AUSTROADS

PART 7

GUIDE TO TRAFFIC ENGINEERING PRACTICE SERIES

Traffic Signals

THIRD EDITION





Standards Australia

STANDARDS NEW ZEALAND

AUSTROADS

Guide to Traffic Engineering Practice

Traffic Signals

THIRD EDITION

Guide to Traffic Engineering Practice: Part 7 – Traffic Signals

First Published 1987
Revised Edition 1993
Reprinted 1997
3rd Edition 2003

National Library of Australia
Cataloguing-in-Publication data:

Guide to Traffic Engineering Practice: Part 7 – Traffic Signals
ISBN 0 85588 622 6

Austroads Publication No. AP-G11.7/03 (formerly NAS 54.9)

Technical writer and editor
Rahmi Akçelik (Akçelik and Associates Pty Ltd)

Austroads project manager
Martin Chelini (VicRoads)

Project coordinator
Michael Tziotis (ARRB Transport Research Ltd)

Technical contributors (in alphabetical order by first name)
Bill Sissons (New Zealand)
Bob Mudford (Roads and Traffic Authority New South Wales)
Branko Stazic (Transport South Australia)
Colin Foot (Transport South Australia)
David Jones (Brisbane City Council)
David Nash (VicRoads)
David Stewart (Queensland Department of Main Roads)
Gary Veith (VicRoads)
Geoff Horni (Department of Infrastrtucture, Planning and Environment, Northern Territory)
Geoff Lake (Roads and Traffic Authority New South Wales)
John Buckland (Transport South Australia)
Jon Douglas (Queensland Department of Main Roads)
Ken Grattan (Department of Infrastrtucture, Planning and Environment, Northern Territory)
Martin Chelini (VicRoads)
Michael Day (Department of Urban Services, Australian Capital Territory)
Peter Freeman (Department of Infrastructure, Environment and Resources, Tasmania)
Peter Lowrie (Roads and Traffic Authority New South Wales)
Ross Thomson (New Zealand)

Published by Austroads Incorporated
Level 9, Robell House
287 Elizabeth Street
Sydney NSW 2000 Australia

Phone: +61 2 9264 7088
Fax: +61 2 9264 1657
Email: austroads@austroads.com.au

www.austroads.com.au

Guide to Traffic Engineering Practice

Traffic Signals

THIRD EDITION

Austroads Profile

Austroads is the association of Australian and New Zealand road transport and traffic authorities whose purpose is to contribute to the achievement of improved Australian and New Zealand transport related outcomes by:

- developing and promoting best practice for the safe and effective management and use of the road system
- providing professional support and advice to member organisations and national and international bodies
- acting as a common vehicle for national and international action
- fulfilling the role of the Australian Transport Council's Road Modal Group
- undertaking performance assessment and development of Australian and New Zealand standards
- developing and managing the National Strategic Research Program for roads and their use.

Within this ambit, Austroads aims to provide strategic direction for the integrated development, management and operation of the Australian and New Zealand road system — through the promotion of national uniformity and harmony, elimination of unnecessary duplication, and the identification and application of world best practice.

Austroads Membership

Austroads membership comprises the six State and two Territory road transport and traffic authorities and the Commonwealth Department of Transport and Regional Services in Australia, the Australian Local Government Association and Transit New Zealand. It is governed by a council consisting of the chief executive officer (or an alternative senior executive officer) of each of its eleven member organisations:

- Roads and Traffic Authority New South Wales
- Roads Corporation Victoria
- Department of Main Roads Queensland
- Main Roads Western Australia
- Transport South Australia
- Department of Infrastructure, Energy and Resources Tasmania
- Department of Infrastructure, Planning and Environment Northern Territory
- Department of Urban Services Australian Capital Territory
- Commonwealth Department of Transport and Regional Services
- Australian Local Government Association
- Transit New Zealand

The success of Austroads is derived from the synergies of interest and participation of member organisations and others in the road industry.

Standards Australia

STANDARDS NEW ZEALAND Paerewa Aotearoa

Handbook Endorsement

In December 1993 Austroads and Standards Australia signed a Memorandum of Understanding regarding the development of Standards and related documents primarily for the development and management of the Australian road system. Standards Australia's support for this handbook reflects the cooperative arrangement between the two organisations to ensure there is a coordinated approach in this area.

In August 1995 Austroads, Transit New Zealand and Standards New Zealand signed an agreement regarding the development of Standards and related documents for endorsement of the appropriate Austroads publications as SNZ handbooks. Standards New Zealand and Transit New Zealand's support for this handbook reflects the cooperative arrangement with Austroads to ensure that there is a coordinated approach in this area.

Handbook No. HB 191:2003

Foreword

Austroads works towards uniformity of practice in respect of design, construction and user aspects of roads and bridges and with this purpose in view, publishes guides and general procedures.

Traffic Engineering Practice, first published in 1965, is a practical guide to traffic engineering for highway and transport engineers in Road Authorities, Local Government and engineering consultants, and as a reference for engineering students.

The guide consists of 15 parts as shown below:

Part 1 Traffic Flow

2 Roadway Capacity

3 Traffic Studies

4 Treatment of Road Crashes

5 Intersections at Grade

6 Roundabouts

7 Traffic Signals

8 Traffic Control Devices

9 Arterial Road Traffic Management

10 Local Area Traffic Management

11 Parking

12 Roadway Lighting

13 Pedestrians

14 Bicycles

15 Motorcycle Safety

The information contained in the various parts is intended to be used as a guide to good practice. Discretion and judgement should be exercised in the light of many factors which may influence the choice of traffic engineering treatment in any given situation.

These guidelines make reference where relevant to current Australian Standards and are intended to supplement and otherwise assist in their interpretation and application.

This is the third edition of *Part 7 – Traffic Signals. Part 7* focuses on technical aspects of designing safe and efficient traffic signal installations. This edition is a major revision of the 1993 publication, and incorporates the latest practice throughout Australia. It has been prepared after extensive consultation with Australian State, Territory and New Zealand authorities. It is hoped that it will give readers a better insight into the Australian and New Zealand practice and be helpful in developing improved control practices for the benefit of road users.

This document presents detailed information and provides guidelines on collection of design data, geometric elements, signal system and components, signal face layouts and display sequences, signal phasing, location of signal equipment, traffic detection, signal controllers, pavement markings, signs, electrical design, coordination of traffic signals, installation checks and maintenance, and special applications including advance warning signals, emergency vehicle facilities, public transport priority, bicycle facilities, roundabout metering signals, ramp-metering signals, special intersection treatments, overhead lane-control signals, single-lane operation and portable signals, left turn on red, and metering signals at sign-controlled intersections.

Appendices provide detailed discussions on human factors and vehicular traffic characteristics relevant to traffic signal control, provide guidelines for determining signal timings, and give a complete worked example. A glossary of terms is included at the start of the document.

Austroads would like to acknowledge the contributions of Ted Barton, Ross Blinco, Frank Hulscher and Cliff Arndt in previous editions of this guide.

Contents

Glossary of Terms

Meanings given here may differ from Australian Standards AS 1348.1 and 1348.2 (1986). Other sources are the Australian Road Rules (NRTC 1999), US Highway Capacity Manual (TRB 2000) and various research reports (Akçelik 1981; Akçelik, Besley and Roper 1999).

Acceleration Lane
A paved auxiliary lane, including tapered areas, allowing vehicles to accelerate when entering the through-traffic lane of the roadway.

Active Warning Device
A device which changes state to display a warning of a hazard.

Actuated Control - see *Traffic-Actuated Control*

Actuation
The electrical action produced by a vehicle (on a vehicle detector) or pedestrian (on a push button switch) to enable the controller to recognise its presence.

Adaptive Engineering - *see Controller Programming*

Advance Warning Signals
An active warning device consisting of a warning sign with Alternating Flashing Yellow displays to warn approaching drivers of their imminent arrival at traffic signal installation.

Algorithm - see *Controller Algorithm*

All-Red Interval
A period of time for the clearance of conflicting movements within the controlled area, during which only red aspects are illuminated for conflicting movements.

Approach
That section of road, consisting of one or more lanes, used by vehicles approaching an intersection or mid-block site.

Approach Speed - see *Speed*

Area Traffic Control System - see *Wide Area Control System*

Arrow Aspect
A masked vehicle aspect that displays an arrow shape when illuminated.

Arrow-Controlled Turn
A left-turn or right-turn movement at a signalised intersection that is made with a green arrow display, and therefore is unopposed. Also see *Unopposed Turn, Full Control, Partial Control*.

Arrow Mask
A mask placed over a vehicle aspect so that an arrow shape will be displayed when the aspect is illuminated. Also see *Symbolic Mask*.

Arterial Demand
A feature of traffic signal controllers whereby a permanent demand is placed for a particular phase or signal group. Also see *Recall Feature*.

Arterial Road
A road that predominantly carries through traffic from one region to another, forming principal avenues of travel for traffic movements.

Aspect
A single optical system (circular, arrow, or symbolic) on a signal face capable of being illuminated at a given time. Red, yellow, green and white aspects are used for vehicle movements. Also see *Pedestrian Aspects, Bicycle Aspect, Special Vehicle Aspects, Lantern*.

Availability
A measure of the probability in signal maintenance that the equipment will be available for use, determined as MTBF/(MTBF + MTTR) where MTBF = Mean Time Between Failures and MTTR = Mean Time To Repair.

Background Intensity
The luminous intensity of the signal background.

Bandwidth
The amount of green time common to all signals along the route in a coordinated system (Green Band). This can be determined as the time between the first and the last vehicle, travelling at the design speed, which can pass through a coordinated system of signals receiving a green signal on arrival at each stop line.

Bicycle Aspect
A masked aspect that displays a bicycle symbol when the aspect is illuminated. Also see *Bicycle Signal Face*.

Bicycle Signal Face
A signal face for the control of bicycle movements that consists of two bicycle aspects (red, green) or three bicycle aspects (red, yellow, green). Also see *Bicycle Aspect*.

Cableless Linking
A mode of signal coordination in which linking is achieved by reference to an accurate clock in each signal controller. The clocks are initially set to exactly the same time and maintained in synchronism by reference to the mains supply frequency. The clock initiates the operation of a certain plan at a certain time of day and day of week, according to a predetermined schedule.

Cable Linking - see *Local Interlinking*

Capacity
The maximum sustainable flow rate at which vehicles or persons reasonably can be expected to traverse a point or uniform segment of a lane or roadway during a specified time period under given roadway, geometric, traffic, environmental, and control conditions; usually expressed as vehicles per hour, passenger cars per hour, or persons per hour.

Channelisation
A system of controlling traffic by the introduction of a traffic island or median, or markings on a carriageway to direct traffic into predetermined paths, usually at an intersection or junction.

Clearance Time
Time given to allow a terminating movement of vehicles or pedestrians to vacate the controlled area, before the beginning of the next movement of traffic. Also see *Pedestrian Clearance Period*.

Column (of Aspects)
A combination of signal aspects arranged in a, vertical assembly.

Conflicting Movements
The vehicle or pedestrian traffic streams at an intersection, whose paths cross or merge when moving simultaneously.

Controlled Area
That portion of a carriageway or intersection, the entry into which is controlled by traffic signals.

Controller
The equipment (including the housing) that switches power to signal lanterns and controls the duration and sequence of signal displays.

Controller Algorithm
Programmed logic sequence internal to the controller, which transforms operator input and traffic demands into traffic control signal sequences.

Controller Personality
A unique program that configures the controller to the specific operational design of the intersection or midblock device it is controlling, including specifications of which signal groups run in each phase, the sequence of phases, detector functions, detector alarm conditions and default time settings.

Controller Programming
The task of configuring a controller to the specific requirements of a particular site. Also called Adaptive Engineering.

Controller Settings
User-defined control parameters within a traffic controller that determine signal timings (together with current traffic demands in the case of traffic-actuated controller).

Coordination
The operation of a traffic signal system where the control of individual installations is interrelated by means of a *Wide Area Control System, Local Interlinking* or *Cableless Linking*.

Cowl - see *Visor*

Critical Intersection
The intersection in a coordinated signal system that operates with the highest overall degree of saturation during a given period.

Critical Lane
The lane in a lane group or approach that has the highest degree of saturation and places the highest demand on green time.

Critical Movements
The set of movements that determine the capacity and timing requirements of a signalised intersection.

Crosswalk Lines
Continuous or broken lines marked transversely across the road to define the limits of a signalised crossing. Also see *Marked Foot Crossing, Signalised Crossing*.

Cycle
A complete sequence of signal phases.

Cycle Length (Cycle Time)
Time required for one complete sequence of signal displays (sum of phase green and intergreen times). For a given movement, cycle time is the sum of the durations of red, yellow and green signal displays, or sum of *Effective Green and Red Times*.

Degree of Saturation
The ratio of arrival (demand) flow rate to capacity during a given flow period.

Delay
The additional travel time experienced by a vehicle or pedestrian with reference to a base travel time (e.g. the free flow travel time).

Demand
The registration of the presence of vehicle or pedestrian traffic waiting for the right of way.

Demand Flow (Demand Volume)
The number of vehicles or pedestrians arriving during a given period as measured at the back of queue (as distinct from departure flows measured in front of the queue). Also see *Flow Rate, Traffic Count, Traffic Volume*.

Density
The number of vehicles per unit distance along the road as measured at an instant in time.

Design Life
The number of years into the future while the intersection operates satisfactorily considering increases in traffic demand volumes.

Detector
A device by which vehicle or pedestrian traffic registers its presence. The most common detectors are the inductive loop detectors for vehicles and the push-button detectors for pedestrians. Other detector types include microwave/radar, infrared, sonic, video image processing, magnetic and pressure detectors.

Detector Loop
One or more loops of wire embedded in the road surface and connected to the controller, energised by a low voltage current. The inductance of the circuit changes when a vehicle passes over the loop, which is detected by a unit in the controller.

Diamond Overlap Phasing
Phasing that allows right turns from opposing directions to operate either simultaneously, or independently with the through movement on the same approach, depending on demand for the right turns and conflicting through movements.

Display
A signal aspect that is illuminated.

Display Sequence
The order in which traffic signal displays occur.
Also see *Phase Sequence*.

Divided Road
A road with a median that separates the opposing directions of travel.

Dividing Line
A road marking formed by a line, or two parallel lines, whether broken or continuous, designed to indicate the parts of the road to be used by vehicles travelling in opposite directions.

Dividing Strip
An area or structure that divides a road lengthways, but does not include a nature strip, bicycle path, footpath or shared path.

Downstream
In the direction of the movement of traffic.

Dual Primary Signal Face
The signal face mounted on a post either on the median at or near the right of the stop line, or if there is no median or median is too narrow, to the right and near the projection of the stop line. Also see *Primary Signal Face*.

Dual Secondary Signal Face
The signal face mounted on a post on the downstream side to the right of that approach, in addition to the secondary signal face located on the median.

Early Cut-Off
The phase interval used at the end of a phase for allowing the termination of some signal groups earlier than others.

Effective Green and Red Times
The movement green and red times for capacity and performance analysis purposes, which are determined by adjusting the displayed green and red times for Start Loss and End Gain effects. Also see *Green Time, Red Time*.

Eighty-fifth Percentile Speed - see *Speed*

End Gain
Duration of the interval between the end of displayed green period and the end of effective green period for a movement. This is used in signal timing and performance analysis to allow for additional departures after the end of green period. *Early Cut-Off* time can be treated as an end gain for the movement that is terminated at the end of the Early Cut-Off interval. Also see *Start Loss*.

Exclusive Pedestrian Phase
The phase 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. Also see *Scramble-Crossing Phase*.

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. Also see *Shared Lane*.

Extension Period
The interval of variable length during the green period that begins after a demand for another phase is registered following the minimum green interval, and extends according to vehicle detector actuations subject to a maximum green extension setting in the controller.

Face - see *Signal Face*

Filter Turn
A turning movement that must give way to and find safe gaps in conflicting (opposing) vehicle or pedestrian traffic before proceeding, e.g. filter right-turn, slip-lane left turn, left turn on red. Also called Opposed Turn.

Finishing-Offset Coordination
Coordination of the end times of green periods using a signal offset that equals the average uninterrupted travel time in the travel direction so as to minimise delay along the route. Also see *Offset*.

Fixed-Time Control
A signal control method that allows for only a fixed sequence and fixed duration of displays.

Fixed-Time Plan Selection
A signal coordination method that uses predetermined signal timing plans introduced according to a weekly schedule or timetable.

Flexilink
The cableless linking mode of operation in the SCATS control system, used to maintain a level of signal coordination in the event of failure of the regional computer or parts of the communication system.

Flow Rate
Number of vehicles or pedestrians per unit time passing (arriving or departing) a given reference point. Also see *Demand Flow (Demand Volume), Traffic Count, Traffic Volume*.

Flow Ratio
The ratio of arrival (demand) flow rate to saturation flow rate during a given flow period.

Full Control
Control of a turning movement using three-aspect (red, yellow, green) turn arrows on a six-aspect signal face, where the green arrow indicates that the vehicle can turn unopposed (with no opposing vehicle or pedestrian traffic) and the red arrow indicates that the vehicle is not permitted to turn (filter turns not permitted).

Fully-Actuated Control - see *Traffic-Actuated Control*

Fully-Adaptive Control
A signal coordination method that generates appropriate signal timing plans on-line in a continuously variable fashion using extensive data provided by vehicle detectors.

Gap Setting
A controller setting equivalent to a predetermined space time measured between successive vehicles at the given (approach) speed, detection zone length and vehicle length values. Also see *Space Time*.

Give-Way Line
A broken line (double continuous lines in New Zealand, known as limit line) marked across all or part of a road, behind which vehicles should slow down and give way to opposing traffic. Also see *Stop Line*.

Green Band - see *Bandwidth*

Green Time
Duration of the green display for a phase or a movement. Also see *Effective Green and Red Times*.

Guide Sign
A sign which is erected to inform and advise road users of directions, distances, destinations, routes and location of services for road users, and points of interest.

Headway
The time between passage of the front ends of two successive vehicles (corresponds to *Spacing*). Not to be confused with the *Headway Setting* in a signal controller.

Headway Setting
A controller setting equivalent to a predetermined space time measured between successive vehicles at the given (saturation, or queue discharge) speed, detection zone length and vehicle length values. Also see *Space Time*.

Intensity - see *Luminous Intensity*

Intersection
A place at which two or more roads meet or cross.

Intergreen Time
Duration of the clearance part of the phase corresponding to the period between the phase change point (the end of running intervals) and the beginning of the green display for the next phase (end of phase). Normally, it comprises Yellow Time and All-Red Time. The *Early Cut-off Green* interval that follows the phase change point is also considered to be part of the Intergreen Time.

Irradiation
Blurring of the edges of a bright object viewed adjacent to a dark background.

Junction - see *Intersection*

Lagging Right Turn
An arrow-controlled right-turn movement that is started and terminated in the phase that immediately follows the phase in which the opposing through movement runs.

Lane
A portion of the carriageway allocated for the use of a single line of vehicles.

Lane-Control Signal
A signal face mounted above a lane in an overhead lane control scheme, which is used to control the direction of vehicle flow in the lane during a particular time.

Lane Group
A set of lanes allocated to a particular movement in exclusive lanes, or to several movements with common shared lanes.

Lantern
A signal assembly of optical components (one or more aspects), together with the means of connecting them to power supply and facilities for mounting the complete assembly. Also see *Aspect*.

Late Start
The phase interval used at the start of a phase for delaying the start of some movements.

Leading Right Turn
An arrow-controlled right-turn movement that is started and terminated in the phase that immediately precedes the phase in which the opposing through movement runs.

Lead-Lag Right Turn Phasing
A phase sequence that commences with a fully-controlled leading right turn from one approach, followed by a through phase, and terminates with a lagging right turn from the opposing approach.

Level of Service
An index of the operational performance of traffic on a given traffic lane, carriageway, road or intersection, based on service measures such as speed, travel time, delay and degree of saturation during a given flow period.

Limit Line - see *Give-Way Line, Stop Line*

Linking - see *Coordination*

Local Interlinking
A signal coordination system comprising a small number of closely-spaced signals, interconnected by a cable, usually with one of the signal controllers assuming the role of master. Also see *Master Controller*.

Louvres
An assembly of mechanical baffles mounted within the visor to reduce sun phantom (horizontal louvres) or to restrict the angular coverage of a signal (vertical louvres).

Luminance
Luminance at a point of a surface and in a given direction is the luminous intensity per unit projected area of a light emitting or reflecting surface.

Luminous Intensity
Luminous intensity in a given direction is the luminous flux emitted by a light source in an infinitesimal cone containing the given direction divided by the solid angle of that cone.

Marked Foot Crossing
A transverse strip of carriageway marked for the use of pedestrians crossing the road (mid block or at an intersection) controlled by vehicular and pedestrian signals. The term *Signalised Crossing* used in this document includes Marked Foot Crossing.

Masterlink
The fully-adaptive mode of operation of the SCATS control system.

Median
A dividing strip that separates vehicles travelling in opposite directions.

Master Controller
A traffic signal controller controlling a system of secondary controllers.

Movement
A stream of vehicles that enters from the same approach and departs from the same exit (i.e. with the same origin and destination).

MTBF
Mean time between failures (a signal maintenance term).

MTTR
Mean time to repair (a signal maintenance term).

Negotiation Speed - see *Speed*

Ninety-fifth Percentile Queue Length
Queue length expected to be exceeded in 5 per cent of signal cycles only, used for designing adequate queue storage length.

Occupancy Time
The time that starts when the front of a vehicle enters the detection zone and finishes when the back of the vehicle exits the detection zone. Thus, it is the duration of the period when the detection zone is occupied by a vehicle.

Off-Peak Period
The periods that have low demand volumes of traffic during the day. Also see *Peak Period*.

Offset
The difference between the start or end times of green periods at adjacent (upstream and downstream) signals.

Opposed Turn - see *Filter Turn*

Opposing Movement
1. A movement that conflicts with, and has priority over, another (opposed) movement.
2. A movement which approaches from the opposite direction as another on the same road regardless of destination.

Outreach (of Mast Arm)
The horizontal distance from the centre line of the vertical member to the centre line of the overhead lantern assembly.

Overhang (of Mast Arm)
The horizontal distance from the kerb alignment to the centre line of the overhead lantern assembly.

Overhead Signal Face
The signal face mounted above the roadway.

Overlap Movement
A movement that runs in consecutive phases without stopping during the associated intergreen period(s). Also see *Overlapping Signal Group*.

Overlapping Signal Group
A signal group that displays green in consecutive phases and during the associated phase transition(s). Also see *Overlap Movement*.

Painted Island
An area of a road, surrounded by a line or lines (whether broken or continuous), on which there are stripes marked on the road surface in white or another colour contrasting with the colour of the road.

Parallel Pedestrian Movement
A signalised pedestrian movement that runs at the same time as the parallel vehicle movement(s) that are controlled by circular green displays.

Partial Control
Control of a turning movement by a green arrow display in one phase (as an unopposed movement) and by a green circle display in another phase (as a filter, or opposed movement).

Passage Detector
A detector which produces a short output (pulse) of relatively constant duration, independent of the mass or type of a moving vehicle within the detection zone.

Peak Period
The period that has the highest demand volume of traffic during the day (peak hour, peak half hour, etc). Also see *Off-Peak Period*.

Pedestrian-Actuated Control - see *Traffic-Actuated Control*

Pedestrian Aspects
Signal aspects for pedestrians, consisting of the Walk aspect (a green walking human figure) and the Don't Walk aspect (red standing human figure). Also see *Pedestrian Signal Face*.

Pedestrian Clearance Period
The Flashing Don't Walk period that immediately follows the termination of pedestrian Walk display to enable pedestrians, who have just stepped off the kerb at the commencement of this period, to complete their crossing to the nearest kerb or refuge. *Pedestrian Clearance Time* is the duration of the Pedestrian Clearance Period.

Pedestrian Crossing
A transverse strip of carriageway marked for the use of pedestrians crossing the road (mid block or at intersections) at a place with a pedestrian crossing sign, and with or without alternating flashing twin yellow lights. Also called *Zebra Crossing* where indicated by parallel white stripes on the road surface.

Pedestrian Green Time
The duration of the green Walk display.

Pedestrian Indicator
An indicator mounted on the pedestrian push-button assembly that is illuminated to acknowledge when a demand has been recorded.

Pedestrian Push-Button Assembly
Device to enable pedestrians to register a demand for right of way. It includes the pedestrian indicator. Push button devices are also used for bicycles and emergency vehicles.

Pedestrian Refuge
A place, usually in a carriageway, set aside for exclusive use of pedestrians.

Pedestrian Signal Face
A two-aspect signal face for the control of pedestrian movements that consists of green Walk and red Don't Walk aspects. Also see *Pedestrian Aspects*.

Perception and Reaction Time
The time between the commencement of a stimulus, e.g. change in signal condition, and the taking of appropriate action, e.g. application of vehicle brakes.

Phase
That part of a signal cycle during which one or more movements receive right of way subject to resolution of any vehicle or pedestrian conflicts by priority rules. A phase is identified by at least one movement gaining right of way at the start of it and at least one movement losing right of way at the end of it.

Phase Sequence
The order of phases in a signal cycle. Also see *Display Sequence, Signal Phasing*.

Phase Split
Duration of each phase (*Green Time* and *Intergreen Time*) within a signal cycle. It is normally expressed as a percentage of cycle length.

Phasing - see *Signal Phasing*

Plan - see *Timing Plan*

Platoon
A group of vehicles or pedestrians travelling together because of signal control, geometric conditions or other factors.

Post
Vertical tubular support for traffic signal lanterns and associated signs.

Presence Detector
A detector that produces a continuous output while a moving or stationary vehicle is present within the detection zone.

Primary Signal Face
The signal face mounted on a post at or near the left of the stop line of the approach. Also see *Dual Primary Signal Face, Secondary Signal Face, Tertiary Signal Face*.

Priority Rule
A traffic regulation which assigns priority to one stream of traffic. Also see *Conflicting Movements, Filter Turn, Opposing Movement*.

Priority Traffic
That traffic which is allocated priority service at an intersection by the operation of signals. It may include emergency vehicles or public transport vehicles. Not to be confused with the term Priority Road (Major Road) for unsignalised intersections (a road on which traffic has right of way over all entering or crossing traffic).

Progression
Progression is a time-relationship, between adjacent traffic signals, which allows vehicle platoons to be given a green signal as they pass through the sequence of intersections.

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 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.

Reaction Time - see *Perception and Reaction Time*

Recall Feature
A feature of traffic signal controllers whereby a demand is placed for a particular phase when no other demands are present and all approach timers have expired. Also see *Arterial Demand*.

Red Arrow Drop Out
A form of partial control that uses three-aspect (red, yellow, green) right-turn arrows on a six-aspect signal face and extinguishes the red arrow for the adjacent green circle display to permit filter turns after a few seconds in the through phase.

Red Time
Duration of the red signal display for a phase or a movement. Also see *Effective Green and Red Times*.

Repeat Right Turn Phasing
Phasing that introduces the arrow-controlled right turn twice in the same cycle.

Reversible Lanes - see *Tidal Flow Scheme*

Right-Turn Trap
A situation where a driver executing a filter right-turn manoeuvre at the start of yellow interval thinks that the signals change to yellow for the opposing traffic at the same time, and therefore proceeds and runs into an opposing through vehicle for which the signal display would still be green. Also known as "lagging right turn problem" or "yellow trap". Also see *Lagging Right Turn*.

Road Marking
A word, figure, symbol, mark, line, raised marker or stud, or something else, on the surface of a road to direct or warn traffic, but does not include a *Painted Island*.

SCATS
A well-known fully-adaptive wide area control system developed in Australia and used in many cities around the world (Sydney Coordinated Adaptive Traffic System).

SCATS DS
Degree of saturation in the SCATS adaptive control method.

SCATS Master Isolated Control
The SCATS adaptive control method for a single (isolated) signalised intersection.

Scramble-Crossing Phase
An Exclusive Pedestrian Phase at an intersection where pedestrians are allowed to cross in any direction including diagonally within the limits of the crosswalk lines. Also see *Exclusive Pedestrian Phase*.

Secondary Signal Face
The signal face mounted on a post on the downstream side to the right of the approach. Also see *Primary Signal Face, Tertiary Signal Face*.

Semi-Actuated Control - see *Traffic-Actuated Control*

Sequence - see *Display Sequence*

Shared Lane
A lane allocated for use by two or more movements, e.g. shared through and right-turn lane. Also see *Exclusive Lane*.

Sight Distance
The distance over which a road user needs to have unobstructed sight to respond to a visual cue, or to safely avoid a conflict.

Sign - see *Traffic Sign*

Signal - see *Traffic Signal*

Signal Aspect - see *Aspect*

Signal Controller - see *Controller*

Signal Coordination - see *Coordination*

Signal Cycle - see *Cycle*

Signal Display - see *Display*

Signal Face
A set of signal aspects in a common assembly, generally in one or two columns placed together with a target board to improve signal visibility, facing traffic from one direction.

Signal Group
A signal group is a set of lanterns with common electrical switching such that the aspects illuminated in each lantern are always identical.

Signal Group Overlap - see *Overlapping Signal Group*

Signal Intensity
The luminous intensity of the signal aspects. Also see *Luminance and Luminous Intensity*.

Signal Lantern - see *Lantern*

Signal Linking - see *Coordination*

Signal Offset - see *Offset*

Signal Phase - see *Phase*

Signal Phasing
Sequential arrangement of separately controlled groups of vehicle and pedestrian movements within a signal cycle to allow all vehicle and pedestrian movements to proceed.

Signal Range (Visual Range)
The distance over which the signal is intended to be clearly visible to approaching traffic.

Signal Sequence - see *Display Sequence*

Signal Timing
The process of determining durations of successive intervals of green, yellow and red displays, actuated signal control settings, as well as offsets for coordinated signals.

Signalised Crossing
An area of the road used by pedestrians when crossing the road with the guidance of pedestrian signals at a midblock or intersection location, and can be used by cyclists if bicycle signals are provided.

Simultaneous-Offset Coordination
Signal coordination where green periods in the travel direction start at the same time (zero offset). This is useful when the back of queue at the downstream intersection interrupts progression at closely spaced intersections. Also see *Offset*.

Slip Lane
A left-turn lane separated from an adjacent lane by a triangular island.

Space Length (Gap Distance)
The following distance between two successive vehicles as measured between the rear end of one vehicle and the front end of the next vehicle in the same traffic lane (spacing less vehicle length).

Space Occupancy Ratio
The proportion of a road section (distance) occupied by vehicles at an instant in time.

Space Time
The time between the detection of two consecutive vehicles when the presence detection zone is not occupied. It is equivalent to gap time less the time taken to travel the effective detection zone length.

Spacing
The distance between the front ends of two successive vehicles in the same traffic lane.

Special Vehicle Aspects
Signal aspects for special vehicles (bus, tram, emergency vehicle) consisting of red, yellow and white B, T and E symbols. Also see *Special Vehicle Signal Face*.

Special Vehicle Signal Face
A single-column signal face for the control of special vehicle (bus, tram, emergency vehicle) movements. Also see *Special Vehicle Aspects*.

Speed
Distance travelled per unit time. In a time - distance diagram, the slope of the trace of a vehicle is its speed. *Approach Speed* is the uninterrupted (midblock) cruise speed of vehicles before being affected by traffic signals. This can be represented by the speed limit. *Negotiation Speed* is the safe speed of a vehicle moving through the controlled area of the intersection. For turning vehicles, this can be determined as a function of the negotiation radius. *Eighty-fifth Percentile Speed* is the speed at or below which 85 per cent of the traffic travels.

Split-Approach Phasing
The signal phasing arrangement that allocates separate phases to opposing approaches, allowing the through and all turning movements from each approach to operate simultaneously.

Staged Signalised Crossing
A system by which a long signalised crossing is divided or "staged" into several time-separated sections, each being a separate group controlled by individual signals.

Start Loss
Duration of the interval between the start of displayed green period and the start of effective green period for a movement. This is used in signal timing and performance analysis to allow for queue discharge time losses at the start of green period due to vehicles accelerating to saturation speed, or due to giving way to opposing vehicle or pedestrian movements. *Late Start* time can be treated as a start loss for the movement that starts after the Late Start interval. Also see *End Gain*.

Starting Display - see *Starting Signal*

Starting-Offset Coordination
Coordination of the start times of green periods using a signal offset that equals the average uninterrupted travel time in the travel direction so as to minimise stops along the route. Also see *Offset*.

Starting Signal
A signal which is located so that the drivers who have stopped at the stop line can see the signal display.

Stop Line
A single continuous line (double continuous lines in New Zealand, known as limit line) marked across all or part of a road, behind which vehicles should stand when required to stop by traffic light signals or regulatory signs. Also see *Give-Way Line*.

Stopping Display - see *Stopping Signal*

Stopping Signal
A signal which is used to enable the approaching driver to make a decision either to stop safely in front of the stop line or proceed into the intersection.

Stopping Sight Distance
The sight distance which is necessary to enable a driver to stop safely in response to a red signal.

Sun Phantom
The internal reflection of light from external sources (especially the sun) onto the lens of a signal lantern which makes it appear to be internally illuminated.

Symbolic Mask
A mask used to create a symbol (e.g. arrow, pedestrian or bicycle) or letter (e.g. B or T) to dedicate the aspect to a particular vehicle movement (e.g. turning traffic) or a special vehicle movement (e.g. bus, tram). Also see *Arrow Mask*.

Synchronous Linking - see *Cableless Linking*

T-Intersection
An intersection where two roads meet (whether or not at right angles) and one of the roads ends.

Target Board
The panel attached to a signal face to improve its visibility by reducing background luminance.

Tertiary Signal Face
The signal face mounted on a post on the downstream side to the left of the approach. Also see *Primary Signal Face, Secondary Signal Face*.

Through Phasing
Phasing that allows through and left-turn movements and filter right turns from opposing approaches to operate in the same phase using the three-aspect circular (red, yellow, green) signal faces.

Tidal Flow Scheme
A traffic management method for increasing capacity under conditions of high traffic demand and marked directional split by means of reversible lanes or carriageways.

Time - Distance Diagram
A graphical representation of the movement of a vehicle or traffic stream in terms of its time and distance coordinates, e.g. used to show signal coordination along a route or for showing vehicles queuing at traffic signals.

Time Occupancy Ratio
The proportion of time in a given period when the passage or occupancy detector at a point along the road is occupied by vehicles.

Timing Plan
A plan that defines the cycle time, green splits and offsets for each intersection in a coordinated signal system.

Traffic
Movement of vehicles and pedestrians (people and goods) along a route.

Traffic-Actuated Control
A control method that allows a variable sequence and variable duration of signal displays depending on vehicle and pedestrian traffic demands. All vehicle movements (phases) are actuated in *Fully-Actuated Control* in contrast with *Semi-Actuated Control* where only minor vehicle movements (e.g. side road traffic) are actuated.

Traffic Composition
The proportions (usually expressed as a percentage) of the different vehicle classes and turning vehicles within the total traffic flow.

Traffic Control Device
Any traffic sign, road marking, traffic signal, or other device, placed or erected under public authority for the purpose of regulating, directing, warning or guiding traffic.

Traffic Count
The process of determining the number of vehicles or pedestrians passing a given point or points during a specified period of time. Also see *Demand Flow (Demand Volume), Flow Rate, Traffic Volume*.

Traffic Demand - see *Demand*

Traffic Flow - see *Traffic Volume*

Traffic Island
A structure on a road to direct traffic, but does not include a *Road Marking* or *Painted Island*.

Traffic-Responsive Plan Selection
A signal coordination method that introduces pre-determined plans by means of algorithms that respond to changing traffic conditions using data collected from detectors.

Traffic Sign
A board, plate, screen, or another device, whether or not illuminated, displaying words, figures, symbols or anything else to regulate, direct or warn road users, and includes a children crossing flag, a hand-held stop sign, a parking control sign and a variable illuminated message sign, but does not include traffic signals.

Traffic Signal
A signal that controls vehicle and pedestrian traffic at an intersection or on a road by means of red, yellow, green or white light displays, and includes circular and arrow signals, pedestrian signals, bicycle crossing signals, B (bus) and T (tram) signals, overhead lane control signals, and twin red or yellow signals.

Traffic Volume
The number of vehicles or pedestrians passing a given point on a lane or carriageway during a specified period of time. Also see *Demand Flow (Demand Volume), Flow Rate, Traffic Count*.

Trailing Right Turn - see *Lagging Right Turn*

Transponder
A device fitted to a bus, tram or emergency vehicle that allows the signal controller to selectively identify the presence of that vehicle in a stream of mixed traffic.

Undivided Road
A road without a median. Also see *Divided Road*.

Unopposed Turn
A left-turn 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.

Urban Traffic Control System - see *Wide Area Control System*

Vehicle-Actuated Control - see *Traffic-Actuated Control*

Vehicle Passage Time
The time between the passage of the front and back ends of a vehicle from a given point along the road.

Visor
An attachment to the face of a signal aspect to minimise the sun-phantom effect and/or to reduce the possibility of a signal being seen by traffic for which it is not intended. Also called Cowl.

Volume of Traffic - see *Traffic Volume*

Walk Time
Duration of the Walk display (steady green person) for pedestrians.

Wide Area Control System
A signal coordination system comprising one or more centrally or regionally located computers controlling relatively large numbers of signals, with all signals connected to the traffic control computers, usually by leased data lines or, in some cases, by dedicated cable systems.

Yellow Time
Duration of the yellow display for a phase or a movement.

Yellow Trap - see *Right-Turn Trap*

Zebra Crossing - see *Pedestrian Crossing*

1. Introduction

1.1 General

It is not practicable to standardise the design of intersections or the signal installations that control them. However, to ensure uniformity it is important to standardise design procedures and the operating characteristics of traffic signals.

This guide deals mainly with the design of traffic signals. Traffic signal design can vary from simple two-phase to very complex phasing control. Signal phasing mainly depends on safe operation, the volume and direction of traffic flows, and intersection geometry. Coordination can also affect signal phasing. To ensure safe operation the signals, roadway, signs and pavement markings should provide consistent operating characteristics and be adequately maintained.

The design, installation, operation and maintenance details given in this guide needs to be tempered by the requirements, practices and regulations of individual jurisdictions.

The guide presents general guidelines for design of signals, and good engineering judgement is required for effective design to resolve issues that may arise in specific situations.

1.2 Scope

Basic information necessary to promote uniformity in the design of traffic signal installations is provided in this guide. Design practice, signal equipment used, and the signs and pavement markings that are uniquely associated with traffic signals are discussed.

The guide can generally be applied in situations where the speed limit is 80 km/h or less. When installed in locations where the speed limit is above 80 km/h, measures should be taken to ensure safe operation.

Although the guide may be applied to situations with higher traffic speeds, allowance should be made for the fact that driver judgement and response are more critical, and the possibility of unsafe operation is increased, in such situations.

It is emphasised that this is not a standards document. The hierarchy of documents in relation to the use of this document is:

(i) Australian and New Zealand Standards,

(ii) Guide to Traffic Engineering Practice series, and

(iii) Local in-house standards and manuals.

Any reference to right-turn and left-turn movements in this document is based on driving on the *left-hand side* of the road as applicable in Australia and New Zealand. Any specification or recommendation related to these movements should be applied to driving on the *right-hand side* of the road by interchanging the terms left-turn and right-turn.

1.3 Statutory Provisions

The installation of and compliance with traffic control devices are the subject of legislation in each Australian State or Territory, and in New Zealand. Before construction of any signal installation, compliance with the relevant statutes and regulations must be assured.

1.4 Associated Standards and Manuals

This guide is complementary to AS 1742 *Manual of Uniform Traffic Control Devices* and other associated Australian Standards dealing with components of signal systems (see *Table 4.1* in *Section 4*). The guide should be used in conjunction with those standards (Standards Australia 1975-2000).

Austroads has issued a number of publications relevant to signalised intersections. In particular, various parts of the Guide to Traffic Engineering Practice (**GTEP**) (Austroads 1988 - 1999) are companions to this guide.

Examples of local guidelines are:

(a) Traffic Signal Practice - Design. Roads and Traffic Authority of New South Wales (RTA NSW 1992).

(b) Traffic Engineering Manual Volume 1 - Traffic Management. VicRoads (VicRoads 1997a).

(c) Road Planning and Design Manual. Queensland Department of Main Roads (QMR 2000).

(d) Manual of Traffic Signs and Markings, Parts I and II. Transit New Zealand and Land Transport Safety Authority (1997, 1998).

1.5 Guidelines

The following general guidelines can be used to determine whether installation of traffic signals is justified at an intersection subject to following considerations:

(a) Where alternative or additional criteria exist in local guidelines, they should be applied.

(b) All other relevant factors should be taken into account and proper engineering judgement should be exercised.

(c) The warrants alone should not be used to justify an installation. If a site satisfies warrants, this does not necessarily mean that signals are the best solution. Alternative treatments such as the use of a roundabout should be considered to determine the optimum solution in terms of traffic performance measures, levels of service, and benefit-cost ratios.

The reader should refer to other parts of the Guide to Traffic Engineering Practice series for information on other intersection types (roundabouts, sign-controlled intersections, interchanges).

1.5.1 Signalised Intersection Warrants

The terms *major road* and *minor road* are used below to indicate roads carrying the larger and smaller traffic demand volumes.

As a guide, installation of signals may be considered at an intersection if one of the following warrants is met.

(a) **Traffic demand volumes**: For each of four one-hour periods of an average day, the major road flow exceeds 600 veh/h in both directions, and the highest volume approach on the minor road exceeds 200 veh/h. OR

(b) **Continuous traffic**: For each of four one-hour periods of an average day, the major road flow exceeds 900 veh/h in both directions, and the highest volume approach on the minor road exceeds 100 veh/h, and the speed of traffic on the major road or limited sight distance from the minor road causes undue delay or hazard to the minor road vehicles, and there is no other nearby installation easily accessible to the minor road vehicles. OR

(c) **Pedestrian safety**: For each of four one-hour periods of an average day, the major road flow exceeds 600 veh/h in both directions (or where there is a central pedestrian refuge at least 1.2 m wide, the major road flow exceeds 1000 veh/h in both directions), and the pedestrian flow crossing the major road exceeds 150 ped/h. For high-speed major road conditions where the 85th percentile speed on the major road exceeds 75 km/h, the above major road traffic flow criteria are reduced to 450 veh/h without refuge and 750 veh/h with refuge. OR

(d) **Crashes**: The intersection has been the site of an average of three or more reported casualty crashes per year over a three-year period where the crashes could have been prevented by traffic signals, and the traffic flows are at least 80 per cent of the volume warrants given in (a) and (b). Signals should only be installed if simpler devices will not effectively reduce the accident rate. OR

(e) **Combined factors**: In exceptional cases, signals occasionally may be justified where no single guideline is satisfied but where two or more of the warrants given in (a), (b) and (c) are satisfied to the extent of 80 per cent or more of the stated criteria.

1.5.2 Midblock Signalised Crossing Warrants

The need for a midblock signalised crossing depends on the probability of pedestrians being able to find suitable gaps in vehicular traffic stream. This probability is decreased with the increased speed, and increased volume and density of vehicles. Other factors to consider include platooning of vehicle flows from upstream signals, number of traffic lanes to cross, pedestrian desire lines, impact of future development, as well as proportion of children, elderly or handicapped pedestrians.

Justification for the provision of a midblock signalised crossing should be based on the potential pedestrian flows rather than the existing flows, considering that this facility may attract additional pedestrians to the site.

Provision of a midblock signalised crossing should be avoided within 130 m of a signalised intersection.

The following guidelines for midblock signalised crossings differ from those given in Austroads GTEP Part 13 (Pedestrians) and AS 1742 Part 10.

As a guide, a mid-block signalised crossing may be considered if one of the following warrants is met.

(a) For each of four one-hour periods of an average day, the pedestrian flow crossing the road exceeds 250 ped/h, and the vehicular flow exceeds 600 veh/h in both directions, or where there is a central pedestrian refuge at least 1.2 m wide, the major road flow exceeds 1000 veh/h in both directions. OR

(b) For each of eight one-hour periods of an average day, the pedestrian flow crossing the road exceeds 175 ped/h, and the vehicular flow exceeds 600 veh/h in both directions, or where there is a central pedestrian refuge at least 1.2 m wide, the major road flow exceeds 1000 veh/h in both directions, and there is no other pedestrian (Zebra) crossing or signalised crossing within a reasonable distance. OR

(c) Where the crossing is used predominantly by *children*, and for each of two one-hour periods of an average day, the pedestrian flow exceeds 50 ped/h, and the vehicular flow exceeds 600 veh/h in both directions. OR

(d) Where at least 50 per cent of pedestrians using the crossing are elderly or handicapped persons, and for each of two one-hour periods of an average day, the pedestrian flow exceeds 50 ped/h, and the vehicular flow exceeds 600 veh/h in both directions. OR

(e) A midblock signalised crossing may also be considered in special situations if one of the following warrants is met:

   (i) The location has been the site of two or more pedestrian casualties over a three-year period where these could have been prevented by a midblock signalised crossing. OR

   (ii) There is a large seasonal variation in the vehicular traffic flow (such as at a holiday resort) and it can be shown to meet the general criteria during the busy season, even if during the rest of the year, the general criteria are not met. OR

   (iii) The flow warrant for a pedestrian (Zebra) crossing is realised (see AS 1742 Part 10 and Austroads GTEP Part 13, Appendix B) but its provision could cause a hazard to pedestrians because of the width of the carriageway, insufficient sight distance to the crossing or the speed or number of vehicles. OR

   (iv) The site meets the warrants for a pedestrian (Zebra) crossing, but a signalised crossing would improve traffic flow by enabling it to be coordinated with another site, or sites.

In accordance with AS 1742 Part 10 and where regulations permit, "Pelican crossings" (Section 6.5.3) may be provided if:

(a) a pedestrian-actuated mid-block signalised crossing is justified (using the above guidelines),

(b) the site would benefit from reduced vehicle delays, and

(c) the site is an area where the 85th percentile speeds are 80 km/h or less.

1.5.3 Warrants for Pedestrian Signals at Signalised Intersections

The following guidelines for pedestrian signals at signalised intersections differ from those given in Austroads GTEP Part 13 (Pedestrians) and AS 1742 Part 10.

As a guide, pedestrian signals may be considered at a signalised intersection if one of the following warrants is met.

(a) Where the pedestrian movement crosses the major road, for each of two one-hour periods of an average day, the pedestrian flow exceeds 30 ped/h. OR

(b) Where the pedestrian movement crosses the minor road, for each of two one-hour periods of an average day, the pedestrian flow exceeds 60 ped/h. OR

(c) A midblock signalised crossing is warranted within 130 m. OR

(d) Where the pedestrian flow criterion is not met but one or more of the following conditions apply:

   (i) A number of young children will use the crossing. OR

(ii) Elderly or handicapped pedestrians will use the crossing. OR

(iii) There will be a hazard to pedestrians due to the width of the carriageway (greater than six lanes or 25 m). OR

(iv) There will be a hazard to pedestrians due to the high speed or number of vehicles.

1.6 Environment

This guide is applicable to most Australian environments. Engineering judgement should be exercised to confirm its relevance where local conditions occur which may obstruct a driver's vision (snow, fog, pollution), affect a vehicle's performance (ice, sand, steep grades), or affect the interaction between drivers, vehicles, pedestrians and traffic signals.

Figure 1.1 illustrates the interaction between the signal system and various external factors including:

(a) road user requirements,

(b) expectations of travel conditions,

(c) public transport policies,

(d) vehicle and pedestrian movements, and

(e) accident rates.

1.7 Design Process

Subsequent chapters of this guide examine the individual tasks of signalised intersection design. The design process is the orderly combination of these tasks into a rational and effective design sequence as shown in *Table 1.1*.

Appendices A and B provide the theoretical background material for users of this guide. *Appendix C* discusses general aspects of signal timing methods, describes actuated signal controller operation, and presents guidelines for determining appropriate values of controller settings.

Appendix D illustrates some aspects of the design process for a sample intersection.

1.8 Construction

Construction methods employed depend on local resources and practices and are not addressed in this guide.

It is important to maintain safe traffic operations during signal installation and reconstruction. Thus suitable staging of works should be considered. The control arrangements at the intersection where the signals are being installed or at adjacent intersections may require special attention during the construction period.

1.9 Operation

Signal installations should be checked periodically to ensure that the signal operation accommodates any changes in traffic or environment that may have occurred (e.g. increased or decreased demand volumes).

In general, feedback from road users may be sufficient to ensure that the phasing and signal timings are appropriate. Feedback from electrical maintenance staff and other traffic professionals should be encouraged to ensure that the signals continue to operate as efficiently as possible.

Figure 1.1 Traffic signal external factors

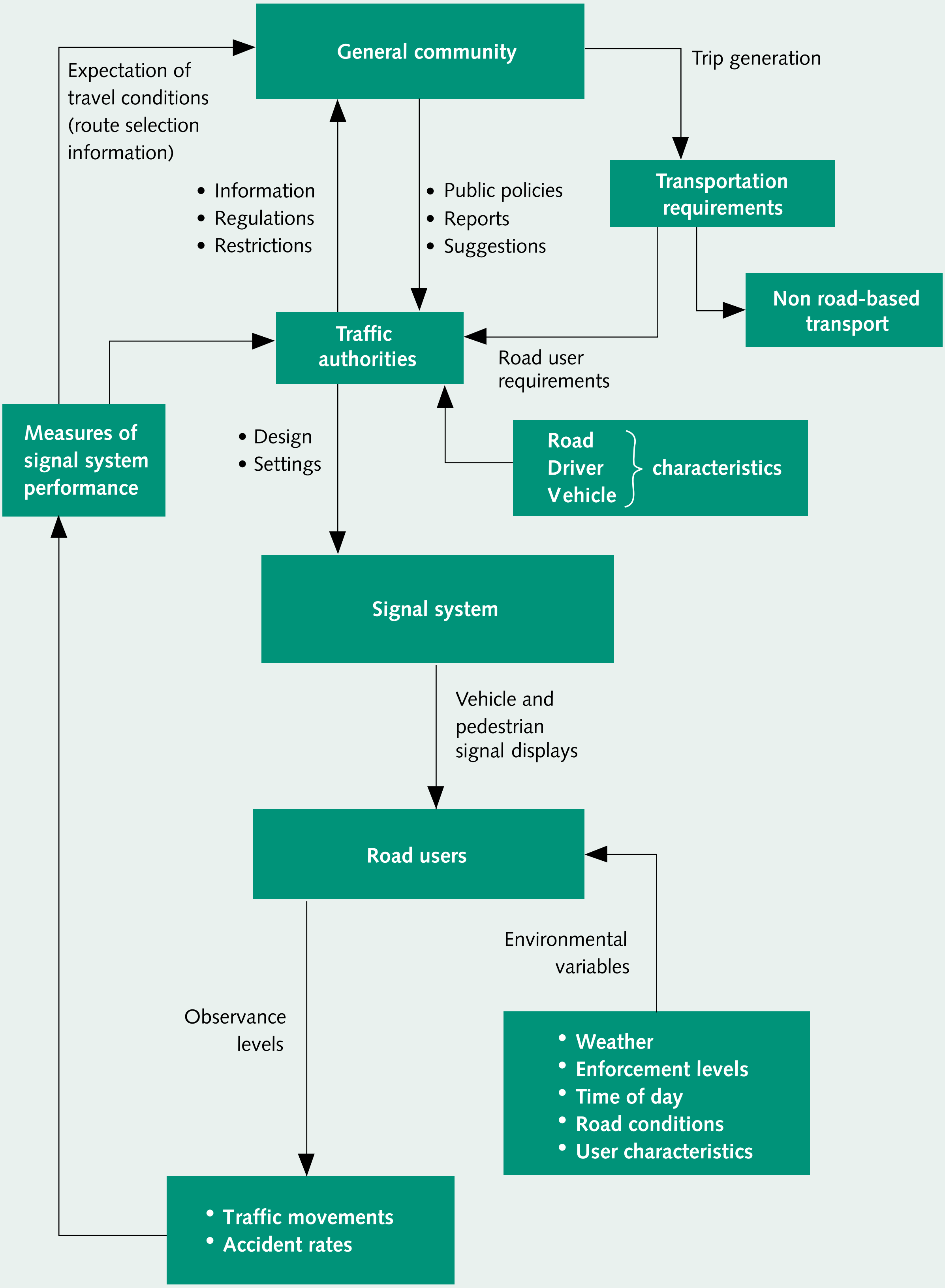


Table 1.1 Signalised intersection design process

	Design Tasks	Section
(i)	Collect design data.	2
(ii)	Determine the geometric requirements.	3
(iii)	Determine signal phasing and time settings: This involves determining capacities and traffic performance characteristics for a number of possible phasing schemes and geometric layouts.	6, App B, C
(iv)	Determine signal face layouts.	5
(v)	Select signal hardware, determining location of signal displays, and appropriate use of pavement markings and signs.	4, 7, 10, 11
(vi)	Determine detector locations and prepare controller program.	8, 9
(vii)	Prepare the electrical design.	12
(viii)	Determine the need for signal coordination, and accordingly, prepare coordination plans.	13
(ix)	Prepare operational documentation necessary for the installation, commissioning and operation of the signals.	14

1.10 Maintenance

Maintenance of traffic signal equipment is essential for effective operation. Integral components of an effective maintenance system are:

(a) speedy and accurate fault reporting,

(b) fast response time to reported faults,

(c) preventative maintenance, and

(d) lamp changing.

1.11 Education and Enforcement

It is essential that road users understand the meaning of signal displays. When unfamiliar displays are first used in a locality, the need for public education should be considered.

Regulations concerning traffic signal operations should be enforced to ensure correct responses from the public and to deter unsafe practices.

1.12 Definitions

Terms used in this guide are those commonly used and accepted in engineering practice. Specialist terms are defined in the Glossary of Terms given at the start of this document (also see AS 1348).

2. Design Data

2.1 Introduction

Design data are used to assess the adequacy of geometric layouts, the location of signal equipment, the signal phasing and time settings. These data should be accurate and up-to-date. Data can be divided into four main categories:

(a) physical layout,

(b) traffic data,

(c) crash data, and

(d) planning information concerning future developments.

Where data are estimated or predicted, the effect of data accuracy levels on the design should also be considered.

2.2 Physical Layout of Intersections

The following features of the site should be shown on a base plan where relevant:

(a) relevant property boundaries and building lines,

(b) type and location of kerbs and channels,

(c) layout and condition of pavements, medians, etc, on all approach and exit roads,

(d) approach grades,

(e) parking restrictions or facilities, bus bays, taxi zones,

(f) location of all poles and aerial cables (note whether high voltage, low voltage or telecommunication lines),

(g) position, type and size of existing road signs, and any other roadside furniture,

(h) location and nature of existing street lighting,

(i) position of any overhead obstructions (horizontal and vertical clearances, to verandahs, signs, power lines, shop awnings, etc should be shown),

(j) location of trees and their probable size when fully grown,

(k) type and location of surrounding development (residential, suburban shopping, industrial, central business district, railway stations, schools, etc),

(l) access to properties (queuing vehicles may block access and detector position may be affected),

(m) location and size of drainage pits and pipes,

(n) the position of telecommunication, sewer, gas, water and any other underground services (these locations should be verified with the relevant authorities).

The following information should be noted for use in the design:

(i) work proposed by other authorities,

(ii) constraints on locations of:

- controller and power supply,
- posts,
- intersection signalised crossings and pedestrian (Zebra) crossings,
- cable ducts,
- junction pits (for ducting),

(iii) any special traffic which uses the intersection (e.g. over-dimensional vehicles, special pedestrian needs), and

(iv) strategic location within the road network.

2.3 Traffic Data

Traffic demand volumes are essential for the design of traffic signal installations. The design should place emphasis on serving transport needs of people and goods rather than vehicles only.

Traffic signals should operate efficiently over a wide variety of traffic conditions. While designs are based on peak traffic conditions, efficient operations at peak and lower volumes are provided by the use of adaptive control. It is usually necessary to provide for a number of peak traffic conditions, e.g. am and pm commuter, retail, recreation, and special event peaks.

Local policies and consideration of demand flow patterns determine the selection of the duration of design period (60-minute, 30-minute or 15-minute peak) for the purpose of capacity and performance analysis.

See Austroads GTEP Part 3 (Traffic Studies), and Section 8 of ARR 123 (Akçelik 1981).

Motor Vehicles

Traffic volumes for the relevant peak periods are expressed in hourly flow rates. These should also include information about traffic composition in terms of turning movements and heavy vehicles. For definitions of different vehicle classes, see Section 5.5 of ARR 123 (Akçelik 1981) and Section 9 of Austroads GTEP Part 2 (Roadway Capacity).

These data are normally obtained from manual counts of at least two-hour duration for each peak period. Usually 15-minute summation intervals are used so the peak flow rates can be identified. Traffic counts may vary by day of the week, or because of weather, school or public holidays or other abnormal conditions. The designer should consider the circumstances of the count and adjust or recount if necessary before determining the volumes for the design.

Pedestrians and Bicycles

Counts should identify the pedestrian volumes crossing each vehicle approach and the proportion of children, aged or other pedestrians with special needs included in these volumes. These are required to enable specific features to be designed where necessary.

Bicycle volumes should also be counted both along and across each vehicle approach to identify the need for special features in the design.

2.4 Crash Data

Crash data should be obtained to identify hazard problems with the existing geometry, or special problems for which traffic signals should cater. Crash data for this purpose are best shown as collision diagrams and it is usual to show data for at least three years. See Austroads GTEP Part 4 (Road Crashes).

2.5 Future Developments

During the design of traffic signal installations, it is desirable to consider potential changes to traffic demand patterns resulting from changes to land use and future traffic growth in the area of the intersection.

A *design life* analysis should be carried out to investigate the amount of traffic that can be accommodated by the intersection in future years. This will determine the adequacy of the geometric layout and phasing. It will also identify future needs for additional road space and more complex phasing (including associated lanterns and detection). The design should take account of these changes particularly with regard to ducting arrangements.

3. Geometric Elements

3.1 General

This section deals with aspects of intersection geometry that are specific to signalised intersections. For a more detailed treatment of intersection geometry refer to Austroads GTEP Part 5 (Intersections at Grade).

When designing traffic signals for installation at an existing intersection, it is important to identify and rectify deficiencies in the geometric layout (see the worked example in *Appendix D*). Detailed geometric characteristics of the intersection as discussed in this section need to be considered when improving an existing intersection, and designing of a new signalised intersection.

3.2 Traffic Lanes

3.2.1 Lane Arrangements

The number of lanes, and thus the capacity of each approach, is determined by the total available width (and the scope for widening) of the approach and the traffic volume on that approach. To increase the capacity of an intersection, it is necessary to provide additional capacity on the critical approach or approaches. An approach is critical if its capacity is limiting the capacity of the intersection with a given flow pattern. Different approaches can be critical with different flow patterns (i.e. different times of day). Increasing the capacity of any critical approach may also increase the capacity of other critical approaches as additional green time can be given to the other approaches.

Increasing the number of lanes in order to increase capacity can be achieved by either reducing the width of existing lanes, or by widening the approach and departure carriageways to introduce short lanes on the approach and departure sides (turn pockets and flares), and providing appropriate tapers to allow proper usage of lanes. Recommended lane widths are given in Austroads GTEP Part 5.

The capacity gained from lanes with limited queue storage space (approach short lanes) can be limited especially when long cycle times are used (Akçelik 1981). Similarly, gains from downstream short lanes can be limited due to underutilisation of the lane on the approach side.

Through lanes across an intersection should be aligned to achieve a clear definition of vehicle paths. When it is desired to store vehicles in separate turning lanes adjacent to through traffic lanes, it is important to ensure that adequate storage length is provided. Where adequate storage length cannot be provided, the signal phasing and time settings may be modified. The design of appropriate storage length is based on a selected percentile queue length, e.g. 95th percentile value (queue length exceeded in 5 per cent of signal cycles).

An important aspect of the design of intersection geometry is the decision about the use of *exclusive lanes* allocated for use by one movement, and *shared lanes* allocated for use by several movements, e.g. shared through and right-turn lane. This should aim to achieve balanced lane use by existing demand volumes.

3.2.2 Right-Turn Lanes

Where through and right-turn vehicles share a lane, the following may occur:

(a) hazardous situations created by a stationary right-turn vehicle in the lane (due to restricted sight distance),

(b) blocking a through lane (reducing capacity, increasing delays and queue lengths), and

(c) an inefficient use of any right-turn traffic phase.

Therefore, exclusive right-turn lanes should be provided where practical. If the right-turn volume is low, a turn ban (prohibition of the right-turn movement) may be considered.

The use of a shared through and right-turn lane adjacent to an exclusive right-turn lane may be considered where right-turn traffic demand volumes are large. Implications of this in terms of signal phasing should be considered carefully (see *Section 6*).

There should be sufficient clearance distance between swept paths for opposing right-turn movements that occur simultaneously.

Where there is insufficient width to allow opposing right-turn movements to occur simultaneously, these turns should be separated in the signal phasing (*Section 6*), or banning one or more right-turn movements may be considered.

3.2.3 Left-Turn Lanes

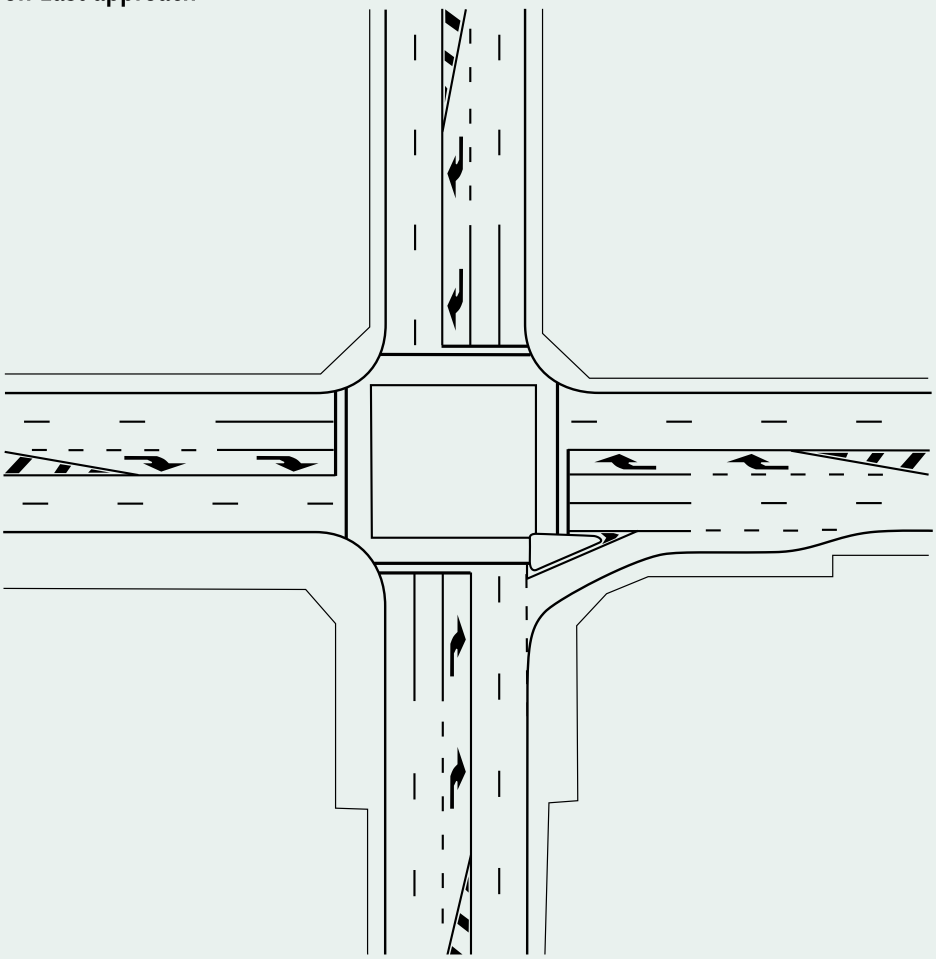
The use of exclusive left-turn lanes should be considered where left-turn traffic demand volumes are large.

Slip lanes may be provided for left-turn movements. These lanes may be controlled by signals or by give-way rule. The TURN LEFT AT ANY TIME WITH CARE (*Section 11.3.7*) or GIVE WAY signs may be used at slip lanes not controlled by traffic signals. A high-entry angle exclusive slip lane subject to give-way control is shown in *Figure 3.1* (East approach).

Safety of pedestrians crossing in front of slip lanes is an important issue that should be addressed carefully in the design of signalised intersections (*Section 6.5.2(d)*). Where regulations permit, two-aspect (red, yellow) signal arrangements can be used to stop traffic at a signalised crossing on a left-turn slip lane, particularly if the slip lane is more than one-lane wide (see *Section 5.3.4*).

Left-turn islands for slip lanes should be designed to accommodate signal equipment, the storage of pedestrians and the ends of any necessary stop line and signalised crossing or pedestrian (Zebra) crossing.

Figure 3.1 Painted five-lane treatment on all approaches and high-entry angle exclusive slip lane on East approach



3.3 Corner Kerb Radius

Corner kerb radii and traffic islands should be designed to cater for the movement of design heavy vehicles. Turning path templates are available to assist with the design of corner kerb radius and traffic islands. See Design Vehicles and Turning Paths (Austroads 1995) and Austroads GTEP Part 5.

When applying turning path templates, it should be remembered that, under Australian Road Rules, vehicles 7.5 m or longer (including any load or projection) legally can use up to two marked lanes to safely turn left or right. The two marked lanes must be nearest to the far left of the road for left turns, or nearest to the dividing line or median for right turns.

It is preferable to keep corner kerb radii to a minimum. The use of larger corner kerb radii can result in the following problems:

(a) greater vehicle turning speeds which can become a problem for pedestrians crossing the road at the intersection;

(b) increased clearance times and delays if stop lines are located further from the intersection;

(c) longer signalised crossings or deviations from their direct route if the crossing is shortened by moving it further from the intersection; and

(d) possible difficulties in achieving optimum lantern positioning and aiming.

3.4 Median Islands

3.4.1 Divided Roads

The following are the more important practices that should be observed when designing median islands at signalised intersections:

(a) a minimum clearance from face of kerb to the signal equipment (usually the edge of the target board) of 0.5 m is desirable to avoid both damage to the equipment and vehicles; additional clearance may be needed to allow for road camber,

(b) where pedestrians are likely to accumulate on medians, the width should be a minimum of 1.5 - 2 m (see AS 1742),

(c) if an exclusive right-turn lane is provided, the residual width of median should satisfy (a) and (b),

(d) the use of wide medians reduces capacity because of increased clearance times, and it may create the problem of interlocking the opposing right-turn vehicles,

(e) the ends of median islands should be set back 0.6 m behind the prolongation of the kerb lines unless a signalised crossing is provided, and

(f) when a signalised crossing is provided, the median should be terminated at the crossing unless a gap in the median as wide as the crossing is provided and the median continued for at least 2 m beyond the crossing.

3.4.2 Undivided Roads with Small Median Islands at the Intersection

The practices listed in *Section 3.4.1* for divided roads also apply to sites with minor channelisation. The median islands should be at least 10 m long to ensure adequate conspicuity. If a signal post is provided the median should be at least 1.2 m wide for single-column lanterns (wider for two-column lanterns).

3.5 Painted Medians and Islands

Painted medians or islands may be used where there is not sufficient carriageway width to construct a kerbed median or island, or where it is desirable to permit vehicles to cross the median. Painted medians may be used with painted five-lane intersection treatments in urban areas as shown in *Figure 3.1*. For this treatment, lane widths on a four-lane undivided road are reduced in the vicinity of the intersection to permit the creation of a separate sheltered right-turn lane. Viability of this treatment depends on being able to achieve acceptable lane widths. See Austroads GTEP Part 5.

Traffic signal posts should not be placed in the painted areas, and they should always be located behind raised kerbing (see *Section 10.4*).

3.6 Kerbside Allocations

3.6.1 Parking

Appropriate management of parking on approach and exit roads is needed for efficient intersection operation. Results of inappropriate management are:

(a) a reduction in the number of effective approach lanes,

(b) a reduction in the number of effective departure lanes,

(c) misleading detector actuations,

(d) obstruction of signal displays and other control devices,

(e) reduced sight distances for vehicle or pedestrian traffic, and

(f) decreased capacity and increased delays and queue lengths.

Where statutory restrictions are not adequate, parking prohibitions and restrictions are necessary to reduce these difficulties. Analysis of how additional parking restrictions and prohibitions can improve the intersection performance can be performed using computer programs for intersection analysis.

3.6.2 Bus Zones

The effect of bus bays or zones close to the intersection is similar to that of short-term parking. Bus stops on the approach to intersections cause detection difficulties when designing bus priority schemes.

Bus stops on the departure side of the intersection can cause following vehicles to queue into the intersection unless a fully indented bus bay is provided.

3.7 Service Roads

Generally, service roads should not be carried through signalised intersections for the following reasons:

(a) reduction in safety, due to the higher number of conflict points, the larger intersection conflict area, and the difficulty for right-turning motorist to select appropriately sized gaps in opposing traffic on two carriageways during the given signal phase, and

(b) reduction in intersection capacity because of increased pedestrian and vehicle clearance times.

Thus, where service roads are provided, problems can be minimised by terminating the service road or by carrying it around the corner as a left-turn movement only.

4. Signal System and Components

4.1 System

4.1.1 Purpose

Signal control is provided to:

(a) reduce traffic conflicts and delays,

(b) share time between conflicting movements,

(c) reduce crashes.

4.1.2 System Process

As seen in *Figure 4.1*, which illustrates the signal system process, demands for traffic movements are identified through vehicle detectors, pedestrian push buttons, and where relevant, externally supplied data from a master control computer. The signal system transforms traffic demands, in a manner determined by the controller algorithms and operational settings, into a sequence of signal displays. Also see *Figure 1.1* in *Section 1* for the interaction between a traffic signal system and various external factors.

4.2 Components

The major components of the signal system are listed in *Table 4.1* together with the purpose of each component, Australian Standards and other sources for technical specifications, and reference to sections of this guide where the subject is discussed in detail. *Figure 4.2* shows various signal components.

4.2.1 Signal Lanterns

Signal lantern is an assembly comprising one or more signal aspects, together with the means of connecting them to power supply and facilities for mounting the complete assembly (AS 1742, 2144). *Signal aspect* is a single optical system on a signal face capable of being illuminated at a given time. See *Section 5*.

Vehicular Lanterns

These lanterns convey the control signals to vehicular traffic. They include 200 mm diameter red, yellow, green and white aspects, as well as 300 mm aspects (see *Section 5.2.3*). Each aspect may have arrow masks, or other qualifying symbols.

Pedestrian Lanterns

These lanterns are provided for the control of pedestrians. Red and green symbol aspects are used.

Figure 4.1 The traffic signal system

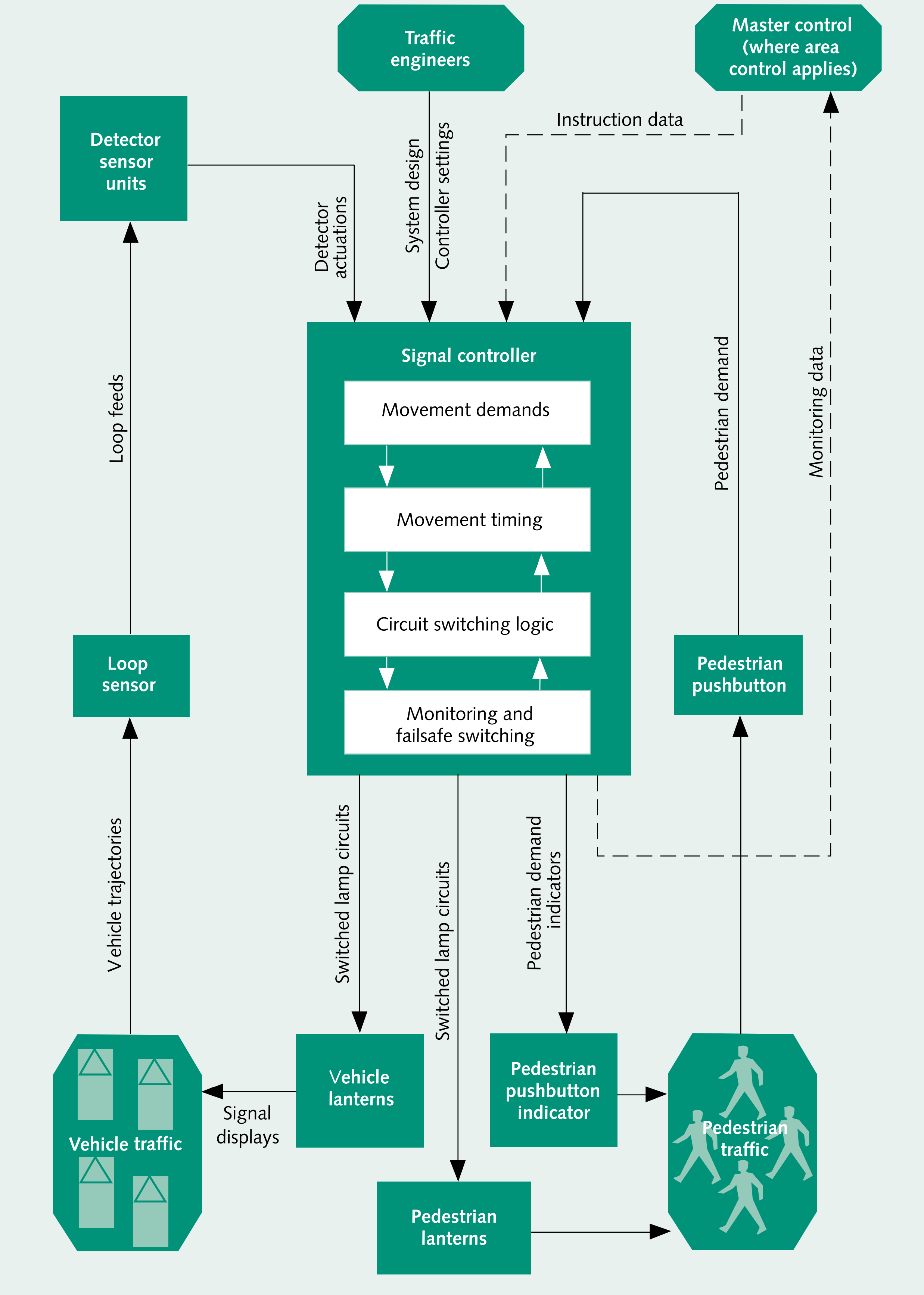


Table 4.1 Traffic signal components (section numbers refer to this guide)

Component	Purpose	Specifications	Section	Comments
Signal lanterns	Provide signal display	AS 2144, AS 1742	5, A	
Signal visors	Restrict visibility and sun phantom	AS 2144	7, A	
Signal louvres	Restrict visibility and sun phantom	AS 2144 and *local**	7, A	
Target boards	Provide good visual background for lanterns	AS 2144	5, 7, A	
Traffic signal lamps	Light source for the lanterns	AS 2144, AS 4113	4, A	Domestic lamps not suitable
Traffic signal posts	Support signal lanterns mounted beside the roadway	AS 2339	7	
Lantern straps	Attach signal lantern to posts	AS 2339	7	
Post brackets	Attach signal lantern to posts	AS 2339	7	
Traffic signal mast arms	Support signal lanterns mounted above the roadway	AS 2979	7	
Joint use mast arms and posts	Support lanterns and other utilities (usually street lights)	*Local**		Agreement with local authorities usually required
Multicore traffic signal cables	Reticulation of power from controller to lanterns and demands from post mounted equipment to the controller	AS 2276 Part 1	12	
Ducts, pits, conduits	Provide for underground installation of cable and access for maintenance	AS/NZS 3000 Parts 1&2 and *local**	12	Variation due to local installation practices
Terminal assemblies	Connect lanterns, push buttons, post mounted detectors, etc to the multicore cable	AS 2339	12	
Signal controller	Determine display sequence and durations and provide switching of power to the signal lanterns	AS 2578 Part 1 and *local**	5, 6, 8 & 9	Variation due to level of complexity at intersections and alternative control algorithms used
Loop vehicle detectors	Detect vehicles	AS 2703	8	Special purpose detectors are available
Loop feed cable and loop cable	Installation of the sensor loop and connection to the detector	AS/NZS 2276 Part 2 & AS 2276 Part 3	8	
Pedestrian push-button assembly	For pedestrians to register demands and obtain acknowledgement	AS 2353	8	May also provide for visually handicapped

* Local traffic administration specifications

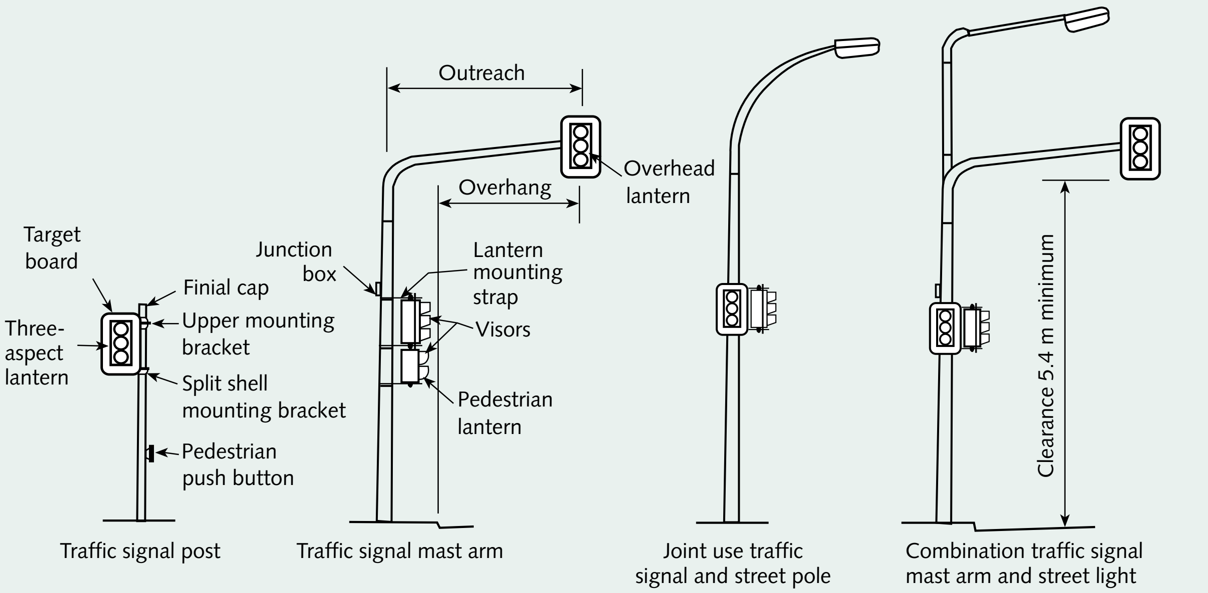
continued over page...

Table 4.1 Traffic signal components (section numbers refer to this guide) continued...

Component	Purpose	Specifications	Section	Comments
Pedestrian sensors	Detect pedestrians waiting to cross the road, or pedestrians who are on the crossing	*Local**	8	
Traffic signs	Regulate, inform and guide traffic	AS 1742	11	
Roadway components	Serve normal road engineering purposes	Austroads Guides and *local**		
Finial cap	Prevent inadvertent contact with live terminals and to protect the terminal assembly and associated wiring from the weather	AS 2339	12	
Arrow and other masks	Permit the display of special arrow symbols that control specific turn movements	AS 2144	5, A	

* Local traffic administration specifications

Figure 4.2 Traffic signal components



4.2.2 Associated Equipment

Equipment associated with the lanterns include (AS 2144):

Lamps

Lamps of special manufacture are required for signal lanterns. They are designed to be compatible with the optical system of the lantern, to produce the specified light output and to obtain the best possible life characteristics to minimise lamp replacement (see *Section 14*).

Visors

Visors are generally used to:

(a) minimise sun phantom effects, and

(b) reduce the possibility of a signal being seen by traffic for which it is not intended.

Louvres

Louvres may be used to:

(a) minimise sun phantom effects when oriented horizontally, and

(b) reduce the possibility of a signal being seen by traffic for which it is not intended.

As louvres constrict light distribution, their use should be restricted to essential locations.

Target Boards

Target boards surround the signal lantern in order to improve the visibility of displays. Black target boards provide the best conspicuity.

Symbolic Masks

A mask can be used to create an arrow symbol or letter (e.g. B or T) to dedicate the aspect to a particular vehicle movement (e.g. turning traffic) or a special vehicle movement (e.g. bus, tram).

4.2.3 Lantern Supports

Posts, poles, brackets and straps are used to support the signal lanterns at the required height (AS 2339). Lanterns may also be fixed to existing power reticulation poles and street lighting poles to reduce the number of poles at a particular site. Typical examples are illustrated in *Figure 4.2* (also see *Section 7.5.8*).

4.2.4 Power Reticulation

The supply of power throughout the signal installation is made via traffic signal cable, which is laid underground in ducting. Changes of direction in the ducting are made at junction pits. Junction boxes and terminal assemblies provide for the connection of the cable to the signal equipment (see AS 2276, Part 1).

The signal cable provides 240 volt (nominal) 50 Hz power to the signal lanterns and circuits for pedestrian push buttons and other traffic demands. This is a low voltage installation and must be installed to requirements of the local electricity authority and AS 3000, Part 1.

4.2.5 Signal Controller

The traffic signal controller regulates the sequence and duration of signal displays (see AS 2578, Part 1). The main features of this equipment include:

(a) power switches for the signal lanterns,

(b) failsafe systems to prevent conflicting signal displays,

(c) vehicle detector systems,

(d) provision for inputs from pedestrian push buttons or any other device,

(e) a logic unit to control the sequence and timing of movements or phases, including minimum greens and safe clearance periods between conflicting movements,

(f) facilities for traffic personnel to monitor and alter its operation, and

(g) facilities to allow data communications between the controller and a master control computer.

4.2.6 Traffic Detection

The most common form of vehicle detector for most traffic control applications is the inductive loop (AS 2703). Several turns of wire are placed in a slot cut in the road pavement (AS 2276, Parts 2 and 3). The wire is connected via a feed cable to a detector sensor unit mounted in the controller cabinet or on a signal post. Presence or movement of a vehicle (as a large mass of metal) over a loop reduces the loop inductance and causes a detector output. This output is the closure of a relay contact or the equivalent operation of a semiconductor.

Alternative forms of detection such as microwave, infrared or video may be used where appropriate.

Pedestrian demands are usually recorded when a pedestrian presses a push button (AS 2353) mounted on the side of the signal post (see *Section 8* for details). Other pedestrian sensors such as overhead infrared or microwave sensors, and pressure pads in the footpath may also be used.

Detection of bicycles and light motorcycles is more difficult, but may be achieved by attention to the design of the loop (see *Section 8.3*).

Priority vehicles may also be detected if special detector systems are used.

4.2.7 Roadway Components

These include islands, medians, pavement markings and signs (AS 1742). Such components are not unique to traffic signal installations but they are an integral part of the installation, and affect its design and performance.

4.3 Component Selection

The selection of the components to be used for a signal installation will be determined by the signal design. Consideration should also be given to factors such as availability of components, maintenance requirements, stock holdings, price, whole of life cost, and standard-isation of installation. Some modifications of design may be required in order to achieve overall economic efficiency for the supply, installation and maintenance of the system.

5. Signal Face Layouts and Display Sequences

5.1 Introduction

This section covers the design of signal face layouts and sequence of signal displays for different situations. The advice is comprehensive and interrelated. Particular advice should not be considered in isolation, nor should variations be introduced without careful evaluation. This section does not cover those special applications and facilities described in Section 15.

5.1.1 Method of Controlling Traffic

Traffic signals control approaching vehicles by displaying red, yellow or green signals, and pedestrians crossing the road by displaying red or green signals. Traffic signals can also control special vehicles such as trams, buses, and emergency vehicles using white symbolic displays.

As with all traffic control devices, it is important that the design of traffic signals follows defined conventions to ensure that a driver is not confronted with a display, or a sequence of displays, which is confusing. Hesitancy, potential for misinterpretation and accidents, and unnecessary delays are reduced by design uniformity.

Basic design criteria aim to:

(a) give a logical and unambiguous presentation,

(b) ensure uniformity of format,

(c) promote displays that are simple and easy to comprehend,

(d) prevent unsafe or conflicting displays,

(e) prevent unsafe sequence of displays, and

(f) ensure appropriate number of lanterns with a view to minimising the cost.

5.1.2 Definitions

The following definitions are important in understanding the presentation in this and other sections of this guide.

Signal aspect is a single optical system on a signal face capable of being illuminated at a given time.

Signal display is an aspect that is illuminated.

Signal face refers to a set of signal aspects in a common assembly, generally in one or two columns placed together with a target board to improve signal visibility, facing traffic from one direction.

Signal lantern refers to an assembly of optical components (one or more aspects), together with the means of connecting them to power supply and facilities for mounting the complete assembly.

5.2 Signal Face Elements

5.2.1 Signal Aspects

Signal faces are made up of a number of signal aspects generally in one or two columns. Their nature is described in AS 1742, Part 14, and design and recommended size of signal aspects, including shapes of symbols, are given in AS 2144.

5.2.2 Colour of Aspects

Vehicle aspects shall be red, yellow or green.

Pedestrian aspects shall be red or green.

Bicycle aspects for two-aspect lanterns shall be red or green, and for three-aspect lanterns shall be red, yellow or green.

Special vehicle aspects for trams, buses or emergency vehicles shall be red, yellow or white.

5.2.3 Size of Aspects

The following considerations apply in relation to the size of signal aspects:

(a) 200 mm nominal diameter *general-purpose* aspects are suitable for most urban applications,

(b) all aspects in the one signal face must be of the same size,

(c) for pedestrian aspects, 200 mm nominal diameter aspects shall be used.

(d) *extended-range* aspects with a 300 mm nominal diameter are more expensive to provide and to operate, and therefore their use should be limited to the following situations:

   (i) in overhead signal faces mounted on mast arms or gantries,

   (ii) where circular displays must provide a greater advance warning than the normal 150 m from the signal stop line, or where the 85th percentile approach speed exceeds 70 km/h, and

   (iii) where an arrow signal display must provide greater advance warning than the normal 80 m from the signal stop line, or where the 85th percentile speed of turning traffic exceeds 40 km/h.

5.2.4 Types of Aspects

Signal aspects currently in use are illustrated in *Figure 5.1*. Some aspects shown are not permitted in some jurisdictions.

Circular Aspects

Circular aspects (disks) are used as a first preference. They are the easiest to comprehend and have the greatest visual range.

Circular aspects control all traffic approaching or waiting at the stop line associated with those aspects if they are the only aspects in the signal face. At an intersection, a circular green display permits left-turning and right-turning traffic to filter (accept gaps in a pedestrian movement or oncoming traffic) unless prohibited by other controls.

Arrow Aspects

Arrow aspects are used to control particular movements at traffic signal installations including U-turn movements as seen in *Figure 5.1*. Arrow aspect orientations to be used are shown in *Figure 5.2*.

Figure 5.1 Signal aspects currently in use (Note: U-turn and E aspects are not permitted in some jurisdictions)

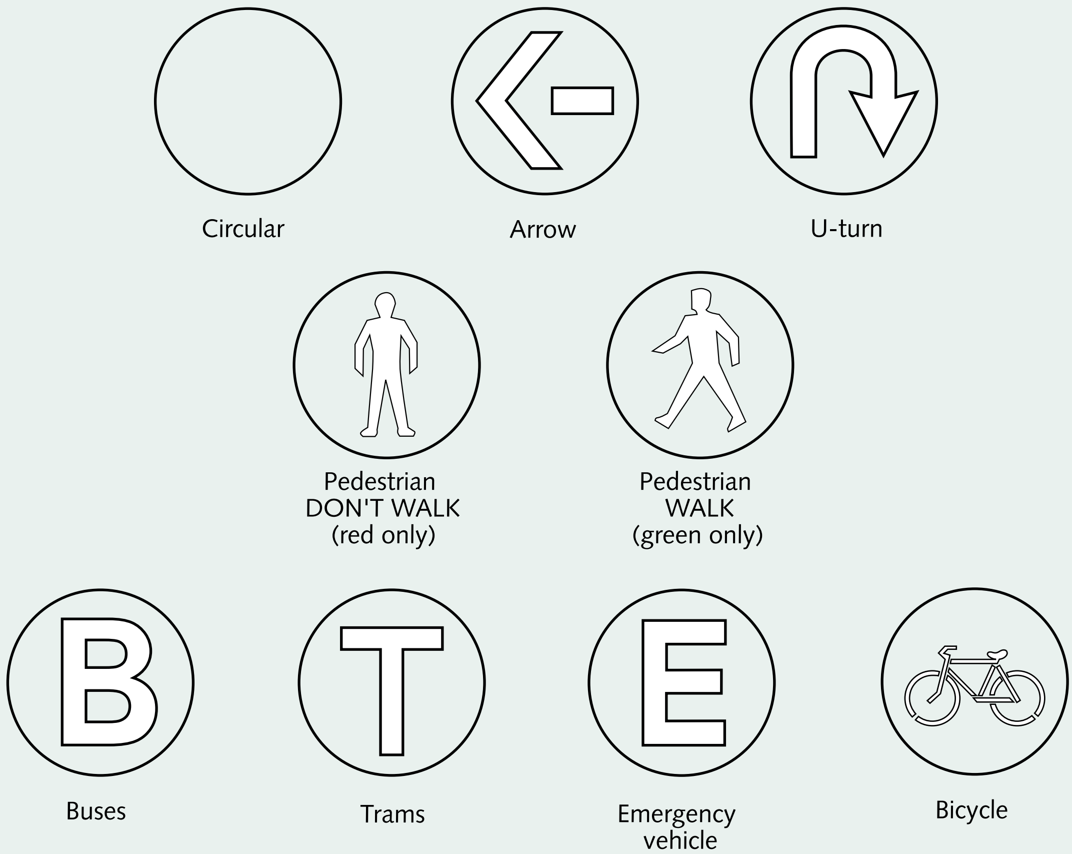
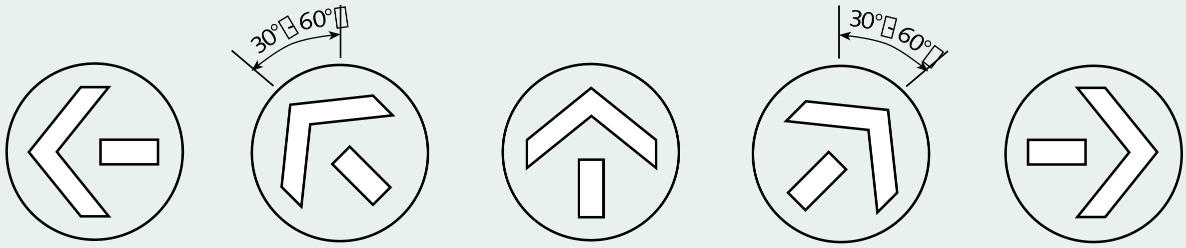


Figure 5.2 Arrow aspect orientations



Directional arrow displays supplement or cancel the intent of any circular displays with which they are associated. Because the mask obscures the greater part of the lens, the visual range is reduced. For this reason, straight through arrows (used to control the faster movements) should preferably not be used in red or yellow aspects and they should only be used in green aspects when absolutely necessary.

Where all traffic on an approach must turn left (and/or right), and there is no conflict with a pedestrian or other traffic movement, extra guidance may be given by replacing green circular aspects with arrows.

Downward pointing arrow aspects should not be used with intersection control signals, their use is confined to overhead control signals.

Pedestrian Aspects

The **Don't Walk** aspect is a red standing human figure, and the **Walk** aspect is a green walking human figure as seen in *Figure 5.1*.

Bicycle Aspects

Where regulations permit, bicycle aspects can be used in a similar way to pedestrian aspects to control cyclists crossing the road, or in a similar way to vehicle aspects to control on-road bicyclists at an intersection. The symbol for bicycle aspects is shown in *Figure 5.1*.

Two aspects, red and green, are used for road crossings. Three aspects, red, yellow and green, are used at road intersections with exclusive bicycle lanes, or at intersections of a road and exclusive bicycle path.

Special Vehicle Aspects

Special vehicle aspects are used to control bus, tram and emergency vehicle movements at traffic signals as regulations permit. The symbols for special vehicle aspects are given in *Figure 5.1*.

The white T or B, and in some jurisdictions, E aspect is used to indicate that trams, buses or emergency vehicles may proceed.

White arrows are also used occasionally to indicate that drivers of special vehicles may proceed in the direction of the arrow.

Combination of Aspects

Pedestrian aspects must not be combined with vehicle aspects in the same signal face. Circular and arrow aspects may be combined as detailed later in this section. Circular or arrow aspects can also be combined with special vehicle aspects.

5.2.5 Target Boards

High ambient or background lighting may decrease conspicuity of the displays. The use of target boards should be considered (see *Figure 4.2* in *Section 4*).

Multi-column signal faces should be provided with a common target board.

Target boards are not used with pedestrian lanterns.

5.3 Vehicle Signal Face Layouts

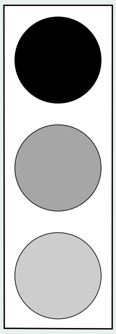
This section discusses general requirements for vehicle signal face layouts. *Sections 5.4 and 5.5* discuss signal face layouts with right-turn and left-turn arrow aspects. The *sequence* of vehicle signal displays is discussed in *Section 5.7*.

5.3.1 Basic Signal Face Layouts

Aspects are arranged in columns with the red aspect upper-most, the yellow aspect central and the green aspect at the bottom. The basic three-aspect signal face consists of red, yellow and green circular aspects in a single column as shown in *Figure 5.3*.

This is the normal minimum permissible signal face layout and should be used as a first preference. In special traffic situations, two-aspect signal faces may be used as discussed in *Section 5.3.4*. Single-aspect signals are not permissible (except for overhead lane control signals as discussed in *Section 15.10*).

Figure 5.3 Basic three-aspect signal face layout



5.3.2 Multi-Column Signal Face Layouts

Multi-column signal faces can contain four, five, or six aspects. Generally, these face layouts have an arrow aspect column adjacent to the basic three-aspect column (*Section 5.3.1*). Six-aspect face layouts, as shown in *Figure 5.4*, are used to control left-turn or right-turn movements independently of the through movement on the same approach.

Multi-column signal faces shall comply with the following:

(a) aspects of the same shape and orientation are located in the same column;

(b) left-turn arrow aspects are located to the left of the circular aspects, and right-turn arrow aspects are located to the right of the circular aspects;

(c) columns containing only a yellow aspect are not permitted;

(d) columns containing only red and green aspects are not permitted;

AND except in the case of a four-aspect single-column display as detailed in *Section 5.3.3*:

(e) aspects of the same colour are located on the same horizontal level;

(f) no column contains more than three aspects;

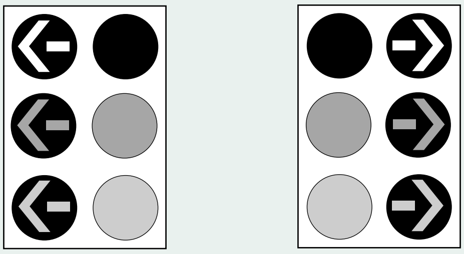
(g) only one aspect of each colour is permitted in each column;

(h) at one time not more than one aspect is illuminated in each column.

The use of three columns in a display is not recommended as they are difficult to comprehend and are not catered for in standard mountings. Therefore, where possible, they should be split into separate two-column displays mounted on different posts or mast arms.

Multi-column display sequences are discussed in *Section 5.7.2*.

Figure 5.4 Six-aspect multi-column signal face layouts

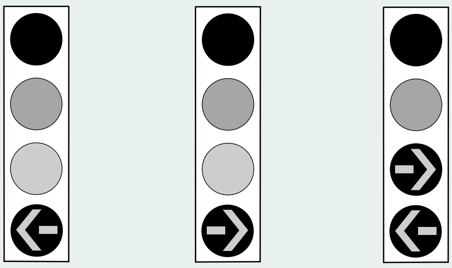


5.3.3 Four-Aspect Single-Column Signal Face Layouts

A single column of four aspects can be used consisting of red and yellow circular aspects and two green aspects (circular and arrow, or two arrows) as shown in *Figure 5.5*. This is not permitted for overhead mounted signals.

Four-aspect columns should not be used in multi-column displays.

Figure 5.5 Four-aspect single-column signal face layouts



5.3.4 Two-Aspect Signal Face Layouts

Where regulations permit, two-aspect signal face layouts (*Figure 5.6*) are used in the following circumstances (also see ramp-metering signals in *Section 15.8*, and metering signals at sign-controlled intersections in *Section 15.13*):

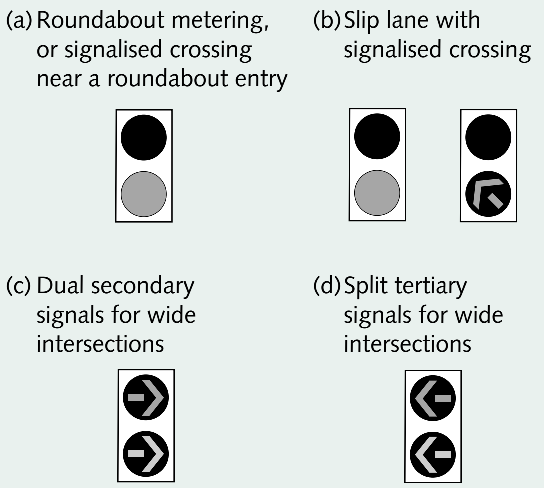
(a) Roundabout metering signals (see *Section 15.7*), or at signalised crossings near a roundabout entry, comprising red and yellow circular aspects (*Figure 5.6a*). In this case, a green circle is not used in order to avoid conflict with the requirement to give way at the roundabout.

(b) To stop traffic at a signalised crossing on a left-turn slip lane where traffic may continue to filter after the pedestrian phase has finished, comprising red and yellow circular or arrow aspects (*Figure 5.6b*). In this case, green circle or green arrow is not used in order to avoid conflict with the requirement to give way to other traffic at the slip lane give-way line.

(c) Yellow and green arrow aspects on the far-right side of a divided road (dual secondary signal as shown in *Figure 7.1b* in *Section 7*) to reassure right-turn traffic in a wide intersection that they may proceed (*Figure 5.6c*).

(d) "Split tertiary" signals comprising yellow and green arrows, which are used where the road that left turners are turning into has a median or island (*Figure 5.6d*). Refer to *Section 7.4.1(b)*.

Figure 5.6 Two-aspect signal face layouts



5.4 Face Layouts with Right-Turn Arrow Aspects

5.4.1 Six-Aspect Signal Face Layouts with Right-Turn Arrow Aspects

A six-aspect signal face layout with red, yellow and green arrow aspects can be used to independently control right-turn movements (see *Figure 5.4*).

The green right-turn arrow should be displayed only when no conflicting traffic movements (vehicle or pedestrian) are permitted.

The yellow right-turn arrow is always displayed following the green arrow display.

The red right-turn arrow should be displayed following the yellow arrow display when the right-turn movement or a conflicting movement (vehicle or pedestrian) must be protected. Vehicle movements include special vehicles such as tram, bus, or train.

5.4.2 Five-Aspect Signal Face Layouts with Right-Turn Arrow Aspects

Right-Turn Yellow and Green Arrow Aspects

A five-aspect signal face layout with yellow and green arrow aspects as shown in *Figure 5.7* may be used in lieu of a six-aspect face layout when:

(a) the right-turn movement may filter at all times when the circular aspect is green (hence no need for red arrow), and

(b) there is no conflicting pedestrian movement or special movement which requires protection from the right-turning vehicle (see *Section 6.3*).

Right-Turn Yellow and Red Arrow Aspects

A five-aspect signal layout with yellow and red arrow aspects as shown in *Figure 5.8* is rarely needed (and is not permitted in some jurisdictions). It may be used to terminate a right-turn filter movement during the circular green display to avoid blockage of the intersection during a nearby tram, bus or train movement.

Figure 5.7 Five-aspect signal face layout with yellow and green right-turn arrow aspects

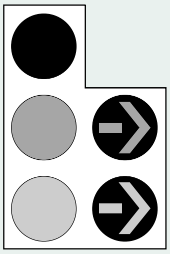
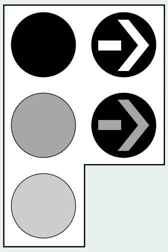


Figure 5.8 Five-aspect signal face layout withred and yellow right-turn arrow aspects



5.4.3 Four-Aspect Signal Face Layouts with Right-Turn Arrow Aspects

Single Right-Turn Green Arrow Aspect

A four-aspect signal layout with single green arrow aspect (*Figure 5.9*) may be used only when the right-turn green arrow display is always terminated simultaneously with the circular green display, i.e. when the circular yellow display is introduced.

Single Right-Turn Red Arrow Aspect

A four-aspect signal layout with single red arrow aspect (*Figure 5.10*) may be used only when its use is restricted to the sequence discussed in *Section 5.7.3* (*Figure 5.22*).

This signal face layout is used infrequently. It may be used to delay a filter right-turn movement for the protection of pedestrians or special vehicles.

Figure 5.9 Four-aspect signal face layouts with single right-turn green arrow aspect

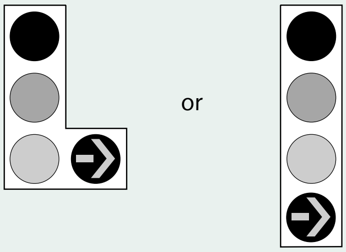
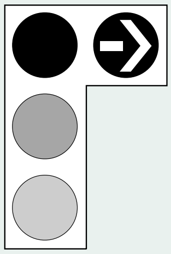


Figure 5.10 Four-aspect signal face layout with single right-turn red arrow aspect



5.5 Face Layouts with Left-Turn Arrow Aspects

5.5.1 Six-Aspect Signal Face Layouts with Left-Turn Arrow Aspects

A six-aspect signal face layout with red, yellow and green arrow aspects can be used to independently control left-turn movements (see *Figure 5.4*).

The green left-turn arrow should be displayed only when no conflicting traffic movements (vehicle or pedestrian) are permitted.

The red left-turn arrow should be displayed following the yellow arrow display when the left-turn movement or a conflicting movement (vehicle or pedestrian) must be protected. Vehicle movements include special vehicles such as tram, bus, or train.

The column of left-turn aspects should be blacked out when the left-turn movement may filter through a parallel walk or other traffic movement, i.e. when the circular green only is displayed.

5.5.2 Five-Aspect Signal Face Layouts with Left-Turn Arrow Aspects

Left-Turn Yellow and Green Arrow Aspects

When it is not required to protect conflicting movements during the display of the circular green, the red left-turn arrow aspect may be omitted from the six-aspect face layout, forming the five-aspect signal face layout shown in *Figure 5.11*. The left-turn green arrow should be displayed only when no conflicting traffic movements are permitted.

Left-Turn Yellow and Red Arrow Aspects

The yellow and red arrow aspects alone (*Figure 5.12*) should be provided when the left-turn movement may be stopped during the circular green display but the requirements for a left-turn green arrow in *Section 5.5.1* are not met. This occurs infrequently but may be required to stop left-turn traffic for trains or trams.

For left-turn traffic, a green period must be assured when the circular green aspect is displayed alone.

5.5.3 Four-Aspect Signal Face Layouts with Left-Turn Arrow Aspects

Single Left-Turn Green Arrow Aspect

A four-aspect signal layout with single green arrow aspect (*Figure 5.13*) may be used only when the left-turn green arrow display is always terminated simultaneously with the circular green display, i.e. when the circular yellow display is introduced.

Single Left-Turn Red Arrow Aspect

A four-aspect signal layout with single red arrow aspect (*Figure 5.14*) may be used only when its use is restricted to the sequence discussed in *Section 5.7.4* (*Figure 5.25*).

This display is used infrequently. It may be used to delay a filter left-turn movement for the protection of pedestrians or special vehicles, in which case the red arrow should be switched off at the earliest practicable time, e.g. at the end of the Walk period.

Figure 5.11 Five-aspect signal face layout with yellow and green left-turn arrow aspects

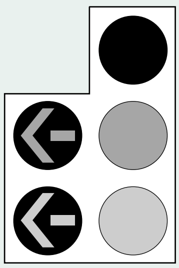


Figure 5.13 Four-aspect signal face layout with single left-turn green arrow aspect

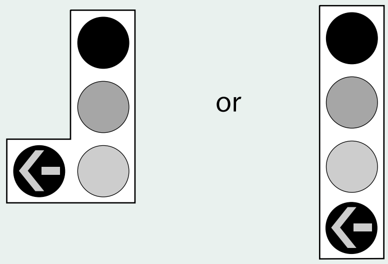


Figure 5.12 Five-aspect signal face layout with red and yellow left-turn arrow aspects

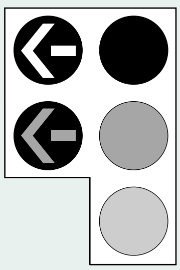
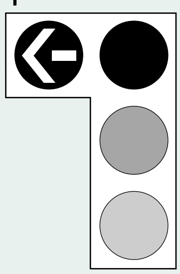


Figure 5.14 Four-aspect signal face layout with single left-turn red arrow aspect



5.6 Permissible and Non-Permissible Signal Face Layouts

Figure 5.15 summarises permissible three- to six-aspect signal face layouts for normal vehicles including the more common layouts discussed in *Sections 5.3 to 5.5*.

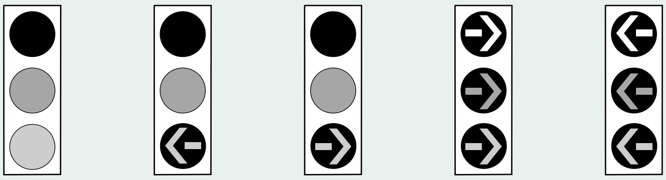
Refer to *Figure 5.6* for permissible two-aspect signal face layouts. Single-aspect face layouts are not permissible except in rare circumstances.

Figure 5.16 contains examples of signal face layouts that are acceptable but should be avoided if possible.

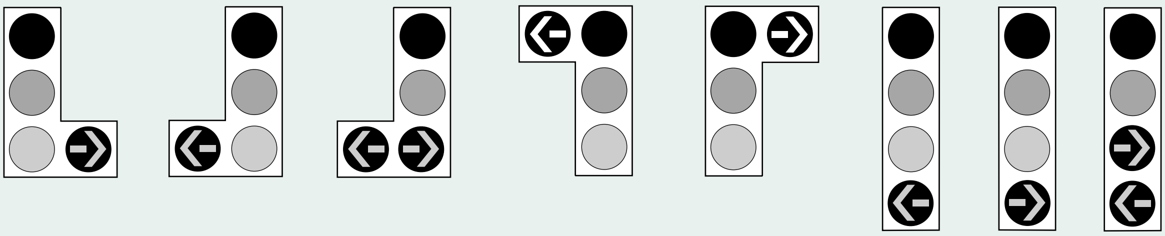
Figure 5.17 shows signal face layouts that are not permissible.

Figure 5.15 Permissible signal face layouts

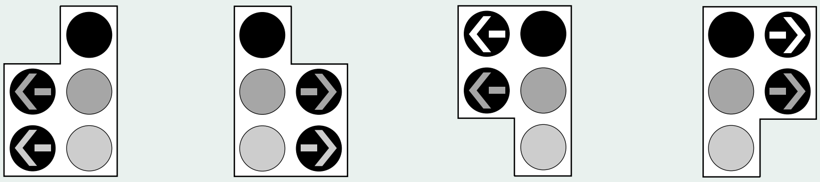
Three-aspect signal face layouts



Four-aspect signal face layouts



Five-aspect signal face layouts



Six-aspect signal face layouts

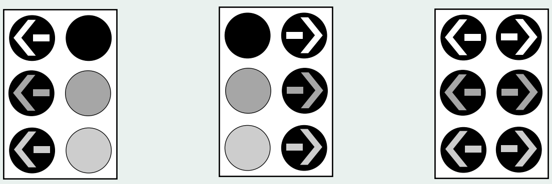
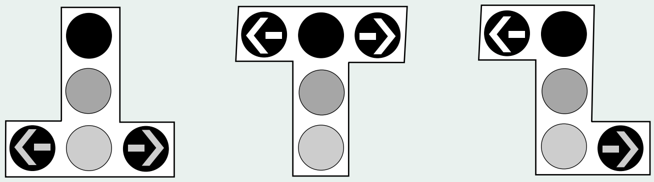
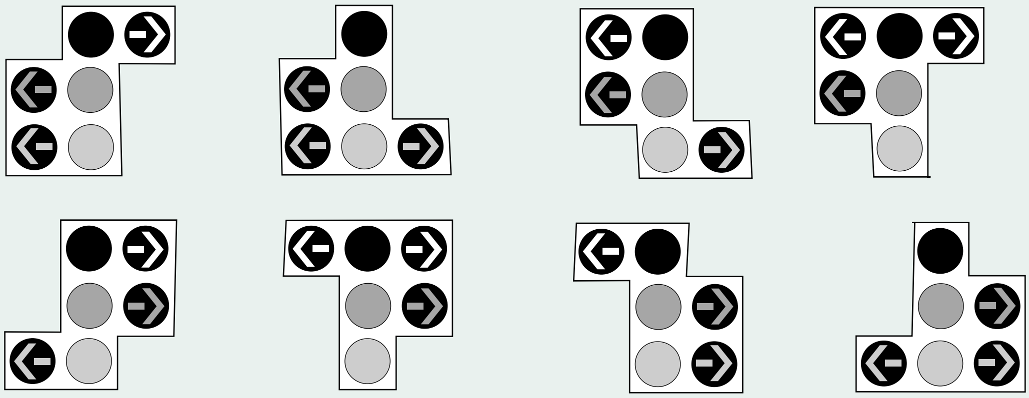


Figure 5.16 Signal face layouts that are permissible but should be avoided if possible

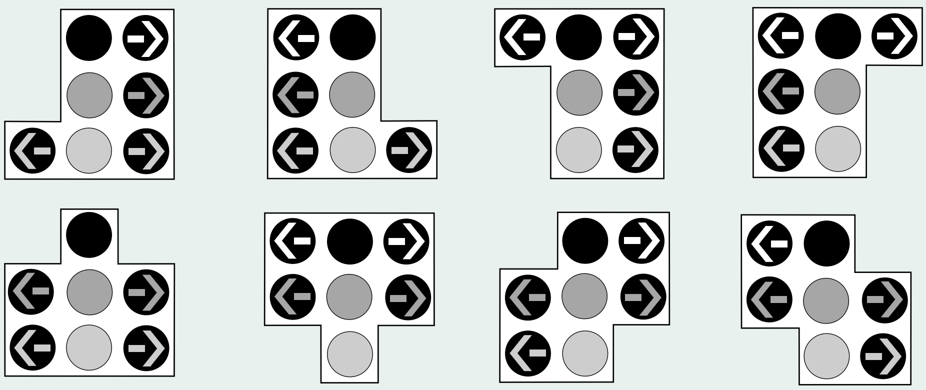
Five-aspect signal face layouts



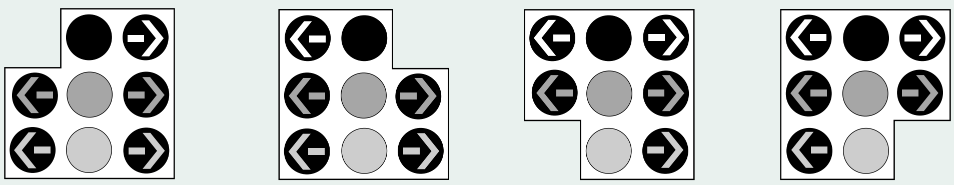
Six-aspect signal face layouts



Seven-aspect signal face layouts



Eight-aspect signal face layouts



Nine-aspect signal face layouts

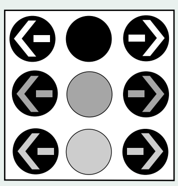
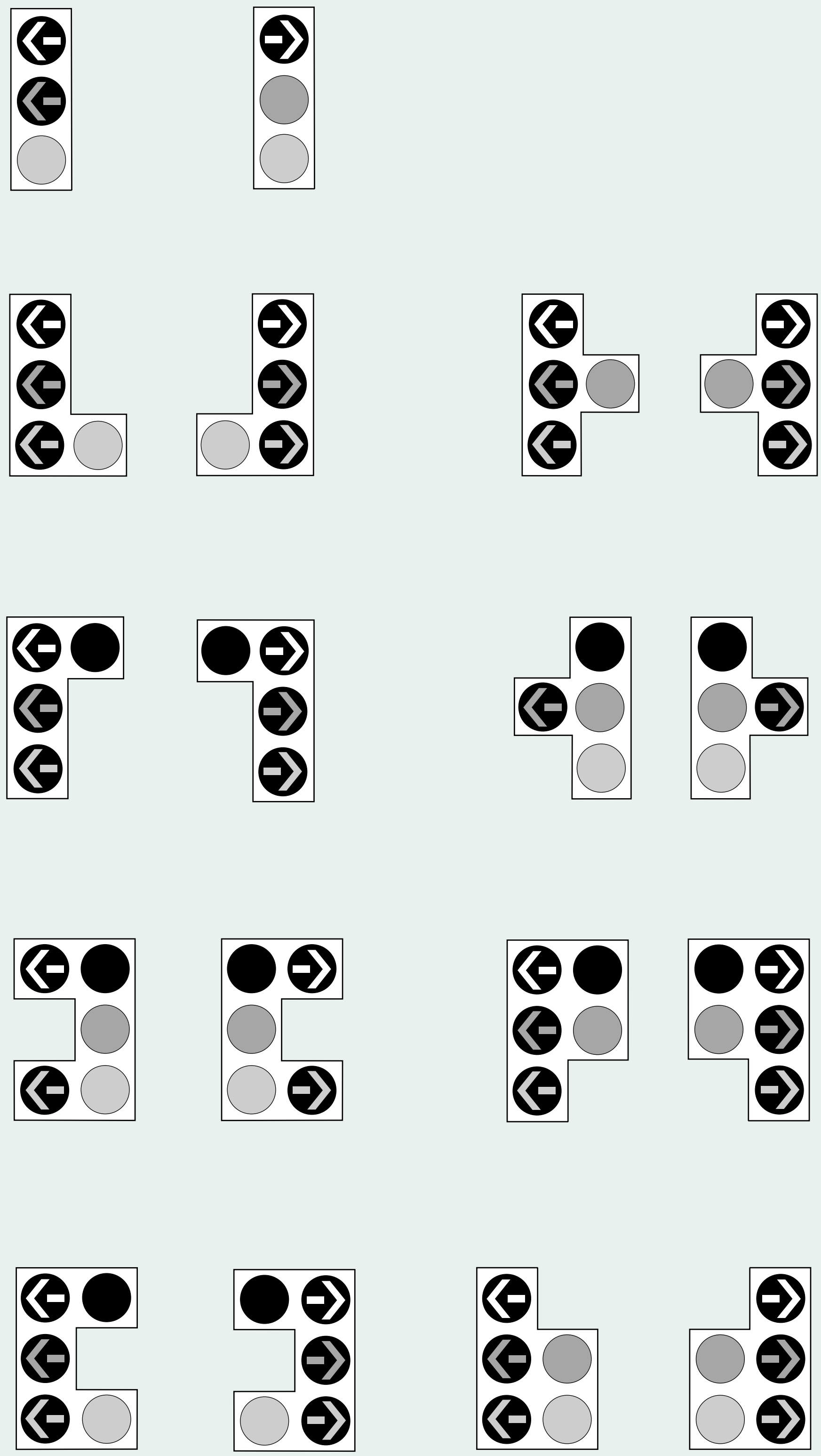


Figure 5.17 Examples of non-permissible signal face layouts



5.7 Sequence of Vehicle Signal Displays

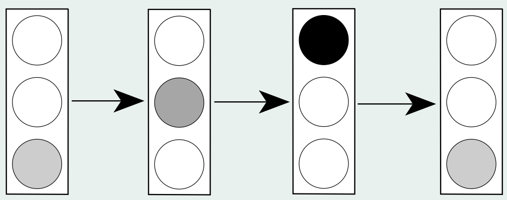
5.7.1 Basic Sequence

The basic sequence of vehicle displays within a signal face shall be **Green** to **Yellow** to **Red** to **Green** as shown in *Figure 5.18*. It applies to three-aspect circular, arrow or symbolic arrangements, and four-aspect arrangements with a green arrow where both greens shall terminate at the same time (see *Figure 5.15*). The exceptions are:

(a) midblock Pelican crossings (see *Section 6.5.3*) where the sequence for vehicle movements shall be **Green** to **Yellow** to **Red** to **Flashing Yellow** to **Green**.

(b) multi-column arrangements without a three-aspect symbolic column, or a single symbolic aspect where the sequence may include an **Off** condition.

Figure 5.18 Basic display sequence for three-aspect signals



5.7.2 Sequences with Arrow Aspects

In sequences with arrow aspects (usually in multi-column displays), the requirements of the basic sequence of displays (discussed in *Section 5.7.1*) are extended as follows:

(a) Where it is desirable to allow for filter movements to take place, the **Off** condition of a column of arrow aspects may be used (**Flashing Yellow** may also be used - see *Section 6.3*).

(b) The alternative permitted sequences for arrows of six-aspect signal faces are:

(i) **Green** to **Yellow** to **Red** to **Off** to **Red** to **Green**;

(ii) **Green** to **Yellow** to **Red** to **Flashing Yellow** to **Yellow** to **Red** to **Green**;

(iii) **Green** to **Yellow** to **Red** to **Flashing Yellow** to **Off** to **Red** to **Green**;

(iv) **Green** to **Yellow** to **Red** to **Off** to **Green**.

(c) The permitted sequences for arrows in five-aspect signal faces are:

(i) Green and Yellow arrows: **Green** to **Yellow** to **Off** to **Green**;

(ii) Red and Yellow arrows: **Red** to **Off** to **Yellow** to **Red**;

(iii) Red and Yellow arrows: **Red** to **Flashing Yellow** to **Off** to **Red**;

(iv) Red and Yellow arrows: **Red** to **Flashing Yellow** to **Yellow** to **Red**.

(d) Any green display shall always be followed by a yellow display applicable to that movement, although not necessarily in the same column, of duration sufficient for termination of that movement.

(e) A red display must be preceded by its associated yellow display where present, or a circular yellow display.

The alternatives for use of the **Flashing Yellow** enables termination of the phase by either a yellow disc or a yellow arrow as considered appropriate for the application.

Figure 5.19 gives examples of fully-controlled right-turn display sequences for six-aspect arrangements.

As a general principle, only one colour change is desirable at a time, and a red or green display change during a yellow circle or yellow arrow display is not desirable, except with diamond overlap phasing where these conditions can occur due to the independent operation of circle and arrow displays.

5.7.3 Right-Turn Sequences

In addition to the examples of right-turn display sequences for six-aspect arrangements shown in *Figure 5.19*, examples of display sequences to initiate and terminate arrow-controlled right-turn movements are illustrated in *Figures 5.20 and 5.21*, respectively.

Figure 5.22 shows a special display sequence using a four-aspect arrangement with a single right-turn red arrow aspect as discussed in *Section 5.4.3*. This figure shows initiation and termination of a filter right-turn movement.

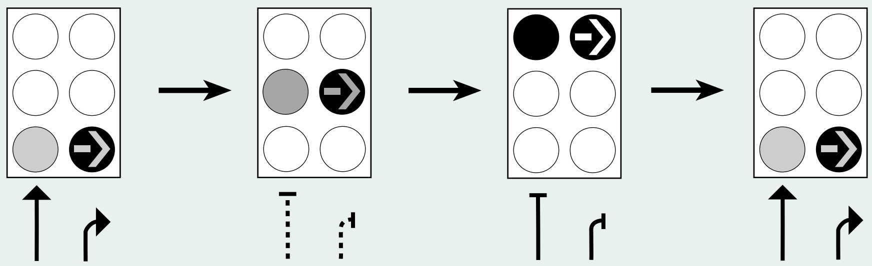
5.7.4 Left-Turn Sequences

Display sequences to initiate and terminate arrow-controlled left-turn movements are illustrated in *Figures 5.23 and 5.24*, respectively.

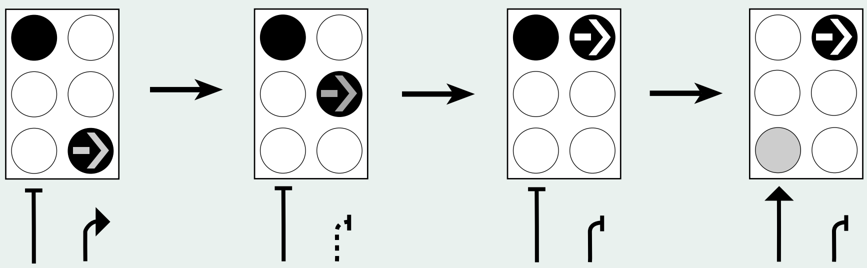
Figure 5.25 shows a special display sequence using a four-aspect arrangement with a single left-turn red arrow aspect as discussed in *Section 5.5.3*. This figure shows initiation and termination of a filter left-turn movement.

Figure 5.19 Examples of fully-controlled right-turn display sequences for six-aspect arrangements

Right-turn arrow displays change simultaneously with circular displays: right-turn and through movement initiated and terminated at the same time



Right-turn arrow and circular displays change at different times: terminating the right-turn movement and initiating the through movement



Right-turn arrow and circular displays change at different times: terminating the through movement and initiating the right-turn movement

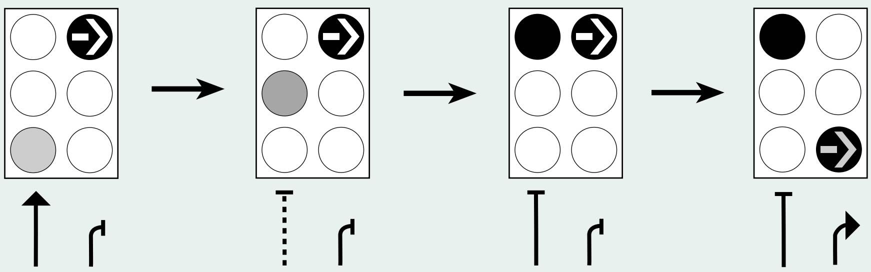
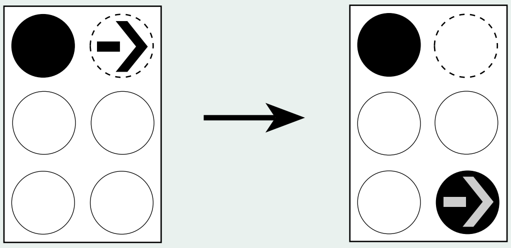
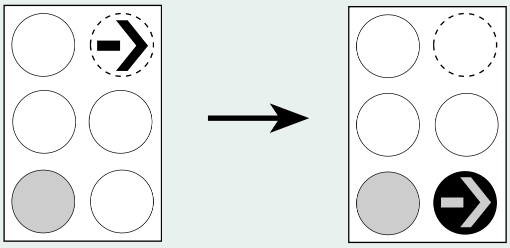


Figure 5.20 Examples of display sequences to initiate an arrow-controlled right-turn movement

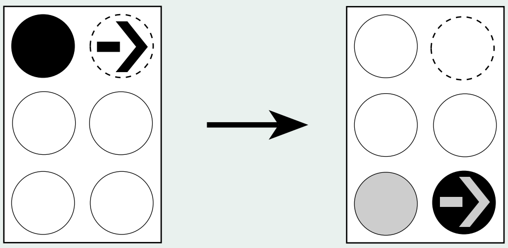
During red circular display



During green circular display



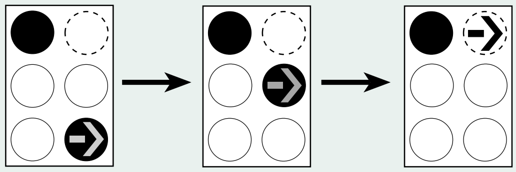
Simultaneously with green circular display



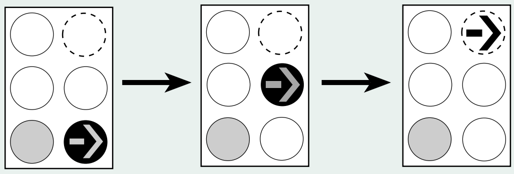
 Displays where provided

Figure 5.21 Examples of display sequences to terminate an arrow-controlled right-turn movement

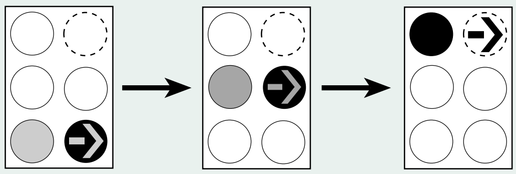
During red circular display



During green circular display



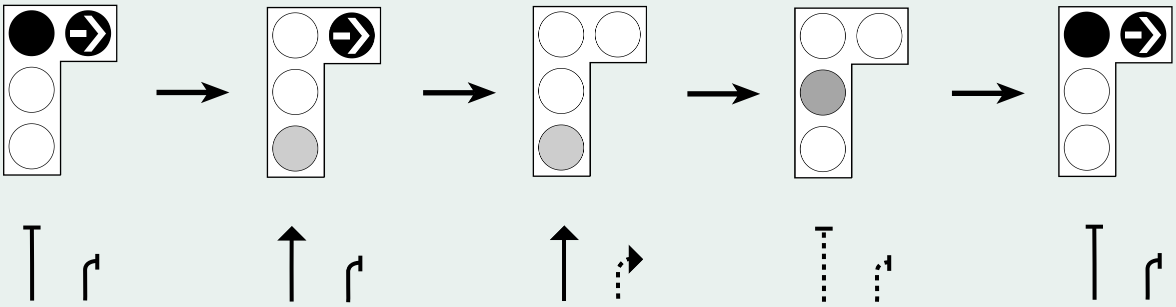
Simultaneously with green circular display



 Displays where provided

Figure 5.22 Display sequences for four-aspect arrangement with single red right-turn arrow aspect for the protection of pedestrians or special vehicles

With pedestrian or special vehicle demand



Without pedestrian or special vehicle demand

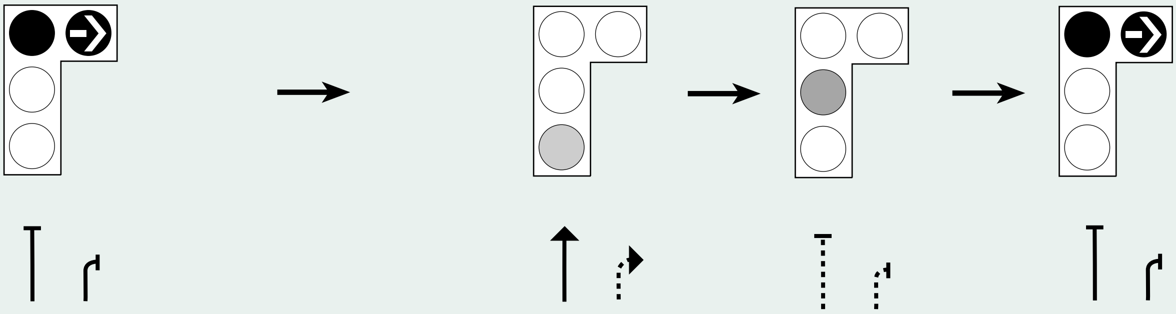
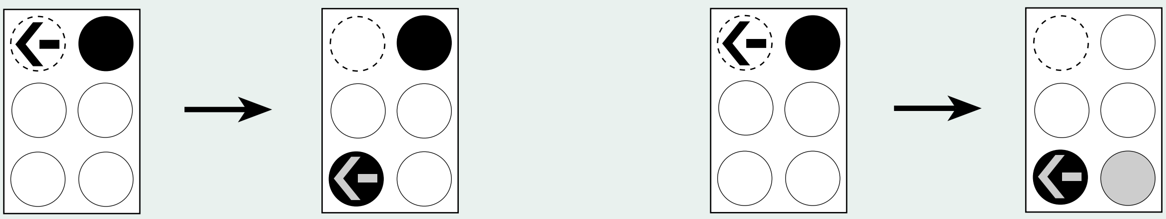


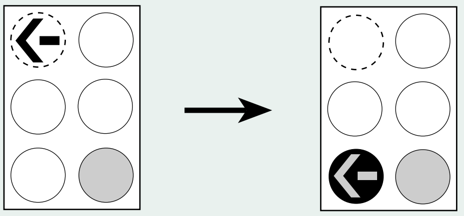
Figure 5.23 Examples of display sequences to initiate an arrow-controlled left-turn movement

During red circular display

Simultaneously with green circular display



During green circular display



Displays where provided

Figure 5.24 Examples of display sequences to terminate an arrow-controlled left-turn movement

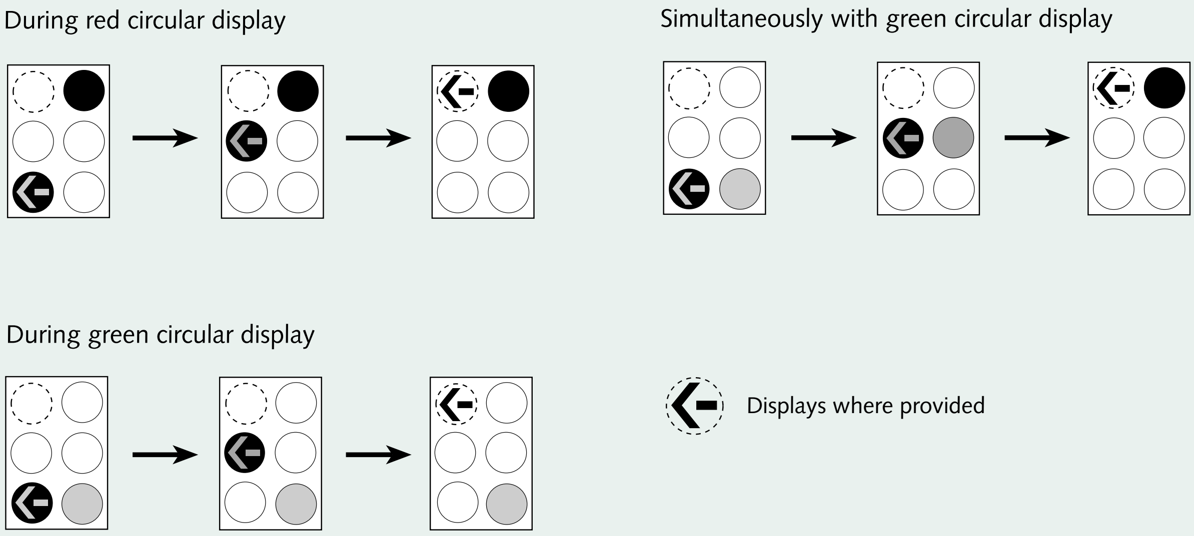
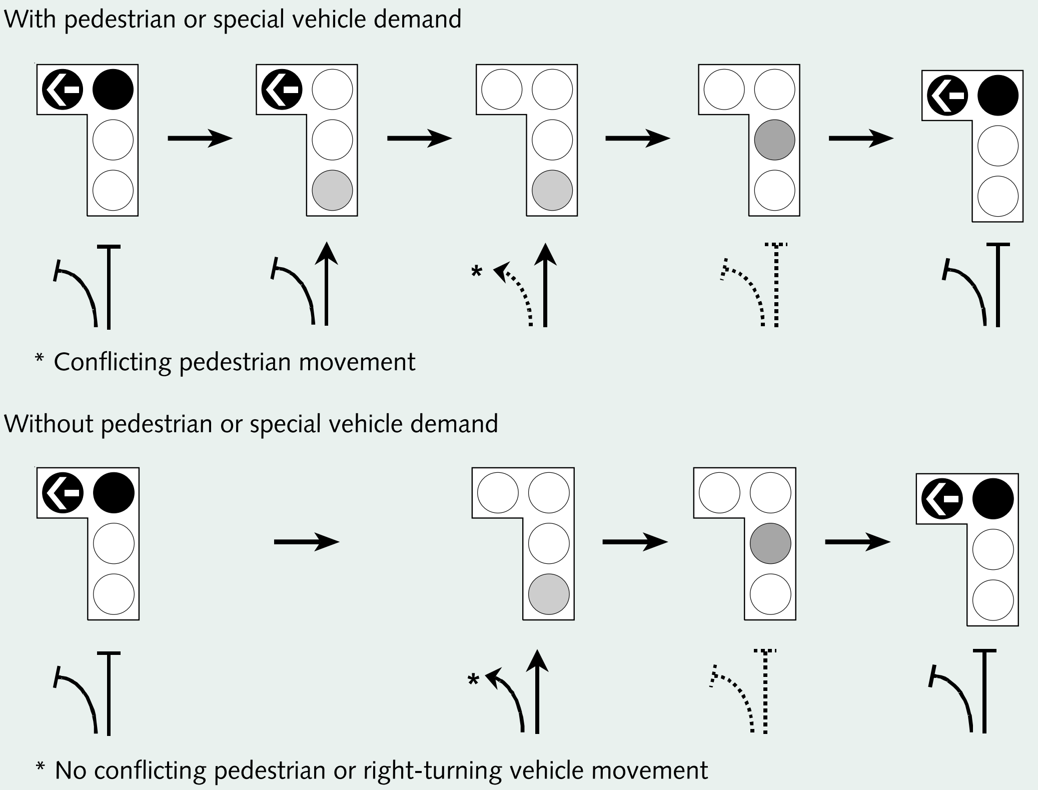


Figure 5.25 Display sequences for four-aspect arrangement with single red left-turn arrow aspect for the protection of pedestrians or special vehicles



5.7.5 Sequences for Two-Aspect Columns

The sequence requirements for two-aspect vehicle signals (where used as regulations permit) are as follows:

(a) at ramp-metering signals: **Green** to **Red** to **Green**,

(b) at roundabout metering signals: **Off** to **Yellow** to **Red** to **Off**,

(c) at far right secondary signals: **Off** to **Green** to **Yellow** to **Off**,

(d) at left-turn slip lanes with signalised crossings: **Off** to **Yellow** to **Red** to **Off**.

For pedestrian and bicycle signalised crossings, see *Sections 5.8 and 5.9*.

5.8 Pedestrian Signals

5.8.1 Signal Face Layout

A pedestrian signal face layout consists of a red pedestrian aspect mounted above a green pedestrian aspect (*Figure 5.1*). Pedestrian aspects must never be incorporated with vehicle aspects in a common signal face.

5.8.2 Basic Sequence

The basic sequence for pedestrian displays is **Steady Red** to **Green** to **Flashing Red** to **Steady Red**.

In some jurisdictions, the red pedestrian signal is extinguished until the pedestrian demand is registered. In this case, the sequence for pedestrian displays is **Off** to **Steady Red** (on pedestrian demand) to **Green** to **Flashing Red** to **Steady Red** (for a short period, e.g. 2 seconds) to **Off**.

5.8.3 Procedure without Pedestrian Displays

When pedestrian signal aspects are not provided or are not operating at an intersection, pedestrians may be controlled by the circular vehicle displays (subject to legislation).

5.9 Bicycle Signals

Signal face layout and sequence requirement for bicycle signals are discussed in this section. For further information on bicycle signals, see *Section 15.6* and *Appendix C.6*.

5.9.1 Signal Face Layout

Where permitted by legislation, a bicycle signal face layout consists of a red bicycle aspect mounted above a green bicycle aspect (*Figure 5.1*). These two-aspect bicycle lanterns must never be incorporated with vehicle aspects in a common signal face.

Three-aspect bicycle signals (red, yellow and green bicycle aspects) can also be used to separately control bicycle movements.

5.9.2 Basic Sequence

The basic sequence for bicycle displays with two-aspect arrangement is **Steady Red** to **Green** to **Flashing Red** to **Steady Red**. The sequence for bicycle displays with three-aspect arrangement is **Green** to **Yellow** to **Red** to **Green**.

5.9.3 Procedure without Bicycle Displays

When bicycle signals are not provided at signalised intersections, bicycles on the roadway are controlled by the vehicle displays.

5.10 Special Vehicle Signals

5.10.1 Signal Face Layout

Where permitted by legislation, a special vehicle signal face layout consists of a single column of red and yellow aspects and a white special vehicle aspect (B for Buses, T for Trams, or E for Emergency vehicles) that provides control of special vehicle movements (*Figure 5.1*).

In some cases, it may be necessary for special-purpose aspects to be mounted and aimed separately from vehicle or pedestrian displays.

Single-aspect white aspects are also used to control special vehicle movements.

5.10.2 Special Vehicle Sequence

The sequence for special vehicle displays is **Red** to **White** to **Yellow** to **Red**. Where white special vehicle lanterns are displayed as single aspect units, the sequence is **Off** to **White** to **Off**.

A single white aspect does not fully control a special vehicle movement, i.e. its absence does not compel a special vehicle to stop.

5.11 Signal Start-up and Failure Displays

5.11.1 Signal Display on Failure

When the intersection cannot be controlled with the normal vehicle displays due to equipment malfunction or maintenance activities, the display recommended is flashing yellow displays at a rate of 1 Hertz with equal **On** and **Off** times.

Flashing yellow displays are safer than blacked out displays. Blanks, Davies and Hulscher (1976) have measured the public acceptability of the incidence of various types of signal display faults. Davies, Hulscher and Syme (1978) showed that the public regard blacked-out signals as being unacceptably hazardous, and that under fault conditions the signals should revert to flashing yellow. Therefore flashing yellow should not be used as a regular, routine mode of operating intersection signals, for example under light traffic conditions. A survey of accident data (Middleton 1969) has confirmed that even under light traffic conditions it is advantageous to retain normal operation of signals.

5.11.2 Signal Display on Start Up

When initiating operation of a signal-controlled intersection the following sequence of displays is recommended:

(a) display **Flashing Yellow** on all approaches for a minimum of ten seconds,

(b) display **Steady Red** on all approaches for three seconds minimum,

(c) display **Green** aspects to the first (usually preselected) movements to proceed,

(d) introduce a cyclic display of all phases and movements,

(e) proceed with normal operation.

6. Signal Phasing

6.1 Introduction and Scope

Signal phase is a state of the signals during which one or more movements receive right of way subject to resolution of any vehicle or pedestrian conflicts by priority rules. A phase is identified by at least one movement gaining right of way at the start of it and at least one movement losing right of way at the end of it.

Signal phasing covers the arrangements of separately controlled traffic movements at a signalised intersection into sequential and concurrent (overlapping) traffic streams to form a complete sequence of phases. This sequence of phases is called a cycle.

Two methods exist for the implementation of phasing arrangements in signal controllers:

(a) *Phase control* whereby the signal timing parameters (intergreen time, minimum green time, etc.) are specified for phases. Phase control tries to minimise the number of phases in order to decrease the intersection lost time.

(b) *Group control* whereby the signal timing parameters are specified for movements. Group control tries to maximise the amount of overlap movements so as to minimise the total time for all critical movements to operate, regardless of the number of phases. This control method permits more flexible and efficient operation, and suits more complicated phasing systems.

These two control methods do not necessarily represent the operation of any particular type or make of controller. The controllers used in Australia employ features of both phase and group control methods.

6.2 General Requirements for Signal Phasing

This section discusses fundamental aspects of signal phasing. All of the guidelines or rules apply irrespective of the number or sequence of phases. *Sections 6.3 to 6.5* present detailed discussions on phasing design. Permissible and recommended signal display combinations and sequences are described in *Section 5*. Detailed discussion of sequences with arrow aspects including various examples is presented in *Section 5.7*.

6.2.1 Fundamental Rules

Signal phasing provides the mechanism by which the basic safety and efficiency requirements of vehicle and pedestrian movements at a signalised intersection are met. Thus, the objectives of signal phasing design are:

(a) **safety**: reduce crashes by managing and minimising conflicts among movements with particular consideration given to conflicts with an accident history, and

(b) **efficiency**: minimise delay, queue length or number of stops, or a combination of these operational performance measures, or maximise throughput (Akçelik 1981).

The above objectives often conflict, and appropriate compromises need to be found. In minimising delay, queue length and number of stops, the average values of these measures for all movements at the intersection as well as the individual movement values should be considered.

Driver understanding and acceptance of the system, and uniformity at the intersections in an area (consistency) are important considerations in signal phasing design.

The choice of phasing system depends on the following factors:

(a) **layout**: the number of lanes available for each movement on the approach and departure of each intersecting road,

(b) **alignment**: the horizontal and vertical alignment in regard to the angle roads intersect and sight distance available to allow safe filtering of right-turn movements,

(c) **traffic flows**: the amount of traffic including proportion of heavy vehicles in each through or turning movement,

(d) **signal coordination**: progression considerations for an intersection within a coordinated signal system,

(e) **pedestrians**: which pedestrian movements need to be controlled and how they will be catered for in the phasing system, and

(f) **special vehicles**: whether or not buses, trams, bicycles need to be separately controlled, and how they will be catered for in the phasing system.

The design of a phasing system cannot be separated from the design of lane arrangements. The allocation of lanes to various movements from each approach road must therefore be considered carefully in designing phasing systems.

Phasing design should also consider safety implications of intersection signal operation during low demand periods when normal phase sequencing may not occur due to phase skipping.

Certain timing constraints are imposed on signal operation for reasons of safety and maximum tolerable delay. Signal controller settings subject to constraints for safety reasons include minimum green time, minimum pedestrian walk time, minimum red arrow display time, pedestrian clearance time, and intergreen time. This subject is discussed in detail in *Appendix C*.

6.2.2 Evaluation of Phasing Design

Alternative signal phasing designs can be developed for a given intersection in accordance with the criteria given in *Section 6.2.1*.

The relative effectiveness of alternative phasing designs can be evaluated using computer software packages that offer analytical or simulation techniques for estimating operational performance measures.

Section 14 describes how the chosen phasing can be checked in operation.

6.2.3 Crash Risk Factors

Safety evaluation is a prime consideration in selecting a phasing design. The following factors are expected to contribute to significant increases in risk of crashes involving turning movements that filter through opposing vehicle and pedestrian movements:

(a) The sight distance from the turning vehicle to conflicting vehicles or pedestrians is inadequate.

(b) There is more than one lane of turning traffic.

(c) Parallel pedestrian movements are exposed to:

  (i) high volumes of turning traffic,

  (ii) high turning traffic speeds resulting from the turn geometry, or

(d) The 85th percentile speed of the opposing traffic is greater than 70 km/h and the right-turning traffic has to turn across three or more lanes of oncoming traffic.

(e) Lagging right turn with opposing filter turn (this conflict must be avoided as discussed in *Section 6.3.3*).

6.3 Phasing Design

Figure 6.1 presents definitions of basic elements of phasing that are applicable to four-way or three-way intersections (cross intersections or T-junctions) and can be adopted to intersections with more than four approaches. Each phasing element is discussed in detail in *Sections 6.3.1 to 6.3.7*.

Movement symbols used in *Figure 6.1* and the phasing diagrams given in this guide do not have any lane use implications, i.e. through, right-turn and left-turn movements are shown separately irrespective of being in shared or exclusive lanes. Any movements stopped by red displays are not shown in the full phase sequence diagrams. Turning movements that give way to opposing vehicle or pedestrian movements are shown in broken lines.

The phasing alternatives shown in *Figure 6.1* are named by the type of right-turn movement operating in the phasing sequence since, generally, right-turn movements determine phasing requirements. Phasing requirements for left-turn and pedestrian movements are discussed in *Sections 6.4 and 6.5*.

The basic phasing elements in *Figure 6.1* show movements on one road only, say East-West road. Left-turn

Figure 6.1 Definitions of basic elements of signal phasing (left-turn and pedestrian movements not shown for clarity)

Through (with filter right turns)

Leading right turn

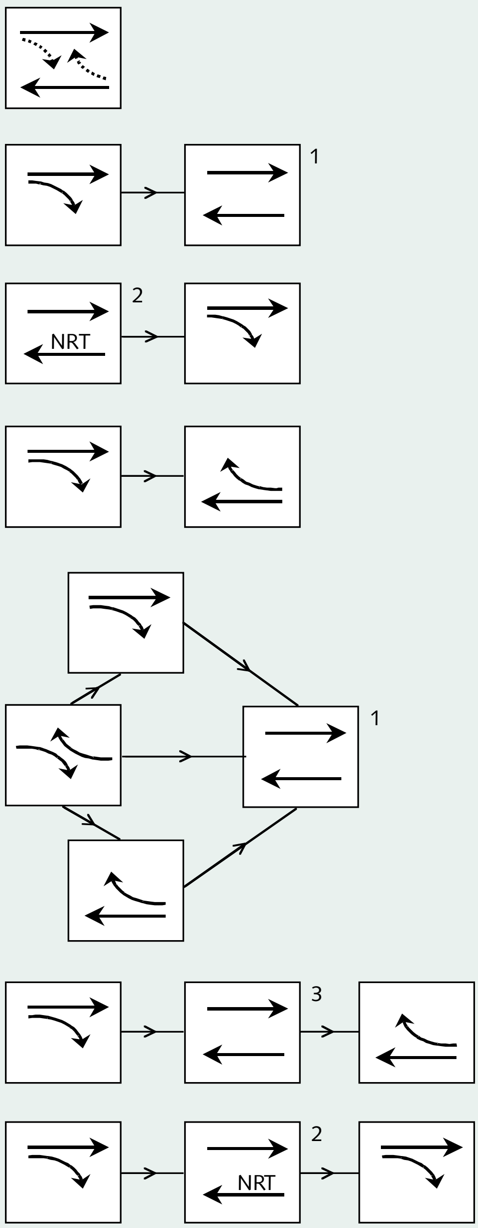
Lagging right turn

Split-approach

Diamond overlap

Lead-lag right turn

Repeat right turn



NRT No Right Turn (right-turn movement must be banned where opposing through movement overlaps).

1 Both filter right turns may be allowed.

2 Filter right turns from approach opposite NRT may be allowed.

3 Leading turn must be fully controlled, and lagging turn may be allowed to filter.

and pedestrian movements are not shown for reason of clarity. The leading, lagging and repeat right-turn phasing options are shown in terms of the right-turn movement from the West approach, but they are equally applicable to a right-turn movement from the East approach. Similarly, the split-approach and the lead-lag phasing options can be in reverse order, i.e. East approach first.

The phasing elements shown in *Figure 6.1* can be used to build a total phasing arrangement for the whole intersection (a complete signal cycle). The simplest signal phasing at an intersection involves two through phases with filter right turns and parallel pedestrian movements as illustrated in *Figure 6.2*.

By allocating right of way to each road alternately, the two-phase system eliminates all crossing conflicts between through traffic movements. However, it leaves four turning conflicts between right-turn and through vehicles, four merge conflicts between right-turn and left-turn vehicles, and eight turning vehicle -pedestrian conflicts as shown in *Figure 6.3*. Some of these turning conflicts can be avoided by using the phasing alternatives given in *Figure 6.1*, or introducing right-turn bans. *Section 11* covers the type of signs that can be used to ban right-turn movements, either full time or part time.

Figures 6.4 and 6.5 show two complete phasing arrangements for a cross intersection, consisting of leading (*Figure 6.4*) or lagging (*Figure 6.5*) right turn phasing on one road and a through phase with filter right turns on the other road. Thus, the signal cycle consists of three phases in these cases.

With lagging right turn phasing, a "right-turn trap" situation can occur as discussed in *Section 6.3.3*. This can also occur with other phasing arrangements due to phase skipping. Various measures to avoid right-turn trap are discussed in *Section 6.3.3*.

With all phasing options shown in *Figure 6.1*, except the split-approach phasing, provision of an exclusive right-turn lane is recommended in order to:

(a) reduce the exposure to the rear-end conflict between through and right-turn vehicles,

(b) avoid lane blockage by vehicles waiting for gaps or stopped by a red display, and

(c) isolate detection of right-turn vehicles (to prevent through vehicles unnecessarily calling the turn phase for leading right turn phasing).

A right-turn bay is a practical solution for providing an exclusive right-turn lane. The length of the right-turn bay should be determined during the evaluation process (*Section 6.2.2*). An exclusive right-turn lane is essential for operation of diamond overlap phasing, and is recommended in the case of fully-controlled right turns.

Where a right turn is banned part time using a switchable electronic sign, the switching of the sign should be coordinated with the signal displays in order to obtain a safe transition. If the right-turn movement is arrow controlled, the sign should preferably switch on at the same time as the arrows change from a yellow display to a red display or red arrow drop-out.

The phasing alternatives shown in *Figure 6.1* can be achieved through the following *types of right-turn control* at traffic signals:

(a) **Filter Only**: No right-turn arrows, i.e. three circular aspects (red, yellow, green) only.

Green circle alone indicates that right-turning drivers can "filter" through gaps in the opposing vehicle and pedestrian traffic. Normally, right-turning vehicles give way to through and left-turning vehicles from the opposing direction. However, right-turning vehicles have priority over left-turning vehicles using a slip lane.

(b) **Full Control**: Three-aspect (red, yellow, green) right-turn arrows on a six-aspect signal face.

The green arrow indicates that the vehicle can turn unopposed (with no opposing vehicle or pedestrian traffic), and the red arrow indicates that the vehicle is not permitted to turn. Filter right turns are not permitted at any time during the cycle.

(c) **Partial Control**

(i) **Two-aspect (green, yellow) right-turn arrows on a five-aspect signal face**: The green arrow indicates that the vehicle can turn unopposed. A green circle without the green arrow permits the vehicle to filter.

Figure 6.2 Two-phase system with filter right turns and parallel pedestrian movements

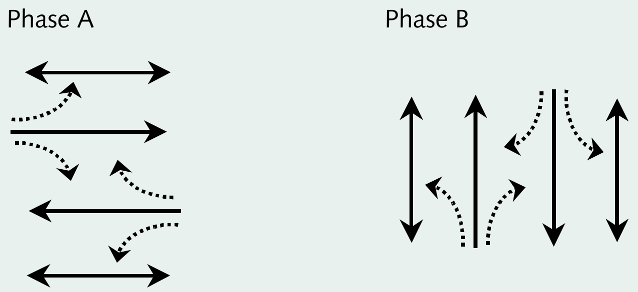


Figure 6.3 Conflict points in the two-phase system shown in Figure 6.2

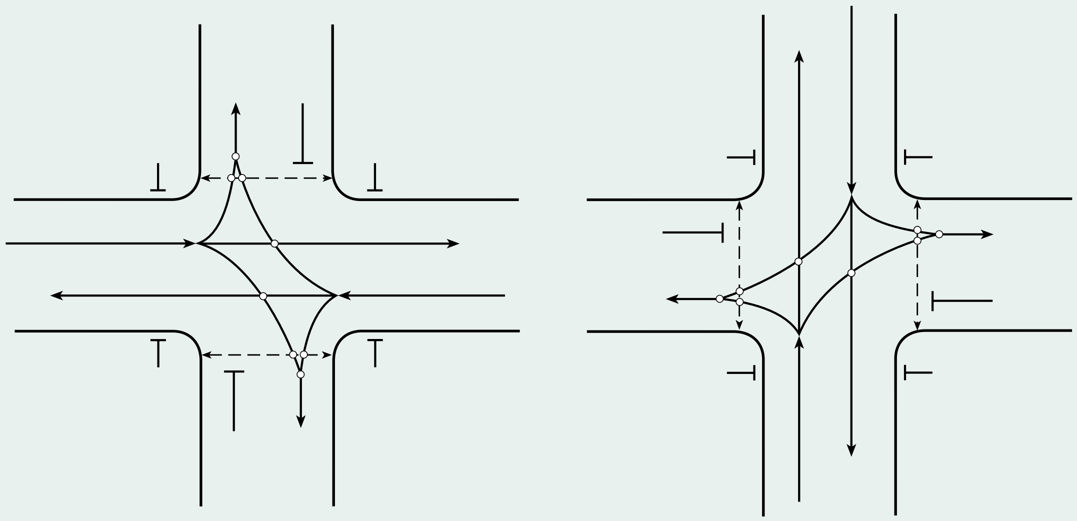


Figure 6.4 Three-phase system consisting of leading right turn phasing on the East-West road and a through phase with filter right turns on the North-South road

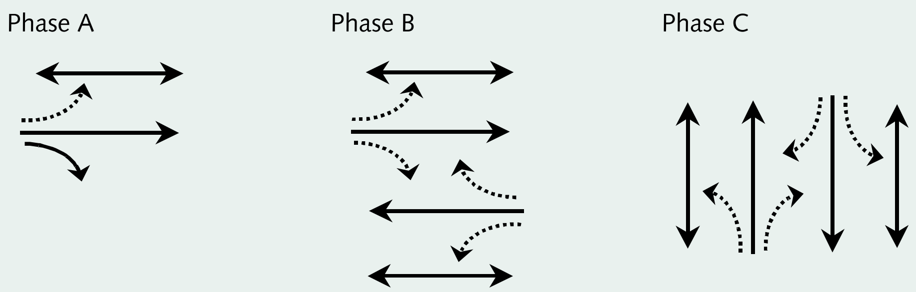
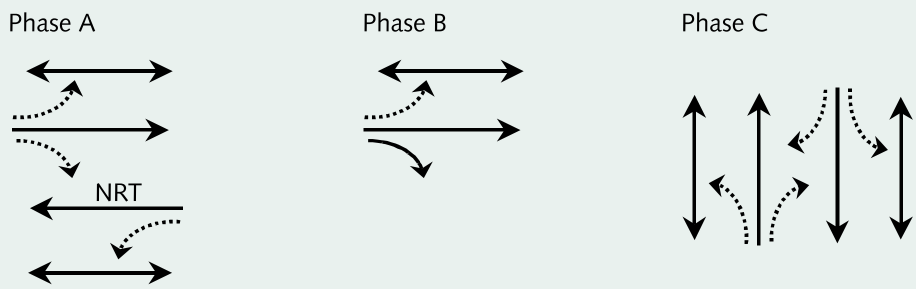


Figure 6.5 Three-phase system consisting of lagging right turn phasing on the East-West road and a through phase with filter right turns on the North-South road



(ii) **Red Arrow Drop Out**: Three-aspect (red, yellow, green) right-turn arrows on a six-aspect signal face are provided but the red arrow extinguishes (drops out) and the adjacent green circle display permits filter turns after a few seconds in the through phase.

(iii) **Flashing Yellow Arrow**: As an alternative to blanking the arrow displays, a flashing yellow arrow may be displayed after the red arrow where regulations permit. This display indicates that a right turn may be made but the driver must give way to other vehicles and pedestrians that also have a signal to proceed.

(d) **Part-Time Full Control**

Full Control operates during certain hours of the day, and Filter Only or Partial Control operates during other times of the day.

6.3.1 Through Phasing with Filter Right Turns

This phasing arrangement (see *Figures 6.1 and 6.2*) allows the through and left- turn movements and filter right turns from opposing approaches to operate in the same phase using three-aspect circular (red, yellow, green) signal faces (see *Figure 5.3* in *Section 5*).

A filter right-turn movement must give way to and find safe gaps in conflicting vehicle or pedestrian traffic before proceeding. A phasing alternative that uses a green right-turn arrow would be considered if:

(a) evaluation of the phasing indicates that the intersection performance is improved by providing a separate right-turn phase (*Section 6.2.2*), or

(b) the filter right turn is considered unsafe due to crash risk factors (*Section 6.2.3*).

If a suitable phasing alternative that can cater for the right-turn movements in an efficient and safe manner cannot be found, consideration would be given to banning the right turns.

If only one right turn can be banned and the other right turn cannot filter efficiently, a lagging right turn sequence may be an option (see *Section 6.3.3*).

If neither right turn can be banned, a leading right turn sequence may be an option if one of the right turns can filter safely and efficiently and the other cannot filter efficiently (see *Section 6.3.2*).

If both right turns cannot filter efficiently, then a diamond overlap sequence may be an option (see *Section 6.3.5*).

If both right turns are required but the diamond turn is not practical, a split-approach sequence may be an option (see *Section 6.3.4*).

6.3.2 Leading Right Turn Phasing

A leading right turn sequence is where a right-turn phase precedes the phase in which the opposing through movement runs (see *Figures 6.1 and 6.4*). In *Figure 6.4*, the leading right-turn movement from the West approach runs in Phase A, and the opposing through movement from the East approach runs in Phase B.

A leading right turn phase is controlled by three-aspect right-turn arrows (red, yellow, green) in a six-aspect signal face, or by two-aspect right-turn arrows (yellow, green) in a five-aspect signal face (see *Figures 5.4 and 5.7* in *Section 5*).

This phasing is a suitable option where an arrow-controlled right turn has a filter right turn from the opposing direction (the right-turn movement from the East approach in *Figure 6.4*), which cannot be banned and is able to filter safely and efficiently.

Where it is safe to do so, the arrow-controlled right turn can be allowed to filter through the opposing through movement during the following phase (the right-turn movement from the West approach in Phase B in *Figure 6.4*). If filtering causes safety problems, this right turn must be stopped, using a red arrow display, when the opposing through movement is operating (full control).

Where the leading right-turn movement is allowed to filter during the following phase in the case of six-aspect signal face, the arrow-controlled turn must be terminated and held on a red arrow display at the beginning of the green circular display (at the start of Phase B in *Figure 6.4*). The red arrow is then extinguished for the remainder of the green circular display (red arrow drop out).

This phasing system becomes inefficient for shared lanes when a through vehicle calls the right-turn phase and there are no right-turn vehicles during that phase. The provision of an exclusive right-turn lane (turn-bay or full-length lane) is recommended.

6.3.3 Lagging Right Turn Phasing

A lagging (trailing) right turn sequence is where a right-turn phase follows the phase in which the opposing through movement runs (see *Figures 6.1 and 6.5*). In *Figure 6.5*, the lagging right-turn movement from the West approach runs in Phase B, and the opposing through movement from the East approach runs in Phase A.

A lagging right turn phase is controlled by three-aspect right-turn arrows (red, yellow, green) in a six-aspect signal face, or by two-aspect right-turn arrows (yellow, green) in a five-aspect signal face (see *Figures 5.4 and 5.7* in *Section 5*).

This phase sequence can be used where a two-phase system (*Figure 6.2*) has safety or efficiency problems with filter right turn operation.

In the case of cross roads, the lagging right turn phasing is a suitable option only where the right-turn from the direction opposing the lagging right turn (right turn movement from the East approach in *Figure 6.5*) can be banned or other measures can be taken to ensure the safety of this movement. This is because the filtering right-turn vehicles would face a yellow circle display while the oncoming through traffic (from the West approach in *Figure 6.5*) faces a green circle display during the phase transition (from Phase A to Phase B in *Figure 6.5*). This situation also applies to T-intersections with filter U-turns.

In this case, a driver who wants to turn right by filtering at the end of the first phase from the direction opposing the lagging right-turn movement (right turns from the East approach filtering at the end of Phase A in *Figure 6.5*) will see the signal display changing to yellow. The driver may think that the signals change to yellow for the opposing traffic (from the West approach in *Figure 6.5*) at the same time, and therefore proceed and run into an opposing through vehicle for which the signal display would still be green ("right-turn trap").

If the right-turn movement from the direction opposing the lagging right turn cannot be banned, this conflict situation must be avoided by:

(a) using a leading right turn sequence (*Section 6.3.2*) rather than a lagging right turn sequence, and ensuring that the transition from the through phase to the right-turn phase is avoided when the intervening phases are skipped (not demanded), e.g. in *Figure 6.4*, transition from Phase B to Phase A when Phase C is not demanded, or

(b) forcing the overlapping through movement (from the West approach in *Figure 6.5*) to stop and then start up again (though this is not an efficient method), or

(c) using another phasing such as split-approach phasing (*Section 6.3.4*), or diamond overlap phasing (*Sections 6.3.5*), or lead-lag right turn phasing (*Sections 6.3.6*).

A similar conflict for filtering right-turn vehicles can occur in any phase sequence where one through movement receives yellow signal display before the opposite through movement (early cut-off). For example, this may happen at paired intersections (see *Section 15*) where through movements are terminated at different times in order to clear traffic from internal approaches.

Where it is safe to do so, the arrow-controlled right turn is generally allowed to filter through the opposing through movement during the preceding phase (the right-turn movement from the West approach in Phase A in *Figure 6.5*). If filtering causes safety problems, this right turn must be stopped, using a red arrow display, when the opposing through movement is operating (full control).

6.3.4 Split-Approach Phasing

Split-approach phasing allocates separate phases to opposing approaches at four-way intersections (see *Figure 6.1*). The through and turning movements from each approach operate simultaneously, and right-turn movements are unopposed under this phasing.

Split-approach phasing is controlled by four-aspect signal faces, i.e. three circular aspects (red, yellow, green) and a green arrow aspect (see *Figure 5.9* in *Section 5*).

Split-approach phasing may also be appropriate where:

(a) side streets at an intersection are slightly offset so right turns cannot make a diamond turn, or sight distance makes opposing filter right-turn movements unsafe;

(b) turn proportions vary significantly during the day requiring flexible shared lane arrangements; or

(c) a particularly heavy right-turn movement is opposed by a very light movement, in which case the right-turn vehicles may fail to give way to opposing through vehicles.

Other phasing options should be evaluated against split-approach phasing before adopting it since it may result in inefficient site operation. However, safety is a prime consideration in the evaluation.

6.3.5 Diamond Overlap Phasing

Diamond overlap phasing allows right turns from opposing directions to operate either simultaneously, or independently with the through movement on the same approach, depending on demand for the right turns and conflicting through traffic on the road controlled by the diamond overlap phasing in each signal cycle (see *Figure 6.1*).

Diamond overlap phasing is controlled by three-aspect right-turn arrows (red, yellow, green) in a six-aspect signal face, or by two-aspect right-turn arrows (yellow, green) in a five-aspect signal face (see *Figures 5.4 and 5.7* in *Section 5*).

The diamond overlap phasing is used where opposing right-turn flows are too large for efficient filter operation alone at four-way intersections, or there are safety reasons that preclude right-turn filtering being allowed.

The right turns can operate as optional filter turns where safety permits. Filter turns are introduced after both right-turn movements are stopped and both through movements are started (red arrow drop out).

The diamond overlap phasing shown in *Figure 6.1* provides leading right turns in both directions, thus avoiding phase transitions that cause lagging right-turn conflict where filter turns are used (*Section 6.3.3*).

6.3.6 Lead-Lag Right Turn Phasing

Lead-lag right turn phasing combines the leading and lagging right turn arrangements, i.e. a right-turn phase precedes the phase in which both through movements run followed by a right-turn phase for the right-turn movement from the opposing approach (see *Figure 6.1*). In this phasing,

(i) the leading right turn must be fully controlled using three-aspect right-turn arrows (red, yellow, green) in a six-aspect signal face, and

(ii) the lagging right turn can be either fully controlled using three-aspect right-turn arrows (red, yellow, green) in a six-aspect signal face, or partially controlled using either three-aspect right-turn arrows with red arrow drop out or two-aspect right-turn arrows (yellow, green) in a five-aspect signal face.

This phasing is useful for signal coordination purposes since it provides more predictable operation than the diamond overlap phasing.

Where it is safe to do so, the lagging right-turn movement may be allowed to filter through the opposing through movement during the preceding through phase (red arrow drop out). If filtering causes safety problems, this right turn must be stopped, using a red arrow display, when the opposing through movement is operating (full control).

The leading right-turn movement should not be allowed to filter during the following through phase (i.e. should be fully controlled) in order to avoid the lagging right-turn conflict discussed in *Section 6.3.3*.

6.3.7 Repeat Right Turn Phasing

Repeat right turn phasing introduces the arrow-controlled right turn twice in the same cycle (see *Figure 6.1*). Effectively, this provides a combined leading and lagging right-turn arrangement for a selected right turn movement, unlike the lead-lag right turn phasing (*Section 6.3.6*) that applies to the right turns from opposing directions.

The right turn associated with the repeat phasing can be

(i) either fully controlled using three-aspect right-turn arrows (red, yellow, green) in a six-aspect signal face, or

(ii) partially controlled using either three-aspect right-turn arrows (red, yellow, green) with red arrow drop out or two-aspect right-turn arrows (yellow, green) in a five-aspect signal face.

Where it is safe to do so, the right-turn movement subject to the repeat turn arrangement may be allowed to filter during the through phase (partial control). If filtering causes safety problems, this right turn must be stopped, using a red arrow display (full control).

The right-turn movement from the opposing direction should not be allowed to filter during the through phase in order to avoid the lagging right-turn conflict discussed in *Section 6.3.3*.

This phasing can be used for either full-time or part-time operation. Its use will depend on the degree to which right-turn traffic flow fluctuates at a site.

Repeat right turn phasing increases short lane capacities by using two short green intervals (applicable to right-turn bays). It is also useful where there is insufficient storage on the immediate departure (downstream) side where traffic may be forced to stop intermittently. In this case, this phasing operates as a metering device.

The use of a repeat right turn phase introduces an additional intergreen period that may impact the efficiency of the intersection if the right turn is a critical movement.

6.4 Left-Turn Movements

Left-turn movements do not control phasing selection. They can run in one or more phases depending on phasing requirements for other movements.

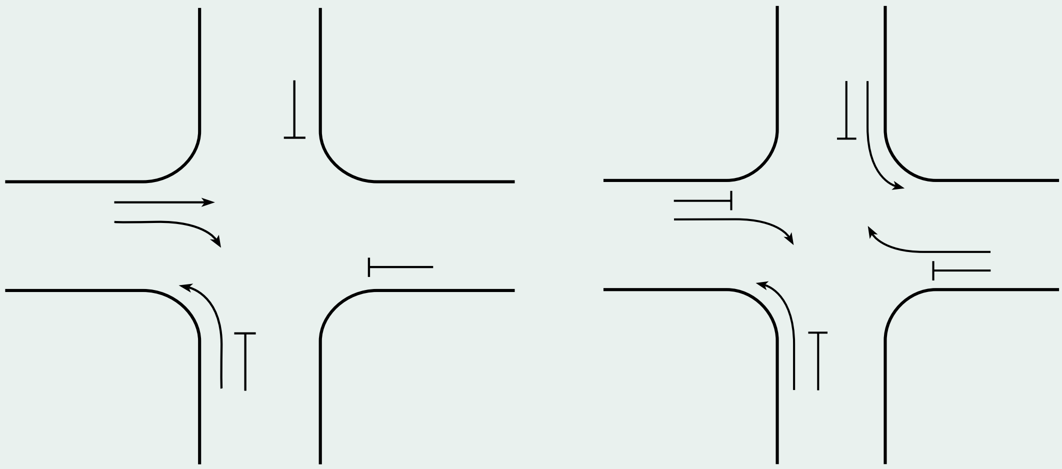
When controlled by circular signals alone, left-turning traffic will filter through gaps in the parallel pedestrian traffic during the green and intergreen periods. **Red left-turn** arrows may be used where this practice is considered unsafe due to an unacceptable accident history, or where the following conditions contribute to an increased risk of accident:

(a) the volume of left-turn traffic is high, or

(b) the speed of left-turn traffic is high due to the turn geometry, or

(c) the visibility of pedestrians by turning vehicles is inadequate.

Figure 6.6 Examples of complementary left and right arrow-controlled turns



An example of the use of left-turn red arrow is holding the left-turn movement on red during pedestrian Walk and/or Clearance intervals. The red left-turn arrow can also be used to provide priority for special vehicle movements (e.g. train or tram level crossings).

Figures 5.12 and 5.14 in *Section 5* show examples of four-aspect and five-aspect signal faces with a red left-turn arrow.

Green left-turn arrows may be used when there is no conflict with other vehicle or pedestrian movements. Complementary left and right arrow-controlled turns as shown in *Figure 6.6* is the most common example of this. See *Figures 5.11 and 5.13* in *Section 5* for examples of four-aspect and five-aspect signal faces with a green left-turn arrow.

Figure 6.7 shows the use of complementary left and right arrow-controlled turns at a T-intersection where five-aspect signal face layouts are used. This example is used to demonstrate some issues regarding the use of green left-turn arrows.

In this example, there is no provision for pedestrians crossing the Eastern leg of the intersection. Left-turn green arrow from the East in Phase A and from the South in Phase B are not displayed because these arrows would be in conflict with the pedestrian movements.

A left-turn green arrow should never be displayed in the same phase as a filter right turn from the opposing approach operates. This is the other reason for not displaying the left-turn green arrow from the East approach during Phase A.

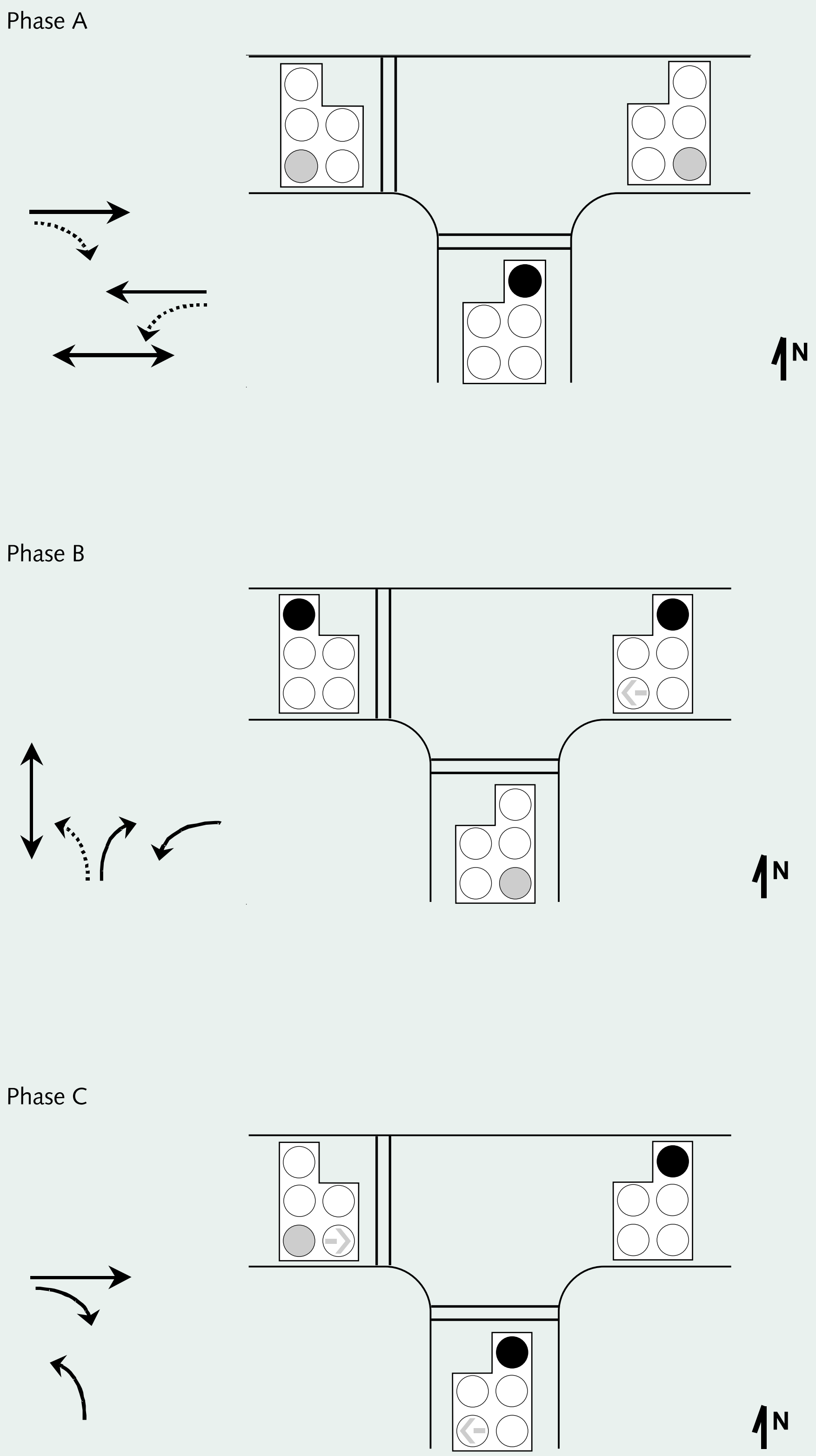
The introduction of the green left-turn arrow is delayed by a few seconds at the start of Phase B in order to minimise the chances of conflicts between left-turning vehicles from the East and filter right-turning vehicles from the West clearing the intersection during the intergreen period between Phases A and B.

In some jurisdictions, a *flashing yellow arrow* is used to protect pedestrian movements (see *Section 6.5.2*). In *Figure 6.7*, this applies to left turn from the East approach in Phase A, and to left turn from the South approach in Phase B.

Some jurisdictions allow *left turn on red* as a delay reduction measure subject to various criteria being met (see *Section 15.12*). This arrangement permits vehicles to turn left through a red circle display after first stopping at the stop line, provided it is safe to do so.

When *unsignalised slip lanes* are provided for left-turn movements, vehicles can turn during all phases subject to giving way to conflicting vehicle movements, as well as pedestrians crossing the slip lane. For example, in *Figure 3.1* in *Section 3.2.3*, left-turn movements using the slip lane on the East approach give way to through traffic from the North approach and the right-turn traffic from the West approach.

Figure 6.7 T-intersection phasing to demonstrate use of complementary left and right arrow-controlled turns



6.5 Pedestrian Movements

6.5.1 General

(a) Control of pedestrian movements is achieved through:

   (i) a **Walk** period indicated by a steady green person display that permits pedestrians to commence their crossing;

   (ii) a **Clearance** period consisting of a red flashing standing person display that permits pedestrians to complete their crossing but prohibits pedestrians starting to cross; and

   (iii) a **Don't Walk** period consisting of a steady red standing person display that prohibits crossing.

   Pedestrian aspects are shown in *Figure 5.1* in *Section 5*. In some jurisdictions, the steady red Don't Walk display is extinguished after a short period until the pedestrian demand is registered (see *Section 5.8.2*).

(b) The flashing rate for the Clearance period should be approximately 1 Hz with an on-off ratio of 60:40.

6.5.2 Pedestrian Movements at Intersections

(a) Under normal conditions the introduction of a green pedestrian display would be subject to a pedestrian demand, but where pedestrian movements are consistent and heavy, automatic introduction of the relevant green pedestrian display may be considered.

(b) Normally, pedestrian movements (Walk displays) are introduced with the parallel vehicle movements. If the number of pedestrian - vehicle conflicts is high or the speed of approaching vehicles is high, *red arrow* or *flashing yellow arrow* displays may be required to protect pedestrians. If this creates phase transitions that are too complicated, or additional phases are needed to fully service the vehicle movements, an *exclusive pedestrian phase* may be considered. During an exclusive pedestrian phase, all Walk displays (and associated clearances) are shown simultaneously while all vehicle movements are stopped by red signals. In a s*cramble-crossing phase*, pedestrians are allowed to walk in any direction including diagonally across the intersection within the limits of the crosswalk lines. However, exclusive pedestrian phases should be avoided as they normally create longer delays to vehicles and pedestrians, compared with parallel pedestrian - vehicle phasing arrangements.

(c) Reintroduction or late introduction of a pedestrian movement (Walk display) may be used subject to sufficient time remaining in the phase to provide adequate Walk and Clearance times. Where reintroduction or late introduction is used, it is recommended that consideration be given to terminating conflicting vehicle turning movements.

(d) Slip Lanes: Pedestrian movements across a slip lane (channelised left-turn carriageway) should be signalised where warranted by pedestrian volumes or when pedestrians require additional protection due to special conditions (vehicle speed, sight distance, pedestrian disabilities). Generally, signals should be provided on a slip lane consisting of two or more lanes. In some jurisdictions, two-aspect (red, yellow) signals are used for slip lanes with one or more lanes. In this case, the left-turn movement is subject to normal give way conditions just downstream of these signals (see *Sections 3.2.3 and 5.3.4*). *Figure 7.6* in *Section 7* shows a signalised crossing on a two-lane slip lane.

(e) "Staged" Crossing: Staged signalised crossings can be considered where median widths provide adequate storage for the pedestrian traffic and large Walk plus Clearance time values cause the intersection performance to deteriorate seriously.

   The staged crossings should be offset to make it clear to the pedestrians that the crossings are separately controlled, and to reduce the chance of pedestrians on one side of the road reacting to a Walk display on the far side of the road.

6.5.3 Midblock Signalised Crossings

At a midblock signalised crossing, all vehicles must face a red display during the pedestrian Walk and Clearance periods, i.e. while the pedestrian signals display green and flashing red signal.

An exception to this is the **Pelican crossing** which permits vehicles to proceed, giving way to pedestrians by displaying a flashing yellow signal to the vehicles, during the pedestrian Clearance 2 interval (see *Sections 1.5.2, 5.7.1 and C.3.2*). This helps to reduce delay to vehicle traffic.

In the case of controlling pedestrians crossing two carriageways separately ("staged" crossing), median widths should provide adequate storage for pedestrians, and the crossings should be offset for the same reasons given in *Section 6.5.2(e)*.

Figures 7.9(b) and 7.9(c) in *Section 7* show midblock two-stage signalised crossings with an offset.

Pedestrian sensors may be used to detect pedestrians waiting to cross the road as well as pedestrians who are on the crossing so as to provide variable length clearance interval for pedestrians, e.g. Puffin crossings (see *Section 8.4.1*).

7. Location of Signal Equipment

7.1 Introduction

Signal face layouts are discussed in detail in *Section 5*. This section discusses location of signal equipment within the area of the intersection, including location of pedestrian signal faces. Signal faces should be located in accordance with specification in AS 1742 Part 14 (Standards Australia 1996*)*. Location of pedestrian push-button assemblies is discussed in *Section 8.4.3*.

7.2 Designation of Signal Faces

The designation of signal faces in relation to their locations for a given approach road are given below and shown in *Figures 7.1 and 7.2* for:

(i) an undivided road approach at a cross-road intersection,

(ii) a divided road approach at a cross-road intersection,

(iii) a terminating road at a T-intersection, and

(iv) an approach road at a midblock signalised crossing.

Various symbols used in figures given in this section to describe signal faces are explained in *Figure 7.3*. Refer to AS 1100 Part 401 and local standards for additional symbols.

Primary Signal Face

The primary signal face for any approach is that signal face mounted on a post at or near the left of the stop line on that approach.

Secondary Signal Face

The secondary signal face for any approach is that signal face mounted on a post on the downstream side to the right of that approach.

Tertiary Signal Face

The tertiary signal face for any approach is that signal face mounted on a post on the downstream side to the left of that approach.

Dual Primary Signal Face

The dual primary signal face for any approach is that signal face mounted on a post either:

(a) if there is no median or median is too narrow, to the right and near the projection of the stop line as shown in *Figure 7.1(a)*, or

(b) on the median at or near the right of the stop line on that approach as shown in *Figure 7.1(b*).

Dual Secondary Signal Face

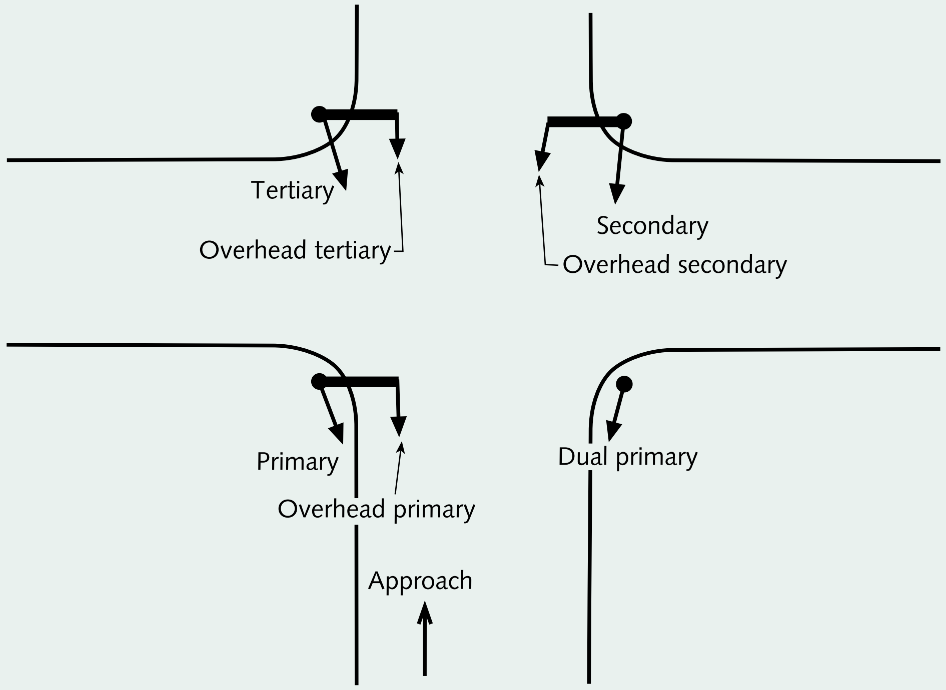
The dual secondary signal face for any approach is that signal face mounted on a post on the downstream side to the right of that approach, in addition to the secondary signal face located on the median (*Figure 7.1(b)*).

Overhead Signal Face

Signal faces mounted on a mast arm (see AS 2979) above the roadway are similarly designated as Overhead Primary, Overhead Secondary and Overhead Tertiary Signal faces.

Figure 7.1 Signal face designations for four-way intersections

(a) Undivided road approach at a cross-road intersection



(b) Divided road approach at a cross-road intersection

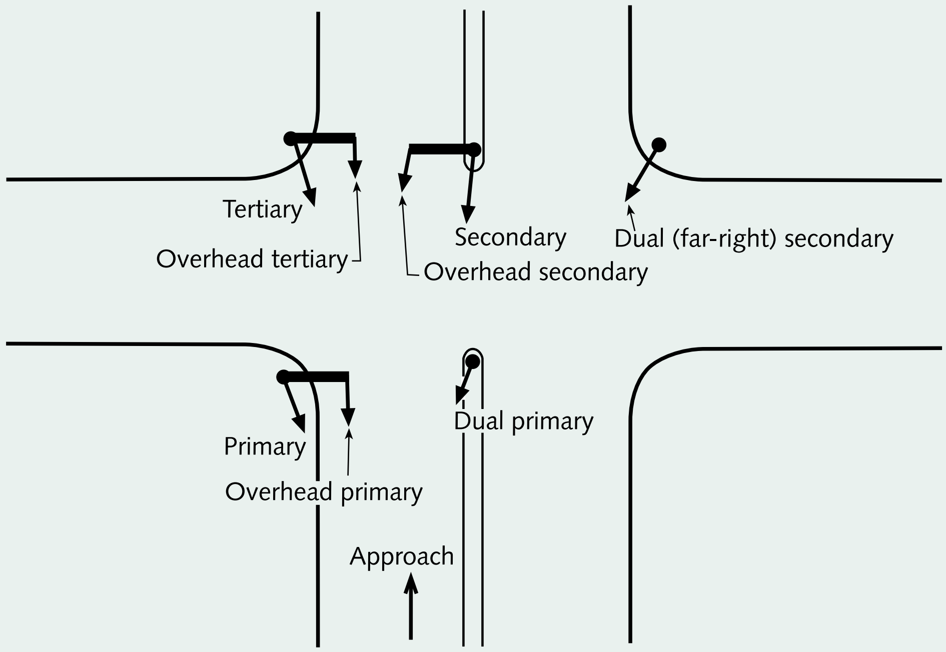
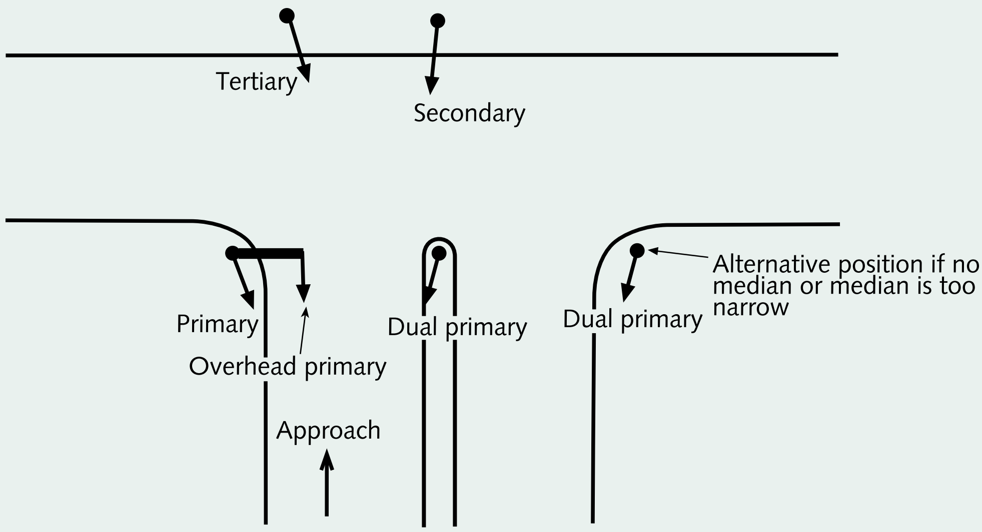
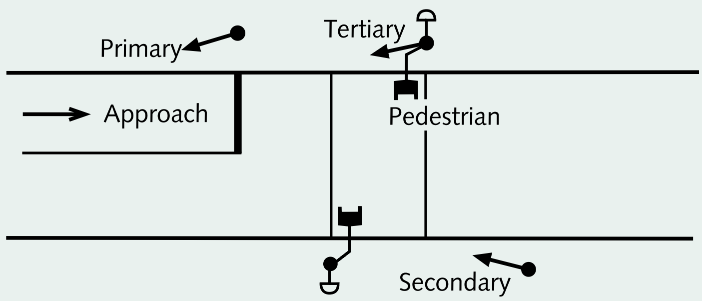


Figure 7.2 Signal face designations for T-intersections and midblock signalised crossings

(a) Terminating road at a T-intersection



(b) Midblock signalised crossing



7.3 Signal Face Functions

A design must provide for the following signal face functions for each approach as relevant.

(a) Warning Display: To alert the approaching drivers to the presence of traffic signal control.

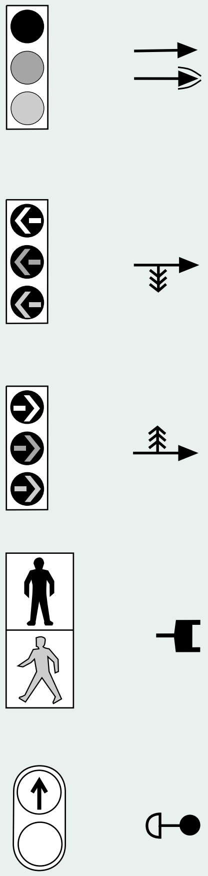
(b) Stopping Display: To inform approaching drivers sufficiently in advance of the stop line that they are required to stop.

(c) Starting Display: To inform drivers stopped at the stop line when they may proceed.

(d) Manoeuvring Display: To inform drivers about to enter the intersection, or within the intersection, of any priority or restriction allocated to them.

Each signal face can provide more than one function as detailed in *Table 7.1*. A signal face does not adequately provide the function if two or more lanes of traffic separate approaching vehicles and the signal face.

Figure 7.3 Symbols used to describe signal faces (refer to AS 1100 Part 401 and local standards for additional symbols)



Three-aspect circular
Three-aspect circular with "closed visor" (optional)

Three-aspect left arrow

Three-aspect right arrow

Two-aspect pedestrian

Pedestrian push button

Table 7.1 Signal face functions

Location of Signal Face	Main Functions Performed Warning	Stopping	Starting	Manoeuvring
Primary	Yes	Yes	No	No
Secondary	‡	‡	Yes	Yes
Tertiary	‡	‡	Yes	Yes
Dual Primary	Yes	Yes	No	No
Overhead Primary	Yes	Yes	No	No
Overhead Secondary	‡	‡	Yes	‡
Overhead Tertiary	‡	‡	Yes	‡

‡ These functions may also be provided depending on site geometry, topography and other conditions.

7.4 Signal Face Site Requirements

7.4.1 Recommended Minimum Number of Signal Faces

(a) The minimum number of signal faces for a given approach is three, with the exception of special applications and facilities (see *Section 15*). An approach with a primary, a secondary and a tertiary signal face satisfactorily provides for all essential signal face functions while still providing a limited degree of safety in case of individual lamp failure.

(b) The minimum number of signal faces for each left-turn movement is two. They should be located in the primary and tertiary locations. Where the road left-turning vehicles are turning into has a median or island, the tertiary signal face may be located on that median or island if a suitable post is provided ("split tertiary" arrangement). Signal faces for a channelised left-turn carriageway are covered in *Section 7.5.2.2*.

(c) The minimum number of signal faces for each right-turn movement is two. They should be located as follows:

 (i) on a divided road with medians of sufficient width, in the dual primary and secondary locations,

 (ii) otherwise, preferably in the overhead primary and secondary locations, or

 (iii) as a last choice, in the primary and secondary locations.

 Furthermore, if both the secondary and overhead secondary are provided, right-turn aspects should be placed on both.

 On a divided road where there are two or more lanes turning right, consideration should be given to installing a right-turn signal face in the dual (far-right) secondary location.

(d) At intersections where geometry, physical features, approach widths or other factors restrict the functions provided by only three signal faces, additional signal faces may be necessary, for example at multiple leg intersections or where the controlled area is exceptionally large or complex.

 Excessive numbers of signal faces add to the visual clutter at the intersection and add to intersection operating costs. The provision of additional signal faces that are not warranted may become confusing.

7.4.2 Dual Primary Signal Faces

A dual primary signal face is normally provided when there is a median island of sufficient width, and:

(a) there are two or more approach lanes and/or

(b) there are right-turn arrow aspects.

7.4.3 Overhead Signal Faces

7.4.3.1 Overhead Signal Warrants

(a) Overhead signal faces are expensive to install and to maintain. Their use should be minimised. They are required in the following situations:

    (i) where the stopping sight distance to the post-mounted signal face is inadequate, e.g. because of vertical or horizontal alignment, awnings, poles, trees or similar sight obstructions, and

    (ii) where the roadway is too wide for kerb-mounted signal faces to fall within the driver's line of sight.

(b) Overhead signals may be omitted if it is likely that they could appear to apply to an adjacent upstream signalised intersection.

7.4.3.2 Overhead Signal Location

(a) The primary signal face location is preferred for overhead signal faces (see *Table 7.1*) because it provides:

    (i) The greatest sight distance from the stop line, and

    (ii) Warning and stopping functions when dual primary signal faces are warranted but cannot be provided.

(b) Provided adequate sight distance is available, an overhead secondary signal face may be used instead of an overhead primary signal face where additional starting and/or manoeuvring functions are required, e.g. if secondary median signal faces are not available or for additional right-turn arrow aspects when dual primary signal faces are not available.

    Where two overhead signal faces are required for each approach, primary and secondary signal faces for opposite approaches are often mounted on the same mast arm to reduce costs.

(c) Provided adequate sight distance is available, an overhead tertiary signal face may be used instead of an overhead primary signal face when additional starting or manoeuvring functions are required, e.g. for additional signal faces incorporating left-turn arrows.

(d) Provided signal face functional requirements are met (see *Section 7.3*), economy in the use of mast arms can be achieved by mounting more than one signal face on a mast arm, e.g. on cross-road intersections, a primary signal face for one approach and a tertiary signal face for the approach from the right.

(e) Unless obstructions such as power lines are present, the mast arm outreach selected should ideally locate the signal face above the second lane from the kerb.

Where obstructions are present and inadequate sight distance is the main reason for providing an overhead signal face, the signal face should be located:

(i) as near as possible to the ideal location, and

(ii) so that necessary safety clearance from the obstruction are maintained.

7.4.4 Pedestrian Signal Faces

The following requirements apply for signalised crossings at intersections and midblock locations. Also see *Section 7.5.2.4* on midblock signalised crossings.

(a) A pedestrian signal face must be provided at each end of a signalised crossing. It should be located within 1 metre of the projection of the crosswalk lines and aimed at the opposite end of the crossing (see *Figures 7.2(b)*, *7.4(a)*, *7.6*, *7.8*, *7.9*).

(b) If the crossing width exceeds 10 m, two pedestrian signal faces should be provided at each end of the crossing (see *Figure 7.4(b)*).

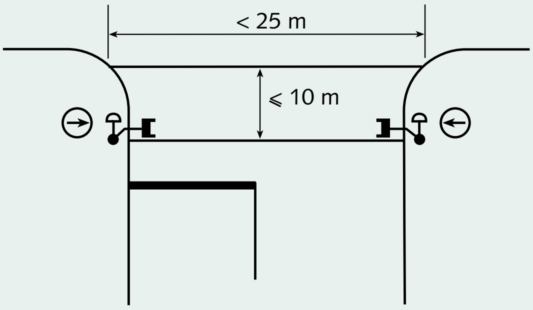
(c) If the crossing distance exceeds 25 m, supplementary pedestrian signal faces should be installed on a median island where practicable.

(d) The pedestrian signal face should be located, and if necessary screened, to ensure that it is obvious which crossing is controlled by the signal face.

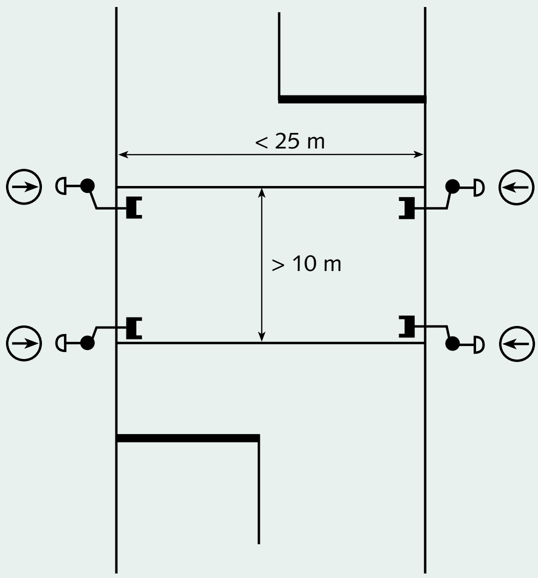
(e) Where a crossing is staged as two separate movements, each stage must be signalised as a separate crossing with due regard to (d) above.

Figure 7.4 Pedestrian signal faces: pedestrian arrow orientations shown in (a) and (b) indicate options available generally

(a) Intersection Signalised Crossing (in this example, arrow legends point horizontally on the push buttons)



(b) Wide Midblock Signalised Crossing (in this example, arrow legends point upwards on the push buttons)



7.5 Positioning of Signal Equipment

The conspicuity of traffic signals is influenced by a combination of factors such as signal colour, intensity, size, background luminance and exposure time, as well as the location of the signal in the driver's visual field.

Figure 7.5(a) illustrates driver lantern visibility templates for use on signal layout design plans to determine if lanterns are located sufficiently close to the driver's line of sight. *Figure 7.5(b)* illustrates a typical application of a visibility template.

The number of signal posts should be minimised for safety and aesthetic reasons, e.g. pedestrian and vehicle signals can be mounted on a common post; or vehicle signals for different approaches can be mounted on a common post.

The recommended positions for signal posts and mast arms are detailed below. It is important that these positions satisfy the requirements of the Commonwealth Disability Discrimination Act 1992 and AS/NZS 1428.

Mast arms are rigid structures and they should only be located where the probability of impact by vehicles is low (AS 2979).

7.5.1 Lateral Post Positions

Kerbside posts and mast arms should be positioned nominally 1 metre from the kerb face, but not closer than 0.6 m.

Median posts should be located centrally in the median, or on wide medians, the post should not be located more than 2 m from the relevant kerb face.

7.5.2 Longitudinal Post Positions

7.5.2.1 Cross-Road Intersections (*Figure 7.1*)

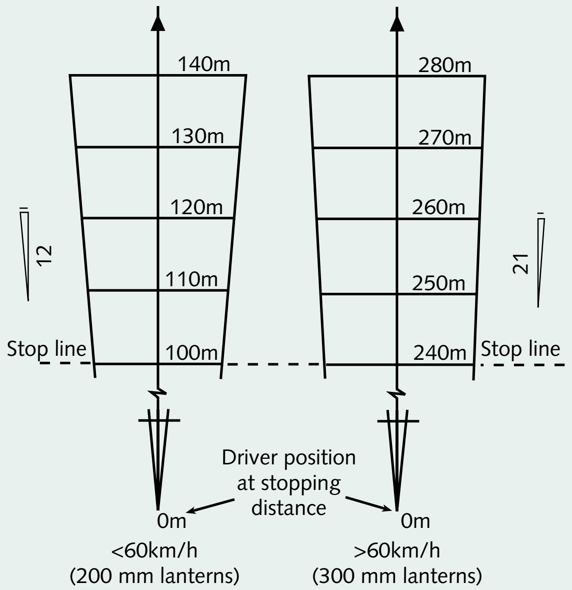
(i) **Primary Signal Faces**: Posts for primary and dual primary signal faces should be placed between the projection of the adjacent stop line and up to a distance of 3 metres downstream. They should not be placed upstream of the adjacent stop line (except as provided for in *Section 7.5.7 (d)*) or on the departure side of a signalised crossing. Posts should be placed not less than 1.2 m from an island nose.

(ii) **Secondary Signal Faces**: Secondary signal faces are usually placed on the primary post (or dual primary post if there is a median) of the opposite approach.

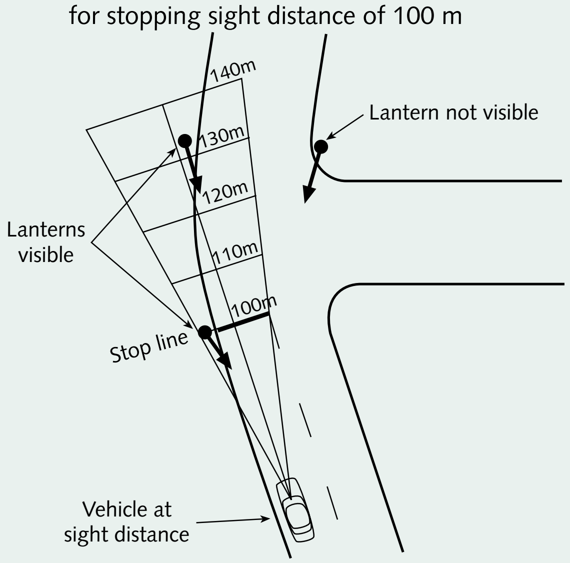
(iii) **Tertiary Signal Faces**: Posts for tertiary signal faces are preferably placed on the projection of the building alignment, or at the tangent point of the curve where large radius curves are used, or a minimum of 2 m from the corner and 1 m from adjacent edges of the triangular island formed by a separate left-turn lane.

Figure 7.5 Signal face visibility templates

(a) Visibility templates



(b) Typical application of visibility template for stopping sight distance of 100 m



7.5.2.2 Separate Controlled Lanes Within an Intersection

(i) **Primary Signal Faces**: Posts for primary and dual primary signal faces are located as described in *Section 7.5.2.1(i)* except that one of these posts should be located at least 6 m beyond the stop line to provide a starting signal (*Figure 7.6*).

Figure 7.6 Signal face location for channelised left-turn control

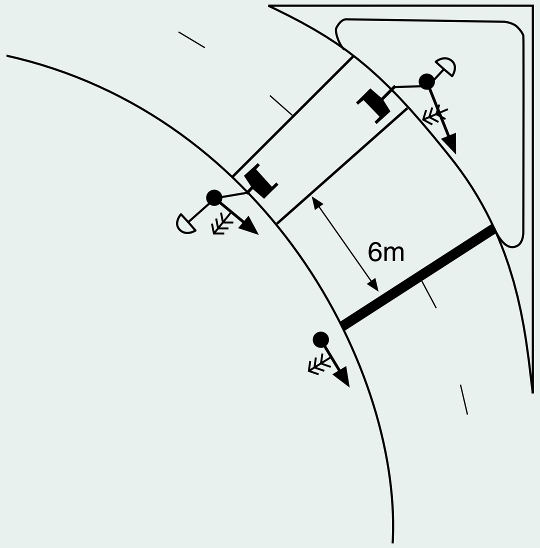
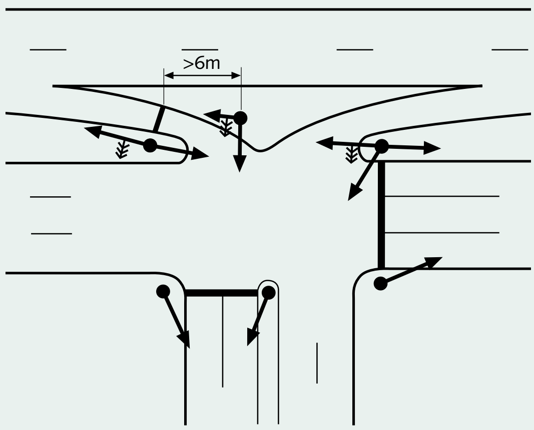


Figure 7.7 Signal face location for channelised right-turn treatment (seagull)



(ii) **Secondary and Tertiary Signal Faces**: Posts for these signal faces are located as shown in *Figure 7.6* to provide starting and/or manoeuvring functions. The provision of both secondary and tertiary signal faces may not always be required.

Where there is a separate departure lane and secondary and tertiary signal faces are provided, the posts should be placed either side of the separate departure lane to reduce the likelihood of driver error and incorrect manoeuvres (see *Figure 7.7*).

7.5.2.3 T-Intersections

(i) **Primary Signal Faces**: Posts for primary signal faces are located as described in *Section 7.5.2.1(i)*.

(ii) **Secondary Signal Faces**: Posts for secondary signal faces at the head of the T are located as described in *Section 7.5.2.1(ii)* but posts for secondary signal faces for the stem of the T are located to the right of the projection of the centre line but closer to the line of sight of the approaching motorist (*Figures 7.2(a) and 7.8(a)*).

The preferred location of the signalised crossing is to the left of the stem as shown in *Figure 7.8(b)*.

Figure 7.8(c) shows the relocation of posts for secondary and tertiary signal faces to allow a common post to be used with a pedestrian signal face.

(iii) **Tertiary Signal Faces**: Posts for tertiary signal faces are located generally as described in *Section 7.5.2.1(iii)* except that some adjustment is normally made to allow the common post to be shared with the secondary signal face for the stem of the T.

7.5.2.4 Midblock Signalised Crossings (*Figures 7.2(b) and 7.9*)

(i) **Primary Signal Faces**: Posts for these signal faces are located as described in *Section 7.5.2.1(i)*.

(ii) **Secondary Signal Faces**: For undivided carriageways, these signal faces are mounted with the primary signal face of the opposite approach on a common post. For divided carriageways, secondary signal faces are mounted with the pedestrian signal face on a common post located on the projection of the crosswalk line.

(iii) **Tertiary Signal Faces**: For both divided and undivided carriageways, these signal faces are mounted with the pedestrian signal face on a common post located on the projection of the departure side crosswalk line.

(iv) **Overhead Signal Faces**: If overhead signal faces are provided, the tertiary signal faces may be omitted.

Figures 7.9(b) and (c) show examples of dual carriageway signalised crossings. In the case of a narrow median, the secondary posts are located closer to the stop line in order to provide more space for pedestrians to wait and move in the median area.

Figure 7.8 T-intersection signal location

(a) Without Signalised Crossings

(b) With Signalised Crossing on the Left

(c) With Signalised Crossing on the Right

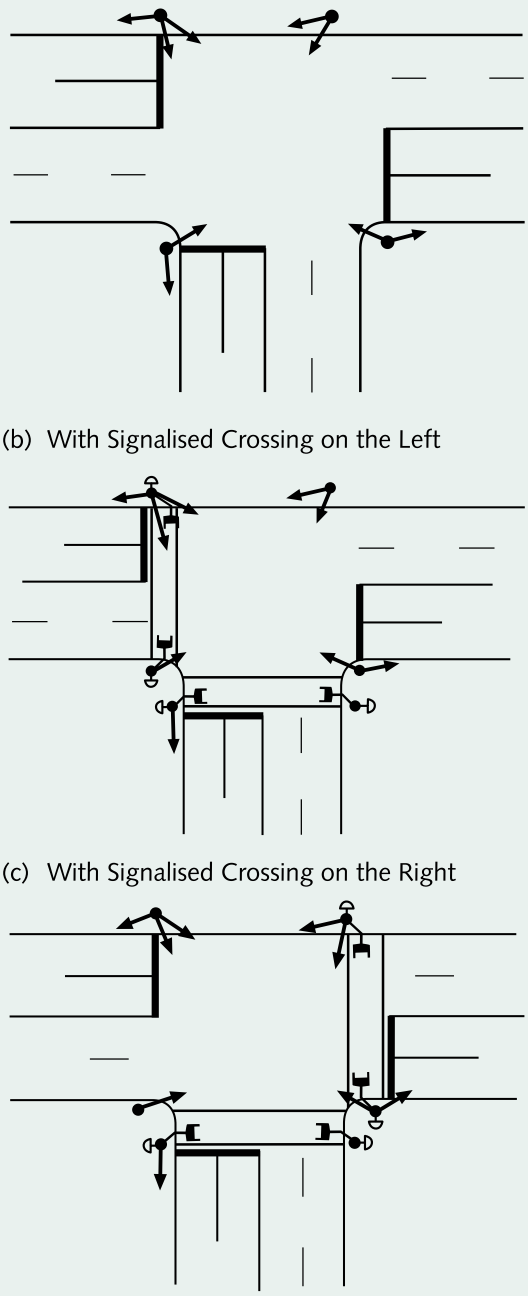
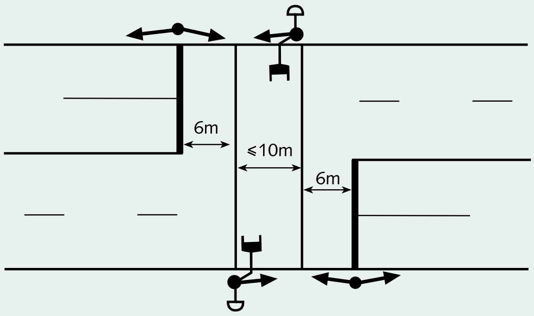
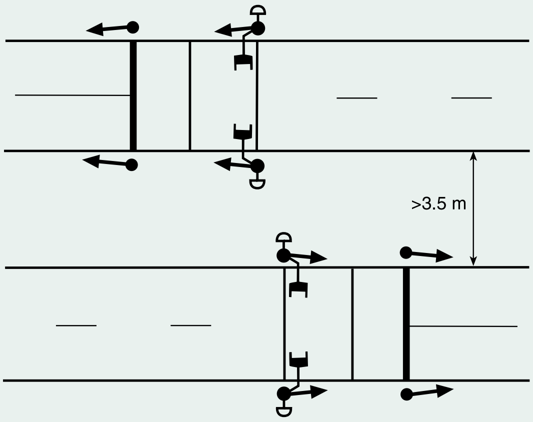


Figure 7.9 Midblock signalised crossings

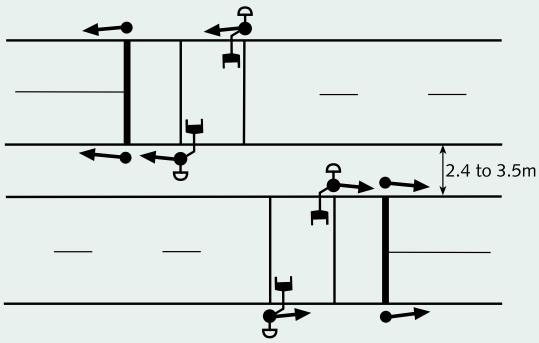
(a) One-stage Signalised Crossing



(b) Two-stage Signalised Crossing with Left-hand Offset: Wide-median



(c) Two-stage Signalised Crossing with Left-hand Offset: Narrow-median



7.5.3 Collision Risk Reduction

Studies by Fox, Good and Joubert (1979) show that poles at the intersection of major roads have the highest risk of accident involvement.

Accidents involving traffic signal equipment contribute substantially to maintenance costs and signal outages. Although traffic signal posts and controllers yield under impact, their location on the outside of curves or near exit or entry points should be avoided if possible.

For unyielding traffic signal mast arms or sign gantry posts, improvements to pavement skid resistance or location well back from the kerb may be necessary.

7.5.4 Lantern Mounting Heights

The mounting height is measured from pavement level to the top of the lantern body.

(a) Where possible all mounting heights should be 4.1 m. Where the lantern is required to be visible within 20 m (e.g. some starting or manoeuvring lanterns), the mounting height may be reduced to 3.2 m. Where reductions in mounting height are necessary to clear obstructions such as awnings, a minimum clearance to the target board of 2 metres must be maintained.

(b) For pedestrian lanterns the mounting height should be 3 m.

(c) Overhead lanterns should be mounted so that a clearance of 5.4 m to 5.8 m between the road surface and the bottom of the target boards is maintained.

Excessive clearance may result in the lantern being located too far above the driver's line of sight.

(d) Clearance from the ground to any lantern target board shall be not less than 2 m.

7.5.5 Clearances from Power Lines

Minimum clearances from overhead power lines to any signal equipment are specified by the electricity authorities. The required clearances vary depending on line voltage, line insulation and local electricity authority practices, therefore the local electricity authority should be consulted if equipment is to be located near power lines.

7.5.6 Lantern Aiming

(a) The visual range of each lantern is determined by its position, photometric performance and its orientation. *Table 7.2* shows the coverage provided by a lantern for various aiming distances.

(b) *Table 7.3* lists the recommended aiming distances from the stop line towards the centre of the approach lanes for stopping and for warning functions.

(c) Starting signals should be aimed at a point 3 metres from the stop line at the centre of the approach.

(d) Manoeuvring signals should be aimed at the centre of the stop line.

(e) A lantern should not be required to be seen from closer than 8 m.

Table 7.2 Visual coverage of lanterns

Aiming Distance (metres from lantern)	**Visual Coverage** Ground Mounted (metres from lantern)	Overhead
40	10 - 70	
60	25 - 95	
80	40 - 120	50 - 110
100	55 - 145	65 - 140
120	75 - 170	
130		90 - 170
140		105 - 195
150		125 - 225

Table 7.3 Recommended aiming distances

Approach Speed (km/h)	**Stopping** (metres from stop line)	**Warning**
40	40	80
50	60	100
60	80	130
70	100	150
80	120	170

7.5.7 Modification for Unusual Geometry and Other Physical Considerations

Alternative positions and/or additional lanterns may be provided where fixed obstructions such as poles, trees, awnings, underground services and background interference including illuminated advertising signs, or the intersection approach geometry are such that standard positions and numbers of lanterns are not adequate to carry out the required functions. These are illustrated in the following examples:

(a) Where the warning or stopping function of primary (or dual primary) lanterns is adversely affected on left-hand curve approaches, an additional lantern should be provided on the right-hand side of the road.

(b) Where it is not practicable to screen a lantern effectively from traffic for which the signal display is not intended (see *Section 4.2.2*), that lantern should be relocated or omitted.

(c) Where it is necessary to prevent a lantern from being seen by traffic at an upstream stop line, tilting of the lantern or other measures to limit the field of view can provide effective solutions. Some agencies tilt only the green face display as the confusion normally only occurs when green is displayed.

(d) Where a railway line is in close proximity to a signal installation, lantern screening and aiming arrangements must ensure that signals do not constitute a source of confusion to train drivers (see *Section 15.3.4*).

(e) Where a low bridge over an approach roadway obstructs visibility of the lanterns, an advance warning sign may be used (see *Figure 15.1*). When the bridge is adjacent to the intersection, an additional primary signal may be placed in advance of the bridge, not more than 10 m from the stop line.

7.5.8 Other Street Furniture

To reduce street furniture clutter, suitably located existing utility poles may be used for the mounting of lanterns, provided that agreement to do so can be obtained from the utility authority. A minimum 1 m clearance should be provided from lanterns to other separate street furniture items.

Where possible, streetlights and lanterns should be located on one common post or structure under a "joint use" arrangement with the local electricity authority. The use of common posts for mounting guide signs and signal hardware is encouraged (see *Section 11.2.1*).

7.6 Visors

Visors are used to modify the angular visual coverage of the lantern (e.g. to hide the lantern from the view of drivers on other approaches) and/or to shield the lantern optical system from incident light that may produce sun-phantom illumination (see *Figure 4.2* in *Section 4*).

(a) *Table 7.4* details the angle at which the signal is totally cut off from view for various visors.

(b) Cutaway visors are used to provide additional visibility on the cutaway side and standard cut off on the other side.

(c) Where no restriction of angular coverage is required an open visor should be used to shield the lantern from incident light.

(d) Closed visors are normally used on secondary and tertiary lanterns. The shorter closed visor should be used unless additional angular cut off is essential. The longer visors are also more difficult to protect from damage.

7.7 Louvres

Louvres are used when visors are unable to provide the necessary visual cut off. Their use should be minimised because louvres reduce the efficiency of the optical system and they produce reflected images that are visible under low ambient lighting.

(a) Louvres should not be used in association with symbolic aspects.

(b) Horizontal louvres are used to:

  (i) minimise sun-phantom illuminations where visors have proved ineffective,

  (ii) restrict the signal display coverage along the approach.

(c) Vertical louvres are used to:

  (i) produce the required signal display where the cut off provided by visors is inadequate (typically at skewed intersections),

  (ii) restrict the visibility of the signal display to a certain lane or lanes of the approach,

  (iii) shield the lantern from the view of train drivers or other persons in the vicinity of an intersection when it is desired that such persons should not be able to see the lantern.

Table 7.4 Cut off angles for visors

Lantern Size (mm)	Visor Type as per AS 2144	Length (mm)	Angle for Total Cut Off of Signal Indication
200	Open Type A	200	No restriction
200	Closed Type B	200	90°
200	Closed Type B	300	67°
200	Cutaway Type C	300	Open side see 7.6(b) 32° on Closed side
300	Open Type A	300	No restriction
300	Closed Type B	300	90°
300	Closed Type B	400	74°
300	Cutaway Type C	400	Open side see 7.6(b) 37° on Closed side

8. Traffic Detection

8.1 Introduction

An important aspect of traffic-responsive signal control systems is the detection of vehicle and pedestrian traffic demands in order to determine the signal displays required, their initiation and duration. For this purpose, detectors are used to register the presence and/or passage of vehicles and pedestrians.

Detectors can be grouped broadly as vehicle detectors, push-button (pedestrian) detectors and special detectors. Many types of detector exist including inductive loop, push button, microwave/radar, infrared, sonic, video image processing, magnetic and pressure. The most common detectors are the inductive loop detectors for vehicles and the push-button detectors for pedestrians. For general information on detectors, refer to FHWA (1996).

8.1.1 Traffic Detection During a Signal Cycle

Traffic can be detected at any time during the signal cycle. In this respect, there are two considerations:

(a) **Initial detection**: Arriving traffic (vehicle or pedestrian) faced by a red signal registers an initial demand (via a detection system) that it requires a green signal.

(b) **Subsequent detection**: Vehicle traffic approaching on a green signal registers (via the same detection system) that it requires the green signal to continue even though the initial detection may have been made by another traffic movement in the same phase.

The type and location of detection systems used determines the parameters of the initial and subsequent detections, and as a consequence the design and operation of traffic responsive signal control are determined.

8.1.2 Vehicle Detection Modes

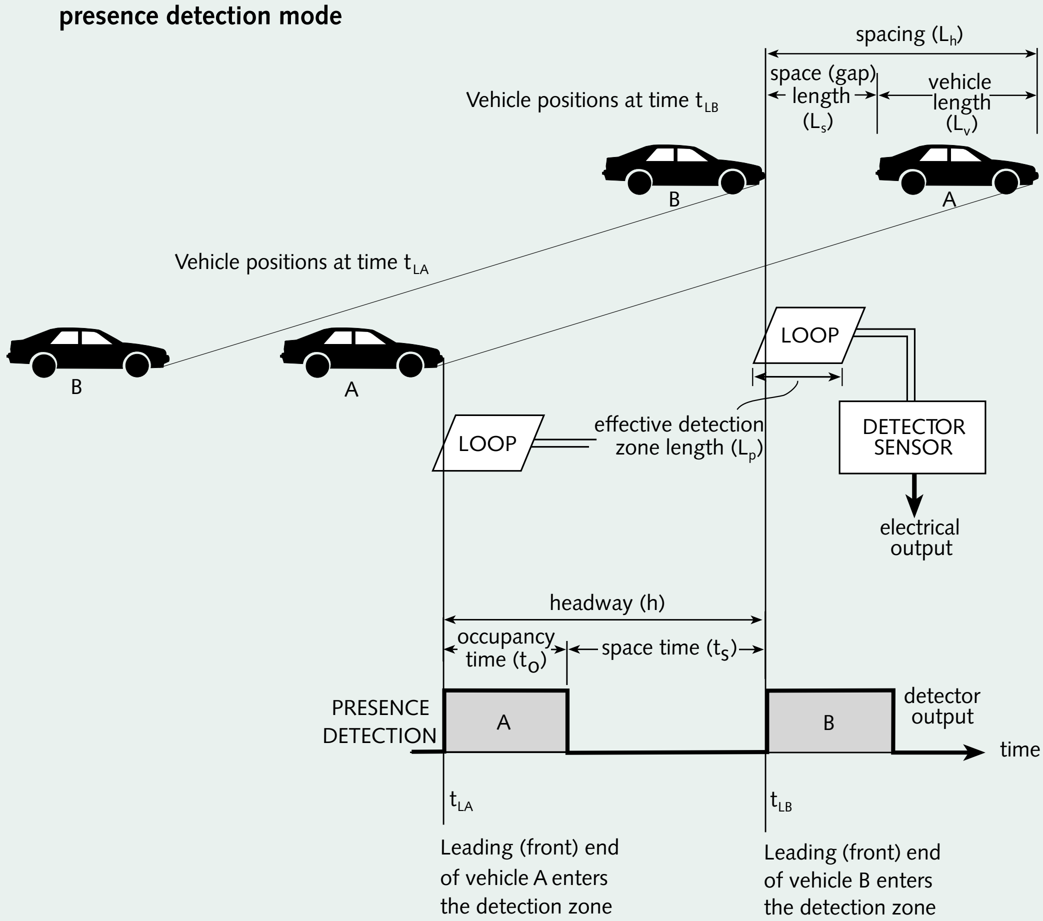
The sensor units for vehicle loop detectors have a switch to allow the detector to be operated in one of two modes.

(a) **Presence mode**: In this mode, the sensor unit produces a continuous output whenever a vehicle is in detection zone. The duration of the output (occupancy time) depends on the length and speed of the vehicle. Both moving and stationary vehicles can be detected in the presence mode.

(b) **Passage mode**: In this mode, the sensor unit produces a brief pulse when a vehicle enters the detection zone, thus detecting only moving vehicles regardless of their length or speed. Passage detection does not provide further pulses if stationary (or very slow moving) traffic occupies the detection zone.

Figure 8.1 shows basic traffic parameters relevant to measurements by a vehicle loop detector system in presence detection mode. These include spacing (distance), headway (time), occupancy time, space (or gap) time and distance, vehicle length, as well as the fundamental traffic parameters speed, flow rate and density, which are not shown in the figure. The definition of spacing and headway parameters with reference to the front ends of the leading and following vehicles is adopted in *Figure 8.1*. Relationships among basic traffic parameters are summarised in *Appendix B*. More detailed discussion on this subject can be found in Akçelik, Besley and Roper (1999).

Figure 8.1 Basic traffic parameters relevant to measurements by a vehicle loop detector system in presence detection mode



Passage detection can only allow a measure of headway time. The only additional information it can provide is the flow rate. Presence detection can provide more information, enabling more characteristics of the vehicle stream to be calculated. For example, besides indicating continuing presence of a vehicle, it allows determination of occupancy and space times, as well as parameters such as the SCATS DS (degree of saturation) (Lowrie 1982, 1990, 1996, 2001). Therefore, presence detection is the preferred type of detection for traffic manage-ment.

8.2 Types of Traffic

Systems are required to detect the following types of traffic:

(a) vehicles generally,

(b) pedestrians,

(c) special vehicles, i.e. buses, trams, bicycles, emergency vehicles (fire engines, ambulances) and trains.

Detection methods used for these types of traffic are discussed in the following sections.

8.3 Vehicle Detection

8.3.1 Detector Types

To satisfy the normal requirements of intersection control, detectors must have a clearly defined detection zone so that interference from adjacent lanes is low. Detectors that emit a broad beam of energy (e.g. microwave and infrared detectors) fail to satisfy this criterion.

Currently, the best type of detector that meets the detection requirements discussed in *Section 8.1.2* is the inductive loop detector. Although there are other types of detectors that satisfy these requirements, they are generally operationally or economically inferior in normal situations, and are not considered further.

Inductive loop detector systems vary mainly in the specification of detector location and size.

Abnormal situations or temporary detection requirements during road works or situations of road surface instability may be satisfied by use of microwave detector units.

Video image processing has found increased use overseas in recent years.

8.3.2 Detection System Functions

Vehicle detectors provide the following functions on a lane-by-lane or approach basis.

8.3.2.1 Demands for a Phase

Detectors initiate a demand for a phase, i.e. "call" a phase. This is usually done for vehicles waiting against a red signal. The demand can be a "locking call" in which case the call is only cancelled when the requested phase runs. The location of detectors for locking calls requires that only vehicles serviced by the demand phase be detected. Presence or passage detection mode can be used.

The demand can be a non-locking call, in which case the call is cancelled when the detector input is removed. Non-locking calls are used for approaches or lanes where the vehicle may leave the approach before the called phase occurs, for example:

(i) a right-turn phase is no longer needed when right-turn vehicles filter before the turn phase is displayed, or

(ii) a side-street phase is no longer required if the waiting vehicle turns left when a left-turn green arrow display occurs in the preceding phase (e.g. a three-phase T-intersection case with overlap left-turn and right-turn movements), or

(iii) where left turn on red is permitted.

Non-locking calls can be achieved by presence detection only. The detector loops must be located so that the vehicle waiting for the called phase is detected.

8.3.2.2 Conditional Demands

In some situations, a conditional demand is required to detect stopped or slow-moving traffic (see *Section 8.3.4.3*). A call is not registered until the detector is occupied for a minimum set time ("presence time"). The call may be locking or non-locking. Presence detection mode is required for conditional demands, and the length and location of the sensor loops is critical for this purpose.

8.3.2.3 Green Extension

Detectors are used to extend green displays when there is a continuous stream of approaching vehicles. The most common way of extending the green period is to compare vehicle space times with a preset "gap setting" (see *Appendix C*).

8.3.2.4 Strategic Functions

For traffic signals operating under wide area control systems (see *Section 13.4.3*), some detectors have a dual role:

(i) **Tactical**: to determine the demand and/or duration of phases in the same way as isolated traffic signals, and

(ii) **Strategic**: to provide information in order to enable computation of cycle length, phase splits and signal offsets for system control.

8.3.3 Loop Shape and Size

Loop size, which determines the detection zone, is dependent on two factors:

(i) **Longitudinal Response**: This is determined by the detection zone required along the roadway. The length depends upon the detection function required, and normally varies between 1 metre and 12 metres.

(ii) **Transverse Response**: This is determined by the transverse width of the detection zone required across the roadway. The width depends upon the dimension of the target vehicles to be detected and the width of the traffic lanes. The accuracy of target vehicle detection, in relation to the detection function required, also affects the loop width chosen.

Figure 8.2 shows different loop shapes, namely (a) rectangular, (b) symmetripole, (c) quadrupole, (d) slanted and (e) double diamond. *Figure 8.2 (a)* shows various applications of the rectangular loop, including its use in a single lane and across several lanes, as well as a loop swung at an angle of approximately 20 degrees to the direction of vehicular travel, which has been found to be effective in detecting cyclists (this application can also be used for symmetripole and quadrupole loops).

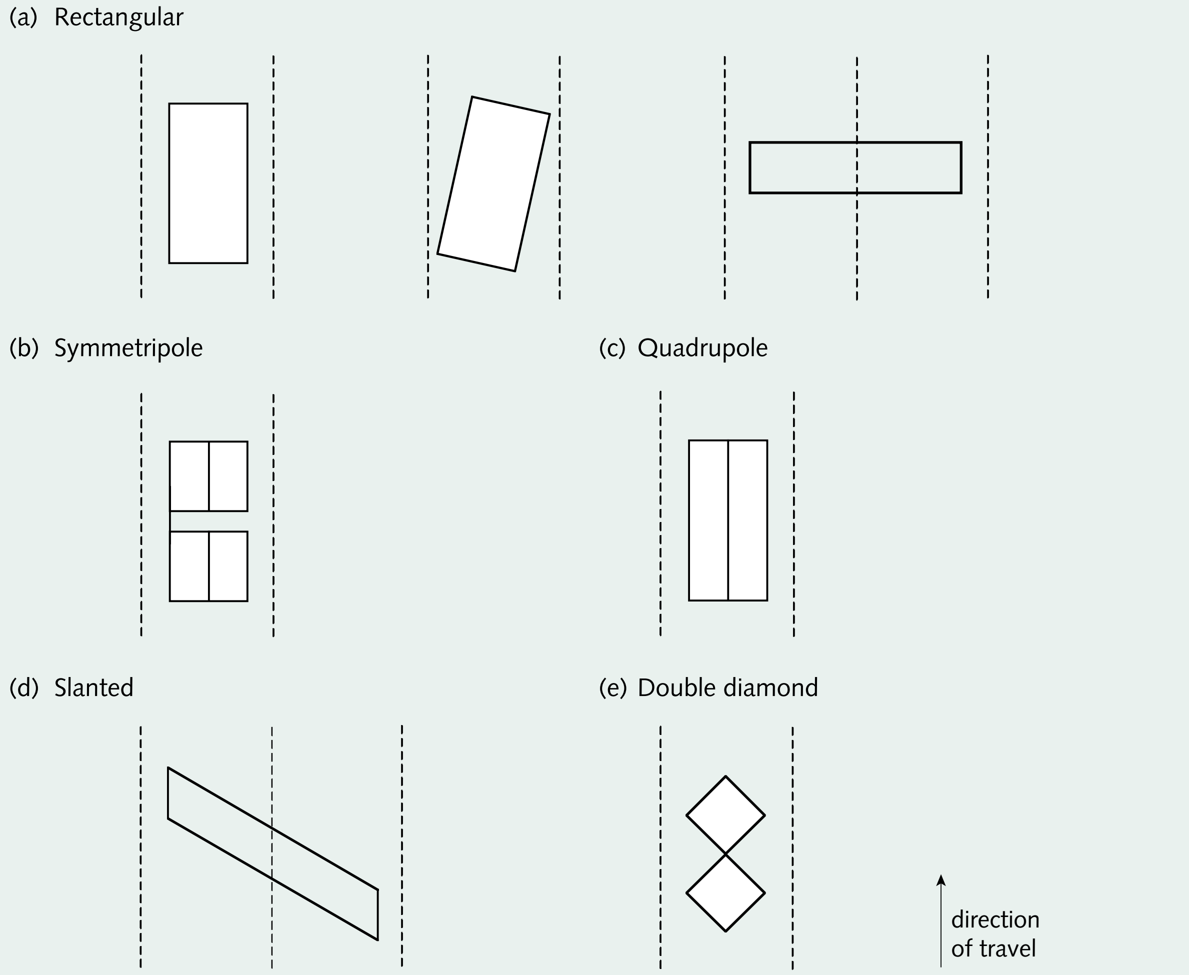
Hulscher and Sims (1974) examined the relative merits of the various configurations with respect to sensitivity, noise immunity, interference and similar performance parameters. The most common loop shape in use is symmetripole but some jurisdictions use a rectangular loop shape.

From electromagnetic considerations, the optimum loop size for presence detectors are the vehicle dimensions. However, as vehicles vary in size a compromise is necessary. To adequately detect small vehicles, a loop size of ten square metres is considered a practical maximum.

The sensitivity of detection within and between lanes is also determined by the shape and size of the loop. Length of the detection zone is not necessarily the same as the loop length due to fringing field effects (as affected by the sensitivity settings of the detector).

The efficiency of the detection system is maximised by providing one loop per lane. The dimensions and placement of loops affect performance and are discussed in the following sections.

Figure 8.2 Typical loop shapes



8.3.4 Location of Detectors

The location of the loop affects the functions that the detector is able to perform. The types of vehicle loop detectors used for traffic signal control include:

(i) stop-line detection,

(ii) advance detection, and

(iii) queue detection.

Based on a study of traffic signal control practice in Australia (Akçelik 1995a) as well as more recent experience:

(a) the setback distance for stop-line detectors is generally 1.5 m but ranges from 0.3 m to 2.5 m;

(b) the detector loop length used for stop-line detection is generally 4.0 m or 4.5 m, however recent research indicates that shorter loop length could be appropriate, especially for right-turn lanes (Akçelik, Besley and Roper 1999);

(c) in Queensland, loop lengths in the range 1.2 to 3.0 m have been used, and the current practice is 2 m loops at setback distances of 35-45 m for major roads and 6 m for minor roads.

8.3.4.1 Stop-Line Loop Detection

A detection system that employs stop-line presence detection on a lane-by-lane basis is the most common method used in Australia. This has been a result of the development of the SCATS wide-area traffic control system (Sims 1979; Sims and Dobinson 1979; Lowrie 1982, 1990, 1996, 2001).

Stop-line loops require greater sensitivity as slow-moving or stopped vehicles must be detected. The location of the loop in relation to the stop line must ensure that the normal stopping position of the first vehicle is in the detection zone.

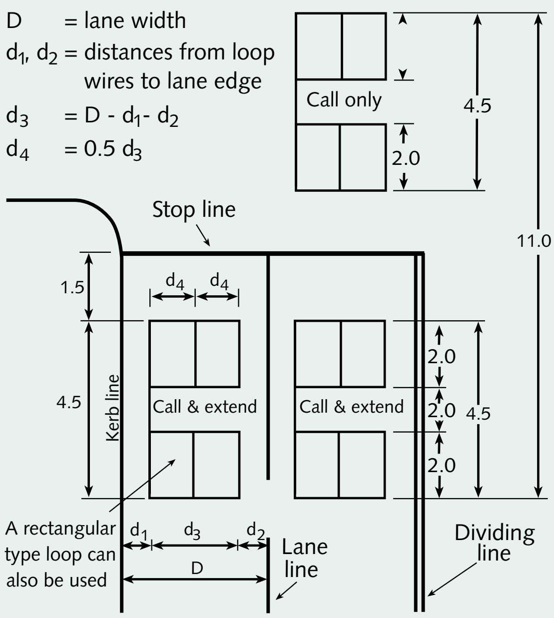
Figure 8.3 shows location and layout of 4.5 m and 11 m loops, and loop configuration. The lateral dimension of the loop should be derived from *Table 8.1* (Dean, Macdonald and Morris 1981) for each situation as indicated in *Figure 8.3*.

The 11 m detector may be used at locations where a shared or exclusive right-turn lane permits filtering and a right-turn phase is also provided (see *Figure 8.3*). In practice, the 11 m detector is split into two 4.5 m sections (designated approach and departure loops) that act together in some conditions and separately in others. Longitudinal position of 11.0 m detector may vary depending upon intersection geometry.

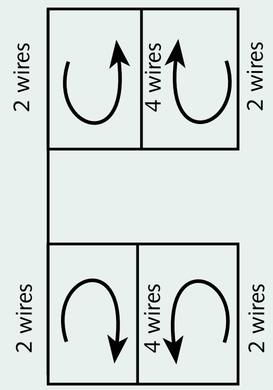
Detectors are not normally required in uncontrolled left-turn slip lanes for signal control purposes but may be installed to allow traffic to be counted.

Figure 8.3 Configuration and layout for stop-line loop

(a) Layout of 4.5 m and 11 m loops



(b) Configuration of loop



The two loop sections are wired in series and connected to one sensor

Table 8.1 Lateral dimensions of symmetripole loops

Spacing from Each Outer Wire of Loop to Lane Edge*			
		When Adjoining	
Lane Width (m)	General (m)	Median Strip (m)	Kerb Side (m)
2.5 - 3.0	0.74	0.55	0.83
3.0 - 3.5	0.73	0.54	0.82
3.5 - 4.0	0.72	0.53	0.81
4.0 - 4.5	0.71	0.52	0.80
4.5 - 5.0	0.70	0.51	0.79
5.0 - 5.5	0.69	0.50	0.78

* d_1 and d_2 in *Figure 8.3*.

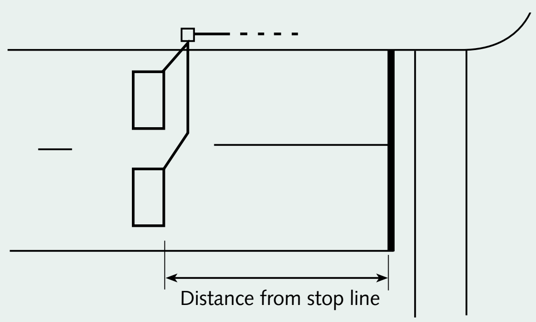
8.3.4.2 Advance Detection

In Australia, detectors located in advance of the stop line for the purpose of detecting moving vehicles are usually used on safety grounds, i.e. used at sites where approach speed is high and particularly when there is a large proportion of heavy vehicles. For this purpose, they should be located to suit the stopping distance required for the 85th percentile approach speed, where possible.

Advance detector loops are used in addition to the normal stop-line detectors. They can be set in presence or passage mode.

Advance detector loops are also used without stop-line detectors as shown in *Figure 8.4*.

Figure 8.4 Advance loop



Generally, advance detector loops are located at a distance from the stop line that corresponds to the actuated signal gap setting. Under free-flow conditions, advance loops are able to terminate phases earlier, since assessment of gaps can be made several seconds before it can be detected at the stop line. The following considerations also apply to advance detector loops:

(i) they are not as effective as stop-line detectors in identifying turning movements if placed upstream of exclusive turning lanes,

(ii) demands lodged are processed on the assumption that vehicles do not change lanes or turn off before reaching the stop line,

(iii) vehicles entering the roadway between the detector loop and the stop line are not detected, or vehicles leaving the roadway between the detector loop and the stop line are detected unnecessarily.

8.3.4.3 Queue Detection

Presence detectors, in conjunction with a presence timer, may be used to detect queues of excessive length. A "presence time" is set, e.g. 5 seconds, and when the loop is occupied for longer than this set time, a demand is registered.

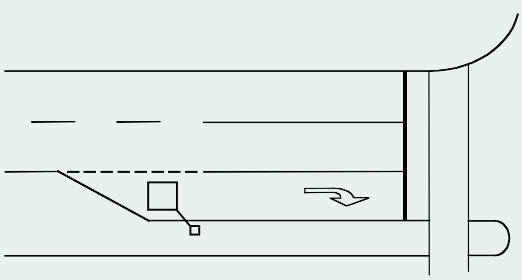
Applications of queue detection include:

(a) registering a demand for a right-turn phase by determining if the queue is too long to filter adequately (see *Figure 8.5*);

(b) detecting critical storage conditions that require the cessation or introduction of certain phases, for example:

- (i) traffic blocking the middle of a major intersection,
- (ii) queues on freeway off-ramps that are likely to overflow onto the freeway,
- (iii) queues on or near a railway level crossing;

Figure 8.5 Use of queue loop for demanding a right-turn phase



(c) use of roundabout metering signals to create gaps for roundabout legs with excessive queuing (see *Figure 15.3* in *Section 15.7*) where the main approach contributing to the circulating stream causing the queuing problem ("metered approach") is stopped by a red signal when the queue reaches the advance queue loop on the "controlling approach" (Akçelik, Chung and Besley 1998); and

(d) use of part-time metering signals at sign-controlled intersections to create gaps in major road traffic to reduce excessive delays experienced by vehicles on the sign-controlled approach by stopping the major road traffic using a queue detector on the sign-controlled approach (*Section 15.13*).

8.3.5 Operational Characteristics of Loop Detectors

In previous sections, only the principal characteristics of presence and passage detection have been discussed. For satisfactory performance, other operational parameters of loop detectors may need to be considered. These include sensitivity, paralysis time, response delay and other factors that are beyond the scope of this guide. Further details concerning operational requirements can be found in Hulscher and Sims (1974).

Figure 8.3 illustrates the recommended loop layout and configuration for stop-line detectors. The derivation of the loop configuration (symmetripole) is given in Dean, et al (1981). The transverse spacing between the outer loop conductors and the lane boundary must be chosen to minimise:

(a) unwanted detection of vehicles in the adjacent lane (overcounting); and

(b) the number of undetected vehicles, especially two-wheeled traffic which do not travel through the loop's detection zone (undercounting).

The optimum transverse spacing is achieved when overcounting errors are equal to undercounting errors.

Similarly, the gap between the two sections comprising each 4.5 m loop must be kept to a minimum to give good longitudinal response for all classes of vehicle. However, the smaller this gap is made, the more overall sensitivity is reduced. A spacing of 0.5 m (as shown in *Figure 8.3a*) is a good compromise figure.

8.4 Pedestrian Traffic Demands

8.4.1 Pedestrian Detection

Push-button detectors are the most common detectors for pedestrians. To register a demand, a pedestrian must actuate the appropriate pedestrian push button. When the button has been pressed an illuminated panel (pedestrian indicator), when present, may be used to indicate to the pedestrian that the demand has been recorded by the controller. The illuminated panel switches off when the demand is satisfied.

Audio-tactile push buttons should be used where needed by visually-impaired or elderly pedestrians (Hulscher 1976).

Additional detectors in the footpath or overhead (usually infrared or microwave) may be used to detect the presence of pedestrians on the crossing and to modify the duration of the Walk or Clearance (Flashing Don't Walk) intervals, e.g. Puffin crossings.

8.4.2 Automatic Introduction of Pedestrian Movements

In addition to push-button detection, controllers may also be set to register a fixed demand for any pedestrian movement so that the movement runs each cycle. This should only be considered where the pedestrian volumes are high and the cycle time is long enough to accommodate all phases with pedestrian movements. Automatic introduction may be invoked by time of day, or on the condition that the coordinated signal cycle time exceeds a certain value.

8.4.3 Push Button Location

(a) **General**: Pedestrian push buttons are normally mounted on traffic signal posts or mast arms. The push buttons shall be located at each end of the signalised crossing and at each pedestrian refuge. Consideration should be given to provision of a push button on any median island signal post.

Typical locations of push buttons are illustrated in *Figure 8.6*. They should be located so as to be clearly visible to approaching pedestrians and should not be obstructed by other road or footpath furniture.

(b) **Height**: The push button should be mounted at a height of 1m ± 0.1 m from the ground.

(c) **Orientation**: Where provided, pedestrian push buttons shall be orientated as follows (see *Figure 8.6*):

   (i) Orientated at the kerbside so that it is either perpendicular to the signalised crossing and facing away from the crossing, or parallel to the crossing and facing towards pedestrians about to use the crossing. Orientation according to one or other of these options should be consistent throughout the region.

   (ii) In narrow medians, one push button may be mounted on the median post with its face parallel to the signalised crossing.

(d) **Arrow Legends**: An arrow legend should be included on the face of the push-button assembly. This is used to give guidance to people with visual disabilities. The arrow should point towards the associated crosswalk lines as shown in *Figure 8.6*.

   (i) Where the face of the push button is at right angles to the direction of the associated cross-walk lines, the arrow legend should point up to indicate a straight ahead walk direction.

   (ii) Where the face of the push button is parallel to the crosswalk lines, the arrow legend should be horizontal pointing in the direction of the associated signalised crossing.

   (iii) Where one push button is mounted in a narrow median, the arrow legend should have a horizontal double-headed arrow. The face of the push button should be parallel to the crosswalk lines.

(e) **Distance from Signalised Crossing**: The push button should be located not more than 1 m outside the projection of the signalised crossing nor more than 2 m back from the kerbline at the signalised crossing.

(f) **Push Button Posts**: A special push button post should be installed if no traffic signal post can be located in a suitable position.

(g) **Audio-Tactile Buttons**: These shall not be closer than 2 m from one another (AS 1742 Part 14). For this reason, two push buttons on one pole is not suitable for audio-tactile push buttons.

8.5 Special Traffic Detection

Special detection methods are used for particular types of traffic including buses and trams (see *Section 15.5.3*), bicycles, emergency vehicles and railway traffic.

8.5.1 Buses

Normal loop detectors may be used for bus detection where "Bus Only" lanes are provided. Where buses share lanes with other traffic, one technique used involves an "on-bus transponder/transmitter" which is a device fitted to the bus. This identifies the presence of a bus to a roadway sensor. In some applications, a bus is detected only when such device is actuated by the driver.

Other techniques may be used which utilise:

(a) combinations of detectors which either identify the bus by its length or its height above the road surface; or

(b) classification detectors which identify the bus by special loop detectors.

8.5.2 Trams

Three methods of tram detection are currently in use:

(a) **Loops**: Trams in a dedicated lane may be detected by inductive loops placed between the rails. They may produce passage or presence actuations.

(b) **Transponder/Transmitter Systems**: In a mixed traffic lane, inductive loops do not uniquely identify trams. Transponder or transmitter systems as described in *Section 8.5.1* for buses can be used.

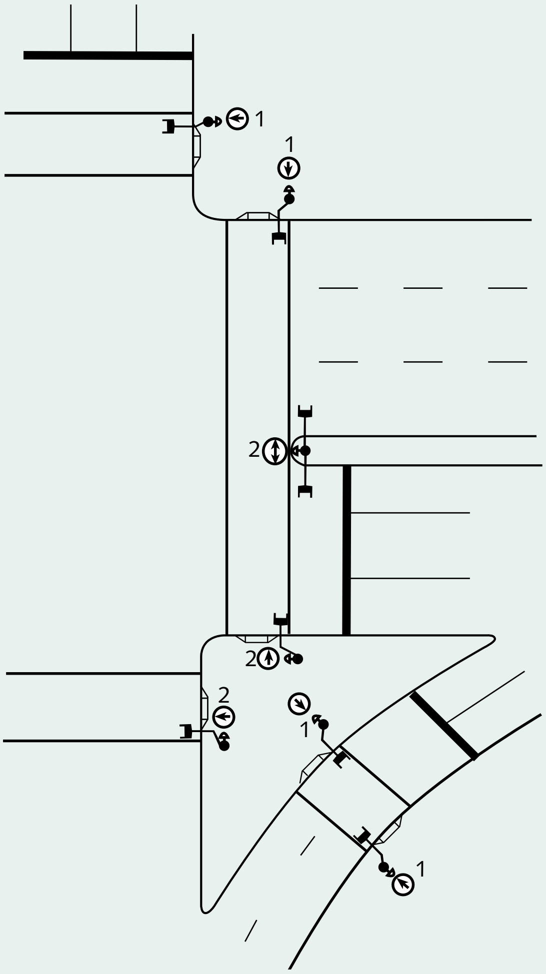
(c) **Skates**: Skates are overhead contacts in the energy supply lines to the tram. As the tram pickup passes, a momentary isolated contact closure is transmitted to the controller. These perform a locked call function only.

8.5.3 Bicycles

When separate bicycle lanes are provided and bicycle detection is required, loop detectors with very sensitive loop arrangements spanning the whole width of the bicycle lane are necessary. An evaluation of inductive loops for bicycle detection has been reported by Leschinski (1994).

Where bicycle traffic shares lanes with other vehicles, it is not possible to ensure detection of bicycles due to their narrow width. In this case, push buttons may be provided in special positions to assist bicycle riders to lodge a demand.

Figure 8.6 Push button location and orientation



1 Arrow legends point upwards on these push buttons

2 Arrow legends point horizontally on these push buttons

8.5.4 Emergency Vehicles

Emergency vehicles can be selectively detected through a transponder/transmitter fitted to the vehicle. The appropriate authority provides the necessary advance warning of the approach of the vehicle and special arrangements are made to ensure their prompt passage.

When emergency vehicle demands are recorded by a controller, existing displays are terminated safely and a special priority traffic phase is introduced and maintained until the demand is removed.

8.5.5 Emergency Service Demand

Emergency service demands are normally recorded by push buttons. Typical applications involve signals in close proximity to fire stations and ambulance depots. The emergency service may require a green movement of fixed duration within a fixed time of the demand being made, or they may be prepared to wait for the required movement and move off when indicated by the control equipment.

8.5.6 Railway Traffic

Where railway level crossing signals are coordinated with road traffic signals, the usual sequence of operations is as follows (see *Section 15.3*):

(i) traffic queued across the line is cleared,

(ii) vehicles crossing the railway line are stopped, and

(iii) if the intersection signals have not reached a safe display by the time railway signals begin to operate, then the intersection signals are switched to flashing yellow.

The precise method of operation required should be obtained from the local rail authority.

Common inputs from the level crossing control equipment are:

(a) Call - activated when the train reaches a point approximately 35 seconds upstream of the crossing,

(b) Release/Force - goes off when the train activates the level crossing and on when the booms are nearly vertical,

(c) Pre-Release - indicates when the train is clear of the crossing and the booms start to rise,

(d) Booms Horizontal - indicates that the booms are horizontal, and

(e) Cable Monitor - permanently on to indicate that the cable is intact.

The time between the Call and Force inputs (35 seconds) is based on whether the train is a stopping or an express train, and the approach speed of the train. It allows for the termination of all pedestrian and vehicle movements in the running signal phase, transition to a track clearance phase, and then starting a phase that does not conflict with the train movement(s), before the railway level crossing signals start operating.

9. Signal Controllers

9.1 General

The traffic signal controller is the equipment (including the housing) that switches power to the signal lanterns and controls the duration and sequence of signal displays. This equipment is placed in a ground-mounted housing or a post-mounted housing.

Figure 9.1 illustrates how the controller interfaces to the other components of the signal system. The physical characteristics of the controller are specified in AS 2578.

9.2 Types of Control

Operation of a traffic signal controller depends on the type of control used. Different types of signal control for isolated (non-coordinated) intersection operation are discussed in this section. For further discussion, refer to RTA NSW (1991, 1992), FHWA (1996), and Akçelik (1995b).

Types of coordinated signal operation are discussed in detail in *Section 13.4*.

9.2.1 Traffic-Actuated Control

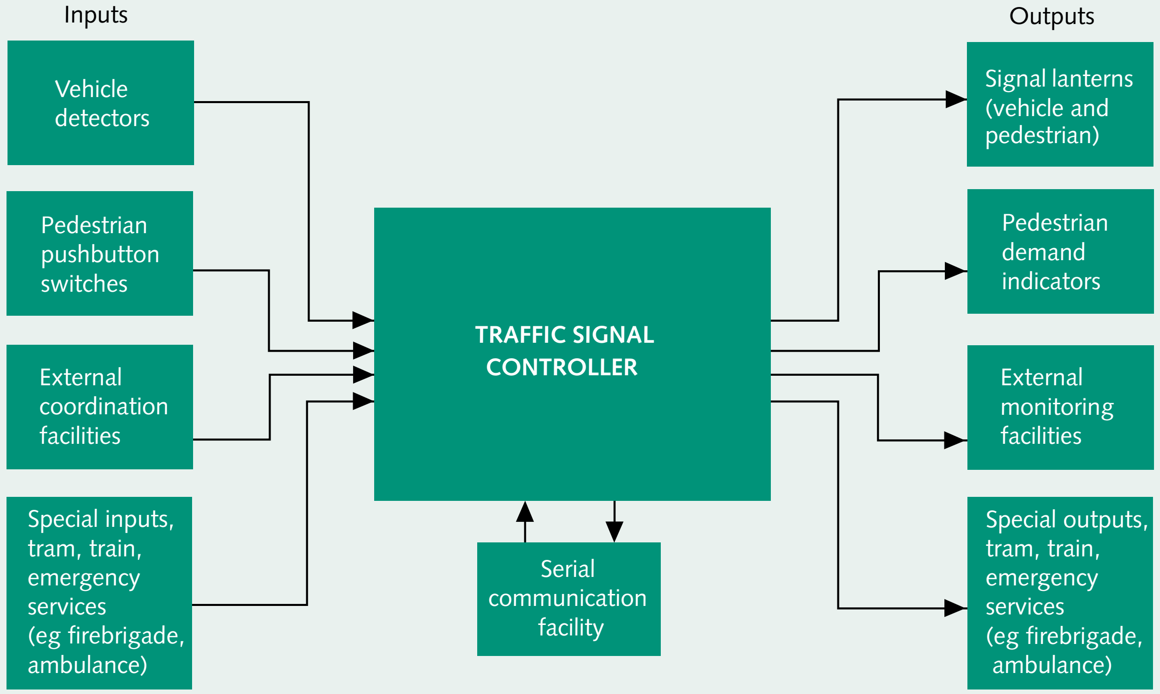
Traffic-actuated control allows a variable sequence and variable duration of signal displays depending on traffic demands. This type of control is also referred to as "fully actuated" since all movements (phases) are actuated in contrast with "semi-actuated" control described in *Section 9.2.3*.

Although fully-actuated control has been the most common type of control traditionally, the use of "SCATS Master Isolated" control described in *Section 9.2.2* has found increased use in Australia.

9.2.2 SCATS Master Isolated Control

Where an intersection controller is linked to a SCATS regional computer (Lowrie 1982, 1990, 1996, 2001), it may be run under normal fully-actuated control or SCATS Master Isolated (SMI) control as alternative forms of isolated (non-coordinated) control.

Figure 9.1 Typical interfacing requirements for traffic signal controllers



SMI control works in the same way as fully-actuated control except that maximum green times are determined by the regional computer (subject to a maximum cycle time using SCATS green split algorithms) on a cycle-by-cycle basis according to varying demand conditions. As a result of this, SMI control offers advantages over traditional fully-actuated control (Akçelik, Besley and Chung 1998).

9.2.3 Semi-Actuated Control

In this type of control, usually only minor movements (e.g. side road traffic) are actuated. Non-actuated phase (usually major movement) receives minimum green duration, but green period is extended indefinitely until an actuated phase demand is received. Midblock signalised crossings with pedestrian actuation only, i.e. where the vehicle movements are not actuated, are of this type.

9.2.4 Fixed-Time Control

Fixed-time control provides only a fixed sequence and duration of signal displays. This is rarely used in Australia, because of its inefficiency and lack of flexibility.

Coordinated signal control has some elements of fixed-time operation, e.g. using a specified cycle time for all intersections in a common coordination area (*Section 13*).

9.3 Selection of Appropriate Control

The selection of signal control appropriate for a particular site is based upon the following criteria:

(a) facilities,

(b) capacity,

(c) operation and maintenance, and

(d) cost and availability.

9.3.1 Facilities

The various control facilities available in the signal controller determine the nature, duration and sequence of signal displays.

As the number of control facilities required increases, the controller logic becomes more complex.

9.3.1.1 Sequence Selection Facilities

(a) **Fixed sequence**: This provides for a fixed duration of signal display to be allocated to each approach cyclically. The sequence never changes, and this is the minimum sequence facility available.

(b) **Skipped sequence (traffic actuated)**: This sequence provides for automatically altering the duration of signal displays in accordance with the measured traffic demands. Phases or groups are designated to run in a predetermined sequence. Phases can be skipped if there is no demand for them when it is their turn in the sequence.

(c) **Variable sequence**: This provides for phases to be run as soon as possible in the sequence subject to a priority of movements and termination of conflicting groups. Rather than use predetermined data, this system uses the most recently measured traffic data, fed into the system via traffic detectors. This sequence facility is available in the most recent microprocessor-based signal controllers.

(d) **Priority sequence**: This provides for the abrupt insertion of a phase into the sequence, e.g. in response to a train, tram or bus demand.

(e) **Forced sequence**: This provides for a sequence of phases to be determined by a master controller and/or external logic. This facility is required in most coordinated and other master controlled systems.

9.3.1.2 Display Duration Facilities

(a) **Fixed duration**: The duration of the display is fixed.

(b) **Traffic actuated**: The duration of the display is determined by the actuations of the vehicle detectors and pedestrian push-button detectors associated with that phase. This facility is available in most controllers in various degrees of complexity.

(c) **Traffic responsive**: The duration of the display is determined by the traffic demands on all approaches of the intersection. This facility is not yet commercially available in isolated controllers.

(d) **Master controlled**: The duration of the display is determined by signals/commands from a master computer or other coordination devices.

9.3.1.3 Coordination and Communication Facilities

These facilities are determined by the coordination requirements and/or area traffic control system such as SCATS (Lowrie 1982, 1990, 1996, 2001) within which the intersection must operate. Some possible facilities are:

(a) time of day linking (synchronous or cableless linking),

(b) linking by dedicated cable,

(c) serial communication (telephone cable, radio).

These facilities are discussed in detail in *Section 13*.

9.3.2 Controller Capacity

The controller capacity required is determined by the number of signal groups which must be switched, and the number of detector and push button input circuits. These requirements can be determined from the intersection geometry and the phasing design. Spare capacity may be required for future expansion of the intersection phasing.

9.3.3 Controller Operation and Maintenance

When selecting a traffic signal controller, consideration should be given to the operation and maintenance requirements of each type. The staff required for these purposes, must be familiar with controller type. For new controller types or controllers installed in remote areas, consideration needs to be given to the ability of staff to operate and maintain the controllers. Arrangements may need to be made for training, operations support and spare parts for maintenance.

9.4 Controller Programming

The task of configuring a controller to the specific requirements of a particular site is known as adaptive engineering. Each controller has a unique program called a "personality" which configures the controller to the specific operational design of the intersection or midblock device it is controlling. Traffic signal controllers can also be used to control overhead lane signals, ramp-metering signals, metered roundabouts and similar devices.

Where two devices are very closely spaced, there can be advantages in using one controller for both devices, provided the controller has sufficient signal groups. This reduces installation and recurrent costs, and guarantees traffic progression (offsets) between the two devices, but increases the complexity of the personality.

The personality specifies which signal groups run in each phase, the sequence of phases, detector functions, detector alarm conditions and default time settings. Signal groups can be controlled conditionally within a phase, e.g. in a diamond overlap phase (see *Section 6.3*) or completely independently of the phasing, e.g. slip lane vehicle and pedestrian groups. Where there are unusual operations, such as a railway interlink, the personality logic can be quite complicated.

9.5 Preventing Hazardous Displays

Hazardous displays arise from failures in the mechanisms that switch power to the signal lanterns. These hazards can be minimised by interlocked switching and/or conflict monitoring.

The general principle is that if a signal group is showing green when it should not, then conflicting signal groups are forced to red.

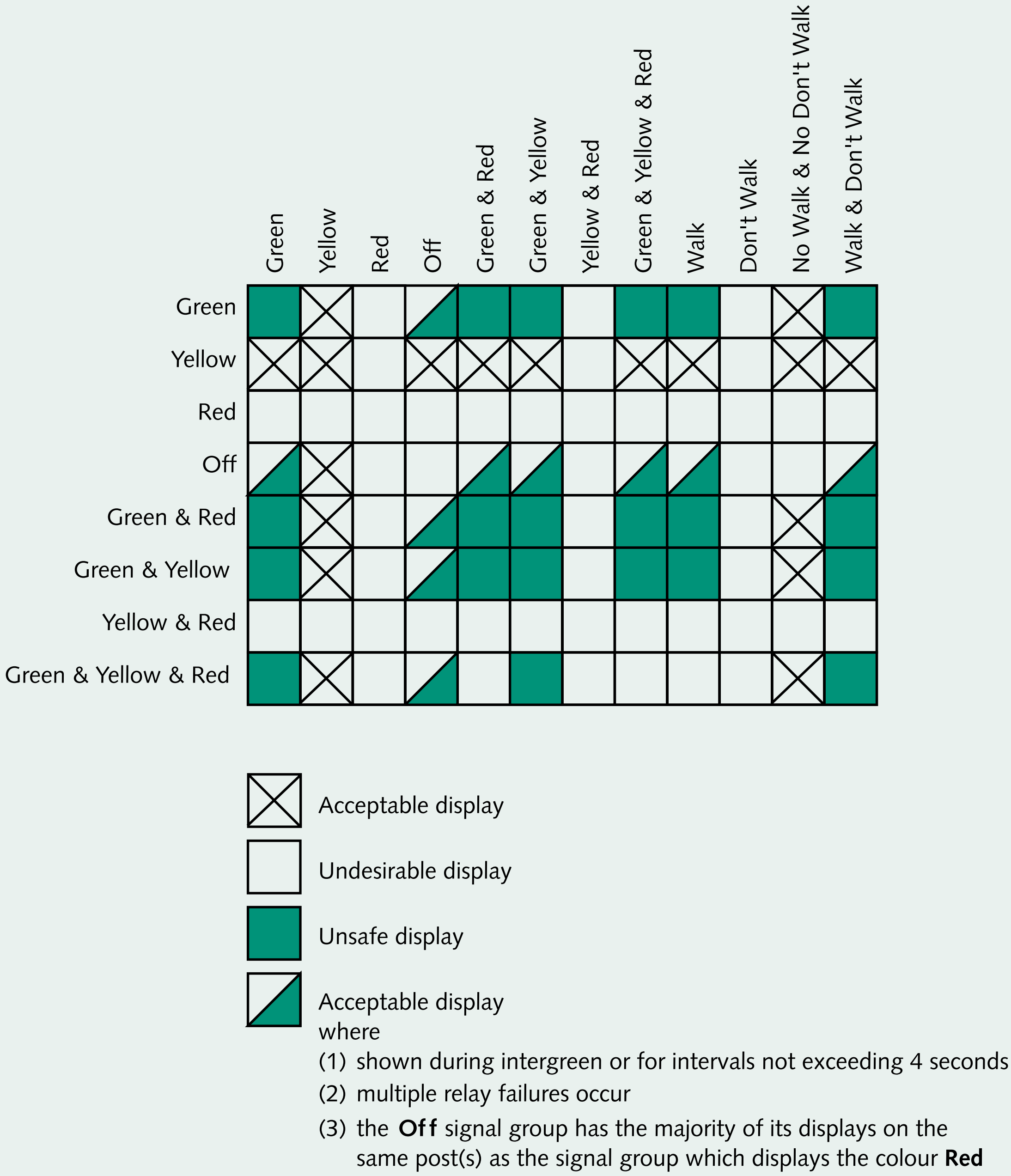
Interlocked switching is used with relay switching of lamp circuits. Switching a green to one signal group will open the circuit to conflicting green signal groups and close the circuit to the red of these signal groups.

One method of interlocking signal groups is effected by connecting relay contacts in series to create a "chain" from the lamp active supply to the green feeds of the signal groups. When a signal group is switched to green, the green feed to signal groups lower down the chain is open circuited (green interlocking). The groups which are higher in the chain must ensure the red is displayed for groups which are lower in the chain (red interlock). Signal groups which are designed to have an **Off** display should be in the lowest positions in the chain. They do not require a red interlock as this would override the off display.

Conflict monitoring is mandatory where solid state lamp switching is used. The circuits to the signal group colours should be monitored as closely as possible to the controller output terminals. The state of each circuit is compared with a table of conflicting signal groups specified in the personality so that unsafe displays are avoided.

A detailed study of the techniques used is beyond the scope of this guide. *Figure 9.2* indicates the acceptable, undesirable and unsafe lantern displays. The adaptive engineering required is equipment dependent.

Figure 9.2 Safety of signal displays



10. Pavement Markings

10.1 General

This section provides information on pavement markings used at signalised intersections. It contains additional and supplementary data to that contained in AS 1742 Part 2 and AS 1742 Part 14, and Austroads GTEP Part 5 (Intersections at Grade). In New Zealand, reference should be made to the Manual of Traffic Signs and Markings, Part II (Transit New Zealand and Land Transport Safety Authority 1997).

Pavement markings at traffic signal installations are subject to constant wear by turning and braking traffic, and they are often obscured by general traffic. Therefore, they must be properly maintained for effective and safe operation of signals.

10.2 Longitudinal Lines

10.2.1 Dividing Lines

Unbroken dividing lines are marked on the roadway to separate opposing traffic movements on the approaches to signalised intersections and midblock signalised crossings on undivided roads.

An unbroken dividing line may be a single unbroken line or a parallel pair of unbroken lines. Both types of dividing lines prevent overtaking. A single unbroken line may be crossed to enter or leave the road, but a parallel pair of unbroken lines may not be crossed to enter or leave the road unless a local jurisdiction road rule permits.

Normally dividing lines should be provided for a minimum of 30 m in approach to the stop line (see *Section 10.3.1*). This length may be extended if road conditions on an intersection approach require it.

10.2.2 Lane Lines

On the immediate approaches to traffic signals, the use of lane lines is essential where the approach width will accommodate two or more traffic streams. Lane lines are generally broken lines but must be unbroken where lane changing is to be prohibited on the approach.

10.2.3 Turn Lines

Turn lines are used to provide guidance for two or more traffic streams turning in the same direction. Turn lines are not used for single turning movements unless in their absence, opposing right turns would be in danger of colliding, or the turning path to the departure is not obvious under all conditions.

Where opposing right-turn movements operate in the same phase, care must be taken with positioning turn lines so that sufficient swept width is provided for each vehicle and a sufficient gap is left between opposing turning traffic. The use of Austroads turning path templates can assist with positioning and determining the radii of turn lines (Austroads 1995). It is suggested that a gap of 1.2 to 2.0 m is provided between the overhang lines of the Austroads templates. At major urban intersections with double right-turn lanes from opposite directions, it is necessary to select the design vehicles for the turns, e.g. car and semi-trailer from both directions.

Turn lines should not be carried through pedestrian crosswalks.

10.3 Transverse Lines

10.3.1 Stop Lines

Stop lines indicate to drivers the point behind which vehicles must stop when required, e.g. during the red interval. Where approach speeds are 80 km/h or above, lines 600 mm wide are preferred, elsewhere lines 300 mm wide may be used.

To minimise the controlled area, stop lines should generally be located as follows:

(a) Intersections with signalised crossings: 1.2 m to 2.0 m desirable (0.6 m minimum) in advance of and parallel with the crossing. This distance is increased where bicycle head-start storage areas are provided (see GTEP Part 14).

(b) Urban intersections without signalised crossings: generally at or just in advance of the primary signal post, and not less than 1 m from the kerbline projection in the intersecting street except as provided for in (c). Additional clearance from the kerbline may be required for occasional pedestrian movement.

(c) Rural Intersections or intersections without kerbing on high-speed approaches: 3 m to 5 m clear from the nearest point of conflict with cross traffic and upstream of the primary traffic signals.

(d) Midblock Signalised Crossings: nominal 6 m in advance of crossing, but not less than 10 m in advance of secondary signal.

10.3.2 Pedestrian Crosswalk Lines

The signalised crossing should be at least 2 m wide and delineated by two parallel lines.

This width should be increased when there are heavy pedestrian volumes. The line nearest the centre of the intersection should be not less than 0.6 m (desirably 1.0 m) clear of the cross street kerbline projection. For scramble crossings (*Section 11.3.4*), the lines nearest the centre of the intersection are removed, and in some jurisdictions, diagonal lines connecting opposite corners of the controlled area are used.

Signalised crossings should generally follow the shortest route across the carriageway, or be angled at no more than 20 degrees to the pedestrian's shortest route.

Pedestrian (Zebra) crossings defined by parallel white stripes on the road surface and two "Walking Legs" signs (*Section 11.3.14*) are not used within the controlled area of signalised intersections. However, some jurisdictions use Zebra crossings at unsignalised slip lanes at signalised intersections.

10.4 Painted Medians and Islands

Painted areas (see *Section 3.5*) may be line-marked to prevent or permit vehicles to cross the area:

(a) A single broken outline will permit vehicles to cross the median or island to overtake vehicles, enter an abutting property, or enter the road from an abutting property.

(b) A single unbroken outline will prevent overtaking, but enable a vehicle to cross the median or island to enter a turn bay, enter an abutting property, or enter the road from an abutting property.

(c) Double unbroken outlines will prevent overtaking, turning to access an abutting property, entering the road from an abutting property, or crossing the painted area to enter a turn bay.

Traffic signal posts must not be placed in the painted areas, and should always be located behind raised kerbing.

10.5 Pavement Messages and Symbols

The use of pavement messages and symbols should be minimised in advance of signalised intersections. They may be hazardous if placed in the path of braking traffic. Where advance warning of signals is required, signs should be used in lieu of pavement messages (see *Section 11.3.11*).

The KEEP CLEAR marking may be used at minor un-signalised intersections and access roads where entering or exiting traffic may be impeded by queues from a nearby signalised intersection.

Pavement arrows in a lane are provided to indicate the direction in which a driver is legally obliged to travel through the intersection from that lane. They should only be used where necessary so that skidding problems for motorcycles are minimised. They should not be used to indicate a turn where the turn is restricted during certain hours of the day.

10.6 Raised Pavement Markers

These devices may be used to augment painted lines at traffic signals where it is considered necessary to improve night or wet weather visibility, or to indicate paths that would otherwise be confusing.

Reflective markers are often used on intersection approaches whereas non-reflective markers may be used to delineate lanes which change direction through the intersection, e.g. curves and misalignment between approach and departure lanes.

11. Signs

11.1 Introduction

This section refers to traffic signs that are associated with traffic signal installations.

Unless otherwise specified in this section, all signs should be designed and located in accordance with AS 1742. Refer to AS 1742 Part 1 for a general index of signs, and Section 2 of AS 1742 Part 2 for treatment at intersections. Sign numbers given in this section refer to those based on these standards. In New Zealand, reference should be made to the Manual of Traffic Signs and Markings, Part I (Transit New Zealand and Land Transport Safety Authority 1998).

11.2 General Requirements

11.2.1 Erection

At signalised intersections signs must not be located where they obscure signal displays or limit the sight distance to conflicting or merging traffic. Sight distance is important in the event of signal failure.

To reduce the number of posts at a signalised intersection, it may be possible to mount small signs on signal posts provided the posts are suitably located and the signs do not interfere with signal operation or maintenance.

11.2.2 Periodic Signs

It is often necessary to prohibit certain movements or classes of vehicles in order to maximise intersection throughput in peak traffic demand periods. At signalised intersections, this may be achieved by:

(a) The use of Regulatory Signs together with supplementary plates showing the times of operation (see *Figure 11.5* in *Section 11.3.5*). This type of prohibition applies regardless of traffic variations, e.g. 4.00 pm - 6.00 pm, Mon - Fri.

(b) The use of switchable signs that are displayed only when the restriction applies. The display may be achieved by internal illumination (*Section 11.2.3*) or by mechanical rotation or shutters.

The restriction can be imposed as required in association with an area traffic control plan and in combination with a suitable signal display. The installation and maintenance costs are higher than fixed signs. Operational safety in the breakdown mode should be ensured.

11.2.3 Illuminated Signs

Internally illuminated, fibre optic and LED signs are used at signalised intersections. This sign can be an illuminated white legend, e.g. NO RIGHT TURN on a black background, or a symbolic sign, e.g. a symbolic no right turn sign (see *Section 11.3.5*).

Illuminated signs may apply continuously or at certain limited times during the day. They may flash continuously or for that part of the signal cycle when emphasis is required.

11.3 Signs at Signal Installations

11.3.1 Parking Signs

Signs controlling or prohibiting parking or stopping are used extensively in the vicinity of signalised intersections in order to improve intersection capacity and to reinforce statutory no stopping requirements associated with traffic signals (see R5 series signs in AS 1742 Parts 1 and 11). See *Section 3.6.1* on parking control.

11.3.2 STOP HERE ON RED SIGNAL/ ARROW Signs

The STOP HERE ON RED SIGNAL and STOP HERE ON RED ARROW signs (R6-6 and R6-14 shown in *Figure 11.1*) are not intended for routine use at signalised intersections. Uses to which it may be put are generally limited to the following:

(a) To define a stopping point which is different from the location of the primary signal, and where the stopping point cannot be adequately defined by a stop line.

(b) In situations where traffic turning with a green signal is required to stop at a red signal in the cross street (e.g. internal approaches of staggered T-intersections) or within a wide median opening where right-turn traffic filtering through an opposing stream is not safe.

(c) As a reinforcement in situations where signals might be unexpected such as at temporary signals (*Section 15.11*).

Figure 11.1 STOP HERE ON RED SIGNAL (R6-6) and STOP HERE ON RED ARROW (R6-14) signs

11.3.3 GIVE WAY TO PEDESTRIANS Sign

The GIVE WAY TO PEDESTRIANS sign (R2-10 shown in *Figure 11.2*) is used at signalised intersections under following circumstances:

(a) Turning vehicles are observed not to give way to pedestrians using a signalised crossing. This may occur with filter right-turn movements through a parallel pedestrian movement where the signalised crossing distance is long. In this case, the right-turn movement may become established before a pedestrian enters the conflict zone, particularly from the same side of the road that the right turn commences.

(b) Turning traffic experiences an unexpected conflict with a signalised pedestrian movement. This can occur where the signalised crossing is located a short distance down the street being entered. In this situation, turning vehicle drivers may assume there is no crossing and may become unaware of pedestrians.

The sign should only be used in the above circumstances. Indiscriminate use would reduce the effectiveness of the sign and the traffic regulation that requires drivers to give way to pedestrians crossing the road drivers are entering.

Generally, this sign is erected on the same traffic signal posts as the signal faces which control the movement.

Internally illuminated or fibre optic GIVE WAY TO PEDESTRIANS signs that are activated by pedestrian demand may be used for greater conspicuity.

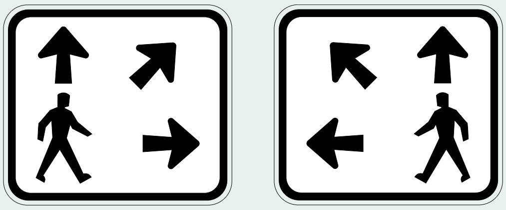
Figure 11.2 GIVE WAY TO PEDESTRIANS (R2-10) sign

11.3.4 Pedestrian Scramble-Crossing Sign

The PEDESTRIANS MAY CROSS DIAGONALLY (or pedestrian scramble-crossing) sign allows pedestrians to cross the road diagonally at signalised intersections where an exclusive pedestrian phase is used (sign R3-5 shown in *Figure 11.3*).

During the scramble-crossing phase, all pedestrian movements including diagonal movements operate simultaneously within the marked limits of crossing (see *Section 10.3.2*). Scramble-crossing phases must operate full time. They should be installed only where there is demonstrated need for pedestrians to cross diagonally and there are delay reductions to vehicles and pedestrians.

Figure 11.3 Pedestrian scramble-crossing (R3-5) signs



11.3.5 Signs to Control Turning Movements

Signs to control turning movements consist of Turn Ban signs and Must Turn signs (*Figure 11.4*). These signs must always be consistent with signal arrow displays and/or pavement arrow markings.

Generally, these signs are erected on the same traffic signal posts as the signal faces which control the movement.

11.3.5.1 Turn Ban Signs

NO LEFT TURN (sign R2-6L), NO RIGHT TURN (sign R2-6R), and NO TURNS (sign R2-7) signs are used for banning turning movements.

Turn bans can be full-time or part-time (limiting its operation to certain times of day). For part-time turn ban, no turn signs R2-6L and R2-6R are used with a Time of Operation supplementary plate (R9-1) showing the times the turn is banned as shown in *Figure 11.5* (also see *Section 11.2.2*).

NO LEFT TURN or NO RIGHT TURN may be controlled by internally illuminated signs as an alternative to R2-6L and R2-6R signs (see *Section 11.2.3*).

Special vehicles may be excepted from the turn ban if necessary. Further supplementary plates for buses (R9-2), bicycles (R9-3), or authorized vehicles (R9-4) can be used for this purpose (*Figure 11.6*).

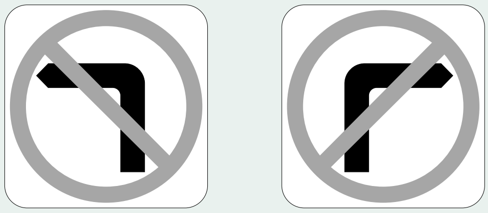
11.3.5.2 Must Turn Signs

LEFT LANE MUST TURN LEFT (sign R2-9L), RIGHT LANE MUST TURN RIGHT (sign R2-9R) are used where a midblock through lane becomes an exclusive turn lane at the intersection.

This lane arrangement practice should be discouraged and avoided if possible as it can lead to lane change accidents.

Figure 11.4 Signs to control turning movements at signalised intersections

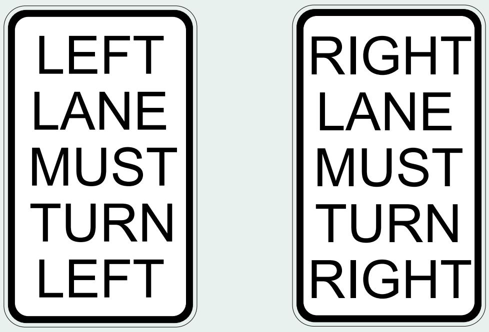
Turn Ban signs



R2-6L R2-6R

R2-7

Must Turn signs



R2-L R2-R

Figure 11.5 Supplementary time of operation plates for part-time turn bans (R9-1)

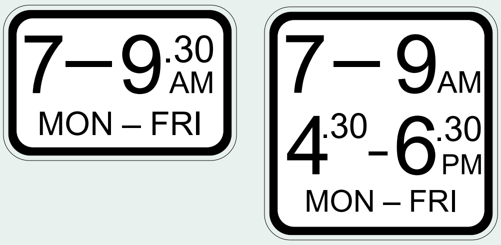


Figure 11.6 Supplementary plates excepting special vehicles from turn bans

R9-2

R9-3

R9-4

11.3.6 U-TURN PERMITTED Sign

U-turns at signalised intersections are prohibited in most Australian jurisdictions by legislation. Where it is considered desirable and safe to relax this general rule, the U-TURN PERMITTED sign is used (sign R2-15 shown in *Figure 11.7*). As a general rule the sign should only be used on intersection approaches with medians and preferably with right-turn auxiliary lanes. U-turns should only be permitted where:

(a) geometry is sufficient to allow the U-turn to be made in one manoeuvre by vehicles of the type likely to U-turn;

(b) there are no more than two opposing through lanes of traffic;

(c) there is adequate visibility of approaching vehicles;

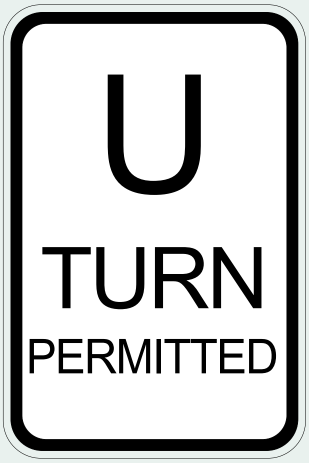
(d) there would be no danger to pedestrians; and

(e) there is no left-turn green arrow control in road to the right.

Where a fully controlled right-turn phase is provided (b) and (c) above may not apply.

Supplementary plates such as LIGHT VEHICLES ONLY can be used with the U-TURN PERMITTED sign in order to advise of site restrictions such as limited turning radii.

Figure 11.7 U-TURN PERMITTED (R2-15) sign



11.3.7 TURN LEFT AT ANY TIME WITH CARE Sign

The TURN LEFT AT ANY TIME WITH CARE sign should only be used at an intersection controlled by traffic signals where a slip lane is provided for left-turn movements not controlled by the signals and where the slip lane falls clearly within the boundary of the intersection (sign R2-16 shown in *Figure 11.8*). This sign shall be located in such a position that it clearly applies to the slip lane.

In some jurisdictions, a GIVE WAY (R1-2) sign is used instead of the TURN LEFT AT ANY TIME WITH CARE sign.

Figure 11.8 TURN LEFT AT ANY TIME WITH CARE (R2-16) sign for slip lanes

11.3.8 LEFT TURN ON RED PERMITTED AFTER STOPPING Sign

The LEFT TURN ON RED PERMITTED AFTER STOPPING sign is used to allow vehicles on any approach where this sign is displayed, to turn left through a red circle display after first stopping at the stop line, provided it is safe to do so (sign R2-20 shown in *Figure 11.9*). See *Section 15.12* for detailed discussion on Left Turn On Red.

This sign is mounted below the primary signal face. A supplementary sign should also be mounted below the tertiary signal face if drivers have difficulty seeing the sign at the primary signal position when stopped at the stop line.

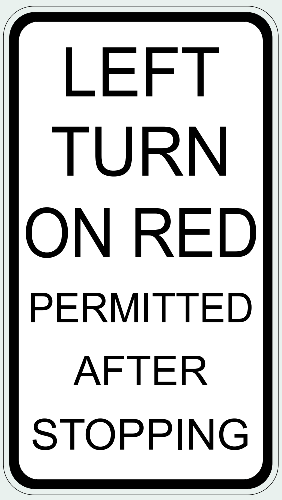


Figure 11.9 LEFT TURN ON RED PERMITTED AFTER STOPPING (R2-20) sign

11.3.9 Hook Turn Only Sign

The RIGHT TURN FROM LEFT ONLY sign (*Figure 11.10*) is used at an intersection controlled by traffic signals where right-turning drivers are required to make a Hook Turn. This manoeuvre consists of entering the intersection from the far left side of the approach road, moving forward while keeping to the left of the intersection and clear of any signalised crossing, waiting in that position until the traffic lights on the road to the right change to green, and then turning into that road.

This sign shall be located in such a position that it is clearly seen by drivers approaching the intersection (e.g. overhead location).

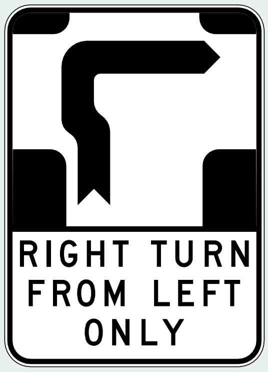


Figure 11.10 Hook Turn Only sign

11.3.10 Traffic Signal STOP Sign

The Traffic Signal STOP sign (*Figure 11.11*) is used to indicate that a driver approaching a signalised intersection, where traffic signals are blacked out or flashing, should stop and give way to traffic as if the sign were a stop sign at an intersection without traffic signals.

This sign is erected on the traffic signal post carrying the primary signal faces.

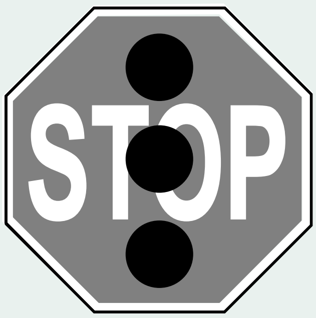


Figure 11.11 Traffic Signal STOP sign

11.3.11 Warning Signs

The symbolic Signals Ahead sign (sign W3-3 shown in *Figure 15.1* in *Section 15.2*) is required where:

(i) the sight distance to the signal stop line or to the back of the stationary queue at the signals is less than the stopping sight distance (e.g. 115 m for a speed of 80 km/h), or

(ii) the signals are located in an unexpected position (e.g. temporary signals in a rural area), or

(iii) high approach speeds may lead to frequent infringement of the signals or to accidents (especially when coupled with large downhill grade).

This sign is usually used at the first set of signals encountered when approaching from a rural speed zone of 80 km/h or more. In some instances, duplication of the sign on the opposite side of the road may be warranted.

A PREPARE TO STOP supplementary plate (sign W8-27 shown in *Figure 15.1* in *Section 15.2*) should also be considered in order to reinforce the Signals Ahead sign. Under circumstances where this is considered to be inadequate, flashing yellow signals should be used to attract special attention to these signs. AS 1742 Part 2 gives stopping sight distance values for various design speeds.

11.3.12 NOT IN USE Sign

When a traffic signal installation is not illuminated, the temporary NOT IN USE sign (*Figure 11.12*) may be used to obscure at least two signal faces on each vehicular approach, usually prior to the commissioning of a new set of signals. Overhead displays are not normally obscured.

The sign has black letters (minimum size 160 mm) on a yellow non-reflective background which may comprise either a rectangular plate shaped so as to obscure the signal display, or a "boot" made of canvas or similar material which fits over the complete signal display.

11.3.13 Fault Reporting Sign

The fault reporting sign is used to inform pedestrians and motorists of the reporting procedure for signal faults (*Figure 11.13*). The use of this sign is recommended to encourage the public to report faults. The sign or signs should be mounted on the signal controller to be visible to passing traffic. It should show the following information in black letters at least 15 mm high:

(a) identification of the maintenance authority,

(b) a 24 hour telephone number to report faults, and

(c) an identification code number for the installation if required.

11.3.14 Other Signs

Other signs used at signalised intersections include FORM 1 LANE (G9-15), FORM 2 LANES (G9-16), NO HOOK TURN BY BICYCLES (R2-22), and Symbolic Walking Legs sign for pedestrian (Zebra) crossings on slip lanes (R3-1).

Figure 11.12 NOT IN USE temporary sign

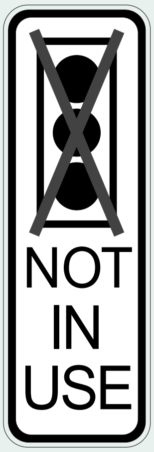


Figure 11.13 Example of fault reporting sign

12. Electrical Design

12.1 General

Electrical design is required for power and lighting circuits for the interconnection of signal components including controllers, lanterns, detectors and push buttons. Cabling and wiring involved may provide one or more of the following:

(a) 240V 50 Hz circuits for lamps and post-mounted detectors,

(b) extra low voltage 50 Hz circuits for pedestrian push button demand indicators,

(c) circuits for vehicle detector outputs,

(d) digital data links associated with coordinated signal systems where dedicated cables or those leased from telecommunication authorities may be used.

The design function will need to provide details of duct sizes and access pits. Cable connection charts are required to identify each core of each cable, its function, connection details and cable routing. Such a chart is an essential document for installation and subsequent maintenance.

Adaptive engineering is required to enable the operation and maintenance of isolated or coordinated signal systems (see *Section 9.4*).

12.2 Installation

All cable systems shall be installed to the requirements of the local electricity authority and the requirements of AS/NZS 3000. This provides safety for both electrical workers and the general public. In this regard specific attention must be given to:

(a) adequate buried depth of cable,

(b) earthing of signal hardware and equipment for electrical safety,

(c) adequate separation/isolation/insulation of 240V and other cabling,

(d) jointing of cables, at terminal strips located on the top of signal posts, and in either junction boxes attached to, or within the cavity of joint use columns and mast arms,

(e) duct and access pit sizes to facilitate installation of cable.

12.3 Cables

Cables manufactured to the requirements of AS 2276 are used.

For reasons of aesthetics and operational benefits, cables are installed underground. Multicore cables have core insulation based on a four-colour system as follows:

(a) Earth core: Green/Yellow

(b) Neutral core: Black

(c) ELV return: Grey

(d) Other numbered cores: White

Installation techniques will depend on local practice and policies. The "common bus" system or the radial routing system are two techniques used.

It should be noted that the conductor sizes of multicore cables are defined by AS 2276 Part 1. For long cable lengths or high electrical loading conditions, calculations of voltage drop and current carrying capacity may indicate that larger conductors are required. The number of circuits required will determine the number of cores required in each cable. Provision must be made for:

(i) one active cable core for each colour of each signal group;

(ii) one cable core for each pedestrian push button demand circuit; and

(iii) a number of spare cores (Spare cores allow for modifications to the signal control mode without recabling. In the event of core damage, it may allow repair to be carried out without the need to replace the cable).

12.4 Vehicle Loop Detector Cables

For vehicle loop detector sensors either post-mounted or located in the controller housing, the feed to the loops should be by screened feeder cable manufactured to the requirements of AS/NZS 2276 Part 2.

The sensor to loop distance should be minimised since long lengths of feeder cable may have adverse effects on detector sensor operation. The loop cable should be manufactured to the requirements of AS 2276 Part 3.

12.5 Data Link Cables

Data link cables are either leased from telecommunication authorities or manufactured and installed to their requirements. The desired data transfer rate determines the cable types that are required. Aspects of *Section 12.2* are also pertinent.

12.6 Cable Connection Design

The cable connection design determines the size, length and routing of cables. The circuits connecting lanterns, push buttons and wait indicators to the controller may be optimised, to produce the most economic solution.

The number of cores in the multicore cable is chosen to provide sufficient circuits for each colour of each signal group, push button, and pedestrian wait indicator. The cores are connected from the post-mounted terminal block, on each post to the controller terminals.

The cable connection chart documents the cable connection design. Details of the connection of individual cable cores to the appropriate terminals in the controller and on each terminal block at each post are shown. A typical example is illustrated in *Appendix C*.

13. Coordination of Traffic Signals

13.1 Introduction

Coordination of traffic signals is implemented to improve the level of service of a road or a network of roads where the spacing of signals is such that isolated operation causes frequent stopping and unnecessary delays to platoons of vehicles formed at upstream signals. Signal coordination also helps to prevent queues forming at a downstream intersection extending back and reducing the capacity of an upstream intersection, particularly where there is limited queue storage space between intersections (Akçelik 1981; Lowrie 1996).

Signal coordination is accomplished essentially by:

(a) operating all signals in the area on the same system cycle time, and

(b) maintaining a time (*offset*) relationship between start or end times of green displays at adjacent (upstream and downstream) signals according to the speed of vehicle platoons so as to obtain a *progression* of green periods along the road.

An exception to the use of common system cycle time is *double cycling* (see *Section 13.2.1*).

The design objective in determining a signal coordination plan (the system cycle time, durations of green displays, and offsets) is to optimise a selected performance measure, e.g. minimise delay or the number of stops or a combination of delay and stops. The performance measure can be applied for the area as a whole, or for selected routes in the area (e.g. major arterial roads).

Signal coordination is an important tool in the achievement of other traffic management and environmental objectives, such as improving the level of service of major arterial roads to reduce the pressure on residential streets and central business district (CBD) areas, and reducing fuel consumption and pollutant emissions.

In addition to improving the level of service of preferred routes, coordination may be utilised to discourage the use of certain routes by providing bad progression (also reducing green times at intersections along the route) to make those routes unattractive.

The benefits of traffic signal coordination were reported in Australian studies by Bastable (1980), Luk, Sims and Lowrie (1983), and Negus and Moore (1984). Further references and a summary of benefits of signal coordination can be found in Lowrie (1996). These benefits include:

(a) reduction in travel time and delay,

(b) reduction in the number of stops,

(c) improved capacity of closely-spaced signalised intersections,

(d) reduction in intersection accidents,

(e) reduction of noise levels, air pollution and energy (fuel) consumption,

(f) achievement of other area or corridor traffic management goals,

(g) benefits from the increased capacity of the road network which helps to avoid expensive road-widening projects.

13.2 Principles of Coordination

13.2.1 Fundamentals of Signal Coordination

There are three fundamental control parameters in preparing a signal coordination plan:

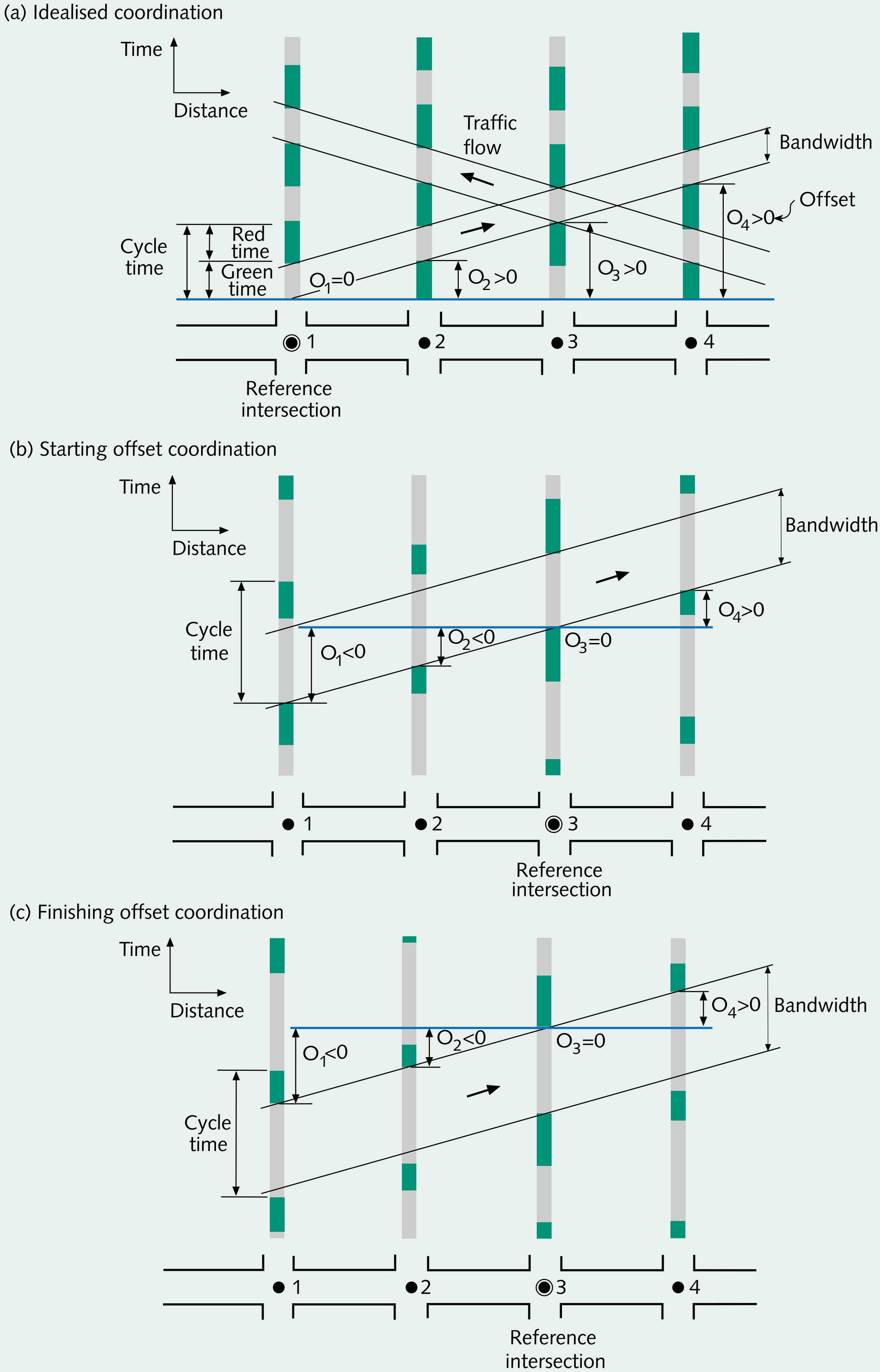
(a) a common system cycle time (one half of the cycle time in the case of double cycling),

(b) green splits, and

(c) offsets.

A system cycle time can be selected by first determining an appropriate cycle time for each intersection in the area, e.g. using the practical cycle time method (see *Appendix C*). Then, the intersection with the largest cycle time can be designated as the critical intersection, and its cycle time can be used as the common system cycle time.

Figure 13.1 Basic strategies for determining offsets for coordinated signals



Some minor intersections in the area can be operated with a cycle time of half the system cycle time (double cycling) when it is found that this can reduce delay to side-road traffic and pedestrians significantly without unduly increasing the number of stops on the main road.

Alternatively, the coordination areas can be re-arranged to achieve a better grouping of the intersections with similar cycle times as far as the network geometry permits. For an overall benefit to be derived from signal coordination, the benefit from progressions must exceed the disbenefit from the operation of some intersections at a higher than required cycle time. Wherever possible, measures should be taken to decrease the cycle time requirement of the critical intersection so as to improve the performance of traffic not only at the critical intersection but also in the control area as a whole.

Since all intersections in the area are to operate with the common system cycle time, the green splits for each intersection are calculated using this cycle time (except in the case of double cycling).

An *offset* is the difference between the beginning (or end) times of the green periods at the given intersection and a selected "reference intersection", i.e. it is the time difference between phase introductions (or terminations). Accordingly, offsets can take positive or negative values. For example, in *Figure 13.1 (a)*, Intersection 1 is the reference intersection (offset, $O_1 = 0$), and Intersections 2, 3 and 4 have positive offset values (O_2, O_3, $O_4 > 0$). In *Figures 13.1 (b) and (c)*, Intersection 3 is the reference intersection (offset, $O_3 = 0$), Intersection 4 has a positive offset value ($O_4 > 0$) and Intersections 1 and 2 have negative offset values (O_1, $O_2 < 0$). The reference intersection is used for offset calculation only, and is not necessarily the critical intersection.

The offset is determined by the distance between signals, the progression speed along the section of road between signals, the sources and flow rates of vehicle platoons entering from the upstream intersection, flows entering and exiting midblock, platoon dispersion characteristics, and the queue of vehicles waiting at the downstream signal.

Ideally, offsets should minimise the need for a platoon to vary its progression speed and should maximise the number of vehicles arriving at the downstream signal during the green period considering all vehicle movements. However, offsets are usually selected to obtain good progression for major movements. Basic strategies for determining offsets are discussed in *Section 13.2.2*.

In addition to the three fundamental parameters discussed above, alternative signal phase sequences should be considered to achieve improved signal coordination (Lowrie 1996).

13.2.2 Offset Strategies

There are four basic offset strategies for coordination along a route. These are:

(i) coordination of the starting offsets, i.e. the beginning of green periods at all signals,

(ii) coordination of the finishing offsets, i.e. the end of green periods,

(iii) simultaneous offsets, i.e. the green periods start at the same time, and

(iv) maximum bandwidth, i.e. maximise the amount of green time available to a platoon along a route.

Figure 13.1(a) shows a time - distance diagram for an idealised situation where the green times on the arterial approaches of all intersections are equal and good progression is provided in both directions. Unequal green times and different spacings between intersections make it difficult to achieve coordination in both directions of a route or on all directions in a network.

Figures 13.1(b) and 13.1(c) illustrate the *starting offset* and *finishing offset* strategies for one-way progressions, respectively. In these cases, the value of offset equals the average travel time based on the design (progression) speed.

The aim of a starting offset strategy is to provide *minimum stops*. The lead vehicles are presented with green signals before they reach each intersection in order to achieve smooth progression. There may be, however, a penalty for vehicles towards the rear of the platoon. At those intersections where less green time is available to the through phase, all vehicles may not have cleared the intersection before the phase is terminated. Consequently the trailing vehicles will be stopped forming *residual queues*. These vehicles must then wait until the next cycle and experience delays, and may also interfere with the progression of the platoon from the next cycle.

By coordinating finishing offsets, *minimum delay* can be achieved since few vehicles travelling on the arterial route will be caught within the system. The disadvantage of this technique is that vehicles may encounter queues or red signals at those intersections where green time is limited. Although the delay before the through phase can be introduced may be short, the smoothness of the progression is disrupted. At some intersections, this may cause all vehicles to stop and the back of queue to extend back towards the upstream intersection.

A compromise between the starting and finishing offset strategies is often possible (e.g. synchronisation of the mid-points of green periods as discussed in Akçelik 1981), but as a general rule, it is more acceptable to coordinate starting offsets.

The simultaneous offset strategy is useful when intersections are closely spaced, and residual queues at the downstream intersection can cause blocking of the upstream intersection (Rouphail and Akçelik 1992).

The *bandwidth* is the amount of green time common to all signals along the route. As shown in *Figures 13.1 (a) to (c)*, the bandwidth can be determined as the maximum time interval which can be drawn on a time - distance diagram between two parallel lines, with a slope corresponding to the design progression speed, enclosing the green periods of all the signals in the system. Though simplistic, the bandwidth gives an indication of the ability of the signals to pass a platoon of vehicles through the system without stopping.

It is necessary to construct different signal coordination plans in order to cater for differing traffic flow (demand) patterns, i.e. am peak, pm peak and off-peak. Each plan consists of the system cycle time, green splits and offsets (*Section 13.2.1*). The plans are selected either by time of day or by using a traffic-responsive method, or calculated on-line by adaptive control algorithms (*Section 13.5*).

The basic offset strategies discussed above do not involve modelling of queues that are likely to exist at downstream signals as a result of the trailing end of the main road platoon being stopped in the previous signal cycle and vehicles turning from the side roads of the upstream intersection. These queues interfere with the progression of platoons. Furthermore, the calculation of signal coordination plans that yield optimum progressions is not an easy task especially for closed-loop network formations, i.e. two-way progressions on an arterial road and grid networks. For this reason, various computer methods have been developed for determining optimum signal offset plans.

Signal timing plans should be verified by on-site observations, and fine-tuned accordingly. See *Section 13.8* for further discussion.

13.3 The Case for Coordination

An isolated intersection is one in which vehicle arrivals at each approach are not significantly affected by other intersections. This situation can be managed by traffic actuated controllers with a high degree of efficiency.

The presence of an upstream signalised intersection or midblock signalised crossing alters the arrival pattern from random to platooned flow. This enables improved traffic flow to be achieved if the green display is arranged to coincide with the arrival of the platoon.

The closer the traffic control signals are spaced, the more platooned (less random) the arrival patterns become, and the greater the opportunities are for improved efficiency afforded by coordination. Generally, benefits result from coordination when traffic signals are provided at successive intersections spaced less than one kilometre apart. At spacings of less than 500 metres, the reductions in delays and stops usually exceed 20 per cent (Bastable 1980). Most studies of installed coordination systems, both fixed-time and adaptive, have shown the systems to be highly cost effective.

13.4 Types of Coordination

There are numerous options available for signal coordination. These options fall into three basic categories in terms of hardware architecture (Lowrie 1996, 2001):

(i) local interlinking (cable),

(ii) synchronous (cableless) linking, and

(iii) wide area control systems.

These are discussed in *Sections 13.4.1 to 13.4.3*.

13.4.1 Local Interlinking

These systems comprise a small number of closely-spaced signals, interconnected by a cable which allows the operation of one signal to affect the operation of the others. In such systems, usually one of the signal controllers assumes the role of *master* and may contain a number of timing plans to suit traffic conditions at different times.

An intersection signal controller with a nearby midblock signalised crossing controller can be coordinated via local interlinking. In this case, the intersection controller imposes restraint periods on the pedestrian signal controller during which the introduction of the pedestrian phase is inhibited.

A variety of local interlinking systems have been used in the past. They have now been replaced by wide area control systems (*Section 13.4.3*).

13.4.2 Synchronous Linking

The synchronous (or *cableless*) linking system can be applied to a large system of signals without relying on a central computer (e.g. the SCATS Flexilink mode of operation as discussed in *Section 13.5.3*). Coordination of signals is achieved by reference to an accurate clock in each signal controller. These clocks are initially set to exactly the same time and maintained in synchronism by reference to the mains supply frequency.

Each controller contains one or more signal timing plans and a weekly schedule for the introduction of the plans according to the time of day and day of the week. The timing plans include the cycle time and green splits to be used and, because the clocks are synchronised, the cycle position of each controller can be synchronised. This allows offsets to be specified and maintained. Synchronous linking uses a fixed cycle time but allows local vehicle actuation of minor phases within the constraints of the timing plan.

Although they provide a low-cost solution, cableless linking systems pose serious problems in maintaining the clocks in synchronism, even in cities with reliable mains power. However, synchronisation of the signal controller clocks can be maintained using a "Dial-in Dial-out" system. This system can be programmed to call each site in a linking system at regular intervals to synchronise the signal controller clock. The Dial-in Dial-out system can also be used to modify linking data as well as monitor on site operation.

Synchronous linking is the fall-back mode of operation in some wide area control systems for use when the central control computer fails.

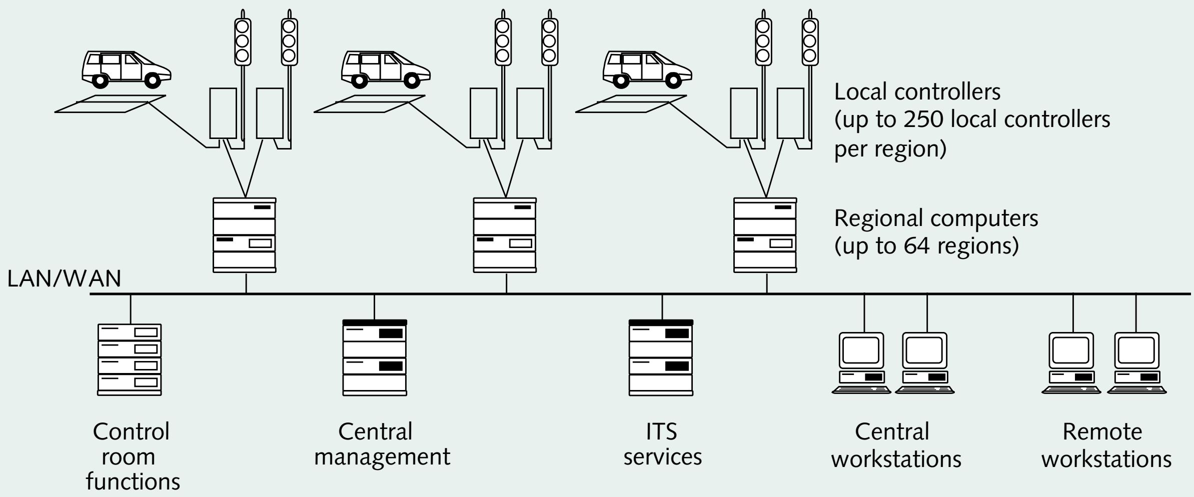
13.4.3 Wide Area Control Systems

Wide area control systems, usually known as area traffic control (ATC) or urban traffic control (UTC) systems, involve one or more centrally or regionally located computers controlling relatively large numbers of signals. These systems provide for centralised monitoring and control, and often include a traffic control centre which is staffed for significant periods of the day to monitor operations and assist with relief of congested traffic conditions which result from traffic incidents and signal equipment malfunctions.

All signals in centrally controlled systems are connected to the traffic control computers, usually by leased data lines or, in some cases, by dedicated cable systems.

In Australia and New Zealand, SCATS (Sims 1979; Sims and Dobinson 1979; Lowrie 1982, 1990, 1996, 2001; Charles 2001) is widely deployed except in Queensland where the STREAMS and BLISS systems are in use. The SCATS system is also used in many cities around the world. Typical system architecture used in the PC-based SCATS 6 system is shown in *Figure 13.2*. For detailed description of the SCATS system, refer to Lowrie (1996).

Figure 13.2 SCATS 6 PC-based wide area control system architecture



13.5 Coordination Methods

Traffic control systems to implement signal coordination can be categorised as follows according to the operating method (control philosophy) employed:

(i) fixed-time plan selection system,

(ii) traffic-responsive plan selection system, and

(iii) fully-adaptive system.

These are discussed in *Sections 13.5.1 to 13.5.3*.

13.5.1 Fixed-Time Plan Selection System

In fixed-time control systems, predetermined signal timing plans are introduced according to a weekly schedule or timetable. Each plan defines the cycle time, green splits and offsets to be used for the duration of the plan. Depending on the complexity and variation of traffic demand patterns, between three and ten plans are usually provided, typically for the morning and evening peak periods, business hours, late night traffic and weekends. Signal timing plans are calculated off-line using manual or computerised methods.

Fixed-time control does not rely on data from vehicle detectors although some variants include a degree of local traffic actuation that requires the use of detectors.

Fixed-time systems offer the advantage of relative simplicity of both equipment and control philosophy. On the other hand, they are unable to cope with unpredicted traffic conditions. Furthermore, as traffic conditions change in time, signal plans become inappropriate (aged). This requires collection and processing of large amounts of data for updating of signal timing plans. Deferral of the development of new timing plans or introduction of ad hoc changes to the plans and timetables result in sub-optimal traffic performance.

13.5.2 Traffic-Responsive Plan Selection System

This system selects predetermined signal timing plans using algorithms that respond to changing traffic conditions based on data collected from detectors.

The simplest form of traffic responsive operation is based on pattern matching. In this method, plan introduction times are modified or selected by comparison of measured traffic parameters (usually flow and/or occupancy) with predetermined levels of these parameters. Typically, these parameters are derived from data measured on a limited number of detectors located so as to capture predominant characteristics of known traffic conditions.

This mode of operation offers flexibility in plan introduction times, but suffers from most of the problems of fixed-time system and cannot allow for unpredicted demand patterns in a satisfactory way.

13.5.3 Fully-Adaptive System

Fully traffic-responsive control employs a large number of vehicle detectors, usually at every controlled signal. Two such systems that have been widely accepted are SCOOT (Hunt, et al 1981) and SCATS (e.g. Lowrie 1996, 2001).

The adaptive mode of operation of SCATS is known as *Masterlink*. SCATS also provides for a fall-back cableless linking mode known as *Flexilink*, which is used to maintain a level of signal coordination in the event of failure of the regional computer or parts of the communication system (*Section 13.4.2*).

A fully-adaptive system generates appropriate signal timing plans on-line in a continuously variable fashion using the extensive traffic flow and density data provided by vehicle detectors. As a result, signal timing plans can suit a wide variety of traffic conditions, responding to wide variations in demand pattern and changes in network capacity caused by incidents and other factors such as road works.

Fully-adaptive control systems require expertise to set up and review if optimal performance is to be maintained. The flexibility of the system is dependent on a large number of detectors. The cost of installing and maintaining these detectors is high compared to lower performing fixed-time systems.

13.6 Design Factors

While detailed aspects of the design process are quite specific to the control system chosen, the following factors are taken into account in designing signal coordination systems.

(a) Traffic Management Policies

The strategies for the routes and networks to be coordinated should be determined, including public transport considerations (see *Sections 13.1 and 15.5*).

(b) Roadway Factors

Information is required on the capacities of roads both at and between intersections. This enables an assessment of the manner in which traffic platoons will behave. The effective capacity of the coordinated system is determined by the capacities of critical intersections that must be identified. In addition, data on the geometry of the intersections in the network, including the location of existing and planned intersections and signalised crossings, and the distances between the stop lines are required.

(c) Geometric Factors

Examination of intersection and roadway geometry may indicate the need for changes to improve the flow of traffic. Examples of geometric improvements include the provision of exclusive right-turn lanes, left-turn slip lanes, and line-marking alterations to minimise lane changing caused by the lack of lane continuity along a road.

(d) Traffic Factors

A complete inventory of traffic movements along a route to be coordinated is required. This enables progression charts (time-distance diagrams) and signal timing plans to be prepared. Each individual intersection must be assessed first, after which appropriate combinations of intersections may be assessed on a coordinated basis using a common cycle time.

(e) Traffic Equipment

An inventory of existing equipment is necessary to identify constraints imposed by this equipment and to determine required changes.

13.7 Coordination Requirements Affecting the Design of Signalised Intersections

When undertaking the design of a set of traffic signals, it is important to consider the effects that coordination will have on the design. The major effects relate to the following factors.

(a) Traffic Signal Controller Selection

A traffic signal coordination scheme will require the use of controllers that are compatible with the type of coordination adopted.

(b) Detector Placement and Function

In many cases, the detection system required, will be specified by the type of master control system to be installed. Detector placement and function options include, individual lane detectors, approach detectors, stop-line detectors, advance detectors or queue detectors (see *Section 8*).

(c) Cycle and Phase Timing

Determination of a common system cycle time and phase green times is discussed in *Section 13.2.1*.

(d) Phasing Design

The phasing design of signals needs to consider the coordination requirements (see *Section 6*). For example, it may be necessary to vary the phase sequence to achieve two-way coordination, and this may not be apparent until the system progression strategy has been determined.

Some isolated signal features such as conditional pedestrian movements can irregularly interrupt associated traffic movements and impair progression or capacity. These features should be removed by redesign of the intersection phasing.

(e) Side Road and Pedestrian Delay

At intersections in a coordinated system, there could be an increase in delays to vehicles entering from side roads and pedestrians crossing the main route compared with operation on an isolated traffic-actuated basis due to a longer cycle time imposed by the critical intersection in the system. Therefore, careful consideration must be given to this factor to ensure minimisation of this adverse effect, e.g. through sub-area optimisation in order to reduce the cycle time.

(f) Public Transport

The needs of public transport should be considered in the overall design. Benefits to public transport may be achieved by either introducing a passive bias to the signal settings, or by actively responding to the presence of a public transport vehicle to adjust the signal operation. It may also be possible to relocate bus or tram stops at certain critical points.

13.8 Coordination Timing Criteria

As discussed in *Section 13.1*, the principal objective of coordination timing is to optimise a selected performance measure. Usually, delay, number of stops or a combination of delay and stops is used as the performance measure. It is generally recognised that the following factors favour minimising stops:

(a) crash risk - this is greatest at the change of signal phases, and is reduced if fewer vehicles are stopped;

(b) fuel consumption, exhaust pollution and operating cost - these are increased by stop-start driving cycles, therefore reduced if fewer vehicles are stopped;

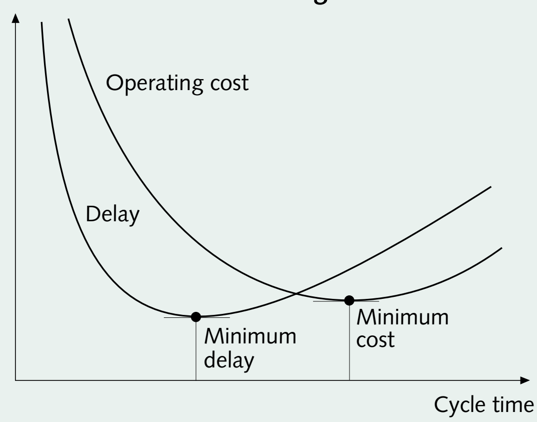
(c) driver expectation - drivers relate coordination more to the number of stops than to overall delay.

Minimising the number of stops, fuel consumption, emissions or operating cost does not yield the same signal timing plans as the minimum delay criterion due to the different offset and cycle time requirements. However, as shown in *Figure 13.3*, such longer cycle times do not involve a significant delay penalty.

On the other hand, long cycle times result in longer delays to side-road traffic and pedestrians, and result in longer queue lengths. In areas such as CBD networks where queue storage spaces are limited, long cycle times may lead to the blockage of upstream signal stop lines (queue spill back), and the resulting loss in the network capacity leads to increased delays and stops.

Signal coordination plans can be prepared manually using time - distance diagrams, or an off-line optimisation software, e.g. TRANSYT (Li 1988; U.S. Department of Transportation 1988; Vincent, Mitchell and Robertson 1980) and SCATES (RTA NSW 1991a). Preparation of signal coordination plans are also relevant to fully-adaptive control systems, e.g. offset plans for the Masterlink mode and timing plans for the synchronous linking fall-back mode in SCATS.

Figure 13.3 Typical relationship between traffic performance and cycle length for coordinated signals



14. Installation Checks and Maintenance

14.1 Precommissioning Checks

14.1.1 General

Prior to commissioning, it is necessary to check the installation to ensure that it is in accordance with the design and that all equipment is correctly installed and operating.

14.1.2 Check List

The following checks should be carried out:

(a) ensure that an insulation check in accordance with AS/NZS 3000 has been completed prior to switching on the controller and detectors; generally the relevant electricity supply authority will not provide connection to mains supply unless their special requirements and those of AS/NZS 3000 have been met;

(b) ensure that the controller has been tested in the workshop for compliance with the controller programming procedures (*Section 9.4*) and phasing requirements of the design;

(c) check vehicle detectors for correct operation (presence or passage), and ensure that the loop detection zone does not encroach on other lane streams;

(d) check pedestrian push-button assemblies to verify the operation of pedestrian indicators, orientation of the arrows, the audio tactile operation including sound levels, and the connection of the audio tactile functions to the correct Walk displays;

(e) energise the controller (but with lamps circuits off) and check the operation in response to demands from vehicle, bus, tram and pedestrian detectors; where special detectors (e.g. for fire stations and trains) are provided these should be similarly checked; and detector presence times should be checked;

(f) momentarily energise each lamp circuit to ensure that the intersection has been wired correctly, i.e. that signal faces not associated with the circuit being energised are not energised;

(g) check that the signal faces for each approach are in accordance with the design plan;

(h) check signal faces for correct aiming and coverage by visual inspection from each approach lane (see *Section 7.5*);

(i) check signal visors and louvres to ensure that sun phantoms are acceptably low and that signal cut off in relation to conflicting movements has been achieved (see *Sections 7.6 and 7.7*);

(j) check that the flashing yellow mode and start-up sequence operate correctly;

(k) with lamp switching circuits energised, check the operation of the signal groups by cycling the controller through all of its phases; this is a further check that the controller programming applied to the site is correct;

(l) check that the site communicates to the central computer if applicable;

(m) check that any necessary changes to the design are recorded and that information specific to the site is documented; complete documentation is essential to facilitate maintenance;

(n) check that the lane configuration and pavement markings are in accordance with the design plan (*Sections 3 and 10*);

(o) check that the required signs have been installed and redundant signs removed (*Section 11*);

(p) have the kerbside controls been installed?

(q) check that the fault reporting sign has been installed on the signal controller (*Section 11.3.13*).

14.2 Monitoring and Evaluation of Operation

14.2.1 General

Following implementation and fine-tuning of signals, monitoring and evaluation of the operation will verify (or otherwise) the adequacy of assumptions made in the design. Inadequate kerbside parking controls or unforeseen variations in traffic (demand) flow, are examples of problems that may be identified.

When a signalised intersection is commissioned, users may experiment with alternative routes during the fine-tuning period. Thus, the timing of the monitoring and evaluation process needs careful consideration. The process may need to be repeated a number of times.

While the design may be based on selected peak traffic flows (see *Section 2.3*), monitoring and evaluation should also consider conditions during off-peak periods, public or school holidays, and unusual traffic flow periods.

The monitoring and evaluation process essentially repeats the design process using the data collected after the commissioning to verify the adequacy of the design in terms of safety and efficiency. If deficiencies are evident it may be possible to implement changes to improve performance, e.g. fine-tuning of signal timings, phase sequencing, restrictions on movements, and extension of kerbside controls.

In some cases, deficiencies can only be corrected by a complete redesign of the channelisation associated with the signal installation, particularly when the design has been constrained. The decision to implement a redesign involves a complex process of engineering assessment.

14.2.2 Check List

The following checks should be made when monitoring and evaluating the operation of a site:

(a) are the signs and road markings appropriate to the phasing as designed?

(b) are the kerbside controls adequate for the required capacity of the site?

(c) are traffic flows actually as predicted or assumed?

(d) is traffic avoiding the signalised site and creating congestion elsewhere?

(e) is equipment (controller) operating as designed?

(f) are signal phasings and timings (*Section 6 and Appendix C*) adequate to ensure that

- (i) the yellow times in relation to vehicle stopping characteristics, and times provided between phases to clear traffic from the controlled area are satisfactory?
- (ii) traffic is not held unnecessarily at a red signal when adequate gaps exist in a running movement?
- (iii) delays to vehicles and pedestrians on each approach are at satisfactory levels ?
- (iv) the numbers of vehicles left in a queue at the termination of the green period and the number of vehicles stopped more than once in each queue are at satisfactory levels?
- (v) the occurrence of queue overflows from turning lanes blocking other movements is minimised?
- (vi) if coordination exists, good progressions are obtained as planned (*Section 13*)?

(g) does platooning by upstream signals or interference from downstream signals indicate a need for coordination (*Section 13*)?

(h) are vehicle detector loops appropriately located to detect traffic as intended in both the passage and presence mode, and is waiting traffic standing in the position anticipated in the design (*Section 8*)?

(i) are unusual vehicles being missed by detectors, and are they in sufficient numbers to justify special detection techniques?

14.3 Maintenance

Traffic signal installations require maintenance to ensure satisfactory operation in terms of capacity and safety.

Regular checks should be made to ascertain whether signal settings are still appropriate for the prevailing traffic conditions (*Appendix C*). This aspect is sometimes overlooked during routine maintenance and only examined when a major problem becomes evident.

14.3.1 Maintenance Management

Signal maintenance management aims to minimise costs while maximising the availability and life of the installation.

The level of maintenance required should be considered during design. For example, lamp burn outs can reduce the number of displays below the minimum considered necessary for safe control. If at the design stage some additional displays were provided, the time taken to respond to advice of a lamp burn out would be less critical.

14.3.2 Maintenance Records

To adequately schedule maintenance it is necessary to estimate the Mean Time Between Failure (MTBF) and Mean Time To Repair (MTTR) for various signal components. If this information is sufficiently detailed it may also be useful in identifying those components that may reduce the reliability of the signal system.

Maintenance records also provide a basis for the review of specifications and guidance in the appraisal of equipment tendered for purchase. A good maintenance record should include the following data:

(a) Fault advice:

- (i) date and time,
- (ii) source,
- (iii) location, and
- (iv) apparent nature.

(b) Service report:

- (i) date and time of arrival and departure,
- (ii) location,
- (iii) travel involved,
- (iv) personnel identification,
- (v) action taken to clear fault,
- (vi) details of further work required, and
- (vii) materials used including description and serial numbers of operational spares installed and removed.

(c) Shop service records:

- (i) date and time, returned for service, service actually started, service completed,
- (ii) description and serial numbers of units,
- (iii) repair-hours involved, and
- (iv) materials used in repair.

14.3.3 Preventative Maintenance

Preventative maintenance involves the provision of service before failure occurs. Periodic maintenance is scheduled so that equipment operates between routine servicing with an estimated probability of breakdown. These techniques (reliability engineering) and preventative maintenance scheduling are beyond the scope of this guide.

14.3.4 Breakdown Maintenance

Despite efforts to maximise equipment availability, random breakdowns will occur and must be repaired. Notification of failures can be expected from Police, other agencies or from the public, and while the details are often insufficient, response to such advice must be seen to occur within a reasonable time if future advice is to be encouraged.

Hulscher (1974, 1977) provided a useful guide to priority that should be assigned to various traffic signal faults and guides to suitable response times.

14.3.5 Lamp Replacements

Lamp failures can occur at any time although the probability of failure increases as the lamp approaches its rated life.

Unless adequate display redundancy is provided in the design, random failures will need to be repaired as breakdown maintenance rather than by routine servicing.

The application of reliability engineering techniques and those of Hulscher (1974) will allow the determination of suitable bulk/group re-lamping intervals to minimise the number of random failures that must be attended to, and to maintain an adequate signal luminance.

14.3.6 Accident Damage

A high priority should be given to actions in response to reports of accident damage. Minor damage may cause significant operational problems, e.g. when conflicting displays are given to traffic. Damaged equipment should be checked as soon as possible to ensure that it is electrically safe. Thus attempts should be made to respond promptly to these reports. It may be necessary to temporarily switch the signals to flashing yellow, or off. The installation should be returned to service as soon as possible.

14.3.7 Cleaning and Painting

Signal hardware should be kept clean and where necessary painted, by routine maintenance. Cleaning of lanterns is important in maintaining light output although the required frequency is related to the environment.

14.3.8 Spare Parts

Maintenance planning must consider the availability of spare parts. Stocks of expendable items such as lamps will differ from those such as controllers that are recyclable, operational spares. Items which are unique to the industry or which have long delivery times should be stocked in sufficient quantity. However having regard to average failure and repair rates, a 10 per cent spares holding is generally satisfactory.

14.3.9 Replacement Scheduling

While maintenance activities aim to keep equipment operational, the rate of failure of components generally tends to increase as the equipment ages. After a period, some specialised components may be either withdrawn from manufacture or manufactured in reduced quantities. These then become harder to acquire and more expensive with the net result that maintenance costs rise.

Advances in technology also render older equipment increasingly unsuitable for the operational demands made upon it. This together with rising maintenance costs eventually makes replacement with new equipment necessary. Reliability engineering techniques can assist in identifying the economic life of equipment and when replacement should be scheduled.

15. Special Applications and Facilities

15.1 Introduction

This section presents information on functional and operational aspects of special traffic signal applications and facilities. For further information, refer to AS 1742 Parts 2 and 14.

15.2 Advance Warning Signals

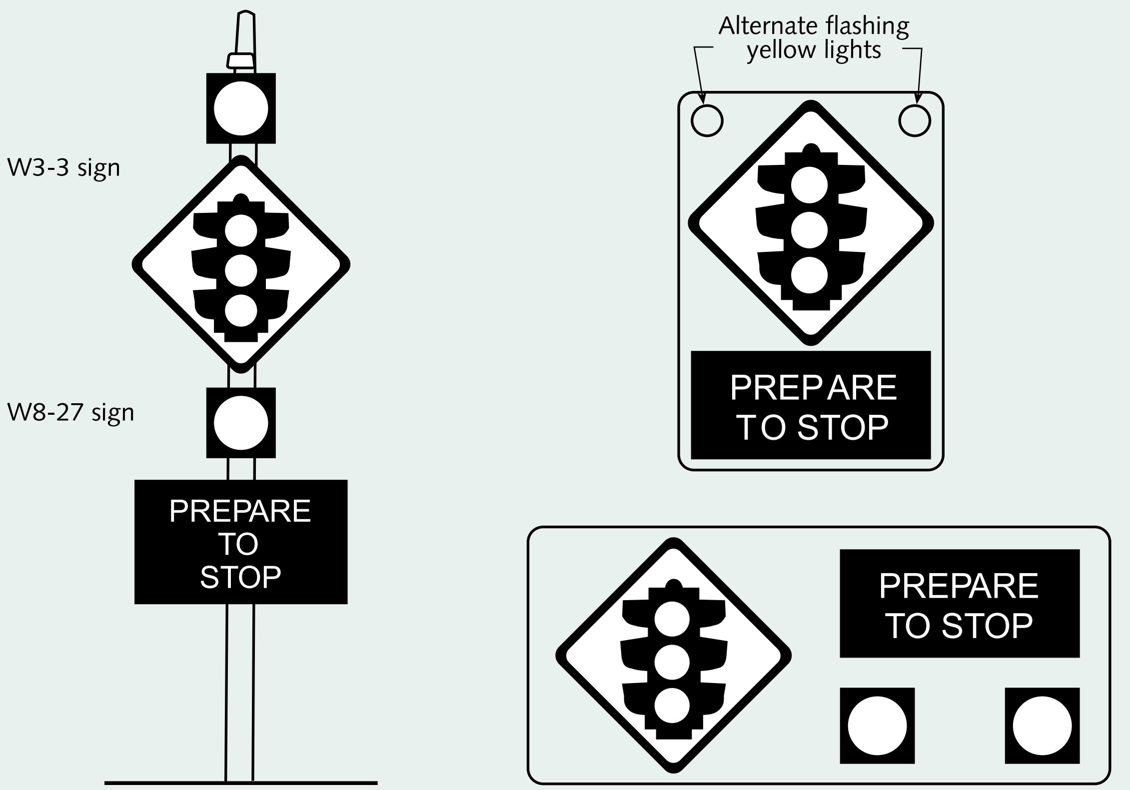
Advance warning signals are an active warning device consisting of a warning sign with **Alternating Flashing Yellow** lights. Alternative formats for advance warning signals are shown in *Figure 15.1*.

The advance warning device is cabled to the traffic controller and timed as a separate signal group. The yellow lights should flash alternately, one being **Off** while the other is **On**, at a frequency of 1 Hz.

There are two main purposes for the use of an active advance warning device (rather than a passive device):

(a) Arterial roads with a high proportion of heavy or long combination vehicles, where there is a high risk of frequent infringement of signals and a high risk of rear-end and cross accidents due to the inability to stop in time for the red display, e.g. due to high approach speeds or significant

Figure 15.1 Alternative formats for advance warning signals (Note: the two alternatives shown on the right-hand side of the diagram are not permitted in New Zealand, where MOTSAM sign PW-64 should be used)



downhill grade: the warning device should be located approximately at the stopping sight distance from the stop line of the intersection, on the approach side of the intersection (see AS 1742 Part 14).

The flashing yellow lights are started a fixed time in advance of the yellow interval when the main through traffic phase is terminating at the intersection, using the early cut-off period timer (*Appendix C.4.5*). The flashing lights may be terminated at the start of the red display for the main through traffic phase. In some jurisdictions, the flashing lights are terminated at the start of the green display.

(b) A traffic signal installation that is obscured from the view of approaching traffic such that there is a high risk of collision with the rear end of traffic queued at the signals: the warning device should be located at not less than the stopping distance in advance of the probable end of the queue.

The yellow lights will need to flash beyond the start of the green display when the sight distance to the back of the queue for the through movement is a problem. The back of the queue will not begin to move until some seconds after the green signal is displayed. This time can be calculated as the 95th percentile queue value (in vehicles) times the queue departure response time. Akçelik, Besley and Roper (1999) reported a typical queue departure response time of 1.15 s observed at intersections in Melbourne and Sydney.

The assembly is generally erected on the left of the approach. However, if it cannot be seen in this position due to restricted sight distance caused by horizontal left-hand curvature, the assembly should be erected on the right of the approach. The assembly may also be mounted overhead if the sight distance to a side-mounted sign is restricted by vertical road curvature.

Refer to *Appendix B.2.1* for a discussion of vehicle braking characteristics and stopping distance.

15.3 Railway Level Crossings

15.3.1 Proximity to Level Crossing

If a road signal installation is located in close proximity to a railway level crossing such that there is a probability that a vehicle queue generated by the road signals will extend across the rail tracks, special provision should be made to force the road signals to a phase that will clear the queue before the arrival of the train.

The signal requirements should be determined in consultation with the appropriate railway authority.

Use of "yellow box" pavement markings and fixed or variable message signs such as KEEP TRACKS CLEAR may be effective in preventing vehicles queuing over rail crossings.

Some examples and guidelines for good practice have been documented by ITE Technical Committee TENC-4M-35 (ITE 1997). Guidelines for the operational requirements of traffic signal controllers linked with railway level crossing controls are given in a VicRoads (1997b) document titled "Linking Traffic Signals to Railway Level Crossings".

15.3.2 Linking Requirements

If linking with the railway level crossing is justified, track switches should be provided by the railway authority to enable the special queue-clearing sequence to be initiated before the flashing red signals commence to operate.

The road signal sequence should be arranged so that after the queue-clearing phase has terminated, no phases or turning movements can be introduced for traffic needing to cross the rail tracks until the train has cleared. The railway track switches should provide an indication when the train has cleared the level crossing. In the case of a rail crossing provided with manually operated gates, no special provision is generally required. When the level crossing opens to road traffic, the normal phase sequence is restored and some compensation can be given to the waiting traffic.

Provision of additional storage may be necessary for vehicles that cannot be released while the railway crossing is closed.

Common inputs from the railway level crossing control system are given in *Section 8.5.6*.

15.3.3 Railway - Road Crossings within the Intersection

It may be possible to include the railway - road crossing within the conflict area. In this situation the train movement will need to be treated as a priority phase. The flashing red railway display should be provided as part of the control.

15.3.4 Conflicting Railway and Road Signals

Special precautions may need to be taken to shield any green roadway display from traffic approaching or stopped by a flashing red railway display. Similarly, roadway displays should be shielded from the view of train drivers.

15.4 Emergency Vehicle Facilities

15.4.1 Facilities Close to a Signalised Intersection

When a fire or ambulance station is close to a signalised intersection, special precautions shall be taken to ensure that stationary vehicles do not block emergency service vehicles that are trying to exit in an emergency. The measures for this purpose include:

(a) relocating the stop line further from the intersection, and

(b) adding a special emergency service phase to the intersection signals.

Relocating the stop line could be appropriate where the exit from the emergency service facility is at the intersection. If the resulting position of the stop line is unnatural from the motorist's point of view, extra facilities such as a wider 600 mm stop line and the STOP HERE ON RED SIGNAL sign (*Section 11.3.2*) may be necessary. It may also be appropriate to provide signs and pavement markings to warn motorists not to queue across the driveway (*Section 10.5*).

When the exit from the emergency service facility is too far from the intersection and relocation of the stop line would require a longer intergreen period, flashing or non-flashing signals may be used (*Section 15.4.2*). These are operated from the emergency service facility to allow safe exit of the emergency service vehicles.

A special emergency service phase may be provided at the intersection if it is warranted on the basis of:

(i) conflict between emergency service vehicles and other traffic;

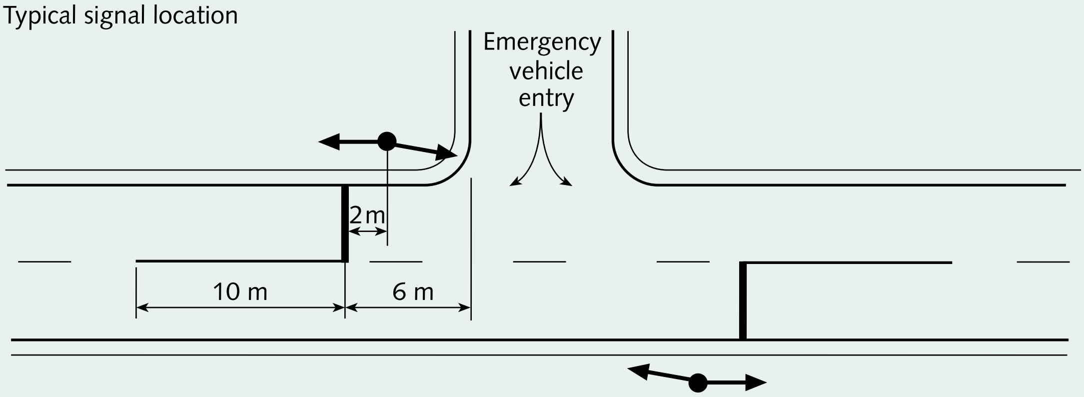
(ii) possibility of queued vehicles blocking the exit from the emergency service facility; or

(iii) delays to emergency service vehicles if the emergency service phase is not provided.

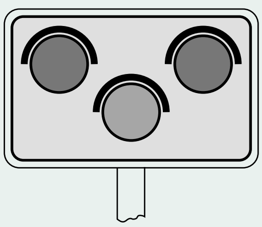
The special emergency service phase should clear any queued vehicles within the path of the emergency vehicle to allow it unimpeded travel in any direction through the intersection.

Figure 15.2 Signals for midblock access points to or from emergency service facilities

(a) Typical signal location



(b) Signal face: flashing signals



15.4.2 Signals for Midblock Access Points

Signals for midblock access points from emergency service facilities shall comprise signal faces provided in accordance with *Figure 15.2(a)* in one of the following forms:

(a) **Non-flashing signals**: If provided as a two-aspect signal face, the display sequence shall be **Off** to **Yellow** to **Red** to **Off**. If provided as a three-aspect signal face, the display sequence shall be **Off** to **Green** to **Yellow** to **Red** to **Off**. Some jurisdictions use the sequence **Off** to **Green** to **Yellow** to **Red** to **Green** to **Off**. The STOP HERE ON RED SIGNAL sign (*Section 11.3.2*) shall be provided on the primary signal post if no stop line is marked.

(b) **Flashing signals**: The signal face containing flashing signals shall comprise a single steady yellow signal surmounted by twin alternate flashing red signals in the configuration shown in *Figure 15.2 (b)*. The display sequence shall be **Off** to **Yellow** to **Flashing Red** to **Off**. Signs shall be displayed at or near the signals indicating to road users that they must stop when the lights are flashing.

Signals shall be visible to all pedestrians and other road users on the approaches. Activation of the signals is initiated manually within the emergency service facility and automatically displays the yellow signal for 4 to 6 s followed by the red or flashing red signal, which then continues to operate until switched off.

15.5 Public Transport Priority

Special public transport priority treatments at signalised intersections, such as special signal phases for buses and trams, are used as a travel demand management measure to encourage the use of public transport. Signal aspects and display sequences for buses and trams are described in *Sections 5.2 and 5.10. Sections 8.5.1 and 8.5.2* discuss detection of buses and trams.

15.5.1 Bus Priority

A three-aspect column is used to control a bus phase. A bus lane must be designated a bus only lane for at least 100 m on the approach to the stop line. This is necessary to legally deny vehicles other than a public bus access to that length of lane. Otherwise, a vehicle could block the bus movement when a white B is displayed. Other vehicles can legally enter a bus lane up to 100 m before turning or leaving the road. Signs and pavement markings can be used to designate a length of bus only lane. The lane adjacent to the bus only lane must be marked with left turn and through arrows if it is a shared lane, or left-turn arrows only if it is an exclusive left-turn lane. This is essential to legally allow other vehicles to turn left across the bus only lane.

A single white B aspect must be in at least a four-aspect signal face. It is used to provide a priority start at the beginning of the phase in which other vehicles moving in the same direction as the buses operate. A single white B aspect is needed only when the buses and vehicles in the adjacent lane merge on the departure. A priority start is not necessary if the bus lane continues on the departure. Conflicting movements between buses and other vehicles must be denied or non-existent. The only exception is a merge conflict on the departure.

It is important to remember that any vehicle classified as a public bus may use a bus or bus only lane. The lane will not be used exclusively by buses on a registered route at all times. For example, if a registered bus route continued left at a signalised intersection, buses on that route would only turn left. However, other public buses in the bus only lane could proceed straight ahead or turn right when a white B is displayed. This must be considered before using B aspects to control buses.

15.5.2 Tram Priority

Tram priority is controlled differently to bus priority. Unlike buses, tram direction is controlled by tracks either located in the centre lanes of a shared roadway or clear of the trafficked lanes in a centrally located tram reserve.

A three-aspect column is used to control tram movements in their own right of way to eliminate conflicts between trams and other vehicles and to provide tram only phases.

A single-aspect white T and five-aspect signal faces as shown in *Figure 5.1 and Section 5.4.2* are used to provide tram priority for trams on shared roadways. The five-aspect signal face is used in conjunction with a tram-actuated leading right-turn phase to clear queued vehicles between the tram and the stop line. The single-aspect white T is used with tram only phases, where trams are on a unique route. Where trams use alternative routes, white arrows are used to indicate the turning direction.

15.5.3 Operation

Public transport priority at traffic signals can be categorised as passive and active priority measures (ITE Australian Section 1985, Taylor 1996). Passive priority measures include reduced cycle time, green time allocation and basic phasing design with bias to favour bus and tram movements, repetition of bus and tram movement phases in one signal cycle, and signal coordination with special consideration for bus and tram movements.

Active public transport priority techniques at traffic signals include:

(a) phase extension, i.e. holding the green display to allow the bus or tram to clear the intersection;

(b) phase early start, i.e. early display of the green signal when a bus or tram facing a red signal is detected;

(c) provision of special tram phases at complex intersections with multiple phases;

(d) phase suppression, i.e. skipping a non-tram phase in some limited circumstances in order to service a tram or bus phase more quickly.

A technique called *flexible window stretching* that combines phase extension and early start methods has been used for tram priority within the SCATS control system (ITE Australian Section 1985, McGinley 1983). This technique has the ability to provide priority at any point in the signal cycle and transfer time between phase extension and early start phases. However, at sites with significant pedestrian activity associated with the side-road phase, the amount of time that can be taken away from the side-road phase is significantly reduced.

A single frequency transponder system has been used for tram detection in the Melbourne tram priority system. The system allows a positive coupling between the transponder and in-ground detector loops to selectively detect trams in a mixed traffic stream.

Bus Only Lanes are used as an effective measure of public transport priority. A white B signal aspect display permits a bus to move in any direction from the stop line of a bus only lane. The movement must be made with safety and in accordance with any regulatory requirements. Detailed information on the use of bus lanterns at signalised intersections can be found in RTA NSW (1998).

A *Queue Relocation* method has also been used for bus priority. This method limits the queue length at the downstream intersection. The bus priority system at the upstream intersection allows buses to advance to the end of the queue at the downstream intersection before other traffic leave the upstream intersection. The buses are then in position to take advantage of the green period at the downstream location.

15.6 Bicycle Facilities

Detailed information on bicycle facilities in general can be found in Austroads (1999) GTEP Part 14 (Bicycles), AS 1742 Part 9, and in Veith (1996).

Usually, bicycle facilities are combined with pedestrian facilities at signalised intersections and midblock signalised crossings. Signal aspects and sequences for bicycle and pedestrian signals are described in *Sections 5.2, 5.8 and 5.9*. Signal face site requirements and positioning of signal equipment for pedestrian signals are discussed in *Sections 7.4.4 and 7.5.2.4*. Detection of cyclists is discussed in *Section 8.5.3*.

Bicycles may be controlled by two-aspect red and green bicycle signal faces, or three-aspect red, yellow, and green bicycle signal faces (*Section 5.9.1*). The type of bicycle path (exclusive, shared, etc) is a factor in the selection of two-aspect or three-aspect signal faces.

It is recommended that, at intersections, a stop line for bicycles is placed 2 m downstream of the normal stop line so that left-turning motor vehicle drivers, in particular bus and truck drivers, will be aware of bicycles waiting for a green signal. If vehicles cannot turn left, there is no need for this treatment.

A bicycle rider is required to dismount when crossing a road from a footpath, bicycle path, shared path or separated path whether traffic signals are installed or not. However, where bicycle lanterns are installed, a bicycle rider facing a bicycle signal may negotiate the intersection or midblock location without dismounting.

15.7 Roundabout Metering Signals

Roundabout metering signals may be used where excessive queuing and delays are observed on one or more legs of a roundabout due to heavy circulating flow rates, especially in the case of heavily directional origin-destination movements. In this case, a dominant approach stream constitutes the major proportion of traffic in the circulating stream that causes a significant reduction in the capacity of the approach that has to give way to that circulating stream (Akçelik, Chung and Besley 1998). These signals are usually employed on a part-time basis since they may be required only when heavy demand conditions occur during peak periods.

Two-aspect yellow and red signals are used for roundabout metering as shown in *Figure 5.6(a), Section 5.3.4*. The sequence of aspect display is **Off** to **Yellow** to **Red** to **Off**. When metering is not required neither aspect is displayed.

Figure 15.3 shows the use of metering signals at a roundabout. The signalised approach is referred to as the “metered approach”, and the approach with the queue detector as the “controlling approach”.

When the queue on the controlling approach extends back to the queue detector (*Section 8.3.4.3*), the signals on the metered approach operate so as to create a gap in the circulating flow. This helps the controlling approach traffic to enter the roundabout. When the red display is terminated on the metered approach, the roundabout reverts to normal operation.

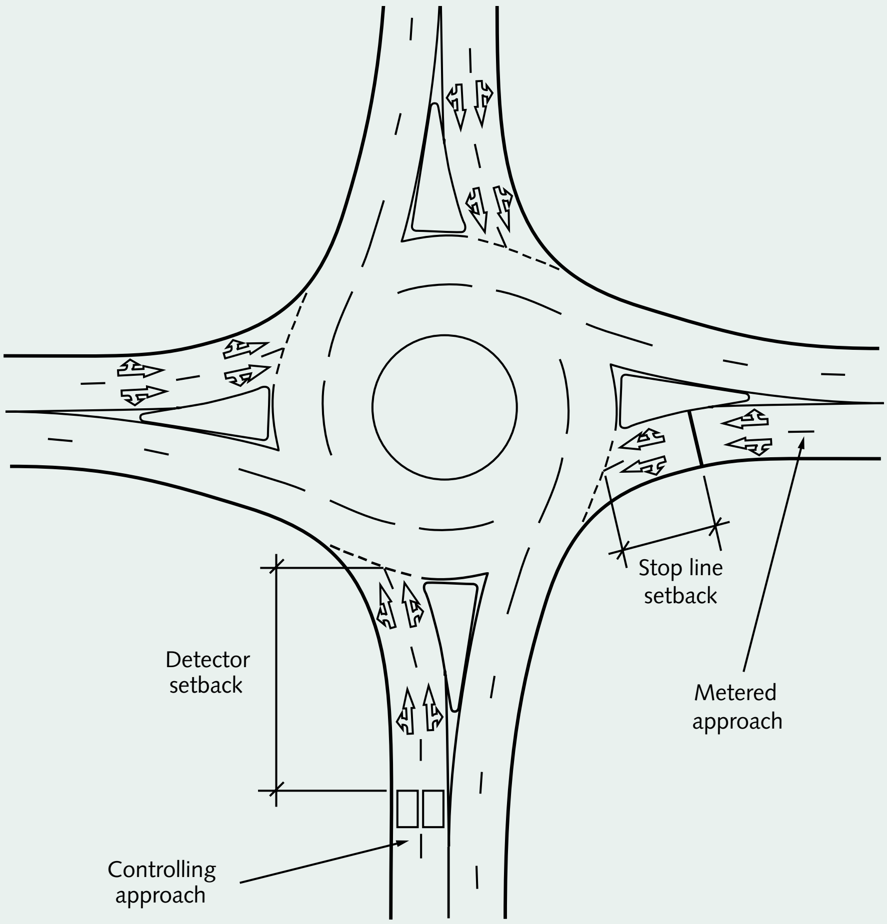
The introduction and duration of the red signal on the metered approach is determined by the controlling approach traffic. The duration of the blank signal is determined according to a minimum blank time requirement, or extended by the metered approach traffic if detectors are used on that approach.

A minimum of two signal faces, one primary and one tertiary, shall be installed. A regulatory sign STOP HERE ON RED SIGNAL (*Section 11.3.2*) shall be fixed to any signal post erected adjacent to the stop line, as drivers do not expect to stop at the advance stop line location. Stop lines shall be located not less than 3 m in advance of the approach holding line but preferably, should be positioned approximately 20 m from the holding line. Queue detector setback distance on the controlling approach is usually in the range 50 m to 120 m.

Various site-specific methods may also be used to meter traffic, e.g. using an existing upstream midblock signalised crossing on the metered approach.

In some cases, it may be necessary to supplement the traffic signals with explanatory fixed or variable message signposting. Where sight restrictions exist, advance warning signals should be considered (*Section 15.2*).

Figure 15.3 Roundabout metering signals



15.8 Ramp-Metering Signals

Ramp-metering systems control the flow of traffic entering a freeway via access ramps in order to prevent the breakdown of flow on the freeway and hence preserve its ultimate capacity, and minimise delay and travel time (Lowrie 1996a). Ramp metering may also be applied to similar situations on ramps leading onto roads other than freeways. Metering signals may be used on a part-time basis.

Two-aspect red and green signals are used for ramp metering. The sequence of aspect display is **Green** to **Red** to **Green**. When metering is not required neither aspect shall be displayed.

A typical ramp-metering signal layout for a one lane entry ramp is illustrated in *Figure 15.4*. The signals are driven by a ramp-metering controller that permits one vehicle to enter the freeway each time the green signal is displayed. In the case of ramps where traffic queues in two lanes at the metering signal, a "dual release" system displays green signals to each queue alternately.

A minimum of two signal faces, one primary and one tertiary, shall be provided. The distance from the associated stop line to the entrance ramp nose shall be sufficient to allow a vehicle stopped at the signals to accelerate to freeway speed before merging with the freeway stream. Adequate provision for queuing at the signals should also be made, including provision for possible queuing back beyond the ramp.

If a sign is used to indicate that the entry to the ramp is restricted, it may take one of the following forms:

(a) A variable message sign with legend FREEWAY ENTRY RESTRICTED.

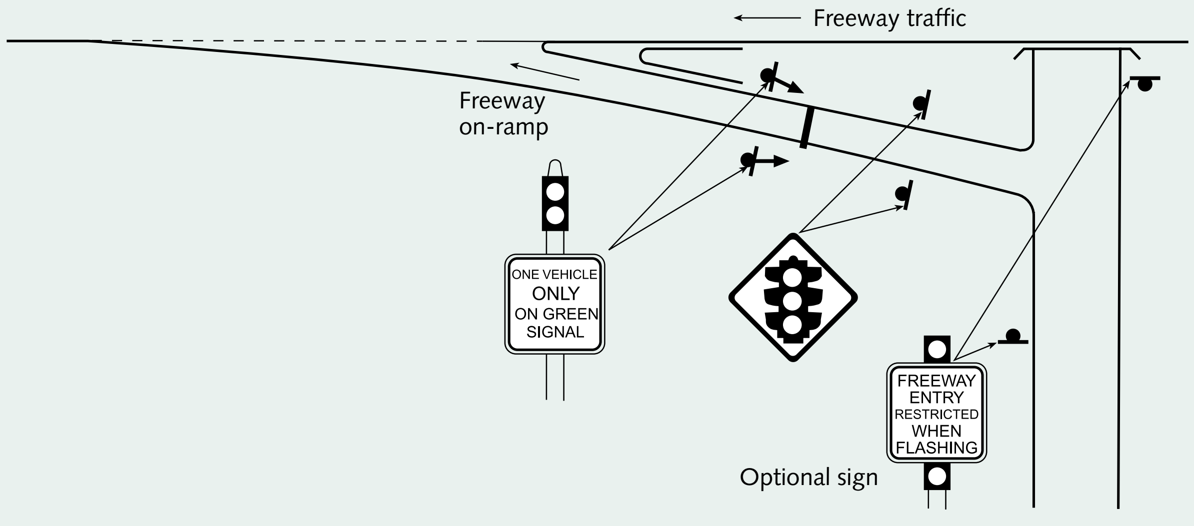
(b) A fixed FREEWAY ENTRY RESTRICTED sign with times of operation below the legend.

(c) A fixed FREEWAY ENTRY RESTRICTED WHEN FLASHING sign in an assembly with flashing yellow lights, e.g. as shown in *Figure 15.4*.

Freeways that operate at or near capacity for significant periods of the day are suitable for the deployment of ramp-metering systems. For motorist acceptance and compliance, the system must operate efficiently and not appear to unnecessarily delay ramp traffic.

Many ramp-metering systems are operated in conjunction with freeway control systems. In this case, ramp-metering controllers are connected to a central computer that processes data from detectors on the freeway and ramps, and computes appropriate ramp flow rates.

Figure 15.4 Freeway ramp-metering signals



15.9 Special Intersection Treatments

15.9.1 Seagull T-Intersections

The purpose of a "seagull" treatment of a signalised T-intersection is to avoid stopping through vehicles on the major road, approaching from the left of the T-junction stem as seen in *Figure 15.5 (a)*. This through movement is not signal controlled and operates continuously as seen in *Figure 15.5 (b)*. However, this movement could be signalised in order to make provision for pedestrians crossing. When there is pedestrian demand, the through movement would be stopped when the side road movement operates, e.g. in Phase C in *Figure 15.5 (b)*.

Generally, traffic signals should be installed on seagull intersections only where right-turn vehicles from the stem of the T-intersection do not have to merge with through traffic on the departure and weave across through traffic to turn left just beyond the signals. Any merging by these right-turn vehicles can result in rear-end collisions.

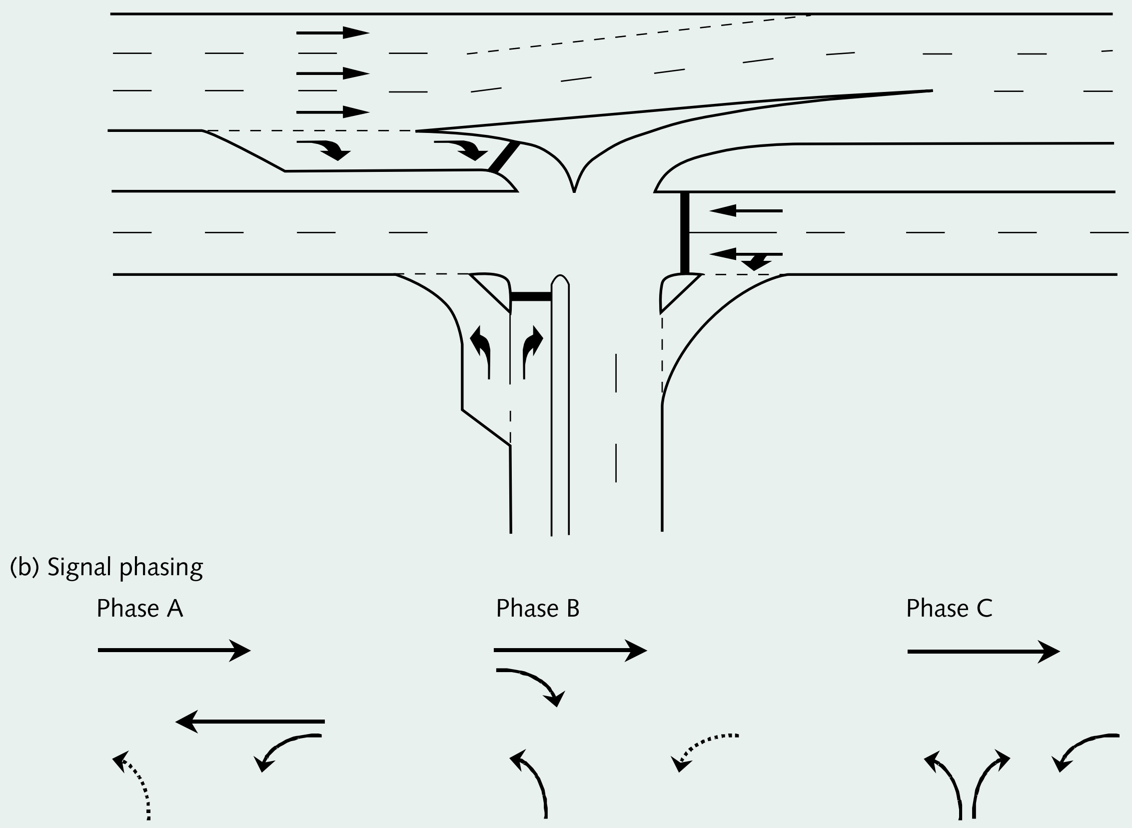
If traffic has to merge on the departure, the safest option is for through traffic in the left-most lane to merge to its right. This means providing right-turn vehicles from the stem of the T-junction with their own lane or lanes on the departure as shown in *Figure 15.5(a)*.

A capacity and performance evaluation should be carried out to determine if the seagull operation is more efficient than other intersection design options. This should account for lane underutilisation on the major approach road from the left of the T-intersection that is likely to be caused by this treatment.

Figure 15.5 "Seagull" T-intersection geometry and signal phasing

(a) Intersection geometry

(b) Signal phasing



15.9.2 Paired Intersections

Paired intersection is a term used for two closely-spaced intersections with limited queuing space between the two intersections (internal approaches). Typical examples are staggered T-intersections and freeway diamond interchanges as seen in *Figures 15.6(a) and (b)*. Intersections with a wide median have similar characteristics.

Paired intersections are regulated either by a single traffic signal controller using built-in offset arrangements achieved through special phasing arrangements, or by two separate signal controllers that are linked under a signal coordination system.

With paired intersections, care should be taken to avoid the potential "see through" problem, i.e. downstream green signals being seen by motorists stopped at the upstream stop line (see *Section 7.5.7*).

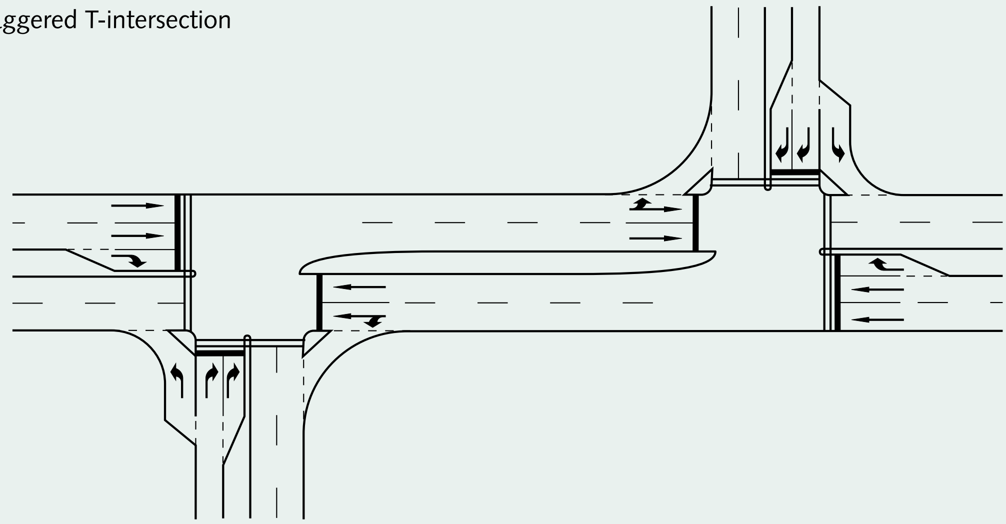
Severe unequal lane utilisation may be observed due to heavy origin-destination flows in paired intersection systems, e.g. "dog-leg" movements at staggered T-intersections. This should be taken into account in designing geometry and signal phasing for paired intersections.

Management of queuing in internal approaches of a paired intersection system is important to avoid blockage of upstream signals by through and turning vehicles queued in internal approach lanes. Early cut-off and early start phasing arrangements, simultaneous offsets (*Section 13.2.2*) and shorter signal cycle times are useful methods for this purpose (*see Appendix C*).

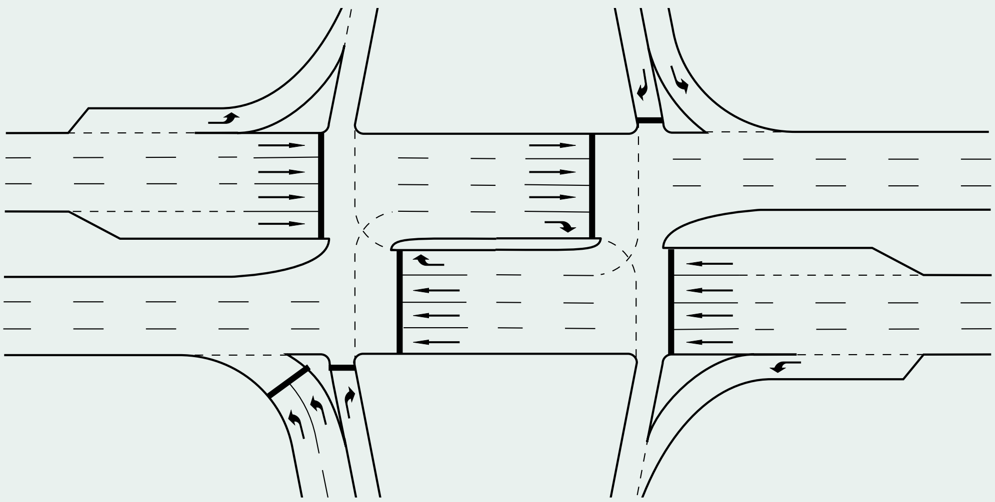
It is important to ensure that adequate queue storage spaces are provided for vehicles turning right from internal approaches to the freeway on-ramps.

Figure 15.6 Examples of staggered T-intersection and freeway diamond interchange

(a) Staggered T-intersection



(b) Freeway diamond interchange



15.9.3 Intersections With More Than Four Legs

At intersections with more than four legs, potentially, there are more than four origin-destination movements from each approach road. The design of lane arrangements (*Section 3*) and signal phasings (*Section 6*) for such intersections is a significantly more complex task. Where allowed, U-turn movements will also need to be considered in the design. Refer to AS 1742 Part 14, Section 6.2.3. Generally, these complex intersections would be treated on a site-specific basis.

An example of a five-way intersection geometry and phasing arrangements is shown in *Figure 15.7*.

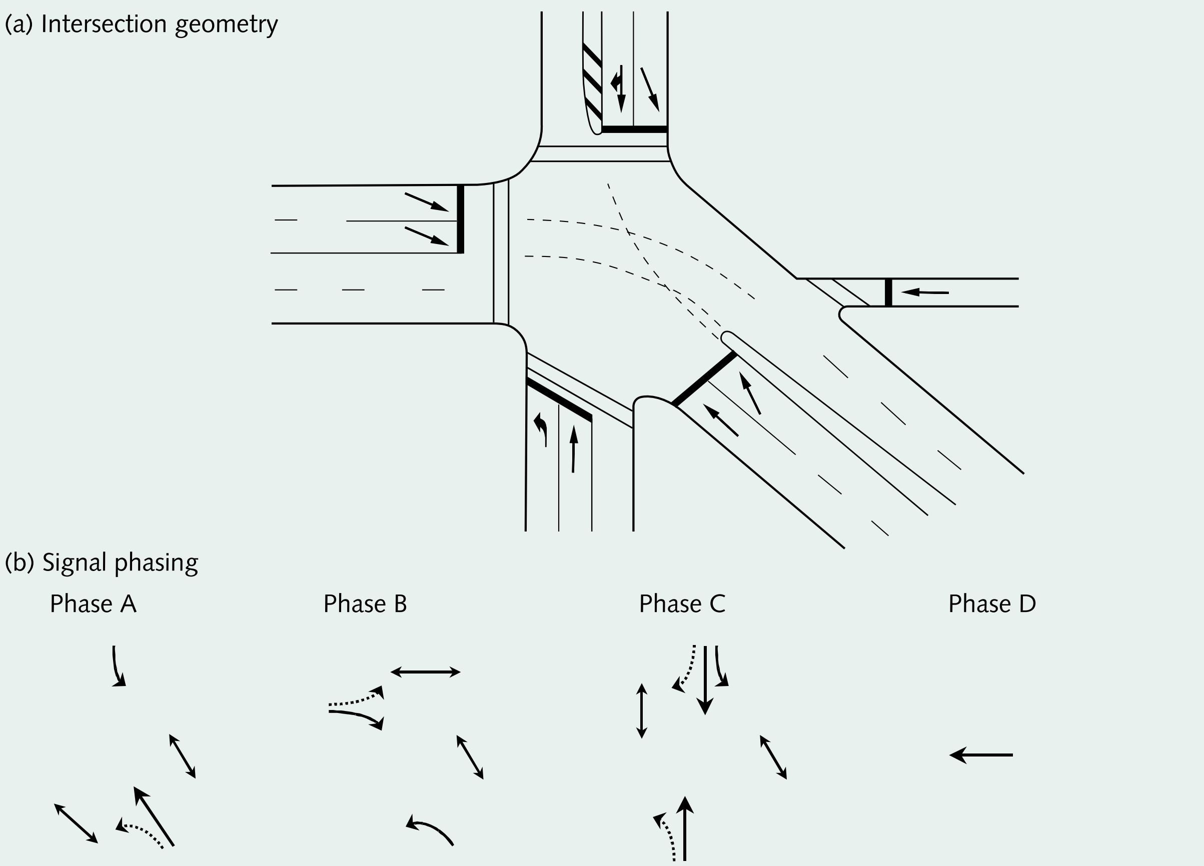
The complexity of signal design for such intersections depends on the number of conflicting vehicle movements. The main aim is to minimise the number of phases as much as possible by eliminating some of the conflicting movements. This may mean banning some movements by using regulatory signs, introducing one-way approach and one-way exit conditions, or introducing partial or total road closure. Where movements are banned alternative routes should be available and may need to be signposted as such. In *Figure 15.7*, the East leg is a one-way approach, and the right-turn movement from the West leg to the South leg is banned.

Pavement markings should reflect the physical direction of travel as appropriate as shown in *Figure 15.7*. This consideration also applies to three-way and four-way intersections where legs intersect at other than 90-degree angles, e.g. Y-junctions.

Signalised crossings may require special attention, depending on the vehicle movements permitted in the same phase, to ensure that there are no safety problems. The inclusion of signal-controlled bus, bicycle, or tram lanes can further complicate the signal phasing for this type of intersection. Where possible these special vehicles should be controlled by normal vehicular displays.

For intersections where legs intersect at other than 90-degree angles, care needs to be taken to avoid the potential see through problem by ensuring that the green signals on one leg are not seen by drivers on an adjacent leg.

Figure 15.7 Example of an intersection with more than four legs



15.10 Overhead Lane-Control Signals

Overhead lane-control signals may be used to control a reversible flow lane as part of a peak period tidal flow scheme, or to control lane usage at a toll station or a similar facility.

Overhead lane-control signals are single-aspect white arrow or red cross as shown in *Figure 15.8*. The white downward pointing arrow permits travel in that lane, the red cross prohibits travel in that lane. White arrows are used to ensure that no confusion exists with traffic signal control displays.

Where a lane-control signal aspect display is not required to change since the traffic is always allowed to use the lane in the same direction, it may be replaced by a fixed sign, subject to various conditions including:

(a) The lane arrow shall be a downward pointing white arrow on a black background or black arrow on a white background.

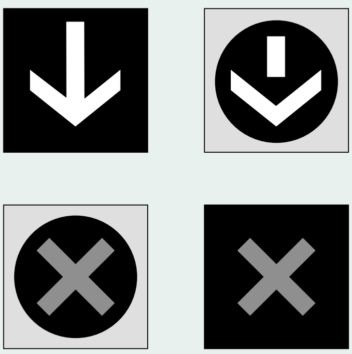
(b) The lane cross shall be red on a white background.

(c) The minimum signboard size shall be 600 x 600 mm.

(d) On each set of signals across a roadway, signals over lanes immediately to the left or right of reversible lanes shall be signal aspects and not sign alternatives.

(e) Sign alternatives shall be as conspicuous as the signal displays. White portion of the sign shall comprise retroreflective material, and external illumination shall be considered for this purpose.

Figure 15.8 Signal face layouts with white arrow and red cross aspects for overhead lane control



15.11 Single-Lane Operation and Portable Signals

15.11.1 Single-Lane Operation

Single-lane roadway operation by means of traffic signals may be applied:

(a) as a *permanent* arrangement at a single-lane bridge or other roadway constriction that is too narrow for two-way traffic (e.g. repair works that will continue for a long period of time), and where the combination of the length of single-lane section, traffic volume and inter-visibility between approaches does not permit the safe use of GIVE WAY or STOP sign control or uncontrolled operation; or

(b) as a *temporary* arrangement using portable traffic signals or temporary fixed traffic signals at roadworks or bridgeworks where the conditions in (a) above apply.

For permanent and temporary fixed traffic signals, signal faces comprise a single column with three circle aspects. A primary signal face must be installed on each approach. Both secondary and tertiary signal faces are recommended for each approach in case of lamp failure. The minimum requirement is two signal faces for each approach. The secondary and tertiary signal faces are installed 6 to 10 m beyond the primary signal face. A regulatory sign STOP HERE ON RED SIGNAL (*Section 11.3.2*) is erected adjacent to the stop line. For portable signals, see *Section 15.11.2*.

The general treatment for single-lane operation is to use two phases where one phase controls each direction of traffic. This requires very long intergreen times to allow one movement to clear the conflict area before the other movement can be started. This causes long delays that could lead to driver frustration. This cannot be avoided in heavy traffic situations, but delays can be reduced in low traffic situations by adding an all-red phase. The controller will normally wait in the all-red phase until one of the other two phases is demanded. That phase can then be introduced immediately with minimum delay to the motorist. The phase is extended and terminated as usual.

Where guard fence is used on the single-lane bridge approaches, it should be extended, if necessary to protect the traffic signal posts and controller.

15.11.2 Portable Signals

Portable traffic signals are intended primarily for short-term application of single-lane operation. If conditions are to continue unchanged for longer than two or three months, consideration should be given to the installation of temporary fixed, rather than portable, traffic signals (see *Section 15.11.1*). Decision regarding this can be made on safety and economic grounds.

Portable traffic signals comprise a single column with three circle aspects, and are usually trailer mounted or in tripod format. One signal face is required to control each direction of travel. This is located at (or 6 m downstream of) the stop line or stopping position on each approach. A regulatory sign STOP HERE ON RED SIGNAL (*Section 11.3.2*) is also erected adjacent to the stop line.

Requirements for the design, construction and performance of portable traffic signal systems are specified in AS 4191. Location and operation of portable traffic signals is described in AS 1742 Part 3.

15.12 Left Turn On Red

A LEFT TURN ON RED PERMITTED AFTER STOPPING (LTOR) sign (*Figure 11.9*) allows vehicles on the signed signalised intersection approach to turn left when facing a red circle display, subject to having first stopped at the stop line on that approach, then proceeding only if it is safe to do so. Location of the LTOR sign is discussed in *Section 11.3.8*.

LTOR may be used as a delay reduction measure, subject to any jurisdictional regulations and the criteria described in the Australian Standard AS 1742 Part 14 to ensure the safety of pedestrians, cyclists and motorists. LTOR may be considered for use where the left-turn movement is controlled by circular aspects only.

In addition to the conditions for use specified in AS 1742 Part 14 , LTOR is not permitted on any approach where the LTOR movement would conflict with a bus or tram movement proceeding on a white display.

The loop detectors in the left lane, where LTOR is used will need to be presence timed to zero to ensure that a vehicle having turned from the lane during the red period does not unnecessarily initiate a phase change.

Slip lanes should not be provided with LTOR signs as other road rules apply to this situation.

15.13 Metering Signals at Sign-Controlled Intersections

The use of metering signals at intersections controlled by give-way or stop signs is an unusual application, and can only be applied where local traffic regulations permit. The system is similar in operation to roundabout metering signals (*Section 15.7*). However, it is only recommended for local urban collector roads where the posted speed limit is 60 km/h or below.

The objective of the system is to reduce excessive delays experienced by sign-controlled movements that have difficulty in finding adequate gaps in priority traffic streams. As an alternative to full signalisation, the metering signals are employed on a part-time basis at sites where they are required only during peak demand periods.

This arrangement consists of two-aspect yellow and red signals (see *Figure 5.6(a)* in *Section 5.3.4*) for metering the major road traffic, and a queue detector (*Section 8.3.4.3*) to detect vehicles waiting on the sign-controlled approach. The sequence of aspect display is **Off** to **Yellow** to **Red** to **Off**.

When metering is not required, metering signals facing the major road traffic are in Off state (blank display). When the queue detector on the approach subject to sign control detects vehicles waiting, the metering signals display Yellow and then Red. When the Red display is terminated on the major road, the intersection reverts to normal operation. In one jurisdiction, two-aspect yellow and green displays were used on the sign-controlled approach. In this case, the display sequence was **Off** to **Green** to **Yellow** to **Off**.

A regulatory sign STOP HERE ON RED SIGNAL (*Section 11.3.2*) is used at the major road stop line as in the case of roundabout metering signals.

Appendix A Human Factors

A.1 General

This appendix discusses aspects of human characteristics relevant to traffic signal control. Road users, including drivers, pedestrians and cyclists, are engaged in a variety of tasks in the road environment, and have unique elements and characteristics in relation to traffic control purposes. Knowledge of human capabilities and behavioural characteristics is a vital input to the successful development of all aspects of traffic engineering and control (Ogden 1996).

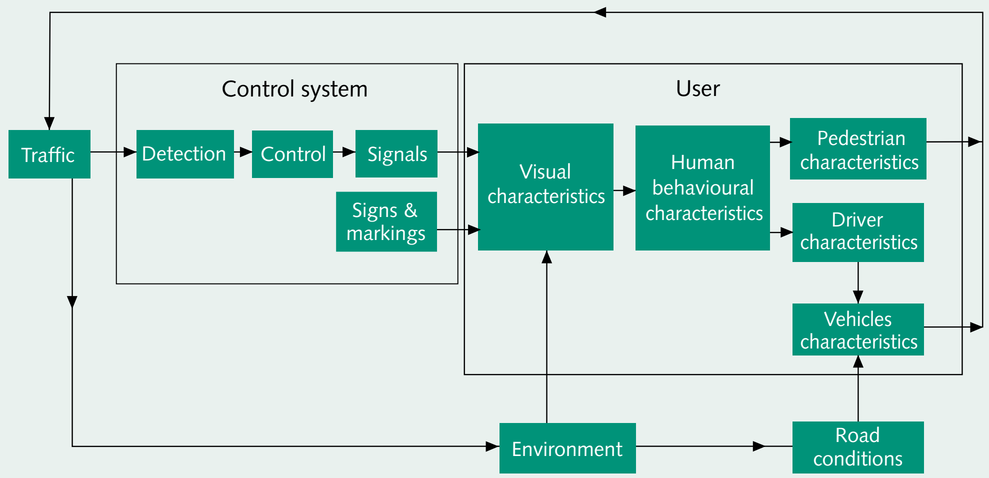
Similarly, some critical characteristics of vehicles using road facilities need to be considered in the design of road and traffic control elements (Gardner 1996). Vehicular traffic factors are discussed in *Appendix B*. Detailed treatment of pedestrian and bicycle traffic characteristics can be found in the Highway Capacity Manual, Chapters 11, 18 and 19 (TRB 2000), ITE (1998), and Austroads GTEP Part 13 (Pedestrians) and Part 14 (Bicycles). Transit (bus, tram, light rail) concepts and analysis methods can be found in the Highway Capacity Manual, Chapters 14 and 27 (TRB 2000). Detailed information on human and vehicle factors can also be found in Lay (1985).

A simplified block diagram that shows the basic elements involved in the traffic control process is given in *Figure A.1*. The interfaces between the human elements and the external world are the *senses*, and the most significant sense is *vision*, which is of particular interest. Information transfer from the traffic control system to the road user is aided if the traffic signals, signs and pavement markings match the human visual characteristics of the majority of the population. This involves visual acuity, sensitivity to light, and colour discrimination, as well as the time-related effects of perception and reaction.

On the other hand, successful application of traffic signal control depends on the extent to which it matches the traffic requirements. At low levels of traffic, conflict between different road users moving at speed increases accident risk, whereas under congested conditions such conflict generates delays and builds up frustration.

Delay and the number of stops experienced by vehicles and pedestrians may not always be reduced by installation of traffic signals, but the efficient use of signals may generally cause delays and the number of stops to be redistributed. Similarly, the number of accidents may not decrease significantly after installation of signals, but the type of accidents will be different, and in general, accident severity will be reduced.

Figure A.1 Basic elements interacting in the traffic situation



A.2 Human Behaviour

The complexity of human behaviour makes it impossible to deal adequately with this vital subject apart from describing a few basic concepts, within the scope of this guide.

Important aspects of human performance relevant to traffic control are information processing and decision-making, visual characteristics and information needs (Ogden 1996). Various aspects of information processing and decision-making are discussed in this section, and visual characteristics are discussed in *Section A.3*. Refer to Ogden (1996) for a discussion of key needs of road users in relation to traffic control, namely conspicuity, legibility, comprehensibility and credibility.

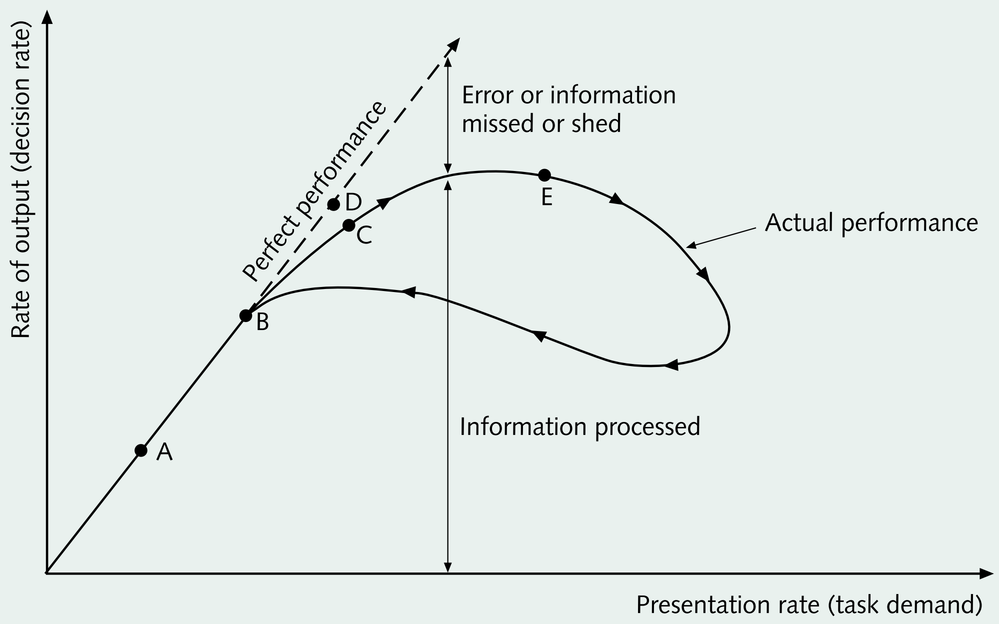
Considerable evidence shows that humans can deal with only a limited amount of information at a time, and that they require a measurable length of time to respond to events in their environment. The length of time required to respond to an event depends, amongst other things, on the number of other activities or events being attended to, the probability of the event occurring, how far ahead the event can be predicted, whether a subsequent important event is anticipated, the number of possible alternative responses and the complexity of the response required (Welford 1969). Measurements of actual response times to changes in traffic lights without any complicating factors has been found to be in the range 1 to 2 seconds.

The human system deals with stress situations in a complex way. A conceptual model of the human decision-making process is shown in *Figure A.2*. At point **A**, the task is well within the ability of the driver, but the demand for mental stimulation inherent in the human system forces him to adjust the overall task to point **B** by adding *self-paced* tasks (such as listening to the radio or having a discussion with a passenger). With an increase in the *externally-paced* task demand, the driver must first reduce the self-paced task. A further increase in the externally-paced task demand brings the driver's performance to point **C**. This may not be recognised by the driver who thinks his performance is at **D**.

This over-estimation of his own decision-making ability is a potentially dangerous human characteristic. If the presentation rate increased to **E**, it may only be the driver's skill in shedding redundant information or good fortune that may avert disaster. A more detailed and informative treatise on this subject is given by Cumming (1964).

Hebb (1955) postulated a relationship to explain how changes in performance result from changes in arousal, as shown in *Figure A.3*. Arousal describes the general state of interaction between influences such as noise,

Figure A.2 Conceptual model of the human decision-making process



sleeplessness, intoxication, incentive, and time-of-day. A rise in arousal yields a rise in performance only up to a certain optimal level, but any increase in arousal beyond this optimal level will produce a drop in performance.

Such limitations in road user performance should be taken into account in the design of traffic signals. The safe and efficient movement of vehicles and pedestrians can be assisted by requiring road users to make simple decisions, one at a time, with adequate time between decisions, and with sufficient advance warning. This is helped by measures such as:

(a) providing the minimum number of signal faces for safe traffic control,

(b) ensuring consistency and uniformity of signal installation and operation,

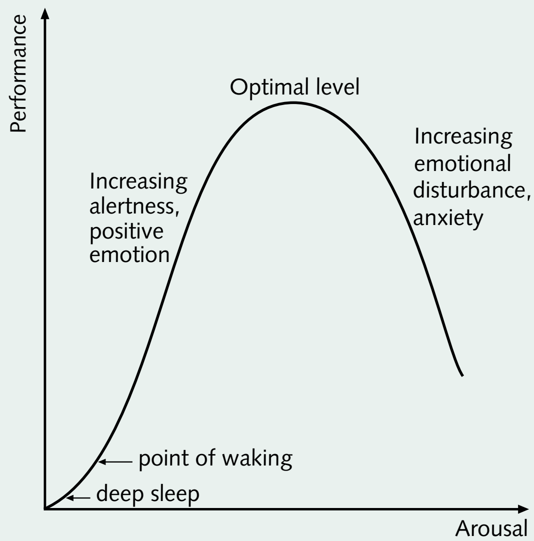
(c) ensuring sight to potential traffic conflicts is not obstructed, e.g. for a filter right turn, or a left turn from a slip lane,

(d) ensuring signs and pavement markings are adequate for special provisions, e.g. turn bans, left turn on red, exclusive pedestrian phase,

(e) providing adequate advance warning of traffic signals, lane discipline, or manoeuvring where required, and

(f) minimising competing information in the immediate vicinity of traffic signals.

Figure A.3 Postulated relationship between performance and arousal (after Hebb 1955)



For safety reasons pedestrian movements must be carefully analysed when designing traffic signals. Pedestrians will ignore the protection offered by pedestrian signals if they are faced with what they consider is an unreasonable delay, or a badly located signalised crossing.

Determination of pedestrian Walk and Clearance times for pedestrian signals is discussed in *Appendix C*.

A.3 Vision

The detection of a signal is dependent on intensity, colour, luminous contrast with the background, position of the signal in the visual field of the observer and its exposure time.

Three visual attributes are of major importance in the context of drivers' ability to perceive and respond to traffic signals. These are:

(a) visual sensitivity,

(b) visual acuity, and

(c) colour perception.

The same attributes apply to pedestrians who are also required to obey traffic signals, but pedestrian response characteristics are not as critical because of their slower movements.

Some pedestrians have visual handicaps and therefore audio-tactile push buttons and tactile ground surface indicators must be provided to cater for their needs.

A.3.1 Visual Sensitivity

Visual sensitivity refers to the ability of the eye to respond to luminance differences in different parts of the scene and is intimately connected with contrast. The threshold for detection of contrast rises with increasing age. Compared with young, visually fit persons, it is 18 per cent higher at age 42 years, and 80 per cent higher at age 64 years. Older drivers therefore require a higher target light intensity to arouse the same response as in young drivers (Cole and Brown 1968).

In the absence of other distracting or confusing light sources, detection of signal displays is performed on the basis of contrast. When a signal is seen against a background of high brightness, such as the clear sky, higher signal light intensity is necessary to maintain a high probability of detection and a short reaction time. The effect of the luminance of the background can be reduced by the provision of a black target board behind the signal (Cole and Brown 1966; Fisher and

Cole 1974). It should be noted that, in the measuring of contrast, there is direct (inverse) relationship between the signal intensity and the amount of background screening provided by a target board of a given size under given conditions of background luminance. Contrast can also be reduced by sun phantom that raises the level of reflected light from un-energised signal aspects making detection of the energised signal difficult.

Because signals cannot normally be placed on the direct line of sight of an approaching driver, an allowance has to be made for the reduced visibility of signals located eccentrically to the line of sight.

As shown by Fisher and Cole (1974), the research into effects of background luminance, visibility range, eccentricity of signals to direct line of sight, sun phantom and related factors can be applied to develop a signal intensity specification based on a high probability of detection and minimum reaction time.

A.3.2 Visual Acuity

Visual acuity describes the ability of the eye to distinguish fine detail (ability to see clearly). Poor visual acuity resulting from congenital or age-related eye defects can usually be corrected by supplementary refraction, i.e. spectacles. However, mild refractive error is not a serious handicap in every day life and is relatively common.

Poor visual acuity is significant in the reading of signs, for example a person with poor acuity may need to stand at half the reading distance of a person with normal visual acuity to read a sign legend equally well. Shape-coded light signals such as arrows and human figure outlines are more tolerant to the effects of blur (Smith and Weir 1975).

Because of the effects of irradiation, especially under conditions of low ambient light levels, the signal luminance of shape-coded signals must be controlled more carefully than the circular signal and the resultant reduced intensity of such signals severely restricts the visibility range as compared to the circular signal.

A.3.3 Colour Perception

Since the primary information of the signal is transmitted as changes in colour, the recognition of colour is an important consideration. Two areas of particular significance in relation to traffic signal displays are *colour vision defect* and the *effects of glare*.

About 8 per cent of males and approximately 0.4 per cent of females have some defect in discriminating colours involving the red and green receptor system. A summary of the main types of colour vision defects in relation to traffic signals is given by Fisher and Cole (1974). In order to make allowance for the incidence of colour vision defects in the signal displays, colour is specified within close limits and at maximum spectral separation. This provides the optimum degree of colour discrimination for people who confuse the red and green colours. Position-coding of signals also assists. In a vertically-oriented system, the red signal is therefore only displayed on the top and the green signal on the bottom (see *Section 5*). In a horizontally-oriented system (e.g. for lane control), the red signal is always on the right and the green signal on the left of the lantern.

It is important to communicate the correct coloured image to the eye, and when glare is present this communication may not happen. Glare results when the light intensity or luminance levels of the signal become so high that the eye is overloaded. A light source that produces this sensory overload communicates false information and reduces the overall effectiveness of the system. Dimming of signals may therefore be necessary under conditions of low ambient light.

The eye is sensitive to only a narrow band of wavelengths. However, colour perception cannot be described only in terms of wavelength, and in practice three inexact terms are used to describe colour:

(a) *hue*, which is related to wavelength,

(b) *saturation*, which refers to the purity of the colour, i.e. how much white is in the mixture, and

(c) *brightness*, which describes whether a colour is vivid or dim.

This "three-dimensional" concept of colour was developed by the Commission Internationale de l'Eclairage (CIE) into a quantitative system of colour coordinates which takes due account of the colour response of the human eye. This quantitative system is based on the normalised quantities X, Y and Z which are inter-related by the equation $X + Y + Z = 1$. The CIE chromaticity diagram uses coordinates X and Y only, and forms the basis of all modern colour specifications (Blevin 1972). The CIE chromaticity diagram can be found in AS 2144 and AS/NZS 2633.

The colour boundaries for red, green and yellow signals apply to a four-colour system, the fourth colour being white. As stated previously, it is important to maintain the maximum separation between colours to allow for colour vision defect. At the same time, the boundaries of the red and green signals should be chosen away from the extremities of the visible spectrum where the sensitivity of the eye is reduced, and much higher signal intensities would be required to satisfy the criteria outlined in *Section A.3.1*. Colour and signal intensity are significantly interconnected and in practice red signals are chosen as close as possible to the "yellow boundary" of the chromaticity diagram, while green signals are selected as close as possible to the "white boundary" for maximum light output.

A.3.4 Photometric Requirements of Signals

The photometric requirements of signals cover not only the intensity distribution of the coloured light and the colour boundaries, but also the amount of sun phantom and size of target boards.

Cole and Brown (1968) determined the actual intensity for rapid perception of a red signal. The standard has been set by the criterion of 200 cd of red light at a distance of 100 m. This distance is equivalent to a stopping distance from a speed of 80 km/h under dry conditions, or 65 km/h under wet conditions. Fisher (1971) developed a specification for the intensity distribution of the signal having regard to eccentric viewing angles met in practical situations. Fisher also deduced that the relative intensities of the three colours should be in the ratios 1:1.33:3 for red, green and yellow signals respectively. He recommended that the amount of sun phantom from the yellow aspect should be limited to 8.3 per cent of the on-axis signal intensity of the energised red and green aspects.

Fisher and Cole (1974) gave a summary of this development. Hulscher (1975) extended Fisher's work to signals for a viewing range up to 240 m. The photometric specification for both types of signal is now incorporated in AS 2144.

Appendix B Vehicular Traffic Factors

B.1 General

As in the case of human factors discussed in *Appendix A*, a sound knowledge of *characteristics of vehicles* using traffic control facilities and a good understanding of relevant *vehicular traffic factors* are essential to successful implementation of traffic control measures.

Important vehicle characteristics relevant to traffic control include vehicle dimensions and manoeuvrability (including overall size, length, width, height, mass and power to weight ratio), braking (deceleration), acceleration, visibility (related to sight distance) and cornering. In this respect, it is important to recognise different characteristics of different vehicle types such as cars, vans, buses, bicycles, motorcycles, trucks, rigid vehicles, semi-trailers, and so on (TRB 2000, Chapters 2 and 8). In order to simplify vehicular traffic analysis, different vehicle types are often classified into *light vehicle* and *heavy vehicle* categories. Consideration of the effect of different ages of vehicles in the general vehicle population is also important in relation to critical vehicle characteristics.

Vehicle braking characteristics are discussed in *Section B.2*. Refer to Gardner (1996), Homburger, et al (2001), Lay (1985) and Pline (1999) for more detailed information. Basic characteristics of vehicular traffic relevant to traffic signal control are discussed in *Section B.3*.

B.2 Vehicle Deceleration and Acceleration Characteristics

B.2.1 Deceleration Characteristics

It is necessary to consider vehicle deceleration characteristics in terms of *braking capabilities*, e.g. for the purpose of determining yellow time, and deceleration characteristics for *normal operational analysis*, e.g. for geometric delay or operating cost calculations.

In terms of braking performance, the vehicle stopping distance, which is one of the most important considerations in traffic signal design, consists of the distance travelled during reaction time, and the distance travelled during braking. It may be expressed as:

$$D_s = D_r + D_b = \frac{t_r\, v_i}{3.6} + \frac{v_i^2}{254(f+G)} \qquad \text{(B.2.1)}$$

where

- D_s = stopping distance (m),
- D_r = reaction distance (m),
- D_b = braking distance (m),
- t_r = reaction time (s),
- v_i = initial speed before braking (km/h),
- f = longitudinal coefficient of friction (assumed constant throughout braking), and
- G = approach grade (per cent grade divided by 100; negative value for downhill grade and positive value for uphill grade, e.g. - 0.05 for 5 per cent downhill grade).

While a general-purpose reaction time of t_r = 2.5 s is recommended in the literature, possibly appropriate for unalert drivers in general driving conditions (Gardner 1996; Lay 1985), a reaction time of t_r = 1.0 or 1.5 s is used in *Appendix C* (*Section C.4.6.1*) for determining the yellow time at signals. Using t_r = 1.5 s, the vehicle stopping distance can be determined from:

$$D_s = 0.42\, v_i + \frac{v_i^2}{254(f+G)} \qquad \text{(B.2.2)}$$

The above expressions assume a constant deceleration rate, a_d (in m/s^2) from an initial speed v_i (km/h) to zero final speed, and calculate the braking distance from $D_b = 0.5\,(v_i^2 / 12.96) / a_d$, where $a_d = g\,(f + G)$ for braking on a road with frictional coefficient f and grade G (g is the gravitational acceleration rate, g = 9.8 m/s^2). The braking time (t_b in seconds) for constant acceleration rate can be determined from $t_b = 7.2\, D_b / v_i = (v_i / 3.6) / a_d$ where v_i is in km/h and a_d is in m/s^2.

The road grade (G) is seen to add to (or subtract from) the value of the friction coefficient *f*. For braking on a level road (G = 0), $a_d = g f$. Thus, the friction coefficient represents the maximum available deceleration expressed in units of the gravitational acceleration rate. For example, the deceleration rate of a_d = 3.0 m/s^2 used in *Appendix C* (*Section C.4.6.1*) for determining yellow time implies a friction coefficient of *f* = 0.31 on a level road (G = 0). In this case, using *Equation (B.2.2)* for an initial speed of v_i = 60 km/h, a braking distance of D_b = 46 m (braking time, t_b = 5.6 s), and a total stopping distance of D_s = 71 m are found.

While *Equations (B.2.1) and (B.2.2)* are based on a constant acceleration model, Akçelik and Biggs (1987) described a polynomial model that better represents the S-shaped speed-time profiles of vehicles in acceleration or deceleration. However, they found that percentage errors in deceleration distances predicted by the constant deceleration model compare reasonably well with prediction errors from the polynomial as well as linear and sinusoidal models.

Note that the friction coefficient varies due to many factors such as types and conditions of tyres and road surface. Clean, wet, hard surface pavements, and tyres in reasonable condition are assumed in determining the value of friction coefficient for traffic control and design purposes (Gardner 1996). Austroads (2000) Guide to the Selection of Pavement Surfacings gives information on the skid resistance and surface texture levels at which investigation might be considered to determine whether remedial treatment is required.

A marked reduction in the friction coefficient occurs with wet pavements (Oliver 1979), a situation that is not always realised by drivers since the friction characteristics of a pavement surface are not apparent from its appearance, particularly where polishing of the aggregate has occurred.

Data given in Glauz and Harwood (1999) indicates that appropriate friction coefficients for cars on wet surfaces are in the range 0.28 to 0.40, corresponding to deceleration rates in the range 2.7 to 3.9 m/s^2.

Glauz and Harwood (1999) suggest that deceleration rates up to 3.0 m/s^2 are comfortable for passenger car occupants, and suggests this value for determining yellow time at signals (see *Appendix C, Section C.4.6.1*).

In terms of deceleration characteristics for normal operational analysis, maximum deceleration rates of 1.7 m/s^2 for cars, 1.5 m/s^2 for light trucks and 1.2 m/s^2 for heavy trucks were observed during deceleration manoeuvres at signalised intersections, roundabouts and priority intersections in urban areas in New Zealand (Dibley and Reid 1990).

The deceleration model for normal operating conditions for light vehicles at intersections described in Akçelik & Associates (2001a) indicates an average deceleration rate of 1.8 m/s^2 and a corresponding maximum deceleration rate of 3.1 m/s^2 for stopping from an initial speed of 60 km/h. For a heavy vehicle with a power to weight ratio of 12, the model indicates an average deceleration rate of 1.3 m/s^2 and a corresponding maximum deceleration rate of 2.2 m/s^2 for stopping from an initial speed of 60 km/h. Based on these values, average deceleration rates are seen to be approximately 60 per cent of the maximum deceleration rates.

B.2.2 Acceleration Characteristics

Acceleration rates observed under normal operating conditions are also smaller than maximum acceleration rates that represent acceleration capabilities of vehicles (the latter is relevant to, for example, design of acceleration lanes at interchanges). Jarvis (1982) observed maximum acceleration rates in the range 1.1 to 3.9 m/s^2, and the corresponding average acceleration rates were in the range 0.8 to 1.2 m/s^2.

Glauz and Harwood (1999) give maximum acceleration rates in the range 1.7 to 2.8 m/s^2 for cars and 0.2 to 0.9 m/s^2 for trucks, and states that normal acceleration rates are less than 65 per cent of the maximum acceleration rates for cars. Akçelik and Biggs (1987) reported that the observed values of the ratio of average acceleration to maximum acceleration in each acceleration manoeuvre were in the range 0.24 to 0.67 (Akçelik, Biggs and Lay 1983).

The acceleration model for normal operating conditions for light vehicles at intersections given in Akçelik & Associates (2001a) indicates an average acceleration rate of 1.5 m/s^2 and a corresponding maximum acceleration rate of 2.7 m/s^2 for acceleration from stopped position to a final speed of 60 km/h. For a heavy vehicle with a power to weight ratio of 12, the model indicates an average acceleration rate of 0.8 m/s^2 and a corresponding maximum acceleration rate of 1.4 m/s^2 for acceleration from stopped position to a final speed of 60 km/h.

B.3 Basic Properties of Vehicular Traffic

B.3.1 General

Various traffic characteristics are used to describe collective behaviour of vehicles in traffic, hence referred to as *traffic flow parameters*. Knowledge of relationships among traffic flow parameters is useful for traffic signal control purposes as discussed in *Section 8.1* in relation to traffic detection.

The basic parameters describing traffic flow characteristics can be summarised as follows:

(i) distance-based traffic flow parameters: spacing (L_h), space (gap) length (L_s), vehicle length (L_v);

(ii) time-based traffic flow parameters: headway (h), vehicle passage time (t_v), gap time (t_g), occupancy time (t_o), space time (t_s); and

(iii) other traffic flow parameters derived from the time-based and distance-based parameters: speed (v), flow rate (q), density (k), time occupancy ratio (O_t), and space occupancy ratio (O_s).

Average values of the above parameters are considered when representing aggregate characteristics of traffic streams. The parameters are explained in *Sections B.3.2 and B.3.3*. For further information, refer to Akçelik, Besley and Roper (1999) and Akçelik, Roper and Besley (1999).

B.3.2 Basic Parameters

This section discusses all parameters listed in *Section B.3.1* except flow rate, density and occupancy ratios, which are discussed in *Section B.3.3*.

Figure B.1 gives a simple diagram that summarises the relationships among basic traffic parameters. See *Figure 8.1* in *Section 8* for a diagram showing parameters relevant to the measurement of traffic parameters by presence detection.

Spacing is the distance between the front ends of two successive vehicles in the same traffic lane. *Space (gap) length* is the following distance between two successive vehicles as measured between the rear end of one vehicle and the front end of the next vehicle in the same traffic lane (spacing less *vehicle length*).

Headway is the time corresponding to spacing, i.e. time between passage of the front (leading) ends of two successive vehicles ($h = t_2 - t_1$ in *Figure B.1*). *Vehicle passage time* is the time between the passage of the front and back ends of a vehicle from a given point along the road. *Gap time* is the time between the passage of the rear end of one vehicle and the front end of the next vehicle, measured at a given point along the road, and is equivalent to headway time less vehicle passage time.

Occupancy time starts when the front of a vehicle enters the detection zone and finishes when the back of the vehicle exits the detection zone. Thus, it is the duration of the period when the detection zone is occupied by a vehicle. *Space time* is the time between the detection of two consecutive vehicles when the presence detection zone is not occupied. It is equivalent to gap time less the time taken to travel the effective detection zone length.

Speed is the distance travelled per unit time. In a time - distance diagram, the slope of the trace of a vehicle is its speed as seen in *Figure B.1*.

The relationships among the basic parameters described above and shown in *Figure B.1* are summarised below (time-based parameters are in seconds, distance based parameters are in metres, and speed is in m/s):

$$L_h = L_v + L_s = h\ v / 3.6 \quad (B.3.1)$$

$$L_s = L_h - L_v = t_g\ v / 3.6 \quad (B.3.2)$$

$$h = 3.6\ L_h / v = t_o + t_s = t_v + t_g \quad (B.3.3)$$

$$t_v = 3.6\ L_v / v \quad (B.3.4)$$

$$t_o = 3.6\ (L_p + L_v)/v = t_v + 3.6 L_p/v \quad (B.3.5)$$

$$t_g = h - t_v = 3.6\ L_s / v \quad (B.3.6)$$

$$t_s = h - t_o = 3.6\ (L_s - L_p) / v \quad (B.3.7)$$

$$v = 3.6\ L_h / h = 3.6\ L_s / t_g \quad (B.3.8)$$

where

L_h = spacing (m),

L_s = space (gap) length (m),

L_v = vehicle length (m),

L_p = effective detection zone length (m),

h = headway (seconds),

t_v = vehicle passage time (seconds),

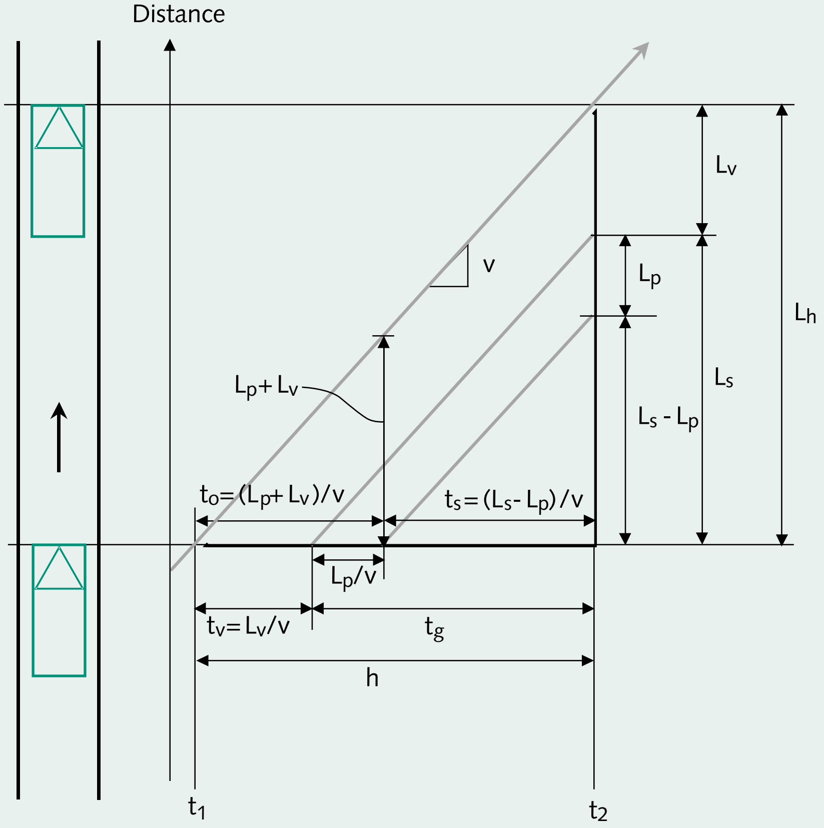
t_g = gap time (seconds),

t_o = occupancy time (seconds),

t_s = space time (seconds), and

v = vehicle speed (km/h).

Figure B.1 Diagram showing the relationships among basic traffic parameters



Where the traffic stream is represented as a mixture of light and heavy vehicles, the average vehicle length representing the actual traffic composition can be calculated according to the proportions of these two classes of vehicles in the traffic stream. For example, using average vehicle lengths of 4.4 m and 9.0 m for light and heavy vehicles, respectively, the average vehicle length with 10 per cent heavy vehicles is approximately 4.9 m.

For general analysis purposes, the effective detection zone length may be considered to be equal to the physical loop length. The typical loop length used in Australia is 4.0 m or 4.5 m.

B.3.3 Flow Rate, Density and Occupancy Ratios

Flow rate is the number of vehicles per unit time passing (arriving or departing) a given reference point along the road. With queuing at interrupted traffic facilities, demand flow rate can be measured as the arrival flow rate at the back of the queue. *Density* is the number of vehicles per unit distance along the road as measured at an instant in time.

Time occupancy ratio is the proportion of time in an analysis period when the passage or presence detector at a point along the road is occupied by vehicles. *Space occupancy ratio* is the proportion of a road section (distance) occupied by vehicles at an instant in time.

The relationships among flow rate (veh/h), density (veh/km) and occupancy ratios (percentage values) are summarised below:

$$q = 3600 / h = 1000\ v / L_h \quad (B.3.9)$$

$$k = 1000 / L_h = q / v \quad (B.3.10)$$

$$q = v\ k \quad (B.3.11)$$

$$O_t = 100\ t_o / h = 100\ (L_v + L_p) / L_h \quad (B.3.12a)$$

for presence detection and subject to $O_t \leq 100$ %

$$O_t = 100\ t_v / h = 100\ L_v / L_h \quad (B.3.12b)$$

for passage detection

$$O_s = 100\ L_v / L_h = L_v\ k / 10 \quad (B.3.13)$$

where

q = flow rate (veh/h),

k = density (veh/km),

O_t = time occupancy ratio (per cent),

O_s = space occupancy ratio (per cent),

v = speed (km/h),

h = headway (s),

L_h = spacing (m),

L_v = vehicle length (m),

L_p = effective detection zone length (m),

t_o = occupancy time (seconds), and

t_v = vehicle passage time (seconds).

In traffic theory, *Equation (B.3.11)* is known as the fundamental traffic flow relationship.

From *Equations (B.3.12b) and (B.3.13)*, it is seen that space occupancy and time occupancy ratios are equivalent with passage detection, $O_s = O_t$.

B.3.4 Basic Relationships at Traffic Signals

The basic relationships given in *Sections B.3.2 and B.3.3* are applicable to queue discharge and uninterrupted flow conditions at traffic signals.

Drivers maintain what they feel is a safe distance when following other vehicles. The minimum spacing (or gap length) values can be observed between vehicles in a queue at signals. The average spacing between vehicles in a queue is called *jam spacing* (L_{hj}). This equals the average vehicle length (L_v) plus the average jam gap length (L_{sj}) measured from the back of the leading vehicle to the front of the following vehicle in the queue:

$$L_{hj} = L_{sj} + L_v \quad (B.3.14)$$

The density that corresponds to the jam spacing is called the *jam density* (i.e. the number of vehicles per unit distance in a stationary queue) in veh/km:

$$k_j = 1000 / L_{hj} \quad (B.3.15)$$

As vehicles speed up from a stationary queue, the gap length between vehicles increases gradually, and therefore the spacing increases as a function of speed. After an initial acceleration period, vehicles departing from a queue at traffic signals cross the stop line with approximately constant headways. This is the *minimum (saturation) headway* (h_n), which corresponds to a maximum flow rate known as *saturation flow rate* ($q_n = s = 3600 / h_n$). Other corresponding parameters include the saturation speed (v_n), spacing at saturation flow (L_{hn}), occupancy time at saturation flow (t_{on}), and so on.

Under uninterrupted flow conditions (as applicable after queue has been cleared at signals), vehicle spacings and headways increase, and the flow rate and density decreases, as the speed increases towards the *free flow speed* (v_f).

The maximum flow rate at traffic signals can be obtained during fully saturated green periods. *Capacity* is the maximum hourly flow rate that can be achieved with allowance for the green time available. Other important parameters used in the timing and performance analysis of signalised intersections include *degree of saturation* which is the ratio of arrival (demand) flow rate to capacity, and *flow ratio*, i.e. the ratio of arrival (demand) flow rate to saturation flow rate. These parameters can be determined from:

$$Q = s\ g / c \quad (B.3.16)$$

$$x = q / Q = q\ c / (s\ g) \quad (B.3.17)$$

$$y = q / s \quad (B.3.18)$$

where Q is capacity (veh/h), s is the saturation flow rate, g is the effective green time (s), c is the cycle time (s), and q is the arrival (demand) flow rate (veh/h).

Traffic flow conditions with demand flow rates below and above capacity are referred to as *undersaturated* and *oversaturated* conditions, respectively.

Akçelik, Besley and Roper (1999) described analytical models for queue discharge and uninterrupted flow conditions at traffic signals. The models were calibrated using data collected at eighteen signalised intersections in Sydney and Melbourne. *Table B.1* summarises the average parameter values for through and right-turn traffic lanes at these intersections (for light vehicles only). The parameters for right-turn lanes are for arrow-controlled movements. For data presented in *Table B.1*, average vehicle length was $L_v = 4.4$ m, and the effective detection zone length was $L_p = 4.5$ m.

Figures B.2 to B.4 show various relationships among the basic parameters, based on the use of data given in *Table B.1* for through traffic lanes.

As seen in *Figure B.2*, each vehicle spacing measurement corresponds to a unique speed value. On the other hand, *Figure B.3* shows that, under all except saturation flow conditions ($v_n = 42$ km/h, $h_n = 1.75$ s), each headway measurement corresponds to two speed values. These represent two contrasting traffic flow conditions, i.e. free-flowing conditions with high speeds vs forced flow (congested) conditions with low speeds. For example, a 3.0 s headway represents both 1200 veh/h at 67 km/h and 1200 veh/h at 11 km/h. This severely restricts the application of passage detectors for traffic control.

In contrast with the headway measurement, each occupancy time or space time measurement by presence detection may correspond to a unique speed value as seen in *Figure B.4*. However, it is seen that occupancy times increase sharply and the space time becomes zero when speed drops to very low values. Zero space time (continuous occupancy) is a result of the *bridging* effect that occurs at low speeds when the front end of the following vehicle enters the detection zone before the rear end of the leading vehicle exits.

Table B.1 Basic traffic parameters observed at eighteen signalised intersections in Sydney and Melbourne

	Through Traffic Lanes	Right-Turn Traffic Lanes
Saturation (or maximum) flow rate, s or q_n (veh/h)	2057	2033
Free-flow speed, v_f (km/h)	69	65
Jam spacing, L_{hj} (m)	7.0	6.4
Jam gap length, L_{sj} (m)	2.6	2.0
Jam density, k_j (veh/km)	144	157
Parameters for queue discharge at saturation (maximum) flow		
Headway, h_n (s)	1.75	1.77
Speed, v_n (km/h)	42	25
Spacing, L_{hn} (m)	20.4	12.0
Gap length, L_{sn} (m)	16.0	7.6
Density, k_n (veh/km)	49	83
Occupancy time, t_{on} (s)	0.76	1.31
Space time, t_{sn} (s)	0.99	0.46
Time occupancy ratio, O_{tn} (%)	44	74
Space occupancy ratio, O_{tn} (%)	22	37

Figure B.2 Spacing and gap length as a function of speed using average parameter values for through traffic lanes surveyed in Melbourne and Sydney (vehicle length = 4.4 m)

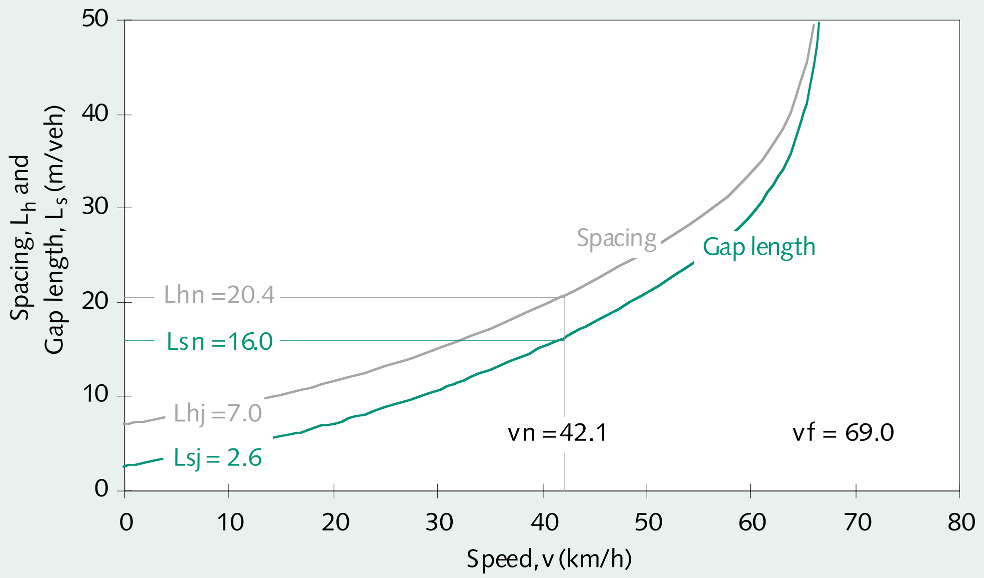


Figure B.3 Headway time as a function of speed using average parameter values for through traffic lanes surveyed in Melbourne and Sydney

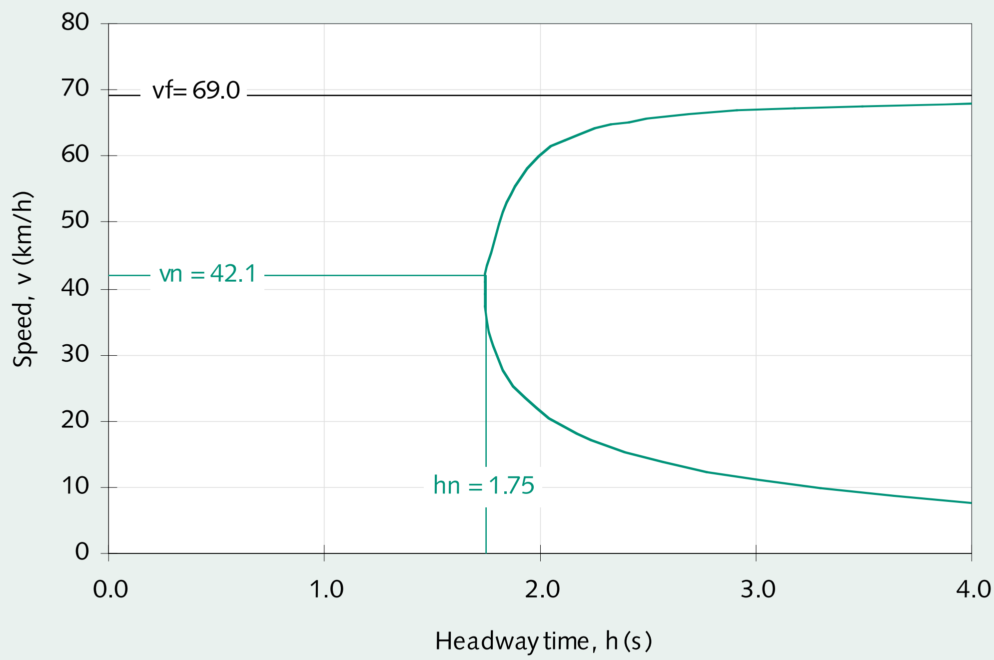
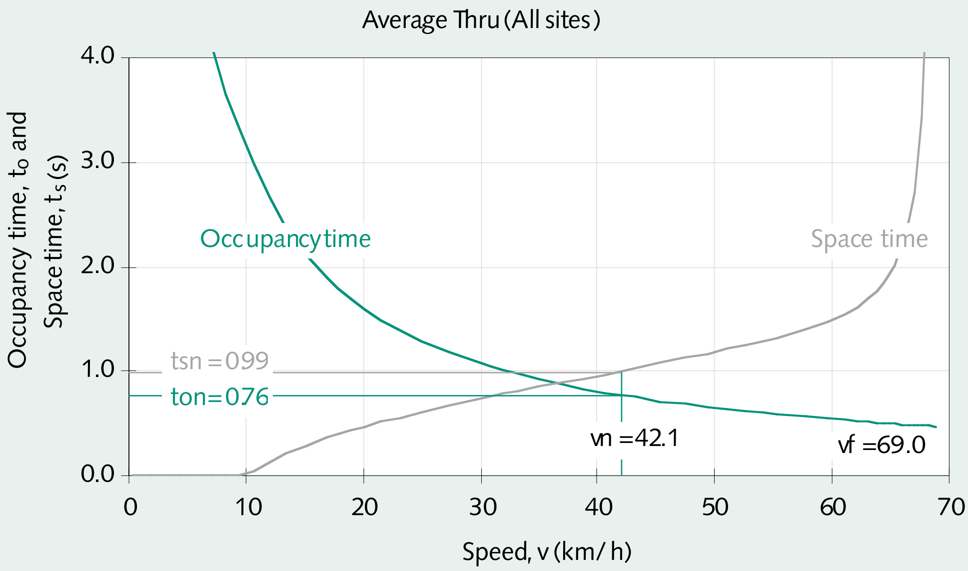


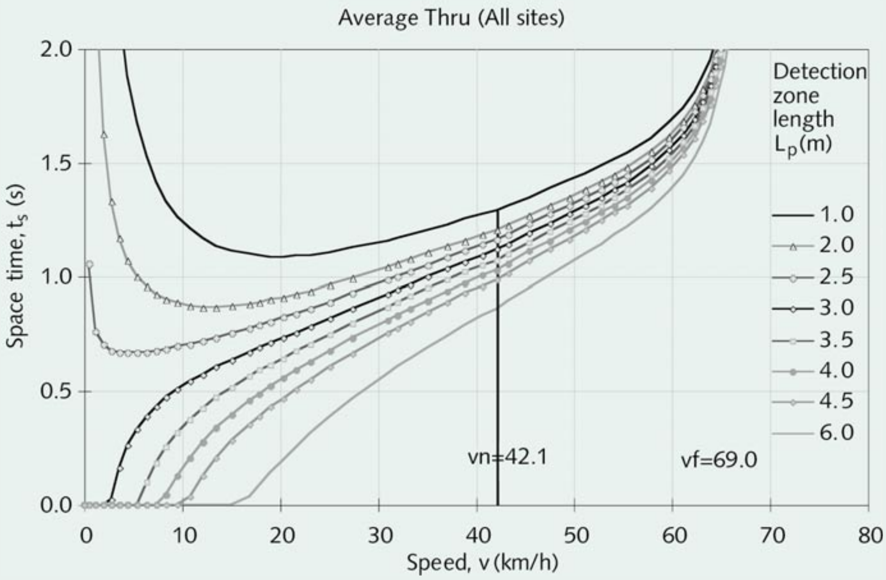
Figure B.4 Occupancy and space times as a function of speed using average parameter values for through traffic lanes surveyed in Melbourne and Sydney (vehicle length = 4.4 m, effective detection zone length = 4.5 m)



As seen in *Figure B.5*, the uniqueness of space time, and the speed below which it becomes zero depends critically on the effective detection zone length (L_p). For low values of L_p, each space time measurement corresponds to two values of speed, and this is not useful for traffic control for the same reasons as stated for the passage detector. For large values of L_p, each space time measurement provides a unique value of speed; but if L_p is excessive, the lower range of speed is restricted because of zero space time values at relatively high speeds.

A discussion of optimum detection zone length based on data collected in Sydney and Melbourne (summarised in *Table B.1*) can be found in Akçelik, Besley and Roper (1999). The optimum length for a detector loop is one that is as short as possible but not so short as to result in a double valued space-time relationship. To determine the optimum loop length, a limiting (low) speed value (v_o) that gives zero space time needs to be chosen. The limiting speed needs to be selected conservatively since, if it is too low, the loop length may be too short under adverse driving conditions (e.g. wet weather or darkness). This is because the gap lengths may increase and speeds decrease under adverse conditions, resulting in a sharp increase in space time at low speeds, and therefore leading to a double valued speed – space time relationship.

Figure B.5 The relationship between space time and speed as a function of the detection zone length using average parameter values for through traffic lanes surveyed in Melbourne and Sydney



It was found that the optimum detection zone length is strongly related to jam gap length (L_{sj}). Using a limiting speed value of v^o = 10 km/h, the following expression can be used to determine the optimum loop length as a simple method:

$$L_p = 1.9\ e^{0.33\ L_{sj}} \qquad \text{(B.3.19)}$$

Jam gap length characteristics vary for individual sites, and therefore should be measured wherever possible. Since it is easier to measure the jam spacing, the jam gap length can be calculated with the help of *Equation (B.3.14)* assuming an average vehicle length.

Using the average jam gap length values given in *Table B.1*, this expression gives optimum loop length values of 4.5 m for through traffic lanes and 3.7 m for right-turn lanes. While these are consistent with the stop-line presence detector loop lengths used in Australia, analyses of individual sites indicated that optimum loop lengths in the range 4.0 to 4.8 m for through traffic lanes and 3.0 to 3.8 m for right-turn traffic lanes. Using a limiting speed value of v_o = 5 km/h, shorter optimum loop length values are determined.

On this basis, the optimum loop lengths were in the range 3.0 to 3.8 m for through traffic lanes and 2.2 to 3.1 m for right-turn traffic lanes.

The saturation space time (t_{sn}) is useful for determining appropriate gap settings for actuated signal control (see *Appendix C, Section C.4.4*), and for obtaining information about green time utilisation. Average values of t_{sn} = 1.0 s for through traffic lanes and 0.5 s for right-turn traffic lanes are given in *Table B.1*. An average space time during a signal cycle that exceeds the saturation space time indicates that the green time is not fully saturated. This principle is used in SCATS to determine the degree of saturation (DS) for each cycle by comparing the total space time measured in each cycle with the space time at *maximum flow* (MF) (Lowrie 1982, 1990, 1996, 2001).

An important advantage of the space time parameter for traffic control purposes is that, unlike the headway and occupancy time parameters, it is independent of the vehicle length. Assuming that the gap length is not affected by vehicle type to a great extent, the above considerations are valid irrespective of the vehicle type.

Appendix C Signal Timings

C.1 Introduction

Allocation of appropriate green times to competing traffic movements at a signalised intersection requires considerations of safety, adequate capacity, efficient traffic operation (minimum delay, queue length and stops) for the intersection as a whole, as well as equity in levels of service provided for different movements (major road vs minor road, and vehicles vs pedestrians), and priority to public transport vehicles.

This appendix discusses general aspects of signal timing methods (*Section C.2*), describes actuated signal controller operation (*Section C.3*), and presents guidelines for determining appropriate values of controller settings (*Sections C.4 to C.6*).

Certain timing constraints are imposed on signal operation for safety reasons. Safety requirements constrain the minimum green time, minimum red arrow display time, minimum pedestrian walk and clearance times, and intergreen time. Maximum tolerable delay needs to be considered due to its implications on safe operation of signals (*Section C.2.2*).

Table C.1 presents a summary of signal controller settings, their purposes and recommended values.

C.2 Signal Timing Methods

C.2.1 Green Times and Cycle Time

Signal timing methods are used to determine appropriate green times and cycle time. Although most modern signals operate in actuated control mode, historically, signal timing calculation methods for fixed-time signals have been applied to actuated signals as well, mainly to determine the maximum green time (Webster and Cobbe 1966, Miller 1968, Akçelik 1981). Such methods calculate an "optimum" or "practical" cycle time, and then calculate green times on the basis of equal degrees of saturation or specified practical degrees of saturation, i.e. maximum acceptable (target) demand flow to capacity ratios.

Signal timing methods that estimate green times directly using actuated controller parameters, and then calculate the resulting cycle time, have been developed more recently (Akçelik 1995a,b,c; TRB 2000).

Table C.1 Summary of signal controller settings		
Setting	Purpose	Range
Maximum Cycle Time	Limit the total cycle time to reduce delays and queue lengths where applicable.	100 -120 seconds (simple two-phase), 150 - 180 seconds (complex phasing).
Late Start	Allow the introduction of some signal groups to be delayed for a preset time.	0 - 6 seconds.
Basic Minimum Green	Ensure that the green signal is displayed for a safe minimum time.	4 - 10 seconds.
Increment (for advance detectors)	Add a small amount of time to the Basic Minimum Green Setting to provide extra green time for vehicles stored between the detector and the stop line.	0.5 - 2.0 seconds.
Maximum Variable Initial Green (for advance detectors)	Limit the initial green period determined by increments.	Depends on the distance of advance detectors from stop line (see *Section C.4.2.2*).
Maximum Extension Green (or Maximum Green)	Control the maximum extension green time (after minimum green intervals) available to each phase or signal group.	Choose for optimum traffic performance under different traffic conditions; avoid unduly long cycle times (see *Table C.2*).
Gap	Set the maximum allowable time period between successive detector actuations before the movement terminates ("gaps out").	1.0 - 4.0 seconds.
Early Cut-Off Green	Allow the termination of some signal groups earlier than others.	0 - 10 seconds.
Yellow Time	To provide sufficient warning of the termination of the phase.	See *Section C.4.6.1*.
All-Red Time	Provide a safe clearance for vehicles that cross the stop line towards the end of the yellow interval.	See *Section C.4.6.2* and *Table C.2*.
Presence	Set the period for which a detector must be occupied before a demand is recorded.	0 - 5 seconds.
Headway (Space)	Set the desirable space time between successive detector actuations for efficient traffic flow.	0.3 - 1.5 seconds.
Waste	Set the value of the sum of the excess of the actual space time over the space time setting at which the phase is terminated.	4 - 12 seconds.
Minimum Red Arrow Time	To allow appropriate red arrow display time considering driver reaction/perception characteristics.	2 - 5 seconds.
Pedestrian Walk Time	Set the duration of the green Walk display.	See *Section C.5.1* and *Table C.2*.
Pedestrian Clearance Time	Set the duration of the Flashing Don't Walk display.	See *Section C.5.2* and *Table C.2*.
Pedestrian Delay	Provide a delay between the push button actuation and the placement of the pedestrian demand.	0 - 10 seconds.

SCATS Master Isolated Control (*Section 9.2.2*) is basically an actuated control method, but differs from the traditional actuated controller operation in determining appropriate green times on a cycle-by-cycle basis (Akçelik, Besley and Chung 1998). The traditional vehicle-actuated control uses Maximum Green Settings, i.e. maximum cycle time is not a setting. SCATS Master Isolated Control determines green times using the equal degree of saturation principle subject to a specified maximum cycle time. These green times act effectively as maximum green times, and the actual green times differ from these values when the phase changes occur by "gapping out" (*Section C.4.4*).

Determination of appropriate cycle time and green times for coordinated signals is discussed in *Section 13.2.1*.

C.2.2 Maximum Tolerable Delay

Drivers and pedestrians will tolerate only limited delay at traffic signals, particularly if a red display appears to be maintained needlessly. Because of the inherent bounds of human patience, drivers and pedestrians may disobey red displays if delays are abnormally long. Therefore, an upper time limit must be set to green time for any movement to ensure that motorists are not kept waiting for an "excessive" period against a red signal (see *Section C.4.3*). The waiting time for traffic facing a red display depends on:

(a) traffic flows on the subject approach as well as flows on other approaches

(b) green time (actuated controller) settings

(c) requirements of signal coordination on a conflicting phase.

The "excessive" time is related to the level of traffic activity at the intersection. The behaviour of drivers is also related to feelings of perceived equity. In other words, drivers can be held against a red display in a minor side street for relatively long periods compared to the waiting time tolerated by drivers on a busy arterial road.

Subjective observations suggest that maximum waiting times (against a red display) range from 20 seconds under light traffic conditions to 120 seconds under heavy traffic conditions. These values relate to the maximum delay experienced by an individual vehicle (or pedestrian). Average delay estimated by analytical methods is for all vehicles (or pedestrians) delayed and undelayed, and therefore, is shorter than maximum delay. For example, the worst level of service has been defined on the basis of average delay being above 70 to 80 seconds (TRB 2000, RTA NSW 1993).

Increased green time for a movement results in increased red times for competing movements, which will then require longer green times. This leads to increased cycle time. Maximum green settings should be selected to avoid very long cycle times in order to ensure acceptable levels of service. The recommended maximum cycle time for a two-phase intersection is 100 to 120 seconds (subject to signal coordination considerations) and is 150 to 180 seconds for sites with complex phasing systems and high traffic demands.

C.3 Actuated Controller Operation

This section presents a description of how actuated signal controllers work. Although the discussion is relevant to actuated controllers generally, some specific aspects of controller operation are valid for the Australian controllers only (RTA 1991, Akçelik 1995b).

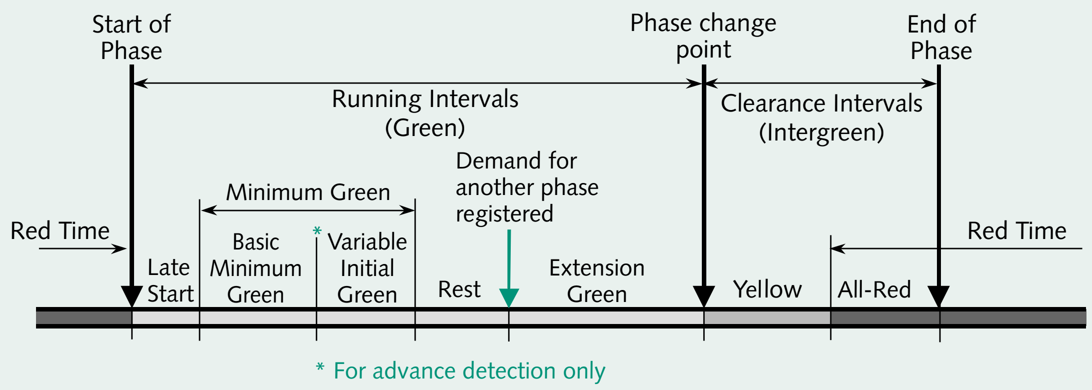
At vehicle-actuated signals, the green times, and hence the cycle time, are determined according to the vehicle demands registered by detectors (*Section 8*). This may be on the basis of phase control or group (movement) control (see *Section 6.1*). Phase sequence may be fixed or variable. A phase can be skipped when there is no demand for it. A phase (or signal group) consists of various intervals as discussed in *Sections C.3.1 and C.3.2*.

C.3.1 Vehicle Phase Intervals

The vehicle phase (signal group) intervals are shown in *Figure C.1*. This does not include the early cut-off interval, which is discussed in *Section C.4.5*.

The *running* part of the phase corresponds to the period when the green signal is displayed. It is the period between the phase start and the *phase change* points. The *clearance* part of the phase corresponds to the period when the yellow and all-red signals are displayed. It is the period between the phase change point (the end of running intervals) and the beginning of the green display for the next phase (end of phase). *Green time* is the duration of running intervals, and the *intergreen time* is the duration of Yellow Time and All-Red Time.

Figure C.1 Definition of phase (signal group) intervals for vehicle traffic



Different signal indications can be displayed to different movements using the phase during the *late start* and *early cut-off green* intervals. The *late start* interval is used to delay the introduction of green signal to some movements in the phase. The durations of these intervals are determined by the Late Start and Early Cut-Off Green Settings (*Sections C.4.1 and C.4.5*).

The two *minimum green* intervals used for safety reasons are the *basic minimum green* interval and *variable initial green* interval (*Section C.4.2*). With stop-line detectors, a Basic Minimum Green Setting determines the minimum green time allocated to a movement (*Section C.4.2.1*). The variable initial green interval is used with advanced detectors to provide additional minimum green time to discharge a queue of vehicles stored between the stop line and detectors during the red period. The duration of this interval varies in response to the number of actuations of the advance detectors and is determined according to the values of the Vehicle Increment and Maximum Initial Green Settings (*Section C.4.2.2*).

The controller cannot enter the *extension green* interval until a demand for another phase is registered. The *rest* interval is an untimed interval after the minimum green time expires, during which the controller rests until a demand for another phase is registered as shown in *Figure C.1*. The rest interval is skipped if a demand is registered for other phases before the end of the minimum green time.

The *extension green* interval is of variable length, and under isolated operation, its duration is determined by extension settings, namely the Gap Setting (*Section C.4.4*), Headway and Waste Settings (*Section C.4.7.2*), and Maximum Extension Green Setting (*Section C.4.3*). In the case of parallel vehicle and pedestrian movements at intersections, the pedestrian Walk and Clearance 1 intervals can hold the extension green interval (*Sections C.3.2 and C.5*).

The Gap, Headway and Waste Settings are used as "space" (non-occupancy) time values as measured by presence detection (see *Appendix B.3.2*). For example, where the Gap Setting is 3.0 seconds and the detector occupancy time at a given speed is 0.7 seconds, and the "headway" equivalent of this setting is 3.7 seconds.

The gap timing logic operates from the start of the green period to enable a green termination at the end of the minimum green period or the rest interval. It operates for the whole of the running part of the phase including the rest interval. The *gap timer* is loaded with the Gap Setting when a detector actuation occurs. With presence detection, the gap timer starts decrementing (from the initial value of the Gap Setting) when detector actuation ceases.

If the gap timer reaches zero before the next detector actuation, the timer is said to have *timed out* (or "*gapped out*"). When this occurs during the extension green interval, the green period is terminated (subject to parallel pedestrian movement timing constraints). This point during the phase is called the *phase change time*. This type of extension green termination will be called a *gap change*. The phase change process starts with the yellow signal display unless there is an early cut-off green interval in which case the early cut-off yellow interval starts (*Section C.4.5*).

The current Australian control method employs Headway and Waste Settings as additional extension settings. The headway-waste control method aims to terminate the extension green interval *before gap change* if the headways are too small for a gap change but too large for efficient traffic operation. The efficiency is measured by difference of measured space times from the Headway Setting. The difference is called a *waste increment*.

A *waste timer* operates throughout the running part of the phase, but its operation is ignored until the start of the extension green interval (i.e. until the end of the minimum green period or until a demand for another phase is received, whichever comes later). At the start of the extension green interval, and at each detector actuation after that, the headway timer is loaded with the Headway Setting. When the detector actuation ceases (i.e. at the end of the occupancy time), the headway timer starts decrementing. If the headway timer reaches zero before another actuation occurs, the timer is said to have timed out. The headway timer may time out many times during a phase.

The value of the waste timer at the start of the extension green interval equals the waste setting. Whenever the headway timer is timed out, the *waste timer* starts decrementing until a new detector actuation occurs. The amount of decrement equals the waste increment. When the waste timer reaches zero, the waste timer is said to have timed out. When this occurs before a gap change, the phase will be terminated. This is referred to as a *waste change*.

In addition to a gap change or waste change, the phase can be terminated by a *minimum change*, or a *maximum change*.

The *minimum change* occurs when the phase ends at the end of the minimum green period when a demand for another phase has been received and the gap timer has timed out before the end of the minimum green period.

The *maximum change* occurs when a gap change or waste change has not occurred during the extension green interval and the total green extension time equals the maximum extension green setting.

In summary, subject to demand for another phase, the green period can be terminated by one of four methods:

(i) a minimum change,

(ii) a gap change,

(iii) a waste change, or

(iv) a maximum change.

C.3.2 Pedestrian Intervals

At a signalised intersection, pedestrian movements can run concurrently with *parallel* vehicle movements, or run in an *exclusive* pedestrian phase. At midblock signalised crossings, vehicle and pedestrian movements run in alternate phases (see *Section 6.5.3*).

Normally, pedestrian movements (phases) are introduced by push-button detection. For parallel crossings at intersections, pedestrian demand needs to be received before the relevant phase starts. Pedestrian movements (phases) can also be introduced automatically in areas where heavy pedestrian movements exist.

The pedestrian movement (phase) intervals, as well as their relationship with parallel vehicle movement intervals (applicable in the case of parallel vehicle and pedestrian movements at signalised intersections), are shown in *Figure C.2*. Pedestrian and vehicle phase intervals at a midblock Pelican crossing are shown in *Figure C.3* (see *Section 6.5.3*).

Pedestrian displays are *Walk*, *Flashing Don't Walk* and *Steady Don't Walk*. The Flashing Don't Walk display corresponds to *Clearance Intervals 1 and 2*. The Clearance 2 interval overlaps with part of the vehicle clearance interval.

The *Pedestrian Delay* interval shown in *Figure C.2* provides a delay between the push button actuation and the placement of the pedestrian demand (*Section C.5.3*).

Figure C.2 Definition of pedestrian movement (phase) intervals and relationship with parallel vehicle movement intervals where applicable

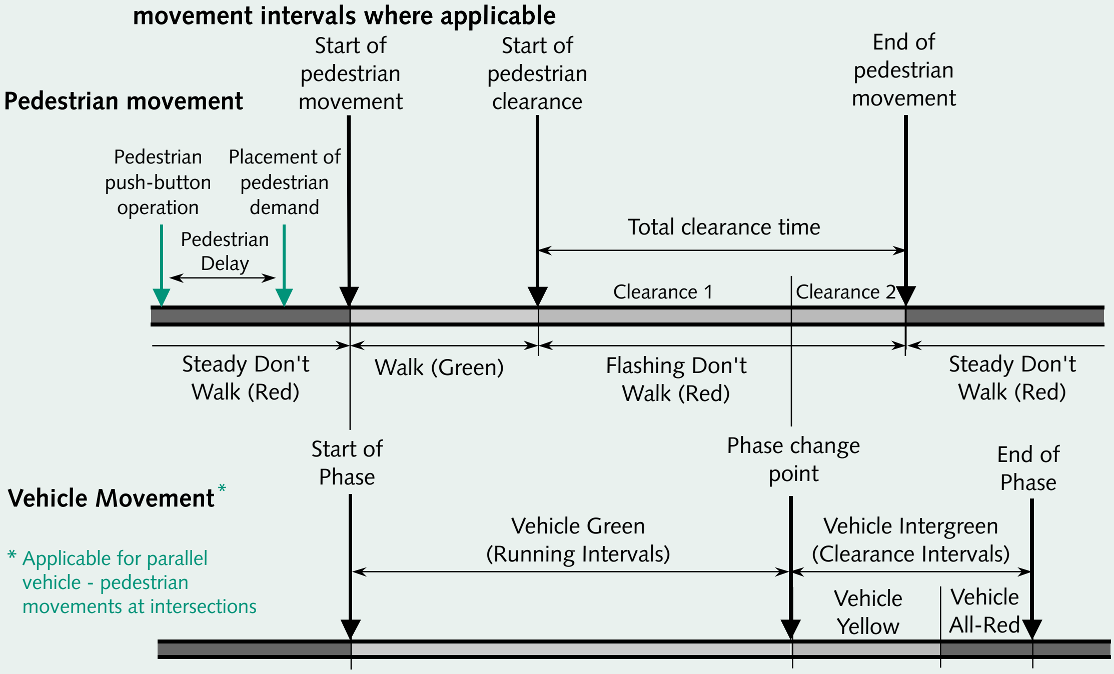
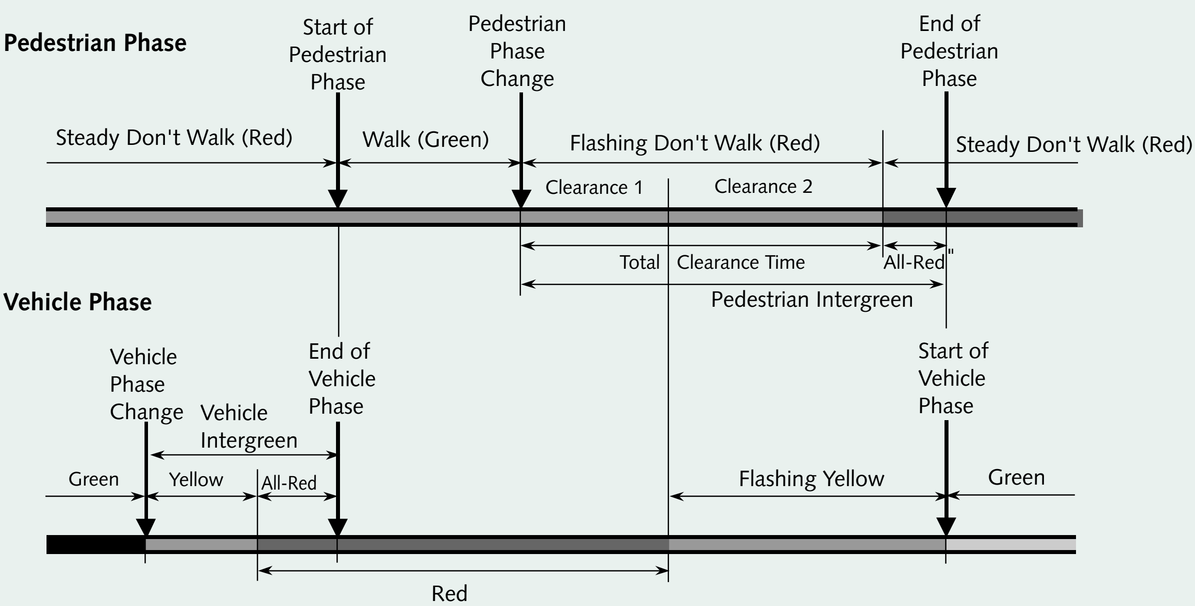


Figure C.3 Pedestrian and vehicle phase intervals at a Pelican crossing



For parallel crossings at signalised intersections, and subject to demand for another phase, a phase will start terminating at the end of the:

(i) pedestrian Clearance 1 interval if the vehicle running intervals expire before, or concurrently with it,

(ii) the vehicle running intervals if the pedestrian Clearance 1 interval expires before them.

For midblock signalised crossings and exclusive pedestrian phases at intersections, the pedestrian phase will start terminating at the end of the Clearance 1 interval regardless of a demand for another phase.

The *minimum phase green time* due to a pedestrian movement is determined as the sum of minimum Walk Time and Clearance 1 interval time. This will govern the minimum phase time when parallel pedestrian and vehicle movements operate concurrently and the minimum phase green time due to a pedestrian movement equals or exceeds the duration of vehicular running intervals for the phase.

Methods to determine pedestrian Walk Time and Clearance Time settings are described in *Section C.5*.

C.3.3 Actuated Controller Settings

Selecting appropriate values of controller settings for efficient operation of actuated signals for a given phasing system is not an easy task. The location, number and other characteristics of detectors affect the choice of actuated signal settings also.

For the purpose of determining the values of actuated controller settings, it is necessary to identify the proportion of flow in the *critical lane*. Critical lane is the lane that places the highest demand on green time in a given phase or signal group considering all movements in the phase or group. In terms of capacity analysis, this is the lane with the largest degree of saturation (demand flow rate to capacity ratio). Where capacities of all lanes are equal and all lanes are utilised equally, this is the lane with the highest demand flow rate. A simple manual method to determine the proportion of flow in the critical lane is given in Akçelik (1995b, Appendix B).

The methods recommended for determining actuated signal controller settings are described in *Sections C.4 to C.6*.

Typical signal controller settings used in Australian practice are given in *Table C.2* (Akçelik 1995a,b).

Table C.2 Typical signal controller settings used with 4 - 4.5 m stop-line detectors in Australian practice (values in seconds)

	Vehicle Settings		
	Through (and Left-Turn) Movements	Arrow-Controlled Right-Turn Movements	Pedestrian Settings
Late Start	2 - 5	0 - 6	
Minimum Green	5 - 10	5 - 6	
Maximum Extension Green	10 - 85	5 - 25	
Gap	2.5 - 4.0	2.0 - 3.0	
Headway	0.3 - 1.5	0.6 - 1.2	
Waste	4 - 11	2 - 8	
Early Cut-Off Green	0 - 8	0	
Yellow Time	3.0 - 5.0	3.0 - 6.0	
All-Red Time	1.0 - 3.0	1.0 - 3.0	
Presence Time	0 - 3	0 - 5	
Walk Time			5 - 16
Clearance Time			6 -20

C.4 Vehicle Settings

Actuated controller settings for vehicle movements are described in the following sections which are presented in the order they appear in *Figure C.1*.

C.4.1 Late Start Setting

The purpose of the Late Start Setting is to allow the introduction of some signal groups to be delayed at the start of a phase for a preset time.

Examples of the use of this setting are:

(a) To delay start of left turns: 3 to 6 seconds depending on intersection geometry.

(b) To delay the start of a filtering right turn immediately following its control by a right-turn green arrow display: 5 seconds.

C.4.2 Minimum Green Setting

The minimum duration of the green signal ("minimum green time") is determined considering the dynamic characteristics of the vehicles in the traffic stream. A starting delay is experienced when a signal changes from red to green. This delay includes allowance for the alertness of drivers (perception and reaction time), preparation of the vehicle (selecting gear, releasing hand-brake) and acceleration to the desired or possible speed (see *Appendices A and B*).

There is also a safety element involved in determining the minimum green time, since drivers expect the signal to remain green for a "reasonable" time, and a green interval which is unduly short leads to erratic behaviour and rear-end collisions.

Motor cycles and passenger cars have greater acceleration capabilities than trucks and, in the interests of safety, minimum green time should be related to the slowest vehicle likely to use the intersection within 95 per cent probability (5th percentile speed).

Minimum green time comprises the *Basic Minimum Green Setting* (*Section C.4.2.1*) plus a variable time determined by the *Increment and Maximum Variable Initial Green Settings* (*Section C.4.2.2*).

The Basic Minimum Green Setting is the minimum time a green aspect can be displayed when stop-line detectors are used. When using only advance detectors, the minimum green time is increased above this value in order to allow for vehicles stored between the stop line and advance detector location. The Increment and Maximum Variable Initial Green settings are used for this purpose. For stop-line detectors, the Maximum Variable Initial Green setting is zero.

A method for determining the Maximum Variable Initial Green and Increment Settings is given in Akçelik (1995b, Appendix B).

C.4.2.1 Basic Minimum Green Setting

With stop-line detectors, the minimum green time is equal to the Basic Minimum Green Setting. A longer minimum green display is required when advance detectors only are used as explained in *Section C.4.2.2*.

A minimum green time is needed to ensure that the green signal (circle or arrow) is displayed for a safe minimum time, i.e. not less than 5 seconds. This is to provide enough time for a stationary vehicle at the stop line to begin moving and enter the intersection. At a particular site, there may be a need to increase the minimum green time to allow for heavy vehicles, a steep upgrade, pedestrians, or clearing of turning traffic. Typical Minimum Green Settings used in practice with stop-line detectors are shown in *Table C.2*.

C.4.2.2 Increment and Maximum Variable Initial Green

The Increment and Maximum Variable Initial Green Settings are applicable when only *advance detectors* are used.

Each vehicle arriving against a red signal adds a small amount of time (equal to the Increment Setting) to the minimum green time. This provides sufficient green time to enable those vehicles stored between the detector and the stop line to clear the intersection. Typical Increment Settings are in the range 0.5 to 2.0 seconds depending on the number of approach lanes and the location of the advance detectors. Careful site observation is required under a range of conditions, especially where lane utilisation varies. It is recommended to allow for an increase for upgrade and a decrease for downgrade at the rate of 0.1 second for each per cent of road grade.

The Maximum Variable Initial Green Setting limits the additional minimum green time (Variable Initial Green time) determined by increments. The value of this setting depends on the distance of advance detectors from stop line. For example, if the distance is 50 m, then for an average spacing of 7 m per vehicle, 7 vehicles will store between the detectors and the stop line in each lane. Using a start loss of 2 seconds for the first vehicle at the start of the green period, and assuming that a car leaves the queue every two seconds, the required setting is 2 + 7 x 2 = 16 seconds. If the Basic Minimum Green Setting is 6 seconds, then the required Maximum Variable Initial Green setting is 16 - 6 = 10 seconds.

Again careful site observation is required to ensure that there is sufficient Variable Initial Green time so that vehicles queued beyond the detectors can move over them and thus extend the phase.

C.4.3 Maximum Extension Green Setting

The Maximum Extension Green Setting is used to control the maximum green time available to each phase or signal group when conflicting demands exist and when operating in the isolated mode (see *Section 13.3*). This setting determines the duration of the extension green interval (see *Figure C.1*).

Maximum green time is the sum of minimum green time (*Section C.4.2*) and the Maximum Extension Green Setting. In some controllers, a Maximum Green Setting equivalent to the maximum green time is used.

As seen in *Table C.2*, typical Maximum Extension Green Settings used in practice are 10 to 85 seconds for through movement phases and 5 to 25 seconds for arrow-controlled right-turn phases.

The maximum green times should be determined with the objectives of ensuring equitable distribution of green time amongst competing signal groups (movements) and achieving optimum traffic performance (e.g. minimum delay, stops or queue length), considering different traffic demand periods. This is a key parameter for optimising the performance of actuated traffic signals.

When determining maximum green times, a balance needs to be achieved between:

(i) erring on the long side considering that the Gap Setting should reduce the green time if necessary, and

(ii) large maximum green time values for individual phases (or signal groups) can add up to unduly long cycle times resulting in intolerable delay (see *Section C.2.2.*).

The optimum values of maximum green times produced by an appropriate software package could be used as a guide to determining the Maximum Extension Green Settings with the above criteria in mind (Maximum Extension Green Setting = maximum green time - minimum green time).

The following formula provides a simple manual method for determining the Maximum Extension Green Setting (Akçelik 1995b, Appendix B):

$$G_{emax} = [y\ R_{max} / (x_p - y)] - G_{min} \qquad (C.4.1)$$

where

G_{emax} = maximum Extension Green Setting (s),

G_{min} = minimum green time (= Basic Minimum Green Setting with stop-line detectors) (s),

y = flow ratio (demand flow rate/ saturation flow rate) for the critical lane,

R_{max} = maximum red time that is acceptable to drivers (e.g. 60 seconds), and

x_p = practical degree of saturation (maximum value acceptable at high demand conditions), e.g. $x_p = 0.95$.

C.4.4 Gap Setting

The Gap Setting is used to set the maximum allowable time between successive detector actuations before the movement terminates due to large gaps between vehicles. If the Gap Setting is too short, the phase may terminate before a platoon of vehicles is passed, and if it is too long, the phase will extend unduly.

Microprocessor-based controllers provide for at least 2 and up to 8 gap timers so that different approach characteristics such as grade and turning radius, can be catered for.

The Gap Setting is determined as a space time value measured between consecutive vehicles by the detector, i.e. as the time when the detector is not occupied.

Table C.2 indicates that typical Gap Settings used in Australian practice are in the range 2.5 to 4.0 seconds for through (and left-turn) movements, and 2.0 to 3.0 seconds for arrow-controlled right-turn movements.

A method to determine gap settings is discussed in Akçelik, Besley and Roper (1999, Section 14.2).

The "Headway Setting" and "Waste Setting" that are used in association with the Gap Setting are discussed in *Section C.4.7.2*. Analytical and simulation studies indicated that these settings do not influence the green duration as much as the Maximum Extension Green and Gap Settings (e.g. Akçelik 1995b).

C.4.5 Early Cut-Off Green and Early Cut-Off Yellow Settings

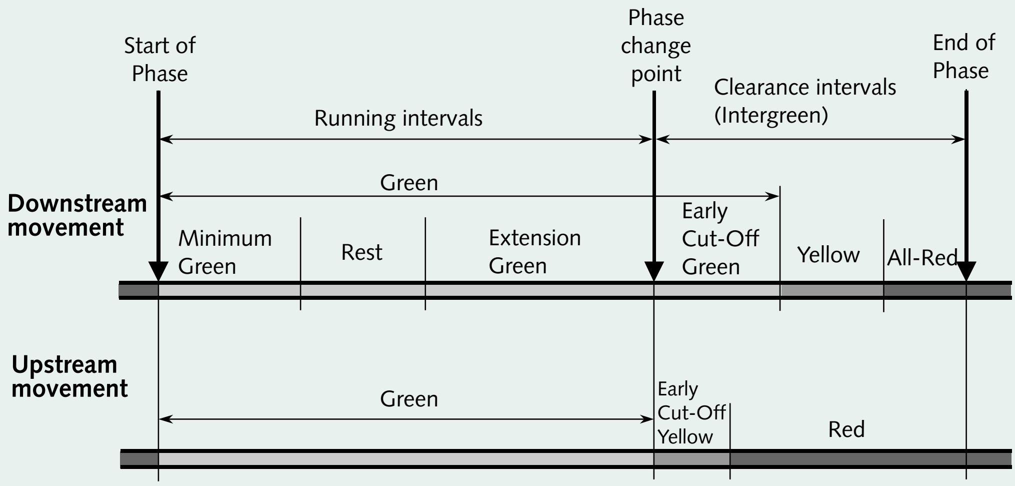
The *early cut-off green* interval allows the termination of some signal groups earlier than others. This arrangement is shown in F*igure C.4*. For example, at paired intersections, the upstream signals may be terminated earlier than the downstream signals in order to minimise queuing on internal approaches (see *Section 15.9.2*).

The Early Cut-Off Green Setting depends on intersection geometry, but normally should not be less than 3 seconds.

The *early cut-off yellow* interval is an auxiliary phase interval used to provide a yellow display for any signal groups that are terminated at the beginning of the early cut-off green interval.

The early cut-off green interval follows the *phase change point*, and is considered to be part of the clearance interval (intergreen time).

Figure C.4 Early cut-off green and Early cut-off yellow (upstream and downstream movements refer to an example of paired intersection)



C.4.6 Vehicle Clearance Settings

Intergreen period as a vehicle change and clearance interval involves two intervals:

(a) a yellow interval to warn approaching drivers that the phase is terminating, and

(b) an all-red interval to enable vehicles within the intersection to clear the controlled area.

There is a large number of publications on determining appropriate values of Yellow Time and All-Red Time (e.g. Hulscher 1980, 1*984;* ITE 1994). It is recommended that the Yellow Time be set as detailed in *Section C.4.6.1* and the All-Red Time be set as detailed in *C.4.6.2*.

C.4.6.1 Yellow Time

The purpose of the yellow interval is to provide sufficient warning of the termination of the phase. A driver must stop for a yellow display provided it can be done safely.

Table C.2 indicates that typical Yellow Times used in practice are in the range 3.0 to 6.0 seconds.

Traffic regulations prohibit the entry of vehicles into a controlled area when a red signal is displayed. The yellow signal is used to allow for the fact that a traffic stream cannot be stopped abruptly at the end of the green interval. The stopping performance of drivers is related to reaction time, braking characteristics of the vehicle, distance from the stop line, road gradient, approach speed, discomfort tolerance and behaviour of following traffic. Since accident risk is highest during the transition from green to one movement (phase) to green to another movement (phase), the timing of this change interval is very important.

The braking capability of modern vehicles is high, and in practice the discomfort incurred by rapid deceleration is the main constraint in controlled stops. Another important consideration is the perceived danger of a rear-end collision with a following vehicle (particularly a heavy vehicle), which may not be prepared for the sudden deceleration. These considerations are so important to many drivers that their first inclination is to attempt to cross the intersection during the yellow period.

Table C.3 Yellow Time values (seconds) determined using a_d = 3.0 m/s^2

	v_D = 50 km/h		v_D = 60 km/h		v_D = 70 km/h		v_D = 80 km/h	
Grade	t_r = 1.0 s	t_r = 1.5 s	t_r = 1.0 s	t_r = 1.5 s	t_r = 1.0 s	t_r = 1.5 s	t_r = 1.0 s	t_r = 1.5 s
-0.08	4.5	5.0	5.0	5.5	5.5	6.0	6.0	6.5
-0.05	4.0	4.5	4.5	5.0	5.0	5.5	5.5	6.0
-0.02	3.5	4.0	4.0	4.5	4.5	5.0	5.0	5.5
0.00	**3.5**	**4.0**	**4.0**	**4.5**	**4.5**	**5.0**	**5.0**	**5.5**
0.02	3.0	3.5	3.5	4.0	4.0	4.5	4.5	5.0
0.05	3.0	3.5	3.5	4.0	4.0	4.5	4.5	5.0
0.08	3.0	3.5	3.5	4.0	3.5	4.0	4.0	4.5

The yellow interval should only be long enough to enable traffic to comply with regulatory requirements. If the yellow interval is too short, vehicles within a certain distance from the stop line will be unable (or unwilling) to stop before the red signal appears, and if the yellow time is too long, motorists will tend to abuse the signal. As Gazis, Herman and Maradudin (1960) have shown, an inappropriate choice of yellow time can place an approaching driver, at the onset of the yellow signal, in the predicament of being too close to the intersection to stop safely and comfortably, and yet be too far from it to clear the conflict area or even reach the stop-line before the red signal appears. This phenomenon is related to approach speed and is generally analysed in terms of the "dilemma zone".

The yellow time should be just sufficient to enable a driver approaching at the design speed who is unable to stop in advance at the stop line to cross the stop line before the red signal appears. In other words, the duration of the yellow signal is dictated by the needs of the driver who requires the maximum deceleration acceptable to the majority of the population (say 85 per cent). This criterion ensures that drivers travelling at or below the speed limit will not be caught in the "dilemma zone" and that the yellow interval is no longer than necessary. Thus, the yellow time should be equal to the sum of the driver's reaction time and the time to reach the stop line at the design speed, v_D.

This can be mathematically expressed as:

$$t_y = t_r + 0.5\,(v_D / 3.6) / (a_d + 9.8\,G) \quad \text{(C.4.2)}$$

subject to $t_y \geq 3.0$

where

t_y = Yellow Time (s),

t_r = reaction time (s),

v_D = design speed (km/h),

a_d = the deceleration acceptable to the majority of drivers (m/s^2), and

G = approach grade (per cent grade divided by 100; negative value for downhill grade and positive value for uphill grade, e.g. - 0.05 for 5 per cent downhill grade).

The Yellow Time values calculated as a function of the approach grade using a_d = 3.0 m/s^2, t_r =1.0 and 1.5 seconds in *Equation (C.4.2)* for the design speeds of v_D = 50, 60, 70 and 80 km/h, rounded to the nearest 0.5 seconds are given in *Table C.3*.

C.4.6.2 All-Red Time

An all-red interval is used between the end of the yellow interval of a phase or signal group and the commencement of the green on the next phase or signal group. The purpose of the all-red interval is to provide a safe clearance for vehicles that cross the stop line towards the end of the yellow interval since they may be in danger of collision with vehicles or pedestrians released in the following phase or signal group.

As seen in *Table C.2*, typical All-Red Times used in practice are in the range 1.0 to 3.0 seconds.

The timing of an all-red interval should take account of the speed of vehicles crossing the stop line at the end of the yellow interval, the distance to the furthest potential point of conflict with vehicle and pedestrian traffic of the next phase, the length of the clearing vehicle and the time for starting traffic to reach the furthest point of potential conflict with vehicles or pedestrians. A detailed method to take these factors into account was described by Hulscher (1980). The following simplified method is recommended for determining the All-Red Time:

$$t_{ar} = 3.6\,L_c / v_D \quad \text{subject to } t_{ar} \geq 1.0 \qquad \text{(C.4.3)}$$

where

t_{ar} = All-Red Time (s),

L_c = clearance distance between the stop line and furthest point of potential conflict with vehicles or pedestrians of the next phase (m), and

v_D = design speed (km/h).

The All-Red Time values calculated as a function of speed for various clearance distances are shown in *Figure C.5*.

While there may be isolated instances when longer All-Red Times are justified to meet unusual traffic situations, additional All-Red Time must not be provided to clear any vehicles waiting to make a right-hand turn. Excessive All-Red Times are likely to give rise to "running the red" behaviour, particularly if yellow times are too short.

Special All-Red setting for a phase is used for phase transitions that require significantly longer or shorter all-red values (e.g. due to phase skipping) compared with the all-red setting for normal phase transition.

C.4.7 Other Vehicle Settings

C.4.7.1 Presence Setting

This is used to set the time for which a detector must be occupied before a demand is recorded, or to prevent a demand being recorded unnecessarily.

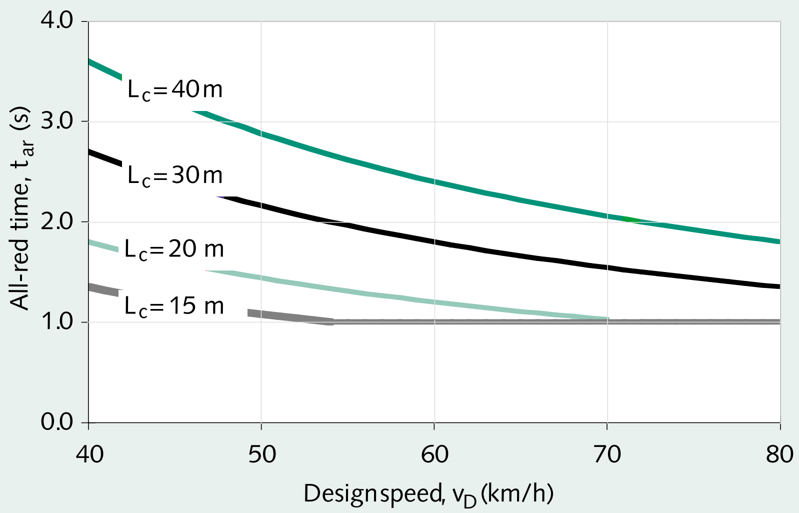
Typical values of the Presence Setting used in practice are in the range 0 to 5 seconds. Examples of the use of this setting are:

(a) shared lane detector for lagging right turn phasing: 2 to 5 seconds.

(b) left-turn detector on overlapped movement: 3 seconds.

(c) left turn on red lane detector: zero.

Figure C.5 All-Red Time as a function of speed (v_D) and clearance distance (L_c)



C.4.7.2 Headway and Waste Settings

The purpose of "Headway" (Space Time) Setting is to set the desirable space time between successive detector actuations for efficient traffic flow. It is used in association with the Waste Setting.

In general traffic engineering usage, the term "headway" means the time between passage of the front ends of two successive vehicles at an observation point, e.g. at the leading edge of the detector. As such, the term "Headway Setting" is a misnomer as it is a "space time" value (see *Appendix B.3.2*).

As seen in *Table C.2*, typical "Headway" Settings used in practice are 0.3 to 1.5 seconds for through movements and 0.6 to 1.2 seconds for arrow-controlled right-turn movements. The "Headway" setting can be related to the SCATS parameter "Space Time at Maximum Flow". The values of this parameter were found to be 0.85 to 1.02 seconds for through movements and around 0.61 to 0.74 seconds for arrow-controlled right-turn movements (Akçelik, Besley and Roper 1999).

The waste is the sum of the excess of the actual space time over the "Headway" Setting. The Waste Setting is used to set the value of this sum at which the phase is terminated (*Section C.3.1*). However, research has indicated that, with efficient Gap Settings as discussed in *Section C.4.4*, the phase (or signal group) is more likely to "gap out" before a phase change due to the Waste Setting.

Where employed, the Waste Setting may be determined as 10-20 per cent of maximum green time (minimum green time plus Maximum Extension Green Setting) subject to a minimum value of 4 seconds and a maximum value of about 12 seconds.

Table C.2 indicates that typical Waste Settings used in practice are 4 to 11 seconds for through movements and 2 to 8 seconds for arrow-controlled right-turn movements.

C.4.7.3 Minimum Red Arrow Time

The minimum duration of a red arrow signal display is governed principally by driver reaction/perception characteristics. It is recommended that, as a safety constraint, a minimum value of 3 seconds be used.

C.5 Pedestrian Settings

Actuated controller settings for pedestrian movements are described in the following sections (see *Figures C.2 and C.3*).

C.5.1 Pedestrian Walk Time

The purpose of the Walk Time Setting is to give pedestrians sufficient time to begin their crossing. This setting determines the duration of the green Walk display. Its value depends on the amount and type of pedestrians using the crossing. *Table C.2* indicates that typical Pedestrian Walk Times used in practice are in the range 5 to 16 seconds.

Pedestrian Walk Times can be determined as follows:

(a) Use a minimum value of 5 seconds. However, where the signalised crossing is on a very narrow carriageway (such as a slip lane), a minimum of 4 seconds is permissible.

(b) Add 2 seconds for each additional rank of pedestrians waiting (optional).

(c) Allow more time for:

- (i) schools,
- (ii) railway stations,
- (iii) elderly, children, and people with disabilities, and
- (iv) crossing of wide roads in one movement (i.e. beyond medians).

When crossing a wide road with median in one movement, the Walk Time may be calculated from:

$$t_{pw} = L_{pw} / v_{pw} \quad \text{subject to } t_{pw} \geq 5 \qquad \text{(C.5.1)}$$

where

t_{pw} = pedestrian Walk Time (s),

L_{pw} = pedestrian walking distance (m), determined as the larger of the "first carriageway width plus median width" measured in each direction, and

v_{pw} = pedestrian walking speed (m/s).

When Walk Time is determined using *Equation (C.5.1)*, the calculation of clearance distance is based on the larger of the two carriageway widths, i.e. excluding the median width, as discussed in *Section C.5.2*.

For pedestrian walking speed in *Equation (C.5.1)*, use the clearance speed, $v_{pw} = v_{pc}$ (see *Section C.5.2*).

Where pedestrian demands are high (such as may occur in shopping areas), signal timings for the intersection may be biased to favour pedestrians. The pedestrian Walk Time can be increased in line with the green display for the parallel vehicle movements.

C.5.2 Pedestrian Clearance Time

The purpose of the Pedestrian Clearance Time is to allow pedestrians, who have stepped off the kerb at the commencement of the pedestrian clearance interval, to complete their crossing with safety. It comprises Clearance 1 and Clearance 2 Intervals as seen in *Figures C.2 and C.3*.

The pedestrian clearance interval is implemented using Flashing Don't Walk display. However, during the intergreen interval terminating the phase, the Flashing Don't Walk or Steady Don't Walk displays can be used as part of the clearance period (except, in some jurisdictions, only the Steady Don't Walk may be displayed when filter right turns are allowed with parallel pedestrian movements).

As seen in *Table C.2*, typical Pedestrian Clearance Times used in practice are in the range 6 to 20 seconds. The Pedestrian Clearance Time should be determined as follows.

(i) Calculate the total clearance time (in seconds) from:

$$t_{pc} = L_{pc} / v_{pc} \quad \text{subject to } t_{pc} \geq 5 \qquad \text{(C.5.2)}$$

where

t_{pc} = total pedestrian clearance time (s),

L_{pc} = pedestrian clearance distance (m), and

v_{pc} = pedestrian walking speed (m/s).

(ii) Determine the durations of the Clearance 1 and Clearance 2 intervals (t_{c1} and t_{c2}) from:

$$t_{c2} = I \qquad \text{(C.5.3)}$$

$$t_{c1} = t_{pc} - I$$

where

I = intergreen time (s) (see *Section C.4.6*), and

t_{pc} = total clearance time (s) from *Equation (C.5.2)*.

The pedestrian clearance distance in *Equation (C.5.2)* is based on the length of the marked crossing between kerb lines. Where the sides of the crossing are of unequal length, the length of the longest side is used.

If a median exists, its width is included in the clearance distance when crossing both carriageways in one movement, i.e. the pedestrian clearance distance includes both carriageway widths as well as the median width. However, if the Walk Time is calculated using *Equation (C.5.1)* for the case when crossing a wide road with median in one movement, the clearance distance in *Equation (C.5.2)* should be based on the larger of the two carriageway widths (i.e. excluding the median width).

Where a median is wide enough to store pedestrians, a staged signalised crossing can be used (see *Section 6.5*). In this case, the crossings are treated separately, and the width of appropriate carriageway is used as the clearance distance for each crossing.

Where an exclusive pedestrian phase is provided at an intersection, the shortest distance between diagonally opposite corner kerb radii for the longest crossing is used as the clearance distance.

The pedestrian walking speed for determining total clearance time is usually 1.2 m/s. A clearance speed of v_{pc} = 1.0 m/s may be appropriate for sites with higher populations of slower pedestrians.

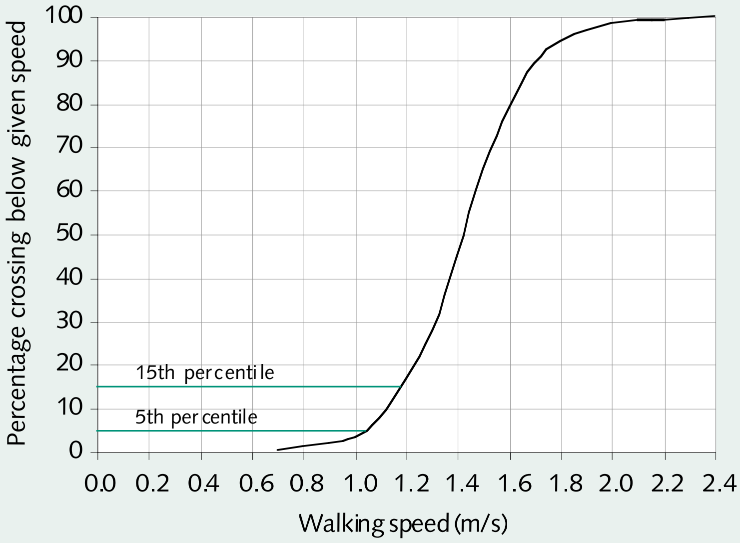
Figure C.6 shows the distribution of walking speeds at mid-block signalised crossings in Melbourne (Akçelik & Associates 2001b). This indicates that the recommended clearance speeds of 1.0 and 1.2 m/s correspond to 5th and 15th percentile speeds, respectively, i.e. approximately 5 per cent of pedestrians were observed to cross with speeds below 1.0 m/s, and 15 per cent of pedestrians were observed to cross with speeds below 1.2 m/s.

C.5.3 Pedestrian Delay Setting

The Pedestrian Delay Setting is used to provide a delay between the push button actuation and the placement of the pedestrian demand (see *Figure C.2*). This helps to form pedestrian platoons and thus avoid unnecessary introduction of the pedestrian movements.

Where used, typical Pedestrian Delay Setting is 5 to 10 seconds, applicable to both midblock pedestrian controllers and intersection controller with completely independent pedestrian feature.

Figure C.6 Walking speeds of pedestrians observed at three mid-block signalised crossings in Melbourne



C.6 Bicycle Settings

Two-aspect bicycle signal faces used at midblock signalised crossings or intersection signalised crossings are connected to the same signal group in the controller that drives the two-aspect pedestrian signal faces. In this case, the pedestrian "Walk" and "Clearance" times apply to the bicycles as well.

Three-aspect bicycle signal faces can also be used at signalised intersections. In this case:

(a) For bicycle movements parallel with a main road and crossing narrow minor roads, the bicycle signal faces are connected to the adjacent vehicle signal group, and introduced with the green display for vehicles and terminated with the vehicle movement.

(b) For bicycle movements across a main road, and for those parallel with a main road and crossing wide minor roads, the bicycle signal faces are driven by a separate signal group with green, yellow and red times that reflect a bicycle speed of 20 km/h.

The following measures can be adopted in order to allow for slower speeds of cyclists compared with vehicle speeds (see Austroads (1999) Traffic Engineering Guide Part 14, Section 5.4.3):

(i) Adjusting the Yellow Time for the bicycle movement to warn cyclists to stop before other traffic in the same phase, i.e. increase the intergreen time only for the cyclists (effectively providing an early cut-off). Since this reduces the bicycle green time, it should be ensured that the combined green plus intergreen time is sufficient for a cyclist accelerating from rest at the stop line to clear the controlled area.

(ii) Allowing the cyclists to move off before the vehicle traffic (late start). This is appropriate where the bicycle lane does not continue through the intersection and bicycles have to merge with other traffic.

Appendix D Worked Example

D.1 Introduction

This appendix presents a worked example to illustrate various aspects of signalised intersection timing, performance analysis and implementation procedures for a signalised intersection design. A four-way intersection controlled by actuated signals is considered. Under current conditions (*Design 1*), a two-phase system is used, which is inadequate due to filter right-turn movements against heavy opposing through flows. As a result, improvements to the intersection geometry and signal phasing are considered (*Design 2*).

Signal timing and performance analyses presented in this section were carried out using the aaSIDRA software package (Akçelik & Associates 2001a). The aim is to ensure that the model replicates the observed conditions for current Design 1, and then to see that the proposed Design 2 provides satisfactory operating performance. The analyses assume actuated signal operation, and signal coordination applies to some movements.

Section D.2 contains listings of the input data and output information required for timing and performance analyses of signalised intersections. *Sections D.3 and D.4* describe input data and analysis results for Designs 1 and 2, respectively.

Decisions regarding improvements to intersection design and operational conditions should be made considering a wide range of operating conditions. Therefore, intersection timing and performance analyses should ideally be carried out for several typical flow periods, including am and pm peak periods, business hours, medium off-peak and light off-peak periods. For the purpose of this worked example, conditions during one peak period only will be considered.

D.2 Input and Output Requirements

D.2.1 Input Data

The first step in timing and performance analyses of a signalised intersection is preparation of input data using an intersection layout plan, and signal phasing, design volumes and other information on traffic characteristics at the intersection. The following is a summary of the input data for timing and performance analyses of signalised intersections.

(a) Geometric Data

- (i) Intersection configuration (cross intersection, T-intersection, etc).
- (ii) For each intersection leg:
  - two-way, one-way approach or one-way exit,
  - signalised crossings and type (one-stage or two-stage),
  - banned movements,
  - number of approach and exit lanes (at the stop line),
  - median width at the stop line if a median strip exists,
  - approach grade (negative for downhill, positive for uphill),
  - upstream and downstream short lanes, any turn bans,
  - bus only or tram only lanes,
  - details of parking restrictions, bus stops, tram stops, emergency access.

(iii) For each approach lane:

- lane type including slip lane, continuous lane, short lane due to turn slot or parking,
- lane discipline (left-turn, through, right-turn, exclusive or shared),
- lane width,
- lane (storage) length,
- free (non-blocking) queue values for shared lanes,
- basic saturation flow,
- number of parking manoeuvres and buses stopping (affecting saturation flow).

(b) Volume Data

(i) Demand volume counts (or estimates) in vehicles per 15 minutes, 30 minutes or 60 minutes, in origin-destination format describing left-turn, through and right-turn movements, as well as any diagonal movements or U-turns.

(ii) Heavy vehicle data for each movement.

(iii) The method of counting heavy vehicles (HVs): percentage HVs, separate light and heavy vehicles, or HVs included in the total count.

(iv) Pedestrian volume counts.

(v) Peak flow factors for peaking effects, and flow scales for design life analyses.

(c) Signal Control Data

(i) Actuated or fixed-time analysis.

(ii) Signal phase sequences to be tested (one or more), showing vehicle (opposed and unopposed) and pedestrian movements which operate in each phase.

(iii) Timing data including intergreen times, start loss and end gain times, minimum and maximum green times, pedestrian Walk and Clearance times.

(iv) Movements for green split priority (for allocation of any excess green times in long cycles).

(v) Phase green times and cycle time if data observed in the field or reported by SCATS or other control system are available (for testing current traffic conditions under current signal timings).

(vi) Signal coordination data (percentage arriving during green or arrival types describing progression quality).

(d) Movement Operational Data

(i) Approach and exit speeds, approach distances, jam spacings.

(ii) Negotiation radius, speed and distance for movements through the intersection.

(iii) Opposing movement specifications and gap-acceptance parameters for opposed turns (filter right-turn and slip lane left-turn movements).

(iv) Practical (target) degrees of saturation for signal timing and spare capacity calculations.

Software packages provide default values for most input data items, representing commonly occurring conditions. These default values can be used where data are not available.

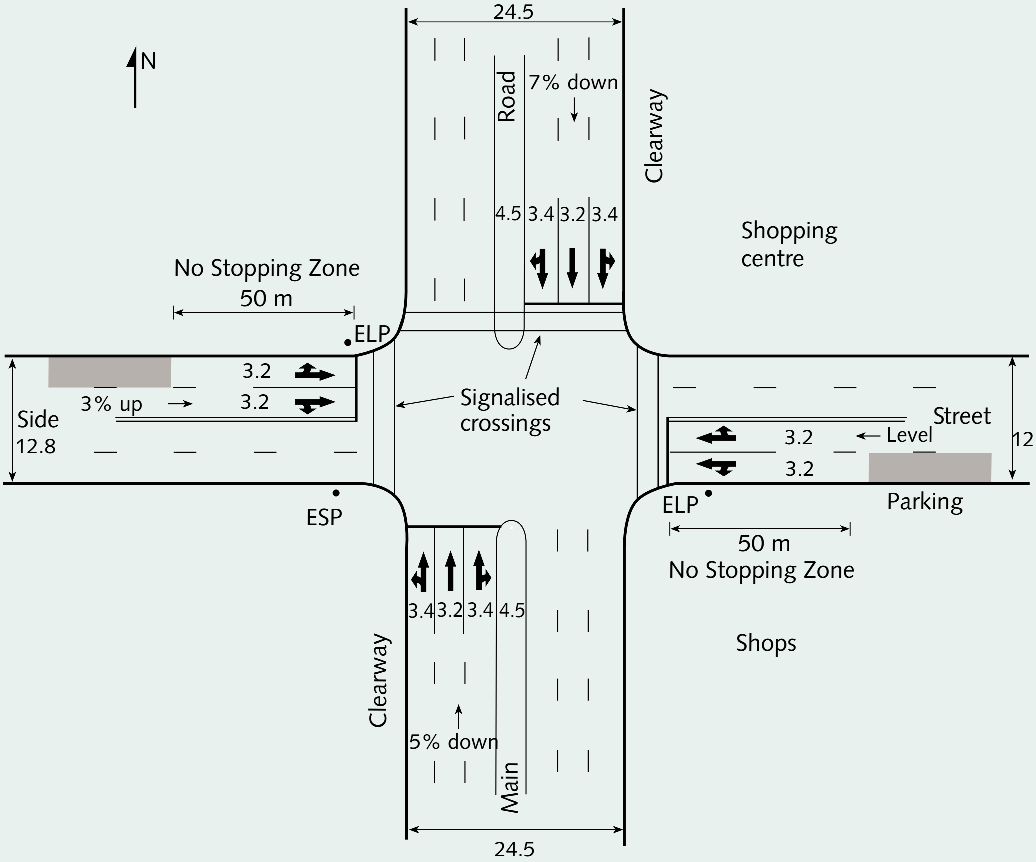
D.2.2 Output Information

Various output statistics for timing and performance analyses of signalised intersections are presented at different aggregation levels, i.e. per movement (vehicle and pedestrian), per lane, per lane group or approach, and for the intersection as a whole. Average, total or maximum values are used as applicable (e.g. average delay, total operating cost, and maximum degree of saturation).

Detailed information about output statistics and analytical models used for predicting them can be found in the aaSIDRA User Guide (Akçelik & Associates 2001a). Output data requirements include the following.

(a) Input Data Listing and Processed Input Data. The listing of input data helps the analyst to check the input data including the default values used. Processed data includes arrival (demand) flow rates that are determined by adjustments to user-specified volumes to take account of the volume counting period, peak flow factors and flow scales.

Figure D.1 Current intersection layout (Design 1)



(b) Signal Timings

(i) Cycle time, displayed green times for phases and effective green times for movements. For actuated signals, the phase green times (therefore the cycle time) are estimated average values.

(ii) Critical movement analysis results.

(iii) Cycle time or maximum green time optimisation results.

(c) Capacity

(i) Saturation flow estimates, including indications of any lane underutilisation and shared lanes that operate effectively as exclusive lanes (de facto exclusive lanes).

(ii) Capacity and degree of saturation.

(iii) Practical spare capacity.

(d) Performance

(i) Delay, queue length (average and percentile), stop rate, etc.

(ii) Level of service.

(iii) Average speed including the effect of delay.

(iv) Operating cost, fuel consumption and pollutant emissions (carbon dioxide, carbon monoxide, etc)

D.3 Existing Geometry and Phasing

D.3.1 Description and Input Data for Design 1

The current intersection layout (Design 1) is shown in *Figure D.1*. The North-South road (*Main Road*) has 3-lane approaches with median and clearway conditions, whereas the East-West road (*Side Street*) has 2-lane approaches without median and with parking allowed up to 50 m to the stop line. All approaches have shared left-turn and right-turn lanes, and all lanes have normal stop lines (no slip lanes or continuous lanes).

Signalised crossings exist in front of all intersection legs except South. Other details such as lane widths, grades, kerb-to-kerb road widths, electric supply pole (ESP), electric light pole (ELP) and so on are shown in *Figure D.1*.

The existing intersection is two-phase operation with filter right turns as shown in *Figure D.2*. Peak hour traffic volumes for each approach and pedestrian volumes for each crossing are shown in *Figure D.3*.

The filter right-turn movements from both North and South approaches encounter heavy opposing flows, and the right-turn movement from North has high volume.

The site has a crash history of 8 right-angle collisions and 2 "right-turn with opposing-through" collisions, and the number of crashes has been increasing in recent years. This trend is in line with increased right-turn volume from the North resulting from the expansion of the shopping centre.

The two-phase arrangement can no longer cater for right-turn volumes against heavy opposing through traffic flows, as evident by very long delays experienced by right-turning vehicles from North approach in particular. The current conditions (Design 1) will be analysed with this problem in mind, and then improvements to the intersection layout and signal phasing will be sought in order to improve the intersection safety and efficiency substantially (Design 2) as discussed in *Section 6*.

Figure D.2 Signal phasing for Design 1

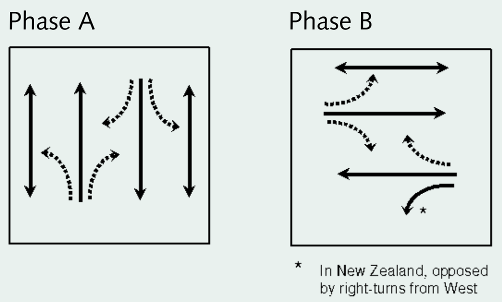
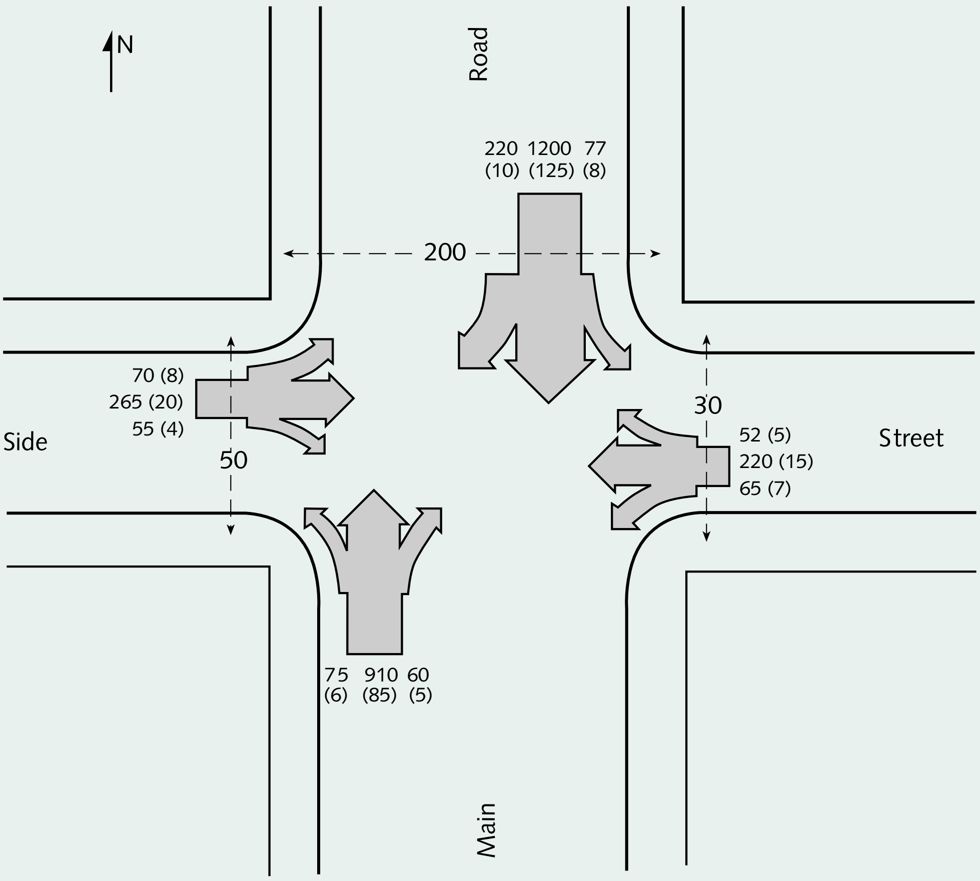


Figure D.3 Traffic volumes



Light vehicle (and Heavy vehicle) volumes are shown for each vehicle movement.

Pedestrian volumes are shown for West, North and East legs.

Vehicle and pedestrian demand volumes (veh/h and ped/h) shown are derived from 30-minute peak count.

Various input data for Design 1 analysis are determined as follows:

(a) The volumes in *Figure D.3* are peak 30-minute values though given as hourly flow rates (i.e. twice the values of 30-min volume counts). Therefore, the Peak Flow Period for performance calculations is specified as 30 minutes, and the Peak Flow Factor is specified as 1.00.

(b) There are no measured saturation flows available, and hence they will be estimated by the program. The site is in a suburban shopping environment. Basic saturation flows of 1950 and 1800 through car units per hour are considered to be appropriate for the North-South and East-West roads, respectively.

(c) The intersection is in a 60 km/h speed limit zone. All approach and exit speeds are therefore specified as 60 km/h. All approach distances are specified as 500 m.

(d) All intergreen times are 6 seconds. They are determined using the method described in *Appendix C*, *Section C.4.6* ($I = t_y + t_{ar}$ where t_y = yellow time, and t_{ar} = all-red time). Yellow times are calculated using *Equation C.4.2* (*Appendix C*) with v_D = 60 km/h, t_r = 1.5 s, a_d = 3.0 m/s^2 and the grades shown in *Figure D.1*. The resulting yellow times are t_y = 4.8 s for South, 5.1 s for North, 4.3 s for East and 4.0 s for West approach. Intersection widths used for all-red time calculations are 13 m for North-South movements and 25 m for East-West movements, and the corresponding all-red times from *Equation C.4.3* are t_{ar} = 0.9 and 1.8 s, respectively. Thus, the use of I = 6.0 s is adequate for all approach movements.

(e) The minimum green times are 8 s for Phases A and B (see *Table C.2*), subject to pedestrian minimum time requirements discussed in point (g) below. Normal start loss values are 3 seconds. Left-turning and right-turning vehicles that conflict with pedestrian movements are assumed to experience a further 8 seconds delay. Therefore, the start loss values for turning vehicles will be 11 seconds. This will impact left-turn traffic performance significantly (for South, North and West approaches), but will have less effect on right-turn traffic (not used for West approach) since start losses due to opposing traffic queue clearance intervals are likely to be longer than 11 seconds.

(f) The pedestrian “Walk” period is selected as 6 seconds for all movements. The pedestrian clearance times are determined by aaSIDRA using *Equation C.5.2* (*Appendix C*) with pedestrian clearance speed of 1.2 m/s (default). Clearance distances of 14 m for North-South movements and 26 m for East-West movements (including both carriageways and the median width as applicable) are used.

Minimum time requirements for pedestrians are determined as the sum of Walk and Clearance 1 time (see *Figure C.2*). Clearance 1 time is determined as the total clearance time less Clearance 2 time (overlap with the intergreen time). The aaSIDRA default value of 2 s Clearance 2 time is used. The resulting "pedestrian minimum green" times (Walk plus Clearance 1) are 16 s for North-South movements and 26 s for East-West movements.

The aaSIDRA method for actuated signals may use a smaller "average" minimum pedestrian time requirement so as to allow for signal cycles with no pedestrian demand. This is likely to come into effect with low pedestrian volumes on the crossings in front of the East and West approaches.

(g) Default values of actuated signal settings (maximum green and gap settings) will be used. Effective detection zone length is 4.5 m for all lanes. Due to the phasing arrangement without any arrow-controlled right-turns in Design 1, maximum green setting = 50 s and gap setting = 2.5 s will be used for all movements.

(h) Actuated coordinated signals are assumed. Arrival types of 5 ("Highly favourable" progression quality) for the through movement on the North approach, and 4 ("Favourable" progression quality) for the through movement on the South approach are specified.

D.3.2 Analysis Results for Design 1

With the default actuated signal settings, an average cycle time of 102 s is estimated with green times of 50 s for Phase A (maximum), and 40 s for Phase B. Highly oversaturated conditions, and therefore very long delays (level of service F) are predicted for the filter right-turn movement from North as seen in *Figures D.4 and D.5*. All other movements appear to operate satisfactorily, with the exception of right turn from South (level of service E).

From *Figure D.5*, the right-turn lanes on North and South approaches are seen to be operating as de facto exclusive lanes (right turns only) due to long delays experienced in these lanes. This indicates inefficient use of the road space available.

Optimisation of cycle time (as coordinated actuated signals) indicates that the performance of right-turn movements can be improved significantly at an optimum cycle time of 84 s (green times of 46 s for Phase A, and 26 s for Phase B). However, the right-turn movement from the North approach is still highly oversaturated (average delay = 322.4 s). Furthermore, the coordination requirements may not allow the use of a shorter cycle time.

These results confirm the need for improvements to the intersection layout and signal phasing to cater for the right-turn movement from the North approach in particular.

D.4 Proposed Geometry and Phasing

D.4.1 Description and Input Data for Design 2

The proposed intersection layout (Design 2) is shown in *Figure D.6*. It is similar to that of Design 1, with the exception of the following changes made to the North approach:

(a) An exclusive right-turn lane 2.8 m wide and 80 m long (short lane) is provided.

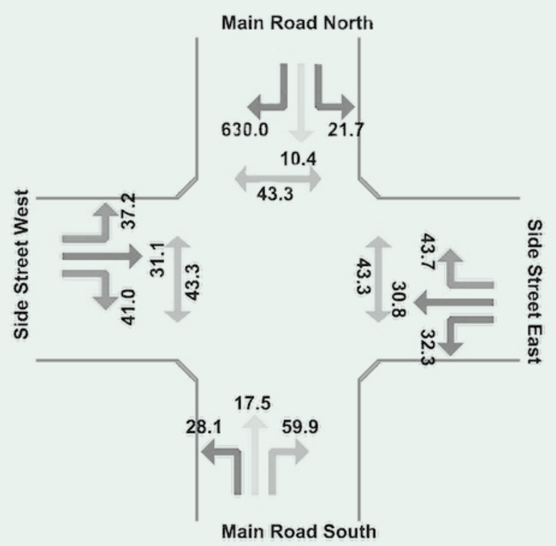
(b) The median strip is reduced from 4.5 m to 1.7 m wide.

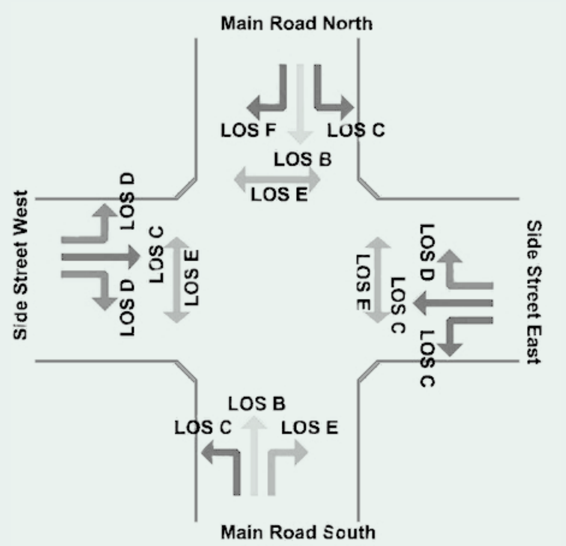
(c) A left-turn slip lane 3.0 m wide and 70 m long (short lane) is provided.

(d) The pedestrian crossing between the footpath and the traffic island is not signalised.

The proposed signal phasing system is shown in *Figure D.7*. Because the exclusive right-turn lane added to the North approach will be arrow controlled, a leading

Figure D.4 Average delay and level of service estimates for Design 1 (based on default actuated signal settings)





right turn sequence is used as the opposing filter right turn has been retained (Phase C added). A lagging right-turn sequence has safety problems in this case (see *Section 6.3.3*). Had the right-turn volume from South approach been considerably higher, a *diamond overlap* phase design would have been assessed (see *Section 6.3.5*). This would have required an exclusive right-turn lane to be provided on the South approach as well.

The left-turn movement from North (slip lane) gives way to right turns from South in Phase A, and to through traffic from West in Phase B. This movement is designated as *undetected*, and therefore, will not affect signal timings.

The right-turn movement from North receives two distinct green periods, namely unopposed during Phase C and opposed during Phase A, stopping during the intergreen time between Phases C and A. On the other hand, the through movement from North has a single green period although it runs during both Phases C and A (it is not stopped during the intergreen time between Phases C and A).

The intergreen time for Phase C is calculated on the basis of the conflict between the right-turn movement from North clearing the intersection and the pedestrian movement in front of the West approach starting. Negotiation radius for this movement is measured as 15 m, and the negotiation speed and distance are calculated as 22 km/h and 24 m. Using t_r = 1.5 s, a_d = 3.0 m/s^2, v_D = 22 km/h and G = - 0.07 in *Equation C.4.2*, yellow time is calculated as t_y = 4.1 s. Using L_C = 24 m in *Equation C.4.3*, all-red time (for 60 km/h zone) is found as t_{ar} = 1.7 s. Therefore, intergreen time for Phase C is selected as I = 6 s.

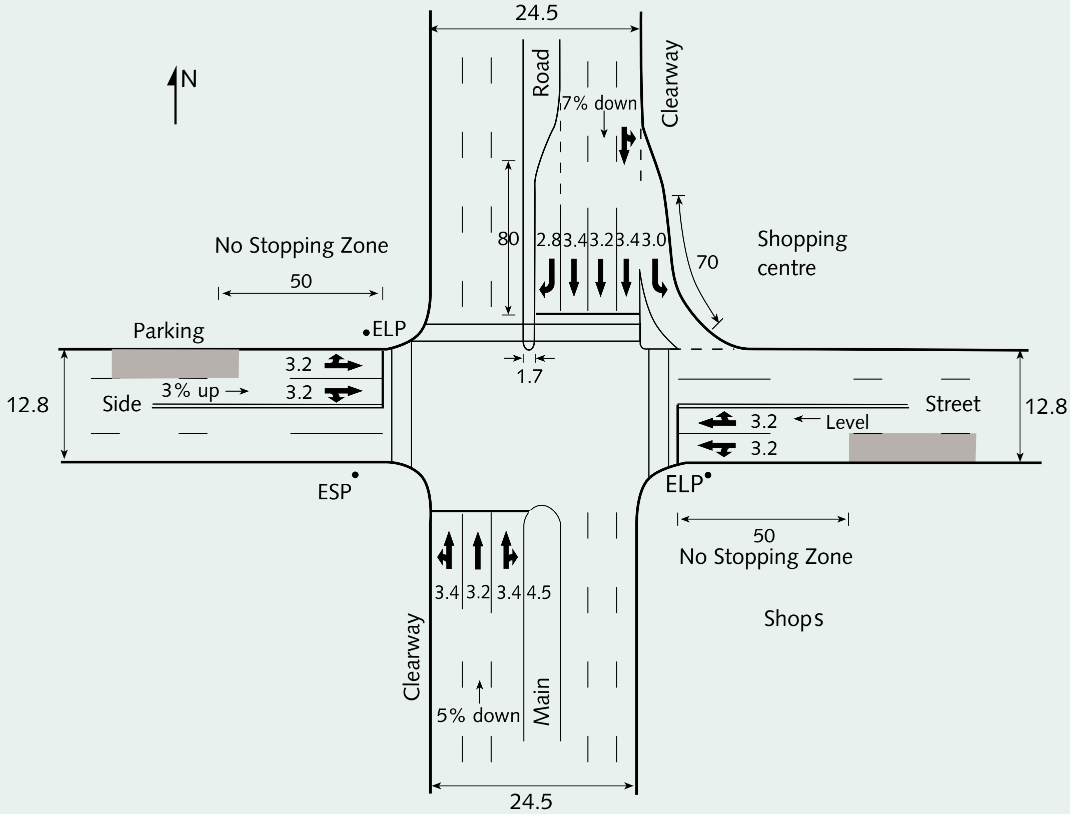
Figure D.5 Lane flow, capacity and performance results for Design 1

Austroads Guide TEP Part 7 (Traffic Signals) Worked Example TEP7D1
Design 1 (Two-Phase)
Intersection ID: TEP7A
Actuated Coordinated Signals, Cycle Time = 102

Table S.7 - Lane Performance

Lane No.	Effective Red & Green Times (sec) R1	G1	R2	G2	Arv Flow (veh /h)	Cap (veh /h)	Deg. Satn x	Aver. Delay (sec)	Eff. Stop Rate	Queue 95% Back (vehs)	(m)	Shrt Lane (m)
South: Main Road South												
1 LT	54	48	0	0	524	857	0.612	20.2	0.62	18.4	136	
2 T	52	50	0	0	552	902	0.612	16.5	0.54	17.9	132	
3 R	86	16	0	0	65	86	0.759	59.9	0.80	4.3	30	
East: Side Street East												
1 LT	62	40	0	0	153	301	0.507	27.5	0.66	6.2	46	50
2 TR	73	29	0	0	211	416	0.507	37.2	0.75	10.7	77	
North: Main Road North												
1 LT	54	48	0	0	691	861	0.802	13.5	0.62	23.1	172	
2 T	52	50	0	0	719	897	0.802	8.8	0.51	21.0	156	
3 R	75	27	0	0	230	142	1.624	630.0	2.32	49.2	330	
West: Side Street West												
1 LT	68	34	0	0	151	275	0.547	32.8	0.70	6.8	50	50
2 TR	69	33	0	0	271	496	0.547	34.1	0.75	13.2	95	

Figure D.6 Proposed intersection layout (Design 2)



Minimum green times for Phases A and B are 8 s as in Design 1, and minimum green time for Phase C is chosen as 6 s (see *Table C.2*). Minimum pedestrian time requirements are not changed as a result of the changes to intersection geometry.

The additional start loss of 8 s is removed from the left-turn movement from North. It is retained for the right-turn movement from North in Phase A, but there is no additional start loss for this movement in Phase C.

For Phase C (arrow-controlled right-turn), maximum green setting = 20 s and gap setting = 2.0 s will be applicable (default values). Signal coordination data are unchanged.

D.4.2 Analysis Results for Design 2

With the default actuated signal settings, an average cycle time of 138 s is estimated with green times of 20 s for Phase C, and 50 s each for Phases A and B. This is the maximum cycle time that results from all critical movements requiring maximum green times.

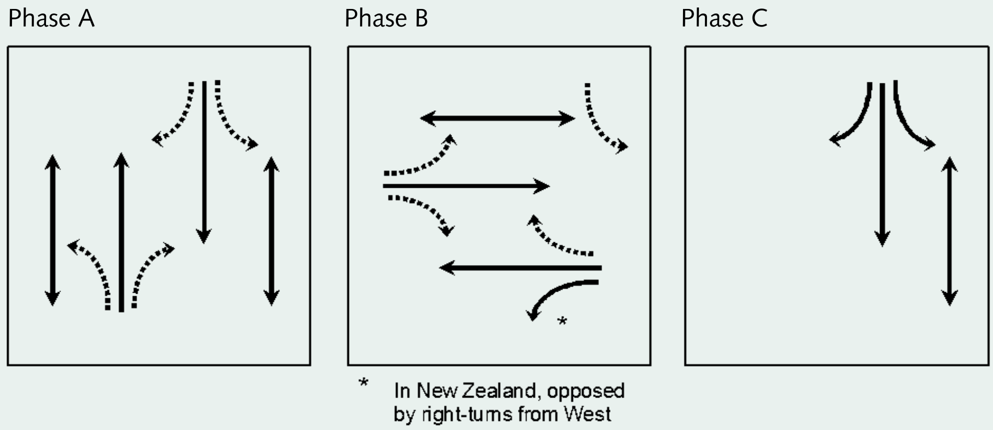
The intersection performance under this set of timings is not quite satisfactory as seen in *Figure D.8*. Although satisfactory performance is observed for the right-turn movement from North, all pedestrian movements and the right-turn movement from East are seen to experience long delays (level of service E).

A sensitivity analysis indicates that shorter maximum green settings for all movements produce better results. The results with the optimum maximum green settings of 23 s for through and left-turn movements and 9 s for the arrow-controlled right-turn movement (45 per cent of default values) is shown in *Figure D.9*. These settings give an average cycle time of 75 s with green times of 23 s for Phase A (maximum), 25 s for Phase B (minimum due to the pedestrian movement) and 9 s for Phase C.

Cycle-time optimisation for coordinated signal operation purposes (using reduced maximum green settings) indicates that the intersection could operate satisfactorily at a low cycle time of 80 s as seen in *Figure D.10*. The green times with this cycle time were 28 s for Phase A, 25 s for Phase B and 9 s for Phase C.

The variable cycle time results indicate that the capacity is maximum at a cycle time of 85 seconds, and significant decreases in capacity are observed with increased cycle times. The loss of capacity with increased cycle times for this example is due to the existence of filter

Figure D.7 Signal phasing for Design 2 (left-turn vehicles from North approach give way to opposing through and right-turn movements in Phases A and B)



turns, lane blockages (by left turns waiting for pedestrians, and filter right turns waiting for gaps) and short lanes.

Given the above results, a cycle time of 90 s is selected for coordinated signal operation (on the basis that this is the critical intersection in the signal coordination area). Maximum green settings of 35 s for through and left-turn movements and 14 s for the arrow-controlled right-turn movement (70 per cent of default values) are selected as reasonably large values.

The resulting green times are 12 s for Phase C, and 30 s each for Phases A and B. The performance results under these timings are shown in *Figure D.11*. The largest degree of saturation is 0.760, average delay is 21.2 s for all vehicles and 37.4 s for all pedestrians.

If this intersection is not the critical intersection in the signal coordination area, a longer cycle time may be imposed by the critical intersection. Considering this, the intersection performance with a cycle time of 120 s and the default maximum green settings is tested.

The resulting green times are 48 s for Phase A, 44 s for Phase B and 10 s for Phase C. This indicates generally satisfactory operation (largest degree of saturation = 0.900, average delay for all vehicles = 24.9 s) although average delay for all pedestrians was significantly higher (52.3 s).

Figure D.8 Average delay and level of service estimates for Design 2 (with default maximum green settings)

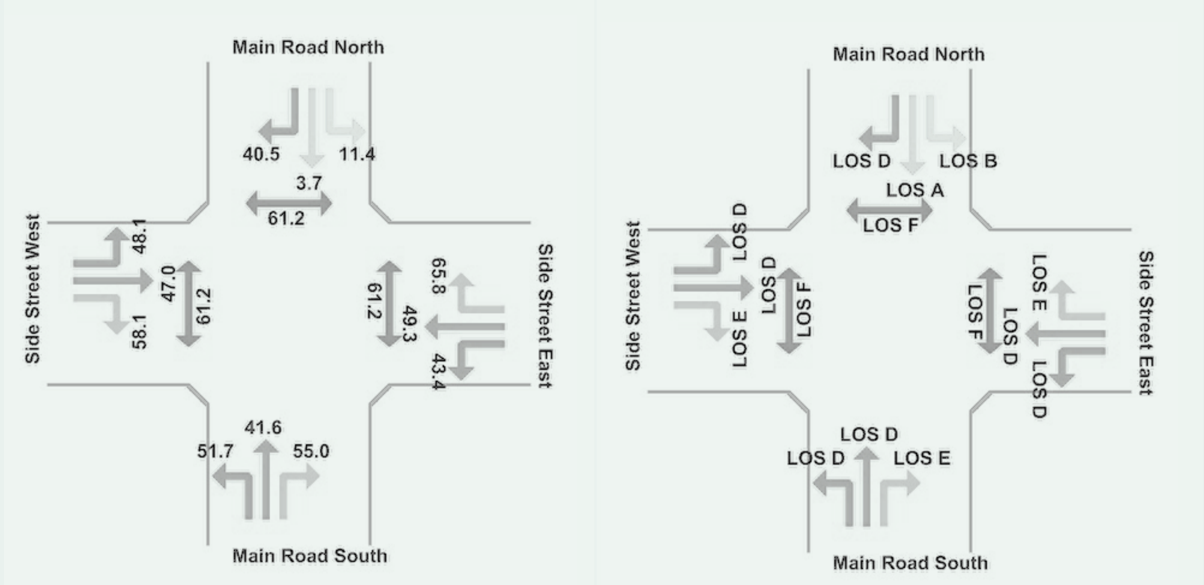
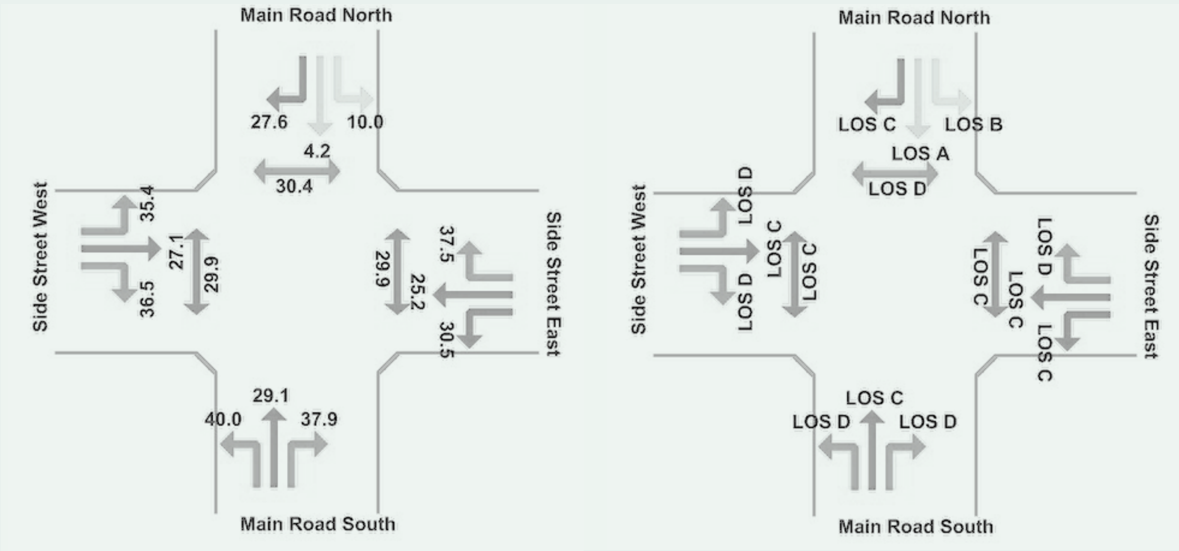


Figure D.9 Average delay and level of service estimates for Design 2 (with reduced maximum green settings)



Finally, a flow scale analysis for design life purposes is carried out using the reduced maximum green settings (70 per cent of default values). In this analysis, all demand flows are increased from current levels by applying an increasing flow scale factor. Average green times and cycle time are recalculated under each demand flow scenario. As seen in *Figure D.12*, these results indicate that the intersection could carry 16 per cent more traffic before it reaches the point when the spare capacity is zero, i.e. the intersection degree of saturation equals the practical (target) degree of saturation of 0.90. With a uniform traffic growth of 2 per cent per year, this would mean that the intersection would be operating at practical capacity after 8 years.

Based on the above analysis results, it may be concluded that Design 2 provides a satisfactory solution to the problems experienced with Design 1.

Figure D.10 Average delay vs cycle time for Design 2 (with reduced maximum green settings)

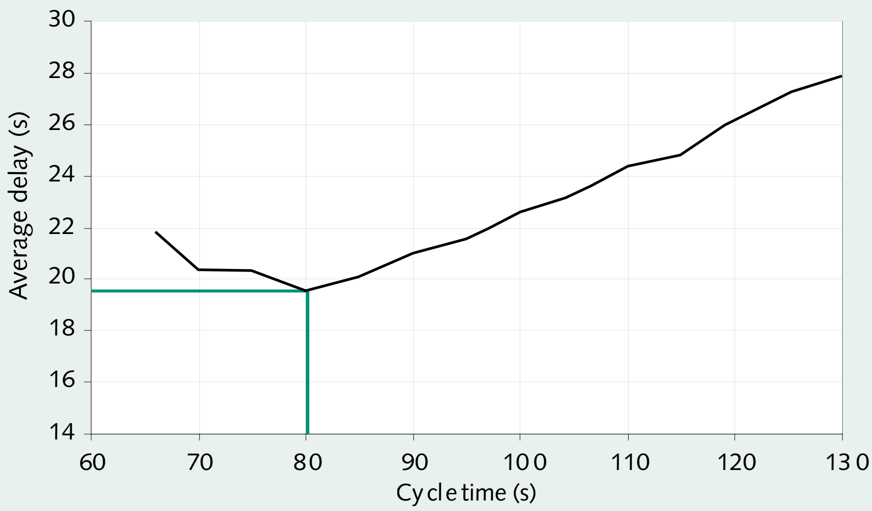


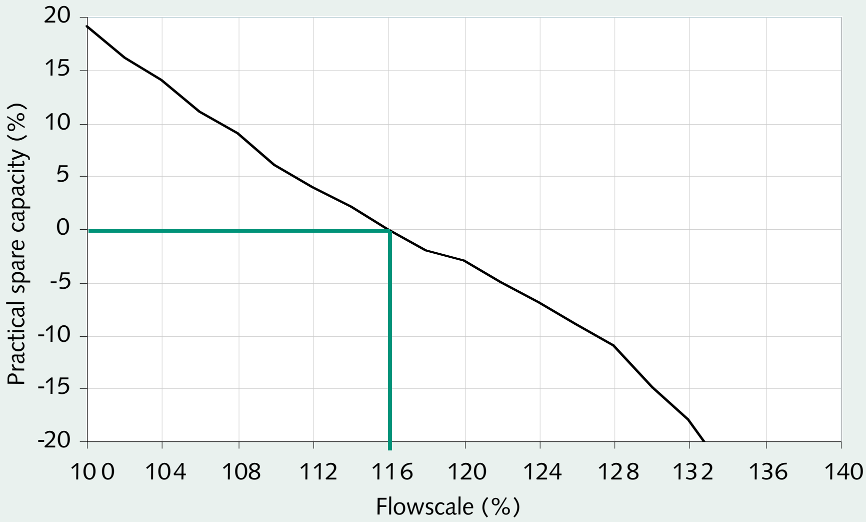
Figure D.11 Lane flow, capacity and performance results for Design 2 for a selected cycle time of 90 s

Austroads Guide TEP Part 7 (Traffic Signals) Worked Example TEP7D2
Design 2 (Three-Phase Option)
Intersection ID: TEP7B
Actuated Coordinated Signals, Cycle Time = 90

Table S.7 - Lane Performance

Lane No.	Effective Red & Green Times (sec) R1	G1	R2	G2	Arv Flow (veh /h)	Cap (veh /h)	Deg. Satn x	Aver. Delay (sec)	Eff. Stop Rate	Queue 95% Back (vehs)	(m)	Shrt Lane (m)
South: Main Road South												
1 LT	63	27	0	0	417	548	0.760	33.9	0.80	18.3	135	
2 T	60	30	0	0	467	614	0.760	29.1	0.77	19.5	144	
3 TR	61	29	0	0	257	339	0.760	33.4	0.79	11.9	86	
East: Side Street East												
1 LT	60	30	0	0	176	307	0.575	29.0	0.70	7.1*	52	50
2 TR	70	20	0	0	188	326	0.575	38.8	0.78	9.1	66	
North: Main Road North												
1 L	6	48	16	20	85	943	0.090	10.5	0.67	0.9	7	70
2 T	42	48	0	0	443	987	0.449	3.4	0.17	4.5	33	
3 T	42	48	0	0	439	976	0.449	3.4	0.17	4.4	33	
4 T	42	48	0	0	443	987	0.449	3.4	0.17	4.5	33	
5 R	42	12	27	9	230	340	0.676	28.9	0.83	7.1	47	80
West: Side Street West												
1 LT	65	25	0	0	178	282	0.630	34.1	0.74	7.8*	58	50
2 TR	67	23	0	0	244	388	0.630	36.3	0.79	11.6	83	

Figure D.12 Percentage spare capacity vs flow scale for Design 2 (with reduced maximum green settings)



D.5 Implementation of Proposed Design

D.5.1 Provision of Signal Hardware and Location

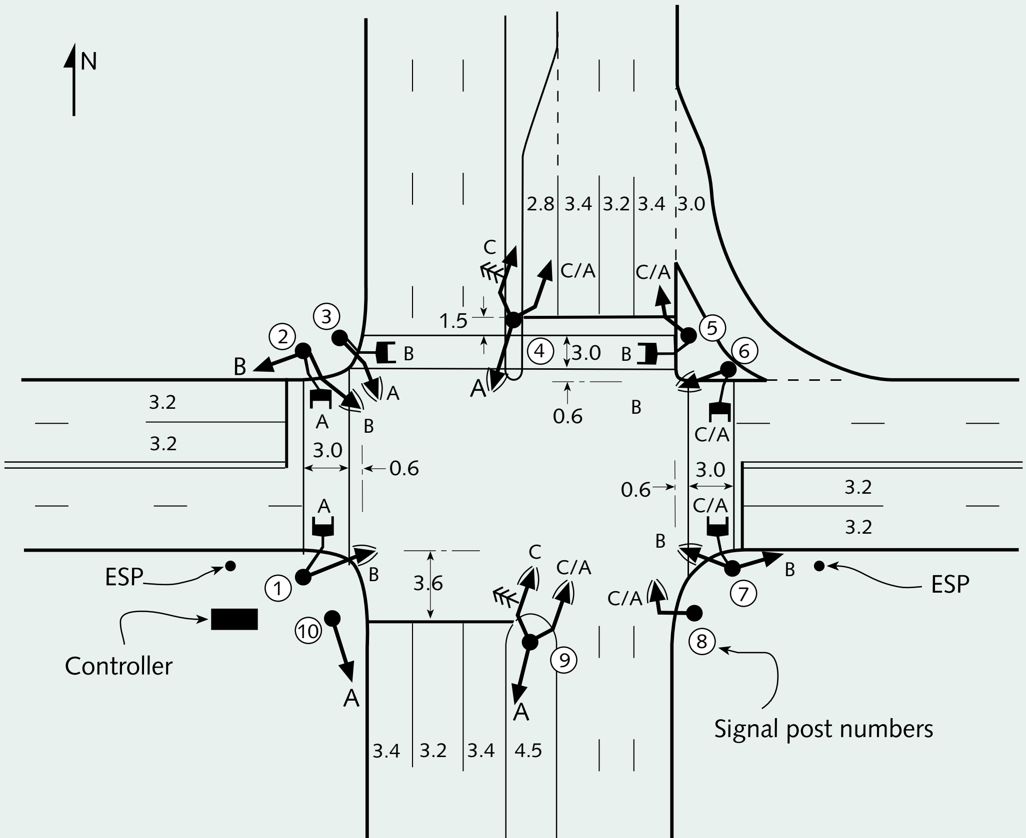
Following the signal timing and performance analyses in the previous sections, the intersection geometry and phasing design can be finalised, and the necessary signal hardware such as signal faces, posts, mast arms, controller, detector etc, as well as the line markings and signposting, may be included on the base plan of Design 2. For detailed information, see *Section 7* for the use and location of this equipment, *Section 8* for the basic logic and installation of detector,. *Section 10* for various types of pavement marking, and *Section 11* for signposting.

Figure D.13 shows the line marking, signal face locations and provision of some accessories. The following discussions are based on this figure.

(a) Signal Faces

Since the movements on the East, South and West approaches do not include any arrow-controlled turning movements, the basic three-aspect signal display is used. However, as the signal faces for the North approach are required to provide for a leading right-turn phase, a six-aspect multi-column signal face is used. This consists of a column of three-aspect (green, yellow and red) right-turn arrows in addition to the basic three-aspect signals (see *Figure 5.4*). This operation could also be implemented using a five-aspect two-column signal face with green and yellow right-turn arrows only (see *Figure 5.7*). In the case of three-aspect right-turn arrows, red-arrow drop out method is used to achieve filter right turns in Phase A as allowed by the adjacent green circle displays (see *Section 6.3*).

Figure D.13 Signal face locations for Design 2



(b) Number of Signal Faces

(i) East and West approaches: Three signal faces (primary, secondary and tertiary) are provided. The green circle is displayed during Phase B.

(ii) North approach: Four signal faces (primary, dual primary, secondary, and tertiary) are provided. The primary and tertiary signal faces are three-aspect circles. The dual primary and secondary signal faces are six-aspect with three-aspect circles and three-aspect arrows. As the medians are of sufficient width, these signal faces are on posts located in the medians. The green arrow is displayed in Phase C only. The green circle is displayed in both A and C phases and the C/A intergreen.

(iii) South approach: Four signal faces (primary, dual primary, secondary, and tertiary) are provided. As the medians are of sufficient width, these signal faces are on posts located in the medians. All signal faces are three-aspect circles. The green circle is displayed in Phase A only.

(iv) Pedestrian signals: Only one pedestrian signal face is required at each end of the signalised crossing as the crossing width and distance criteria are satisfied (see *Section 7.4.4*). Note that the East-West crossing distance is close to the limit value of 25 m. Pedestrian signal faces display green Walk signal during the appropriate phases C/A, A or B (see *Figures D.7 and D.13*).

(c) Size of Signal Aspects

Only 200 mm aspects are used as recommended in *Section 5.2.3*, since there are no grounds for providing 300 mm signals.

(d) Use of Mast Arm

The use of mast arm or overhead signal faces is not warranted at this site. For the South and North approaches, the dual primary signal face can be accommodated on the median islands as its width is greater than the 1.5 m recommended for dual column aspects of 200 mm size.

(e) Target Boards

All vehicle signal faces are provided with a target board, appropriate to the signals being used.

(f) Visors and Louvres

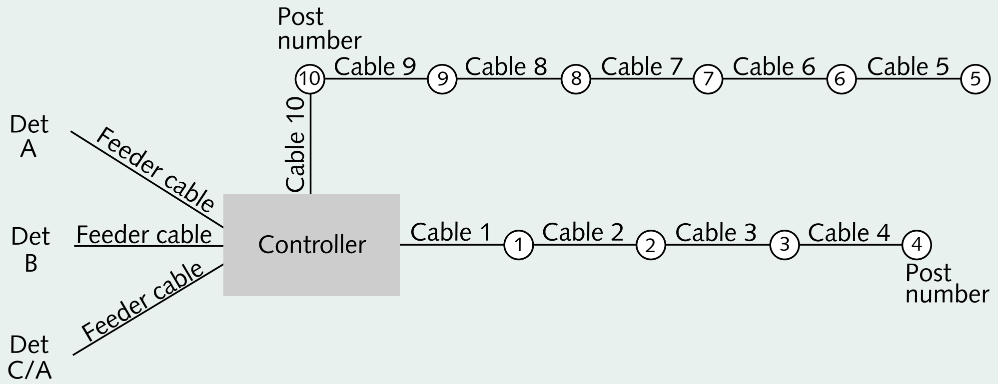
Closed visors are to be provided on all secondary and tertiary signal faces except the three-aspect right-arrow signal faces (see *Section 7.6*). The use of louvres is not warranted in this case.

(g) Location of Controller Housing and Signal Posts

The controller should be located in an unexposed position in close proximity to the intersection and available power supply. In *Figure D.13*, this is located on the South-West corner.

The posts are numbered sequentially (1 to 10) in a clockwise manner for the identification used in the cable connection diagram. Note that the number of posts has been minimised by accommodating the various signals where practicable on a common post.

Figure D.14 A typical cable layout diagram for Design 2



An optional cable can be added between Posts 4 and 5. This cable is available to restore the service quickly in the event of a breakage elsewhere in the loop.

D.5.2 Cable Connection Design

The cable layout for the intersection is prepared next, according to the general requirements indicated in *Section 12*. The layout, which uses the *open-loop* system, is shown in *Figure D.14*. Two parallel circuits are set up to connect all signal faces and pedestrian push buttons to the controller.

A closed-loop system may be achieved by adding a cable between Posts 4 and 5. This helps to restore the service quickly in the event of a breakage elsewhere in the loop. However, this cable would not normally be terminated at Post 5 as it would affect the lamp monitoring.

The vehicle detectors are connected to the controller separately via screened feeder cables. The cable size is chosen to provide sufficient cores to cater for signal requirements with adequate spares.

The circuits are arranged to achieve the most economic solution in terms of cable size and length, and the associated costs of ducting under the prevailing site conditions and existing services. Adequate spares in cores must be provided in each cable for possible future expansion. The cable size is chosen to provide sufficient cores to cater for signal requirements with adequate spares.

In view of the above considerations, the first circuit caters for Posts 1 to 4, the second circuit caters for Posts 5 to 10.

D.5.3 Selection of Controller Settings

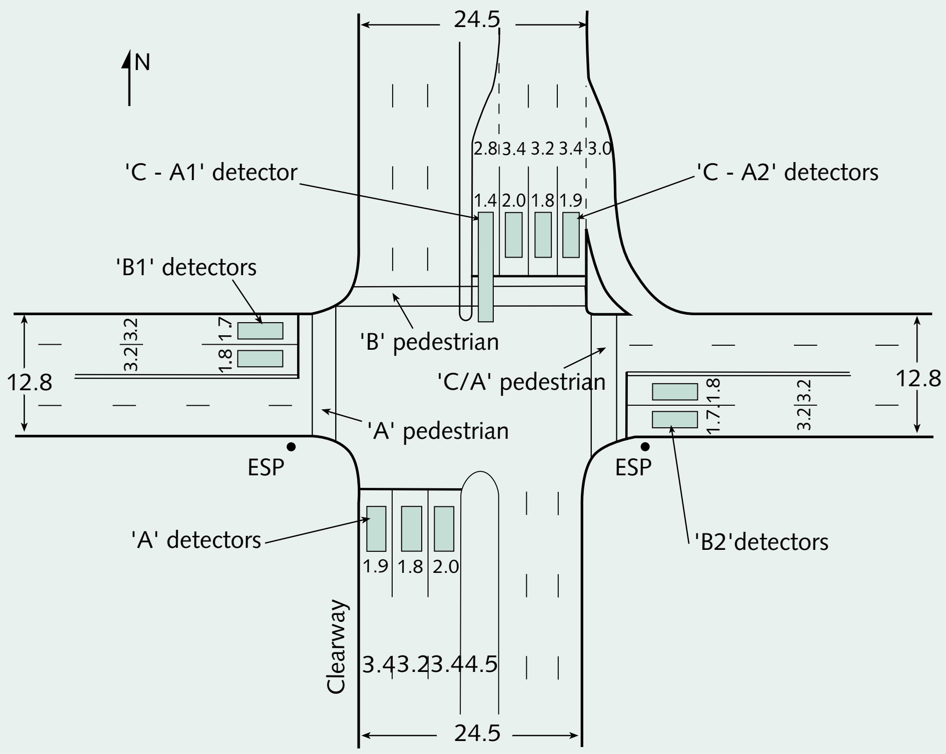
The results of the signal timing analysis for Design 2 (*Section D.4*) can be used in conjunction with the method described in *Appendix C* to determine initial controller settings.

D.5.3.1 Controller Operation Sheets

Controller Operation Sheets are used to record operational specifications and all related information including controller type, signal group allocation, detector map (layout and numbering), detector functions, phasing diagram, approach timing details, controller time settings including pedestrian time settings, signal coordination details, and special functions.

Utilising the Controller Operation Sheets, a personality to adapt a controller to the intersection is prepared by use of a generation program specific to the brand and model of controller being used. These programs require considerable experience and expertise to implement effectively. The manufacturer or a professional with expertise in the particular controller being used should be consulted.

Figure D.15 Location of detectors for Design 2



D.5.3.2 Detectors and Approach Timers

Detectors and approach timers must be decided before the controller settings are determined. These are detailed below.

(a) All detectors are 4.5 m presence detectors located at the stop line in each lane, except for the C phase right-turn detector, which is an 11.0 m detector because both an arrow-controlled turn and a filter turn are provided (see *Figure D.15*, also *Figure 8.3* in *Section 8*). Individual detector loops are labelled for identification purposes. Method of labelling varies from jurisdiction to jurisdiction and may reflect detector operational functions.

(b) The approach timers are allocated as follows:

Phase A, approach timer 1: A detectors

Phase A, approach timer 2: C-A2 detectors

Phase B, approach timer 1: B1 detectors

Phase B, approach timer 2: B2 detectors

Phase C, approach timer 1: C-A1 detector (approach section)

Phase C, approach timer 2: C-A2 detectors.

(c) Pedestrian features will be as follows:

Pedestrian feature number 1: C/A pedestrian

Pedestrian feature number 2: A pedestrian

Pedestrian feature number 3: B pedestrian.

Figure D.16 Phase and pedestrian time settings recorded in a typical Timing Card for Design 2

Controller Time Settings

Phase Time Settings

Time Setting No.	Description	Limit	Phase A (1)	B (2)	C (3)	D (4)	E (5)	F (6)	G (7)
1	RED/YELLOW	5	-	-	-				
2	LATE START	20	5	-	-				
3	MINIMUM GREEN	20	8	8	6				
4	INCREMENT	5	-	-	-				
5	MAXIMUM INITIAL GREEN	40	-	-	-				
6	MAXIMUM EXTENSION GREEN	90	27	27	8				
7	EARLY CUT OFF (ECO)	20	-	-	-				
8	YELLOW	7	5.0	4.0	4.0				
9	ALL RED	15	1.0	2.0	2.0				
10	SPECIAL ALL RED	15	-	-	-				
11	GAP 1	10	2.5	2.5	2.0				
12	GAP 2	10	2.5	2.5	2.5				
13	GAP 3	10	-	-	-				
14	GAP 4	10	-	-	-				
15	HEADWAY 1	5	0.7	0.7	0.6				
16	HEADWAY 2	5	0.7	0.7	0.6				
17	HEADWAY 3	5	-	-	-				
18	HEADWAY 4	5	-	-	-				
19	WASTE 1	50	4.0	4.0	2.0				
20	WASTE 2	50	4.0	4.0	2.0				
21	WASTE 3	50	-	-	-				
22	WASTE 4	50	-	-	-				
SPECIAL ALL RED SEQUENCES			-	-	-				
PROHIBITED SEQUENCES			-	A-C	-				

Figure D.16 Phase and pedestrian time settings recorded in a typical Timing Card for Design 2 (continued)

Controller Time Settings continued

Pedestrian Time Settings

Time Setting No.	Description	Limit	P1 (1)	P2 (2)	P3 (3)	P4 (4)	P5 (5)	P6 (6)	P7 (7)	P8 (8)
1	DELAY	20	-	-	-					
2	WALK	40	6	6	6					
3	CLEARANCE 1	40	10	10	20					
4	CLEARANCE 2	10	2	2	2					
AUTO SWITCH			OFF	OFF	OFF					
PEDESTRIAN PHASES			C/A	A	B					

Note: the column headers P1–P8 are grouped under the heading "Pedestrian".

D.5.3.3 Timing Card

A Timing Card is used to record controller settings. Part of a typical Timing Card completed for Design 2 is shown in *Figure D.16*. Values given in this figure are based on those used in the aaSIDRA analysis for Design 2 where applicable. Dashes (-) have been used for those time settings that are not applicable. These should not be confused with zeros that, if used, would produce zero time settings.

The entries in the Timing Card shown in *Figure D.16* are discussed below. The following paragraph numbers match the Time Setting Numbers in the Timing Card (and in the controller).

PHASE TIME SETTINGS

1. RED/YELLOW

   Not used (this controller feature is found in old sites only; practice has been discontinued and is not in accordance with current standards as seen in *Section 5.7*).

2. LATE START

   The Phase A late start interval is used to hold the Phase C right-turn red arrows at the start of Phase A in order to protect the pedestrian movement in front of the West approach.

3. MINIMUM GREEN

   Minimum green is G_{min} = 8 s for Phases A and B, and 6 s for Phase C.

4. INCREMENT

   This is not applicable since there are no passage detectors.

5. MAXIMUM INITIAL GREEN

   This is not applicable since there are no passage detectors (see *Section C.4.2.2*).

6. MAXIMUM EXTENSION GREEN

   These are calculated as the maximum green settings (reduced values) used in the aaSIDRA analysis less the minimum green time, $G_{emax} = G_{max} - G_{min}$. Therefore, G_{emax} = 35 - 8 s = 27 s for Phases A and B, and G_{emax} = 14 - 6 = 8 s for Phase C are recorded in the Timing Card.

   It is important to note that maximum green extension settings should be selected on the basis of analyses carried out for different flow periods (see *Section D.1*) to satisfy requirements of different demand patterns and different demand flow levels in those periods.

7. ECO (Early Cut Off) Green

   Not applicable since there are no staged terminations of movements.

8. YELLOW

   The values shown are based on the calculations given in *Section D.3.1 (d)*.

9. ALL RED

   The values shown are based on the calculations given in *Section D.3.1 (d)*.

10. SPECIAL ALL RED

    There are no special all red features.

11. GAP 1

    This is the first gap setting for each phase. In *Figure D.15*, these are A, B1 and C-A1 detectors. The gap setting is e_s = 2.5 s for A and B1 detectors, and e_s = 2.0 s for C-A1 detector.

12. GAP 2

    This is the second gap setting for each phase. In *Figure D.15*, these are B2 and C-A2 detectors. The gap setting is e_s = 2.5 s for these detectors.

13, 14. GAP 3 and GAP 4

    These are not applicable since there are only two approach timers per phase (see *Figure D.15*).

15-22 HEADWAY and WASTE

Similar to the GAP time settings, HEADWAY and WASTE time settings are required for the first and second approach timers only.

Headway settings are 0.7 s for A, B1, B2 and C-A2 detectors, and 0.6 s for C-A1 detector (right-turn movement).

Waste settings are usually determined as 10 per cent of maximum green values, implying 3.5 s for Phases A and B, and 1.4 s for Phase C. However, these are less than the minimum values (see *Appendix C, Table C.2*). Therefore, waste settings are 4.0 s for A, B1, B2 and C-A2 detectors, and 2.0 s for C-A1 detector.

SPECIAL ALL RED SEQUENCES

This is not applicable.

PROHIBITED SEQUENCES

Transition from Phase A to Phase C (due to skipping of Phase B) is prohibited so that both approaches of Main Road display yellow signals simultaneously to avoid a possible filter right-turn conflict problem for the South approach of Main Road (see *Section 6.3.3*).

PEDESTRIAN TIME SETTINGS

1. DELAY

   Pedestrian delay setting is not used.

2. WALK

   Walk time is 6 seconds for each pedestrian movement.

3. CLEARANCE 1

   Clearance 1 time (see *Figure C.2*) is 10 s for P1 and P2, and 20 s for P3. These are based on the use of clearance distances of 14 m for P1 and P2, and 26 m for P3 (see *Section D.3.1*).

4. CLEARANCE 2

   Clearance 2 time is 2 s for all pedestrian movements (2 s overlap with yellow time of the terminating intergreen, i.e. with Phase A intergreen for P1 and P2, with Phase B intergreen for P3.

AUTO SWITCH

This is not applicable since actuated pedestrian movements are used (this is used for introducing the pedestrian feature automatically with the associated phase).

PEDESTRIAN PHASES

This indicates the phase(s) associated with each pedestrian movement.

Other Time Settings

Further time settings not shown in *Figure D.16* are recorded on the Timing Card. These include special movement time settings, presence time settings, signal coordination features, and so on.

In this example, there are no special movements, and the only presence-timed detector is the 11 C-A1 detector (11 m long), where a presence time of 2 s is appropriate.

A-phase operates as the "recall" phase to facilitate signal coordination along North-South approach.

References

AKÇELIK, R. (1981). *Traffic Signals: Capacity and Timing Analysis*. Research Report ARR No. 123 (*6th reprint: 1995*). ARRB Transport Research Ltd, Vermont South, Australia.

AKÇELIK, R. (1995a). Australian vehicle-actuated control practice: survey results. *Road and Transport Research* 4 (3), pp 63-70.

AKÇELIK, R. (1995b). *Signal Timing Analysis for Vehicle-Actuated Control*. Working Paper WD TE 95/007. ARRB Transport Research Ltd, Vermont South, Australia.

AKÇELIK, R. (1995c). *Signal Timing Calculation Methods for Vehicle-Actuated and Fixed-Time Signals*. Working Paper WD TO 95/020. ARRB Transport Research Ltd, Vermont South, Australia.

AKÇELIK & ASSOCIATES (2001a). *aaSIDRA User Guide*. Akçelik and Associates Pty Ltd, Melbourne, Australia.

AKÇELIK & ASSOCIATES (2001b). *An Investigation of Pedestrian Movement Characteristics at Mid-Block Signalised Crossings*. Technical Report. Akçelik and Associates Pty Ltd, Melbourne, Australia.

AKÇELIK, R., BESLEY M. and CHUNG, E. (1998). An evaluation of SCATS Master Isolated control. *Proc. ARRB Transport Research 19th Conference (Transport 98)* (CD), pp 1-24. ARRB Transport Research Ltd, Vermont South, Australia.

AKÇELIK, R., BESLEY M. and ROPER, R. (1999). *Fundamental Relationships for Traffic Flows at Signalised Intersections*. Research Report ARR 340. ARRB Transport Research Ltd, Vermont South, Australia.

AKÇELIK, R. and BIGGS, D.C. (1987). Acceleration profile models for vehicles in road traffic. *Transportation Science*, 21(1), pp 36-54.

AKÇELIK, R., BIGGS, D.C. and LAY, M.G. (1983). *Modelling Acceleration Profiles*. Internal Report AIR 390-3. ARRB Transport Research Ltd, Vermont South, Australia.

AKÇELIK, R., CHUNG, E. and BESLEY, M. (1998). *Roundabouts: Capacity and Performance Analysis*. Research Report ARR No. 321. ARRB Transport Research Ltd, Vermont South, Australia (*Revised edition 1999*).

AKÇELIK, R., ROPER, R. and BESLEY, M. (1999). *Fundamental Relationships for Freeway Traffic Flows*. Research Report ARR 341. ARRB Transport Research Ltd, Vermont South, Australia.

AUSTROADS (1988 - 1999). **Guide to Traffic Engineering Practice (GTEP)**. Association of Australian State Road and Transport Authorities, Sydney, Australia.

Part 2 *Roadway Capacity*. 1988.

Part 3 *Traffic Studies*. 1988.

Part 4 *Road Crashes*. 1988.

Part 5 *Intersections at Grade*. 1988.

Part 6 *Roundabouts*. 1993.

Part 8 *Traffic Control Devices*. 1988.

Part 13 *Pedestrians*. 1995.

Part 14 *Bicycles*. 1999.

Part 15 *Motorcycles*. 1999.

AUSTROADS (1995). *Design Vehicles and Turning Paths*. Association of Australian State Road and Transport Authorities, Sydney, Australia.

AUSTROADS (2000). *Guide to the Selection of Pavement Surfacings*. Association of Australian State Road and Transport Authorities, Sydney, Australia, pp 12-17.

BASTABLE, A.J. (1980). The economic and social impact of dynamic signal co-ordination in Sydney. *Proc. ARRB 10th Conf.* 10 (4), pp 245-251. ARRB Transport Research Ltd, Vermont South, Australia.

BLANKS, H.S., DAVIES, L.W. and HULSCHER, F.R. (1976). Failsafe requirements of road traffic signal equipment. *Proc. ARRB 8th Conf.* 8 (5), pp 27-35. ARRB Transport Research Ltd, Vermont South, Australia.

BLEVIN, W.R. (1972). *Colour Specification*. IES Convention.

CHARLES, P. (2001). Time for a change. *Traffic Technology International*, June/July issue, pp 68-71.

COLE, B.L. and BROWN, B. (1966). A preliminary examination of the optimal performance of road traffic signal lights. *Australian Road Research* 2 (8), pp 24-32.

COLE, B.L. and BROWN, B. (1968). Specification of road traffic light intensity. *Human Factors* 10 (3), pp 245-254.

CUMMING, R.W. (1964). The analysis of skills in driving. *Australian Road Research* 1 (9), pp 4-14.

DAVIES, L.W., HULSCHER, F.R. and SYME, J.W. (1978). Failsafe requirements of road traffic signal equipment II. *Proc. ARRB 9th Conf.* 9(5), pp 69-78. ARRB Transport Research Ltd, Vermont South, Australia.

DEAN, K.G., MACDONALD, D.E. and MORRIS, D.J. (1981). *Vehicle Detector Loop Configurations (Phase 2)*. Report No R81-3. AWA Research Laboratory.

DIBLEY, T. and REID, J. (1990). Acceleration / Deceleration Profiles at Urban Intersections. Report for Transit New Zealand. Australasian Traffic Survey Pty Ltd, Melbourne.

FISHER, A.J. (1971). *A Photometric Specification for Vehicular Traffic Signal Lanterns*. Report (3 parts). University of New South Wales, Sydney, Australia.

FISHER, A.J. and COLE, B.L. (1974). The photometric requirements of vehicular traffic signal lanterns. *Proc. ARRB 7th Conf.* 7(5), pp 246-264. ARRB Transport Research Ltd, Vermont South, Australia.

FHWA (1996). *Traffic Control Systems Handbook*. Federal Highway Administration Report No. FHWA-SA-95-032. Washington, D.C., U.S.A.

FOX, J.C., GOOD, M.C. and JOUBERT, P.N. (1979). *Collisions with Utility Poles*. Summary Report. Department of Transport, Office of Road Safety, Canberra.

GARDNER, R. (1996). Vehicle characteristics. In: *Traffic Engineering and Management* (Eds: K.W. Ogden and S.Y. Taylor), Institute of Transport Studies, Department of Civil Engineering, Monash University, Melbourne, Australia (Reprinted: 1999), pp 3-20.

GAZIS, D., HERMAN, R. and MARADUDIN, A. (1960). The problem of the amber signal light in traffic flow. *Operations Research* 8(1), pp 112-132.

GLAUZ, W.D. and HARWOOD, D.W. (1999). Vehicles. In: *Traffic Engineering Handbook* (Ed: J.L. Pline), Prentice Hall, Eaglewood Cliffs, New Jersey, U.S.A. Fifth Edition, pp 50-77.

HEBB, D.O. (1955). Drivers and the conceptual nervous system. *Psychological Review* Vol 62, pp 243-254.

HOMBURGER, W.S., HALL, J.W., REILLY, W.R. and SULLIVAN, E.C. (2001). *Fundamentals of Traffic Engineering*. Course Notes UCB-ITS-CN-01-1. Institute of Transportation Studies, University of California, Berkeley, U.S.A. 15th Edition.

HULSCHER, F.R. (1974). Practical Implementation of performance objectives for traffic light signals, *Proc. ARRB 7th Conf.* 7(5), pp 226 - 245. ARRB Transport Research Ltd, Vermont South, Australia.

HULSCHER, F.R. (1975). Photometric requirements for long-range road traffic light signals. *Australian Road Research* 5 (7), pp 44-51.

HULSCHER, F.R. (1976). Traffic signal facilities for blind pedestrians. *Proc. ARRB 8th Conf. Session 25*, pp 13-26. ARRB Transport Research Ltd, Vermont South, Australia.

HULSCHER, F.R. (1977). Reliability aspects of road traffic control signals. *Traffic Engineering and Control* 18 (3), pp 98 - 102.

HULSCHER, F.R. (1980). *Determination of intergreen time at phase changes. In: Driver Observance of Traffic Light Signals* (Hulscher, F.R., et al), Appendix E. Report to Traffic Authority of New South Wales, Sydney.

HULSCHER, F.R. (1984). The problem of stopping drivers after termination of the green signal at traffic lights. *Traffic Engineering and Control* 25(3), pp 110-116.

HULSCHER, F.R. and SIMS, A.G. (1974). Use of vehicle detectors for traffic control. *Traffic Engineering and Control* 15 (19), pp 866-869.

HUNT, P.B., ROBERTSON, D.I., BRETHERTON, R.D. and WINTON R.I. (1981). *SCOOT - A Traffic Responsive Method of Coordinating Signals*. Laboratory Report LR 1014. Transport and Road Research Laboratory, Crowthorne, Berkshire, U.K.

ITE (1994). *Determining Vehicle Signal Change and Clearance Intervals*. An Informational Report of the Institute of Transportation Engineers. Prepared by the ITE Technical Council Task Force 4TF-1, Washington, D.C., U.S.A.

ITE (1997). P*reemption of Traffic Signals at or near Railroad Grade Crossings with Active Warning Devices*. A Recommended Practice of the Institute of Transportation Engineers. Prepared by the ITE Traffic Engineering Council Committee TENC-4M-35, Washington, D.C., U.S.A.

ITE (1998). *Design and Safety of Pedestrian Facilities*. A Recommended Practice of the Institute of Transportation Engineers. Prepared by Traffic Engineering Council Committee TENC-5A-5, Washington, D.C., U.S.A.

ITE Australian Section (1985). *Management and Operation of Traffic Signals in Melbourne, Australia*. Prepared by the ITE Australian Section Committee on Traffic Signals, Melbourne, Australia.

JARVIS, J.R. (1982). In-service vehicle performance. In: *Traffic Energy and Emissions*, Joint Society of Automotive Engineers Australasia and ARRB 2nd Conference, Melbourne, Australia.

LAY, M.G. (1985). *Source Book for Australian Roads* (3rd Edition). ARRB Transport Research Ltd, Vermont South, Australia.

LESCHINSKI, R.E. (1994). Evaluation of inductive loops for bicycle detection. *Proc. ARRB Transport Research 17th Conf.* 17 (5), pp 119-131. ARRB Transport Research Ltd, Vermont South, Australia.

LI, M. (1988). Modeling oversaturated conditions in TRANSYT-7F Release 8. *McTrans Newsletter*, Volume 13 (Summer 1998), Transportation Research Center, University of Florida, Gainesville, Florida, U.S.A.

LOWRIE, P. (1982). The Sydney Coordinated Adaptive Traffic System - principles, methodology, algorithms. *Proc. International Conference on Road Traffic Signalling*. Institution of Electrical Engineers, London, pp 67-70.

LOWRIE, P. (1990). *SCATS - A Traffic Responsive Method of Controlling Urban Traffic*. Roads and Traffic Authority of New South Wales, Sydney.

LOWRIE, P. (1996). Signal linking and area control. In: *Traffic Engineering and Management* (Eds: K.W. Ogden and S.Y. Taylor), Institute of Transport Studies, Department of Civil Engineering, Monash University, Melbourne, Australia (Reprinted: 1999), pp 461 - 480.

LOWRIE, P. (1996a). Freeway Ramp Metering Systems. Paper presented at the *ITE Inaugural Regional Conference - Transport and Liveable Cities*, Melbourne, Australia.

LOWRIE, P. (2001). SCATS - The history of its development. Paper presented at the *8th World Congress on Intelligent Transport Systems*, Sydney, Australia. Paper No. ITS00738, Session No. 147 (CD).

LUK, J., SIMS, A.G. and LOWRIE, P. (1983). *Parramatta Experiment - Evaluating Four Methods of Area Traffic Control*. Research Report ARR No. ARR 132. ARRB Transport Research Ltd, Vermont South, Australia.

McGINLEY, F.J. (1983). Active tram priority in co-ordinated signal systems. *Australian Road Research* 13 (3), pp 173-184.

MIDDLETON, I.J. (1969). *Study of Accidents at Intersections*. Civil Engineering Thesis, University of Melbourne.

MILLER, A.J. (1968). *Australian Road Capacity Guide*. Bulletin No. 4. Australian Road Research Board Vermont South, Australia (reprinted as Research Report ARR 79, 1978; superseded by Research Report ARR 123).

NEGUS, B.J. and MOORE, S.E. (1984). Benefits of SCRAM - the Maroondah Highway survey. *Proc. ARRB 12th Conf.* 12 (4), pp 1-16. ARRB Transport Research Ltd, Vermont South, Australia.

NRTC (1999). *Australian Road Rules*. National Road Transport Commission. Printed and distributed by the NSW Government Information Service, Sydney, New South Wales, Australia.

OGDEN, K.W. (1996). Human factors in traffic engineering. In: *Traffic Engineering and Management* (Eds: K.W. Ogden and S.Y. Taylor), Institute of Transport Studies, Department of Civil Engineering, Monash University, Melbourne, Australia (Reprinted: 1999), pp 3-20.

OLIVER, J.W.H. (1979). Skid Resistance Reduction in Wet Weather Due to Hydroplaning of Vehicle Tyres, *Pavement Surface Drainage Symposium, Sydney, May 1979*, ARRB Transport Research Ltd, Vermont South Australia.

PLINE, J.L. (Ed) (1999). *Traffic Engineering Handbook*. Prentice Hall, Eaglewood Cliffs, New Jersey, U.S.A. Fifth Edition.

QMR (2000). *Road Planning and Design Manual*. Queensland Department of Main Roads, Brisbane.

ROUPHAIL, N.M. and AKÇELIK, R. (1992). A preliminary model of queue interaction at signalised paired intersections. *Proc. ARRB 16th Conf.* 16 (5), pp 325-345. ARRB Transport Research Ltd, Vermont South, Australia.

RTA NSW (1991). *Traffic Signal Operation*. Document No. RTA-TC-106. Roads and Traffic Authority of New South Wales, Sydney, Australia.

RTA NSW (1991a). SCATES User Manual. Roads and Traffic Authority of New South Wales, Sydney, Australia.

RTA NSW (1992). *Traffic Signal Practice - Design*. Roads and Traffic Authority of New South Wales, Sydney, Australia.

RTA NSW (1992a). *Portable Traffic Signals - Guide To Use*. Roads and Traffic Authority of New South Wales, Sydney, Australia.

RTA NSW (1993). *Guide to Traffic Generating Developments*. Roads and Traffic Authority of New South Wales, Sydney, Australia.

RTA NSW (1998). *Bus Lanterns at Signalised Intersections*. Technical Direction 98/4 (77M1776). Roads and Traffic Authority of New South Wales, Sydney, Australia.

SIMS, A.G. (1979). The Sydney Co-ordinated Adaptive Traffic System. *Proceedings of the Engineering Foundation Conference on Research Directions in Computer Control of Urban Traffic System*, ASCE, New York, pp 12-27.

SIMS, A.G. and DOBINSON, K.W. (1979). SCAT - The Sydney coordinated adaptive traffic system, philosophy and benefits. *Proceedings of the International Symposium on Traffic Control Systems*, Vol. 2B, pp 19-42. Univ. of California, Berkeley.

SMITH, G. and WEIR, R. (1975). *Visibility Studies of Symbols Used for Traffic and Pedestrian Control Lanterns*. Research Report ARR No. 38. ARRB Transport Research Ltd, Vermont South, Australia.

STANDARDS AUSTRALIA (1996). *Manual of Uniform Traffic Control Devices - Part 14: Traffic Signals. AS 1742.14*. Standards Australia, Sydney.

STANDARDS AUSTRALIA (*175–2000*. Sydney. (For online search: http://www.standards.com.au/).

AS 1100.401 (1984)	Technical drawing - Engineering Survey and Engineering Survey Design Drawing
AS 1158 (1986-1999)	Road Lighting
AS 1348 (1986-1992)	Road and Traffic Engineering - Glossary of Terms
AS/NZS 1428.4 (1992)	Design for Access and Mobility - Tactile ground surface indicators for the orientation of people with vision impairment
AS 1580 (1992-2000)	Paints and Related Materials
AS 1742 (1990-2000)	Manual of Uniform Traffic Control Devices
AS 1743 (1992-1995)	Road Signs
AS 1744 (1975)	Forms of Letters and Numerals for Road Signs
AS 1798 (1992)	Lighting Poles and Bracket Arms
AS 1906 (1981-1997)	Retroreflective Materials and Devices for Road Traffic Control Purposes
AS 2009 (1991)	Glass Beads for Road-Marking Materials
AS/NZS 2053 (1995-1997)	Conduits and Fittings for Electrical Installations
AS 2144 (1995)	Traffic Signal Lanterns
AS/NZS 2276 (1992-1998)	Cables for Traffic Signal Installations
AS 2339 (1997)	Traffic Signal Posts and Attachments
AS 2353 (1999)	Pedestrian Push-Button Assemblies
AS 2578 (1983)	Traffic Signal Controllers
AS/NZS 2633 (1996)	Guide to the Specification of Colours
AS 2700 (1996)	Colour Standards for General Purposes
AS 2702 (1984)	Acoustics - Methods for the Measurement of Road Traffic Noise
AS 2703 (1987)	Vehicle Loop Detector Sensors
AS 2898 (1992)	Radar Speed Detection

AS 2979 (1998)	Traffic Signal Mast Arms
AS/NZS 3000 (2000)	Electrical Installations (Wiring Rules)
AS 4113 (1993)	Traffic Signal Lamps
AS 4191 (1994)	Portable Traffic Signal Systems

TAYLOR, M.A.P. (1996). Planning and Design for On-Road Public Transport. In: *Traffic Engineering and Management* (Eds: K.W. Ogden and S.Y. Taylor), Institute of Transport Studies, Department of Civil Engineering, Monash University, Melbourne, Australia (Reprinted: 1999), pp 335-355.

TRANSIT NEW ZEALAND AND LAND TRANSPORT SAFETY AUTHORITY (1998). *Manual of Traffic Signs and Markings, Part I: Traffic Signs*. Wellington, New Zealand.

TRANSIT NEW ZEALAND AND LAND TRANSPORT SAFETY AUTHORITY (1997). *Manual of Traffic Signs and Markings, Part II: Markings*. Wellington, New Zealand.

TRB (2000). *Highway Capacity Manual*. Transportation Research Board, National Research Council, Washington, D.C., U.S.A.

U.S. DEPARTMENT OF TRANSPORTATION (1988). *TRANSYT-7F Users Guide*. Transportation Research Center, University of Florida, Gainesville, Florida, U.S.A.

VEITH, G.J. (1996). Roads for Cyclists. In: *Traffic Engineering and Management* (Eds: K.W. Ogden and S.Y. Taylor), Institute of Transport Studies, Department of Civil Engineering, Monash University, Melbourne, Australia (Reprinted: 1999), pp 313-333.

VICROADS (1997a). *Traffic Management*. Traffic Engineering Manual Volume 1. VicRoads, Melbourne.

VICROADS (1997b). *Linking Traffic Signals to Railway Level Crossings*. Unpublished Document. VicRoads, Melbourne.

VINCENT, R.A., MITCHELL, A.I. and ROBERTSON, D.I. (1980). User Guide to TRANSYT version 8. Transport and Road Research Laboratory, Report LR 888, Crowthorne.

WEBSTER, F.V. and COBBE, B.M. (1966). *Traffic Signals*. Road Research Technical Paper No 56. HMSO, London.

WELFORD, A.T. (1969). *Fundamentals of Skill*. London, Methuen.

Information Retrieval

Austroads (2003). Guide to Traffic Engineering Practice Part 7 – Traffic Signals. Sydney. A4, 184 pp, AP-G11.7.

Keywords:

Bicycle, Cycle (traffic signals), Delay, Design, Design speed, Detection, Dividing line, Driver behaviour, Fixed time (signals), Gap acceptance, Junction (intersection), Interchange, Lantern, Layout, Level of service, Linked signals, Parking, Pavement marking, Pedestrian, Pedestrian crossing, Performance, Public transport, Queue, Road marking, Road user, Roundabout, Safety, Sight distance, Signalisation, Signalised crossing, Traffic control, Traffic flow, Traffic lane, Traffic island, Traffic management, Traffic sign, Traffic signal, Vehicle actuated, Vehicle spacing

Abstract:

The Austroads Guide to Traffic Engineering Practice provides a comprehensive coverage of traffic surveys, analysis, layout, design, traffic management, and road safety standards and practices in Australia. To date, 15 parts of the guide have been published.

Part 7 - Traffic Signals (2003) is a major revision of the 1993 publication. It incorporates the latest practice in the safe and efficient design of traffic signal installations.

Part 7 presents detailed information and provides guidelines on collection of design data, geometric elements, signal system and components, signal face layouts and display sequences, signal phasing, location of signal equipment, traffic detection, signal controllers, pavement markings, signs, electrical design, coordination of traffic signals, installation checks and maintenance, and special applications including advance warning signals, emergency vehicle facilities, public transport priority, bicycle facilities, roundabout metering signals, ramp-metering signals, special intersection treatments, overhead lane-control signals, single-lane operation and portable signals, left turn on red, and metering signals at sign-controlled intersections. Appendices provide detailed discussions on human factors and vehicular traffic characteristics relevant to traffic signal control, provides guidelines for determining signal timings, and give a complete worked example. A glossary of terms is included.

AUSTROADS

PART 7

GUIDE TO TRAFFIC ENGINEERING PRACTICE SERIES

AP-G11.7/03
ISBN 0 85588 622 6
HB 191:2003

AUSTROADS