{dec,i}}{q_{S,i}}}$$

= 21(1-0.615) = 54.55 s

$$t_{cycle} = \frac{1{,}5 \cdot \sum_{i=1}^{p} t_{IG,nec,i} + 5}{1 - \sum_{i=1}^{p} \frac{q_{dec,i}}{q_{S,i}}}$$

= (1.5*21+5)/(1-0.615) = 94.8

~ 95 s

$$t_{GREE,nec,i} = \frac{q_{lane,dec,i} * t_{cycle}}{x * q_{S,i}}$$

X = load factor...between 0.80 and 0.90

Chosen x for the example = 0.90

$t_{GREEN,1}$ => 17.03 s → 21 s [28.4 %]

$t_{GREEN,2}$ => 34.06 s → 36 s [48.6 %]

$t_{GREEN,3}$ => 13.84 s] → <u>17 s</u> [23.0 %]

74 s

<u>+ 21 s</u> … intergreen necessity

+ 95 s … cycle time

Table 4.14: Germany - 95 Seconds Cycle Time

Stream	Load	Degree of Saturation
V1	260	0,73
V2	320	0,73
V3	420	0,56
V4	340	0,52
V5	545	0,85

Because the cycle time is a bit higher than 90 s with a chosen cycle time of 90 seconds the green split and degree of saturation results to:

$t_{GREEN,1}$ = > 16.14 s → 19 s [27.5 %]

$t_{GREEN,2}$ = > 32.27 s → 34 s [49.3 %]

$t_{GREEN,3}$ = > 13.11 s] → 16 s [23.2 %]

69 s

\+ 21 s … intergreen necessity

\+ 90 s … cycle time

Table 4.15: Germany - 90 Seconds Cycle Time

Stream	Load	Degree of Saturation
V1	260	0,74
V2	320	0,76
V3	420	0,56
V4	340	0,52
V5	545	0,85

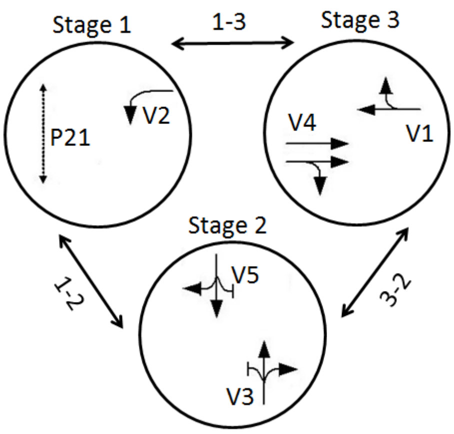
Above the cycle time dependent green periods for the individual motor traffic is calculated. For the case, that there are reserves within the cycle, they can be shared out according to the individual planning goals. A total sharing of the possible green periods in relation to traffic volume can be reached with the formula above. The formula shares green periods in a way, that for the decisive streams of all stages the same load factor can be reached. Requirement for the usage is a cycle time, which equals at least the necessary cycle time. Here the optimal cycle time was calculated. If beside the cycle time dependent green periods there are also fixed green periods as decisive green periods of a stage, they need to be, similar to the cycle time, added to the sum of interim periods. The given minimum green was 8 seconds. The interim period was calculated without the minimum green, but every stage has enough green duration to satisfy the minimum green of 8 seconds.

[FGSV, FGSV 2009]

UNITED KINGDOM:

Table 4.16: Intergreen Settings - United Kingdom

Intergreen			**Used Settings**	UNITED KINGDOM
Stage 1-2	15 s		Minimum Green	8s
Stage 1-3	14 s		Minimum Red	1s
Stage 2-1	16 s			
Stage 2-3	14 s		**Guideline determined Settings**	
Stage 3-1	16 s		t_{amber}	3s after
Stage 3-2	15 s		$t_{red/amber}$	2s before
Stage sequence: 1 – 2 – 3 …. 45 s 1 – 3 – 2 …. 45 s				



Manual preliminary assessment

To check that the main vehicular flow do not exceed the overall junction capacity potential. It can be carried out using the basic concepts of the analyses developed by Webster and Cobbe. The calculation is based on the assessment of **y value**.

y value = the ratio of demand to saturation flow as proportion of time a signal has to be green to allow the demand flow to pass.

critical y value = the highest value for each stage in cycle

Y = reached through summation of the y-values for all stages in cycle. If Y is higher 1 the junction has insufficient capacity whatever timings are applied. A practical capacity [Y_{pract}] of maximum 90% (0,9) is recommended, but 0,8 is more practicable.

A flow of 100 pcu/h crossing a stop line with capacity of 2000 pcu/h needs a signal which is green for at least 50% of time → y value would be 0,5.

The loss time is the total cycle time which is not effective green, often taken as the total interstage period minus 1 second for each individual interstage period. Here just the interstage period is taken:

$$L = 45–3-(8*3) = 42-24 = 18 \text{ s}$$

Table 4.17: Saturation Degree Calculation - United Kingdom

Stream	**Flow [pcu/h]**	**Saturation flow [pcu/h]**	**Stage**	**y value**	**Critical y**	
V1	260	**1810.0**	3	**0.144**	**0.144**	**24.0%**
V2	320	**1934.9**	1	**0.165**	**0.165**	**27.6%**
V3	420	**1977.2**	2	**0.212**	**-**	
V4	340	**3233.6**	3	**0.105**	**-**	
V5	545	**1883.4**	2	**0.289**	**0.289**	**48.4 %**
				Y	**0.598**	
				L	**18 s**	

Note: for more complex junctions, stages may not be defined at this early stage and groups of conflicting streams are used instead. With simple junctions it will often be easy to identify a single set of conflicting stages.

$$Y = 1-(L/t_{cycle}) \qquad Y_{pract} = 0.9(1-(L/t_{cycle}) = 0.9Y = 0.5382$$

$$t_{cycle,min} = L/(1-Y) = 18/(1-0.5382) = 38.98 \sim 39s$$

→ **Without consideration of minimum green time!**

$$t_{cycle,pract} = 0.9L/(0.9-Y) \quad = (0.9*18)/(0.9-0.5382) = 44.78 \sim 45\ s$$

→ **Without consideration of minimum**

$$t_{cycle,opt} = 0.8L/(0.8-Y) = 55.01 \sim 56\ s$$

t_{cycle}... cycle time

L ... loss time

Remark:

When using the Table for the x value and intergreen times, pedestrians have often very short intergreen times, which are not acceptable in reality. Due to this the cycle time is very short. If pedestrians are included to the signal program, the cycle time must be heighted. In the Traffic Advisory Leaflet 1/06 they state an enhancement of around 20 s. Because at the example there is just one pedestrian crossing, the cycle time is just enhanced by 10 seconds, because 20 seconds would be very high.

$$t_{cycle,opt} = 55 + 10\ s = 65\ s$$

Green Split → $65 - 21 = 44$ s

1 $44 * 27.6\% = 12.14 \rightarrow 13$

2 $44 * 48.3\% = 21.25 \rightarrow 22 \rightarrow 13 + 22 + 11 = 46$

3 $44 * 24.1\% = 10{,}60 \rightarrow 11$

$\underline{t_{cycle,cho} = 67\ s}$

[Department for Transport, Scottish Executive, Welsh Assembly Government, Kimber]

Table 4.18: Chosen Cycle Times - Austria, Germany, UK

	AUSTRIA	GERMANY	UK
Cycle time	**69**	**90**	**67**

4.5 Degree of Saturation / Capacity Analysis

UNITED KINGDOM:

The formula used to calculate saturation flow is taken to calculate saturation flow of individual lanes. For unopposed streams in individual traffic lanes:

$$S_1 = \frac{(S_0 - 140\, d_n)}{(1 + 1.5\, \frac{f}{r})} \quad \cdots pcu/h$$

where:

$$S_0 = 2080 - 42\, d_g \times G + 100\, (w - 3.25)$$

- d_n = 1 for nearside lanes or = 0 for non-nearside lanes
- f = proportion of turning vehicles in a lane
- r = radius of curvature (m)
- d_g = 1 for uphill or = 0 for downhill
- G = gradient in %
- w = lane width

V1)

S01 = 2080 – 42 * 0 * 2,5 + 100 * (3,25 – 3,25) = 2080

= 2080 + 0 + 0 = 2080 pcu/h

S1,1 = (2080 – 140 *1) / (1 + 1.5 * (0.385/8)) = 1940/1.029 = 1810.1 pcu/h

---

V2)

S02 = 2080 – 42 * 0 * 2,5 + 100 * (3,25 – 3,25) = 2080

S1,2 = (2080 – 140 *0) / (1 + 1.5 * (1/20)) = 2080/1.075 = 1934.88 pcu/h

---

V4a)

S02 = 2080 – 42 * 1 * 2,5 + 100 * (3,25 – 3,25) =

= 2080 – 105 + 0 = 1975 pcu/h

S1,2 = (2080 – 140 *1) / (1 + 1.5 * (0/8)) = 2080/1.075 = 1835.0 pcu/h

---

V4b)

S04b = 2080 – 42 * 1 * 2,5 + 100 * (3,25 – 3,25) =

= 2080 – 105 + 0 = 1975 pcu/h

S1,4b = (1975 – 140*0) / (1 + 1.5 * (0.455/8)) =1975/1.034 = 1398.6 pcu/h

---

V4)

= V4a + V4b = 3233.6

For opposed streams containing opposed left-turning traffic in individual lanes the saturation flow S_2 is given by: $S_2 = S_g + S_c$

- S_g is the saturation flow in lanes of opposed mixed turning traffic during the effective green period (pcu/h)
- S_c is the saturation flow in lanes of opposed mixed turning traffic after the effective green period (pcu/h)

$$s_g = \frac{s_0 - 230}{1 + (T-1) f} \qquad t_1 = \frac{12 (X_0)^2}{1 + 0.6(1-f) N_s} \qquad sc = \frac{P(1+N_s)(f * X_0)^{0.2} * 3600}{\lambda * c}$$

$$T = 1 + 1.5/r + t_1/t_2 \qquad t_2 = 1 - (f * X_0)^2 \qquad X_0 = \frac{q_0}{\lambda * n_l * S0}$$

- X_0 is the degree of saturation on the opposing arm, that is, the ratio of the flow on the opposing arm to the saturation flow on that arm.
- N_s is the number of storage spaces available inside the intersection which left turners can use without blocking following straight ahead vehicles.
- λ is the proportion of the cycle time effectively green for the stage being considered, that is, the effective green time divided by the cycle time
- c is the cycle time (seconds)
- q_0 is the flow on the opposite arm expressed as vehicles per hour of green time and excluding non-hooking left turners
- n_l is the number of lanes on the opposing entry
- S_0 is the saturation flow per lane for the opposite entry (pcu/h)
- T is the through car unit of a turning vehicle in a lane of mixed turning traffic, each turning vehicle being equivalent of T straight ahead vehicles.
- P is the conversion factor from vehicles to pcu and is expressed as $P = 1 + \sum i (\alpha i - 1) pi$
- α_i is the pcu value of vehicle type *i*
- p_i is the proportion of vehicles of type *i* in the stream

Most traffic signal approaches are marked out in several lanes and the total saturation flow for the approach is then the sum of the saturation flows of the individual lanes.

V3

$S_{g3} = (S_0 - 230) / (1+(T-1)f) = 1850 / (1+(1.192* 0.762)) = 969.26$ pcu/h

$f = 0.762$

$S_{03} = 2080 - 42 * 0 * 2,5 + 100 * (3,25 - 3,25) = 2080$

$T = 1+1.5/r + t_1/t_2 = 1 + 1.5/20 + 0.844/0.942 = 2.192$

$t_1 = 12 (X_0)^2/(1+0.6(1-f)N_s) = 12 * (0.351)^2 / (1 + 0.6*(1-0.762)*3) = 1.037$

$t_2 = 1-(fX_0)^2 = 1-(0.762*0.351)^2 = 1- 0.058 = 0.928$

$X_0 = q_0 / (\lambda n_l S_0) = 240 / (0.328 * 1 * 2080) = 240/757.12 = 0.351$

N_s = 3 vehicles

$\lambda = 22/67 = 0.328$

$S_{c3} = (P(1+Ns)((fX_0)^{0.2}) * 3600)/\ \lambda c = (1+3)(0.762*0.351)^{0.2}\ 3600/(22) = 502.91$ pcu/h

$P = 1 + \sum i\ (\ ai - 1)pi = 1$ (supposing that there is just one vehicle type)

$S_{g3} + S_{c3} = 969.26 + 502.91 = 1472.17$

V5

$S_{g5} = (S_0 - 230)\ /\ (1+(T-1)f) = 2080/(1+0.943*0.642 = 1152.29$ pcu/h

$f = 0.642$

$S_{05} = 2080 - 42 * 0 * 2{,}5 + 100 * (3{,}25 - 3{,}25) = 2080$

$T = 1+1.5/r + t_1/t_2 = 1 + 1.5/20 + 0.828/0.953) = 1.943$

$t_1 = 12\ (X_0)^2/(1+0.6(1-f)N_s = 12 * (0.0.337)^2\ /\ (1+ 0.6*(1-0.642)*3) = 0.828$

$t_2 = 1-(fX_0)^2 = 1-(0.642*0.304)^2 = 1- 0.038 = 0.953$

$X_0 = q_0\ /\ (\lambda\ n_l\ S_{0)} = 230\ /\ (0.328 * 1 * 2080) = 0.337$

$N_s = 3$ vehicles

$\lambda = 22/67 = 0.328$

$S_{c5} = (P(1+Ns)((fX_0)^{0.2}) * 3600)/\ \lambda c = (1+3)(0.642*0.337)^{0.2}\ 3600/(22) = 481.85$ pcu/h

$P = 1 + \sum i\ (\ ai - 1)pi = 1$ (supposing that there is just one vehicle type)

$S_{g3} + S_{c3} = 1152.29 + 481.85 = 1634.13$pcu/h

Table 4.19: Saturation Degree Calculation - United Kingdom (1)

Stream	Flow [pcu/h]	Saturation flow [pcu/h]	Stage	y value	Critical y	Green s
V1	260	1885,33	3	0,138	0,138	11
V2	320	1934,88	1	0,165	0,165	13
V3	420	1472,17	2	0,285	-	22
V4	340	3844,94	3	0,088	-	11
V5	545	1634,13	2	0,334	0,334	22
				Y	**0,637**	**sufficient**
				L	**18 s**	**67 s**

Table 4.20: Degree of Saturation - United Kingdom (2)

Vehicle Stream	Maximum Saturation per hour	percentage of hour	Through Amount	Traffic Volume	Degree of Saturation	Green s
V1	1885,33	16,4%	309,53	260	0.84	11
V2	1934,88	19,4%	375,42	320	0.85	13
V3	1472,17	32,8%	483,40	420	0.87	22
V4	3844,94	16,4%	631,26	340	0.54	11
V5	1624,13	32,8%	533,30	545	1.02	22
						21
Total	**10932,36**		**2485.34**	**1885**	**0,82**	**67 s**

Because the degree of saturation is too high at vehicle movement V5 the intergreen time should be increased. At the following page two more steps for calculating are depicted.

[Department for Transport, Scottish Executive, Welsh Assembly Government, Kimber]

With a chosen cycle time of 70 seconds which means a green of 25 (+3 seconds) for the movement V5, the following degree of saturation results from it.

Table 4.21: Saturation Degree Calculation - United Kingdom (70s)

Stream	Flow [pcu/h]	Saturation flow [pcu/h]	Stage	y value	Critical y	Green s
V1	260	1885,33	3	0,138	0,138	11
V2	320	1934,88	1	0,165	0,165	13
V3	420	1540,64	2	0,273	-	25
V4	340	3844,94	3	0,088	-	11
V5	545	1694,35	2	0,322	0,322	25
				Y	**0,625**	**sufficient**
				L	**18 s**	**70 s**

Table 4.22: Degree of Saturation - United Kingdom (70s)

Vehicle Stream	Maximum Saturation	percentage of hour	Through Amount	Traffic Volume	Degree of Saturation	
V1	1885,33	15,7%	296,27	260	0,88	11
V2	1934,88	18,6%	359,33	320	0,89	13
V3	2540,64	35,7%	907,37	420	0,46	25
V4	3844,94	15,7%	604,20	340	0,56	11
V5	1694,35	35,7%	605,13	545	0,90	25
						21
Total	**10932,36**		**2485.34**	**1885**	**0,56**	70

Because the vehicle streams V1, V2 and V5 are lower or equal 0.90 the result is sufficient but not good. Because of that one more cycle time increase was calculated. Therefore a cycle time of 77 seconds was chosen.

V3

$Sg3 = (S0 – 230) / (1+(T-1)f) = 1950 / (1+0.971 * 0.762) = 1120.75$ pcu/h

$f = 0.762$

$S03 = 2080 – 42 * 0 * 2,5 + 100 * (3,25 – 3,25) = 2080$

$T = 1+1.5/r + t1/t2 = 1 + 1.5/20 + 0.844/0.942 = 1.971$

$t1 = 12 (X0)^2/(1+0.6(1-f)Ns = 12 * (0.317)^2 / (1 + 0.6*(1-0.762)*3) = 0.844$
$t2 = 1-(fX0)^2 = 1-(0.762*0.317)^2 = 1- 0.058 = 0.942$

$X0 = q0 / (\lambda\ nl\ S0) = 240 / (0.364 * 1 * 2080) = 240/757.12 = 0.317$

Ns = 3 vehicles

$\lambda = 28/77 = 0.364$

$Sc3 = (P(1+Ns)((fX0)^{0.2}) * 3600)/ \lambda c = (1+3)(0.762*0.317)^{0.2}\ 3600/(28)= 387.086$ pcu/h

$P = 1 + \sum i (ai – 1)pi = 1$ (supposing that there is just one vehicle type)

$Sg3 + Sc3 = 1120.75 + 387.09 = 1507.84$

V5

$Sg5 = (S0 – 230) / (1+(T-1)f) = 2080/(1+0.776*0.642 = 1388.44$ pcu/h

$f = 0.642$

$S05 = 2080 – 42 * 0 * 2,5 + 100 * (3,25 – 3,25) = 2080$

$T = 1+1.5/r + t1/t2 = 1 + 1.5/20 + 0.674/0.962) = 1.776$

$t1 = 12 (X0)^2/(1+0.6(1-f)Ns = 12 * (0.304)^2 / (1+ 0.6*(1-0.642)*3) = 0.674$

$t2 = 1-(fX0)^2 = 1-(0.642*0.304)^2 = 1- 0.038 = 0.962$

$X0 = q0 / (\lambda\ nl\ S0) = 230 / (0.364 * 1 * 2080) = 230/757.12 = 0.304$

Ns = 3 vehicles

$\lambda = 28/77 = 0.364$

$Sc5 = (P(1+Ns)((fX0)^{0.2}) * 3600)/ \lambda c = (1+3)(0.642*0.304)^{0.2}\ 3600/(28)= 370.925$ pcu/h

$P = 1 + \sum i (ai – 1)pi = 1$ (supposing that there is just one vehicle type)

$Sg3 + Sc3 = 1388.44 + 370.93 = 1759.37$ pcu/h

Table 4.23: Saturation Degree Calculation - United Kingdom (77s)

Stream	Flow [pcu/h]	Saturation flow [pcu/h]	Stage	y value	Critical y	Green s
V1	260	1885,33	3	0,138	0,138	13
V2	320	1934,88	1	0,165	0,165	15
V3	420	1507,84	2	0,279	-	28
V4	340	3844,94	3	0,088	-	13
V5	545	1759,37	2	0,310	0,31	28
				Y	**0,613**	**sufficient**
				L	**18 s**	**77 s**

Table 4.24: Degree of Saturation - United Kingdom (77s)

Vehicle Stream	Maximum Saturation	percentage of hour	Through Amount	Traffic Volume	Degree of Saturation	
V1	1885,33	16,9%	318,30	260	0,82	13
V2	1934,88	19,5%	376,92	320	0,85	15
V3	1507,84	36,4%	548,31	420	0,77	28
V4	3844,94	16,9%	649,15	340	0,52	13
V5	1759,37	36,4%	639,77	545	0,85	28
						21
Total	**10932,36**		**2485.34**	**1885**	**0,76**	**77**

This cycle time achieves regular degree of saturation and average utilization of the light signals at every approach. The load factor is always under 0.9 and thus sufficient. It would be better to have a degree of saturation which is under 0.8 at every approach.

AUSTRIA:

To check out if the left turning performance is good enough, all left turning streams without separated signalisation must be considered. The performance of a traffic stream results from the sum of performances of the singular lanes. The performance for left turning vehicles without separate signalising comes out of two parts (P_1 and P_2). The maximum traffic volume (P1), is the traffic which can flow off at the stage change at the end of the green period. Therefore the following formula is used:

$P = t_{GREEN} / t_{cycle} * M_S$

11s ...P_{V1} =	11 / 69 * 1800 = 286.96	[260]
13s ...P_{V2} =	13 / 69 * 1800 = 339.13	[320]
22s ...P_{V3} =	22 / 69 * 1800 = 573.91	[420]
11s ...P_{V4} =	11 / 69 * 3800 = 605.80	[340]
22s ...P_{V5} =	22 / 69 * 1800 = 573.91	[545]
	2379.71	1885

Because the left turning of access East has its own lane, the left turning of access South was measured with 140 pcu/h and the left turning of access North with 100 pcu/h, the performance is good enough (no left turning at access West).

The metered traffic volume [ ] can be satisfied with a cycle time of 69 seconds. To get a better impression of the degree of saturation the following computation is made:

$x = M / P = t_{cycle} / t_{GREEN} * M / M_S$ [-]

$x_1 = 260 / 296.96 = 0.91$

$x_2 = 320 / 339.13 = 0.94$

$x_3 = 420 / 573.91 = 0.73$

$x_4 = 340 / 605.80 = 0.56$

$x_5 = 545 / 573.91 = 0.95$

$x_{total} = 2089/2379 = 0.79$

Other Possibility:

$P = P_1 + P_2$ [pcu/h] $P_1 = n * 3600 / t_{cycle}$ $P_2 = M_N * f$

n… max. number of left turning vehicles in pcu,

which find the line-up between conflict area and stop line ($n_{min} = 2$)

[FSV]

GERMANY:

$$g = \frac{q * t_{cycle}}{q_s * t_{GREEN}} = \frac{q}{f * q_S} \qquad f = \frac{t_{GREEN}}{t_{cycle}}$$

f … Green Period Amount

g … Degree of Saturation

g1 = (260*90)/(1983 *16) = 0.73

g2 = (320*90)/(1983 *19) = 0.76

g3 = (420*90)/(1983 *34) = 0.56

g4 = (340*90)/(3676 *16) = 0.52

g5 = (545*90)/(1689 *34) = 0.85

$$\bar{g} = \frac{\sum_{i=j}^{k} g_i * q_i}{\sum_{i=j}^{k} q_i}$$

(0.73*260 + 0.76 *320 + 0.56*420 + 0.52*340 + 0.85*545)/1885= 1314.2/1885 = 0.70

[FGSV 2009]

Table 4.25: Degree of Saturation - Austria, Germany, UK

Degree of Saturation			
	AUSTRIA	GERMANY	UNITED KINGDOM
Cycle Time	69	90	77
V1	0.91	0.73	0.88
V2	0.94	0.76	0.69
V3	0.73	0.56	0.77
V4	0.56	0.52	0.57
V5	0.95	0.85	0.85
Total:	0.79	0.70	0.76

4.5.1 Signal Control – Performance Measures

[Fellendorf, FGSV 2009, FGSV]

The measures of effectiveness are used as surrogates to define quality of a signal controlled junction. The level of Service can be determined using:

- Delay
- Number of sops
- Queue length (average and maximum, 95%-value)
- Total hourly volume of all approaches
- Travel Time
- Travel Speed

DELAY:

The average delay **of person-cars** in seconds is given with the formula below (from HBS/RiLSA):

$$d = \underbrace{\frac{t_{cycle} * (1 - t_{GREEN} / t_{cycle})^2}{2 * (1 - q / q_S)}}_{\textit{delay because of cyclic release}} + \underbrace{\frac{3600 * N_{GE}}{t_{GREEN} / t_{cycle} * q_S}}_{\textit{traffic based delay because of tailback}}$$

d	... average delay of person-cars [s]
t_{cycle}	... cycle time in [s]
t_{GREEN}	... green time of movement in [s]
q	... lane specific volume of decisive movements within stage I [veh/h]
q_s	... associated saturation flow rate in [veh/h]
N_{GE}	... mean queue at end of green within series of cycles (15 min or 1h) in [veh]

[FGSV 2009]

The average delay **of trams** in seconds is given with the formula below (from HBS/RiLSA):

$$d = \frac{t_{cycle} - t_{GREEN}}{t_{cycle}} * \left(\frac{t_{cycle} - t_{GREEN}}{2} + t_{ac} \right)$$

t_{ac} … additional time need because of the process of acceleration (i.e. 9s at 50km/h] [s]

The average delay **of pedestrians** in seconds is calculated as shown underneath

[FGSV, FGSV 2009]

$$d = \frac{(t_{cycle} - t_{GREEN})^2}{2 t_{cycle}}$$

QUEUE LENGTH:

The performance of the residual queue N_{GE} is calculated in the following way, concerning to the degree of saturation. [FGSV, FGSV 2009]:

N_{GE} is the average tailback at Green-end during duration T with number of cycles U.

Degree of Saturation less or equal 0.65 $N_{GE} = 0$

Tailback is not time dependent and constant

Degree of Saturation is 0.9

$$N_{GE,g} = \frac{1}{0.26 + (q * t_{cycle} / 150T)}$$

Tailback is not time dependent and constant

Degree of Saturation is 1.00

$$N_{GE} = 0.3476\sqrt{ncU \wedge 0.565}$$

Tailback is time dependent and continues to grow throughout analysis period of U cycles

Degree of Saturation is 1.20

$$N_{GE} = nc(g-1)U + 25 - 20g)/2 = 0.1ncU/2$$

Tailback is time dependent and continues to grow throughout analysis period of U cycles

Degree of Saturation is bigger than 1.20

$$N_{GE} = nc(g-1)U/2$$

Tailback is time dependent and continues to grow throughout analysis period of U cycles

Interpolation $$N_{GE,g} = N_{GE} + \frac{N_{GE,gi+1} - N_{GE,gi}}{g_{i+1} - g_i}(g - g_i)$$

NUMBER OF STOPS:

The number of stops of cars can also make a statement of degree of saturation. The within the HBS or RiLSA given formula is shown in the following lines [FGSV, FGSV 2009]:

$$N_S = \frac{q * ((t_{cycle} - t_{GREEN}) + N_{GE} * t_B) / 3600}{(1 - q / q_s)}$$

with

N_s	Number of Vehicles, which need to stop during a cycle [veh]
t_{cycle}	cycle time in [s]
t_{GREEN}	green period in [s]
q	lane specific traffic volume of decisive movements within stage I [veh/h]
q_S	related saturation flow rate [veh/h]
N_{GE}	average tailback at green-end after a fixed number of cycles (i.e. 15 min or 1 h) in [veh]
t	discharge rate at stop line [s/veh]

4.6 Fixed Time Signal Timing Plan

The signal timing plan with a timescale is a graphical description of the signal program of a traffic signal plant. It includes the singular signal groups of the traffic signal plant. Within a timing plan the signal times, so called green periods and red periods appear in seconds. Between the stages there are interstages the fixed time signal timing plan is time dependent, the traffic volume is only considered when establishing the fixed time signal timing plan, afterwards the stage sequence and process remains the same.

The whole process is depicted over time, beginning at the left hand side. Normally the signal timing plan is developed EDP-aided, because bigger intersections with a high number of signal groups and traffic streams are complicated to handle. Without EDP it is very hard to stay on top of things. Beneath the signal timing plan also the intergreen matrix is very important for the traffic signal plant (already given in Chapter 4.2).

The intergreen matrix depends on the number of stages of the signal timing plan. Following tree different stage numbers are given for the before defined example. The first one just uses two stages to handle the traffic volume and the second one uses (as calculated before) three stages. The last one would not be used in practice very often, because of the relatively high intergreen and waiting times, is a four stage signal timing plan.

4.6.1 2 Stages

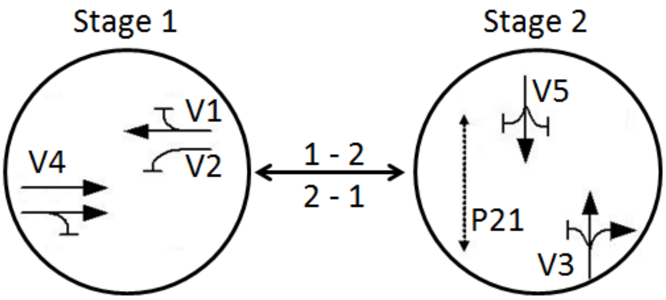


Figure 4.9: Stage sequence - Fixed Time Plan with 2 Stages

Every stage includes semi-compatible (partially conflicting) movement. The traffic safety is not that high as with a 3-stage or 4 stage control. Vehicles unblocked at stage 2, need to be attentive of walking persons (P21). Underneath the intergreen matrix is shown. There are no values given, there are just the boxes filled with “x” which need an intergreen time. The same is valid for the 3-stage and 4-stage example matrix. The more stages the timing plan has, the more intergreen times need to be considered.

Table 4.26: Intergreen Matrix for the Fixed Signal Timing Plan – 2 Stages

		Starting Signal Group					
		V1	V2	V3	V4	V5	P21
Ending Signal Group	V1			x		x	x
	V2			x		x	
	V3	x	x		x		
	V4			x		x	x
	V5	x	x		x		
	P21	x			x		

4.6.2 3 Stages

At a 3-stage control there are two possibilities of stage sequences: 1-2-3 or 1-3-2. For choosing the right stage sequence the intergreen time sum is important. With the intergreen matrix, (calculated in chapter 4.2), the fixed time signal timing plan is developed. The intergreen Matrix is not symmetric considering the values because the clearing and entering distances are calculated in a different way, as shown before, but it must be symmetric when considering if filled out or not filled out. Underneath just the filled out boxes are given. There are more filled boxes, because there are more possibilities of in different stages conflicting one after the other following movements.

Table 4.27: Intergreen Matrix for the Fixed Signal Timing Plan – 3 Stages

		Starting Signal Group					
		V1	V2	V3	V4	V5	P21
Ending Signal Group	V1			x		x	x
	V2			x	x	x	
	V3	x	x		x		x
	V4		x	x		x	x
	V5	x	x		x		x
	P21	x		x	x	x	

Because of the possibility that green periods of the singular signal groups of a stage start at different points of time or end at different points of time, normally the higher loaded traffic streams of a stage are considered. Normally low loaded streams or pedestrians suit to the signal program without problems. Despite this assumption should always be proved.

For the stage interims it is necessary to know the boundary conditions. As given in the example before, the stage interims consists of 8 seconds minimum Green and 1 second minimum Red and the normal calculation resulting from the clearance and entrance times. The permissive Speed is 50 km/h. The red + amber period is 1 second for calculating in Germany (in Austria and UK it would be 2 seconds).

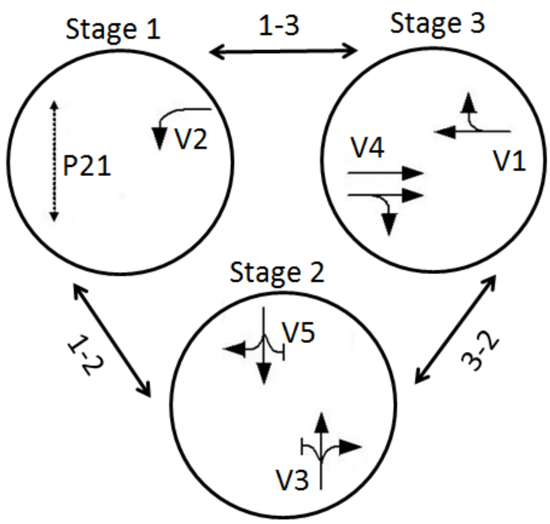


Figure 4.10: Stage Sequences for a fixed Time Plan with 3 Stages

At the following figure a signal timing plan of exact one cycle is given as an example. The interstage periods, intergreen times and green, amber and red periods are shown.

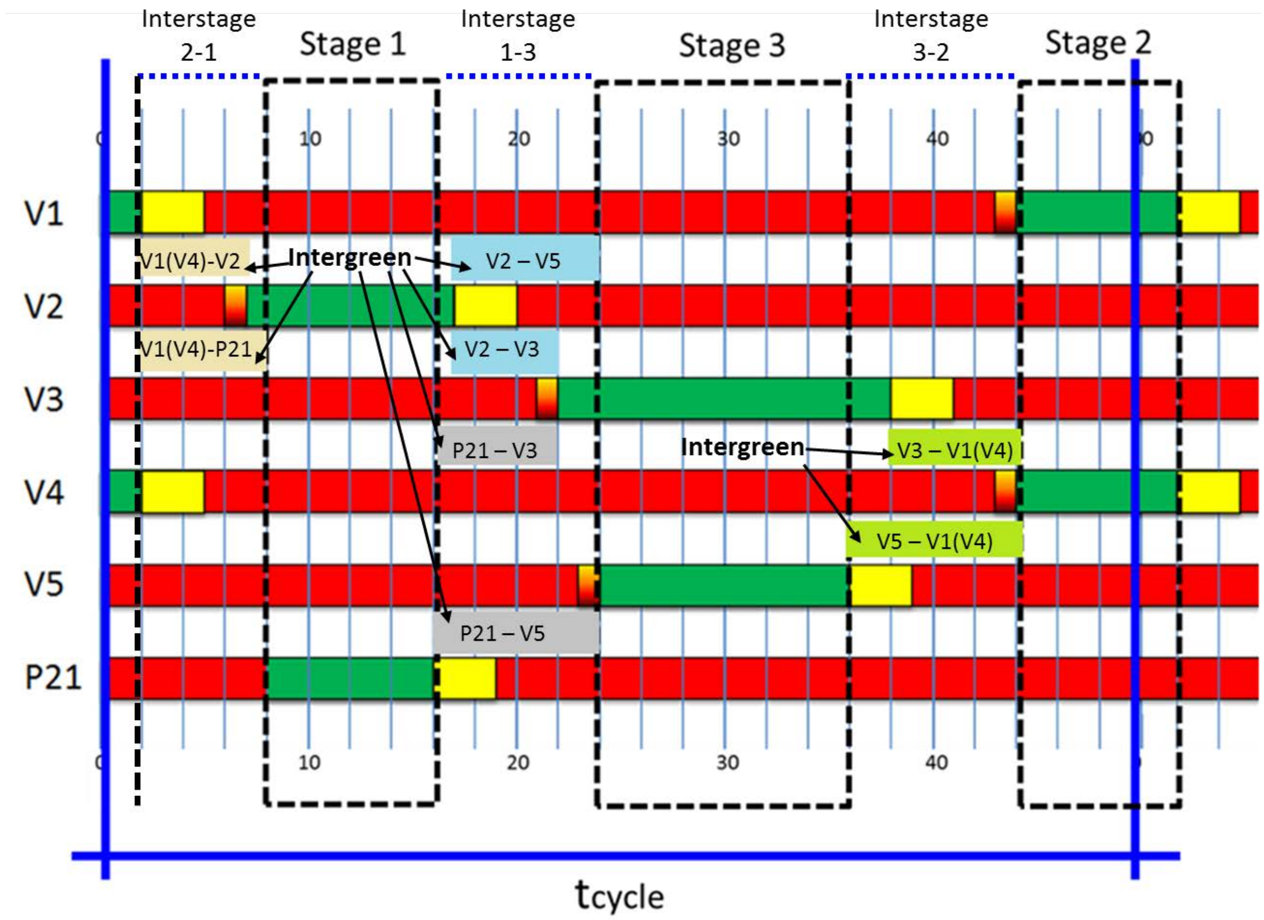


Figure 4.11: 3-Stage-Fixed-Time-Control with Descriptions

4.6.3 4 Stages

There are six possibilities of arranging the stages to find the shortest possible sum of intergreen times (1-2-3-4, 1-2-4-3, 1-3-4-2, 1-3-2-4, 1-4-2-3, and 1-4-3-2). With the given stages 1,2,3,4 there is no conflict point within one stage anymore. This option is the best concerning traffic safety, but normally not the best one in general, because there are inacceptable high waiting times.

Table 4.28: Intergreen Matrix for the Fixed Signal Timing Plan – 4 Stages

		Starting Signal Group					
		V1	V2	V3	V4	V5	P21
Ending Signal Group	V1			x		x	x
	V2			x	x	x	
	V3	x	x		x	x	x
	V4		x	x		x	x
	V5	x	x	x	x		x
	P21	x		x	x	x	

Because all points of conflict are now within the stage change, the intergreen matrix has the most possible filled boxes. The unfilled black boxes are the same stages, so they cannot have a conflict. The unfilled grey boxes are streams which do not have any conflict, even if they are signalised together. Movement V1 and V2 are compatible movements, as well as V1 and V4 and the movements P21 and V2. They will never have a filled box.

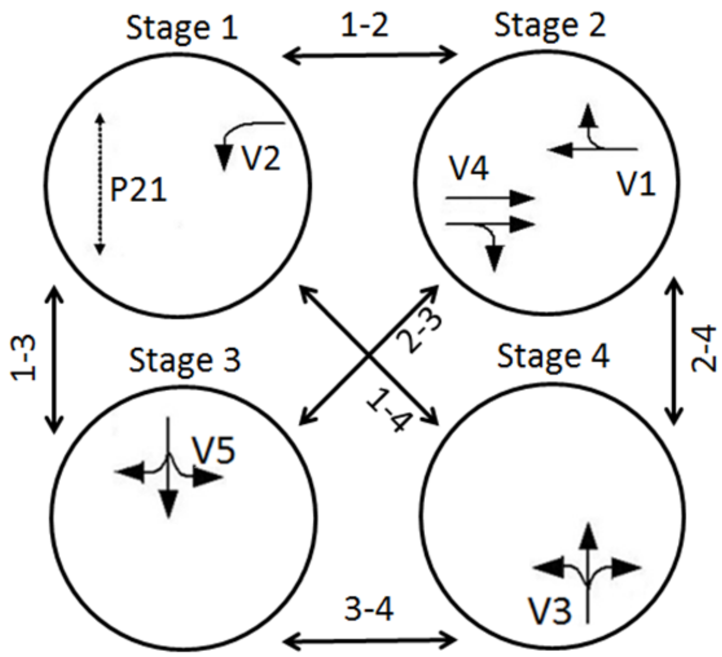


Figure 4.12: Stage Sequences for a fixed Time Plan with 4 Stages

5 Coordination

Coordination of light signals is a traffic technical effective method to handle through going traffic streams at arterials in a fluent way. If there are disabling times at the coordination system because of unfavourable intersection distances, the stronger loaded direction should be coordinated. The functionality of a green wave and the concerning program of coordination at the practice operation is determined through a sufficient number of metering-drives at not over-saturated traffic conditions. Establishing coordination is easiest to justify when junctions are in close proximity to one another and when traffic volumes between the adjacent junctions are large. If arriving traffic includes platoons that have been formed by the release of vehicles from the upstream intersection, coordination should be implemented. If vehicle arrivals tend to be random and are unrelated to the upstream intersection operation, then coordination may provide little benefit to the system operation.

The coordination can be vividly shown in a time-way-diagram. Such a diagram shows the movement of road users in so called green-ribbon (time-way-ribbon). The width of the ribbon is the value for the number of road users which are inside the coordination. The width of the ribbon (which can vary along coordinated roads) can be seen as the traffic volume which can pass within green.

New entering road users can be stand out in form of pre running and last running of the continuous green ribbon at a time-way diagram. For the development of coordination, direction and strength of traffic streams need to be known. Essential changes of traffic conditions during the day or for special events require differentiated designs. [Wilson]

5.1 Goals

Coordination is the adaption of green periods of one after another lying signalised sections through fitting time offsets. In this way it should be reached, that the majority of affected road users can pass various light signal plants without stopping.

Coordination is relevant at singular, tightly neighbouring light signal plants, for public transport, motor vehicles, bicyclists and pedestrians. At arterials or in traffic networks the coordination is especially for motored vehicles and public transport vehicles relevant, for bicycle traffic just relevant to some extent, due to the extensive speed-distribution. The coordination is used to minimize the travel time of motor vehicles and reduce fuel consumption and emission by reducing the number of halts. Therefore (and for better traffic safety) the distribution of speed of singular vehicles as well as the number of stops of all vehicles should get possibly low. For the street-network it should be strived for a total optimisation.

Beneath the traffic and environmental advantages a line-shaped coordination (green wave) for the motored vehicle supports the urban development objectives of concentrating the motor vehicle streams on main traffic roads and to alleviate the load of surrounding secondary roads.

For planning of coordination all different interests need to be considered. The fair contemplation of the different road user groups means that temporal and local solving must be found, for not discriminating one group. It’s favourable to reconcile planning goals. According to the planning requirements different coordination of road users can be found, for example orienting at possible waiting times of pedestrians, at the number of stops of the motored traffic or the optimisation of fluent passing of the public transport. [Wilson, Otto, Schlabbach]

5.2 Coordinating of Intersections and Arterials

At wide intersections and big roundabouts with more than one signalising sector, one after each other, coordination is of special interest to keep congestion areas free. Results can be forced conditions for choosing the stage organisation and stage sequences.

For coordination of public transport in addition to the framework of motor vehicles, times for passenger changes at stops need to be considered.

A coordination of pedestrian streams at intersection is appropriate at:

- split crossings at streets with central reserves,
- consecutive crossings for crossing more than one intersection.

Bicycle signals should be normally matched progressively, due to higher speed compared to pedestrians and bigger setting space/waiting area for consecutive crossings.

For coordination the following design basics need to be considered:

- The offset time of consecutive bicycle-signals should be fixed concerning enough slow speed
- The green period begin of bicycle-signals should be coordinated in a way, that the next crossing is only reached at green period start, also if moving with higher speed.
- If there is a joint signalisation of bicyclists and pedestrians, all boundary conditions should be considered, if beneath the pedestrian crossing also bicycle crossings are marked. [FSV, FGSV]

Constructional Requirements

For the development of green waves for the motor vehicle traffic the following boundary conditions need to be considered, because they could have a main impact onto quality of coordination.

- More than one continuous lane or a bicycle lane are positive for the quality of coordination, because the possibly on the road guided bicycle traffic can be passed.
- “No stopping areas” avoid negative restriction of quality of traffic flow, due to stopping and parking vehicles.
- For turning vehicles, there should be turning lanes intended, for not disturbing the through traffic and to avoid rear end accidents.
- For green waves pedestrian crossings without signalisation are not permissible
- Green Waves for motor vehicles are effective at distances of are up to 750 m, for special cases up to 1000m between the light signal plants. For longer distances the vehicle crowds disperse in a way which makes coordination ineffective. [FSV, FGSV]

Consideration of Cyclists

Cooperation can be necessary at important main routes of bicycle traffic. Bicycle coordination is also shown with a time-way diagram. For better clarity it can be necessary to draw an own time-way-diagram.

It must be weight up, if the bicycle traffic should be a secondary wave of the green wave. The wide range of cycling speeds between 10 and 25 km/h causes problems when designing a bicycle-coordination). Normally a speed of 16 to 20 km/h is chosen.

[FSV, FGSV]

Vehicular Traffic

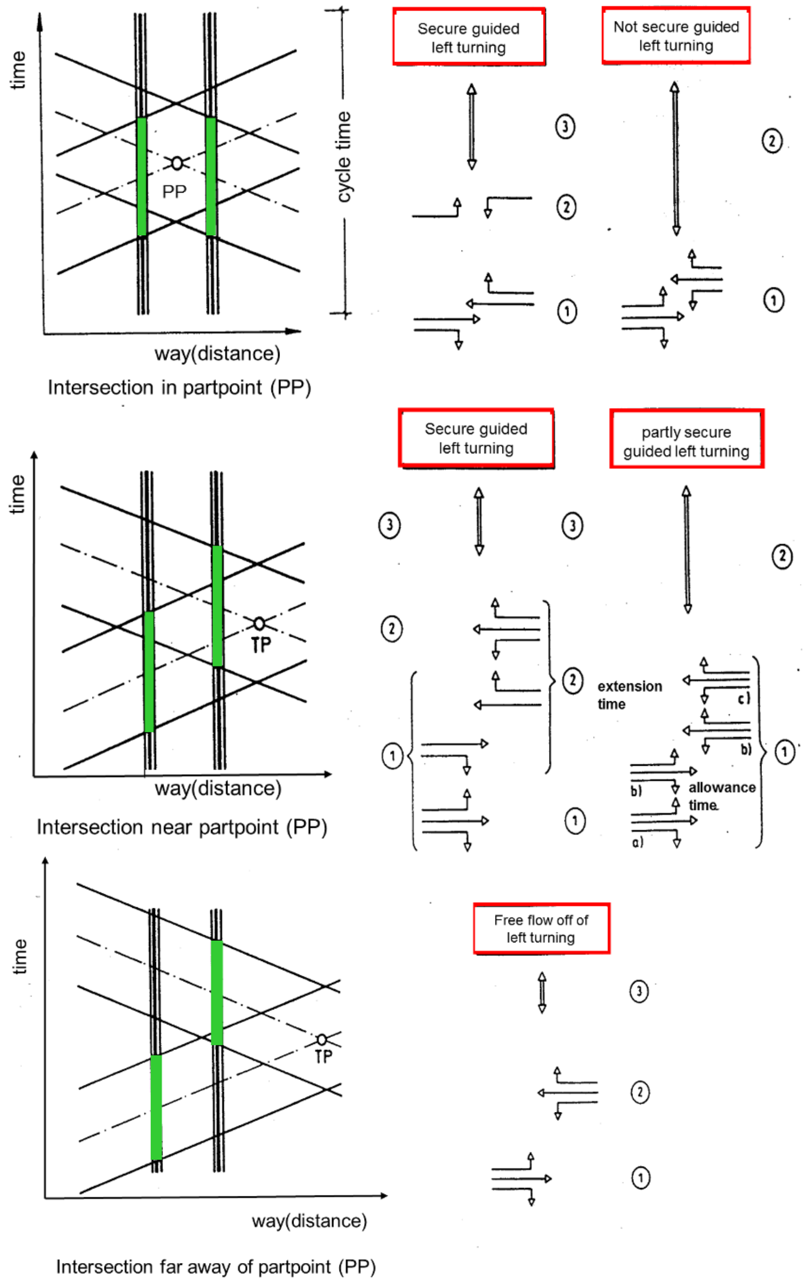


Figure 5.1: Examples for Time-Way (Distance) depending to Part-Point Distance

[Fellendorf]

If an intersection lies exactly at the part-point, the maximum freedom at the disposition of green period distribution exists. The further afar an intersection is away of the part-point, the less are the possible green periods for the crossing traffic. At slightly out of the part-point lying intersections, the developing time offsets can be used for left turning without oncoming traffic. In case of left turning before the oncoming crowd, because of safety reasons a secure turning stage should be aspired.

If it is necessary to interrupt a green wave, because of unfavourable intersection distances, it should be done in a way, that the total arriving crowd gets a red sign. At in small distance behind each other lying intersections (less than 100m) it must be paid attention that the offset time of the green period end corresponds to the real present driving speed. If it is not possible, a green-end at the same time for both light signal plants is suggested (simultaneously switching).

5.2.1 Green Waves

In urban areas controlled intersections lie regularly very near to each other. Because of this it is possible that the vehicle crowd of a junction is influenced by the downstream intersection. The influence can have wanted or undesired effects onto traffic handling. It is possible that traffic of the upstream lying junction arrives directly after the green period end at the downstream intersection. If a vehicle crowd of the earlier intersection comes to the following intersection exactly when green period starts, a green wave establishes. The crowd can run through without interference and there are low or no loss times. A Green Wave is not always desired, i.e. if there is one lane at a junction followed by a two lane junction upstream, because of the capacity reduction it would be better if there is just a one direction Green Wave. The capacity of the upstream lying junction is better used because the arriving vehicles must adapt themselves to the two lanes. A relatively short green period for the two lanes is normally sufficient.

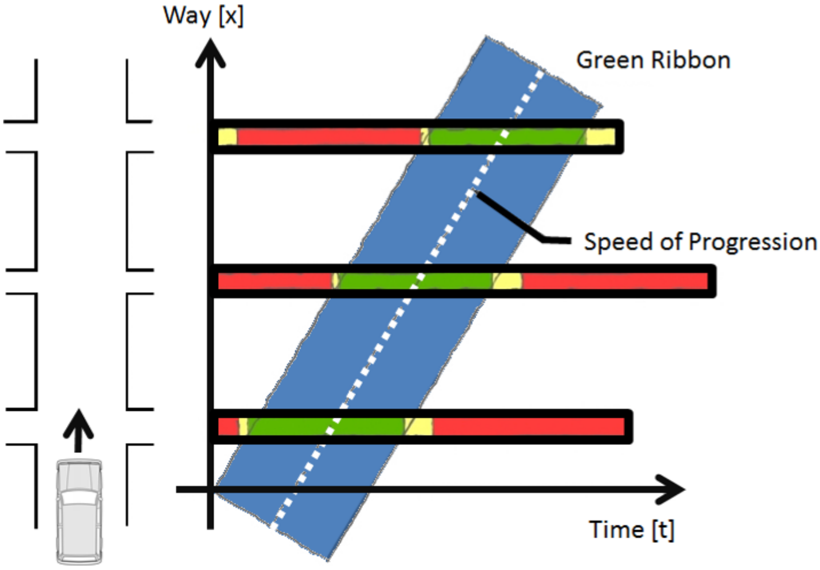


Figure 5.2: Green Ribbon

In practice coordination are normally adapted to realise green waves between junctions. A green wave between two controlled directions A and B means a regulation at which the total or main traffic which passes the stop line at junction A can also pass the junction B without stop and also without considerable time losses. There can be a green wave in just one or in two directions. Green Waves can be used for motor vehicles, bicycles and pedestrians At Green Waves the signals of an arterial are switched in a way, where a vehicle if driving at a certain speed reaches every traffic signal when green is shown. The advantage is a continuous traffic flow. This system can often only be used for one direction. Just in rare cases green waves can be used for both driving directions. For planning a green Wave a lot of parameters must be considered. [Wilson, Bosserhoff]

Table 5.5.1: Parameters for the Green Wave

Speed of progression [V_P]	Speed which must be driven to pass the green wave without stop
Part-Point distance [l_{pp}]	Distance of two neighbouring Part-Points
Light-Signal-Plant distance	Distance of the singular junctions of a street
Cycle time	Duration until the same state of signalisation is shown again
Available green period	Green period, which is available for the driving direction of a green wave
Signalised turning streams	Through signals controlled, turning traffic streams, which exist the street of the green wave
Entering traffic	Cross-traffic which is entering the street of the green wave and moves on there.

Because of different distances of the cross roads (junctions not at same distance to each other) the green wave is often just possible in one direction. At green waves for two direction roads, part points (PP) are the characteristic points of the time-way-diagram. As mentioned before they come out as point of intersection of the middle lines of two adverse green ribbons.

A green wave for both directions is just possible if the distance of the light signal plants matches to the part point or a multiple of it. At a cycle time of 90 seconds and a permissive maximum speed of 50 km/h the part point distance is 635 m, for 70 seconds 486 m. If an intersection lies directly at the part-point the available green period durance of the crossing direction and the necessary interim period by the given cycle time reach the maximum. The green ribbons fully overlap. The best possible Green Ribbon is depicted below. [Wilson, Bosserhoff, Schnabel]

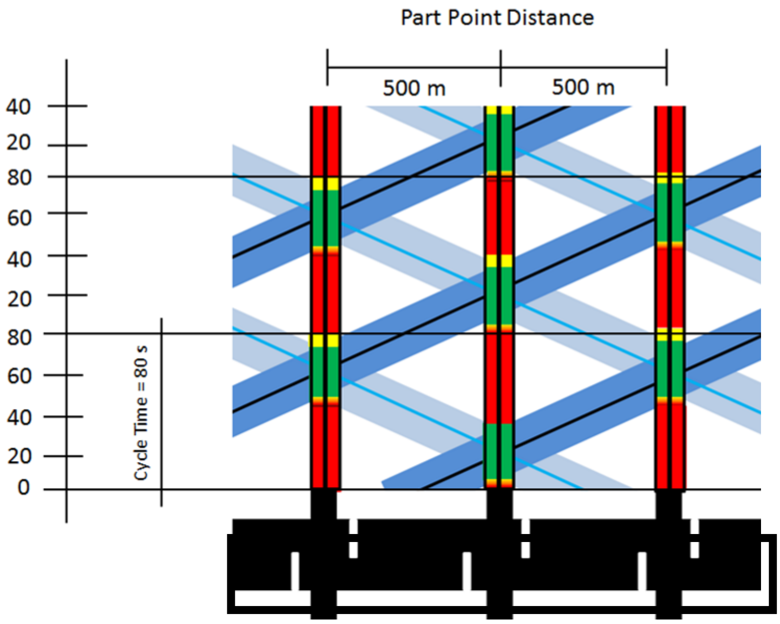


Figure 5.3: Best possible Green Ribbon

Normally the green wave is used due to the load/traffic volume. The signalisation is done into or out of town. The opposite direction needs to stop more often. Through the vehicle crowds a consistently traffic load is possible, but the traffic volume of involved traffic lights decreases, because green periods are given to the green wave which normally are given to the cross roads. At a load factor of 80 to 85% the green wave breaks down because of vehicles driving at the end of crowd needs to stop in front of the intersection because of red. Especially at high loaded streets green waves must be given up at the peak times in favour of maximum traffic volume. There are two systems used for the coordination, the simultaneous system and the alternative system.

The simultaneous system unblocks all junction of the green ribbon at the same time. The intersection distance [S] can be calculated with:

$$S = M * t_{cycle} * V_P$$

At the alternative system the intersection-unblocking is pushed back by a half cycle. The intersection distance can be calculated with:

$$S = (2 * M + 1) * t_{cycle} * V_P / 2 = l_{pp}$$

S = intersection distance
M = constant
tcycle = cycle time
vP = speed of progression
l_{pp} = part point distance

Off-line Method

The draft of green waves is normally time-consuming, but the switching of signals during traffic process is very time-critical. Because of this, most green waves are designed offline. The used Systems determine the quality standards of the green wave and must be evaluated. In practice most green waves are graphically drafted. When EDP is used, a traffic model is needed. Here, with more or less effort the traffic process is depicted, the model is an optimising model. The more realistic the model of traffic flow, the more complicated the target functions for finding the best solution. There is the necessity of simplifying the model for exact optimisation or the planner must accept approximation-solutions of the optimising problem for getting realistic traffic flows.

The model should be appropriately exact for the wanted use. Optimisation models must have an acceptable effort of calculation-time for specific solutions and different target criteria. Because of measurement combinations a mathematical exact optimisation is just very rarely possible and efficient, heuristic algorithms are aspired. Heuristic algorithms are intelligent experiences and practicable ideas using optimising-methods, finding the best solution for the use. [Otto]

Evaluation attributes could be:

- Involved road user groups
- Oversaturated/ not saturated traffic conditions
- Traffic relations (matrix, approach-load)
- Optimisation methods (linear/dynamic programming)
- Target criteria
- Input values
- Decision variables (offset, green period split, cycle time, stage sequence)
- Usage frequency and effectiveness

Through weighting of coordination the method can be transferred to an arterial. At open networks with tree structure this has no influence on quality of optimisation. At closed network-mesh the extent of interference depends to the network-size (4-5 intersections 20-25%, 20 intersections 1-2%). That means that in intermeshed networks there is a lot of different optimal coordination possible, which has in total the same quality. For the final choice additional criteria are needed, because the used target sizes bring uniform results.

During real-time consideration the offset time is practically proven, methods with higher flexibility are continuously enhanced.

In the following figure a theoretical simple example for designing a green wave offline is illustrated. The graphic shows some problems by developing a green wave. This is just a short part of street, so in reality the development mostly is much more sophisticated.

Four intersections, one T-junction and two four armed junctions, are considered for the green wave. The distances from the intersections are 350m, 275m and 400m. As depicted in the figure the part point of these junctions lies in-between the junctions. For the given part point distance of 512.5 m the cycle time would be 82 s. Because there is no green wave possible for both directions (like shown in the figure before), only a green wave for one direction can be implemented.

Therefore the relation entering the arterial from West is considered. The chosen speed of progression is 12.5 m/s (45 km/h). With i.e. a cycle time of 50 seconds it is possible to have a continuous green ribbon for one direction (grey). Vehicles can move through all four junctions without stopping and without deceleration/acceleration at speed of 12 m/s , if only light signals are considered (oversaturated traffic can lead to both). There is just very little loss time (speed 45 instead of 50 km/h).

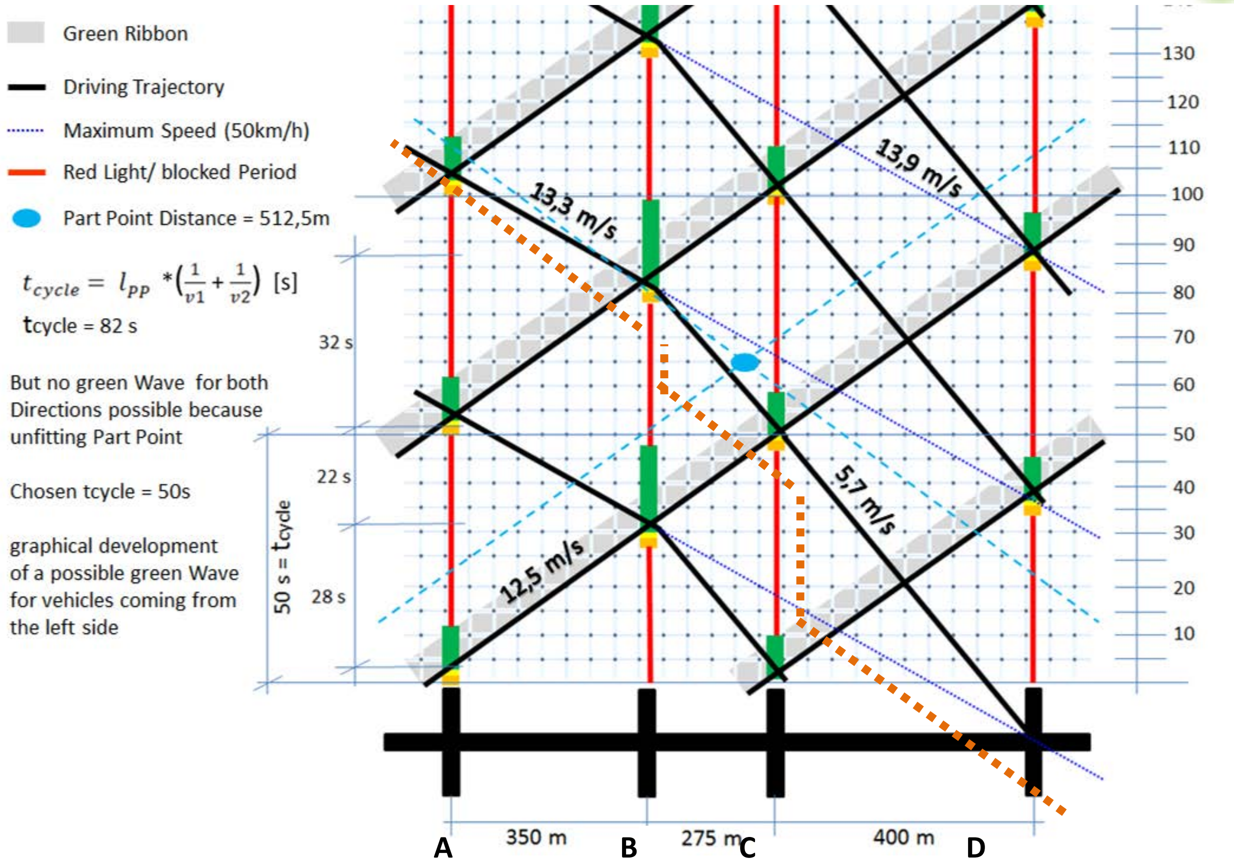


Figure 5.4: Example for Green Wave Development

Considering the other direction there is no real green wave possible. When moving with the speed of progression after waiting for green at the first junction of the coordinated street they arrive long time before green is shown and need to wait at the second intersection (dotted orange line). Waiting times of 25 seconds (maximum) must be taken. Otherwise it would be possible, for better traffic flow, that a speed for drive-through without stop is given. Between junction D and B the speed for driving through without stop would be 5,7 m/s (20 km/h), between junction B and A the speed must be heightened to at least 12,5 or at maximum 13,3 m/s (48 km/h) to pass the fourth crossing at green lights. In reality the speed of 20 km/h is too low, that someone would use that speed.

It is also possible to display a green wave to the other direction. Always the opposite direction has much more loss time. Normally the decision is made through giving the green wave to the direction with much higher traffic volume.

Green Wave Information

Speed-signals reports the drivers (when used at green waves) the speed, with witch (if kept) the signal of the following intersection will show green (no stop necessary). Through delaying the first vehicles and accelerating the last vehicles of the same crowd, a tighter jointing and with it a better capacity-use can be reached. Because the speed details refer to the green periods of a signal at the following light signal plant, reliable speed details are just possible at fixed time controls. [Otto]

Stationary Green Wave Information

Stationary speed-recommendations are used since a lot of years for urban arterials. Their goal is to give the driver information about the optimal speed for reaching the following light signal plant at green. Static green wave information is in the easiest way a sign with the given speed of progression (“green wave at 50 km/h”). Beneath the static display also stationary but dynamic speed signals are used. [Otto]

Mobile Green Wave Information

There is the possibility to bring the information of speed directly to the end user. This is done when the information can be read directly in the car. The principal is to show the situation of the car within the green wave. It is very intuitive, but the first realisation was done in 1983 with infrared-technology. [Otto]

5.3 Coordination for the Public Transport

Because of scheduled stops as well as the lower accelerating and breaking speed (standing passengers) public transport vehicles have considerable lower travel speed than motor vehicles. Different station-stop-length leads to unregularly vehicle arrivals at the light signal plants. To guarantee a good traffic quality for public transport specific properties must be considered by planning green waves.

Light signals after BOStrab can improve the green wave [FGSV]:

- Door-closing-signal is preferable, if the light signal plant is directly behind a station.
- Station about 100 m before the light signal plant → additional signal placement recommendable. Breaking and stopping processes between the station and intersection can be avoided.
- Station more than 100 m before the light signal plant → advance notice signals are possible. They do not show a signal if continuing driving needs a stop at the intersection.

The time-way-planning for public transport is determined by an unsteadily driving curve because of the station-stays. The coordination is based on driving diagrams from the traffic enterprises with acceleration and deceleration. If coordination is matched to a driving curve of buses or tramways, at the green ribbons of the public transport a distribution range for differently long station stays must be calculated. Basically a joint coordination with the motor vehicles should be realised. Therefore the position of the stations (before/after the intersection) must be checked, considering the time-way-planning. At tight connection with the signal control, the time-way-planning must be determined, to avoid time losses for the public transport.

The following situating must be checked [FSV]:

- The station stop before a signal controlled intersection can be put into the blocking time, between end and begin of one after the other following green ribbons of the motor vehicles. The position of station before the intersection has the advantage that signal based loss times can be used for passenger change.
- Through the arrangement of stations before or after the signalised intersections by turns, the green wave of the motor vehicles can be used twice, and afterwards the public transport can move on without waiting for green (stop was already behind the intersection)
- In coherence with a green period request the position behind the intersection has the advantage that the green period for the public transport can be timely switched and the consideration of different longer station stays is not applied. It must be considered, that a tailback behind the stopping public transport vehicle is not allowed to reach to the intersection area. (station-island, bays)

5.4 Coordinating of Traffic Networks

A coordination of road network should be an aim if the road sequences with light signal plants crossing each other. There are the same rules as for the coordination of road sequences, especially for the same system-cycle time. The problems which exists at the road sequences, is more complex for road networks because there are more conflicts.

- Meeting of more than one road-based green wave, often at central intersection points with high loading.
- Increasing number of vehicle streams with high or similar traffic volume as well as instable traffic stage because of overloaded intersections
- Increase of possible goal-conflicts between the different road user groups at road network

Langer road networks should be divided into smaller parts of networks. Therefore it must be considered that the parts of networks do have appropriate bordering points.

At street sequences, where motor vehicles and public transport vehicles should be coordinated, it must be checked, if a traffic dependent control can be implemented for the public transport to offer the green wave of the motor vehicles and to enable through public transport-dependent interferences a minimisation of the light signal plant-based delays.

5.5 Coordination Mechanics

In this chapter the cycle length, part-points, speed of progression, splits and offsets are explained.

[FSV, FGSV, U.S. Department of Transportation, Federal Highway Administration, Department for Transport, Scottish Executive, Welsh Assembly Government, Bosserhoff, Schnabel, Wilson, Kobbeloer]

5.5.1 Cycle Length

The **cycle time** must be equally high at all intersections of the green wave. The cycle time of coordinated intersection is called system-cycle time. At first the most attractive cycle time of all intersections of the coordination needs to be calculated. The intersection with the biggest cycle time is decisive. At first with this enclosure of cycle time, an operative processing (without condition of coordination) of all traffic streams is guaranteed. Differences of the system-cycle time at short notice, due to green period adaption and green period request, must average out. Cycle length defines the time required for a complete sequence of indications.

Cycle lengths must be the same for all junctions in the coordination plan to maintain a consistent time based relationship. (One exception would be an intersection that "double cycles," serving the stages twice as often as the other junction in the system.)

Short-circulation inside the system-cycle time can be planned for controlling the traffic flow.

Short-circulation:

- for weak loaded roads, which are connected to the main roads
- for singular meagre calculated congestion areas
- for pedestrian-light signal plants
- for intersections with weak diagonally traffic

The sum of the cycle times of the short circulations must be the same as the system-cycle time. It is possible that some intersections have the half cycle time of the system-cycle time.

The **load factor / degree of saturation** must be lower than 0.85 (at least 0.9 in UK) for a good quality of coordination. The aim must be saving a sufficient capacity, through appropriate structural and operational activities (at all intersections in case of green wave)

5.5.2 Part-Point / Yield Point

At green waves for two direction roads yield points, also called **part-points** (PP) are the characteristic points of the time-way-diagram. They come out as point of intersection of the middle lines of two adverse green ribbons. The distance between the neighbouring part-point is called **part-point-distance** (l_{PP} [m])

If an intersection lies exactly at the part point, the available time durance of green periods of the crossing direction and the necessary interim period by given cycle time, reach the maximum. Then the green ribbons fully overlap. The minimum is reached, if the green ribbons do not overlap. The intersection lies far away from the part-point. Between the cycle time, the speed of progression in direction and opposite direction and the part-point-distance the following relation exists:

$$t_{cycle} = \frac{3.6 * l_{PP}}{V_{p,\,dir1}} + \frac{3.6 * l_{PP}}{V_{p,\,dir2}}$$

$$t_{cycle} = l_{PP} * \frac{1}{v_1} + \frac{1}{v_2} [s]$$

t_{cycle}	cycle time [s]
l_{pp}	part-point distance [m]
v_1	progression speed at direction 1 [m/s] ($v_{p,dir1/2}$ in [km/h])
v_2	progression speed at direction 2 (opposite direction) [m/s]

[FSV, FGSV]

5.5.3 Speed of Progression

The **speed of progression** (V_p) is shown at the time-way-diagram as slope of the middle line of the green ribbon. Normally a speed of progression of 90 to 100% of the possible high speed is recommended. Influences (high truck-holding, high slopes, narrow curves, bad state of road), which leads to the reduction of driving speed must be considered by designing a coordination. The planned speed of progression of the singular directions ($V_{p,dir1}$ and $V_{p,dir2}$ in km/h) results the green ribbons of through traffic, together with the calculated green periods for the coordinated vehicle streams. The green ribbons are normally shown in the time-way diagram.

5.5.4 Splits

Within a cycle, splits are the portion of time allocated to each stage at a junction. These are calculated based on the intersection staging and expected demand. Splits can be expressed in percentages of the cycle or in seconds.

For implementation in a signal controller, the sum of the stage splits must be equal to (or less than) the cycle length, if measured in seconds, or 100%. In traditional coordination logic, the splits for the non-coordinated stages define the minimum amount of green for the coordinated stages.

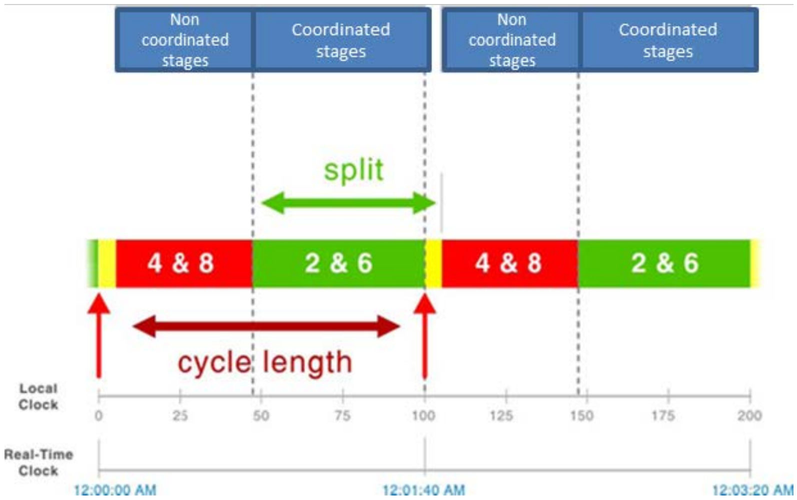


Figure 5.5: Cycle Length and Split

The figure above is a time-way diagram that shows a simplification of the signal indications for the coordinated and non-coordinated stages. The measured split for a stage includes its green time, amber change, and red times. The cycle length is the sum of time for the complete sequence of indications.

Force-offs are used in some controllers as an alternative way to control the stage split. Force-offs are points where non-coordinated stages must end even if there is demand.

5.5.5 Offset Time/Offsets

At coordinated junctions a offset time exists. It is the time due to which all cycles are delayed, so that for example a green wave or public transport priority develops.

The usage of unique cycle times is especially at network control useful, if singular green period areas must be integrated into the cycle in a way that a coordinating with neighbouring junctions arises. Therefore the offset time needs to be known. The offset time is the temporal difference between the start of one green period to the green periods of spatial neighbouring signal groups.

Modern control methods have the ability to adapt green period areas in a flexible way, based to the actual traffic conditions at the cycle. The coordinating at the network survives through certain delay of the offset time. Therefore special algorithms are necessary, to adapt the singular control programs so that an optimisation of control at the whole network gets reached. The calculation of the output and the modified signal programs is normally dune via central control unit, which controls the light signal plant. The flexibility of a light signal control is limited through cycle time.

This can i.e. lead to just certain possible stage-sequences or unblocking of fix defined time-slots for signal groups. [Kobbeloer]

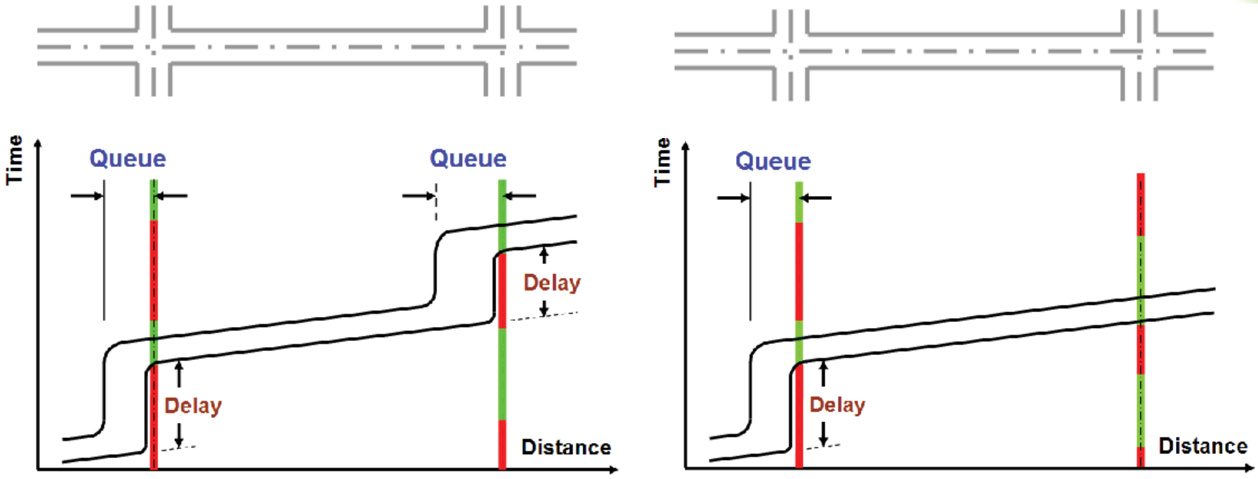


Figure 5.6: Uncoordinated and coordinated Signal Time Offset[2]

The Offsets are used therefore that at adjacent intersections the green times occur at a given time, relative to a reference intersection. The Offset depends on the distance between signals, the progression speed along the road between the signals and the queues of vehicles waiting at the red signal. If there is an uncoordinated signal time offset, a vehicle can be delayed at the second intersection (left picture). If a vehicle should not be delayed at the second intersection, a coordinated signal time offset is necessary (right picture) [SCATS]

At the Traffic Signal Timing Manual from the U.S. [U.S. Department of Transportation] the term offset defines the time relationship, expressed in either seconds or as a percentage of the cycle length, between coordinated stages at subsequent traffic signals. The offset is dependent on the offset reference point, which is defined as that point within a cycle in which the local controller's offset is measured relative to the master clock. It is not necessarily the same as the yield point (part point) within the cycle. The master clock is the background timing mechanism within the controller logic to which each controller is referenced during coordinated operations.

This point in time is used to establish the reference points between every intersection. Each signalised junction will therefore have an offset point referenced to the master clock. Moreover each will have a relative offset to each other. It is through this association that the coordinated stage is aligned between junctions to create a relationship for synchronised movements. The location of the part point and the offset reference point describes the relationship between the coordination plan at the individual intersection and the master clock. [U.S. Department of Transportation]

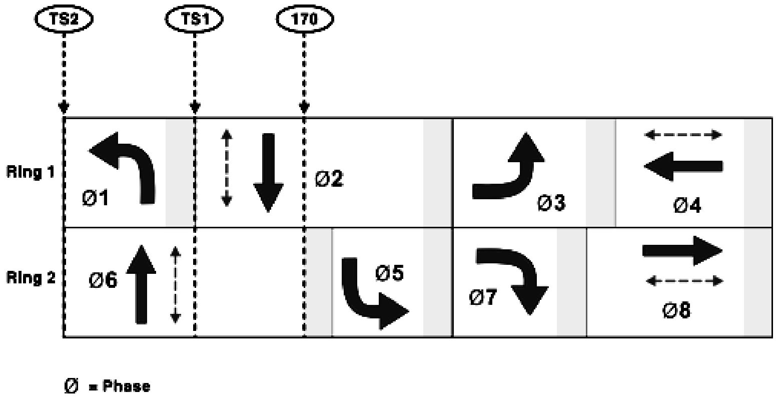


Figure 5.7: Standard Offset Reference Points for different Controller Types

[2] http://www.scats.com.au/product_signal_coordination.html

Different offset reference points are associated with each of the three major controller types: NEMA TS1, NEMA TS2, and the Type 170.

- The NEMA TS1 references the offset point at the start of the coordinated stages.
- The NEMA TS2 references the offset point from the start of the green indication of the first coordinated stage.
- The 170 typically references the offset point from the start of the coordinated stage amber.

For each of these controller types, software may allow variations of these designations.

Of the three reference points, only the use of the start of coordinated stage amber is readily observable in the field. Under this type of designation, if Intersection B has an offset of 20 seconds after Intersection A, one should see Intersection B's amber twenty seconds after Intersection A's amber. For both NEMA designations, the use of start of coordinated stage green as an offset reference point is not a fixed point due to the variability in the start of green (early return to green) under typical actuated-coordinated operations. However, knowledge of the assigned split for the coordinated stage can allow one to calculate the observable fixed point in the cycle. [U.S. Department of Transportation]

Once the reference point is identified, the offset is defined as the time that elapses between when the reference point occurs at the master clock and when it occurs at the subject junction. In the example above, the offset reference point is at the start of coordinated stage amber, and cycle duration of 100 seconds is used for both junctions. The offset of the junctions on the bottom of the figure is zero and matches the master clock, which is in the figure above referenced to midnight. The top junction is set to an offset of 30 seconds. The coordinated stage begins its amber at 30 seconds and 130 seconds (12:00:30 AM and 12:02:10 AM), always 30 seconds after the bottom intersection. The relative offset is observed by the user from intersection to intersection, but this can be different from the offset to the master clock. [U.S. Department of Transportation]

6 Traffic dependent Signal Control

With using this control, the light signals get adapted due to traffic conditions. According to different traffic condition or different traffic demands changeable processes of light signal control will happen.

6.1 Partially Traffic dependent Control

At such signal programs within a fixed cycle time, singular signal program elements (number of stages, stage sequences, green period) can be changed due to traffic conditions. The process of traffic dependent control is done in, a so called, control logic in form of flow charts, structure charts or decision tables.

6.1.1 Stage Change

At the stage change, under continuing the same number of stages, the given stage sequence can be changed because of request. The method is appropriate, if for actions of accelerating the public transport, the forecasted arrival time is not fitting into the time window of a possible green period adaption.

Table 6.1: Stage Change

Control methods		**Traffic dependent changeable elements of signal programs**				
Generic term	**Main feature of changeability of signal programs**	**Cycle time**	**Stage sequence**	**Number of stages**	**Green period**	**Offset time**
Signal program adaption	Stage change		X			

Example: A junction is signalised in a four-stage system. The normal process is 1-2-3-4. Because of a request there is any stage change possible. At the table the stage "4" is brought forward. Because of that five blocked time intervals establish, which are in total higher than the cycle time. The blocked time interval is the time before a stage can be served at the normal process again. Between the handling of stage 2 and 3 there are three instead of four blocked time intervals. To reduce the negative effects of the stage change for the stages 2 and 3 the handling should be done as shown in the second table. If one more stage change must be realised, afterwards also an unsteadily handling exists. To avoid extreme unsteadiness at the operation, the stage change must be restricted if necessary. [FGSV, Bosserhoff]

Table 6.2: Stage Change - Type 1

1	2	3	4	1	4	2	3	1	2	3	4
						5blocked time intervals					
Normal process				Stage change				Normal process			

Table 6.3: Stage Change - Type 2

1	2	3	4	1	4	2	3	1	4	2	3
		4blocked time intervals									
Normal process				Stage change							

6.1.2 Offset Time Adaption

The beginning times of all green periods during the cycle can be varied by a defined value. This is especially mattering, when the green periods of the singular stages should be coordinated with the inlet of the neighbouring light-signal-controlled intersections.

The offset time adaption suits very good to consideration of changing traffic flow.

Table 6.4: Offset Time Adaption

Control methods		Traffic dependent changeable elements of signal programs				
Generic term	Main feature of changeability of signal programs	Cycle time	Stage sequence	Number of stages	Green period	Offset time
Signal program adaption	Offset-time adaption					X

6.1.3 Stage Request (Demand Stages)

At the stage request a stage gets inserted into a given stage sequences, only because of request to enable the walking/driving across the intersection of not always occurring traffic streams, due to their need. To hold the waiting for the requesting road user as short as possible, the stages should not be set into motion to a fixed time in the cycle, but up to a latest possible point of time (which makes coordination possible). It is good, when the stage can be available at more than one spot at the signal program. At the stage request of public transport, the logging-in should be as early as possible before reaching the stop line.

Because the request-point, dependent on the speed and the local facts, can lie up to 500 m before the stop line, at dense intersection- or station distances additional query-criteria are necessary. Because of combination of green period adaption with the stage request for public transport, a great extent of interference-free driving can be reached, although there are just section-wise public transport lanes. The easiest way of a stage request is a fixed location during the stage sequence. [FGSV, Bosserhoff]

Table 6.5: Stage request

Control methods		Traffic dependent changeable elements of signal programs				
Generic term	Main feature of changeability of signal programs	Cycle time	Stage sequence	Number of stages	Green period	Offset time
Signal program adaption	Stage request			X	X	

The advantage of stage requests is that needless time-losses through stage changes can be avoided, if a singular stage is not always necessary, because of very low load.

6.1.4 Green Period Adaption

The green period is adapted to the actual need of arriving vehicles, after passing the chosen minimal green period time or after reaching an earlier time of cycle. For the adaption of green periods there are methods which distinguish in criteria with which an on-going green period can be shortened for advantaging a different traffic stream/movement.

Criteria can be:

- Time intervals
- Occupancy grades
- Length of congestions
- Key figures of models, like waiting times or stops

The green period adaption is also called time-gap-control or green period stretching. It is an easy and effective way to match the signal control to the actual traffic conditions.

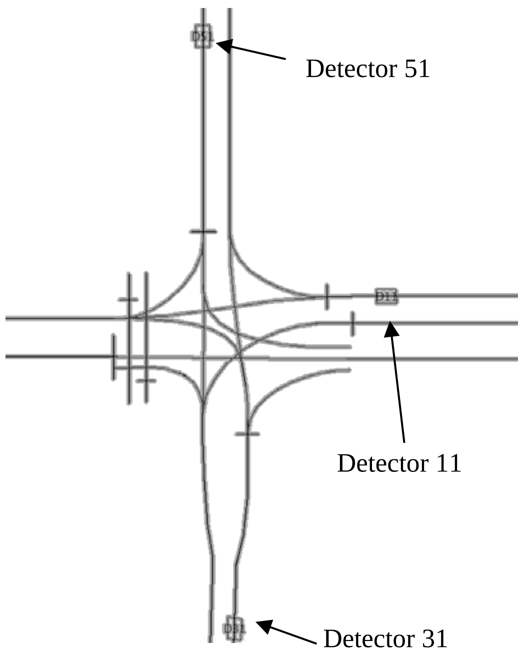


Figure 6.1: Detector-Placement

At the time gap control the net time gap [tTG] of two (one after the other following vehicles) at a signal access gets measured through the help of a detector. After a fixed minimum green period or after reaching a certain point of time the green period can be widened until maximum green is reached. [Bosserhoff, Schnabel]

Requirement for an extending green period is that the fixed period following gap is not exceeded. At normal conditions time-gap values of tTG = 2…3s are used. Just at high heavy traffic and at inclined roads values of more than 3s are appropriate.

Like the fixed time control also the green period adaption has concretely specified cycle time, number and order of stages, but the starting and ending times of green periods are variable.
The green period cannot be changed spontaneous, but just within certain boundaries. Characteristic signal program elements are the earliest and latest stage insertion point of a stage. With the insertion points the boundaries are fixed, within which the green periods can vary.

Table 6.6: Green Period Adaption

Control methods		Traffic dependent changeable elements of signal programs				
Generic term	**Main feature of changeability of signal programs**	**Cycle time**	**Stage sequence**	**Number of stages**	**Green period**	**Offset time**
Signal program adaption	Green period adaption				X	

The insertion point gives the beginning of an interstage between an ending stage and the following stage. The earliest stage insertion point is the point of time where the core green period is over (minimum green gets reached), and the latest insertion point where the stretching area is fully reached. Because of the clear interstage period also the earliest and latest start of the following stage (start of stretching area and start of core green period) is determined.

Since the stage insertion is possible (earliest stage insertion point reached) the control logic checks every second if the conditions for a break-off of the present stage are fulfilled. If the latest stage insertion point is reached, the stage-change is implemented.

[FGSV, Bosserhoff, U.S. Department of Transportation, Federal Highway Administration]

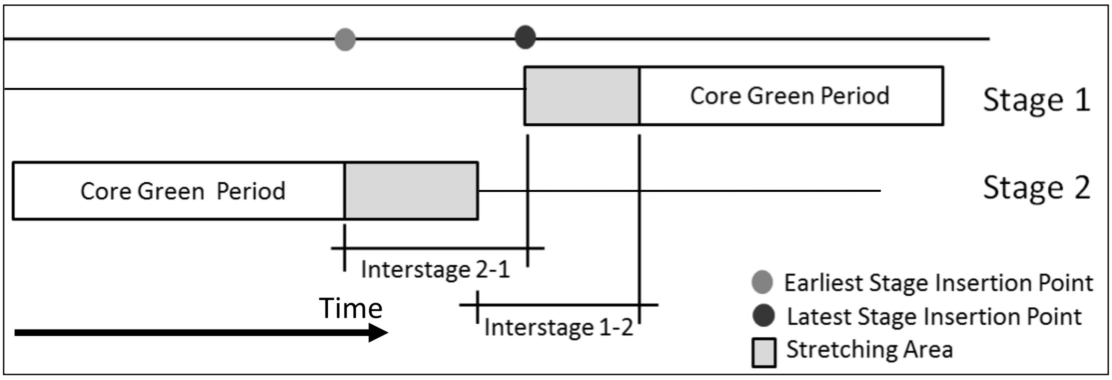


Figure 6.2: Stage Insertion Points at Green Period Adaption

For the stage break-off ahead of time (before latest stage insertion point is reached)

- The running stage cannot be loaded (no more vehicles exist)
- A second condition can be, that a request (demand) of the following stage exist

To check these conditions an appropriate detector position and suitable detector measurement parameters are necessary.

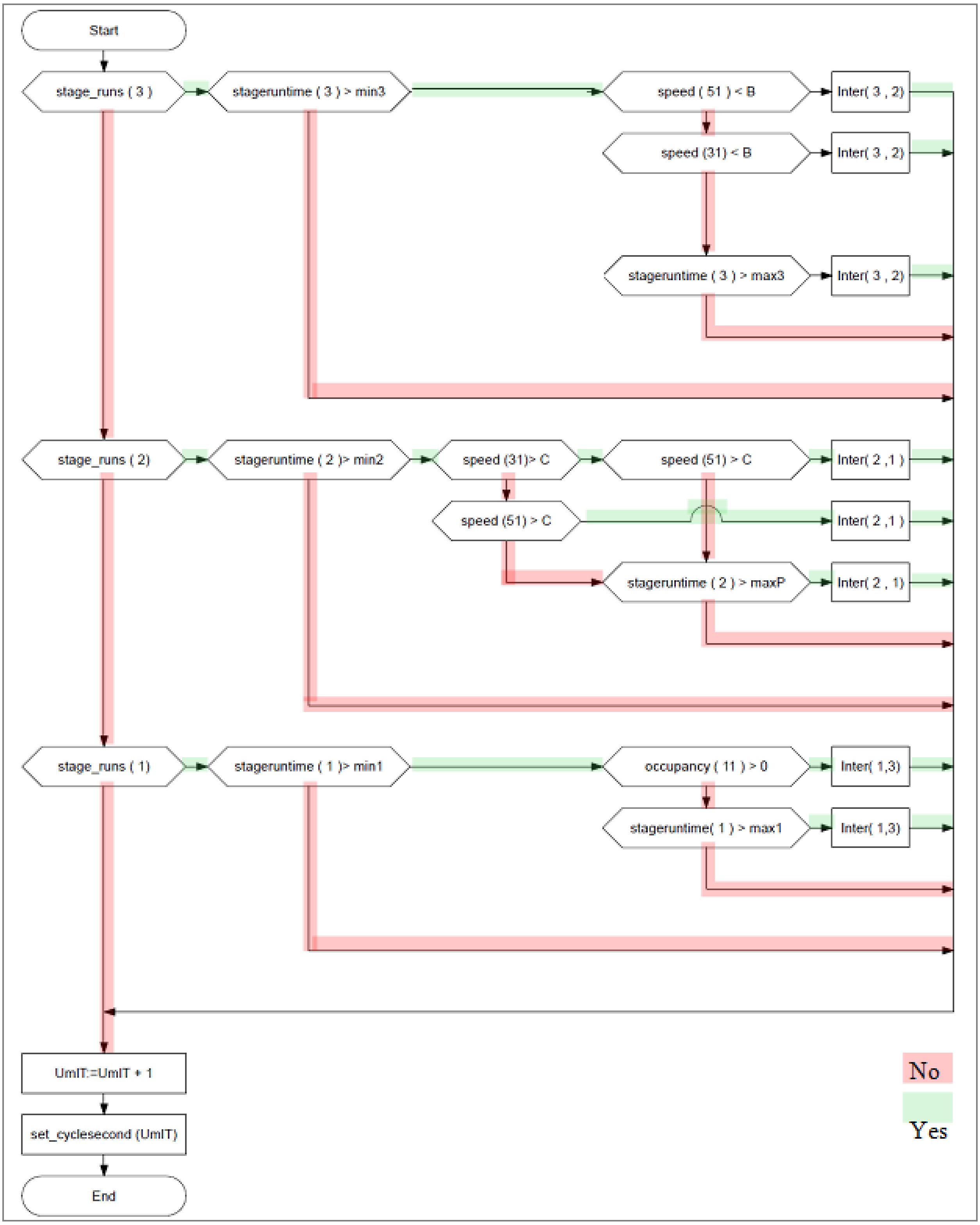


Figure 6.3: Partly Traffic dependent Control - Flow Chart

In reality normally occupancy detectors or time-gap detectors are used instead of speed detectors. The flow chart above shows just a fictional example, which should allow the understanding and function of the method of partly traffic dependent control.

6.2 Fully Traffic dependent Signal Control

All Methods for the signal program development are named after their basic state of signalling which is characteristic for the method. The basic state of signalling is that signalling, which is switched, if there is no request/demand of any vehicle or pedestrian signal groups. The most important signal program developments are:

- Principal direction permanent green
- All-Red/ immediately green
- Up-keeping of the last state of signalling

At methods of the signal program development all signal program elements are variable. The elements cycle time, green period duration, stage sequence and number of stages are dropped. The actual traffic conditions are decisive for which sequence and which duration of signalling is used.

Characteristic elements of the methods are the minimum and maximum green period (or blocked period) of all stages, maximum waiting times and the priority levels of the stages. All traffic streams which should have effect onto the signal program must be detected through a detector.

6.2.1 Control Logic

The requirements for the realisation of traffic dependent interferences into the signal program need to be fixed at the control logic. The control logic must include the logical conditions for the correlation of traffic dependent elements of a signal program, due to the used key figures of traffic flow as well as conditions for the temporal frame of the program processes. For at the same time appearing contrary desires of decisions, the priorities of interferences must be fixed. The definitions due to measurements because of disturbed detectors (replacement-functions like switching over to fixed time program), deleting of saved requirements and specialities at change and the turning on/off of signal programs must be made. Simple traffic dependent interferences can be clarified at the signal program (request of demand-stages). For a clear unmistakably standard of programming the device-software, in a lot of cases verbal descriptions of traffic technical concepts, boundary conditions and intended traffic dependent interferences are sufficient. If not, for the fixation of control logic, flow charts or a depiction at the decision matrix are recommended. It must be strived, to specify changeable values in form of parameter lists, to enable a flexible adaption of control logic via parameter-change. To avoid mistakes at the traffic technical requirements and at the realisation, a traffic technical check of the control logic should be made at a software-test station before starting the operation with signal programs on site. The testing of the traffic technical concept concerning compliance with the wanted effects onto traffic flow must be done on-site.

6.2.2 Actuated Signal Control

Actuated control uses information on current demands and operations, obtained from detectors within the intersection, to alter one or more aspects of the signal timing on a cycle-by-cycle basis. Timing of the signals is controlled by traffic demand. Actuated controllers may be programmed to accommodate:

- variable stage sequence
- variable green times for each stage
- variable cycle length caused by variable green times

Such variability allows the signal to allocate green time based on current demands and operations. A proper clearance interval between the green and red stages is also ensured. Advantages are a reduced delay, adaptable to short-term fluctuations in traffic flow, increase in capacity, providing continuous operation under low volume conditions, effective at multiple stage intersection.

The main disadvantages are that if traffic demand pattern is very regular, the extra benefit of adding local actuation is minimal (to non-existent) and the installation cost is two to three times the cost of a pre-timed signal installation. [FSV, FGSV, Bosserhoff]

Moreover actuated controllers are much more complicated than pre-timed controllers, increasing maintenance costs and actuated signals require careful inspection and maintenance to ensure proper operation.

The following control methods are common for the traffic dependent (actuated) signal control.

For the green period adaption the following methods can be used:

- Time gap control (breakup of green period because of the appearing of a bigger time gap)
- Calculation of green periods because of occupancy-degree metering
- Green period adaption by the use of congestion detection

The traffic dependent adaption of signal program concerning the stage sequence can be realised with two basically control systems:

- Selection of a certain stage sequence from prepared signal program structures with alternative stage sequences (request of demand stages, stage-change)
- Signal program establishment through combination of traffic dependent elements of a signal program with development of permissive stage sequences and stage-compositions

At traffic dependent controls the following control-values can be directly detected: Logging on/off of vehicles, Logging on of pedestrians and bicyclists, Time gap, Traffic volume, Speed

Due to appropriate preparation other key figures can be gained:

- Occupancy degree (ratio of the sum of dwelling time of vehicles at the facial area of a detector during a time interval – to length of that time interval)
- Traffic density (number of vehicles per path unit at a point of time)
- Load quotient (ratio of the sum of vehicles, which are waiting at the beginning of time interval at a flow-off cross section or are arriving during these time intervals – to number of vehicles which can pass the flow-off cross section at the same time interval)
- Priority criteria of public transport [FSV]

All changeable elements of the signal program are determined in a traffic dependent way, based on actual measuring values. The method suits for light signal plants at intersections, which do not lie within coordination. Priorities of traffic operation can be considered through the signal program development.

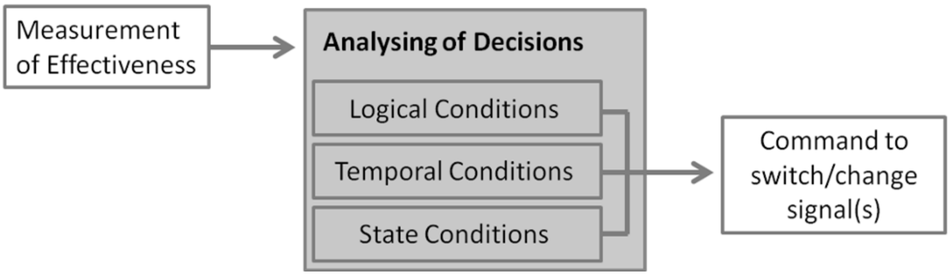


Figure 6.4: Actuated Signal Control

- The interim periods and if needed the offset times
- The minimum and maximum duration of green period
- Rules, after which the signal group is switched … must be predetermined.

In addition,

- The stage interims for all stage sequences,
- The maximum number of stages,
- The maximum red/blocked period after request,
- The best possible stage sequences for different requirements

can be predetermined.

The changeable elements of signal program can be different at different daytimes. The requirements must consider especially the priorities of traffic operation and the available lengths of congestions. [FGSV]

Actuated Signal Program Choice

For the registration of the actual traffic key figures, measurement sections are set at the road network. They need to fulfil the following requirements:

- Not lying at areas with frequently lane change
- For registration of traffic volume they must lie in an area of free flowing traffic
- Measurement sections for getting the level of occupancy should lie at congestion-danger areas, but out of the space where vehicles must stop during normal drive.

The following points need to be considered:

- For excluding coincident at the recognition of situations, more measurement sections or more condition equations should be considered for deciding, therefore key figures can be linked.
- A delay is implemented into the decision, to avoid a too often signal program switching (condition of time, trend-counter). The trend counter only allows a signal program change, if the same change-wish was confirmed n-times.

Semi-actuated, fully-actuated and Volume-Density Control

These are the basic types of actuated control, each using signal controllers that are somewhat different in their design. [U.S. Department of Transportation]

<u>Semi-actuated Control</u>

It is used at intersections where a major street has relatively uniform flow. This street is crossed by a minor street with low traffic load. Detectors are placed only on the minor street. The green is on the major street at all times unless a demand of the side street is detected. The number and duration of side-street green is limited by the signal timing.

<u>Full-actuated Control</u>

It is used at intersections of streets or roads with relatively equal volumes but varying traffic distribution. In full actuated operation, every lane (of approaches) is monitored by a detector. The stage sequence, green allocations and cycle length are all subject to variation. This control-method is effective at two-stage but also at multistage operations.

<u>Volume-Density Control</u>

It is basically the same as full actuated control with additional demand-responsive features. It is designed for intersections of major traffic flows having considerable unpredictable fluctuations.

This means that at a signal program only a total stage, including all signal groups can be cancelled or started, if all conditions are fulfilled. If Stage 1 is shown by the signals and gets cancelled because of request of one at the moment blocked stream of a signal group, all signal groups of stage 1 must be checked if the conditions for stage change are fulfilled. After checking the stage can be changed.

Between the stages always the interstage takes place. The interstages must be always fulfilled. Because of the chosen 8 seconds minimum Green the interstage consists at least of 3 seconds interstage amber, 1 second red (in Germany needed minimum red) and 1 second red/amber (in Austria and UK it would be 2 seconds red/amber). Because between stage 2 and stage 1 (interstage 1-2) the signal groups cannot start after 5 seconds (8+3+1+1 = 13) because the intergreen matrix requirement needs a longer interstage , the interstage lasts longer. [FSV]

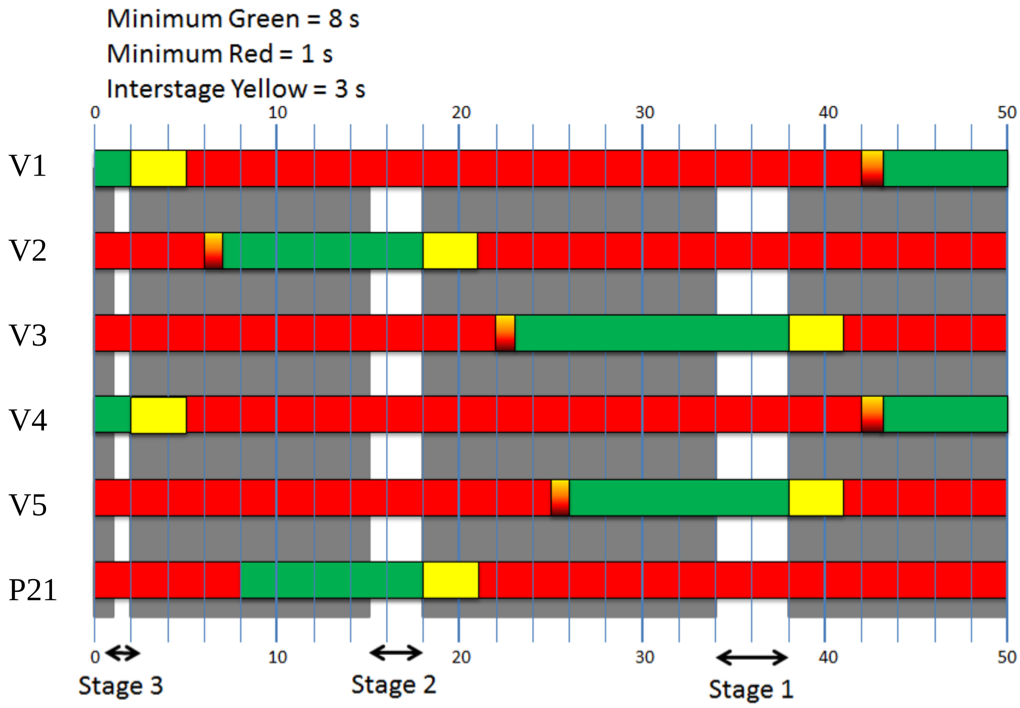


Figure 6.5: Stage based actuated Signal Control

6.2.2.1 Signal Group based actuated Control

At the signal group based actuated control only the declaration into compatible and not compatible (conflicting) signal groups is needed. The signal program procedure is not bound to stages. [FSV]

- All combinations of compatible movements are allowed
- The green period end of a signal group is not linked with another signal group.
- The green period start of a requested signal group depends to the break-off conditions (minimum green, threshold values of time gaps…) of unblocked conflicting signal groups and if requests of blocked signal groups with higher priority exist

A signal group based actuated control is much more flexible than a stage based control. At a signal group based control it is not possible to work with stages and interstages, because the priority levels, content of singular stages at other stages,… would bring problems concerning a useful signal program process.
At signal group based controls the following points must be checked:

For unblocked signal groups:

- Is the minimum green already over?
- What load factor exists?
- Is a conflicting signal group requesting?
- Was the maximum green reached?
- Was the maximum blocked time of a requesting conflicting signal group reached?

For blocked signal groups:

- Does a request exist?
- Unblocking of conflicting signal groups
- Breakup conditions for the unblocked signal groups
- If more than one signal group requests – who has the higher priority level?
- Intergreen times – for all conflicting signal groups

[U.S. Department of Transportation, Federal Highway Administration, Wilson]

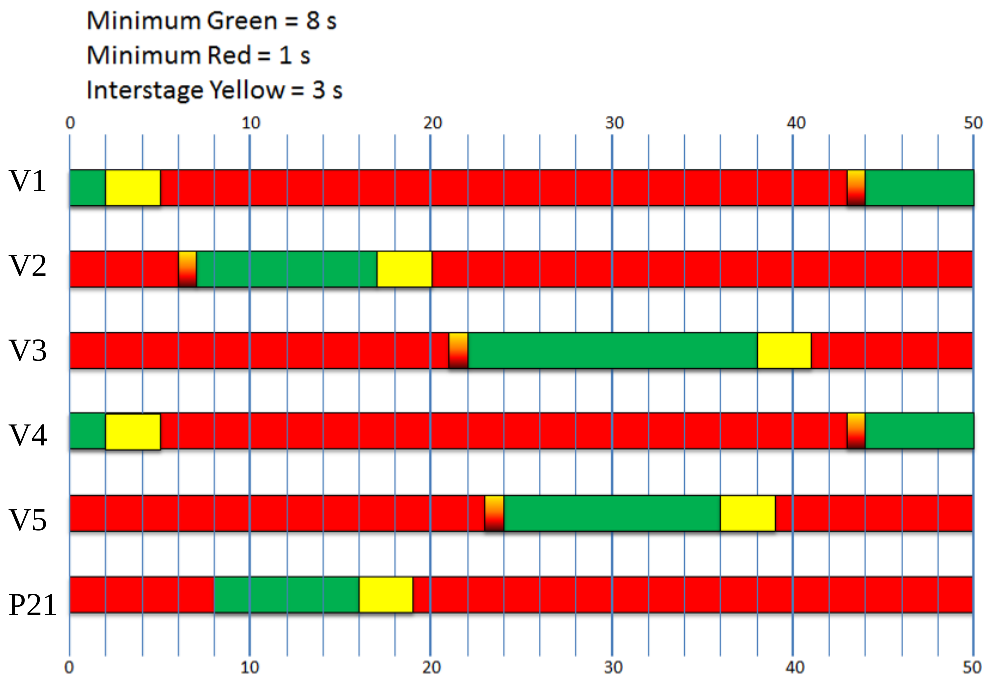


Figure 6.6: Signal Group based actuated Signal Control

Example for actuated Signal Control for Prioritising Buses

As example a simple bus priority with additional green period adaption for not public transport vehicles is explained. The used stages are the same as at the fixed time signal control. They are given at the figure below.

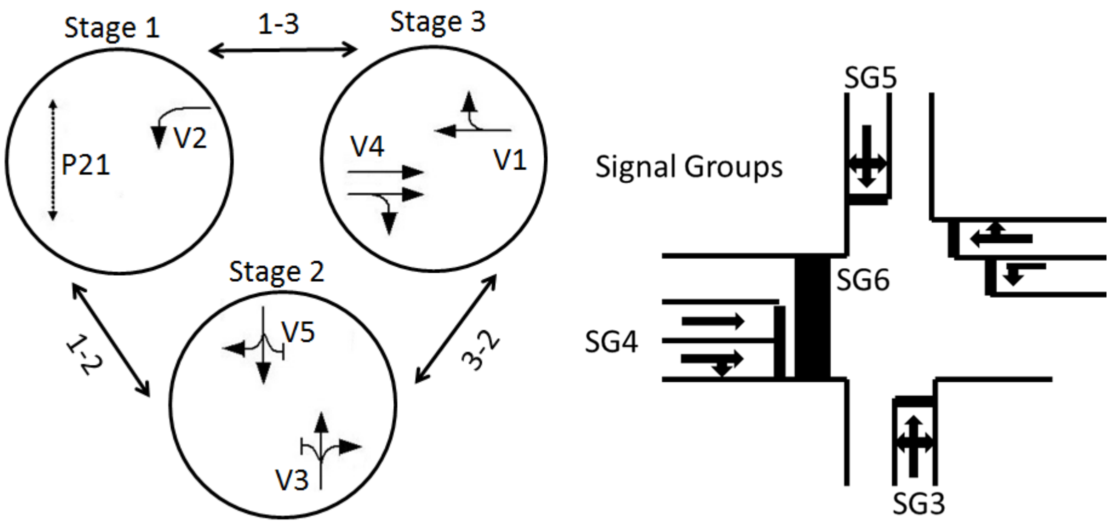


Figure 6.7: Used Stages and Signal Groups for Bus Priority (Example)

For an actuated signal control detectors are needed. Therefore four detectors are situated. Three vehicle detectors for partly traffic dependent green period adaption and two bus detectors for prioritising buses are installed. The line-buses move in East-West or West-East direction. Their regular interval was chosen in a 300 second (5 minutes) desistance. The buses from East and from West do not arrive at the same time at the station.

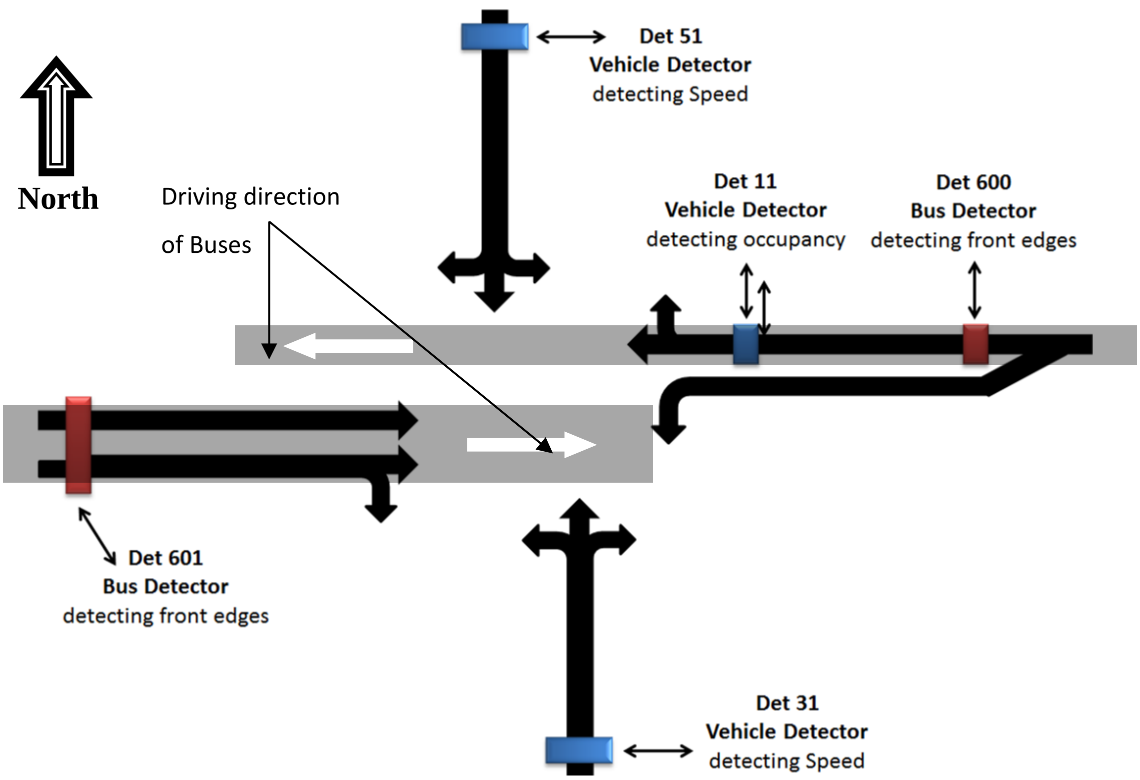
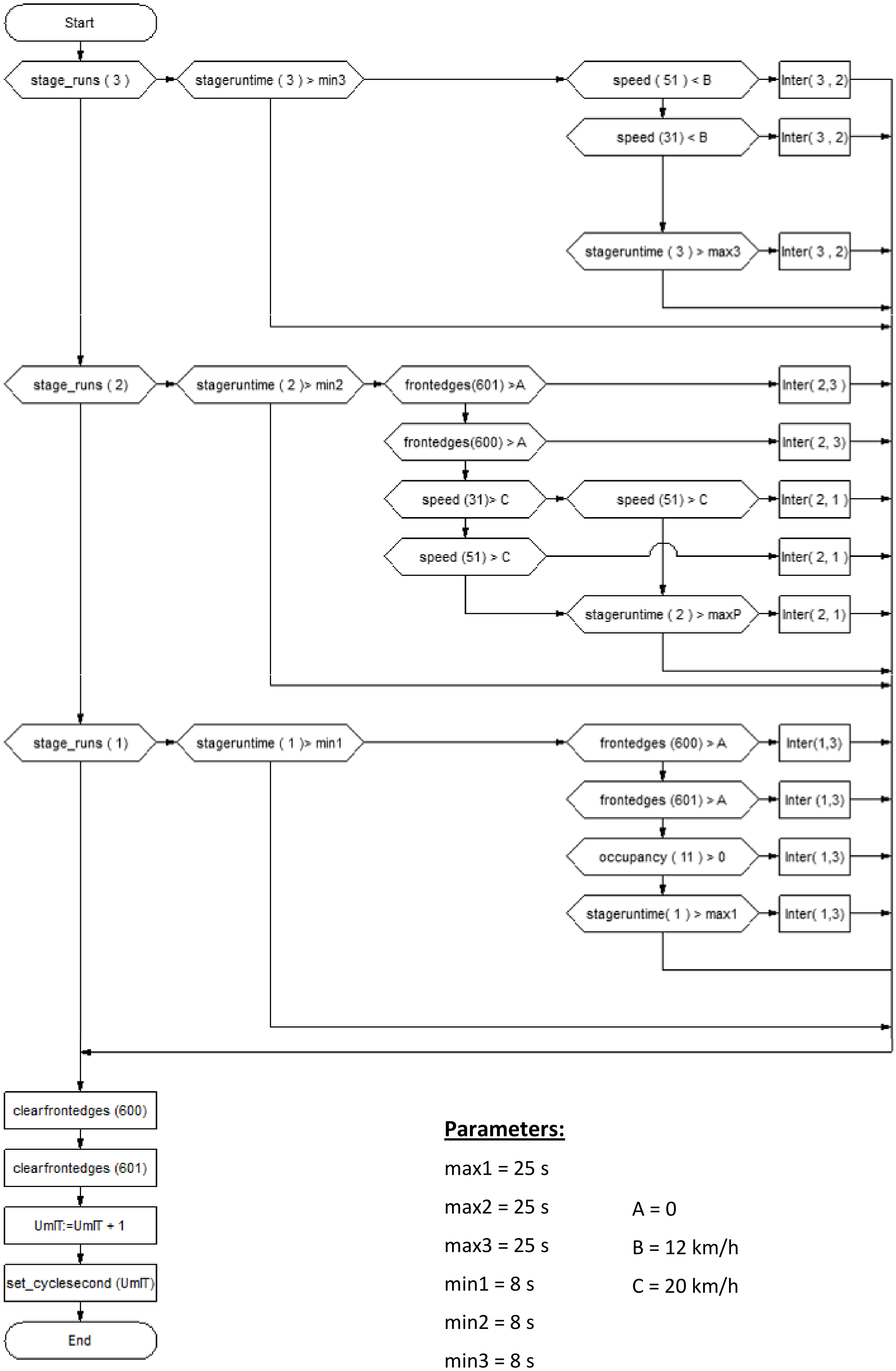


Figure 6.8: Detector placement for Bus Priority (Example)



Parameters:

max1 = 25 s

max2 = 25 s

max3 = 25 s

min1 = 8 s

min2 = 8 s

min3 = 8 s

A = 0

B = 12 km/h

C = 20 km/h

Figure 6.9: Flow Chart for Bus Priority (Example)

For the actuated signal control a flow chart was created. With the mentioned detectors the following logic can be realised.

If stage 3 is running it can only be switched to another stage, if the minimum stage runtime is reached. At this example a breakup of the stage 3 (after achievement of minimum runtime) is conducted, if the speed of the north-access (detector 51) or the south-access (detector 31) is lower than 12 km/h (normally time-gap detectors are used). Then there is a transition from stage 3 to stage 2. This is done because if the speed at the detector location is that low, a congestion is quite likely. If the speed at the north- and south-access stays higher than 12 km/h, the stage gets changed by reaching the maximum runtime.

If stage 2 is running it can also only be switched to another stage, if the minimum stage runtime is reached. Because the buses get green during stage 3 the front edges are counted by the detectors 600 and 601. If more than 0 front edges are counted, the transition from stage 2 to stage 3 is implemented, if not it is checked if speeds at north- and south-access are both already higher than 20 km/h, the stage 2 can have a breakup. If no bus was requesting and the speed is higher than 20 km/h (detector 31 and 51) and the minimum stage runtime was reached, the transition from stage 2 to stage 1 takes place. If there is no detector fulfilling a rule for breakup the stage transition is implemented when reaching the maximum stage runtime.

For stage 1 the breakup conditions are a reached minimum stage runtime plus a) a detected bus front edge (detector 600 or 601) or b) a speed level higher than 20 km/h (detector 31 or 51). The second possibility for a transition is the reached maximum stage runtime.

The flow chart is read every second so at the end of the flow chart cycle for having a timeline the cycle time is raised by one second. To delete the number of front edges the front edges of every detector (600 and 601) must be cleared every second. After reaching the end, the flow chart starts from the beginning.

The following shows a signal timing plan. All detectors are given in blue. The signal groups (SG) are the lines with the amber and green beams and red line and the stages are given with green, and hollow green beams and red lines.

As given at the picture before (“Detector Placement”) the detector 600 and 601 show arriving buses, if the bus reaches the detector at the stage 2 a changed interstage will follow, if the bus reaches the detector at stage 1 just a shorter green period of that stage can be implemented (green period of stage 1 in the figure mostly already the minimum runtime).Also the green period adaption is shown in the figure above. Mostly the green period adaption takes place for stage 2. Through the green period adaption and the changeable stage sequence here a simple traffic dependent control with low bus waiting times can be realised. In practice more precise adapted control systems are appointed. This example just shows one really easy option of implementing.

At second 35 a bus triggers the detector, because stage 2 was running a changed interstage 2-3 is implemented. The normal stage sequence is 3 – 2 – 1. At the second 460 stage 2 is shorter than i.e. the following stage 2, because the detector 31 and 51 are not requesting a demand that means for the example, that speed level is higher than 20 km/h so the interstage 2-1 follows at second 483.
The normal stage sequence changes if a bus is arriving while stage 2 is operated. Then the normal stage sequence 3 – 2 – 1 changes to 3 – 2 – 3. If there are a lot of buses (this example in average every 2,5 minutes) it must be guaranteed that after a 3 – 2 – 3 stage sequence the normal stage sequence is implemented, because if there would be 3 – 2 – 3 – 2 – 3 … the waiting time of vehicles using the stage 1 can get infinitely high.

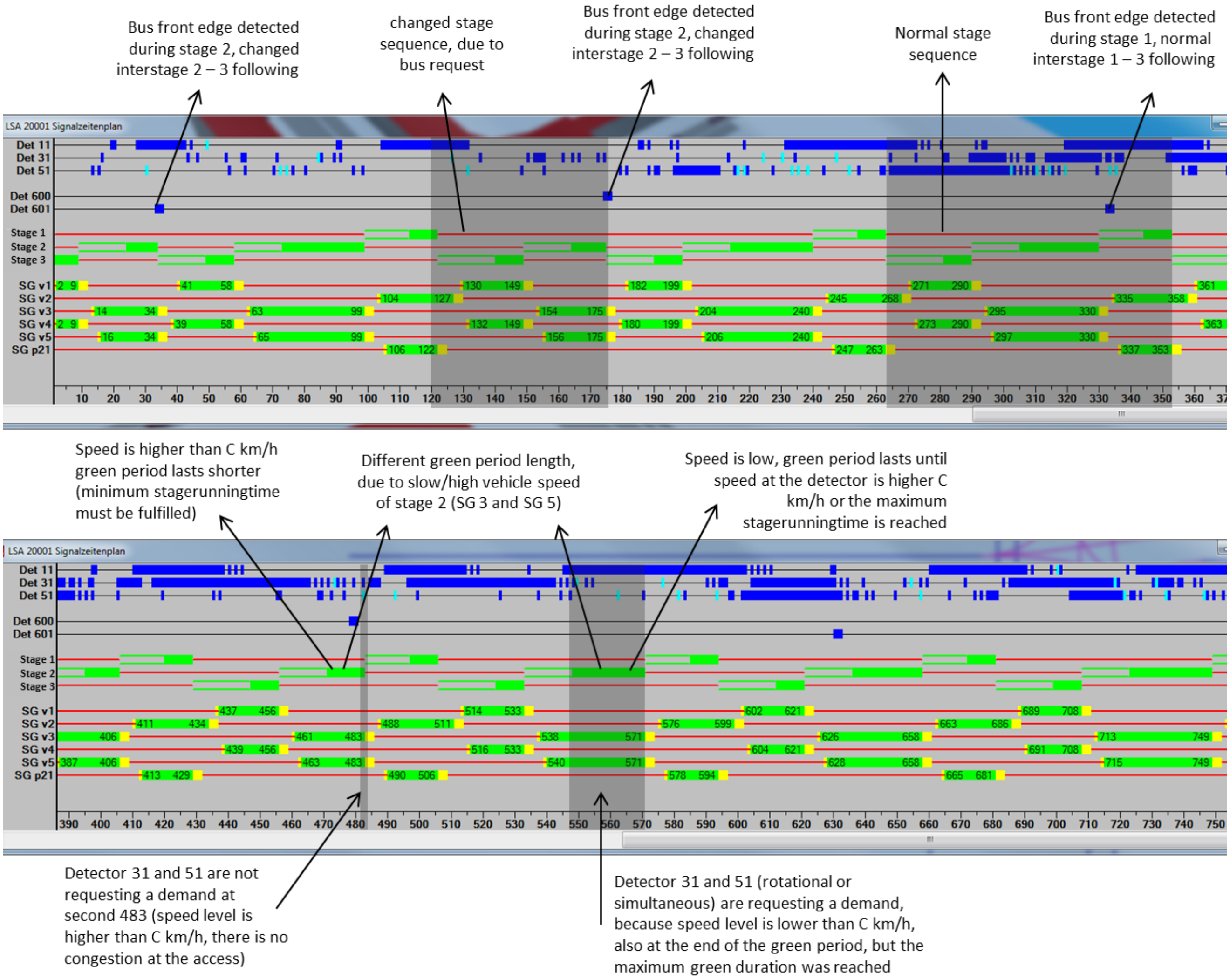


Figure 6.10: Signal Timing Plan - Bus Priority (Example)

6.2.3 Further Development of Signal Control Systems

At the traffic dependent control basically methods with free programmable logic and standardised methods can be differed. Mixed versions are also possible.

The whole process of establishing a traffic technical document, up to saving data at the control facility is nowadays done IT-based and very often in an automatic way. To guarantee an effective and faultless control complete logics and parameters are necessary. The operation of logic and their parameters differ due to their method of control.

The data and parameter transfer should be done by standardised interfaces. The process should be completely and clear documented, to make easy understanding of the control possible. The exact realisation of traffic technical requirements to the program language of the certain control unit must be considered.

At standardised methods the control algorithms are determined. For control systems there is a differentiation between metre value based control systems (rule based) and model based control systems.

They can also be called metered value based controls. Here the control decisions are made step by step. The choice of the available traffic key figures must be well considered to make right decisions. This control system reacts to short-term stochastic fluctuations. Possibilities are green period adaptions, stage changes, demand-adaptions and signal program developments.

At the beginning the logical conditions are scanned. If these conditions are true, the related temporal conditions are checked. If additional a suitable condition exists, an action in form of a switching-order follows. Comparison values and threshold values like time gaps, occupancy degree and driving time as well as frame requirements as green period allowance time, delayed green period start or priority of a control are defined per parameters. Especially at high traffic load this method comes to its limit, the signalisation approaches to a fixed time control.

There are decision-elements for a conditional query. The process is defining values for the variables at the picture in the right. Also predefined functions are needed for the rule based system. Parameter values can be:

- Values of detectors (presence, occupancy)
- Public transport vehicle detection
- Check values for
    - Minimum and maximum Green or Reed
    - Stage sequence
    - Priority-values of signal groups or stages
    - Parameter amounts can vary dependent to the signal program, signal programs get set up due to daytime

Normally programs should be well structured; therefore subprograms and modules can be used.

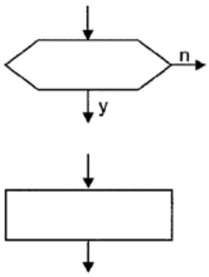


Figure 6.11: Rules for the Rule based Control System

[Fellendorf, FGSV, FSV]

Most intersections in the Netherlands use this method of actuated control. The standard CCOL is a library of methods in the programming language C that creates traffic light control programs. Multiple generators for these programs exist that allow a user to just select options and specify conditions for the intersection and using that input the generator creates the code. An example generator can be found at [Traffick]. The resulting traffic control program is in between stage based and signal group based. Stages are called “blocks” and allow alternative signal groups to become green when one or more primary signal groups have no demand anymore. The basic mechanism for switching between the blocks is when all signal groups have had a gap in the flow larger than a specified amount of time. Extensions for public transport priority, couplings between intersections for coordination, green light extension for HGV’s and many other features are part of the toolkit.

6.2.3.1 Model based Control System

Here the control decision is made as a whole, by bringing all available traffic key values to a traffic model. Decisions are made by optimising the target values, based at the quality criteria of traffic flow. The criteria cannot be detected directly; traffic models are used for calculation. This method is overall used for network control. Parameters like waiting time or number of stops are used for calibration of the model and for describing the topographic given conditions as well as weighting the target values. A technical realisation of traffic political targets through weighting and resistors of the target function are possible relatively hassle-free.

There are three elements which are used…

- the traffic model,
- the control-model and
- the effectiveness-model

[Fellendorf, FGSV, FSV]

Public Transport Prioritising with early Detection

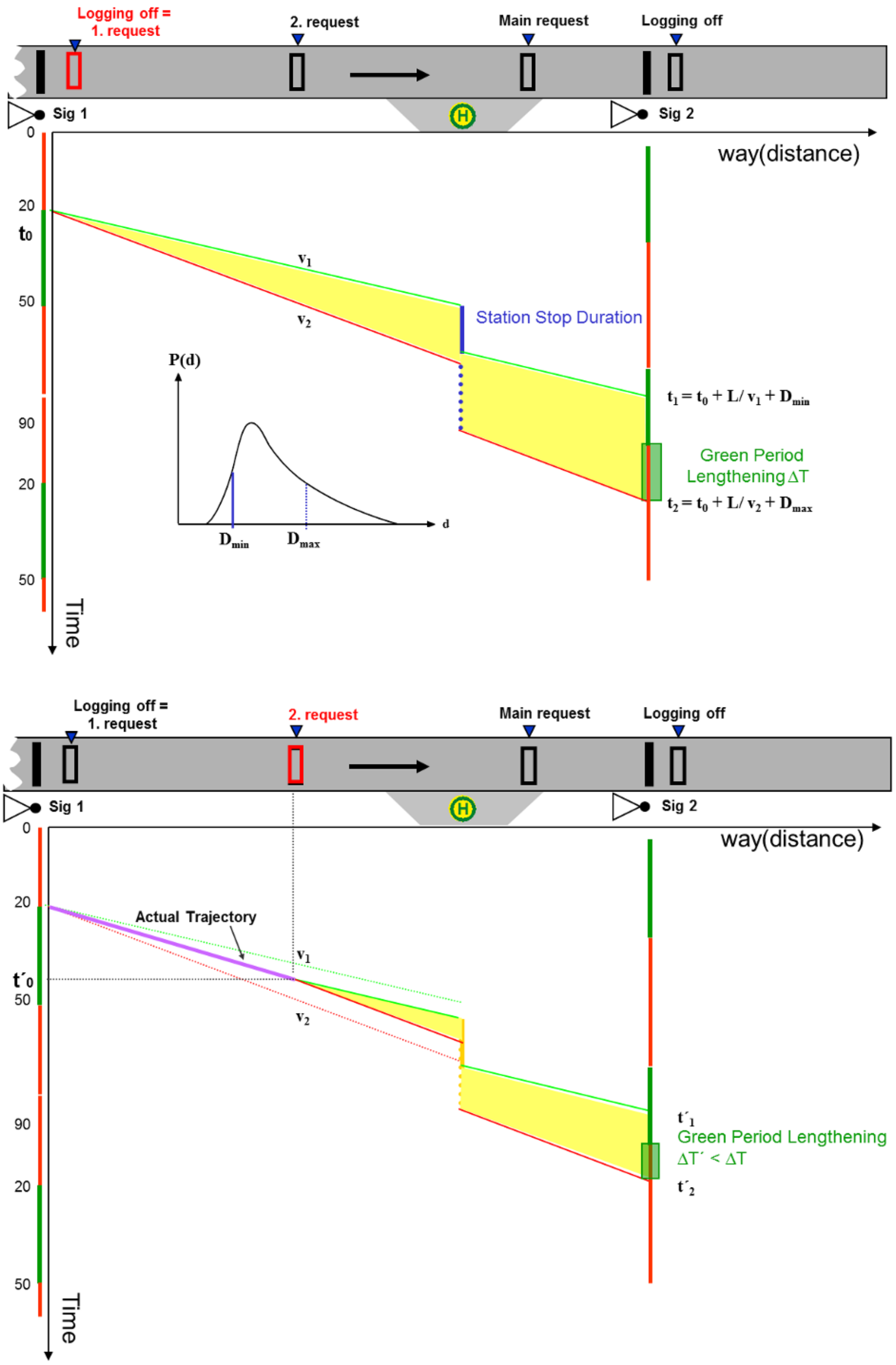


Figure 6.12: Public Transport Priority

[Fellendorf]

7 Adaptive Signal Control

Adaptive or model based control systems are used for singular intersections, arterials and parts of networks. Requirement for adaptive signal controls is an exact knowledge of the actual traffic conditions which can only be won through various detectors. Adaptive Signal Control Technologies normally use real-time traffic information to reduce congestion by determining which lights should be red and which should be green at a certain point of time. Through detectors/sensors which monitor traffic and software and compares the data with the baseline timing plan the timing gets changed if necessary. This progress always repeats and reacts onto different traffic conditions.

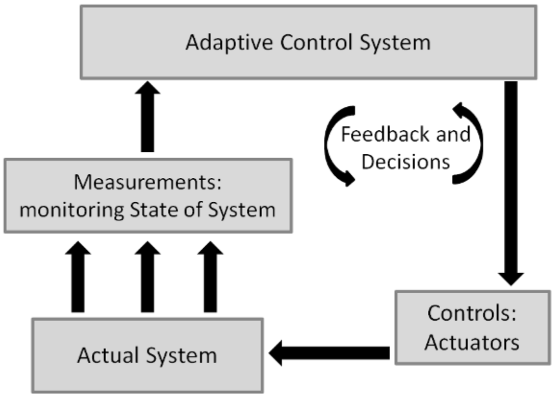


Figure 7.1: Adaptive Signal Control

Adaptive Traffic Control Systems (ATCS) adjust, in real time, signal timings based on the current traffic conditions, demand, and system capacity. The system requires extensive surveillance, historically in the form of pavement loop detectors, and infrastructure that allows communication with the central and/or local controllers. There are a lot (25+) of ATCS deployments. Such systems are considered expensive and complex and require high maintenance of detectors and communications. Generally the ATCS systems are well accepted. At a survey from the Transportation Research Board of the national Academics 73% of the ATCS users would install the same system again. [Stevanovic]

The figure below shows different signal control systems. Adaptive signal control works in such small intervals, that there is an adaption all time long. Periodic retiming works after some time and points out the best possibility of program control at a certain point of time. Until the next adaption takes place, the system works with a certain consistent state. The benefits of adaptive signal control are the highest because the delay is the smallest and there are fewer stops a better travel time reliability as well as less fuel consumption. If the different systems are compared with each other there are differences in travel time, delays and stops.

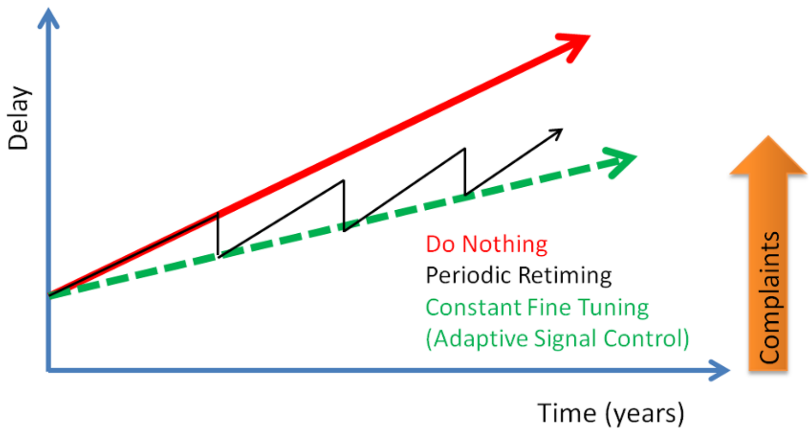


Figure 7.2: Signal Timing and Delay

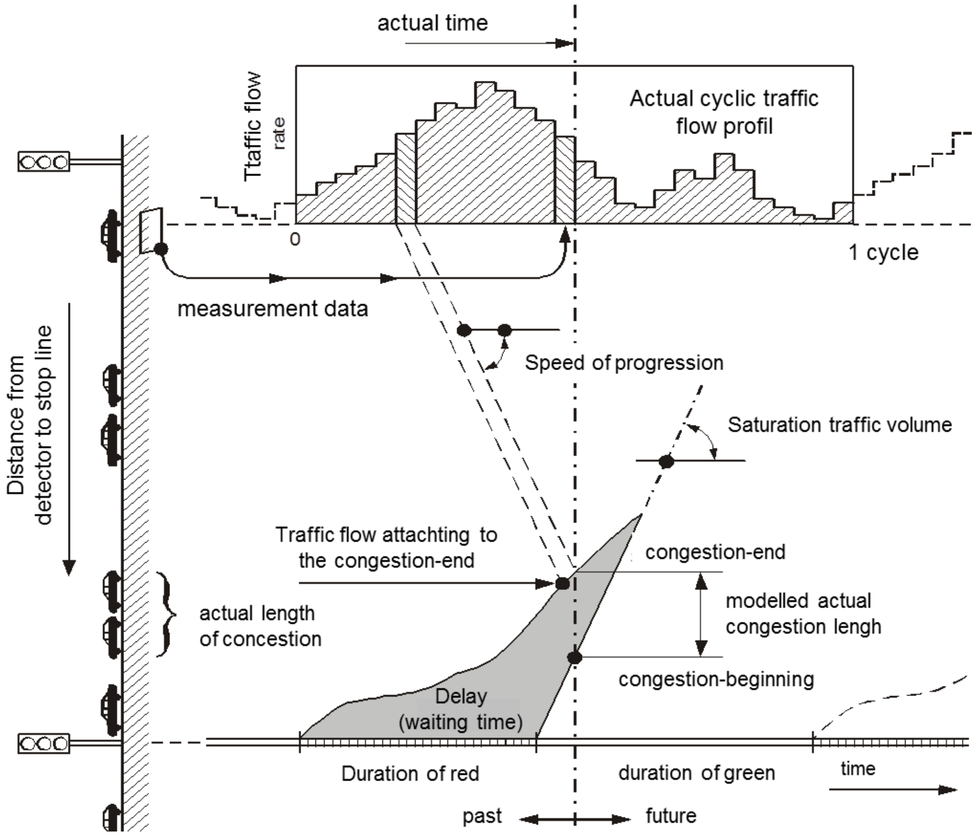


Figure 7.3: Traffic adaptive Control Systems

7.1 Basics

The development of the first really successfully used ATCS systems SCATS and SCOOT was followed by a series of other new ATCSs. Some of these new systems abandoned conventional signal timing structures constrained by cycle lengths and offsets. OPAC and PRODYN established. Soon thereafter UTOPIA was combined with SPOT to account to changes at the network level. Most of these developments were taking place in Europe in the United States a research project called RT-TRACS was developed. It was successfully tested and implemented. More or less RT-TRACS was a modified version of OPAC and RHODES. Although there were significant benefits shown while testing OPAC and RHODES, these two systems were not widely accepted in the United States (maybe because of the complexity of their logics, extensive detection requirements, hardware upgrades and the need to acquire new knowledge). Because of that the FHWA launched the development of another ATCS whose major role was to be more simplistic, user-friendly, compatible with existing infrastructure and overall less expensive to operate and maintain. ACS Lite had been developed. [Stevanovic]

Europe struggled for a long time to keep up with the development in the UK, USA and Austria. French systems, such as CRONOS and PRODYN which were early ATCS leaders in continental Europe were not widely deployed in France or elsewhere.

UTOPIA/SPOT appeared to work well in the networks of Italian cities for many public transit operations. Development and application of German ATCSs, where SITRAFFIC MOTION and BALANCE represent the most notable systems suffered from their more extensive deployments, but benefits were recognized. Two major characteristics make German ATCSs distinctive. They attempt to address optimisation of traffic signals based on network-wide changes in traffic demand by taking into consideration the estimated origin-destination flows in the network and their logics are adjusted to work with German industry standards for local traffic controllers and public transit priority. [Stevanovic]

Table 7.1: Benefits per adaptive System

System	Benefits (percentage change in)		
	Travel Time	Delays	Stops
ACS Lite	-28 to + 7%	-38% to +2%	-35% to – 28%
OPAC	-26% to + 10%	-	-55% to 0%
RHODES	-7% to +4%	-19% to – 2%	-
SCATS	-20% to 0%	-19% to + 3%	-24% to +55%
SCOOT	-29% to -5%	-28% to -2%	-32% to -17%
Reference: http://www.nc-ite.org/images/files/Adaptive%20Signal%20Control%20Technology%20Overview%20Presentation.pdf			

Generally ATCSs have been used since the early 1980s.

The main reasons for implementing an ATCS are given in the figure below. The figure is made from a survey where 45 agencies were included (34 of North America and 11 agencies from other countries). Some of the reasons may indicate that sometimes decisions are made at higher political levels (availability of funding or an interest in being an early deployer of a new technology). If these ATCS deployments are made they also can have negative consequences. [Stevanovic]

The benefits of adaptive signal control techniques are:

- Improving arterial performance by maintaining the effectiveness of traffic signal timing
- Solving problems for operators
  - Reducing complaints
  - Address variability & unpredictability in demand
- Providing values
  - Retiming costs
  - Reduces emissions
  - Safety
- Delivering better service to road users
  - Less congestion
  - Higher travel time reliability
  - Less fuel consumption

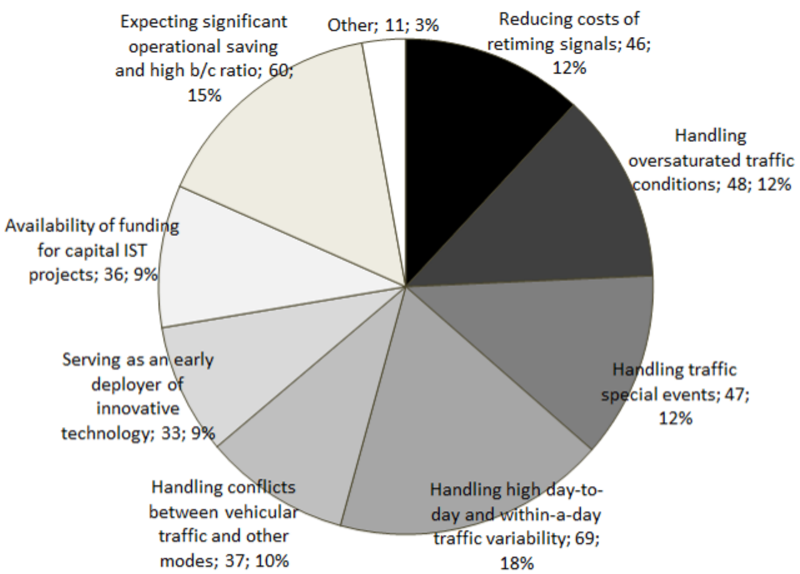


Figure 7.4: ATCS major reasons for implementing

Because there are more than 20 different ATCS, all developed during the last 30 years, just a few of them will be explained, because just a dozen of them have been applied in the real world and have more than one field implementation. [Stevanovic]

At the following pages we focus on just these systems which are implemented in the field. More detailed information will be given about 9 different systems:

- **ACS Lite**
  - FHWA/Siemens ITS
- **BALANCE**
  - University of Hanover, Germany/Gevas Software, Germany
- **lnSync**
  - Rhythm Engineering
- **MOTION**
  - Technical University Munich, Germany/Siemens, Germany
- **OPAC**
  - University of Massachusetts, Lowell/PB Farradyne
- **RHODES**
  - University of Arizona, Tucson/Siemens ITS
- **SCATS**
  - Road Transit Authority, Sydney, NSW, Australia/TransCore
- **SCOOT**
  - Transport Research Laboratory, UK/Siemens UK
- **UTOPIA/Imflow**
  - MIZAR Automazione, Italy/McCain

SCOOTS and SCATS can be seen as market leader, because they have the highest market share of various ATCSs. SCOOTS and SCATS are most dominant although they were developed almost 30 years ago. SCOOTS and SCATS are also dominant among larger ATCS deployments (with 50 or more intersections under an ATCS). The major reason for the popularity of SCOOT and SCATS may be found in the ripeness of these systems and because they are strongly supported from their developers and consultants [Stevanovic].

Table 7.2: ATCS Initial Capital Costs

SYSTEM	ACS-Lite	RHODES	SCATS	SCOOT	OPAC
Initial Capital Cost (per intersection)	\$ 8,000 to \$ 12,000	\$30,000 to \$50,000	\$ 25,000 to \$ 30,000	\$ 30,000 to \$ 50,000	\$ 20,000 to \$ 50,000

[Otto]

Within the survey of the Transportation Research Board they analysed the satisfaction of the participating agencies. 80% of the ATCS users are satisfied with their ATCS. About 11 % are neutral and just 9% are dissatisfied, with another 2% not satisfied at all.

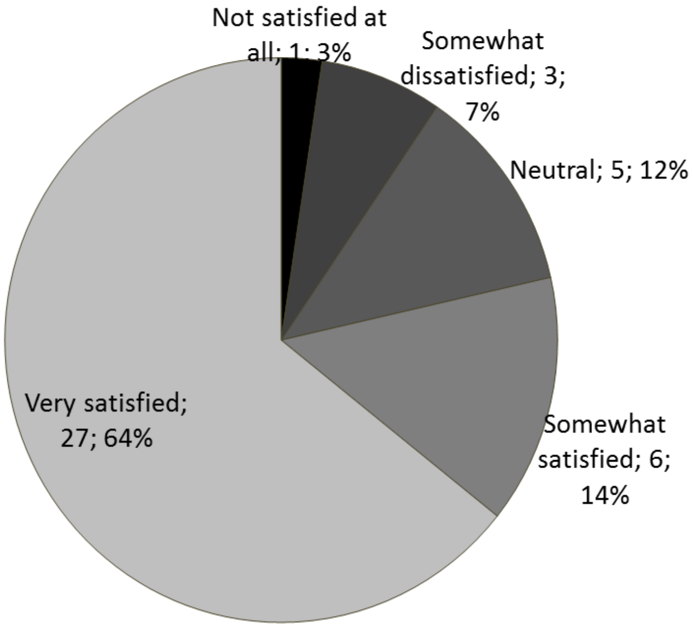


Figure 7.5: ATCS Satisfaction of the users with their system

Working Principles of major ATCS

The different systems use different detection, types of action, adjustment methods, time frames for implementing new signal timings, hierarchical levels, estimation, support, signal timings…

The following table lists the differences between different ATCSs.

ATCS	ACS Lite	BALANCE	InSync	LA ATCS	MOTION	OPAC	RHODES	SCATS	SCOOT	UTOPIA
Detection	SL, MB/ US	NSL	NSL	SL & US	NSL	MB & SL	MB & SL	SL, NSL, MB	US & SL	US & SL
Action	P & R	P & R	P & R	P & R	P & R	P	P	R	P & R	P
Adjustment	DCO	TCO	DCO	RA, TCO, DCO	TCO	TCO	TCO	RA	DCO	TCO
Time Frame	5–10 min	5 min	Phase/ Cycle/ 15 min	Cycle	5–15 min	Phase/ Cycle/ 5 min	Sec by sec	Cycle	Cycle/ 5 min	3 sec — Cycle
Level	C/L	C/L	C/L	C/L	C/L	C/L	C/L	C/L	C/L	C/L
Model	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
Timings	S, O	S, Cl, O, PS	S, Cl, O, PS	S, Cl, O	S, Cl, O, PS	S, Cl, O	S	S, Cl, O	S, Cl, O, PS	S, PS
Flexi Region	No	No	Yes	Yes	No	No	No	Yes	Yes	Yes
Vehicle Actuated	Yes	Yes	No	Yes	Yes	No	No	Yes	Yes	Yes
TSP	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Detection: SL = stop-line; NSL = near-stop-line; MB = mid-block; US = upstream.
Action: P = proactive; R = reactive.
Adjustment: RA = rule-based adjustment; DCO = domain-constrained optimization; TCO = time-constrained optimization.
Level: L = local; C = central.
Timings: S = splits; Cl = cycle length; O = offset; PS = phase sequencing.

[Stevanovic]

Figure 7.6: ATCS Operational Categorisation

System	Controller	Software	Communications
ACS Lite	Siemens NEMA (M50 series) or 2070 (2002 TEES or later) with SEPAC NTCIP 4.01F firmware. Also run with Econolite ASC/2 with NTCIP firmware w/ACS lite support. Peek 3000E with external NTCIP translator. McCain 170E with BI-TRAN 233 firmware with ACS Lite support.	ACS Lite software running on field-hardened PC or central server (Windows XP).	Comm: Serial or Ethernet. Serial is single channel, where 9600 baud supports up to 8 signals. Faster serial can support more signals.
BALANCE	European controllers	GEVAS VTnet/View	ISDN dial-up line 2400 bps-modem wireless
InSync	Existing Controllers Cabinets require InSync processor to communicate with controller using detector cards	Internet access to InSync System through a local computer InSync System	Ethernet communication
LA ATCS	Model 170 Controllers/ 172.3 Firmware Type 2070 Controllers/ City of LA Software	PC ATCS/Traf Graph Editor	Dedicated central to field connection 1200 bps using time division multiplexing 4 intersections/communication channel No Peer-to-Peer communication needed Supports multiple communication media
MOTION	SITRAFFIC C8xx,C9xx Controllers Signalbau Huber Actros Controllers Older Siemens controllers	PC SITRAFFIC	V34 modem Ethernet Fiber-optic cable … Central control via wireless links using public communication channels such as Internet/GPRS
OPAC	Model 2070/multiple firmwares Model 170 with 68360 Processor/multiple firmwares NEMA Controllers VME Bus or equivalent	PC MIST	Dedicated central to field connection at 9600 baud or higher Peer-to-Peer possible through Central Supports all communications media
RHODES	2070 ATC with NextPhase-Adapt Controller Software Econolite ASC/2 with Adapt X interface	RHODES Software on OS9/Windows/ Linux field-hardened, single-board computers	Peer-to-Peer over Ethernet; Bandwidth ≥96000 bps. Supports all communications media; preference is fiber optic.

SCATS	Model 170 controllers with SCATS conversion kit, which includes a new processor board with embedded software with 2070 or 2070 N controllers with SCATS proprietary controllers. NEMA AWA Delta 3N controllers. There are several RTA type approved SCATS controllers in current use sourced from Australia; i.e., Tyco Eclipse, QTC, Aldridge ATSC/4, Tyco PSC and a myriad of legacy controllers still supported; e.g., Phillips PTF.	PC SCATS	Requires 300 bps link to each controller using two-wire or equivalent. Multidrop system is supported that requires a two-wire line or equivalent to the first intersection in a cluster and then to each intersection in the cluster in a daisy chain " configuration. SCATS supports various configurations that can utilize TCP/IP, leased line, and conventional telephony services (i.e., dial-up).
SCOOT	Eagle NEMA Eagle 2070/ SEPAC support for 170 can be provided	PBS with MS Windows Server 2003 SCOOT algorithm and ACTRA	Both SCOOT and ACTRA require a separate channel to controller from the central—at 9600 baud, 8 controllers can be supported. Supports all communications media; wireless typically not used.

[Stevanovic]

Figure 7.7: ATCS Software and Hardware Specifications

ATCS	Microsimulation Tool
ACS Lite	CORSIM, VISSIM
BALANCE	NONSTOP, VISSIM
InSync	VISSIM
LA ATCS	CORSIM (offline post-processing interface)
MOTION	VISSIM
OPAC	CORSIM
RHODES	CORSIM, Q-Paramics
SCATS	S-Paramics, VISSIM, AimSun
SCOOT	VISSIM, CORSIM, S-Paramics, AimSun
UTOPIA	VISSIM, AimSun, S-Paramics

[Stevanovic]

Figure 7.8: ATCS Available Interfaces to Micro-Simulation Tools

The used communication media between the central system and the field controller can be:

- Wireless (application protocol or broadband systems) ~ 9%
- Microwave (terrestrial or satellite) ~ 3%
- Fibre optic ~ 28%
- Telephone line ~ 26%
- Twisted pair ~25%
- Other ~ 9%

The distribution can be explained by noting that ATCSs that need central-system-to-field-controller communication require very reliable communication for their ATCS operations, which is ensured through the use of physical media between various elements in the ATCS architecture. [Stevanovic]

Institutional Aspects of ACTS

ACTS can be a powerful tool, but it requires staffing for the right operation and maintenance. An ACTS cannot be seen as a hands-off type of system. It is important that the agency has a certain level of knowledge to enable proper deployment, operation and maintenance. If the agency has no sufficient expertise, they need to hire external consultants for occurring operational problems. If they forbear to do so, the system will suffer. The system will operate, but the performance will slowly degrade. In general, found out through a survey, approximately 77% of ATCS users stated that they had adequate training. The ATCS working principles should be understand for a proper operating. About 62% of ATCS users rely on their in-house expertise. The others contracted out (10%) for all tasks, or only for major modifications in the operation of their ATCS (28%). [Stevanovic]

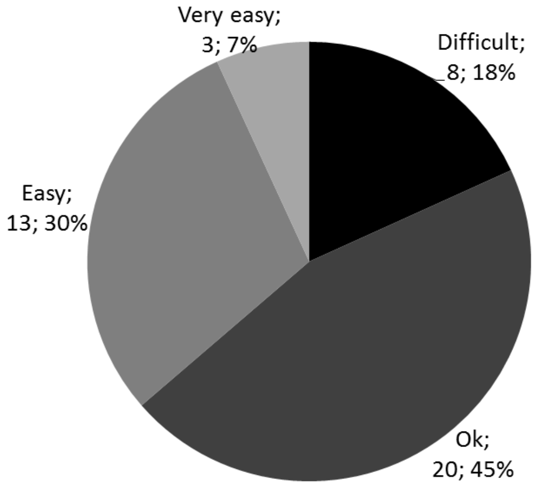


Figure 7.9: ATCS Difficulty in Understanding Working Principles

When considering the difficulty in understanding of the working principles more than three quarters think their understanding of the principles is at least enough sufficient for the operating and specify their knowledge at least as ok (45%). 18% think that the working principle is too difficult to understand. Also the maintenance level of difficulty was analysed by a survey of the Transportation Research Board.

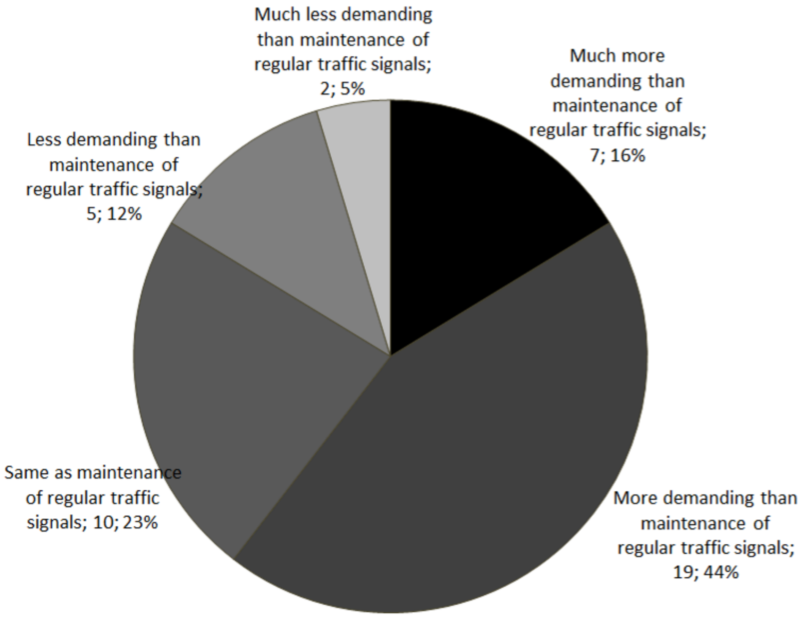


Figure 7.10: ATCS Maintenance Effort

7.2 ACS Lite

(Adaptive Control System Lite)[3]

The development of ACS Lite started in March 2002 and was completed in 2007; a lot of companies were involved. The research and development has been done by Siemens, Eagle, Econolite, McCain and Peek. The software was developed through a public private partnership. ACS Lite nowadays is a specific adaptive signal control technology, designed to be a low-risk approach to delivering adaptive signal control techniques. Moreover ACS Lite can be described as a lower cost and more easily managed system, to surmount the major deployment impediments and bring this rarely used state-of-the art technology to the mainstream state of practice. Therefore it offers significant cost savings relative to earlier FHWA-sponsored adaptive systems by better leveraging existing infrastructure. ACS Lite is used for closed-loop systems. The Goals of ACS Lite were a low cost design, leverage existing infrastructure, the integration of major signal system vendors and that NTCIP standards are used. The System is effective, compatible, easy to use and inexpensive.

The System is designed for simple configuration and setup:

- Existing hardware with firmware upgrade
  - Stage timing status object
  - Detector Status Object
  - Configuration objects
  - Polled once per minute (with second by second accuracy)
  - Stitched together for cycle by cycle performance assessment
- Configuration of ACS Lite Processor
- Uploads and maintains controller database
- User configures
  - Detector assignments
  - Links (Upstream, Downstream)
  - Adaptive Settings (Split Turning, Offset Turning)

It works within the context of signal timing and reduces delays and smoothen flow (Tuning Splits and Offsets). The System responds to variable and unpredictable shifts in demand.

The ACS Lite System Computer can be operated from a traffic management center, such as a traditional central system or in on-street manner, such as a traditional field master. In either case, the adaptive control software was to be encapsulated in just one computer.

By establishing the intersection controllers (local controllers) it was focused on cost minimisation. An intangible and often overlooked cost saving benefit comes from using a familiar controller firmware. The time and effort of learning using and maintaining a completely new controller was not that significant, through using known components.

ACS Lite was designed to use National Transportation Communications for ITS Protocol (NTCIP) as its communications protocol, wanted to encourage adoption of this national standard. Communication should also be able to communicate over low-speed serial communications, by the possibility of using the existing infrastructure.

[3] Curtis E.; *Adaptive Signal Control Technology Overview*
Curtis E.; *ACS-Lite, The Next Generation of Traffic Signal Control*
Gettman D.; *ACS Lite Performance Measures*
Ghaman R., Gettman D., Shelby S.; ACS Lite Project Overview
Stevanovic A., Transportation Research Board 2010 Executive Committee; *NCHRP Synthesis 403, Adaptive Traffic Control Systems: Domestic and Foreign State of Practice*

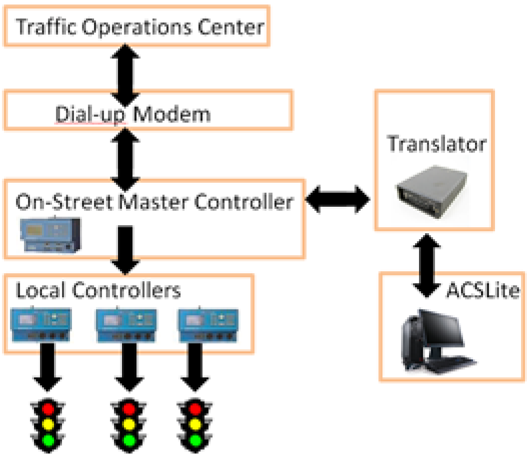


Figure 7.11: ACS Lite Design Architecture

ACS Lite maximises the life cycle of existing control hardware which is flexible (integrated with controllers from four manufacturers, detector configuration) and can operate standalone or in system. It is retiming (data collection, optimisation, fine tuning) reactive to proactive and the software documents and reports decisions and outcomes. The System needs the detection of volume and occupancy per stage. The ACS Lite Algorithm Architecture is shown in the figure above.

The TOD (Time-of-Day) plans realise large and fast parameter changes of cycle, splits, offsets and pattern switch times. This is implemented by the time-of-day tuner which periodically re-tunes the TOD plans. Measures are adjusting cycle, offsets and splits. That changes are permanent, a fine-tune schedule of pattern switch times also exists. The Time-od-Day Tuner works day by day.

The active plan smoothens and increments parameter changes. The rung-time refiner works cycle by cycle. The run-time refiner adjusts active timing plans and monitors real-time statuses.

The plan changes must be fast and non-disruptive parameter changes. The transition manager manages the controllers' transition from one plan to the next one by selecting existing transition modes and commanding sequences of changes. Also transition objectives are fixed here.

The philosophy behind are a data driven parameter tuning and limited/no traffic modelling. Therefore recent past predictions are brought to near future. The first step are the splits like stage utilisation, the second step the offsets like capture efficiency. The occupancy is checked at every interval and the split tuning gets determined.

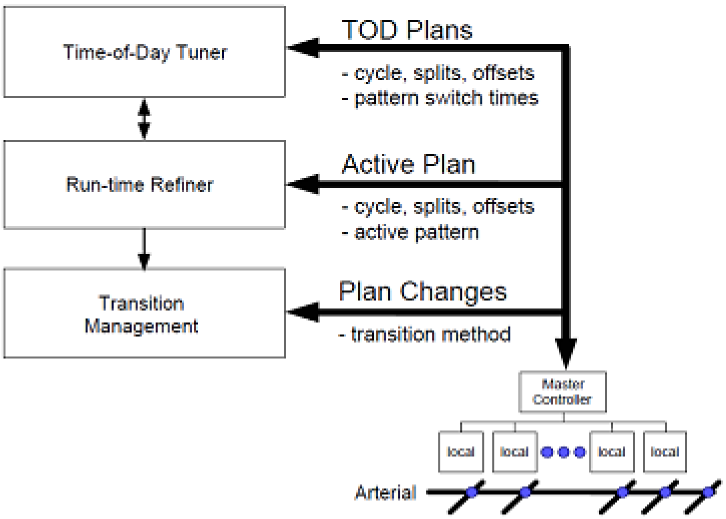


Figure 7.12: ACS Lite Algorithm Architecture

The green occupancy refers to the stage utilisation therefore the following points are checked:

- Average available Green (AAG) → green used + time to min (force-off point, stage max)
- Average used Green (AUG) → occupied green + fill in the unusable gaps time
- Stage utilisation = AUG /AAG
- Average stage utilisation over last few cycles → tune split times

The performance measure for offsets is the capacity efficiency. It is inbound and outbound considered at each signal to tune the offset value. Also the following applications are measured for performance:

- Capture efficiency → link travel times
- Utilisation and capture efficiency → delay
- Delay → level of service
-

7.3 BALANCE

(Balancing Adaptive Network Control Method)[4]

BALANCE belongs to the generation of newest German traffic signal control systems. It is an adaptive control system and was developed firstly in 1994 and further in 1998 during several European research projects with origins at the Technical University of Munich. For the advancement also the companies GEVAS software and TRANSVER worked on it. Finally 1999 the whole algorithm was composed. Since 2002 GEVAS software is responsible for maintenance and further development. BALANCE has a two level concept that enables to react quickly and flexibly to changes in traffic volumes and provides a comprehensive view of traffic situation throughout the entire road network without restricting the range of local control options. BALANCE was implemented in several cities including Hamburg, Ingolstadt and Remscheid.

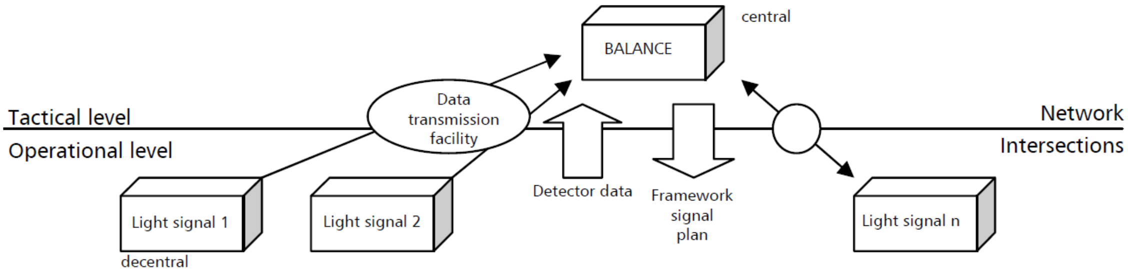


Figure 7.13: BALANCE Two Level Structure

On the strategic level, the transportation politics and the target function of the system is defined. Medium term traffic forecast and frame signal plan Traffic Signal Control optimisation is realised in tactical level (MacroBALANCE). The local level (MicroBALANCE) also called local control, considers to the short-term stochastic traffic flow variations. The local control realises fast reactions and microscopic processing of measured data. Unlike SCOOT the queue lengths or delay times are based not directly on the measurement (cyclic flow profiles), but on a model approach. This enables the optimisation of coordination despite of failure in local components.

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[4] Curtis E.; *Adaptive Signal Control Technology Overview*
GEVAS; Interface *BALANCE – Traffic Computer Overview*
GEVAS; *BALANCE – intelligent signal control for sustainable road traffic*
Gündogan F.; *Simplified traffic responsive signal control method for developing large cities*
Stevanovic A., Transportation Research Board 2010 Executive Committee; *NCHRP Synthesis 403, Adaptive Traffic Control Systems: Domestic and Foreign State of Practice*

BALANCE analyses and estimates the traffic state both in the tactical and local level. The frame of estimation (origin-destination matrix estimation) is done at a tactical level and after that the local variations in traffic state (i.e. effect of change in green time to the traffic state) are analysed at a local level. In consideration of computer power BALANCE offers a simplified method for local traffic state estimation. BALANCE uses Hill-Climbing algorithm for the optimisation of traffic signals. The system is implemented and tested in several German and other European cities.

The entry data of BALANCE can consist of two types and can be measured data from detectors in the network or status data from the control units (field level). The output data of BALANCE consists of three types which are the control commands for the light signal in the network, the data from the traffic and effect model as well as protocol information. BALANCE influences the light signals in the network by two kinds of control commands.

Framework signal plans: For every interstage, the earliest and the latest point of interstage starting are defined. The interval between these points is the for traffic-actuated control available interval. Framework signal plans for light signals contains of a time stamp, the validation mode, the validity in seconds, the data for consistency check, index signal program, cycle, version, offset for local cycle and for every interstage the local control.

Signal Program:

BALANCE selects the program with the best cycle time for the current traffic conditions from a pre-arranged set of signal programs. The signal program index serves as output data. The selection is done at the same time for all light signals of one control group. A control group is a subset of light signals in the network.

The provided data packages are small and are transmitted only every 5 minutes. Because BALANCE uses traffic modelling, it allows minimal use of traffic detectors. BALANCE develops optimal signal timings for the existing detection in the field and does not require that every intersection is equipped with detectors.

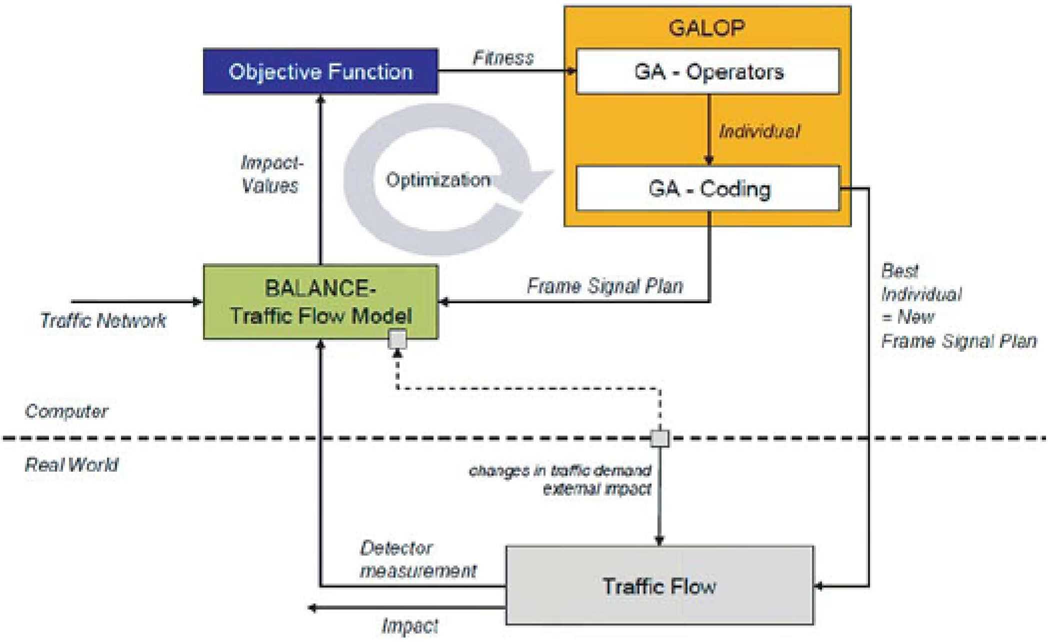


Figure 7.14: BALANCE Genetic Algorithm (GA) Optimisation Process

The optimisation is done by Genetic Algorithm (GA), which imitates the process of natural evolution. Interaction between optimisation and field implementation is shown in the figure above. The final signal timings are achieved through several generations in the constrained time interval of 5 min. Although the solution area for the appropriate signal timings is very complex, the GA has proven that a solution near to the theoretical optimum can be reaches.

Advantages and Disadvantages of BALANCE:

Advantages

- Dynamic green waves without high planning efforts
- Improving traffic flow and reducing fuel consumption
- Easily integration into existing infrastructure
- Model-based system
- Only few detector requirements
- Extensive instruments for operational supply and quality assurance
- Local control remains active
- High economic advantages by minimising waiting times and stops
- Flexible reaction on changing amounts of traffic
- Comprehensive view on the situation over the whole network

Disadvantages

- Every intersection stand for itself
- Traffic control is coordinated only for single roads
- Practically no potential for anticipatory reactions on changing amounts of traffic

7.4 lnSync

It is also an adaptive traffic system and was developed by Rhythm Engineering (Lenexa, Kansas). lnSync uses innovative sensor technology, image processing and artificial intelligence. lnSync automatically optimises and coordinates signals, according to real-time traffic demand. The usage of lnSync eliminates the need for static signal coordination plans. [Stevanovic]

InSync is the traffic control solution for more than 950 intersections across the U.S., in 26 states lnSync is enhancing traffic signals with real-time adaptive traffic control technology. [rhythm engineering]

lnSync Breadth of Deployments			
AS of July 2013	Deployed	Scheduled	Total
Intersections	739	251	990
Corridors	128	39	167
Cities	39	23	80
States	23	13	26

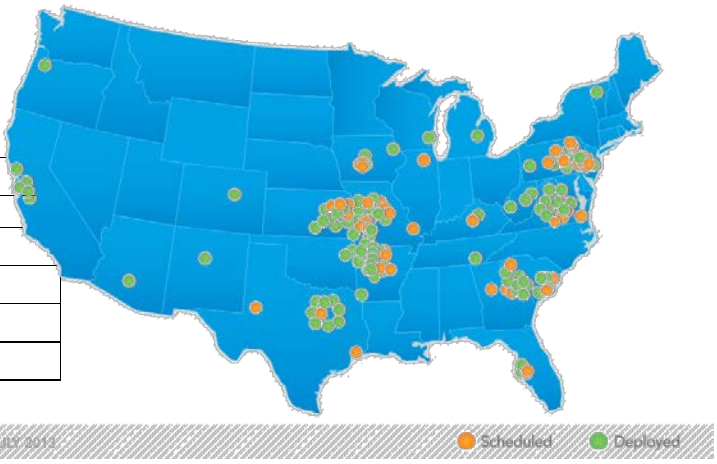


Figure 7.15: lnSync Deployment

There are two kinds of signal optimisation that deal with the conflicting objectives of providing a green for vehicle crowds and the clearance of vehicles involved with secondary traffic movements.

There is the global and the local element. The global element is there to set time tunnels and adjustable periods for optimising progression. Users need to fix the main direction within the grid, redefining and automatically toggling between arterials by time of day/time of week is possible. Time tunnels are used for optimisation. The local element is there to set logic and features of the optimisation algorithm. The following points are considered here: [Stevanovic]

- Emptying queues,
- Duration of different states,
- Termination of States
- Calculating a Sequence
- Early Release
- Period Length Evaluation

lnSync can set cycle lengths, splits and offset to a fixed point in the cycle that have traditionally been considered essential for signal coordination. lnSync is an artificially intelligent/digitally based finite-state changing machine. By its method of externally influencing a controller it causes any controller to effectively function digitally. The digitalisation is not referring to the nature of the component parts of the controller, but to a digital methodology, of how traffic signal stages are chosen. In relation to traffic movements a maximum of 16 possible sequences of stage pairs (states) at any quad intersection can be taken. Because lnSync knows the real-time traffic demand, it is able to instantaneously select and input to the controller any user permitted stage pair associated with the 16 possible sequences.

lnSync is not limited in its choices or duration times by a set cycle length, split or offset. Except for minimum and maximum times, as well as passage times, all typical volume density inputs to the controller are disabled so that the free mode is realised. The free mode permits the controller to react quickly and change traffic signals according to the optimised calls coming in. [Stevanovic]

Hardware and Software Requirements

lnSync uses high end IP digital cameras in weatherproof versions that are normally mount on mast arms with standard brackets. The cameras are connected to the lnSync processor installed within each local traffic cabinet through a CAT-5 Ethernet cable and a 24-volt electrical wire that provides power. The processor is placed in the local traffic cabinet and interfaces with the local signal controller using detector cards that are plugged into existing detector card racks. Also a 110/24 volt transformer is included. Surge protectors, an unmanaged Ethernet switch and a pigtail cable for red/green returns are also needed. If coordination takes place, communications between the networked intersections must be realised.

lnSync is both Ethernet and web-centric in its functionalities. Each processor and every camera has an IP address. These components can be accessed directly by means of the network without any proprietary software. Al the necessary configurations or and any software upgrades to the system software can be accomplished remotely over the Ethernet network. The onsite cameras are properly aimed, zoomed, focused and tightened to effectively view vehicles arriving at and progressing through the signal. [Stevanovic]

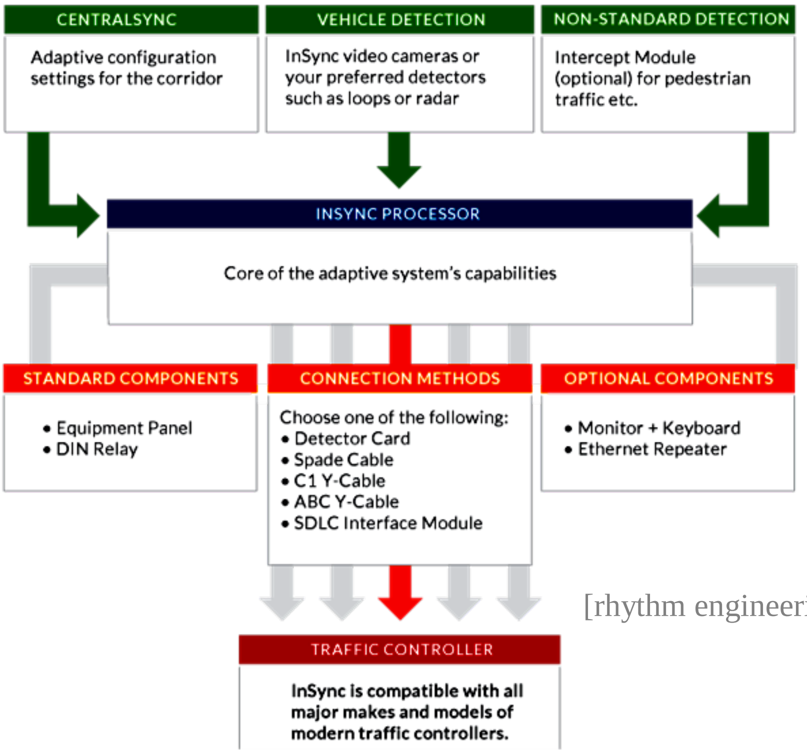
lnSync in numbers

“Statistics and stories from actual deployments across the U.S. tell a consistent story – InSync works. It makes a difference in traffic operations and safety, which tangibly improves the quality of life in our communities.” [rhythm engineering] Numbers given at the website http://rhythmtraffic.com/insyncs-performance are the following.

Communities using lnSync save up to:

- $ 8,000,000 in wasted time and fuel

- 27 tanker trucks of fuel reduction
- about 33 years of wasted time
- millions of pounds of air pollution
- dozens of crashes, considering one corridor



[rhythm engineering]

Figure 7.16: InSync Architecture

CITY	STOPS	DELAY	TRAVEL TIME	FUEL	EMISSIONS	ANNUAL SAVINGS TO MOTORISTS
Columbia, MO	73%	56%	20%	12%	19%	$1,984,411
Evans, GA	77%	81%	34%	17%	23%	$2,624,802
Grapevine, TX	47%	42%	16%	8%	9%	$8,067,234
Lee's Summit, MO	84%	72%	23%	10%	23%	$2,452,493
Salinas, CA	64%	69%	39%	N/A	N/A	$1,722,152
San Ramon, CA	56%	51%	27%	15%	14%	$2,333,636
Springdale, AR	88%	80%	36%	19%	29%	$5,083,254
Topeka, KS	79%	68%	43%	33%	28%	$2,087,501
Wichita, KS	82%	68%	31%	21%	30%	$975,260
Upper Merion, PA	21%	34%	26%	N/A	N/A	$802,204

[rhythm engineering]

Figure 7.17: InSync documented Results - Performance Measurement in Terms of Reduction

7.5 MOTION

(Method for the Optimisation of Traffic signals in online controlled Networks)[5]

It is an adaptive control, which also includes a multi-layer traffic control. MOTION can be seen as a response to the permanently increasing traffic load in German cities, where previous traffic-actuated control was not able to cope with. Optimal cycle length, state sequence and coordination are defined in tactical level in every 5 to 15 minutes. The green times of each signal groups are readjusted with consideration of private traffic and public transport at the local level in every second. MOTION can also estimate a local origin-destination matrix with the turn-rates. The optimisation occurs in three steps. In the first the split-optimisation occurs. The cycle length is optimised in the second step, and the optimisation of the coordination takes place in the last step.

System Architecture and Communications

The general process in MOTION consists of four models.

The traffic state estimation module estimates the traffic state based on measured traffic counts and occupancy data. It includes the estimation of queue lengths, turning rates and traffic volume.

The parameter selection module activates predefined parameters for corresponding traffic condition. If no control strategy is activated, the default parameters are selected.

The Cycle and split optimisation module works by optimising the timing plans, which are based on estimated traffic situation and the predefined parameter set. The estimated queue lengths are also considered as the additional number of vehicles in the process to timing plan calculation.

The offset optimisation module realises green wave in the control area based on the parameter set, the estimated turning rates and the cycle time and splits of each intersection.

- Network Cycle Time → necessary for coordination of traffic signals
- Green Time Split → adapted to the traffic load of the network, prevents congestion
- Stage Sequence → relevant for security and optimisation aspects
- Offset Time → important for green waves and minimisation of delays and stops

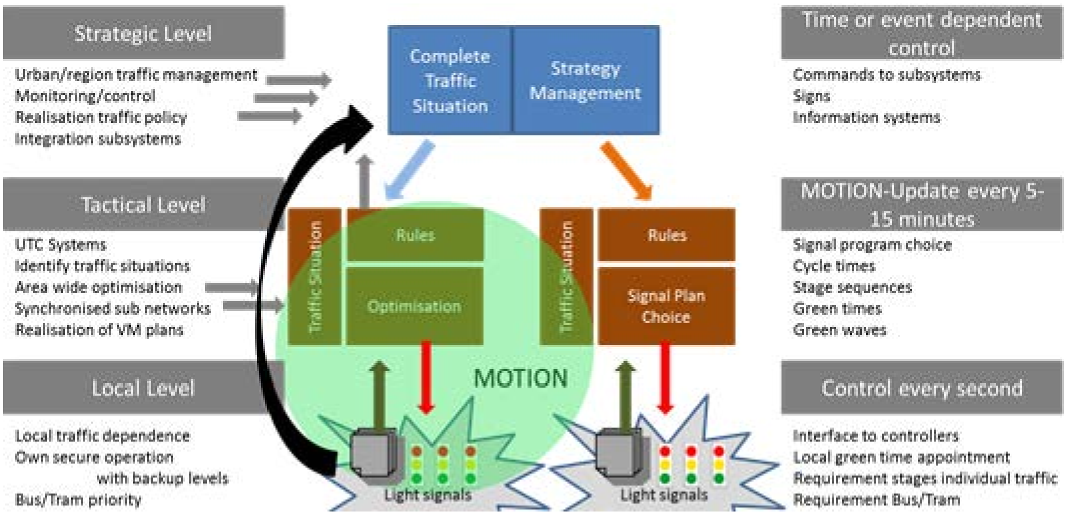


Figure 7.18: MOTION Operation Overview

[5]*Cagran B.; Verkehrssteuerungssystem Graz; Stadt Graz, Straßenamt, Januar 2013*
Curtis E.; *Adaptive Signal Control Technology Overview*
Gündogan F.; *Simplified traffic responsive signal control method for developing large cities*
Kroyer B.; *Adaptive Traffic Light Control in Denmark, MOTION*
Stevanovic A., Transportation Research Board 2010 Executive Committee; *NCHRP Synthesis 403, Adaptive Traffic Control Systems: Domestic and Foreign State of Practice*

The abilities of MOTION are:

- Improvement of capacity
- Incident and congestion management
- Green waves for main streams
- Public transport priority
- Network optimum of delays and stops
- Environmental control

The MOTION also offers congestion and incident management for the control center. The parameters (i.e. discharge time, weights for delays and stops) are determined differently for the splits and offset time determination for several situations.

Public transport priority and the consideration of adjustments for local fluctuation in traffic demand at intersections are some advantages of MOTION. The system is used in over 15 cities in Germany and also other cities in Europe.

The main difference between MOTION and conventional ATCSs (SCOOT, UTOPIA, SCATS) is that the operational second-by-second control of the signal groups is separated from the adaptive control level. Controllers make the operational decisions, whereas the adaptive control logic updates the controller every 5 to 15 minutes. The controller gets new framework plans, which brings the following benefits to the concept. There is no traffic state estimation on a second by-second basis needed, state estimation algorithms can be based on the data aggregated per minute or per cycle. Missing detector measurements can be replaced by using averaged values without the need to model them in a short interval. There is sufficient time for central processing units to run extended algorithms for the optimisation for network-wide coordination.

7.5.1 MOTION in Graz (Austria)

In Graz, a 270,000 inhabitants city and the second largest city in Austria MOTION is used as traffic control system. In Graz there are in total 286 light signal plants. 201 of them are connected to the central computer. Graz has 25 routes with green waves and 85 signal plants where the public transport is prioritised. For the operation with MOTION there are about 800 induction loops installed, which detects vehicles. Also a local green period measurement is realised. All intersections which are controlled dynamically are controlled with MOTION.

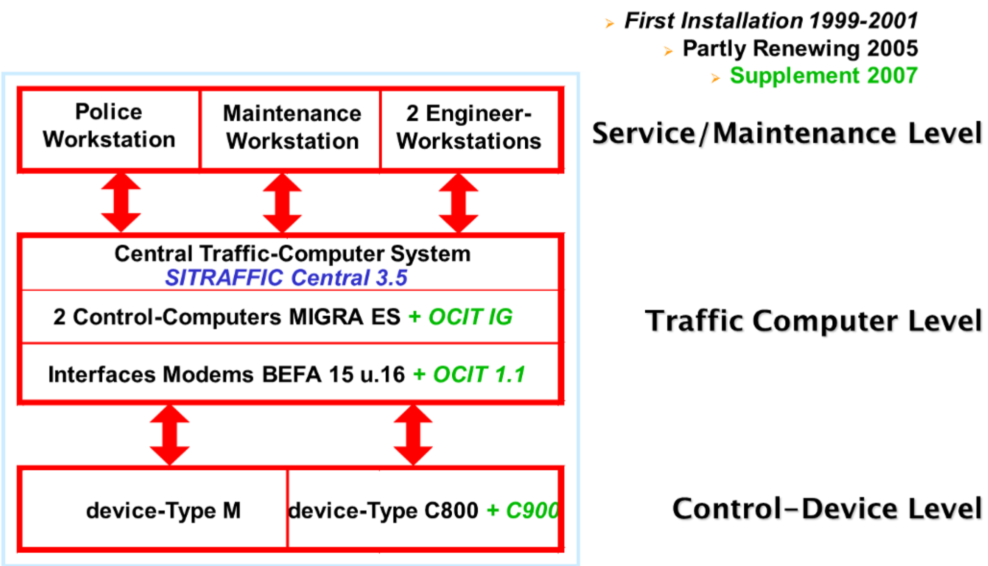


Figure 7.19: MOTION in Graz

Network Operation in Graz with MOTION

The traffic data detection is made online out of 90 detectors, then a traffic allocation is realised. Signal programs are optimised. The optimisation is done by generating signal plans or by choosing cycle times. The decision is made through part-areas with total optimisation or separated, also the offset times can get optimised by the optimising plan. The control must get edited by implementation-point-control or coordination-impulses. In Graz the taken interval lasts 15 minutes. Every 15 minutes the stage sequence, cycle time, green periods and offset times were optimised.

In Graz MOTION is handled in the following way:

- The road department is the operator
    - Traffic technical proofing
    - Planning of signal program
    - Commissioning of realisation

- The police does the operating/service
    - Traffic monitoring
    - Incident management
    - Interventions into control

- The company SIEMENS is charged to do the system maintenance
    - Programming and realisation
    - Continuous maintenance
    - Failure service/duty

7.6 OPAC

(Optimised Policies for Adaptive Control) [6]

It is a distributed real-time traffic signal control system and calculates signals. OPAC was originally developed at the University of Massachusetts, Lowell. OPAC continuously adapts signal timings to minimise a performance function of total intersection delay and stops over a pre-specified horizon and can operate as an independent smart controller or as part of a coordinated system. The algorithm of OPAC uses measured as well as modelled demand to determine stage durations that are limited just by minimum and maximum green times or by virtual cycle length and offset that are updated based on real-time data.

The principles for the development of OPAC:

- Providing a better performance than off-line methods
- Requirement of development of new concepts
- System must be truly demand-responsive (adapt to actual traffic conditions)
- Must not be restricted to arbitrary control periods, but capable of frequent or continuous updating of plans.

The following actions can be realised by OPAC:

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[6] Gartner N. H.; *Optimized Policies for Adaptive Control (OPAC)*
Gartner N. H.; *Developments in Network Control Systems, Adaptive Control*
Gündogan F.; *Simplified traffic responsive signal control method for developing large cities*;
Pooran F.; *TR-TRACS Adaptive Control Algorithms, VFC-OPAC*
Stevanovic A., Transportation Research Board 2010 Executive Committee; *NCHRP Synthesis 403, Adaptive Traffic Control Systems: Domestic and Foreign State of Practice*

- Developing flow profiles and queuing
- Stage length optimisation
- Offset optimisation
- Virtual fixed cycle concept and optimisation
- Staging Flexibility
- Oversaturated Conditions → isolated intersection mode, coordinated mode

Hardware and Software Requirement

OPAC works with a variety of traffic signal controllers and firmware, including NEMA (TS-2), 170-ACT, 2080, and 2070 Lite controllers. With NEMA controllers, OPAC uses Single Board Computers and with ATC controllers it uses VME cards. At a central location OPAC requires multiple PCs for Operator Interface, a server, a database, device drivers and a communication server. OPACs configuration can usually control up to 250 junctions with no additional hardware upgrade. Normally OPAC comes integrated within MIST.

System Architecture and Communications

OPAC works with three layers. The local layer implements rolling horizon procedure and continuously calculates optimal switching sequences for the projection horizon. The coordination layer optimises the offset for each intersection one per cycle and the synchronisation layer calculates the network wide virtual-fixed-cycle for every few minutes.

Layer 1: optimal switching sequences for projection horizon, subject to VFC constraint

Layer 2: real-time optimisation of offsets at each intersection

Layer 3: signal synchronisation: network wide calculation of VFC

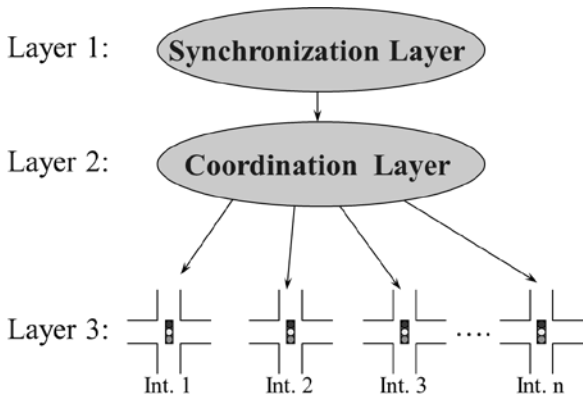


Figure 7.20: OPAC Multi-layer Network Architecture

OPAC needs sensors/detectors for detecting the actual traffic conditions. Therefore inductive loop detectors, video detectors, sonar detector radar detectors… can be used.

OPAC consists of two models, the uncongested model and the congested model. In the uncongested model, the timing plans can be determined either due to obtaining the fixed-time plans in offline or calculating a virtual cycle dynamically. In the congested model, the system considers the saturation flow rate and maximises the number of vehicles that can pass through the intersection. This model also considers the critical links of networks. Except the cycle time calculation, OPAC is not controlled by a central computer. Thus, OPAC can still work despite a communication failure with the control center.

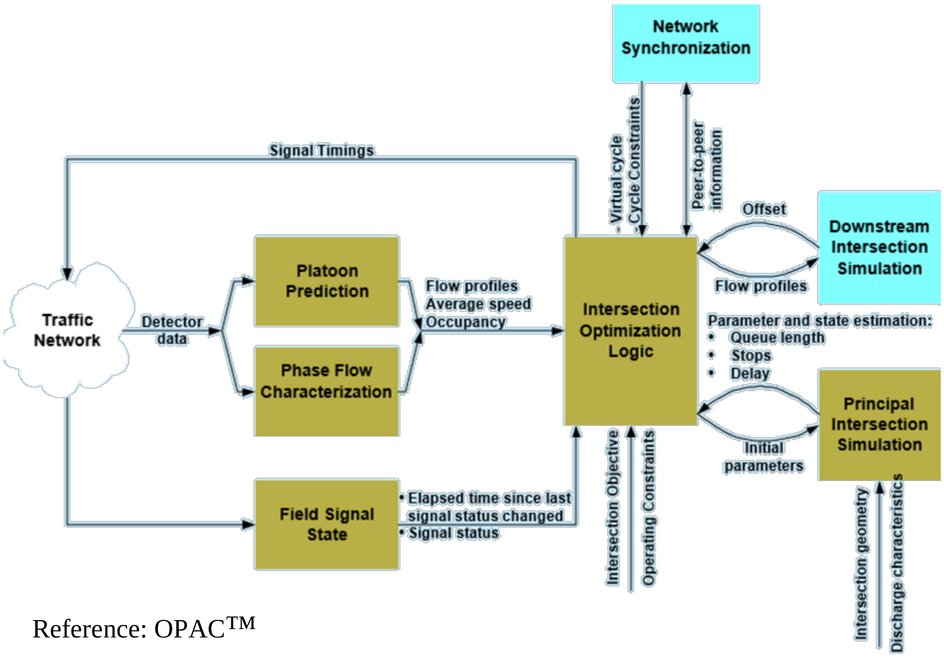
At oversaturated conditions two modes are possible:

Isolated intersection mode → provides maximum green to the affected stage if occupancy exceeds a user specified threshold

Coordinated mode → provides maximum green to congested stages, subject to the current cycle length and adjusts cycle length in response to increasing congestion

The following figure shows a typical two-level distributed OPAC system configuration. The local level consists of Type 2070 controllers, hosting the OPAC real-time adaptive control strategy. The adaptive strategy is done on a separate central processing unit card. MIST provides the central system functionality, including operator interface, server, database and communications between the central system and the field controllers as well as between adjacent controllers.

Upstream loop detectors are used to provide real-time traffic data. For isolated junction control OPAC architecture is fully distributed. Cycle length for example is defined at the central level and communicated periodically the junction controller. Also if controllers are not physically connected then peer-to-peer information is communicated through the central level.



Reference: OPAC™

Figure 7.21: OPAC Conceptual Design

For reliable operations OPAC needs a dedicated central to field connection (9,600 baud or higher). OPAC can use phone lines, fibre optics or wireless communication media. The reliability of communication is crucial for the proper operation. If communication between local controllers and central level fails OPAC will run autonomously, then it still runs its adaptive logic, but the coordination between junctions can get degraded. There are four communication levels at OPAC.

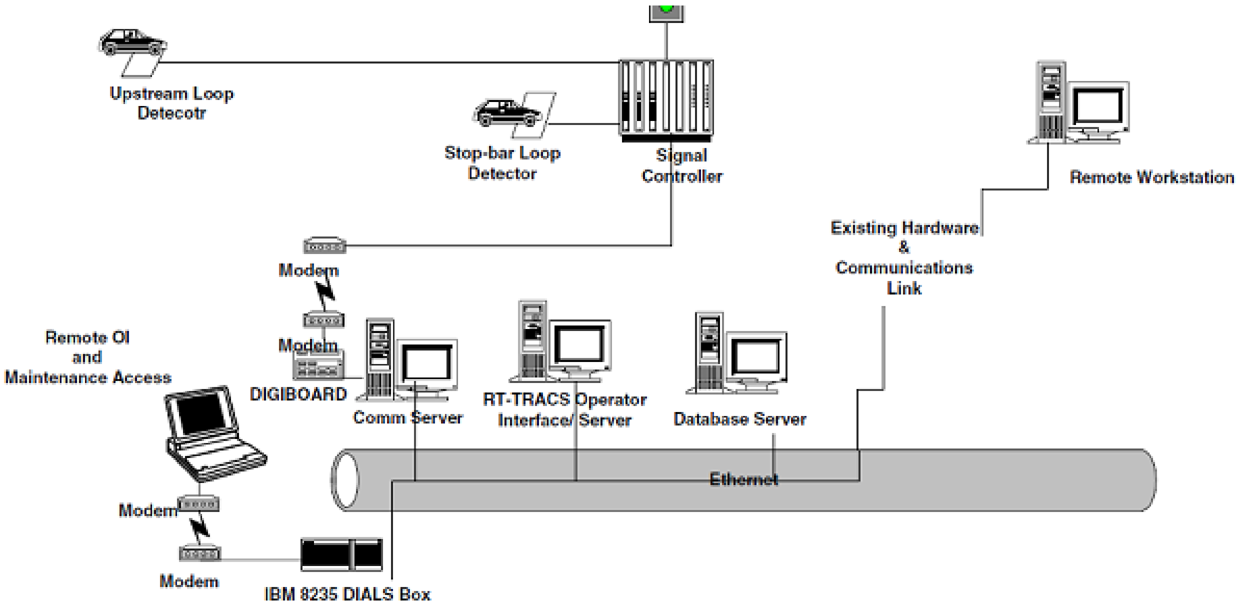


Figure 7.22: OPAC System Architecture

Detector Requirements:

OPAC can use loop, radar, video and any other detection technology that can provide the required data, which is volume, occupancy and speed (measured/calculated). Ideal detector location are about 10 seconds upstream of the stop line or upstream of the worst queue on each lane of all through stages. OPAC also requires one count detector in each lane of separated left-turning as far upstream as possible.

7.7 RHODES

(Real-time Hierarchical Optimised Distributed and Effective System)[7]

RHODES uses a three-level hierarchy for characterising and managing traffic. It explicitly predicts traffic at these levels utilising detector and other sensor information. Therefore it requires lane traffic data, real-time communication to/from processors and PC-level computational capability. RHODES is a real-time traffic adaptive signal control strategy which seeks to optimise the real-time performance of a corridor or network of junctions. To provide optimal control of traffic through a network RHOTES takes real-time input from vehicle detectors and predicts the future traffic streams. The outputs are optimal signal control settings based on these predictions.

[7] Curtis E.; *Adaptive Signal Control Technology Overview*
Gündogan F.; *Simplified traffic responsive signal control method for developing large cities*;
…Mirchandani P., Head L.; *RHODES – Traffic-Adaptive Control Systems*
Mirchandani P. Head K. L., Sheppard D., Whalen S.; *Next Generation Real-time Traffic Adaptive Management Systems*
Stevanovic A., Transportation Research Board 2010 Executive Committee; *NCHRP Synthesis 403, Adaptive Traffic Control Systems: Domestic and Foreign State of Practice*

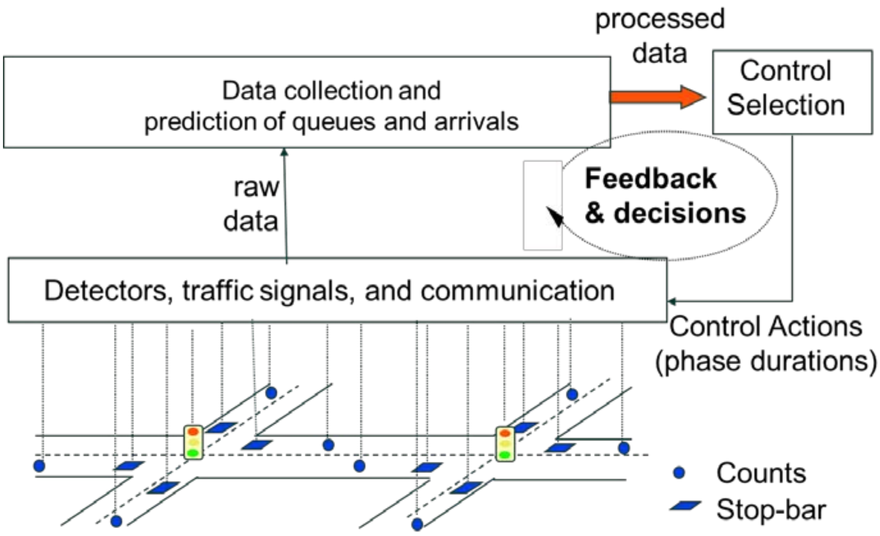


Figure 7.23: RHODES System Architecture

The basic concept is to set signal staging that proactively responds to stochastic variations in traffic flow. This needs the identification of certain traffic objects at different levels of aggregation like individual vehicles, vehicle crowds (platoons), and overall traffic flow in terms of vehicles per minute. Moreover the identification of their natural dynamic and responsiveness to signal control is needed. Also setting stage durations for allowing these traffic objects to move according to their objective are needed.

RHODES uses peer-to-peer communications and predictive algorithms to identify the changes and make accordingly preparation. The cycle length by using RHODES will vary from cycle to cycle, depending on the current demand and conditions.

The highest level of Traffic Signal Control has the “dynamic network loading model” (network load). The slow-varying characteristic of traffic is captured in this level. The middle level is the “network flow control model” (network flow) that allocates the green time based on the different demand patterns. The lowest level has the “intersection control model” (intersection flow). The required stage change patterns are determined in this level.

<u>Intersection control logic:</u> Effectively, the algorithms determine for a given signal group order what time durations should be given to it and consider a given decision time horizon T, with time increments of 1 second. The intersection control logic allows various objectives like stops, delays, queues. They are implementable in real-time. The logic easily accommodates operational constraints like minimum green times, fixed/variable sequences, and coordination.

<u>Each level has two components:</u> Estimation/prediction and control.

The <u>RHODES</u> consists of several algorithms for prediction, control and optimisation. RHODES is responsible for the real-time control of an intersection’s traffic signal control. The used information are provided by presence detectors at the stop-line of each approach and passage detectors located upstream of each approach. It determines the stage sequence, green times, to minimise delay…

The <u>PREDICT</u> predicts traffic flow at intersection level, while the APRES-NET predicts platoon arrivals/ crowds at network level. It provides estimates of departures that are heading toward neighbouring, or peer junctions, in effect to extend the upstream detection capability of those junctions receiving information from PREDICT. The REALBAND algorithm optimises the timing plans. RHODES enables also public transport priority and has a link to microscopic traffic flow simulation tool CORSIM.

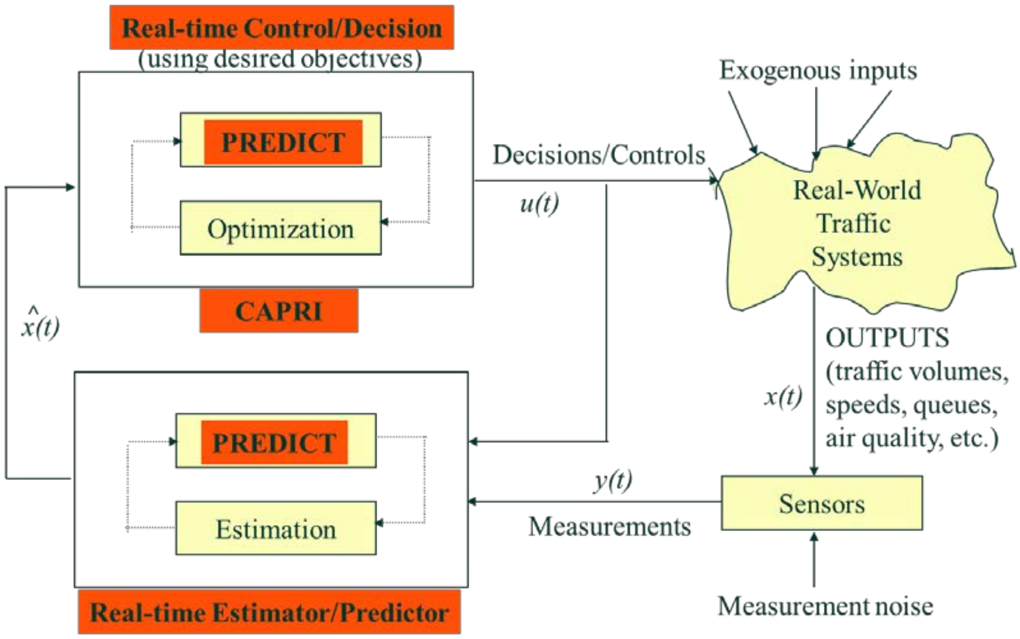


Figure 7.24: RHODES General Proactive Idea

The benefits of RHODES are an improvement in traffic performance, responding to current congestion and to incidents (through "learning") and a decrease in traffic operations effort because operators need not "time" signal periodically. Moreover the clear interface with Transit/Emergency/Rail allows transit priority at intersections and allows pre-emption for emergency vehicles and railway.

RHODES intersection control logic allows efficient optimisation and allows various objectives (stops, delays, queues) for different classes (cars, buses…). It is implementable in real time and easily accommodates operational constraints like minimum green times, fixed/variable stage sequences and coordination.

Rhodes for example is currently used in Seattle, Washington (10 Intersections) in Santa Clara County, California (9 Intersection), Oakville, Ontario (7 Intersections), and Pinellas County, Florida (17 Intersections).

<u>Hardware Requirements and Configurations:</u>

A field-hardened single board computer is used for RHODES. Additionally to O"9 it is capable of running under Windows or Linux operating systems for added flexibility considering how to integrate it within an existing traffic control system.

RHODES has operated under three different controller configurations:

- With 2070 advanced Traffic Controller (ATC)
- With Econolite ASC/2S
- With RHODES Adaptive Control Unit (RACU)

RHODES does not interact directly with its environment, instead relying on the traffic controller and controller software to provide data about signal status, detector calls….RHODES is independent of the actual traffic cabinet environment. As long as the traffic controller software supports it, the cabinet environment has no direct impact. The support is only provided through two software products (Adapt and AdaptEx, both from SIEMENS ITS). Adapt is an adaptive control module that provides an interface between RHODES and the NextPhase traffic control software used at 2070 ATC. AdaptEx provides similar functionality in an external module that interfaces with the ASC controller software.

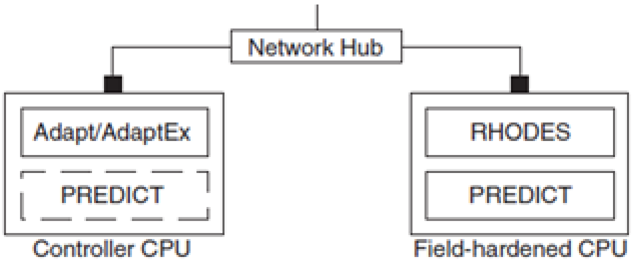


Figure 7.25: RHODES System Architecture

Communications

The communication network of RHODES must be capable of providing reliable transmission of data between peer junctions on a second-by-second basis. The component providing this peer-to-peer data is the PREDICT module. It is responsible for calculating the number of vehicles that depart the local intersection en route to the peer junction. Instead of a proprietary protocol, just the IP is used. Each junction is assigned to a set of unique IP addresses to identify it among its peers. To manage the communication networking configurations are required to support proper routing and identification between peers

Detector Requirement

RHODES requires a number of detectors to model the flow of vehicles into and out of an junction properly while operation. Stop line or presence detectors are required at each approach and they are used to identify the absence or presence of queues. Queues are associated with individual movements on an approach in RHODES. The movements are left, through or right. Multilane movements need only one detector spanning these lanes.

The performance of RHODES is highly depending on the accuracy and quality of the detection system, but not on a particular type of detection technology. Proper maintenance and monitoring of the detection system is important.

7.8 SCATS

(Sydney Coordinated Adaptive Traffic System)[8]

SCATS is an innovative computerised traffic management system developed and maintained by Roads and Maritime Services, Traffic Authority of New South Wales (RTA) in Australia. The evolution started in the 1970s and is continually being improved to manage traffic signal networks around the world. SCATS was developed and first installed in Sydney in Australia. Now, SCATS is used in more than 50 cities worldwide.

It is a system consisting of hardware, software and a unique control philosophy that operates in real time. SCATS is an area wide traffic management system that operates under the Windows environment and controls the cycle time, green splits and offsets for traffic control intersections and mid-block pedestrian crossings. With the inclusion of vehicle detectors, it can adaptively modify these values to optimise the operation to suit the prevailing traffic. Alternatively it manages intersections in fixed-time mode where it can change plans by time of day, day of week, etc. SCATS was designed to coordinate traffic signals for networks or for arterial roads.

Unlike SCOOT and other adaptive methods, SCATS does not have any traffic model, it optimises splits and cycles according to an objective function. Although the objective function is determined

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[8] Transport Roads & Maritime Services, NSW Government; *SCATS Products*
Roads and Traffic Authority of NSW for Australia, New Zealand and Singapore; *SCATS, The New Generation SCATS 6, Functional Description*

according to delay and number of stops, the degree of saturation of intersection approaches is used as a main parameter in the optimisation.

SCATS supports four modes of operation:

- Normal Mode – provide integrated traffic responsive operation
- Fall-Back Mode – implement the time plans when computer or communication failure occurs
- Isolated Control Mode – vehicle actuation with isolated control works
- Forth mode – signal display flashing amber or red at all approaches [IIT]

SCATS controls traffic at two levels: strategic and tactical level, which are also used in newer adaptive systems. In the tactical level the regional computers of SCATS control up to 10 intersections. These regional computers are connected to the main system. The Central Manager can manage 64 regional computers and with this up to 250 intersections.

7.8.1 Computer System Requirements

SCATS has been designed in a modular configuration to suit the varying needs of small, medium, and large cities. In its simplest form, a single regional computer can control signals at up to 250 intersections. Expansion of the system is achieved by installing additional regional computers. All systems have a Central Management Computer to manage global data, access control, graphics data as well as data backup.

Regional Computers

The regional traffic control function uses standard personal computers operating under the Windows operating system. A range of intersection communication methods are provided and include network (TCP/IP), serial, dial-out and dial-in.

Central Management Computer

The Central Management computer is also a personal computer operating under the Windows operating system. Communications with regional computers and workstations is via TCP/IP.

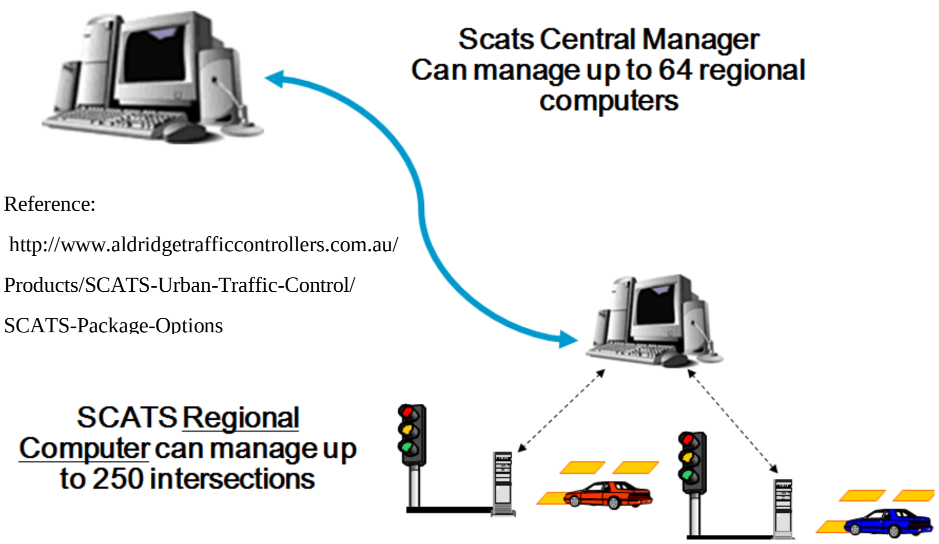

Figure 7.26: SCATS - Central Manager and Regional Computer

7.8.2 Adaptive Control in SCATS

SCATS has, as mentioned before, a two level architecture. The two levels determine the three principle signal timing parameters of traffic signal coordination – cycle time, stage split and offset. The levels are called strategic and tactical.

Strategic control is based to determination of suitable signal timings for areas on average prevailing traffic conditions. Strategic control is managed by the regional computers, using flow and occupancy data collected from loop detectors in the road by the local controllers. The computers determine the optimum cycle length, stage splits, and offsets to suit the prevailing traffic conditions, based on an area

Tactical control refers to control at the individual intersection level within the constraints of the regional computer's strategic control. Tactical control is done by the local controllers, meeting the cyclic variation in demand at each intersection. Tactical control basically allows for green stages to be terminated early when the demand is low and for stages to be omitted entirely from the sequence if there is no demand. The local controller bases its tactical decisions on information from vehicle detector loops at the intersection, some of which may also be strategic detectors.

Both (strategic and tactical) functions are measured using inductive loop vehicle detectors. All detectors are capable of performing the tactical function and capable being defined as strategic detectors and information from these is pre-processed in the local controller and then sent to the regional computer for strategic calculation.

The cycle time is taken to complete one sequence of all stages and must vary to meet the overall level of traffic demand. All signals which are coordinated using SCATS must share, as at every co-ordination a common cycle time (or sub-multiple). SCATS adjusts cycle time dynamically to maintain the highest degree of saturation in a coordinated group of signals within acceptable user defined limits. Cycle length is increased or decreased to maintain the Degree of Saturation at around 0.9 on the lane with the greatest saturation. Cycle time can range between 20 seconds and 240 seconds, but a lower limit for cycle time (usually 30 to 40 seconds), and an upper limit (usually 100 to 150 seconds), are specified by the user. Cycle time can vary by up to 21 seconds.

Stage split refers to the division of the cycle into a sequence of green signals for the competing movements at each intersection and must reflect the relative demands for green time on each approach. SCATS determination of stage splits is essentially one of maintaining equal degrees of saturation on competing (representative) approaches.

Stage splits are specified as percentage of cycle time and are varied by a small amount each cycle in a way as to maintain equal degrees of saturation on competing approaches.

The minimum split which can be allocated to a stage is either a user definable minimum or, a value determined from the local controller's minimum stage length. The current cycle length and the minimum requirements of the other stages limit the maximum split that can be allocated to a particular stage. Fixed time stages can have their stage time specified in seconds.

Offset refers to the time relationship between the stage introduction points of adjacent signals. The pattern of offsets in a series of coordinated signals must be varied with traffic demand to minimize the stops and delay associated with travel through a network of signals. SCATS selects offsets, based on free flow travel time and degree of saturation, which provide minimum stops for the desired traffic streams. Offsets are selected for the signals within each subsystem, and also between the subsystems which can link. Subsystems carrying lower flows may not receive good coordination if the cycle time is inappropriate. When traffic conditions permit the use of a cycle time that can provide good offsets over a number of subsystems, the system tends to maintain this cycle time even though a smaller cycle time would provide sufficient capacity. SCATS does this because optimal offsets on the heavy flow links minimize the total number of stops in the system, reducing fuel consumption and increasing the capacity of the network.

Degree of Saturation

The adaptive SCATS bases its adjustments on a traffic demand measurement known as 'Degree of Saturation'. However, in this context, the degree of saturation represents how effectively the road is being used. Using the loop detectors in the ground at the critical junction, the local controller collects flow and occupancy data during the green period. The data is sent to a regional computer which calculates the degree of saturation. Values greater than unity (insufficient green time to satisfy demand) will occur in congested conditions, and SCATS will quickly respond to such an over-saturated situation.

Stage Sequencing

The signal cycle is divided into stages, which are labelled A, B, C, etc., and can be introduced in any defined sequence. Any stage, except for that on the most important road, can be skipped if no vehicle is waiting for a green on that road (e.g. if no vehicle is waiting for B stage the sequence would be A–C–A). In isolated and Flexilink modes, the sequence is as defined in the local controller settings. In Masterlink mode, the regional computer determines the sequence.

Subsystems

Every subsystem contains a single critical intersection, one which demands accurate and variable stage splits. The junctions in a subsystem form a discrete group which are always coordinated together, and they share a common cycle length, with an inter-related stage split and offset. Stage splits for all the other junctions in the subsystem are non-critical, and are therefore either non-variable, or are allocated stage splits which are compatible with the splits in operation at the critical intersection. To give coordination over larger groups of signals, subsystems can link with other subsystems to form larger systems, all operating on a common cycle length. These links may be permanent, or may link and unlink adaptively to suit to the traffic conditions. A region can have up to 250 subsystems.

7.8.3 Available Operating Modes

SCATS local controllers can operate in any of several modes. These modes can be invoked manually or automatically by the regional computer or at the local controller:

Masterlink

This is the real-time adaptive mode. Here the regional computer determines the stage sequence, the maximum stage duration, and the duration of the walk displays. The local controller may terminate any stage under the control of the local vehicle actuation timers or skip an undemand stage, unless prohibited by instructions from the regional computer. The regional computer controls the stage transition points in the local controller, but subject to the local controller safety interval times being satisfied (e.g. minimum green, pedestrian clearance). On completion of the transition to a new stage, the local controller times the minimum green and minimum walk intervals, and then waits for a stage termination command from the regional computer. On receipt of the command to move to the next stage, the local controller then independently times the necessary clearance intervals (e.g. amber, all red) for stopping the stage. These safety settings prevent communications errors or regional computer faults from causing the local controller to produce dangerous signal displays, such as short greens or all-red periods. The termination of pedestrian walk signals is also under the control of the regional computer so as to allow the walk timing to be varied to match prevailing traffic conditions. As for the other settings, however, the duration of the walk signal cannot be less than the minimum time programmed into the local controller.

Hurry Call

The local controller invokes a pre-programmed mode usually associated with an emergency stage or local pre-emption such as a train or tram stage.

Flexilink

In the event of failure of a regional computer or loss of communication, the local controllers can revert to a form of time-based coordination known as Flexilink. In this mode, adjacent signals are synchronised by the power main frequency or an accurate crystal controlled clock. The stage sequence and duration of each are determined by the current plan according to the time of day. Local vehicle actuation facilities are still operational in this mode. The local controller may terminate any stage under the control of the local vehicle actuation timers or skip an undemand stage, unless prohibited by instruction within the plan. Flexilink is the usual fall-back mode of operation.

Isolated Mode

Signals may also operate in isolated mode, with local vehicle actuation (by detector loops) being the sole operating strategy. In isolated mode the sequence and the maximum duration of each stage is the one specified in the local controller time settings. The local controller may end any stage under the control of the local vehicle actuation timers or skip an undemand stage, unless prohibited by the local controller settings. Isolated mode may be specified as a fall-back mode of operation.

Police Red

All lamps at the junction have been turned to red using a facility key to actuate a special switch provided on the controller housing.

Police Off

The lamp state at the local controller has been turned off using a facility key to actuate a special switch provided on the controller housing.

Police Manual

The stages at the local controller are being manually implemented using a facility key to actuate a special switch provided on the controller housing.

Maintenance Mode

A technician on-site services the controller.

Flashing Amber

The normal signal display is replaced by flashing amber lights on all approaches, or flashing amber and flashing red to competing approaches. Provided communications are functional, signal operation can still be centrally monitored in Flexilink, Isolated and Flashing modes. Any of them may be applied by an operator using a SCATS workstation, or be programmed by time of day. Flashing amber is also the fall back mode if the controller has a fault.

7.8.4 Control

Operator Control

SCATS provides the operator with a range of manual functions to override the normal automatic operation. These functions allow manual control of:

- Signal lamps to on, flash, or off;
- selection between Masterlink, Flexilink or Isolated mode;
- Alteration of stage split, cycle time or offset, either at an individual junction or for a whole subsystem;
- A dwell facility which allows any signal to be held on a nominated green for as long as required.

Variation by Timetable and Special Routines

SCATS also allows scheduled operation for system. Almost any function which can be executed manually can also be set up to occur at specified times on specified days. A range of special routines is also available in SCATS which allows the user to vary operations to suit special conditions. These routines can be used to detect events and address requirements not covered by the general operation of SCATS.

7.8.5 Fall-Back Operation

Default Fall-back

In the event of regional computer failure, loss of communication between the computer and any local controller, failure of all strategic detectors, or certain other local malfunctions, the affected intersection/s will revert to a user-specified mode of operation. This may be either Flexilink (coordinated) or Isolated (uncoordinated) operation.

Coordination Maintained During Fall-back

If specified by the user, fall-back at one junction will also cause other junctions in the subsystem to fall back and, optionally, junctions in adjacent linked subsystems. In this way, if Flexilink is specified as the fall-back mode, a degree of coordination can be maintained between junctions affected by the failure.

Alternate local signal timings, as well as plans and schedules for Flexilink operation are stored in RAM at the local controller. The master copy of this data is held in the regional computer, so that it may be downloaded from the regional computer to the local controller in the event of it being lost.

7.8.6 Monitoring, Control Facilities and Graphics

User Interfaces

A graphical user interface provides the full range of operator commands and monitoring functions. Up to 200 users are catered for with full access control. The data display includes:

For Intersections: Lamps ON/OFF/Flashing, Current stage demands, Detectors occupied, Cycle length, Operational mode, Alarms, stage running, Time in stage,

For Subsystems: Current splits, Current offset plan, System cycle length, System detector data

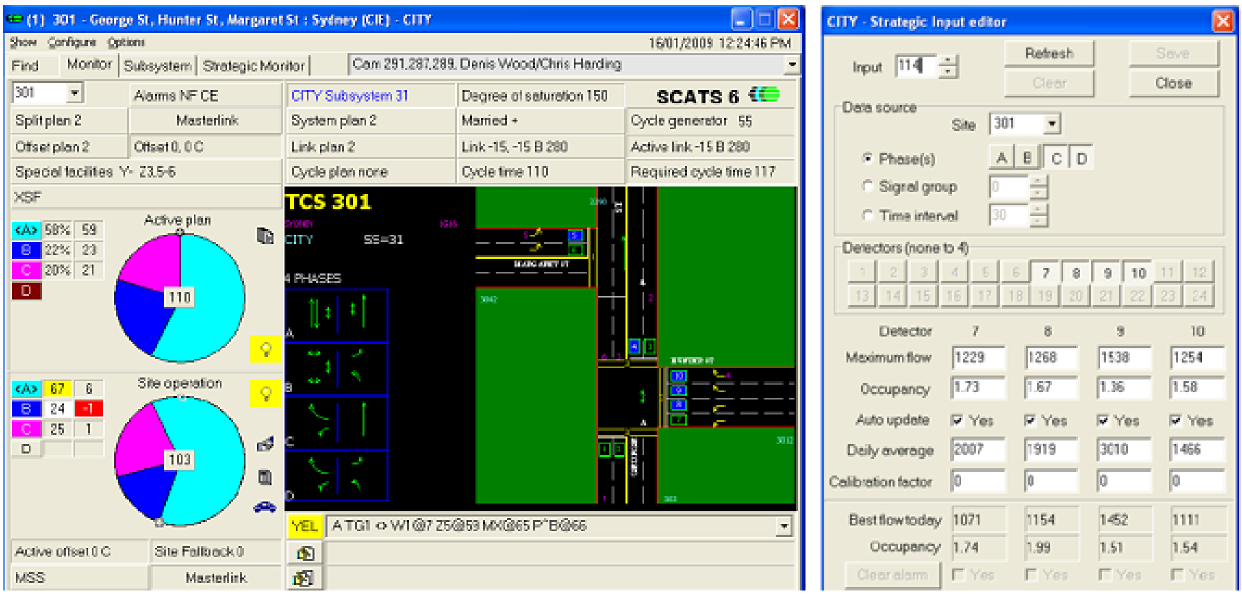

Figure 7.27: SCATS Monitoring Interface and Strategic Input Editor

Graphics

The workstation supports full colour graphics. The user may choose to view the system as a whole, a region, a subsystem or just a single junction. These four levels of display are described and illustrated below. The server window shows a map of the whole system, showing by colour the boundaries of each region, with the coloured bar graphs on the left side.

The window regional graphics shows a map of the selected regional area. There is an on-line representation of traffic flow conditions using five different colours. These represent traffic conditions have a bandwidth from very light traffic to heavily congested traffic. The colour legend is shown on the left side of the interface.

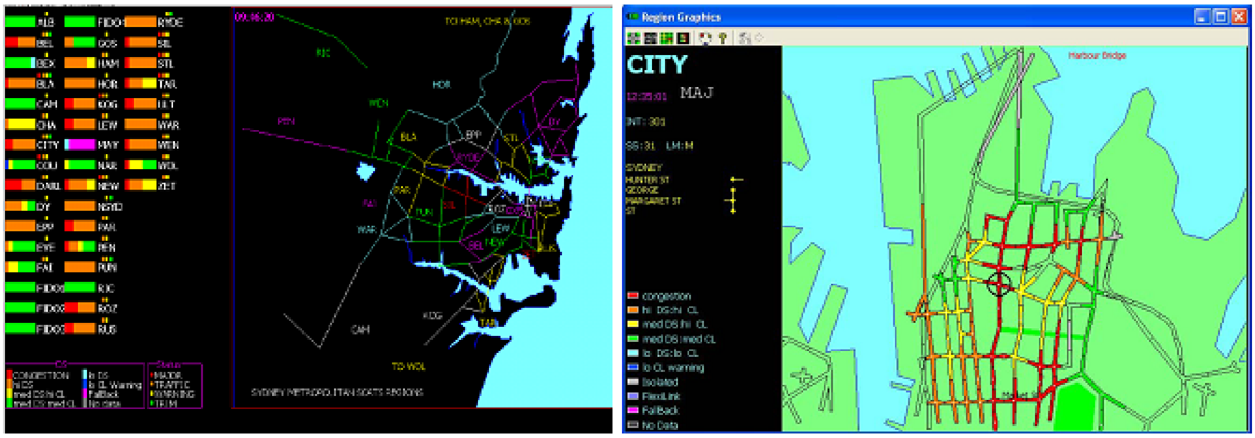

Figure 7.28: SCATS Graphics (whole System and Region)

The graphics windows subsystem display shows the selected subsystem layout together with an on-line graphical bar chart representation of traffic flow and density, as measured by the strategic detectors in the subsystem. The subsystem number is displayed below the region name.

The graphics window intersection display shows the selected intersection layout and staging design, with real time display of detector operation and stage greens.

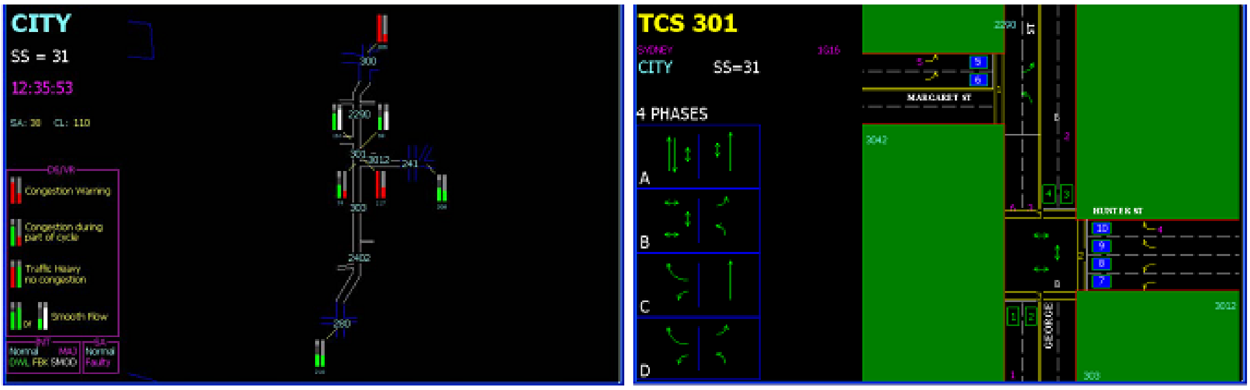

Figure 7.29: SCATS Graphics (Subsystem and Intersection)

On-line Control

It is possible to display and/or change all adaptive control parameters from any workstation while the regional computer is on-line. This can be achieved either by operator command or automatically by time of day. There is no need to take the regional computer off-line when altering data. Manual control of any intersection is also possible from any workstation.

Route Pre-emption

Route pre-emption allows a user to manage the sequential introduction of a green window through a set of intersections and is typically used for emergency vehicles.

Time / Distance (Way) Diagram

The time distance diagram shows the relationship of the stage splits and the offsets in real-time.

Figure 7.30: SCATS Time/Distance Diagram

Alarm Conditions

The system provides a comprehensive set of alarm conditions to warn the operator of all unusual or fault conditions. These alarms are logged automatically on occurrence and clearance, and can be queried at any time. Alarms are also provided for congested traffic conditions in each subsystem.

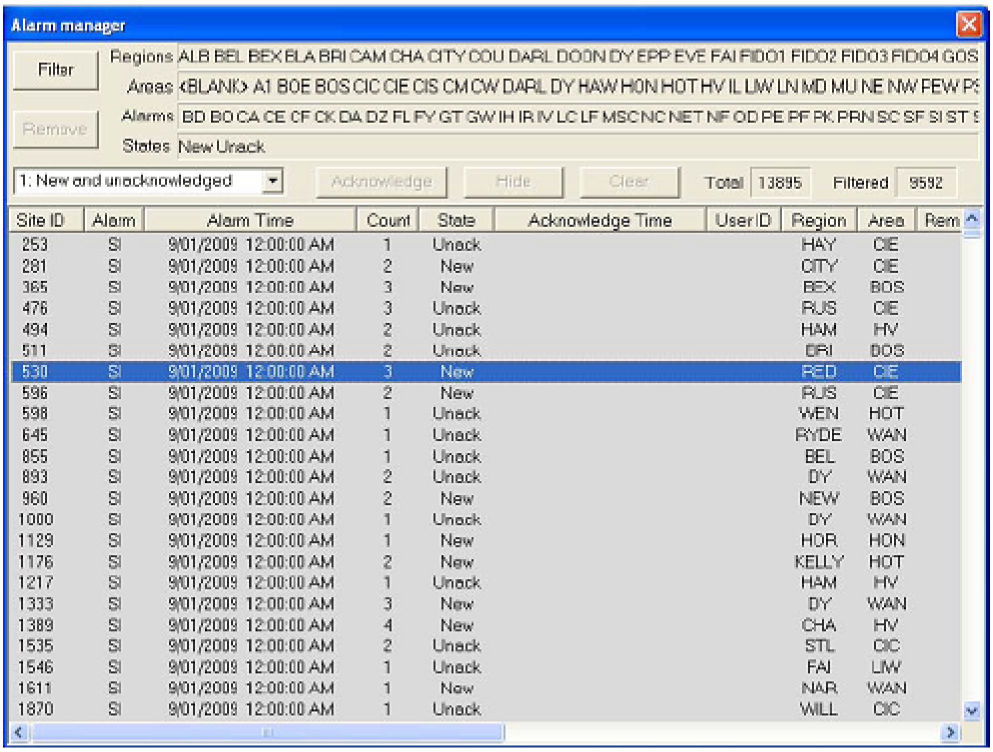

Figure 7.31: SCATS Alarm Manager

7.8.7 Detection

Stop Line Detection

There are loop detectors for both strategic and tactical level control. All detectors (both strategic and tactical) are normally located at or near the stop line (one in each lane). The detector length is crucial for accurate calculation of degree of saturation. If they are too short they may register large values of space under conditions of slow moving, closely spaced traffic (which would appear to a detector to be the same as light traffic widely spaced), if they were too long they would not measure any spaces when traffic moves freely. Research has shown the optimum length of the detection zone to be 4.5 meters.

Strategic Detectors

Strategic detectors are located at the stop line in order to measure how effectively the green time is used by signal-controlled traffic. If the strategic detectors were placed remotely from the stop line, assumptions would have to be made about the flow rate actually achieved during the green period.

Tactical Detectors

Tactical detectors located at the stop line enable differentiation between the left turn, straight ahead and right turn movements at the intersection, both by knowledge of the lane usage in lanes of exclusive use, and by speed differential in a lane shared by two or more movements. If the detectors were remote from the stop line, it would not be possible to identify the intended movement (direction) of detected vehicles due to subsequent lane changing. Additional detectors may be installed in advance of the stop line but this has been found unnecessary.

Detector Requirements

Tactical detectors should be provided on all lanes of an approach (or movement) that would benefit from tactical control, the minor movements being the most suitable. It can be seen that approaches most requiring strategic detection are those least requiring tactical detection, and vice-versa. There will be a need for detection of one kind or the other on most approaches. In general, the approach lanes which can be left undetected are lightly used kerb lanes on approaches which otherwise require strategic detection, and at minor intersections on the main road approaches which are not immediately upstream of a major junction.

7.8.8 Communication and Software

Communication

SCATS supports the following communication methods between a region and junction:

Serial – e.g. leased line; **Network –** e.g. dial IP or ADSL using TCP/IP; **Dial out, Dial in –** using the dedicated DIDO unit

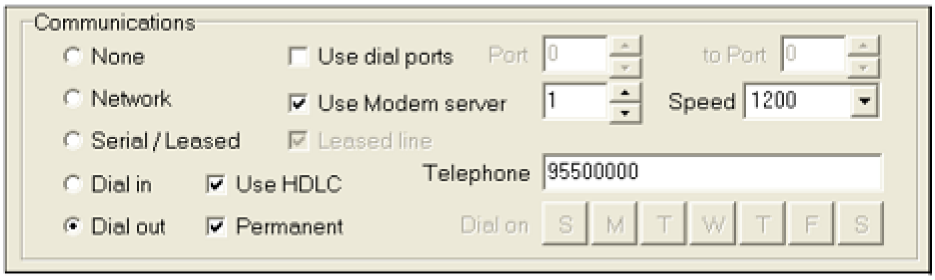

Figure 7.32: SCATS Communication Options

There are messages to and from each junction controller every second. The minimum requirement is 300 bits per second. The low speed rate required for SCATS communications allows for a high degree of tolerance in the reliability of the communications network.

Scats Core Software

SCATS core <u>client software</u> includes the following:

- SCATS Access, incl. Graphics
- Picture
- SCATS Log

SCATS core <u>server software</u> includes the following:

- Central Manager, incl. Configuration
- Region, incl. Configuration

Optional Scats Software

SCATS client software option suite

<u>Traffic Reporter:</u> This utility provides reports for detector volumes and traffic performance in graphical or tabular form.

<u>SCATS Alert:</u> This program allows a user to be alerted when a nominated event is detected for a user definable period.

<u>SCATS Alarm Analyser:</u> Alarm analyser can report on a specific fault over an extended period. It produces a detailed tabulated summary that includes alarms by duration, occurrences per site and occurrences by generation time.

<u>SCATS Communication Monitor:</u> Communications monitor is used to evaluate the communications between intersections and their SCATS regions with particular emphasis on loss of communications and loss of adaptive control due to fall-back. Similar to Alarm Analyser, a detailed summary is produced that includes communications uptime and adaptive uptime.

SCATS History Reader: History reader allows a user to view the stage sequence and stage time at any intersection after the event.

SCATS Server Software option suite

Event Generator

Allows alarms to be raised from non-SCATS devices

SMS Server

Component to send SMS alerts

SCATS Congestion Server c/w Unusual Congestion Monitor

Server component to report Unusual Congestion

SCATS Map

A PC Windows based program used to display SCATS data in control rooms

ITS Port Activation

SCATS has an ITS port that allows operational data to be exchanged with other Intelligent Transport Systems. Enabling of the port to third party applications is subject to an additional licence fee.

7.9 SCOOT

(Split Cycle Offset Optimisation Technique)[9]

It is adaptive and responds automatically to traffic fluctuations. It is an effective and efficient tool for managing traffic on signalised road networks. SCOOT is used in over 170 towns. Using it, an online computer is continuously monitoring traffic flow over the whole network and makes a series of frequent small adjustments to signal timings for reducing delays and improving traffic flow.

Benefits of SCOOT:

- Reduction delays (i.e. 23% in Worcester, 30% in South Hampton)
- 12% reduction against up to date signal settings, 20% over typical fixed time signal control
- Ability to react to unusual events
- Financial benefit (less personnel coast)
- Providing priority to selected vehicles (i.e. buses)

SCOOT-Process

The additional software which links SCOOT kernel to on-street equipment and which provides the user interface is specific to the supplier. SCOOT sends out instructions to the on-street equipment. The equipment replies to the central computer confirming the acceptance of instruction or dealing a fault condition. SCOOT obtains information on traffic flow from detectors. As an adaptive System it

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[9] Day I.; SCOOT-Split, Cycle & Offset Optimization Technique
Department for Transport, Scottish Executive, Welsh Assembly Government; *Traffic Advisory Leaflet (TAL)*
TAL 7/99 – The “SCOOT” Urban Traffic Control System, (1999)
TAL 7/00 – SCOOT gating, (2000)
TAL 8/00 – Bus Priority in SCOOT, (2000)
TAL 9/00 – SCOOT Estimates of Emissions from Vehicles, (2000)
TAL 9/09 – Integration of pedestrian traffic signal control within SCOOT (2009)

depends on good traffic data, so that it can respond to changes in flow. Detectors are needed on every link and their location is important (usually at the upstream end of the approach link). When a vehicle passes the detector, SCOOT converts the information into a “link profile unit” [lpu], a hybrid of link flow and occupancy. “Cyclic flow profiles” of lpu’s over time are constructed for each link.

A SCOOT network is divided into “regions” each containing a number of “nodes” (signalled junctions and pedestrian crossings that all may be “double cycles” run at the same cycle time to allow co-ordination). Region boundaries are located where links are long enough for lack of co-ordinations not to matter. SCOOT has three optimisation procedures for adjusting signal timings. The three optimiser tools give SCOOT the name. Each optimiser estimates the effect of a small, incremental change in signal timing in the overall performance of the regions traffic signal network. Therefor a performance index is used; it is based on prediction of vehicle delays and stops on each link.

7.9.1 SCOOT System Architecture

SCOOT is a second by second system with timing algorithms in a central processor. The local controllers deal with clearance and minimums and the local vehicle actuation is determined by traffic engineering priorities. There is a hierarchical transmission system with flexibility to suit local traffic control needs. SCOOT works on both arterial streets and grid networks (networks from <10 to > 100 intersections).

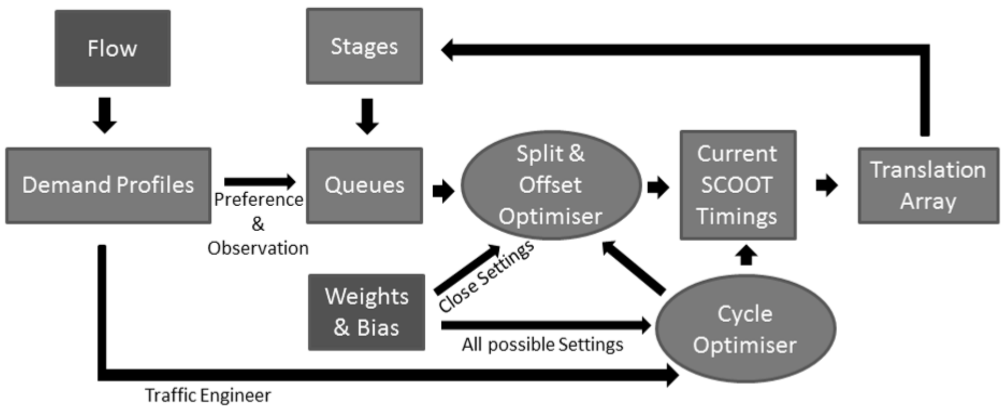


Figure 7.33: SCOOT System Architecture

The main input data is the traffic flow which results in real-time from detector data. From the traffic flow demand profiles are made which are needed for adapting cycles, splits and offsets or for getting impression about the main queues. The second important input data are weights and bias which are needed for choosing the right settings. With the three optimiser tools the current timings are chosen and translated to the stages. The process always remains the same, but input data will change due to traffic demand and traffic conditions.

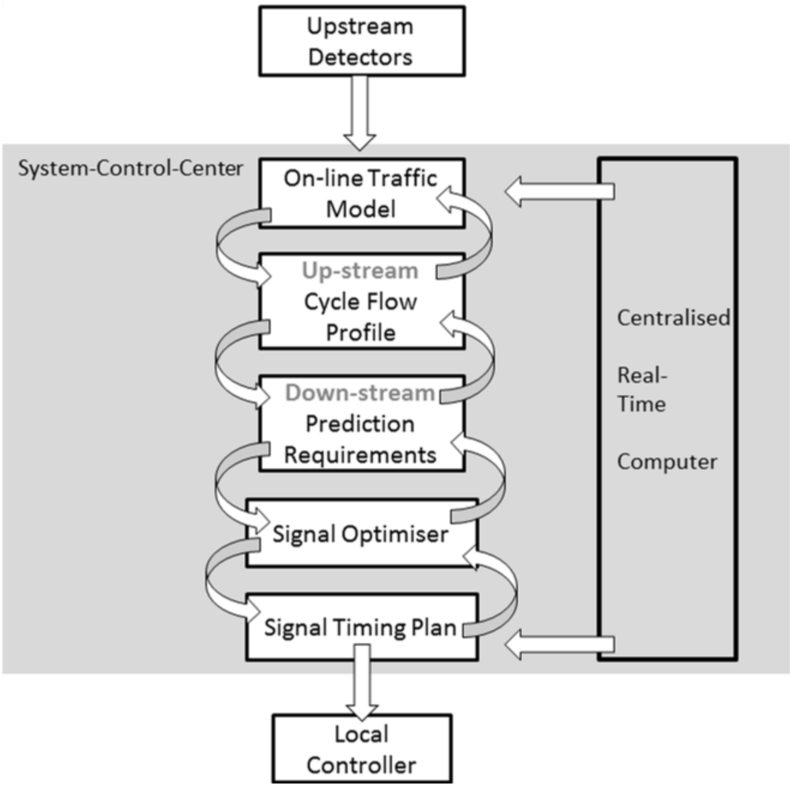


Figure 7.34: SCOOT Work-Cycle

<u>Vehicle Detection</u>

The detectors are placed at the upstream of the stop line, they should be as far upstream as possible. The distance between the detector and the stop line should be larger than the maximum potential queue length. For specific bus priority control, a set of bus detectors should be installed additionally. [NCTU]

<u>Cyclic Flow Profiles (CFP)</u>

It is a measure of the average one-way flow of vehicles at any point on the road during every part of cycle time of the upstream signal. CFP records the crowd of vehicles successively and updates it every 4 seconds. The data was collected from detectors and is stored here. Accuracy of calculation depends on accuracy of data on average flows, saturation flows and cruise times. [IIT] The profile patterns tend to be repeated and coupled with new data in a cyclic sequence to avoid large random fluctuation in the profile. The profiles contain the information needed to decide how best coordinate adjacent pair of signals and cause the signal optimiser to search for a new best timing. [NCTU]

The CFP (1) shows that there is a traffic platoon recognisable at the graph. Most of the traffic crosses the detector as a dense “platoon” during the first half of the signal cycle time. With such an flow profile a good progression could be achieved by ensuring that the downstream signals remain green when the vehicle crowd crosses the stop line. The CFP (2) shows no tendency. There are no vehicle crowds recognisable; there is no vehicle crowd for which the signals should stay green, because the traffic volume is balanced distributed over the whole cycle. The CFP (3) shows that there are two platoons within the signal cycle. In such a case, the green time at the downstream signal may be arranged to give progression to the first, or to the second vehicle crowd.

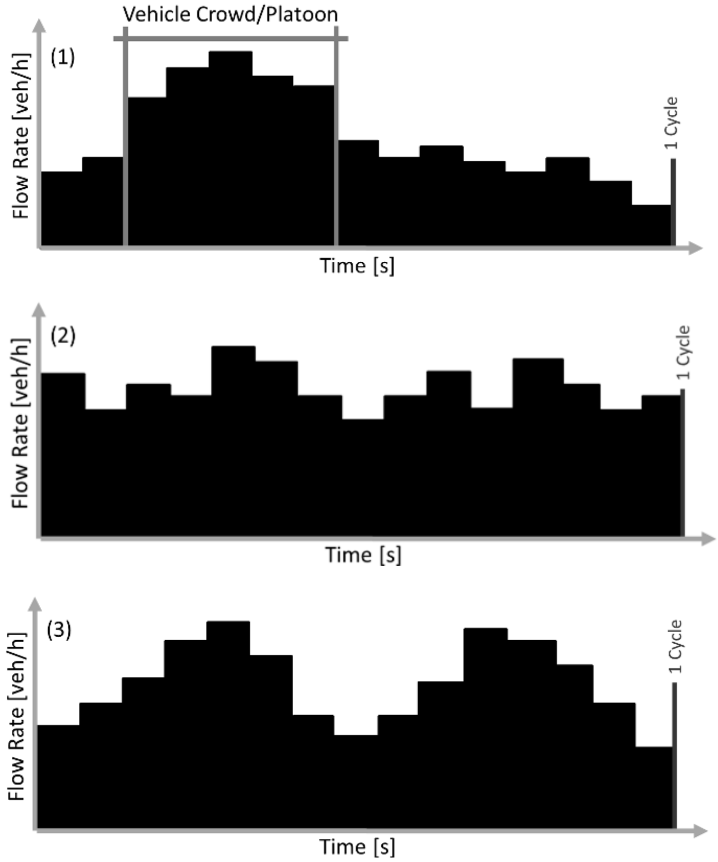


Figure 7.35: SCOOT CFP Example

Queue Estimation

New signal timing must be predicted due to the queues after alteration according to the situation after knowing CFP. The computer for example can be programmed in a way that no vehicle will reach the downstream signals during a red stage, because of that size of queue and duration to clear the queue can be calculated. Known cruising speed must be known (some dispersion). [IIT]

For the prediction of queues the cruise time is used, when the recorded vehicle flows are likely to reach the stop line. Vehicles which reach the stop line during the red time must be added to the back of queue, so that the queue grows until the next green period starts. The predictions of queue lengths cannot be completely accurate, errors may become serious and so various validations have been incorporated into SCOOT.

The traffic model measures the proportion of cycle time at which the detector is occupied, the optimiser uses this information to reduce the likelihood of queue blocking at upstream junctions. SCOOT takes these estimates to calculate an average value for the sum of the queues, which is used as measure of inefficiency of traffic movement (Performance Index PI) SCOOT tries to make the PI as small as possible. [NCTU]

Incremental Optimisation

It is done to measure the coordination plan that it is able to respond to new traffic situations in a series of frequent, but small increments. The incremental optimisation includes the split optimiser, cycle time optimiser and offset optimiser. [IIT]

Split Optimiser

It works at every change of stage by analysing the current red/green timings to determine a change (+-) or to stay the same. It works in increments of 1 to 4 seconds. The aim of the split optimiser is to equalise saturation and congestion considering one stage at a time.

Temporary change is made to the change of green durations to take account of the cycle-by-cycle random traffic variations.

Permanent change is made to the stored values of green duration so that longer term trends in traffic demands can be followed.

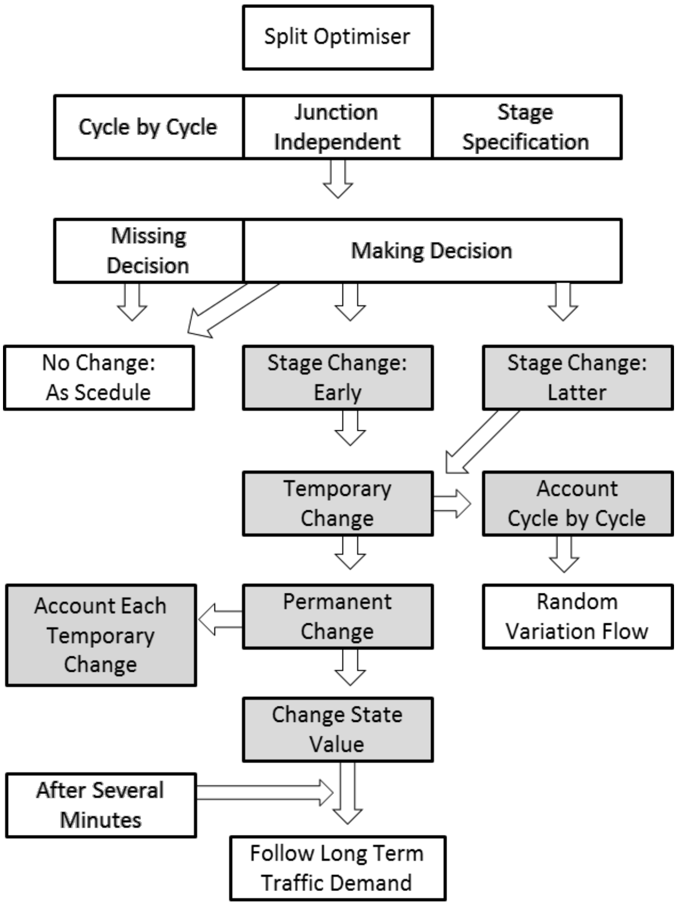


Figure 7.36: SCOOT Split Optimiser

Over a period of several minutes the proportions of green time can be completely revised by SCOOT to meet a new pattern of traffic flows. Each junction is threaded independently. This optimiser performs more frequently than other optimisers. [NCUT]

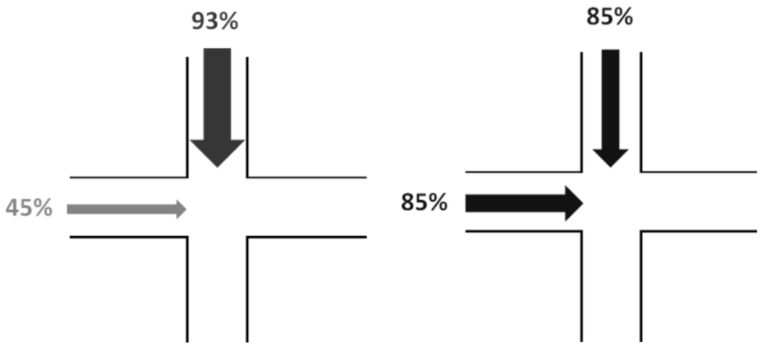


Figure 7.37: SCOOT Junction without/with Split Optimisation

Offset Optimiser

It works once per cycle for each node by analysing the current situation at each node using the cyclic flow profiles predicted for each of the links with upstream/downstream nodes. It advances the existing action time and retards it or remains the same. It works in an increment of 4 seconds.

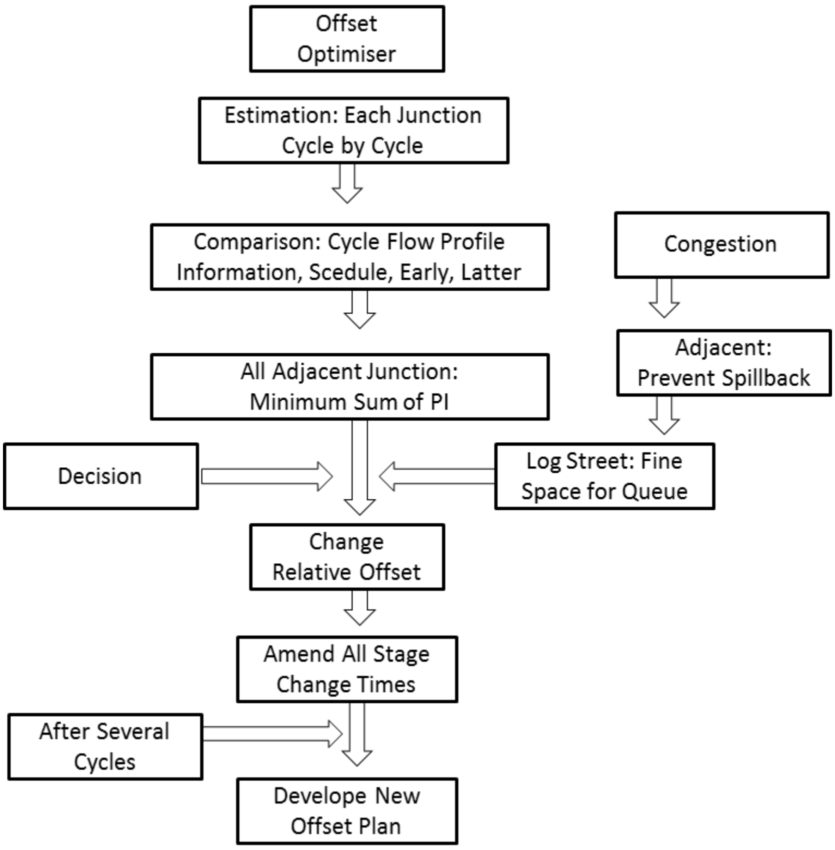


Figure 7.38: SCOOT Offset Optimiser

Because the offset is done once a cycle and is altered relative to adjacent intersection, the offset between an adjacent pair of junctions may alter twice per cycle. Decisions are taken during a predetermined stage within every cycle time. The offset optimiser is always modified when congestion occurs. The offset is optimised to improve the coordination on shorter streets at the expense of longer street, since the longer street has a larger queue storage space to prevent potential spillback. SCOOT will automatically move the offset to congested directions, to provide the congestion movements with a larger green band. [NCTU]

Cycle Time Optimiser

It operates on a region bases once every 5 minutes (2.5 minutes minimum when cycle times are rising rapidly). It identifies the critical node in a region and will attempt to adjust the cycle time to maintain this node with 90% link saturation on each stage. If a change in cycle time is required it increases or decreases the cycle time in 4, 8 or 16 second increments.

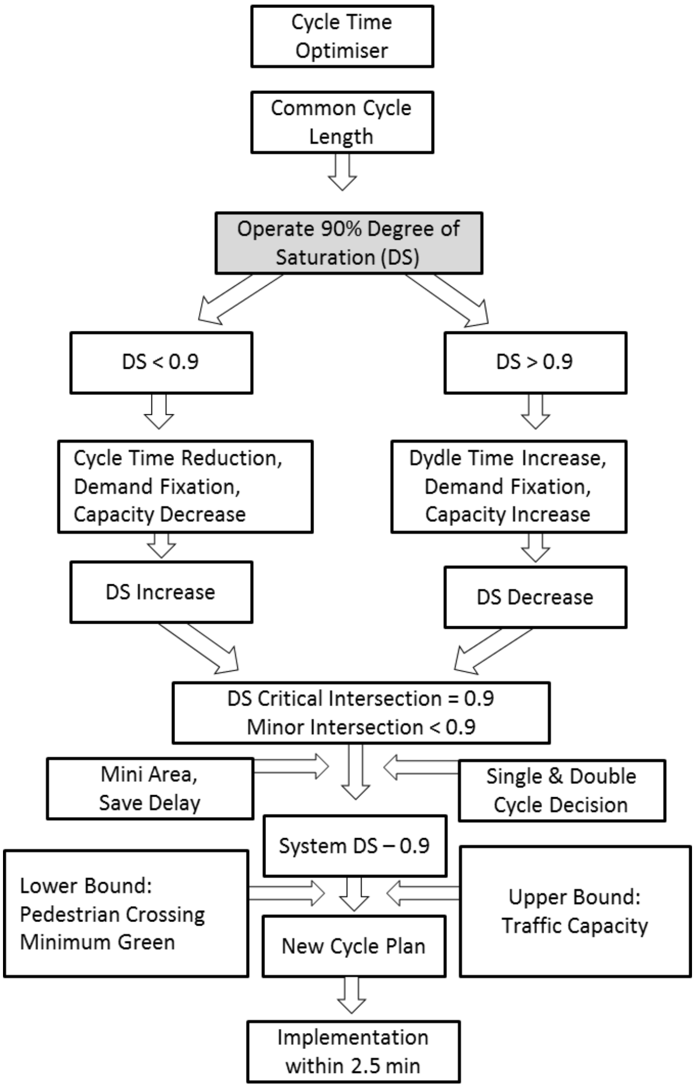


Figure 7.39: SCOOT Cycle Time Optimiser

All signal controlled intersections are grouped into “sub areas” which have pre-set boundaries. All signs within that area are operated with SCOOT at a common cycle length (or half = double-cycling) The lower bound is determined by the considerations of safety (intergreen time), pedestrian crossing time and minimum green time (30-40 s), the upper bound is set to give maximum traffic capacity but without unduly long waiting times. In SCOOT the cycle length will increase when traffic demand is increasing [NCTU].

All optimisers together build the Signal Optimiser. So with all Optimiser Tools SCOOT makes frequent changes by small alternations to the parameters so as to adapt the fixed time plan to variations in the traffic behaviour. A few seconds before each stage change, SCOOT estimates every junction whether to change is or not, to minimise the degree of saturation on the junction approach. Calculation is to take account of current queue length, approach congestion measurement and minimum green time constrains [NCTU].

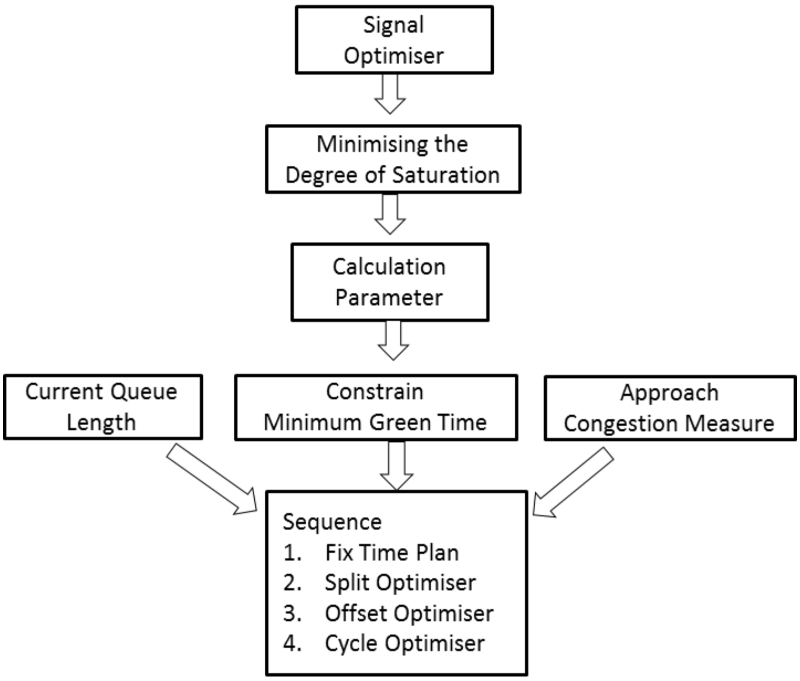


Figure 7.40: SCOOT Signal Optimiser

The SCOOT based UTS system includes a central processor unit, transmission equipment, PC operator terminals and printers. A number of PC's, workstations and printers may be linked to the system. Usually also a roving terminal exists. Fault management and remote monitoring systems support the SCOOT. SCOOT can also be linked to other systems (Variable Message Signs, Emergency Green Wave Routes, Fleet management Systems for Buses, Fault Identification and Management, Diversions, Fixed time plans…)

SCOOT is used and designed for dense urban road networks (London and larger cities) but it is also effective and suitable for small networks. It is effective where traffic flows are unpredictable (random changes), but it should not be used for junctions more than 1 km apart (MOVA would be more appropriate)

SCOOT has speciality use-cases:

- Gating,
- Bus priority,
- ASTRID (Automatic SCOOT Traffic Information Database),
- INGRID (Integrated Incident Detection),
- improved faulty detector logic,
- flexible optimiser Authorities,
- Estimate of vehicle emissions,
- use of historic data in cycle time optimiser,
- use of existing non-SCOOT-loops,
- enhancements for the cycle time optimiser,
- fire priority, and
- transit priority

Hardware Requirement:

- Central computer – DEC Alpha workstation/s, running Open VMS
- Operator workstations – dedicated network possible, interface to existing network/workstation
- Data transmission – copper cable, fibre optic or combination
- On-street equipment – no need to replace existing one

Data Requirement:

- Detection on every link for which full optimisation is required
- Detectors are generally located at the upstream end of link
- Connection to central computer achieved via upstream intersection
- Links with no detection run fixed length or can have can have data from upstream links
    - Fixed length stages can be varied by time of day

Two Control Strategies:

There are two control strategies at scoot. Providing settings for discharging vehicles or limiting traffic flows because of sensitive areas or priority of special vehicles.

The Upstream Control Strategy, also called gating facility limits the traffic flows. The Downstream Control Strategy discharges vehicles with proper signal settings as soon as possible.

7.9.2 SCOOT Gating

It is used for the control of traffic inflow into sensitive areas where it is particularly important to prevent serious congestion. Gating is also used to assist in clearing traffic from sensitive areas or to relocate queues in conjunction with bus priority measures. Gating is not universally applicable although it is appropriate to help prevent serious exit blocking of junctions and particularly gyratory (roundabout) systems, where the exit blocking delays cross-traffic.

The gating logic allows one or more links to be identified as critical or bottleneck links. The bottleneck link can affect the green time on the gate links. Gated links are those that have been designated to store queues which would otherwise block the bottleneck links. When the bottleneck link is too busy, the green time is reduced on the gated links. The traffic engineer would specify a link as a bottleneck if it was important to avoid large queues on the link and those queues could be relocated to one or more gated links.

The gating logic can also be used for opening up/down stream links enabling the bottleneck link to clear.

SCOOT Gating is used

- for bus operations,
- for metering the entry of private traffic,
- for Relocating queues to roads with bus lanes off bus roads/routes,
- for Relocating queues to more acceptable positions,
- to protect sensitive areas,
- for clearing traffic,
- to transfer emissions to not sensitive areas.

Method of Gating:

1. Define an area to be protected
2. Define the allowable congestion or degree of saturation of each link
3. Define the relocating and the minimum green period allowed when gating is relocating queues to those links
4. Define the saturation level at which SCOOT gating will operate automatically as required by conditions in protected areas

Bating is most beneficial to general traffic where a) a gyratory may-grid lock, particularly if there is a restriction on the exit from the gyratory b) there is a substantial amount of cross-movement traffic.

7.9.3 Bus Priority in SCOOT

Passive priority can be given using the split and offset weighting parameters that can be applied to give priority to links and routes. It does not differentiate between vehicles (low level of priority). For active priority to operate buses they need to be separately detected and priority is then given to the individual bus.

Bus Detection:

The detection is done by selective vehicle detectors (i.e. bus loops/ bus-borne transponders) or by automatic vehicle location systems (AVL).

Bus loops and AVL, where bus detection points can be specified, have advantage of placing them at optimum positions. The position is chosen, due to need for detection as far upstream as possible, due to the need for accurate journey time prediction downstream of any bus stop (because SCOOT does not consider bus-station-stops). Moreover a location having a bus journey time from 10 up to 15 seconds to the stop line is recommended.

Modelling:

Buses are modelled by SCOOT as queuing with other vehicles. This allows buses to be given priority even though other vehicles may delay them. The effect of bus lanes can also be modelled, including those, which end before the stop line.

Optimisation:

It is done by the benefit of buses, either by extending a green signal (extension) or causing succeeding stages to occur early (recall). Extensions can be awarded centrally, or the signal controller can be programmed to implement extensions locally on street (local extension). At a three stage junction, if a bus is detected towards the end of stage 1 (green period on Link A) it will receive an extension (stage 1 is extended)

At the example buses arrive on link A only. If the bus is detected during the red period, it will receive a recall.

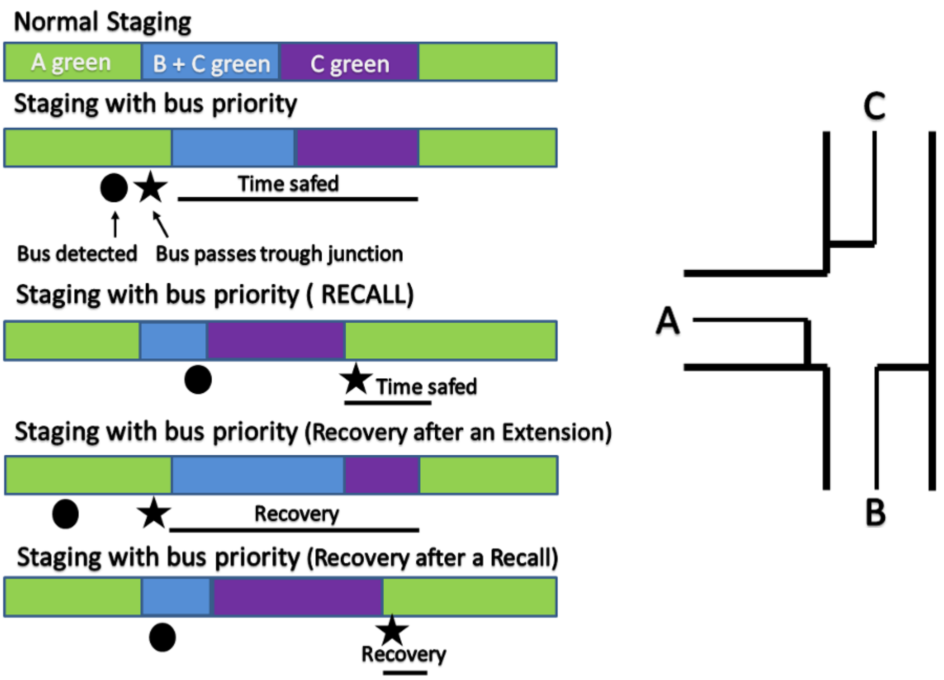


Figure 7.41: SCOOT Extension, Recall and Recovery

Recovery:

Once the bus has passed through the intersection, a period of recovery occurs to bring the timing into line with the SCOOT optimisation. Several different methods are available for use.

Restrictions on Priority:

One of the main advantages of providing priority through SCOOT is that the extent of priority given to buses can be controlled. Priority can be restricted depending on the saturation flow of the junction as modelled by SCOOT. This is managed by specific target degrees of saturation for extensions and recalls. There is no oversaturation possible. Bus priority will be most effective at junctions that have spare capacity.

Likely Benefits of Bus Priority:

Stages which are not running close to their minimum length, the benefits of priority are dependent on the traffic conditions. When degree of saturation is low up to 50% delay reduction can be reached. When degree of saturation is high just 5 to 10% delay reduction is possible.

At low degrees of saturation the increase in delay is small (to private traffic). At high degrees of saturation the increase in delay can be large. The disruptive effect of providing priority by recalls is much greater than by extensions. Benefit per buses decreases when bus flow increases. Small but significant improvement in regularity of buses can be made.

Very high Priority:

If it is desired to provide higher levels of priority than by using the active priority facility, it is possible with overriding SCOOT. This can be done by using the controller hurry call facility or by other means. It is recommended that this is only used for emergency vehicles and other important but infrequent services such as Light Rail transit. Frequent uncontrolled overriding of SCOOT is likely to be very disruptive and can be counter-productive, particularly at high levels of saturation. New recovery logic in SCOOT version 4.2 enables to recover efficiently from such a request.

7.9.4 SCOOT Estimates of Emissions from Vehicles

SCOOT has been modified to provide information on the contribution as road traffic to air pollution. The pollutants estimated are: carbon dioxide (CO_2), carbon monoxide (CO), oxides of nitrogen (NOX) volatile organic compounds VOC, particulate matter with an aerodynamic diameter of less than 10 µm.

The estimates are based on relationships between link speed, vehicle type and pollutant emissions. The SCOOT model provides estimations of the delay on all links. With the addition of information on link length, the model converts the delay estimation into link speed to produce a rate of emission per vehicle.

The total emission on each link is the estimated rate of emission multiplied by the link length. A standard mix of vehicles is used, it can also be adapted.

Estimates of emissions are available for individual links or aggregated. They are provided numerically as standard, but can also be input to the ASTRID data base → storage and analyses.

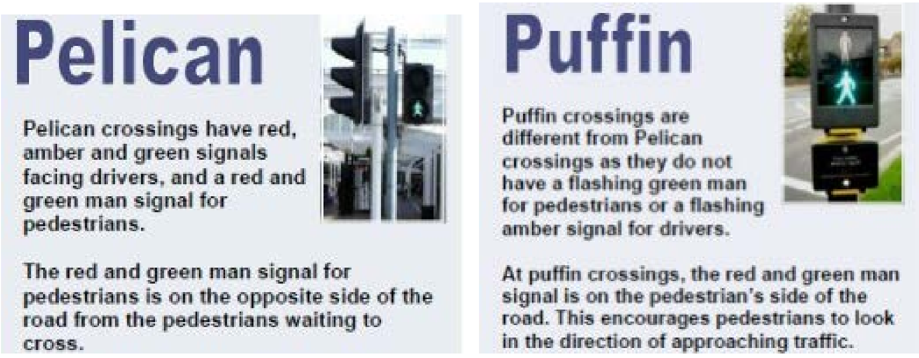
SCOOT can help lower the overall level by reducing delays. The results are 5-6% lower peak emission. Large increase in pollutants is estimated at a relocated queue. The average exposure to pollutants has been reduced. Reducing emissions is done by reducing delays, managing emissions (relocating queues), estimation and evaluation.

7.9.5 Integration of Pedestrian Traffic Signal Control within SCOOT-UTC

When signal-controlled installations are controlled by a SCOOT UTC system, nodes in the same region are all constrained to operate at the same cycle time. The pedestrian stage is called at the same fixed position in the stage order with its start time dependent on vehicle demand and region coordination. One consequence can be that pedestrians have to wait longer for an invitation to cross than they would if the crossing or junction was operating independently.

At Puffin crossings, pedestrians are presented with near-side indicators and vehicle movements are controlled using conventional three aspect signals and the same light sequence as at junctions.

Pelican crossings use far-side pedestrian signals and do not positively control all vehicle movements – during the flashing vehicle amber it is individual drivers who decide whether to proceed or not. The rules are clear, that drivers must give priority to pedestrians, but the drivers are not held at a red signal.



Reference: http://www.lferesident.co.uk/news/2011/301112_1c.html

Figure 7.42: Pelican and Puffin Crossing[10]

The SCOOT kernel software was modified to correctly model the variable intergreen period that follows the pedestrian stage, rather than assuming it runs for a fixed length. As a consequence SCOOT now accurately models the on street behaviour of stand-alone Puffins and variable pedestrian intergreens at junctions, thus providing improved control and reductions in delay to vehicles.

The pedestrian priority strategies work by reducing the time before the next pedestrian stage can be initiated on the street. Within SCOOT, the offset optimiser seeks the optimum time in cycle such that the pedestrian stage can run when it will cause minimum delay to vehicles. The advantage of the priority strategy does reduce as pedestrian demands increase, especially when there is pedestrian demand every cycle.

It is important that the various SCOOT parameters controlling the operation of junctions and pedestrian crossings are set correctly to achieve the intended effect.

<u>General Considerations</u>

<u>Double Cycling</u>

Pedestrian waiting times are directly related to cycle time. Puffin and pelican stand-alone crossings normally have only two stages and the pedestrian stage is not as long as many vehicle stages. Therefore, when giving priority to pedestrians, the first action recommended both under fixed time and SCOOT control is to double cycle all Puffin and pelican crossings, unless the consequential extra vehicle delay will be prohibitive at a particular crossing.

[10] http://www.lferesident.co.uk/news/2011/301112_1c.html

Gap Out

Another strategy that has been used to reduce waiting time of pedestrians is to allow the pedestrian stage to come in early when a gap is detected in the approaching traffic (gap out). It can be used at both Fixed Time and SCOOT UTC controlled crossings, however it requires suitable Vehicle Actuated (VA) detectors on each approach, additional to the SCOOT detectors.

Importance of Coordination

Crossings running VA control which are close to neighbouring junctions are likely to cause considerably more vehicle delay than those some distance away. Where pedestrian crossings are close to junctions, good coordination is important as VA operation in busy conditions would be expected to result in a large increase in vehicle delay.

Limiting Pedestrian Waiting Time

If it is desired to set a limit on the maximum waiting time of pedestrians, this can only be achieved in UTC systems by limiting the cycle time and under VA operation by setting the maximum vehicle stage length.

Pedestrian Facilities at Junctions

The modelling of the variable intergreen in SCOOT can give valuable benefits at junctions with Puffin type pedestrian facilities on an all-red pedestrian stage. Where the pedestrian stage is called every cycle, the benefits of the enhanced feedback are likely to be in the order of a 10% saving in delay to vehicles.

The improved modelling of the variable intergreen will, however, not be of direct benefit to pedestrians. There is no facility at present to provide priority to pedestrians at junctions. The pedestrian stage will be served once per cycle at the same point in each cycle. To reduce pedestrian waiting times at junctions it is necessary to reduce the cycle time.

A junction with a pedestrian stage will operate at least 3 stages (two vehicle stages and the pedestrian stage). Consequently, it is unlikely to be able to double cycle without causing appreciable delay to vehicles unless it is very much less heavily loaded than the busiest junctions in the region.

Therefore, the main way of limiting pedestrians' waiting times is to set the maximum region cycle time to be as low as possible. The decision on the maximum cycle time and the consequent effects on pedestrian waiting time and vehicle delay will be a local policy matter.

7.10 UTOPIA

(Urban Traffic Optimisation by Integrated Automation)[11]

UTOPIA can be used with a wide range of strategies designed to suit to any road network. In the fully adaptive mode, it constantly monitors and forecasts the traffic status and optimises the control strategy according to flow efficiency and/or environmental criteria. UTOPIA was developed in the 1980s. It is used in dozens of metropolitan areas today. (Europe: Sweden, Norway, Denmark, Netherlands, Belgium, Poland, Romania, Ukraine, Russia, Ireland, Italy…)

It was developed as a hierarchical and distributed architecture, which consist of a higher level (centre) and a lower level. The higher level is responsible for setting the overall control strategies

[11] Gündogan F.; *Simplified traffic responsive signal control method for developing large cities*
Mauro V.; UTOPIA – Urban Traffic Control – Main Concepts;
SWARCO MIZAR S.p.a; *UTOPIA, Optimiert den Verkehrsfluss Strassennetzübergreifend*, 2013
SWARCO MIZAR; *UTOPIA – Urban Traffic Control System Architecture*; 2012

like long-term forecasting and network optimisation, while the traffic signal control is implemented by means of the SPOT (System for Priority and Optimisation of Traffic) software at a lower level.

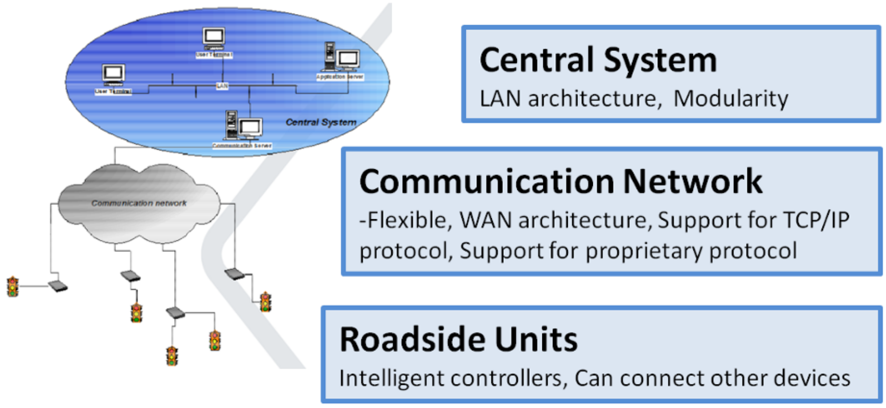


Figure 7.43: UTOPIA Physical Architecture

The weighted and selective priority of public transport vehicles at signalised intersections is made possible with SPOT at the lower level. The system has a modular architecture, which is significant to extend the system and add additional intersections. Each local control unit is further subdivided into two main parts; the observer and the controller. The observer updates the estimations of traffic states based on collected data. The observer also performs also the estimation of slow time-varying intersection parameters such as travel times, turning percentages and saturation flows. The controller determines the suitable timing plans for actual situation at the intersection. It performs an optimisation on the ‘time horizon’ consisting of the next 120 s, and is repeated every 6 s.

SPOT uses delay and number of stops as cost and in order to give priority for public transport vehicles higher unit costs are used for those vehicles. The weights of costs are updated at the network level. The local level has also an important feature for local oversaturation problems. If the observer detects local unpredictable change in demand or in network parameters on the single link, the controller does two actions successively. The first action consists of relaxing constraints on green times both in the actual intersection and the receivers. Additionally, the queue weights of the critical links are increased. If the first action does not succeed, the second action is performed. During the critical period a new cost element is evaluated. In order to obtain a smoothed traffic for each demand situation in the whole control area, the area control chooses the suitable functional and parameters for the local level.

The system was further developed through the addition of the public transport fleet management system FLASH. The FLASH generates the forecasts that used by UTOPIA for public transport priority. UTOPIA/SPOT is implemented at more than 30 European cities, controlling large areas (like Turin, Rome and Milan) and smaller networks (like Oslo, Bergamo, Cremona and Eindhoven)

UTOPIA offers unmatched performance, especially in congested and unpredictable traffic conditions. Field trails have demonstrated the following benefits:

- 15% decrease in travel times for private traffic,
- 50% reduction in queuing time,
- 10% decrease in emissions and fuel consumption in urban areas.

A range of strategies are available: from plan selection to traffic responsive and fully adaptive, to permit the ideal solution for each specific site.

8 COLOMBO Traffic Policies

Both, a macroscopic level control method as well as different microscopic level control methods are developed within COLOMBO. These methods rely on traffic information to operate and are all based on approaches from the area of “swarm intelligence”. In the following, the term "Policy" is introduced to indicate them.

8.1 Self-organizing Traffic Lights: the Concept

The developed traffic lights “constrain” vehicle flow and act in an emergent system by applying local policies selected on the basis of traffic information. The main concept is inherited from swarm intelligent systems applying natural computing techniques implementing natural metaphors. Some examples of swarm intelligent systems are ant colony algorithms, bee colony algorithms and particle swarm optimization. Despite these systems are different, they have some common overlying concepts that characterise swarm intelligent systems: the presence of multiple and simple agents that are not necessarily aware of the system they are part of, the very simple form of interaction between agents and the environment or among agents possibly based on stigmergy, and the capability of the agents of adapting the behaviour on the basis of past experience, thus providing a form of positive (reinforcement) or negative feedback on the system. Stigmergy is a form of self-organization, with indirect interaction and coordination between the agents wherein an agent responds to a modification of the environment caused by another one [Bonabeu].

We conceive a traffic light system as a self-organizing system such as depicted in Figure 8.1. The system works in a continuous loop like every classic digital control system: sensing, evaluation, action. In particular, information is acquired from sensors, elaborated and used to feed stimulus functions that probabilistically select one out of a set of rule-based policies, specifically defined for different traffic conditions, the one to be executed for the next time span.

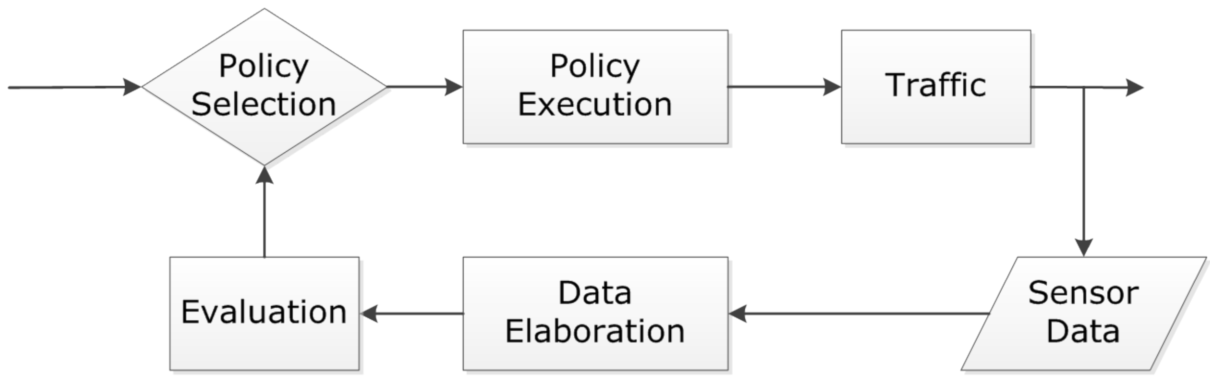


Figure 8.1: Self-organizing traffic light system

The concept of static timing and phases for traffic lights is abandoned: a traffic light does not change according to any clock but after sensing. This gives traffic lights the capability to react with the smallest possible delay to traffic density changes in incoming and outgoing lanes. In comparison to conventional phase cycles, a reactive control based on sensor-aware decisions allows a larger flexibility in giving green for certain vehicle flows across the intersection. The **system evolves autonomously and learns from previous experience, thus adapting to drivers behaviour**. In the simplest case, each agent (i.e. a traffic light controller) that controls an intersection acts on the basis of local information and **does not explicitly communicate with neighbouring intersections**. Neighbours then communicate indirectly through stigmergy. It can produce complex, seemingly intelligent structures, without a need for any explicit planning, external control, or direct communication between the agents. As such it supports efficient collaboration between simple agents that lack any memory, planning capabilities or even awareness of each other.

We will consider the usage of self-organizing traffic light systems at several levels. At the lowest level, we consider the possibility of adding individual, self-organizing traffic lights into an existing network of traffic lights. Here the goal is to design appropriate control policies for the (few) traffic lights that will be based on self-organized control. We also consider progressively increasing fractions of traffic lights that are controlled using self-organizing principles until reaching a full network of self-organizing traffic lights. The main effort of the COLOMBO project is dedicated towards making self-organizing traffic lights an effective means for practical traffic light systems.

The common founding principle of the policies developed for the COLOMBO project is that each traffic light controller, controlling one or more interconnected junctions, operates independently of all other controllers and gets information only on the traffic flow on its incoming and outgoing lanes. This principle is derived from autonomous agents theory where each agent – a traffic light controller in our case – can rely only on local information, and no central coordination can or should take place. Likewise, no connection between neighbouring traffic lights controllers is assumed.

The main reason for choosing this local information approach is that a centralized control to decide which policy should be executed for each junction at each step in time would be computationally too expensive and would be very difficult to optimize. In most cases, such an approach would mean trying to predict traffic behaviour, while the intrinsic nature of traffic makes it highly unpredictable, and would mean having a control that cannot easily react to the actual traffic conditions vs. the predicted ones.

On the other hand, an emergent distributed control system that uses a self-organized approach where each traffic light controller senses local traffic conditions, selects the proper policy and then executes it reduces computational complexity, is simpler to implement, and favours the reactivity of the control system to the rapidly varying conditions.

8.2 Macroscopic Level Policy - Swarm

As will be presented in the next paragraph, each microscopic level policy performs best in different traffic conditions: some very reactive policies that cause the traffic light to switch as soon as possible are suitable for very low traffic conditions, when the overhead introduced by the amber period and all transitory stages is easily compensated by the fact that very few cars could be forced to slow down or halt. On the other hand, in high traffic conditions the policies should be smoother and ensure that the traffic light does not switch too often. The goal of the macroscopic level policy is to select which microscopic level policy should be executed at each time step, given the current traffic level and the performance of each microscopic policy for the current junction.

8.2.1 Measuring Traffic - Pheromone Level

There is some uncertainty in the definition of “high” vs. “low” traffic and on how to measure it, because it depends on the number of lanes and their width, the geometry of the intersection, and the vehicles’ paths. The measure of the traffic should be rather insensitive to very short peaks, like a singular platoon, but should react rapidly to more persistent traffic changes where we expect a burst in traffic from a single direction that will last for fifteen to twenty minutes.

For these reasons, an abstraction of the level of traffic is used, using simulated **pheromone levels.** In nature, pheromone is an olfactory trail left by some animals like ants on the path they walk. This pheromone is additive: the more ants walk on a path, the higher the level of pheromone. Pheromone also evaporates over time, allowing ants use this as a guidance to choose their direction: the shorter the path from home to food, the less the pheromone evaporates and the higher the level.

In this project, pheromone levels are used to calculate the level of traffic: cars driving down a lane or waiting at a red traffic light leave a virtual pheromone trail. It will quickly sum up if a significant increase of the traffic volume happens, and will evaporate in a short time when the number of cars decreases. For reasons that are most clear considering the *Congestion* policy, the pheromone level at a junction is computed separately for incoming and outgoing lanes, but using the same equation structure. The measured input is the mean vehicles' speed.

The pheromone accumulates proportionally to the difference between the allowed speed on a lane and the current mean speed. This is taking into consideration the speed-density relation of the fundamental diagram [Greenshields, 1935], that is the number of cars in a lane does not count as long as the traffic is freely flowing.

Some parameters, presented in Table 8.1, affect the computation of the pheromone level: the accumulation and evaporation coefficients both for incoming and outgoing lanes, and a maximum value that pheromone levels can have.

The pheromone for each input lane is then calculated as:

```
double pheroAddIn = lane.getMaxSpeed() - getSensors()->meanVehiclesSpeed(lane);
double pheroIn =
        getBetaNo() * lane.pheroIn +       // Evaporation
        getGammaNo() * pheroAddIn;           // Accumulation
lane.pheroIn = min(pheroIn, getPheroMaxVal()); // Limit to max value
```

Similarly, the level of each output lane:

```
double pheroAddOut = lane.getMaxSpeed() - getSensors()->meanVehiclesSpeed(lane);
double pheroOut =
        getBetaSp() *  lane.pheroOut + // Evaporation
        getGammaSp() * pheroAddOut;       // Accumulation
lane.pheroOut = min(pheroOut, getPheroMaxVal());// Limit to max value
```

The average of the pheroIn and pheroOut on the lanes values are then used as the pheromone_{in} and pheromone_{out} levels for the swarm policy:

```
double pheroIn = 0;
double pheroOut = 0;
foreach (MSLaneId lane:lanes) {
        pheroIn += lane.pheroIn;
        pheroOut += lane.pheroOut;
}
pheroIn = pheroIn/lanes.size();
pheroOut = pheroOut/lanes.size();
```

8.2.2 Stimulus Function

As noted before, the microscopic level policy that performs best in a junction depends on the current level of traffic and on the geometry of the intersection. For a given junction, simulations are carried out simulating each policy with different traffic levels. Performance Indicators such as the average waiting time of vehicles or the average delay are used to estimate at which level of pheromone in the incoming and outgoing lanes each policy performs best. Based on this information, each microscopic level policy is mapped in the pheromone_{in} x pheromone_{out} (i.e. $\varphi_{in} \times \varphi_{out}$) space using a **stimulus function**. At run time, the swarm policy will measure the pheromone levels at each simulation step, and will use this mapping to select the microscopic level policy.

A stimulus function is the way to compute the current level of stimulus for every policy a traffic light controller is able to execute, with respect to pheromone levels: the more desirable the policy, the higher the stimulus. The stimulus function has two inputs: the current pheromone level in the input lanes and the current pheromone level in the output lanes. The output is a value in [0-1]:

$$s_{i,j}: [0, \varphi_{in\_max}] \times [0, \varphi_{out\_max}] \rightarrow \mathbb{R}^+$$

where $s_{i,j}$ is the stimulus of the *j*-th policy calculated for the *i*-th agent. The domain is a subset of $\mathbb{R}^2$. The chosen type of function is a Gaussian that is centred where the policy performs best. The parameters of the Gaussian are computed off-line by testing the performance of each policy in different traffic situations. The definition of the stimulus function may vary from an agent to another and the distinction over the *i*-th agent reflects this possibility.

Moreover, the stimulus function must be normalized over its domain:

$$\iint\limits_{[0,\varphi_{max}]\times[0,\varphi_{max}]} s_{i,j}(\varphi_{in}, \varphi_{out})\, d\varphi_{in} d\varphi_{out} = 1 \tag{8.1}$$

Note that this formulation makes the stimulus similar to a probability density function. This is important since it allows expressing the level of specialization of a policy: a stimulus function must have high values in the neighborhood of specialization and decrease rapidly outside.

As stated before, the type of function used for describing the stimuli of our policies is the normalized Gaussian. The expected value and variance are suitably adapted for every different policy. This type of function describes well the behavior of the policy since it has high values in the neighborhood of its maximum value and decreases rapidly outside it.

The stimulus function that describes probability density of the normal distribution is:

$$s_{i,j}(\varphi_{in}, \varphi_{out}) = \frac{1}{\sqrt{4M^2|\Sigma|}} e^{-\frac{(\varphi_{in}-\mu_{in})^2}{2\sigma_{in}^2} - \frac{(\varphi_{out}-\mu_{out})^2}{2\sigma_{out}^2}} \tag{8.2}$$

where M is the vector of the expected values $[\mu_{in}\ \mu_{out}]^T$ and Σ is the covariance matrix. It is not possible to use directly this form since the normalization coefficient is valid for an integration over the whole real domain. For our policies, we need a normalization coefficient for a limited domain, so the generic stimulus function will be:

$$s_{i,j}(\varphi_{in}, \varphi_{out}) = \frac{1}{V} e^{-\frac{(\varphi_{in}-\mu_{in})^2}{2\sigma_{in}^2} - \frac{(\varphi_{out}-\mu_{out})^2}{2\sigma_{out}^2}} \tag{8.3}$$

with

$$V = \iint\limits_{[0,\varphi_{max}]\times[0,\varphi_{max}]} e^{-\frac{(\varphi_{in}-\mu_{in})^2}{2\sigma_{in}^2} - \frac{(\varphi_{out}-\mu_{out})^2}{2\sigma_{out}^2}}\, d\varphi_{in} d\varphi_{out} \tag{8.4}$$

Figure 8.2 shows one of such Gaussian, where φ_{in} denotes the level of pheromone in the input lanes and φ_{out} is the pheromone level in the output lanes.

The following code implements equation 8.3:

```
double MSSOTLPolicyStimulus::computeDesirability(double vehInMeasure, double vehOutMeasure) {
	double stimulus = getStimCox() * exp(
	 -getStimCoxExpIn()/getStimDivisorIn()*pow(vehInMeasure - getStimOffsetIn(), 2)
	 -getStimCoxExpOut()/getStimDivisorOut()*pow(vehOutMeasure - getStimOffsetOut(), 2)
		);
	return stimulus;
}
```

Each function is described through a set of parameters (see Table 8.1 for further details): two parameters affect the width of the Gaussian for both input and output lanes: `StimCoxExpIn/Out` and `StimDivisorIn/Out`, respectively. In section 8.3.3 we present the Gaussian curve and its behaviour for each policy.

The normal way to define a Gaussian is to use only the divisor (i.e. the $2\sigma^2_{in/out}$ term of equation (8.3), but in some cases, as concerns the congestion policy, we need to cancel the effect of one of the dimensions. As we cannot divide by infinity, in these cases the `StimCoxExpIn` (or `Out`) is set to 0, while in all other cases it is set to 1.

Table 8.1: Stimulus function parameters (their values depend on the policy)

Parameter	Symbol	Meaning
`StimCoxExp`	$\frac{1}{V}$	Global scaling factor.
`StimOffsetIn`	μ_{in}	Offset relative to the pheromone level of input lanes, moves the Gaussian along the $\boldsymbol{\varphi_{in}}$ axis.
`StimOffsetOut`	μ_{out}	Offset relative to the pheromone level of output lanes, moves the Gaussian along the $\boldsymbol{\varphi_{out}}$ axis.
`StimCoxExpIn`		0 if the $\boldsymbol{\varphi_{in}}$ should not be considered in the stimulus function, 1 otherwise.
`StimCoxExpOut`		0 if the $\boldsymbol{\varphi_{out}}$ should not be considered in the stimulus function, 1 otherwise
`StimDivisorIn`	$2\sigma^2_{in}$	Scales the width of the Gaussian along the $\boldsymbol{\varphi_{in}}$ axis.
`StimDivisorOut`	$2\sigma^2_{out}$	Scales the width of the Gaussian along the $\boldsymbol{\varphi_{out}}$ axis.

8.2.3 Policy Selection

The selection of the policy occurs after the evaluation of the stimulus functions. The choice is probabilistic. The probability $P(i,j)$ of the *i*-th agent to choose the *j*-th policy for his intersection is determined with the following equation:

$$\boldsymbol{P(i,j) = \frac{T_{\theta,j}(s_{i,j})}{\sum_j T_{\theta,j}(s_{i,j})}} \qquad (8.5)$$

where,

$$\boldsymbol{T_{\theta,j}(s_{i,j}) = \frac{s^2_{i,j}}{s^2_{i,j} + \theta_{i,j}}} \qquad (8.6)$$

Note that the stimulus functions $s_{i,j}$ are not taken into account directly in the calculation of the probability $P(i,j)$. $\theta_{i,j}$ is the sensitivity threshold for the *i*-th agent to the adoption of the *j*-th policy. The sensitivity threshold $\theta_{i,j}$ represents the level of sensitivity of the agent to the adoption of that policy. This threshold is variable in time, decreasing if a policy is selected in a stable way, and increasing in time as a policy is not selected. This is called **reinforcement** because as a policy is selected and found to be working well, it is learned and its probability to be selected again (stable policy) increases. At the same time, even a policy that has a nearly-zero stimulus function will always have a non-zero probability to be selected, because the threshold cannot go above a maximum θ_{max} value, as well as a policy that is stably selected for a long time will not be reinforced too much, as the threshold cannot go over a below θ_{min} value. These two values are also bounded: $0 \leq \theta_{min} < \theta_{max} \leq 1$.

The threshold for each microscopic level policy is computed at each simulation step:

```
if (policy == currentPolicy) { // The policy is active
    //Learning
    newSensitivity = policy->getThetaSensitivity - getLearningCox() * elapsedTime;
} else { // The policy is not active
    //Forgetting
    newSensitivity = policy->getThetaSensitivity + getForgettingCox() * elapsedTime;
}
newSensitivity = max(min(newSensitivity,getThetaMax()),getThetaMin());
policy->setThetaSensitivity(newSensitivity);
```

Where `elapsedTime` is the time that has passed since the threshold was last updated.

The new policy is then selected in a probabilistic way: the higher the stimulus function for a policy, the higher the probability that that policy will be selected. According to the model given by (Theraulaz, Bonabeau, & Denuebourg, 1998), at each step in simulation, a *Swarm* macro-policy updates the pheromone levels of the controlled incoming and outgoing lanes and selects a new microscopic policy for execution with a probability of p_{change}. The value of the stimulus function for each policy is calculated according to the current pheromone level. It is clear that if $p_{change} = 1$ the process of policy selection occurs at every iteration. On the other side, with $p_{change} = 0$ the controller is insensitive to traffic density variations. This value should be sufficiently low to mitigate the indecision of the agent and to guarantee its reactivity at the same time.

Given the pheromone levels, the stimulus function and the threshold for each policy, the *Swarm* algorithm selects the future policy in a probabilistic way, where each microscopic level policy has chance to be selected proportional to its reinforced stimulus:

```
void MSSwarmTrafficLightLogic::decidePolicy() {
       MSSOTLPolicy* currentPolicy = getCurrentPolicy();
       // Decide if it is the case to check for another plan
       double sampled = (double) rand();
       double changeProb = getChangePlanProbability();
       changeProb = changeProb * RAND_MAX;

       if (sampled <= changeProb) { // Check for another plan
              double pheroIn = getPheromoneForInputLanes();
              double pheroOut = getPheromoneForOutputLanes();
              MSSOTLPolicy* oldPolicy = getCurrentPolicy();
              choosePolicy(pheroIn, pheroOut);
              MSSOTLPolicy* newPolicy = getCurrentPolicy();
       }
}

void MSSwarmTrafficLightLogic::choosePolicy(double phero_in, double phero_out) {
       vector<double> thetaStimuli;
       double thetaSum = 0.0;
       // Compute simulus for each policy
       for (unsigned int i = 0; i < getPolicies().size(); i++) {
              double stimulus = getPolicies()[i]->computeDesirability(phero_in, phero_out);
              double thetaStimulus = pow(stimulus, 2)
                     /(pow(stimulus, 2)+pow(getPolicies()[i]->getThetaSensitivity(), 2));
              thetaStimuli.push_back(thetaStimulus);
              thetaSum += thetaStimulus;
       }

       // Compute a random value between 0 and the sum of the thetaVal
       double r = rand();
       r = r / RAND_MAX * thetaSum;
       double partialSum = 0;
       for (unsigned int i = 0; i < getPolicies().size(); i++) {
              partialSum += thetaStimuli[i];
```

```
            if (partialSum >= r) {
                activate(getPolicies()[i]);
                break;
            }
        }
}
```

8.3 Microscopic Level Policies

A microscopic level policy takes short-term decisions: when the green light should go on and off and on which lanes, the duration of the red period and so on.

Usually, microscopic level policies operate on a base sequence of stages and apply variations to this base sequence. The most common decisions taken by an adaptive policy concern the duration of the green for different lights, or including/excluding parts of the whole base sequence. As recalled in previous chapters, a traffic light controller may introduce a sub-sequence of stages, for example upon pedestrian crossing request, thus varying the overall sequence of stages and the cycle time.

However, most traffic-dependent policies will always execute stages in a pre-fixed order. The dynamic policies developed for COLOMBO introduce a different variation: sub-sequences of stages may be executed in varying order. This concept of a “chain” is introduced next to understand how the sub-sequences are defined and their order varied. Afterwards, the execution of the program, plan that consists of single chains is described, followed by a presentation of the developed microscopic policies.

8.3.1 Chains

The basic sequence of stages defined in the traffic light logic can usually be partitioned in a small number of chains, if the sequence of stages presents two or more all red stages. The basic idea is that, when all the lights are red, there is no constraint that forces the traffic light to select the stage that immediately follows, but any stage that follows an all-red stage can be selected.

On the other hand, when there are green or amber lights on, the basic sequence of stages cannot be altered, and only in some cases the stage duration can be altered. Namely, stages where amber lights are on cannot usually be shortened or lengthened, while the duration of stages where there are only green and red lights can be altered, within the safety constraint imposed by the traffic light program and its intergreen matrix.

To describe a chain, the stages are classified in:

- *Target stage*: any stage that can immediately follow an All Red stage
- *Commit stage*: any All Red stage
- *Intermediate stage*: any stage that is neither a *Target stage* nor a *Commit stage*

A chain has therefore a first stage that is always a *Target stage* and a last stage that is a *Commit stage*. The stages in the default TLS that follow the *Target stage* and precede the *Commit stage* (both including) are all executed in the predefined order. Variation of the order of stages happens only after a commit stage, when the traffic light can select any other target stage to execute its plan. The stages can be classified also according to the possibility that the policy might change its duration:

- *Decisional stage*: a stage where the duration can be adjusted. Different policies will adjust this value using different criteria. Usually, for each decisional stage a minimum and maximum duration are defined, derived from the safety constraints of the traffic light program.
- *Transient stage*: a stage with a fixed duration that cannot be altered. Usually, the duration of stages where there is at least one amber light on cannot be altered.

8.3.2 Plan Execution

A dynamic policy acts as follows: at start-up the traffic light is initialized to the first phase defined in the traffic light base plan, then, each time it is invoked, the controller checks the type of the current phase. If the phase is

- *Decisional*: the controller checks whether the current phase should be persisted or if the rest of the chain should be executed in order to start another chain. This decision lasts for a single simulation step (one second in SUMO). Then the policy is invoked again. This is the step where the various policies differ;
- *Transient*: the controller lets the current phase execute until the predefined duration has elapsed;
- *Commit*: the controller knows that the current chain has completed and decides which is the next chain to execute.

8.3.3 Implemented Policies

Several different microscopic level policies are implemented. They differ mainly in the implementation of the "`canRelease()`" method that, during a decisional stage, decides the actual stage duration, returning true when the stage should be ended and the subsequent stage should be activated.

This method relies on the definition of a threshold that is computed multiplying the number of vehicles waiting at a red light by the time they have been waiting, for each incoming lane that is currently red:

```
bool MSSOTLTrafficLightLogic::isThresholdPassed() {
	for (map<size_t, unsigned int>::const_iterator iterator = targetPhasesCTS.begin();
iterator!= targetPhasesCTS.end(); iterator++) {
		//Note that the current chain is not eligible to be directly targeted again,
it would be unfair
		if ((iterator->first != lastChain) && (getThreshold() <= iterator->second)) {
			return true;
		}
	}
	return false;
}
```

Static policy

The default SUMO policy is statically defined: the traffic lights loop continuously through the phases in the order in which they are defined, and each phase is executed for a fixed amount of time. This policy does not take any run-time input about the traffic. The program plans can be changed by a controller for activating pre-defined plans for the night or the weekend vs. rush hours, but this change usually occurs only few times a day. Once a logic is activated, its phases are executed in the fixed order until the whole logic is changed. This approach is predictive: the logic is selected according to the expected amount of traffic, but does not take into account the real situation on the road or any unexpected variation in the flow of traffic.

Actuated policy

Traffic actuated control is a common control type, to be found especially in dense urban areas. Herein, a fully-activated control is used what means that traffic at all incoming lanes is measured using inductive loops[12]. As long as an incoming stream has green and a vehicle belonging to this stream passes the according detector, the actuated traffic light may extend the duration of the green light for this stream. The order of the phases is fixed as in a static policy. Different parameters

[12] http://ops.fhwa.dot.gov/publications/fhwahop08024/chapter5.htm

control the process. In the following evaluations, the SUMO defaults are used which correspond to the values usually used in the real world. The defaults are listed in Table 8.2.

Table 8.2: Default actuated traffic light algorithm parameters

Parameter	Explanation	Default Value
`MAX_GAP`	Determines the maximum time distance since last detection. If a vehicle was detected but the time headway to the prior vehicle is >= `MAX_GAP`, it will not be used for actuation.	3.1 s
`PASSING_TIME`	Multiplied with the number of cars passed the detector, `PASSING_TIME` defines the new duration of the current phase. This duration is bound by minimum maximum duration values.	1.9 s
`DETECTOR_GAP`	Determines the position of the inductive loop, relative to the stop line; the position is obtained by multiplying `DETECTOR_GAP` with the allowed velocity (usually 50 km/h)	3.0 s

Phase policy

This policy will terminate the current chain as soon as another chain has reached the threshold, but respecting the minimum duration constraint of the current decisional phase. It's less reactive than the request policy, releasing the green light less often. The policy has the following parameters configuration:

$$\frac{1}{V} = 0.127326;\ \mu_{in} = 5;\ \mu_{out} = 0;\ \sigma_{in} = \sqrt{4};\ \sigma_{out} = \sqrt{4}$$

$$s_{i,Phase}(\varphi_{in}, \varphi_{out}) = \frac{1}{V} e^{-\frac{(\varphi_{in}-5)^2}{8} - \frac{\varphi_{out}^2}{8}}$$

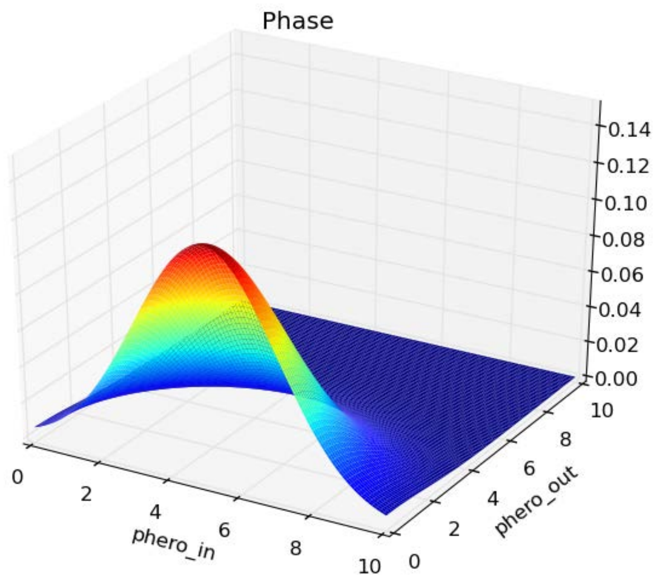


Figure 8.2: Stimulus function for *Phase* policy

This policy is adequate in medium-low traffic situations, where this early termination will not make the traffic lights switch too often.

If no chain reaches the threshold, then the current phase is kept on indefinitely, ignoring the maximum duration parameter. The implementation of the `canRelease()` method for this policy checks if the stage minimum duration has elapsed and if any of the incoming lanes has passed the threshold of waiting vehicles:

```
bool MSSOTLPhasePolicy::canRelease(int elapsed, bool thresholdPassed,
            const MSPhaseDefinition* stage, int vehicleCount) {
        if (elapsed >= stage->minDuration) {
            return thresholdPassed;
        }
        return false;
}
```

Platoon policy

This policy will try to let all the vehicles in the currently green lanes pass the intersection before releasing the green light.

$$\frac{1}{V} = 0.0805782;\ \mu_{in} = 0;\ \mu_{out} = 0;\ \sigma_{in} = \sqrt{5};\ \sigma_{out} = \sqrt{5}$$

$$s_{i,Platoon}(\varphi_{in}, \varphi_{out}) = \frac{1}{V} e^{-\frac{\varphi_{in}^2}{10} - \frac{\varphi_{out}^2}{10}}$$

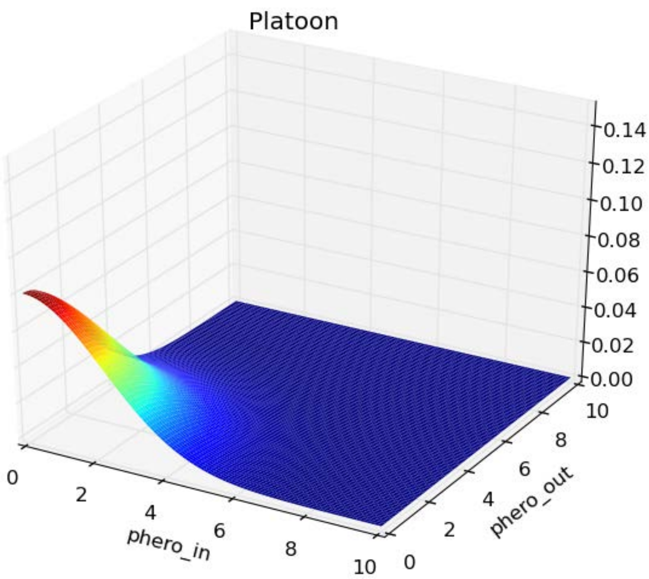


Figure 8.3: Stimulus function for *Platoon* policy

The current chain will be terminated only if

- the minimum decisional phase duration has elapsed AND
- some other chain is above the threshold AND
- there are no other vehicles in the current chain lanes OR the maximum duration has elapsed

It is worth noting that even the *Platoon* policy will not switch chain unless other lanes are requesting the green light.

The maximum phase duration is only taken into account in order to pre-empt the current chain execution even if there are approaching vehicles. In intense traffic situations, each decisional phase will execute for the maximum allowed time. The definition of the maximum allowed time for a phase will greatly impact the performance.

The implementation of the `canRelease()` method for this policy checks whether the minimum duration has elapsed and if any of the incoming lanes has passed the threshold for waiting vehicles, but releases the green light only if the currently green lanes are empty or if the maximum duration has elapsed:

```
bool MSSOTLPlatoonPolicy::canRelease(int elapsed, bool thresholdPassed,
            const MSPhaseDefinition* stage, int vehicleCount) {
      if (elapsed >= stage->minDuration) {
            if (thresholdPassed) {
                  //If there are no other vehicles approaching green lights
                  //or the declared maximum duration has been reached
                  return ((vehicleCount == 0) || (elapsed >= stage->maxDuration));
            }
      }
      return false;
}
```

Marching policy

This policy is adequate when the traffic looks too intense from all directions to take any online decision regarding the input lanes. In this case, there are two possible approaches: either use a static duration for decisional stages or consider the output lanes, do not allow traffic to lanes that are too heavily loaded.

$$\frac{1}{V} = 0.0407958;\ \mu_{in} = 5;\ \mu_{out} = 5;\ \sigma_{in} = \sqrt{4};\ \sigma_{out} = \sqrt{4}$$

$$s_{i,Marching}(\varphi_{in}, \varphi_{out}) = \frac{1}{V} e^{-\frac{(\varphi_{in}-5)^2}{8} - \frac{(\varphi_{out}-5)^2}{8}}$$

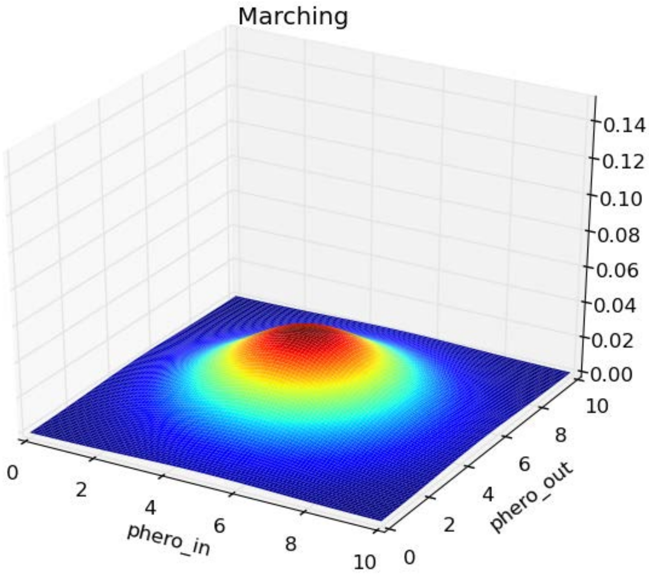


Figure 8.4: Stimulus function for *Marching* policy

So far, only the first approach is implemented in SUMO, defaulting to static-duration but dynamic chain selection. Implementing the second approach requires the definition of the chain output lanes, in addition to the chain target lanes. The implementation of the `canRelease()` method will then just check if the maximum duration of the current stage has elapsed:

```
bool MSSOTLMarchingPolicy::canRelease(int elapsed, bool thresholdPassed,
              const MSPhaseDefinition* stage, int vehicleCount) {
       return (elapsed >= stage->duration);
}
```

Congestion policy

This policy is used when the output lanes are congested and there are vehicles waiting in the intersection. To avoid gridlocks, all input lanes are inhibited, i.e. the current executing chain is terminate following the pre-defined plan to the commit step, then no other chain is activated until the congestion has been solved.

$$\frac{1}{V} = 0.0407958;\ \mu_{out} = 10;\ \sigma_{out} = \sqrt{3}$$

$$s_{i,Congestion}(\varphi_{in}, \varphi_{out}) = \frac{1}{V} e^{-\frac{(\varphi_{out}-10)^2}{6}}$$

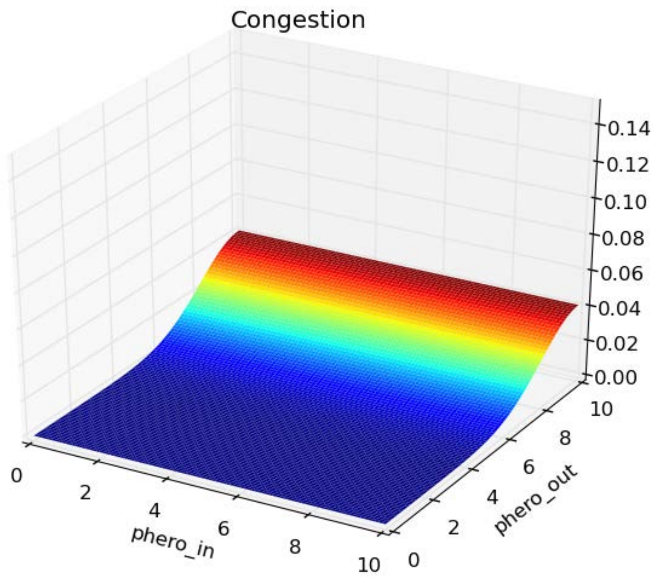


Figure 8.5: Stimulus function for Congestion policy

NOTE: in order to implement this with the current SUMO code, without dynamically defining the lights, it is mandatory that each chain ends with an all red stage.

In this case, the policy will release the green light as soon as possible, but when the plan gets to a commit stage, with all the red lights on, this policy does not select a new chain to be started, until the macroscopic level swarm policy selects a different microscopic level policy to be execute. The implementation of the `canRelease()` method is:

```
bool MSSOTLCongestionPolicy::canRelease(int elapsed, bool thresholdPassed,
              const MSPhaseDefinition* stage, int vehicleCount) {
       return (elapsed >= stage->minDuration);
}
```

The implementation of the `decideNextPhase()` method differs from the one used by the other policies and it's the following:

```
size_t MSSOTLCongestionPolicy::decideNextPhase(int elapsed,
            const MSPhaseDefinition* stage, size_t currentPhaseIndex,
            size_t phaseMaxCTS, bool thresholdPassed, int vehicleCount) {
      if (stage->isCommit()) {
            // stay here
            return currentPhaseIndex;
      }
      if (stage->isTransient()) {
            //If the junction was in a transient step
            //=> go to the next step and return computeReturnTime()
            return currentPhaseIndex + 1;
      }
      if (stage->isDecisional()) {
            if (canRelease(elapsed, thresholdPassed, stage, vehicleCount)) {
                  return currentPhaseIndex + 1;
            }
      }
      return currentPhaseIndex;
}
```

Policies summary

A set of traffic light control policies was defined and presented. Each policy is designed to cope with a certain traffic situation that is defined by the deviations of the current average speed at incoming and the outgoing lanes. Determination of the policy to instantiate is done using stimulus functions that describe the policies' applicability for a measured situation. Figure 8.6 shows the used stimulus functions.

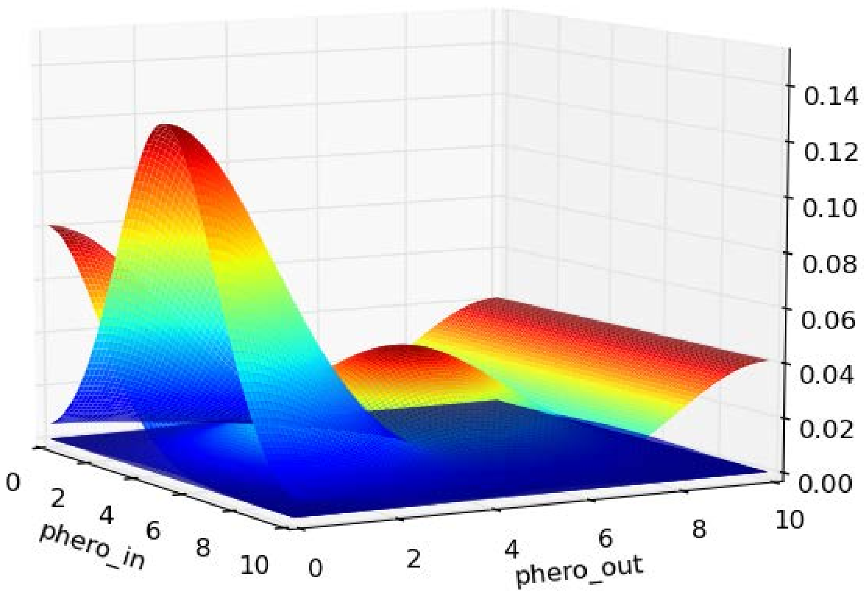


Figure 8.6: Combined view of the different stimulus functions

Each policy attempts to cope with the respective situation by applying certain aspects of regulation as summarized in Table 8.3.

Table 8.3: Comparison of Policies

Policy	Respect min duration	Respect max duration	try to empty lanes
Phase	YES	NO	NO
Platoon	YES	YES, if threshold passed	YES, respecting max duration
Marching	NO, only fixed duration is used		
Congestion	NO, all lights are red until the congestion is resolved		

8.4 Evaluation Scenarios and Results

A set of investigations was performed to determine how the developed algorithms perform under different traffic conditions. They will be presented in the following.

8.4.1 Single Intersection Performance

At first, a single intersection as shown in Figure 8.7 is used where two roads cross. Both roads consist of a single lane only, the maximum velocity is limited to 50 km/h. The traffic light located at the intersection has a fixed cycle of 80 s. Each stream gets green for 32 s, followed by a yellow phase, and an all-red phase, both with a duration of 4 s.

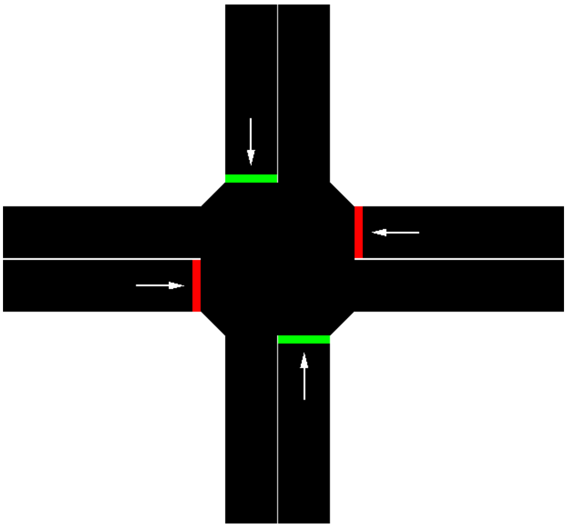


Figure 8.7: The intersection used within the single intersection investigations

In subsequent simulation runs, the number of vehicles ($n_{i,t}^{\text{vehs}}$, see D1.1, p. 18) is increased from 0 veh/h (vehicles per hour) to 1800 veh/h in steps of 200 veh/h. All vehicles run straight. Each simulation includes a preparation phase of 3600 second to obtain a completely filled network. Then measures are collected for further 10000 seconds. The obtained individual waiting times are summed and averaged afterwards to obtain matrices of average waiting times depending on the flows for the simulated policies. Figure 8.8 compares the behavior of the macroscopic policy to the established static and actuated (based on inductive loop measures) algorithms.

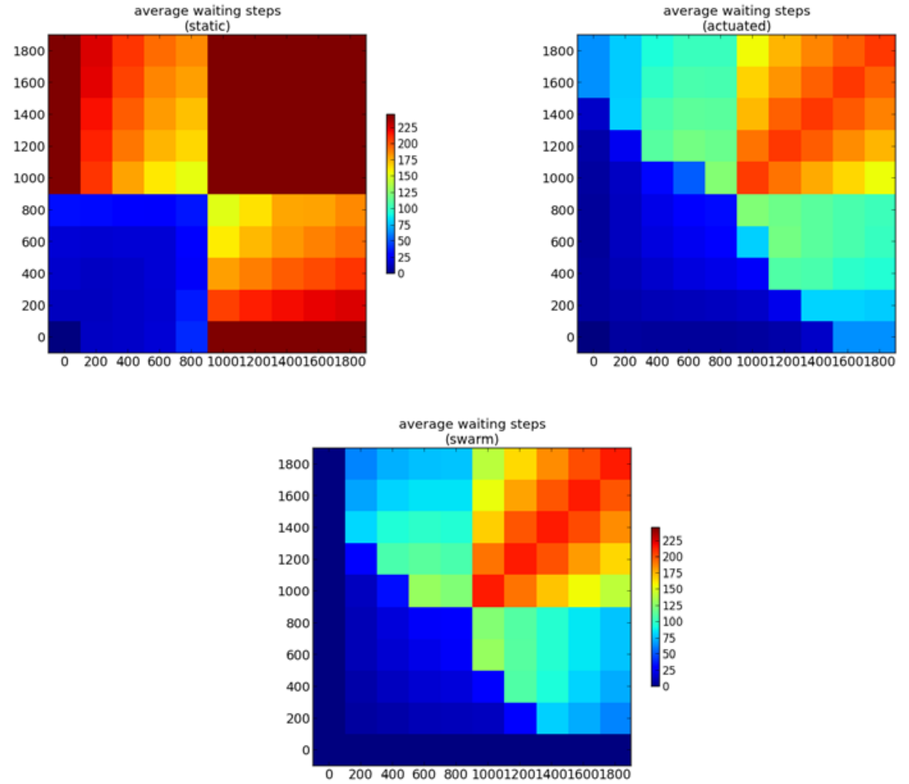


Figure 8.8: Average waiting time for the investigated policies given different vehicle flows

This Figure shows that, indicated by dark red plateaus – the static policy is not capable to pass the incoming flow starting at around 1000 veh/h. The static traffic light policy is outperformed by both the conventional actuated policy as well as by the macroscopic "swarm" policy in all cases. Figure 8.9 shows the difference between the average travel times as seen in the "swarm" policy and the ones from actuated traffic light algorithm. One may note that in almost all cases the swarm policy performs better than the actuated control and in the other cases (1200 vs. 600 veh/h) the difference is low.

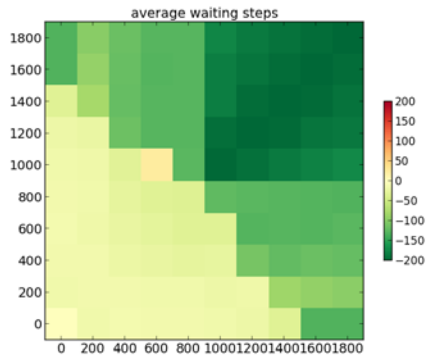


Figure 8.9: Differences in average waiting times between the actuated and the swarm policy (green: lower waiting time, red: larger waiting time)

8.4.2 Policy Behaviour

The following evaluations show how the individual policies cope with traffic in means of assigning green to incoming streams. The same settings were used as for the "Single Intersection Performance" evaluation, but only a single combination of streams is regarded in the following: 1200 veh/h for the East/West direction and 400 veh/s for the North/South direction. It should be noted that the following Figures show snapshots of the simulation and the initial situation is not the same as the respective policy has been applied to the fill-up steps as well.

As shown in Figure 8.10, a static traffic light which assigns the same amount of green to both streams cannot cope with the incoming traffic – about 20 vehicles running in East/West direction remain in the queue at each time. One can as well notice the static repetition of the cycle after each 80 seconds.

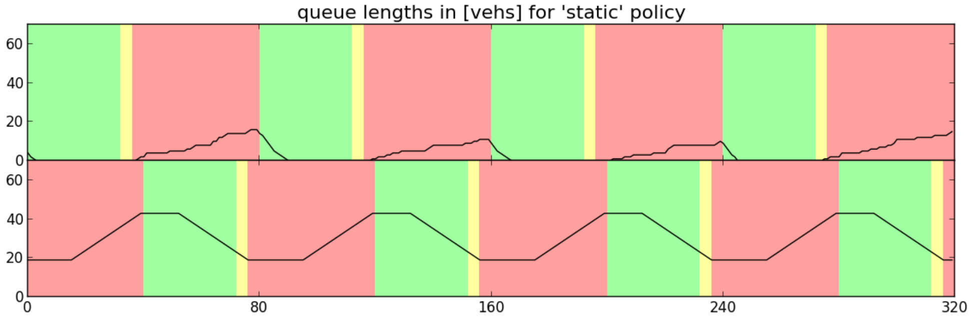


Figure 8.10: Development of queues in front of the traffic light for "static" policy and the according assignment of signal colors; top: East/West-direction, bottom: North/South direction

The actuated policy adapts the green times to the incoming traffic, assigning a larger portion of the cycle time to the heavier occupied stream as shown in Figure 8.11. This allows the queues to dissolve completely for all directions. Nonetheless, one may note that some of the green time is still wasted as no vehicles are waiting in East/West direction but the while the light shows green.

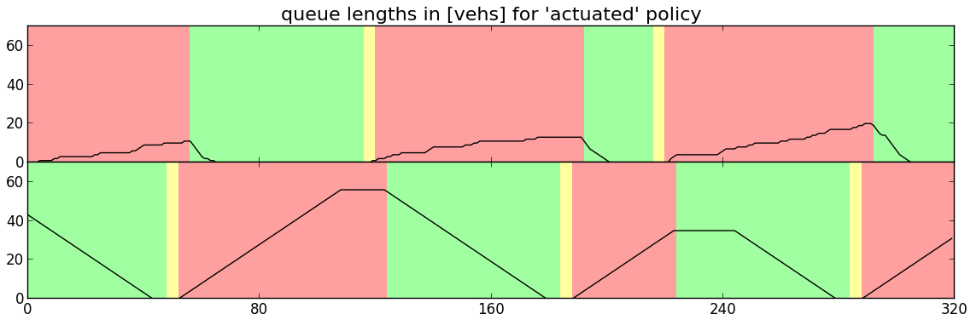


Figure 8.11: Development of queues in front of the traffic light for "actuated" policy and the according assignment of signal colors; top: East/West-direction, bottom: North/South direction

This "waste" of cycle time is reduced by the macroscopic policy as shown in Figure 8.12. The queues are dissolved completely and even for the major flow, the average number of waiting vehicles is reduced.

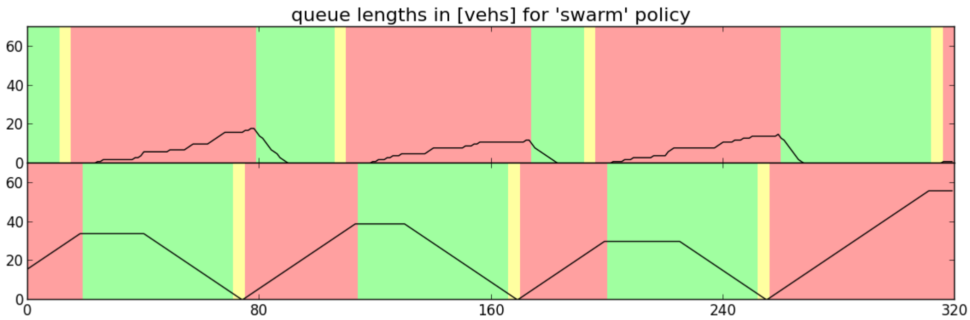


Figure 8.12: Development of queues in front of the traffic light for "swarm" policy and the according assignment of signal colors; top: East/West-direction, bottom: North/South direction

8.4.3 Performance in a Grid Network

A second synthetic scenario was built with the aim to generate critical traffic conditions. Simulations have been run using one single policy at a time and measuring how the average waiting time of the vehicles varies, depending on the traffic load. The comparison involved the following policies:

1) *Swarm* macro-policy
2) *Static* policy
3) *Actuated* policy
4) *Platoon* policy
5) *Phase* policy
6) *Marching* policy
7) *Deterministic* macro-policy

The *Deterministic* macro-policy is equivalent to the *Swarm* macro-policy with $p_{change} = 1$ and without reinforcements. The selection of the policy is also deterministic: the chosen (low level) policy is always the one with the highest stimulus given the current pheromone levels.

The evaluation was run on different traffic conditions. A saturation value of 2000 veh/hour per lane was calculated and then six different traffic segments were identified, starting from 500 veh/h per lane to 2000 veh/h per lane in increments of 250 veh/h per lane.

The traffic is synthetically generated interleaving directions like N/S and E/W. The evaluation scenario is a 3x3 grid as shown in Figure 8.13. The grid is composed by three horizontal three vertical streets, forming nine intersections. Each intersection has the same policy. However note that the control of each intersection is independent.

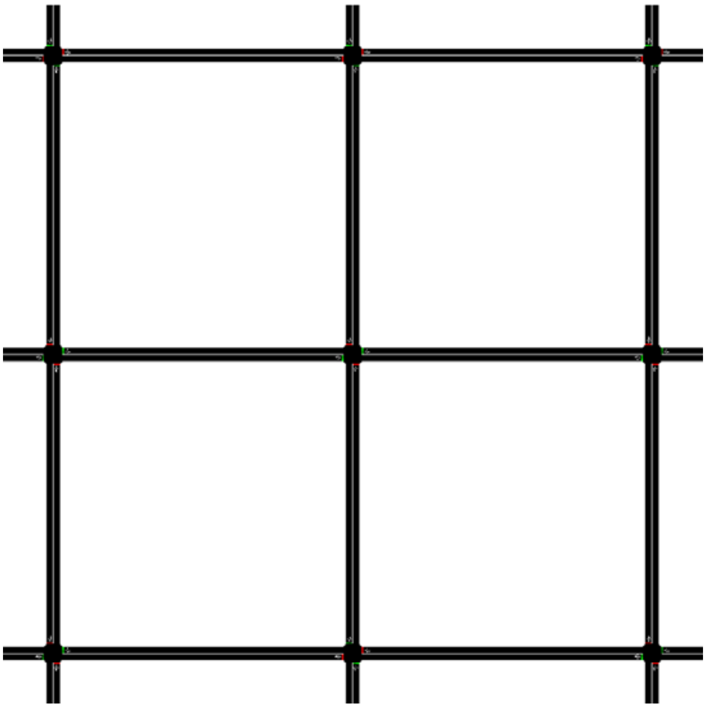


Figure 8.13: 3x3 grid scenario

The experiments run on different traffic conditions. A saturation value of 2000 vehicles per hour per lane was computed (see 4.4.1, using a lane width of 2.75 m as it is the minimum allowed in [RENCS]) and then six different traffic segments were supposed, starting from 500 veh/h per lane to 2000 veh/h per lane in increments of 250 veh/h per lane. For each traffic segment a set of 36 instances has been created increasing the traffic loads in steps of 50 veh/h.

We have therefore outlined the following traffic segments:

1) low traffic (from 500 veh/h to 750 veh/h on each direction)
2) medium-low traffic (from 750 veh/h to 1000 veh/h on each direction)
3) medium traffic (from 1000 veh/h to 1250 veh/h on each direction)
4) medium-high traffic (from 1250 veh/h to 1500 veh/h on each direction)
5) high traffic (from 1500 veh/h to 1750 veh/h on each direction)
6) saturated traffic (from 1750 veh/h to 2000 veh/h on each direction)

Figure 8.15 and Figure 8.16 depict in details the performance of the policies for each traffic segment. For each instance (x-axis) the graphs plot the mean waiting time (y-axis).

As shown in Figure 8.15, for low and medium-low traffic conditions (first and second graph) the *Static* policy performs slightly better w.r.t the *Swarm*. The *Platoon*, the *Phase*, the *Deterministic*, and the *Actuated* policies are not suitable for low traffic conditions. As the traffic flow increases, the *Swarm* macro-policy starts to reveal its potential.

In fact, in the last graph of Figure 8.15 (i.e. medium traffic condition), the *Swarm* policy outperforms almost all the other approaches but the *Platoon*, which seems to be equivalent. It's worth notice that the deterministic approach used by *Deterministic* is worse than any other policy, excluding the *Phase*, which is comparable to.

The graphs of Figure 8.16 confirm the behaviour seen in the third traffic segment. *Swarm* and *Platoon* are confirmed as the best policies for very high traffic conditions and *Actuated* is comparable to them only in the last traffic segment. Again, the *Deterministic* macro-policy is the worst one, meaning that the probabilistic approach used in *Swarm* gives significant improvements.

The performance of the tested policies is summarized per traffic segment in Figure 8.14.

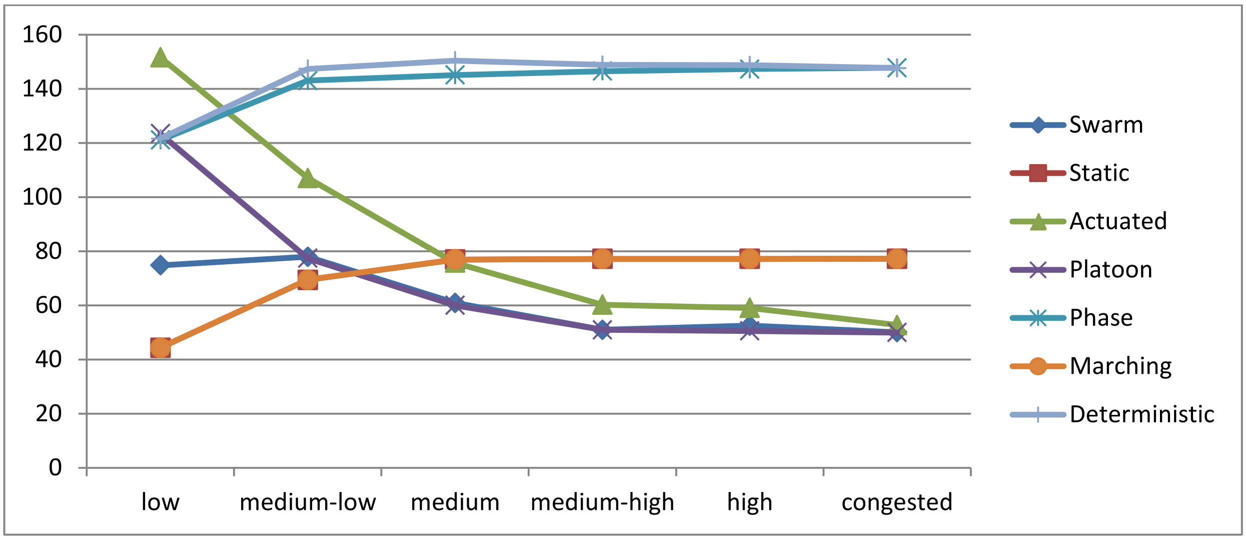


Figure 8.14: Waiting times averaged per traffic segment

An important point to notice is that the swarm policy is highly affected by the parameter tuning, as happens for all algorithms belonging to the swarm intelligence field. The parameters used so far were determined by manual inspection and are probably far from the optimal configuration. This means that the (already good) results might be further improved by to parameter tuning, which is developed in WP3.

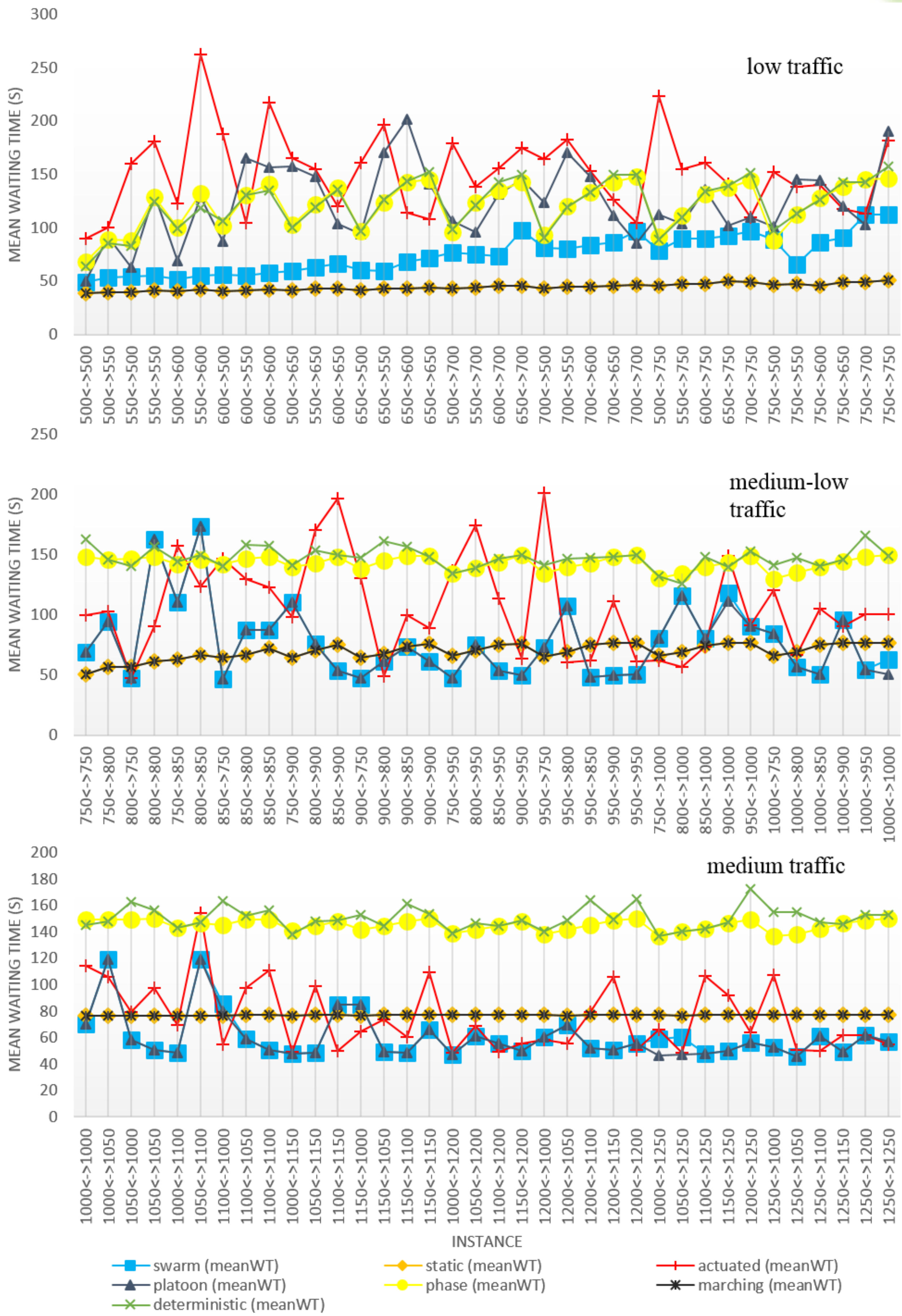


Figure 8.15: Average waiting times for the first three traffic segments (*low*, *medium-low* and *medium*)

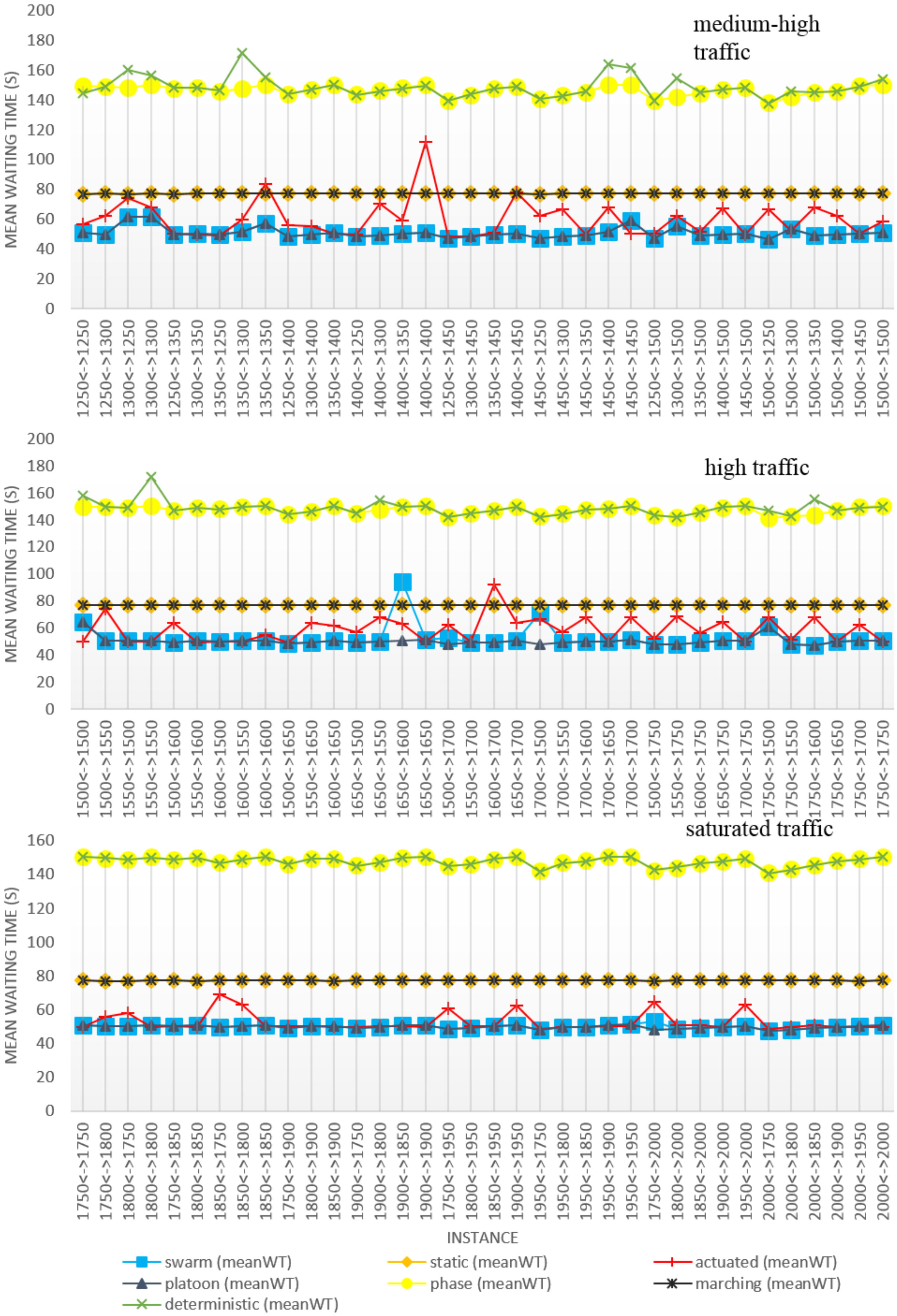


Figure 8.16: Average waiting times for the last three traffic segments (*medium-high, high* and *saturated*)

8.5 Applied Parameters

The parameters used in the dynamic policy selection are presented in the following table. All of these parameters can be set with the same values for all junctions or defined per-junction. This list of parameters is a starting point between the tasks performed in WP2 with those in WP3 on automatic parameter tuning. Identifying parameters that could be tuned and that influence the behaviour of the control algorithm is of paramount importance and enable optimization and through a close interaction between WP2 and WP3.

We have basically identified two sets of parameters: the first set comes from the swarm based policy, so these parameters influence the selection of the proper policy and can be tuned once for the overall system. The second set of parameters, instead, characterise each single policy and mainly concern parameters of the stimulus function.

Table 8.4: SWARM Policy parameters

Parameter	Symbol	Value	Meaning
`pheroMaxVal`	φ_{max}	10.0	Maximum value of the pheromone level, both for input and output lanes
`betaNo`		0.2	Pheromone evaporation coefficient for input lanes
`gammaNo`		0.1	Pheromone accumulation coefficient for input lanes, to be multiplied by the vehicle count.
`betaSp`		0.27	Pheromone evaporation coefficient for output lanes.
`gammaSp`		0.18	Pheromone accumulation coefficient for output lanes, to be multiplied by the vehicle count.
`pChange`	p_{change}	0.03	Probability to select a new policy each time the algorithm is invoked.
`thetaMax`	θ_{max}	0.85	Maximum threshold value.
`thetaMin`	θ_{min}	0.1	Minimum threshold value.
`thetaInit`		0.5	Initial threshold value.
`learningCox`		0.1	Threshold update learning coefficient.
`forgettingCox`		0.04	Threshold update forgetting coefficient.
`threshold`		200	Threshold for the product of the number of vehicles waiting at a red light for their waiting time.
`maxCongestionDuration`		80	Maximum duration in seconds of an all red stage decided by the *Congestion* policy before a reset of the pheromone levels is performed.

8.6 COLOMBO Algorithms in the Context of Traffic Lights Adaptation

In this section, we will show how the COLOMBO philosophy fits the literature classification provided in the document as provided in Section 7. Control methods are roughly divided into macroscopic and microscopic control level methods. The former react to macroscopic key figures such as mean congestion length and mean traffic density and acts on the signal program choice or the development of the frame signal program. The latter include changes at short notice based on changes at traffic flow: they include methods for signal program adaptation and development.

COLOMBO inherits from traditional control methods a number of features. It contains both macroscopic and microscopic control level methods. In fact, at a macroscopic level it implements a Traffic dependent Choice of Signal Programs where a program is chosen out of a number of given signal programs, based on actual detected traffic data.

At a microscopic level, each element can be changed depending on traffic. In COLOMBO, we employ green period adaption, i.e., the duration or length of green periods can be adapted in dependence of the traffic situation. Therefore, a fixed green time respecting legal constraints is used and depending on the policy green is extended based on detection or there is a cycle in which adaptations to the green splits and offsets are made.

In addition, with the stage request it is possible to insert demand stages into the given stage sequence at one or more locations of the signal program, by temporarily shortening the green periods of other stages. This can be used for emergency or public transport priority, which is also supported by other existing traffic control methods.

Besides macroscopic level control methods, COLOMBO implements the original feature of the project, namely the swarm-based, self-organizing policy selection method. Policies described in the previous sections (*Marching*, *Platoon*, *Phase*, *Congestion*) are then selected on the basis of the pheromone on in and out lanes and on the stimulus functions.

It means that besides the different policies implemented for each junction that can be controlled with the above-mentioned methods, the meta-level control method allows to select the best policy for each specific traffic condition. From this perspective, we have in COLOMBO an additional level, we call it meta-level, where policies are selected on the basis of the current traffic situation.

To monitor the traffic situation, actuated control relies on sensors (detectors) that extract the traffic information within the intersection. Timing of the signals is then controlled by traffic demand. Actuated controllers may be programmed to accommodate

- variable stage sequences;
- variable green times for each stage;
- variable cycle length caused by variable green times.

Advantages of actuated controllers are a reduced delay, an adaptation to short-term fluctuations in traffic flow, an increase in capacity, a provision of continuous operation under low volume conditions, and their effectiveness at multiple stage intersection.

The main disadvantages are that if the traffic demand pattern is very regular, the extra benefit of adding local actuation is minimal (to non-existent) and the installation cost is two to three times the cost of a pre-timed signal installation. [FSV, FGSV, Bosserhoff]. Moreover, actuated controllers are more complicated than pre-timed controllers, increasing maintenance costs, and actuated signals require careful inspection and maintenance to ensure proper operation.

What we propose with COLOMBO goes in line with actuated control. However, on one hand the COLOMBO system does not rely on expensive detectors, but rather on a distributed monitoring infrastructure that enables to opportunistically harvest traffic data from communication infrastructure. On the other hand, being the control algorithm based on swarm intelligence concepts, the algorithms are not complicated, as they smoothly adapt and learn from previous experience.

Also discussed in this document are safety and regulatory requirements for the signal controllers that can be different per country. For instance Austria has 4 seconds of green flashing and 3 seconds of amber before red, while there is also 2 seconds of red/amber before green. This means there is a total of 7 seconds of fixed time elements per stage that cannot be changed by the program. This significantly influences the freedom the controller has to make signal programs when comparing to the Dutch regulations, which only require 3 seconds of amber time. Therefore, all these regulatory elements should be configurable and known by the algorithm, in order for the optimization process to take this into account.

9 Summary

This document showed important differences and available control strategies concerning light signal planning and establishing. It makes clear that it is not easy to make one matching light signal throughout Europe to one fitting optimising algorithm, because the signal sequences are different in timing and aspect. Nevertheless there are already certain adaptive signal control methods that can be used independent of the city and country. It is very important to understand the difference between fixed time control (time dependent control), traffic dependent control and adaptive signal control. Adaptive signal control is the most adjustable tool and can give any spot of the cycle to any signal. This is not possible when using time dependent or traffic dependent control.

What we found out is that the basics of light signal control are similar within all regarded countries; there are a lot of according/consisting points of view at the considered countries, while at the moment the handling and calculation is done differently. Explanations and definitions of different terms are more or less exactly the same, but the implementation is done depending on the country by different kinds of strategy, because there are different points of opinions concerning time requirement, signal head set-up and handling. Because of that, the intergreen times and the use of the signal sequence and heads are different, but even though the same control strategies can be used.

Whereas there are a lot of different methods for controlling a junction, the junctions with strong volume and high degree of saturation are often controlled by using adaptive signal control systems. These systems operated well, but steadily further development or renewal should be taken into consideration, to make the systems more reliable with less error-prone equipment and lower costs. Because nowadays the environment and its pollution is more and more topic of conversation, more features and factors will be important to be included by refining or newly developing such systems.

Following this consideration, we have shown the adaptive control method proposed by COLOMBO and how it adapts to traffic at different levels, both macroscopic and microscopic. We have found that the combined microscopic level policies perform better than the static control method at any rate of traffic on some simple scenarios. When being compared to a conventional actuation algorithm which requires inductive loops at all incoming lanes, the algorithm developed in COLOMBO performs better in most cases. This encourages comparison with other adaptive control methods.

The macroscopic policy selection algorithm proves to select a most proper policy using the vehicles' waiting times as the base source of traffic surveillance that is used as a pheromone in the swarm paradigm. Further optimisation of the selection parameters will be performed within the work package 3 where both, an off-line adaptation (Task 3.2) as well as an on-line adaptation of parameters to current traffic (Task 3.3) will be tangled.

It should be noted that the macroscopic selection can be used in conjunction with other traffic light algorithms that are not developed within COLOMBO. Equipped with a stimulus function that fits their performance, they could be selected for traffic states they perform best. Therefore, the (macroscopic) policy selection algorithm should be treated as an additional benefit of the overall design of traffic light policies.

Appendix A – References

Appendix A.1 – Presentations

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Appendix B – Abbreviations

AAG	average available green
ACS	adaptive control system
ADSL	asymmetric digital subscriber line
AM	ante meridian
ASTRID	automatic SCOOT Traffic Information Database
AUG	average used green
AVL	automatic vehicle location system
BALANCE	balancing adaptive network control method
BMVIT	Bundesministerium für Verkehr, Innovation und Technologie
BoStrab	Straßenbahn Bau- und Betriebsordnung
BR	Bundesrepublik
CFP	cyclic flow profiles
CO	carbon oxide
CO_2	carbon dioxide
DIDO	dial in dial out
EDP	electronic data processing
GA	Genetic Algorithm
h	hour
HBS	Handbuch für die Bemessung von Straßenverkehrsanlagen
HGV	Heavy goods vehicle
INGRID	integrated incident detection
IP	internet protocol
km	kilometre
l	length
lpu	link profile unit
m	metre
MOTION	method for the optimisation of traffic signals in online controlled networks
NCTU	National Chiao Tung University
NO_X	nitrogen oxides
OPAC	optimised policies for adaptive control
P	Pedestrian(s)
pcu	passenger car units

PI	Performance Index
PP	part point / yield point
RENCS	Regolamento di esecuzione ed attuazione del nuovo codice delle strade
RHODES	real-time hierarchical optimised distributed and effective system
RiLSA	Richtlinien für Lichtsignalanlagen
RTA	Roads and Maritime Services, Traffic Authority of New South Wales
RVS	Richtlinien und Vorschriften für das Straßenwesen
s	second
S	distance
SCATS	Sydney coordinated adaptive traffic system
SCOOT	split, cycle and offset optimisation technique
SPOT	system for priority and optimisation of traffic
StVO	Straßenverkehrsordnung
t	time
TCP	transmission control protocol
TOD	time of day
TSRGD	Traffic signs regulation and general directions
UK	United Kingdom
USA	United States of America
UTC	Urban Traffic Control
UTOPIA	urban traffic optimisation by integrated automation
VA	vehicle actuation
veh	vehicle(s)
VMS	variable message sign
VOC	volatile organic compounds
V_p	speed of progression