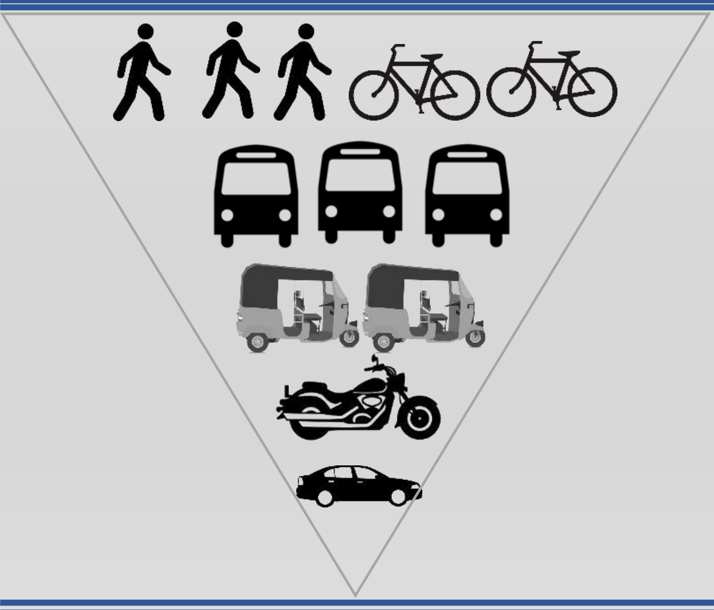
SHAKTI SUSTAINABLE ENERGY FOUNDATION

IBI

BEST PRACTICES FOR TRAFFIC SIGNAL OPERATIONS IN INDIA



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Final Report

Best Practices for Traffic Signal Operations in India

Prepared for Shakti Sustainable Energy Foundation
by IBI Consultancy India Private Limited

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Shakti Sustainable Energy Foundation works to strengthen the energy security of India by aiding the design and implementation of policies that support energy efficiency and renewable energy.

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1 Introduction

The problem of traffic is a complex one requiring design, planning, engineering and institutional inputs for developing a proper solution. Dealing with traffic at crossroads requires, many a times, the study and installation of traffic signals. Signalized intersection locations form the most common bottleneck points in cities across the world. Traffic in Indian cities add more levels of complexity through heterogeneity, lack of discipline, inconsistent geometric design – to name a few. This document, using a combination of review and modelling provides a set of best practices for traffic signals for Indian cities.

1.1 Purpose of the Document

Traffic engineering is an evolving field in India with traffic signals still being controlled by traffic police. While the traffic police understand the ground conditions, lack of expertise in the area of traffic engineering puts the Indian traffic police at a disadvantage while designing and timing the traffic signals. In the Indian context, improving the efficiency of traffic signals is expected to improve the pollution at signalized intersections by 20-30% in most situations, due to reduction in fuel consumption due to vehicle idling etc.[1]. The biggest beneficiary of an efficient traffic signal remains the traffic police who faces the brunt of the pollution throughout the day.

This document is aimed at identifying various best practices that should be implemented at a rule-of-thumb level which in-turn can support improving the efficiency of the traffic signal.

1.2 Audience

The report is aimed at any and all personnel involved in timing traffic signals in Indian cities or international cities that have similar characteristic as Indian cities. This includes traffic police, transportation/traffic engineers, etc.

1.3 Key Concepts

At the core, traffic engineering is about the road user and his/her expectancy of travel time?.

- User is a specific category of persons receiving service at a traffic signal. Users include pedestrians, cyclists, two-wheelers, passenger cars, light commercial vehicles (LCVs), trucks, tractor-trailers, bus, emergency vehicles, etc. – essentially, each user group has homogenous characteristics such as speed, size of vehicle, requirements of headways, etc.
- Violations happen when user expectancy is not met. A user like pedestrian does not expect to stand for more than a minute or two at a signal, when this user expectancy is not met, the pedestrian tries to venture out and violate the signal (specific to Indian cities). However, the challenge in India is more extreme since the expectancy is not set. It is important that operational standards are set for traffic signals so that there is a clear user expectancy which will reduce violations and make traffic flows smoother.
- The smooth movement of conflicting vehicles is determined by the availability of gaps in traffic. This is true for both pedestrians and vehicular traffic. Understanding of gaps is important for justifying the type of traffic control device, including a traffic signal.
- Finally, the right-of-way rules assign the legal right of a pedestrian or vehicle to proceed with precedence over others in a particular situation or place. Again, this lack of right-of-way rules in the driving license codes in India has created a lack of clarity on who gets the precedence when two persons are at conflict at an intersection. Right-

[1] *Estimate by Authors based on modelling results*

of-way rules have to be published to support smoother and safer movement of traffic at an intersection.

While many other concepts exist for traffic signals, the user expectancy and right-of-way rules are basic key concepts that have to be established for the best practices identified in this report to be relevant.

1.4 Traffic Signals

A Traffic Signal is a power-operated traffic control device by which traffic is warned or directed to take some specific action. These devices do not include power-operated signs, steadily-illuminated pavement markers, warning lights, or steady burning electric lamps (MUTCD, 2009)[2].

Simply put, traffic signals assigns the right-of-way to a movement or a group of movements to increase efficiency and safety.

1.5 Benefits

Traffic signals that are properly designed, located, operated, and maintained will have one or more of the following advantages (MUTCD, 2009):

A. They provide for the orderly movement of traffic.

B. They increase the traffic-handling capacity of the intersection if:

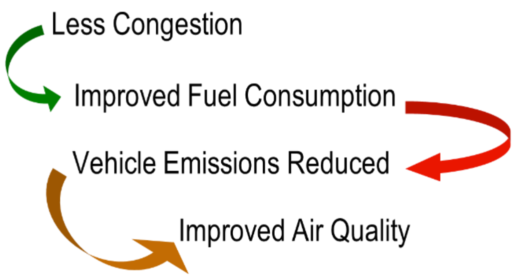
a. Proper physical layouts and control measures are used, and

b. The signal operational parameters are reviewed and updated (if needed) on a regular basis to maximize the ability of the traffic control signal to satisfy current traffic demands.

C. They reduce the frequency and severity of certain types of crashes, especially right-angle collisions.

D. They are coordinated to provide for continuous or nearly continuous movement of traffic at a definite speed along a given route under favourable conditions.

E. They are used to interrupt heavy traffic at intervals to permit other traffic, vehicular or pedestrian, to cross.



Additionally, properly designed, operated and maintained traffic signal systems yield significant benefits on fuel consumption and air pollution.

1.6 Report Scope

Traffic signal implementation is a very complicated and vast subject. The scope of this report is limited to various implementation concerns that are specific to India that can increase the capacity of the intersection and reduce emissions.

[2] *Manual of Uniform Traffic Control Devices, Federal Highway Administration, 2009, http://mutcd.fhwa.dot.gov/*

1.7 Limitations of the Report

The results presented in this report are based pseudo data. While the authors made every attempt to make the data as realistic to actual ground scenarios found in India, more data-centric research is required to improve this report. The parameters for best practices are based on a combination of simulation results and engineering judgement. The authors suggest additional research on specific recommendations to be conducted over time to validate the parameters provided in this report. Notwithstanding the disclaimer on the limitations, the authors do believe that the recommendations in this report can be used as an excellent starting point for improving traffic signal implementations in India and other countries with similar traffic and road-environment conditions.

1.8 Report Structure

The following structure was followed for this report:

- Chapter 1 provides the introduction with purpose and audience
- Chapter 2 presents background on traffic signals
- Chapter 3 provides the study methodology
- Chapter 4 details the best practice for signal timings
- Finally Appendix A summarizes the adaptive control system.

2 Background

2.1 Signal Timing Process

The key aspects of signal timing process[3] are dependent on the user responsibility/need in terms of planning, design, operations and/or maintenance. Signals manage needs of traffic, namely: motor vehicles, buses, emergency vehicles, pedestrians and bicycles. These needs are sometimes conflicting. Ideally, the steps that a user need to consider for signal timing consist of:

- The timing process should start with a clear policy initiative of priority of the traffic modes.

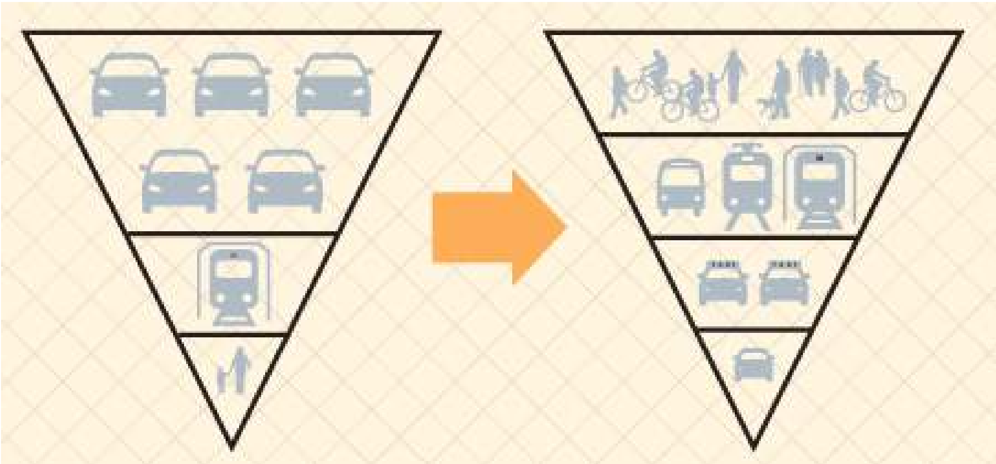


Exhibit 1: An Example of Change in Policy Priorities for People-Centric Design

- Geometry of the intersection is the next step in the signal timing process. Determining the lane use (which traffic mode), dedicated vs. shared lane, type of roads interacting (arterial with arterial, arterial with collector, etc.), type of road infrastructure (ramps, one way streets, etc.) will impact the timing.
- Phasing is the third step in the timing process. Split phasing, protected left-turns, overlapping movements, etc., are all outputs of the geometry and local understanding of user expectancy.
- Basic signal timing parameters comes next. Pedestrian walk times, flashing don't walk, yellow time, all red clearance interval, detector gap times all need to calculated or established.
- Coordination Plan calculates/establishes the need for coordination based on the distance between the junctions and the location of junctions (arterials, collectors, etc.).
- Mode of operation could be fixed time, semi-actuated, fully-actuated or adaptive mode. This effects the detection needs of the intersection. Further, the type of adaptive algorithm (SCOOT, SCATS, CoSiCoSt, etc.) will determine the location of the detectors.
- Finally, performance measurement in terms of average delay, travel time, stops, etc., ensure whether the signals are performing as per expectations.

[3] *Signal Timing Manual, FHWA-HOP-08-024, Federal Highway Administration, 2008*

The signal timing user process is illustrated in Exhibit 2.

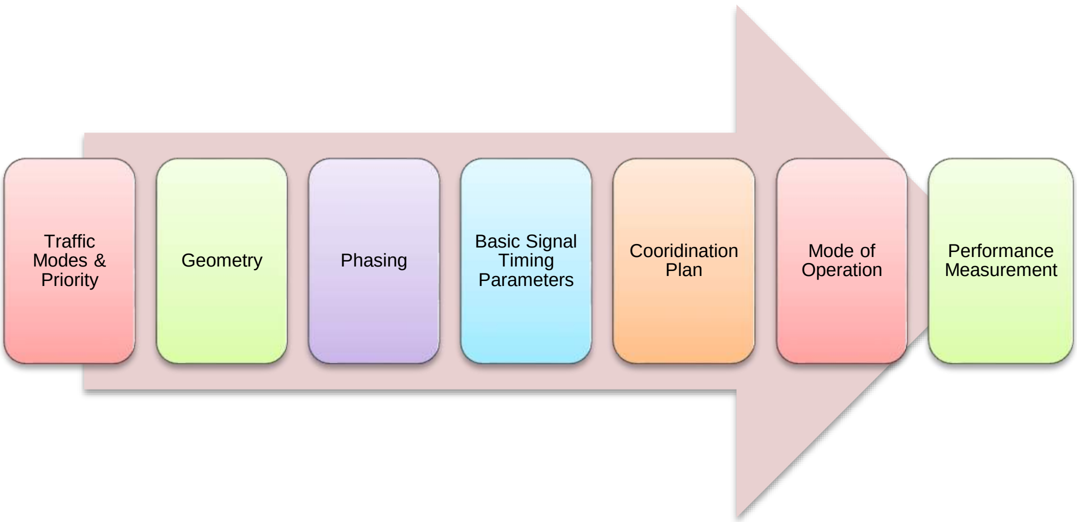


Exhibit 2: Signal Timing User Process

The actual process itself from an input and process perspective is shown in Exhibit 3:

Exhibit 3: Signal Timing Environment[3]

2.2 Characteristics Affecting Signal Timing

The four main characteristics that impact signal timing are[3]:

- **Location**: Urban areas have lower speeds and higher congestion, while rural areas have higher speeds resulting from lower volumes. Buses, pedestrians and cyclists also impact urban areas more than rural areas. Hence, the focus on rural areas is to safely manage high speed vehicles including the dilemma zone problem (whether or not to stop when a signal turns to yellow). In urban areas, controlling onset of oversaturation and providing progression form the major objectives. Suburban areas provide a challenging mix of these characteristics.

- **Transportation Network Characteristics**: While isolated intersections can be timed without consideration for any other signals, allowing setting cycle length and timings that are optimal for the subject intersection. Good detection at isolated intersections can substantially improve the performance of the signal at the intersection. On the other hand, signals on arterials require coordination to enhance the performance. Common cycle length or a multiple of the cycle length (0.5 *C or 2*C) has to be implemented. Each intersection might be suboptimal, however the arterial system might be performing better than if each intersection was optimized, individually. Grid networks increase the complexity of timing signals exponentially. Downtown (Central Business District) networks with closely spaced intersections are quite often timed as pre-timed with no detection. The spacing of intersections has a huge impact on both arterial and grid networks. Quite often, signals between 150 meters and 800 meters spacing get benefit from coordinated operation. Blocking, spillback and green starvation considerations are key for timing signals within 150 meters of each other.
- **Intersection Geometry**: Saturation flow of a 3.5 lane is limited to around 1890 PCUs per hour (as per IRC SP41-1994); while walking speed is around 1.2 meters/second. It is important to note that more the number of lanes provided for vehicular traffic (which improves vehicular capacity), the longer it takes for pedestrians to cross these lanes. Pedestrian and bicycle safety and perception of safety generally reduces as a factor of larger size of intersection. Another factor is skewed vs right angled legs at an Intersection. The sight distance for crossing vehicles and walking distances increase for skewed intersections.
- **User Characteristics**: User characteristics, especially the lack of discipline in Indian roads, clearly impact the effectiveness of signal timing. Heterogeneity of traffic (cars, two-wheelers, trucks, Auto Rickshaw, bicycles, pedestrians, etc.), mix of users (inexperienced, rash, etc.) all play a huge part in timing of signals. India has many first time drivers whose driving ranges from extremely aggressive to very tentative, which again impact the performance of a signal.

2.3 Basic Signal Timing Parameters

Some of the basic parameters that need to be understood include:

Signal Group: There are essentially two distinct methods of specifying basic signal control logic. The method standard in much of Europe is based on “signal groups”, while the method that is standard in the United States is based on “phases”.

A signal group[4] is actually a set of traffic streams which are controlled by identical traffic signal indications. In other words, signal group is defined as a set of signals on various traffic lights that must always show identical indications. A signal group controls one or more traffic streams/flows that are always given right-of-way simultaneously. The number of signal groups is less than or equal to the number of traffic streams being controlled at a junction.

The timing for a signal group is specified by “periods”, which are the durations in which the indication of that signal group does not change. An example is shown below, the intersection is shown in Exhibit 4 and the signal group is illustrated in Exhibit 5. In India, signal groups are more commonly used.

[4] Basics of Traffic Control Signals, Lecture 2, University of Dublin, Trinity College

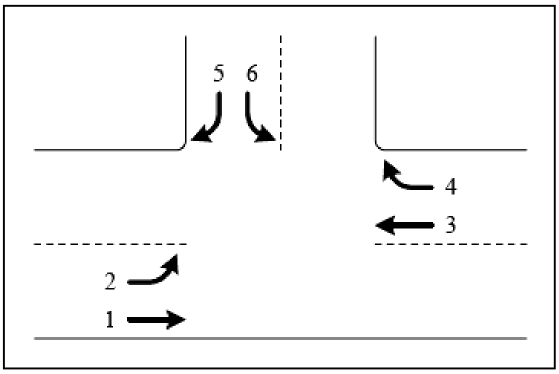


Exhibit 4: Intersection Diagram for Illustrating Signal Groups and Phases[4]

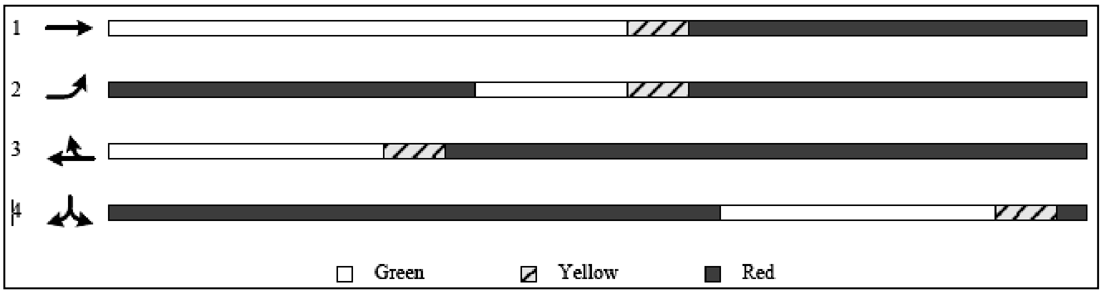


Exhibit 5: Signal Group Illustration[4]

Phase: In traffic signal operation, specified combinations of movements receive right-of-way simultaneously. A "phase" is the portion of the signal timing cycle that is allocated to one of these sets of movements. Each phase is divided into "intervals," which are the durations in which all signal indications remain unchanged. A phase is typically made up of three intervals: green, yellow, and all red[4].

A phase will progress through all its intervals before moving to the next phase in the cycle. An example of phase diagram for the intersection is shown in Exhibit 6.

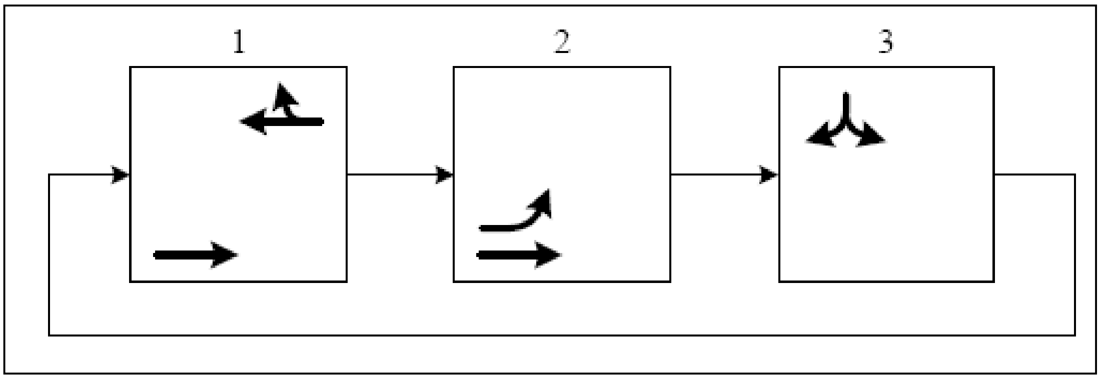


Exhibit 6: Phasing Diagram Example[4]

In this example, the cycle is divided into three phases. Movements 1, 3, and 4 are active in Phase 1; movements 1 and 2 are active in Phase 2; and movements 5 and 6 are active in Phase 3. Each phase represents a distinct time period within the cycle, and in operation the controller moves from one phase to another in the specified order. The timing for the signal is defined by specifying the phase "splits," which are the percentages of the cycle length allocated to each phase. This split time is further divided among the intervals of each phase, resulting in a specified duration for every interval in every phase.

The relationship between the Signal Group and Phase is shown in Exhibit 7.

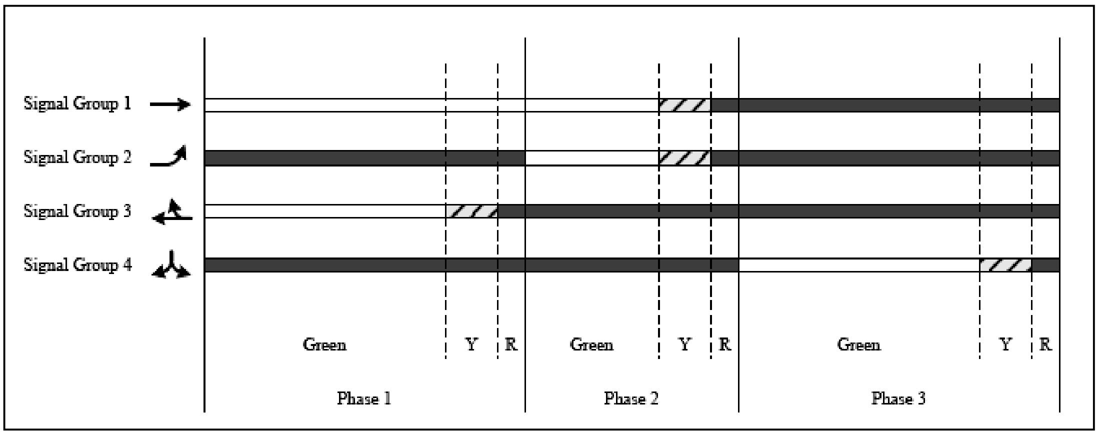


Exhibit 7: Relationship between Signal Group and Phase[4]

All Red Interval: The display time of a red indication for all approaches

Clearance Interval (or inter-green or change interval): The yellow plus all red times (intervals) that provide for clearance of the intersection before conflicting traffic movements are provided right-of-way (green indication).

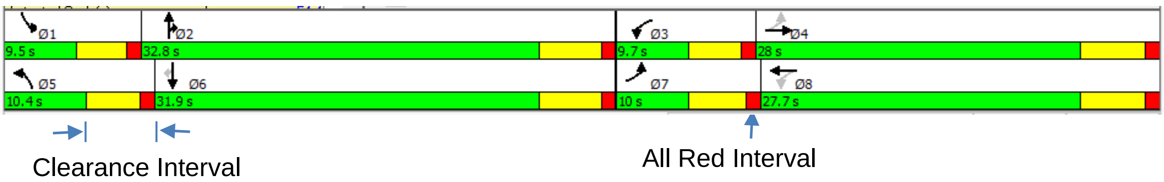


Exhibit 8: Illustration of All Red and Clearance Intervals

Key Optimization Parameters: Signal timing optimization occurs by changing one or all of these four variables in a fixed time signal. In addition to these, gap settings can be optimized for actuated and adaptive signals. The definitions of these are provided in Exhibit 9.

Variable	Definition
Cycle Length	The time required for a complete sequence of signal indications.
Green Split	The percentage of a cycle length allocated to each signal group/phase in a signal cycle. This includes the Green, Yellow and All Red clearance time.
Offset	The time relationship, expressed in seconds or percent of cycle length, determined by the difference between a defined point in the coordinated green and a system reference point.
Phasing Sequence	The order of a series of phases
Gap time	The time between two successive vehicles activating a detector (applicable for actuated signals).

Exhibit 9: Key Optimization Parameters

Signal Coordination: Coordinating signals means timing two signals that are close enough to each other work as a system to ensure minimal negative impact to the vehicles. The impact measure or commonly known as Measures of Effectiveness that are commonly used for establishing signal coordination are:

- Minimise fuel consumption
- Minimise pollution emission
- Minimise stops
- Minimise delay

- Maximise throughput (volume)
- Maximise capacity
- Minimise queue length
- Minimise arrival of platoons at red lights

The common optimization methods for coordination are either in terms of signal synchronization (also called progression bandwidth optimization) as shown in Exhibit 10 or delay optimization as shown in Exhibit 11. A combination of MoEs is also used in certain optimizations.

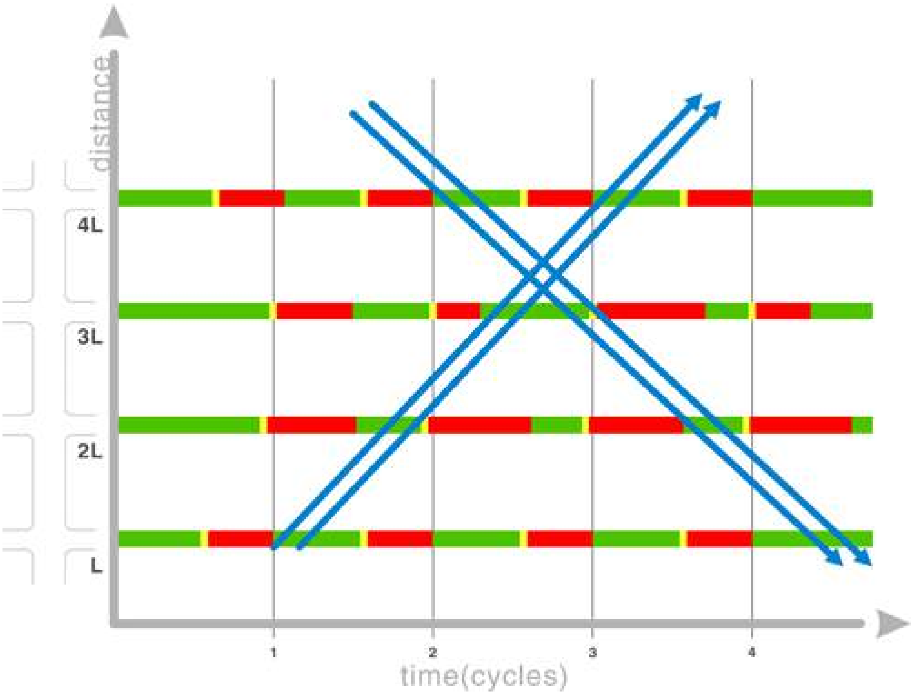


Exhibit 10: Two-Way Progression Bandwidth (Signal Synchronization)

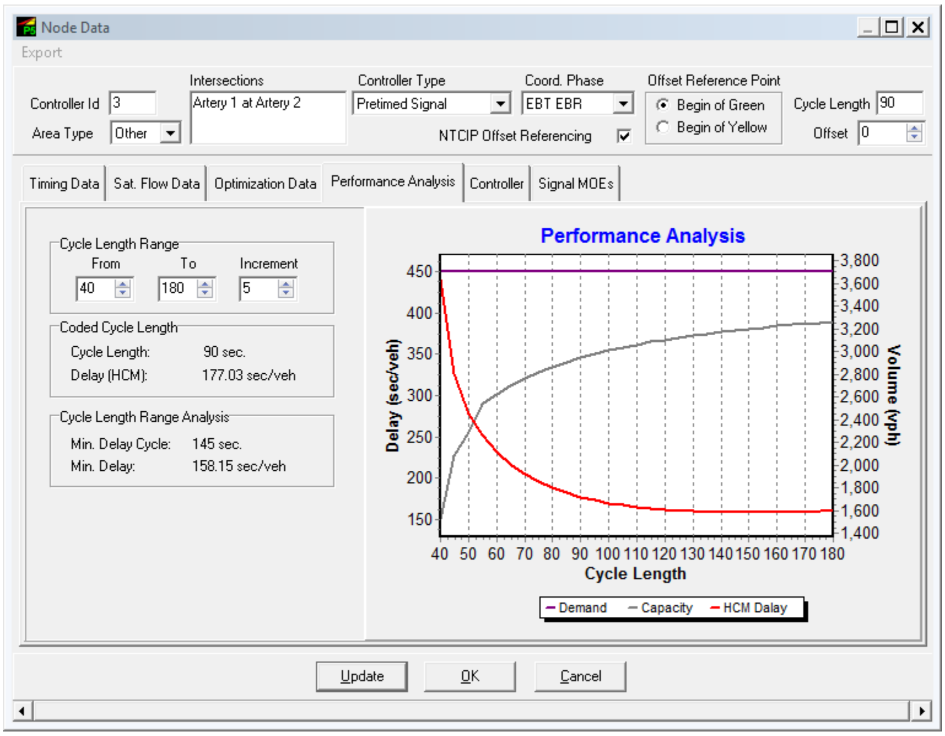


Exhibit 11: Delay Optimization

Lost Time: A portion of the beginning of each green period and a portion of each yellow change plus red clearance period that is not used by vehicles. The start-up lost time is due to perception-reaction times, while the end-lost time is to account for vehicles not travelling throughout the yellow time.

Headway (h): is the average interval of time between vehicles moving in the same direction on the same route.

Saturation Flow Rate (s): is defined as the number of vehicles per hour that could cross the stop line for the movement if the signal remained green all of the time. It is simply the headway in seconds between vehicles moving from a queued condition, divided into 3600 seconds per hour; i.e. s= 3600/h. Typical flow at a signal and the corresponding saturation flow rate are shown in Exhibit 12.

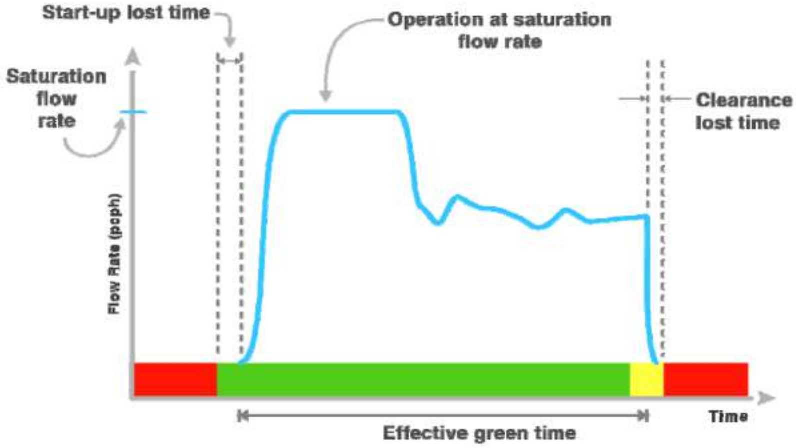


Exhibit 12: Typical Flow Rates at a Signalized Intersection[4]

Capacity (c): is the maximum number of vehicles that can travel through the signal at the prevailing conditions. It is defined as c = s * (g/c).

Signal Optimization Software: A listing of various signal optimization software along with brief description is provided here in Exhibit 13:

Software	MoE Optimized	Description
TRANSYT	Delay & Stops	A UK based software for arterial and networks that can be used for Indian conditions.
LinSig	Delay & Stops	Another UK based software for arterials and networks that can be used for Indian conditions
PASSER II	Progression Bandwidth	US software that optimizes Arterials
PASSER III	Delay	US software for interchanges
PASSER IV	Progression Bandwidth	US software that optimizes networks
PASSER V	Delay, Progression Bandwidth	US Software that optimizes both delay and bandwidth for Arterials and interchanges. It can also optimize for oversaturated conditions.
TRANSYT-7F	Delay & Stops	Based on TRANSYT logic for US conditions.
Synchro	Delay	Popular US based software that can optimize arterials and networks.
Sidra	Delay	Australian software popular for optimizing roundabouts, arterials and networks.
TEAPAC	Bandwidth, Delay	US software for isolated intersections and arterials
OSCADY	Delay, Intersection Capacity	UK software for isolated intersections.
ARCADY	Capacities, Queues, Delay	UK Software for roundabout modelling
PICADY	Capacities, Queues, Delay	UK Software for priority intersection modelling

Exhibit 13: Popular Signal Optimization Software

2.4 Signal Timing Challenges

The traffic signal controllers and signal timing space has mostly remained the exclusive space of Traffic Police in India. While an engineering science, the lack of participation of traffic engineers in controller architecture and timing signals meant that the traffic signal controllers to a great extent suffer from:

1. Little to no innovation until recently;
2. Lack of standards and protocols for communication ensuring that that proprietary controllers with no communication capabilities with other controllers thrive in the market;
3. Lack of features to implement advanced controller strategies to reduce delays;
4. Lack of workforce capable of timing signals for efficiency of traffic flows;
5. Lack of continuous oversight of traffic signal plans and improvement in signal timing strategies;
6. Lack of, to the most part, independent monitoring and evaluation of strategies that work well in Indian conditions; and
7. Lack of implementable research and wide spread dissemination of any research conducted on traffic controllers and timing plans.

All these complexities are in addition to the inherent complexities of timing signals in Indian conditions as illustrated in Exhibit 14.

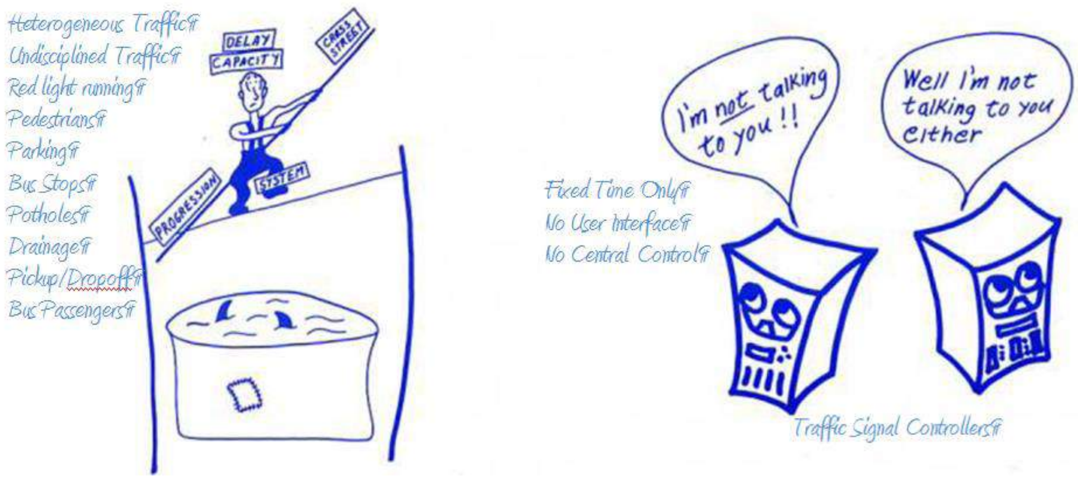


Exhibit 14: Complexity of Signal Timing in India[5]

2.5 Mode of Operation

Traffic signals have evolved over the years from manually operated signal in London in 1868 to full adaptive signal systems that available in all parts of the world. A simple diagram of traffic signal evolution is shown in Exhibit 15:

[5] *Illustration based on "Why is the Signal Always Red? Denver Regional Council of Governments (DRCOG), http://www.signaltiming.com/files/WhyRed.pdf"*

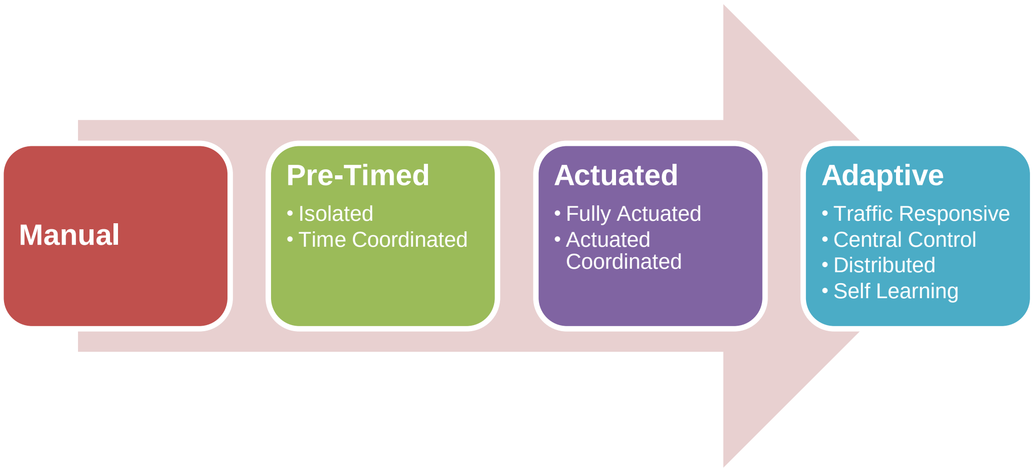


Exhibit 15: Traffic Signal - Modes of Operation

A comparison of the various modes of operation is provided in Exhibit 16.

Controller Strategy	Advantages	Disadvantages
Pre-timed Signals	Simplest to implement and widely used across India.	Does not respond to varying traffic flows and hence has highest delays.
	Traffic Police can manage the signals without expert help.	Require multiple Time of Day (ToD) plans with well-set time periods for it to work efficiently
	Does not require central control. Although central control is preferred.	Traffic volumes surveys and timing optimization should be conducted whenever traffic volumes change (mostly ever year).
	Controllers available locally from multiple firms.	No communication protocols exist for local controllers which will make it difficult to run controllers from different companies from a central control.
Actuated Coordinated Signals	Efficient for arterials for setting progression while optimizing minor street greens.	Detectors are required, which is generally a challenge in Indian conditions
	Green starvation delays for minor movements are reduced due to the introduction of activation.	Certain amount of expertise is required in timing the signals and setting the detector parameters.
	Does not require central control. Although central control is preferred.	Traffic volumes surveys and timing optimization should be conducted whenever traffic volumes change (mostly ever year).
Adaptive Control Signals	Automatically adjust timings to respond to the traffic, thus Delivering better service to road users in terms of Congestion, Travel Time Reliability and Fuel Consumption	SCOOT & ITACA require upstream detection, which is a concern where parking is allowed/happens upstream. The parked vehicles will be counted towards occupancy.
	Automatically addresses variability & unpredictability in demand	Requires greater expertise to run the system compared to other controller strategies
	Provides value in terms of reducing retiming costs, emissions and increased safety	Requires central control which requires that preferably no communication failures occur.
		Detection is extremely important and connectivity from signal controller to detectors is a strong requirement.

Exhibit 16: Comparison of Traffic Signal Modes of Operation

3 Study Methodology

This section describes the process, parameters and assumptions used in this report to develop the recommendations.

3.1 Microsimulation Modelling

The analysis and recommendations in this report are a product of traffic engineering experience and output of microsimulation models.

Microsimulation modelling has become an important and popular tool for modelling transportation scenario mainly with the objective of improving operations. Microsimulation models simulate individual vehicles in a traffic stream. Hence, they are very detailed and closest to replicating reality. This study uses VISSIM, a popular microscopic simulation tool. The name VISSIM is derived from “Verkehr In Städten - SIMulationsmodell” (German for “Traffic in cities - simulation model”). VISSIM provides microscopic, time step based simulation through pyscho-physical modelling of road user behaviors. The model is robust for analysing both private and public transport operations under constraints of lane configuration, vehicle composition, traffic signals, etc.

Exhibit 17: VISSIM Microsimulation Model Application Interface

3.1.1 The Model network

The VISSIM microsimulation modelling was performed on the two isolated intersections and one four lane arterial. The screen shots of the VISSIM Network for all these junctions is shown in below exhibits.

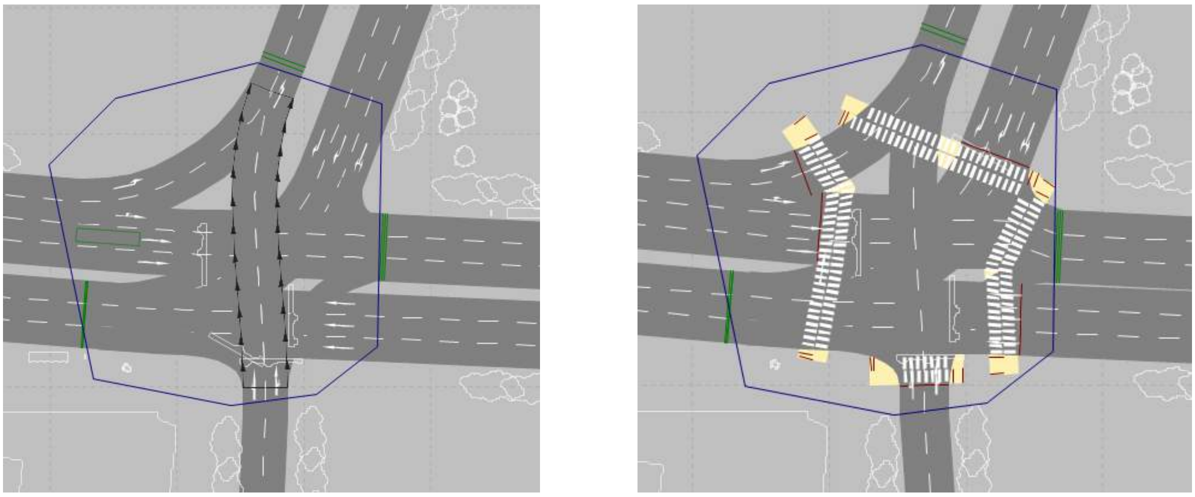


Exhibit 18: Isolated Intersection 1

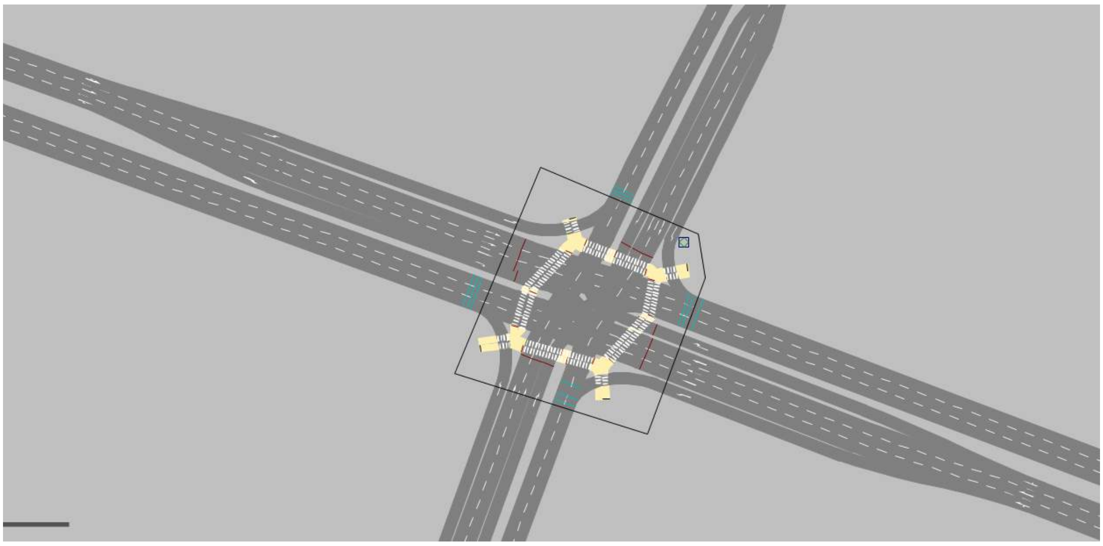


Exhibit 19: Isolated Intersection 2

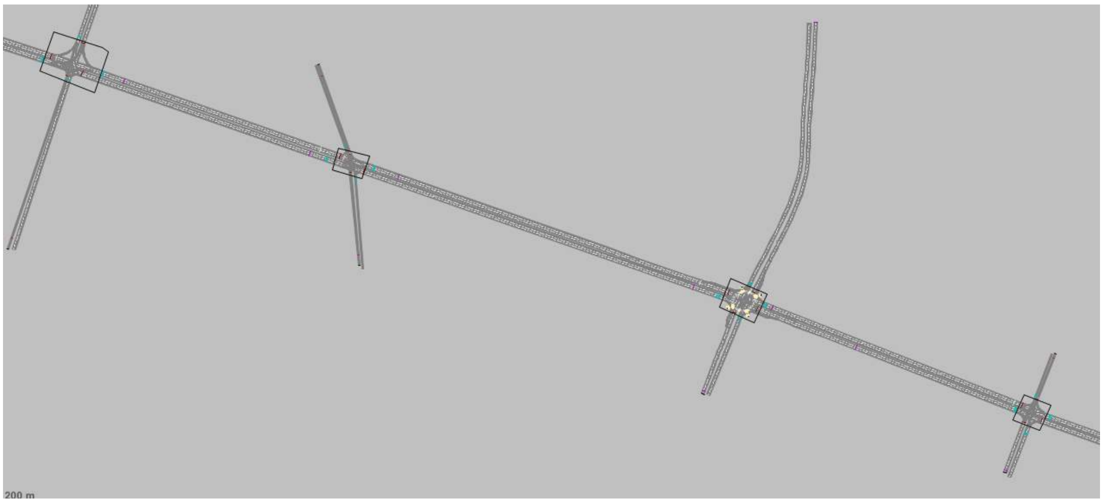


Exhibit 20: Arterial Corridor with Four Intersections

The below Exhibit 21 shows what network is utilized for analysing different experiments as part of developing the best practices.

Experiment/Scenario	Utilized network
Alternative cycle lengths	Isolated Intersection 1
Impact of Bus stop location	Isolated Intersection 1
Potholes	Isolated Intersection 1
Fixed vs Actuated Control	Isolated Intersection 1
Split vs Lead Phasing	Isolated Intersection 2
Pedestrian Phasing	Isolated Intersection 2
Impact of Synchronization	Arterial Corridor

Exhibit 21: Different VISSIM networks used for analyzing various scenarios/experiments

3.1.2 VISSIM Parameters & Assumptions

The modelling was conducted for cycle lengths varying from 60 seconds to 600 seconds (10 minutes), and volume-to-capacity (v/c) ratio varying from 0.5 to 1.5 for the intersection. The parameters used in VISSIM for modelling are as follows:

- Vehicular Composition
    - Two Wheeler – 70% ; Car – 15%; Auto-10% ; Bus – 5%
- Volume to Capacity Ratios
    - Volumes are converted to PCU as per factors in IRC:106:1990
    - Alternative v/c Ratios: 0.5, 0.75, 1, 1.25
- Occupancy:
    - TW - 1 ; Car – 2; Auto-2 ; Bus – 50
- Cycle Lengths and Timing Parameters
    - Cycle Lengths-Sec: 60; 90; 120; 150; 180; 210; 240; 270; 300; 400; 450;600
    - Yellow Change Interval : 3 sec
    - Red Clearance Time: 1 Sec
- Measures of Effectiveness – for 1 hour period
    - Average Delay per vehicle
    - Average Queue Length
    - Absolute person and vehicle delay
    - Fuel Consumption
    - Emissions
- Simulation Period: 3600 Sec (+ Warm up period of 3600 Sec)
- Output: Average of 5 runs
- Driving Behaviour: Driving behaviour in VISSIM set based on calibrated parameters of car following model[6] (Wiedemann 99) and lane change models for Indian Mixed

[6] Methodology for the Calibration of VISSIM in Mixed Traffic, TRB, 2012, http://docs.trb.org/prp/13-3677.pdf

Traffic Conditions. The below exhibit shows the car following and lane change model parameters used for the running the simulation.

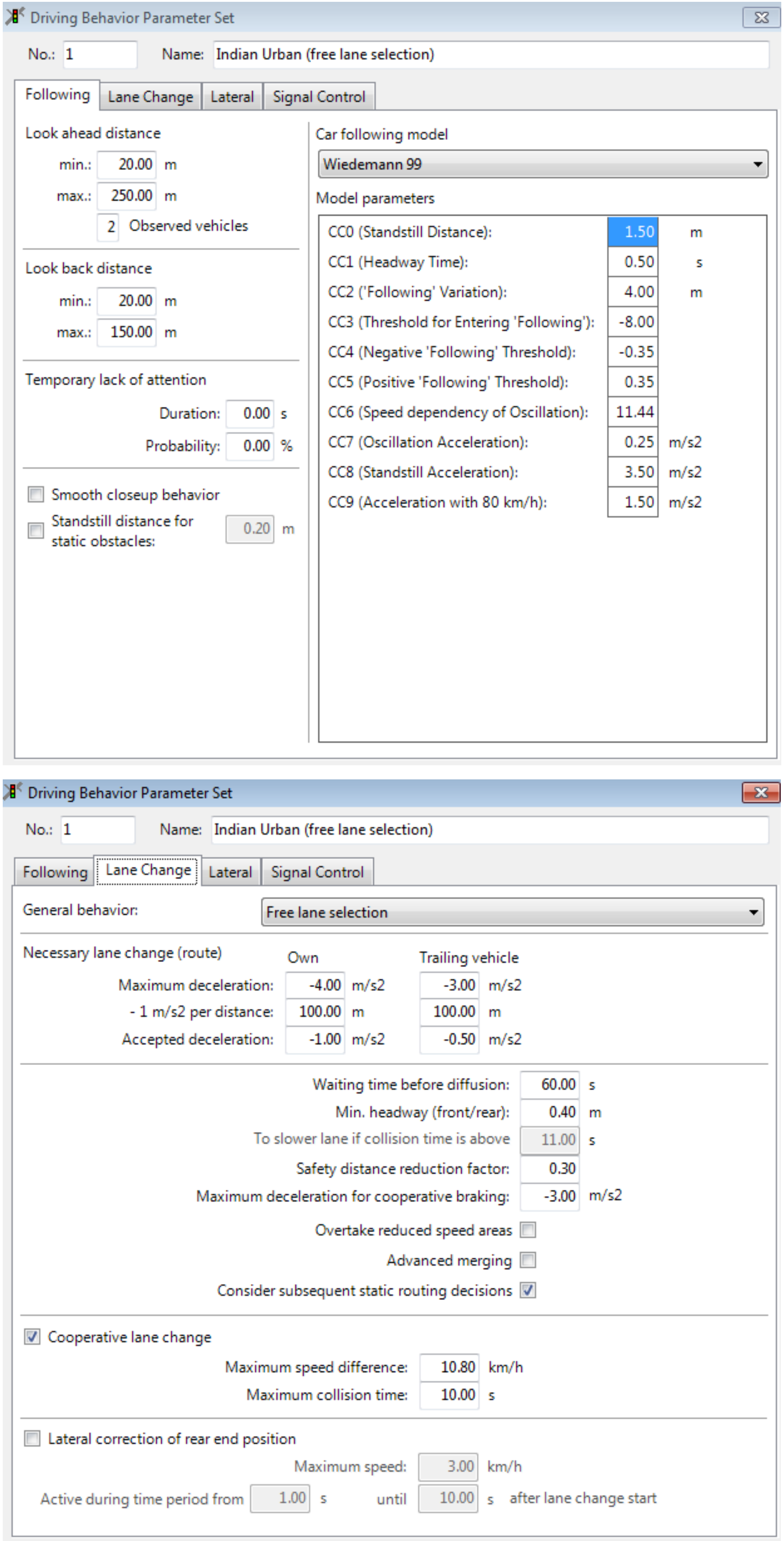


Exhibit 22: Car following and Lane change model parameters for VISSIM simulation

3.1.3 PCU Factors

IRC 106-1990 values as shown in Exhibit 23 were used for the PCU factors in this report

Traffic Modes	Vehicle Composition	
	<10%	>=10%
Bicycle	0.4	0.5
TW	0.5	0.75
Bus	2.2	3.7
Mini Bus	1.4	2
Auto	1.2	2
Car/Jeep/Van	1	1
LCV	1.4	2

Exhibit 23: PCU Factors

3.1.4 Fuel Consumption Calculation Assumptions

Exhibit 24 provides the assumptions on the mix of petrol and diesel users, fuel consumed during idling and fuel efficiency by mode - that were used in developing the plots for fuel consumption.

MODE	Fuel Consumed while Idling (Liters/Hour)			Fuel Efficiency (Km/Lit)			Mix of Users		
	Petrol	Diesel	CNG	Petrol	Diesel	CNG	Petrol (%)	Diesel (%)	CNG (%)
TW	0.5			60			100%	0%	0%
Bus		3	3		3	3	0%	80%	20%
Auto	1		1		25	25	65%	0%	35%
Car	1	1	1	12	14	12	50%	20%	30%

Exhibit 24: Fuel Consumption Calculation Assumptions

3.1.5 Emissions Assumptions

Exhibit 25 values for emissions[7] were applied while calculating the particulate matter impacts.

MODE	Standard Average Emission Factors (gm/Km)																	
	PM 10			SO2			Nox			CO			CO2			HC		
	Petrol	Diesel	CNG	Petrol	Diesel	CNG	Petrol	Diesel	CNG	Petrol	Diesel	CNG	Petrol	Diesel	CNG	Petrol	Diesel	CNG
TW	0.1			0.02			0.15			2.5			40			1.5		
Bus		1.5	0.02		1	0		10	2.5		3.5	3.5		850	450		1	0.1
Auto	0.2		0.1	0.02		0	0.1		0.35	8		3.5	80		70	5		0.15
Car	0.1	1	0.05	0.1	0.4	0	0.2	1.25	0.2	5	2	1	200	250	100	1	0.4	0.02

Exhibit 25: Emission Calculation Assumptions

[7] *Indicative Impacts of Vehicular Idling On Air Emissions, Sarath Guttikunda, http://www.indiaenvironmentportal.org.in/files/Idling-On-Roads.pdf*

4 Best Practices for Signal Timing

As mentioned earlier, the objective of a traffic signal is to provide an equitable balance of safe and efficient traffic and pedestrian movements through the intersection. In United States of America, estimates show that there is 1 traffic signal for every 1000 persons. Bangalore has around 400 traffic signals for around 10 million population, which translates to about one traffic signal per 25,000 population. The number of signals per thousand people trends are similar across India cities. Many intersections are controlled by traffic police manually without a signal during peak periods.

This chapter looks at various categories in which best practices suitable for Indian cities can be established for timing signals. This chapter is organized in a question and answer format to address the most common issues with timing signals. Where appropriate, the responses are supported by detailed VISSIM microsimulation model results.

4.1 Subject Area: Justifying Traffic Signal Installation

Q1. Should intersections be controlled using traffic signal or by traffic police during peak period?

Justification of a traffic signal should be mainly based on **traffic signal warrants.** While a certain amount of qualitative engineering judgement should be included, it should only be applied in situations where less restrictive measures than traffic signal (give-away sign, stop sign, etc.), even when the signal warrants are satisfied, will provide movement efficiency without sacrificing safety.

Where traffic signal is warranted, regulation by traffic police should still happen for accidents and special events. However, it should not be a regular occurrence that police regulate the traffic signal. While research exists that shows better compliance by road users when traffic police are standing at the intersection; the culture of following rules even when traffic police are not present should be inculcated. Making traffic police into regulators rather than enforcers impacts the police personnel health without providing long term solution to the problem.

In addition, large intersections require multiple traffic police to control the junction when not signalized. This is not the best use of limited man power of traffic police

Recommendation: Vehicular emissions are highest at intersections due to the many stop-and-go maneuvers. Hence, regulating traffic at intersections throughout the day is highly detrimental to the health of traffic police. Use traffic signals and develop processes for enforcement to reduce traffic police intervention at signals.

Q2. When do we require traffic signal operation at junction?

IRC 93 – 1985 provides a list of traffic signal warrants that are applicable to India. Newer guidelines are being developed by IRC and other agencies. Another good resource is the United States of America's Manual of Uniform Traffic Control Devices (MUTCD), 2009 for signal warrants analysis. Based on IRC 93, the following warrants should be analysed for intersections:

1. Warrant 1 -The minimum vehicular volume warrant: intersecting volumes higher than a thresholds below for 8 hours in a 24 hour period. See Exhibit 26.

2. Warrant 2 - The interruption of continuous traffic warrant: major street volume is so heavy that traffic on minor street faces excessive delay. See Exhibit 26
3. Warrant 3 - The minimum pedestrian volume warrant: ensures that pedestrians can safely cross the intersection. See Exhibit 27.
4. Warrant 4 – The Accident Experience: to reduce accident occurrence is satisfied when:
   - Adequate trial of less restrictive remedies with satisfactory observance and enforcement have failed to reduce the accident frequency
   - Five or more reported accidents within a period of 12 months, each accident involving personal injury or property damage to an apparent extent of Rs. 2000 or more
     - Type of accidents that can corrected by installation of signal (right-angle collisions, etc.)
   - Signal installation will not seriously disrupt the traffic flow

   Warrant 4 is outdated in terms on the monetary impact of the accident. A current equivalent amount could be around Rs. 20,000
5. Warrant 5 – Combination of Warrants: In exceptional cases, signals may be justified occasionally where no signal warrant is satisfied but where two or more of the warrants 1, 2 and 3 above are satisfied to the extent of 80% or more.

Signal Warrant Volumes[1]					
Number of Approach Lanes		Motor Vehicles Per Hour on Major Street (total both approaches)		Motor Vehicles Per Hour on Higher Volume Minor Street Approach (one direction only)	
Major Street	Minor Street	Percent of standard warrants		Percent of standard warrants	
		100%	70%	100%	70%[1]
Warrant 1: Minimum Vehicular Traffic[2]					
1	1	650	455	200	140
2 or more	1	800	560	200	140
2 or more	2 or more	800	560	250	175
1	2 or more	650	455	250	175
Warrant 2: Interruption of Continuous Traffic[3]					
1	1	1000	700	100	70
2 or more	1	1200	840	100	70
2 or more	2 or more	1200	840	150	105
1	2 or more	1000	700	150	105

Note:

[1] The volume threshold to be satisfied for any 8 hours on an average day. Both major and minor street volumes to be satisfied for the same 8 hours.

[2] 70% threshold used when the 85th percentile speed of major street traffic (or average approach speed) exceeds 50 kmph or when the intersection lies within the built-up area of an isolated community having a population less than 2.5 lakhs.

[3] 70% threshold used when the 85th percentile speed of major street traffic (or average approach speed) exceeds 60 kmph or when the intersection lies within the built-up area of an isolated community having a population less than 2.5 lakhs.

Exhibit 26: Traffic Signal Warrants 1 and 2

Warrant 3 – Pedestrian Volume[1]				
Motor Vehicles Per Hour on Major Street (total both approaches)		Pedestrians Per Hour (on highest volume crosswalk crossing major street)		Condition
Percent of standard warrants		Percent of standard warrants		
100%	70%[2]	100%	70%[2]	
600	420	150	105	
1000	700	150	105	With Raised Median Island > 1.5 m width

Note:

[1]Same 8 hours for pedestrian volume as motor vehicle volumes

[2]70% threshold used when the 85th percentile speed of major street traffic (or average approach speed) exceeds 60 kmph or when the intersection lies within the built-up area of an isolated community having a population less than 2.5 lakhs.

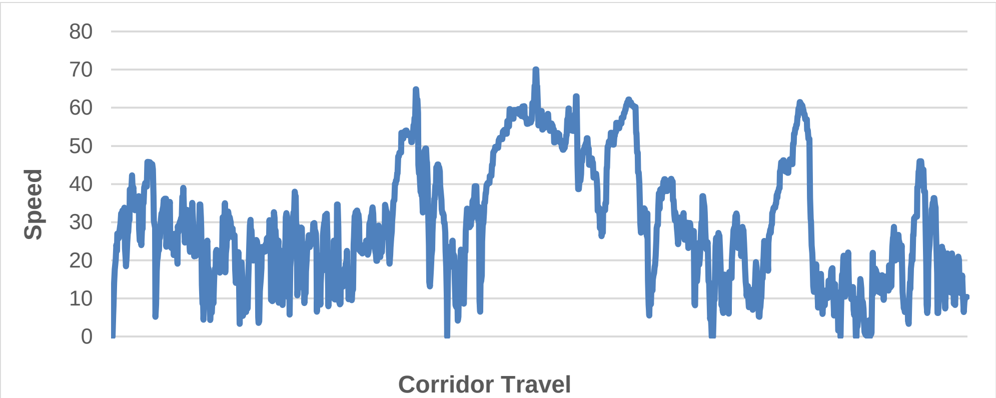
Exhibit 27: Pedestrian Warrant 3

Recommendation: Warrant analysis and engineering judgement shall form the justification of traffic signals.

Q3. How do I approach traffic signal installation justification?

Ideally, one conducts a traffic volume count at each junction for which public complaints reveal a recommendation for traffic signals and then the signal warrants specify if a traffic signal is justified. Even then, the project analyst conducts an detailed engineering investigation, before recommending a traffic signal installation. Since, this kind of public process does not exist in India, the following process is proposed:

- Get inputs from traffic police and other users on corridors which are congested from a perception point of view.
- Get police reports on accident incidence with location, plot these locations. If information on type of accident is available, check if there is a large incidence of right-angled collisions.
- Conduct multiple runs in two-wheeler, four-wheeler and bus on the corridor using a smart phone based tracking system (MyTracks for android as shown below is an example)



- Check if the speeds are low for different modes of traffic at the same locations over different time periods. This indicates recurring bottlenecks at these locations.
- If these locations are not already signalized, review if they satisfy eye-test of needing a traffic signal (large arterial volumes, lack of gaps for minor street traffic, lack of gaps for pedestrians to safely cross the junction.).
- Conduct warrant studies to identify if the location requires a signal. While quite often, the eye-test may indicate that a signal is required – it is a good practice is do a proper engineering study in determining the warrant being satisfied.
- If the signal warrants are satisfied, review other traffic control measure and potential for their success in managing traffic before deciding on a signal. The other remedial measures to be explored include:
    - Geometric improvements such as the addition of turn lanes either by construction or by restriping the existing cross section;
    - Sight obstruction removal to increase intersection sight distance;
    - Street lighting if night time crashes are predominant; and
    - Improved signing and pavement markings to better define the intersection and its operational characteristics.
- Please note that due to higher incidence of two-wheelers the gaps for conflicting traffic in Indian cities are more readily available than in locations where there is predominantly car oriented traffic. Hence, adding additional conditions like at least 15% of the total volume comprising of cars and buses to the warrants should be considered, while determining the installation of traffic signal.

Recommendation: Identify bottlenecks, review conditions, conduct warrant analysis and use engineering judgment in determining traffic signal installation

Q4. What studies should I conduct for installing traffic signal?

The following primary and secondary surveys required for signal warrant analysis shall be conducted for justifying a traffic signal:

- Primary
    - Speed-Delay survey for two-wheeler, car and bus with at least 3 trips in each peak hour (morning, afternoon and evening).
    - Classified traffic volume count survey including pedestrian counts
    - Secondary
    - Accident analysis

The following primary and secondary surveys shall be conducted for implementing a traffic signal including installation of signal and timing the junction[8]:

[8] *ADOT Traffic Engineering Guidelines and Processes, June 2015*

- A 24-hour turning movement count which includes all entering traffic for at least four typical days (two typical weekdays, Saturday and Sunday).
  - Determine AM and PM peak hour traffic volumes
  - Pedestrian volumes
  - Percentage of trucks and buses
- If 24 hour count is not possible, factors of 1.20 and 1.35 can be applied on 16 hour or 12 hour counts, respectively to obtain the 24 hour counts. If historic data is available, these factors should be revised as per local data.
- Condition diagram which includes roadway geometrics, parking, driveways, sidewalks, signing, pavement markings, development of intersection quadrants, and any other features pertinent to the study peak hour delay study
- A conflict analysis
- Approach speed limits and/or approach speeds
- Analysis of the existing progression in a coordinated system
- Capacity analysis of the intersection for current and future years using growth expectations of the location
- Other data which are desirable for a more precise understanding of the operation of the intersection

Recommendation:

1. Ensure that green is used efficiently with no green starvation.

2. Maximize throughput (vehicle discharge) during oversaturated conditions

4.2 Traffic Signal Timing

Q5. Experts keep mentioning shorter cycle lengths are better, is this true?

Analysis of multiple intersections in many locations in India and in other countries has shown that there exists a cycle length range that is optimal for signalized intersections, which generally varies between 60 sec and 150 sec. The exact optimal cycle length is a factor of:

- Whether the intersection is part of a coordinated system or is isolated
- The volume to capacity ratio at the intersection
- The volume to capacity of individual movements

Exhibit 28 to Exhibit 32 show results for delay, queue lengths, fuel consumption, PM10 emissions and absolute delay for isolated intersection 1 for volume to capacity ranges varying from 0.5 to 1.5 as shown below. The results are from VISSIM microsimulation modelling. VISSIM modelling for Indian conditions is accurate enough that the comparison of scenarios are mostly correct; i.e., if VISSIM says Scenario 1 is better than Scenario 2, it is also the case in the field.

What the exhibits show is that at all volume conditions, shorter cycle lengths have lower delay, queues, fuel consumption and delays. In most situations, cycle length of 60 to 150 seconds lead to better efficiency. When you look at total absolute delay (not delay per vehicle), as shown in Exhibit 31, it is even more evident the impact of longer cycle lengths especially when the volume conditions are oversaturated (demand being greater than capacity). From the trends shown in bellows exhibits it is clear that, the longer cycle lengths lead to have more delays and hence more fuel consumption and hence more emissions. The emissions again impact of the health of the users and also the traffic police badly. For the v/c ratios of 0.5, 0.75 and 1.25, the 60 cycle length is found to be the minimum delay cycle length and for v/c ration of 1.0, the 120 sec is found to be the minimum delay cycle length. It is also inferred from the results that, the increase in delay is steeper after 150 sec of cycle length for saturated scenarios (v/c of 1 and 1.25).

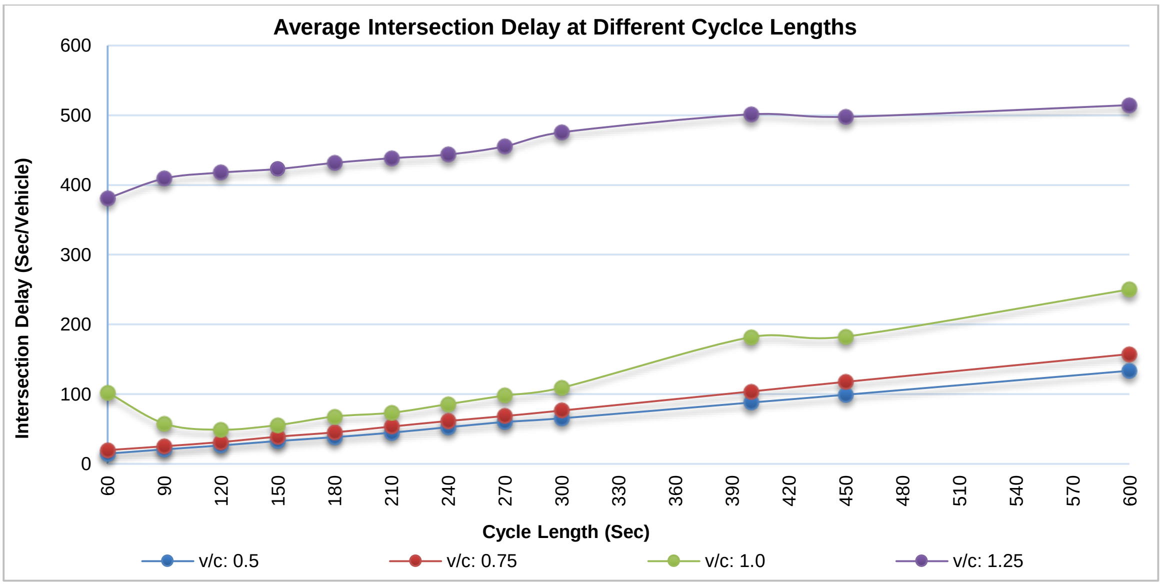


Exhibit 28: Cycle Length Impact on Intersection Delay for Different Volume Levels

The similar observations have been found for queue lengths for different cycle lengths. The below exhibit shows the average queue lengths for various alternative cycle lengths for all the v/c ratios from under saturated to over saturated.

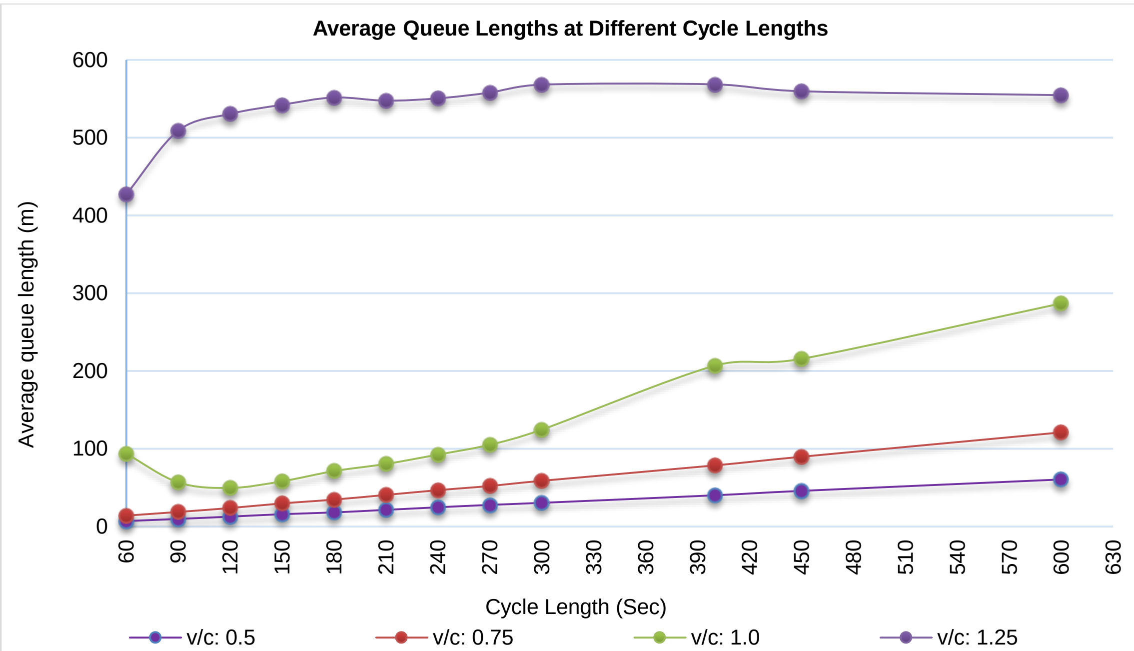


Exhibit 29: Cycle Length Impact on Intersection Queue Length for Different Volume Levels

The below Exhibit 30 expresses the delay for any cycle length as factor of minimum delay observed for that particular v/c ratio. It is found from the exhibit that, the delay for cycle lengths 180 and more is 3 to 10 times of the minimum delay which shows the adversity of impact of longer cycle lengths. It also proves that the myth of having longer cycle lengths for more volumes is not valid. Hence, it is recommended to restrict the cycle length 150 sec however it is always critical to determine the optimum cycle length before implementation into the field.

Cycle Length (Sec)	Factor of Minimum Delay			
	@ v/c : 0.5	@ v/c : 0.75	@ v/c : 1.0	@ v/c : 1.25
60	1.00	1.00	2.09	1.00
90	1.41	1.70	1.18	1.07
120	1.80	2.11	1.00	1.10
150	2.22	2.63	1.14	1.11
180	2.60	3.05	1.39	1.13
210	3.03	3.61	1.50	1.15
240	3.56	4.15	1.75	1.16
270	4.06	4.63	2.00	1.19
300	4.42	5.17	2.24	1.25
400	5.95	7.01	3.72	1.32
450	6.70	7.94	3.74	1.31
600	9.03	10.63	5.12	1.35

Exhibit 30: Cycle Length Impact Factors for Different Volume Levels

The below exhibit shows the absolute vehicular delay which is sum of delay occurred for all the vehicles using the junction during one hour period. The trends are similar to the delay per vehicle but it shows the how user's time at the intersection gets impacted absolutely. At the v/c ratio of 1.0, absolute delay at minimum delay cycle length is around 500 hours of users time but with the increase of cycle length by just 30 sec will translate to 577 hours of users time as delay.

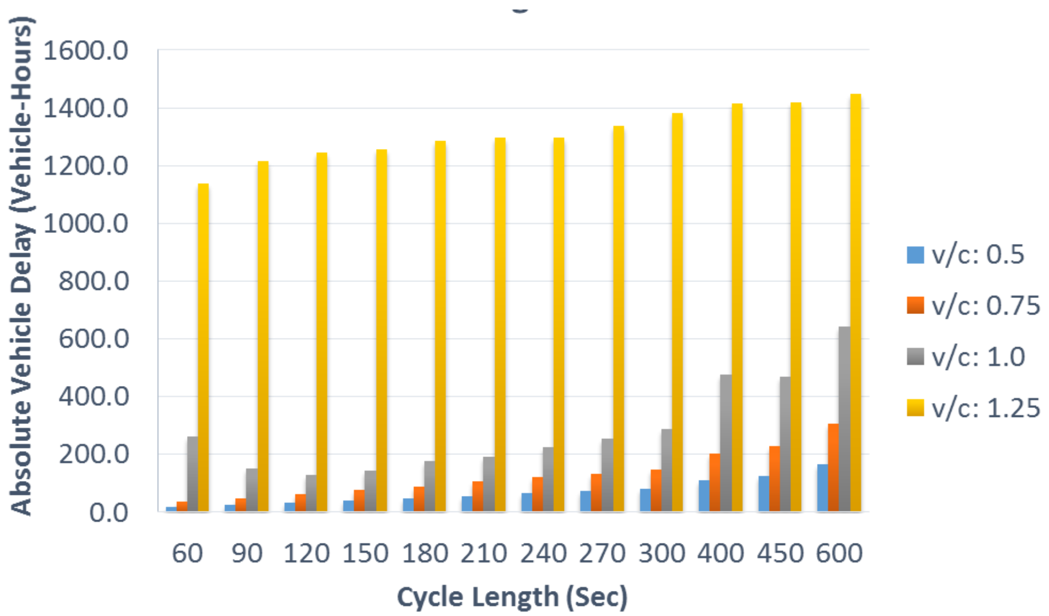


Exhibit 31: Cycle Length Impact on Total Intersection Delay for Different Volume Levels

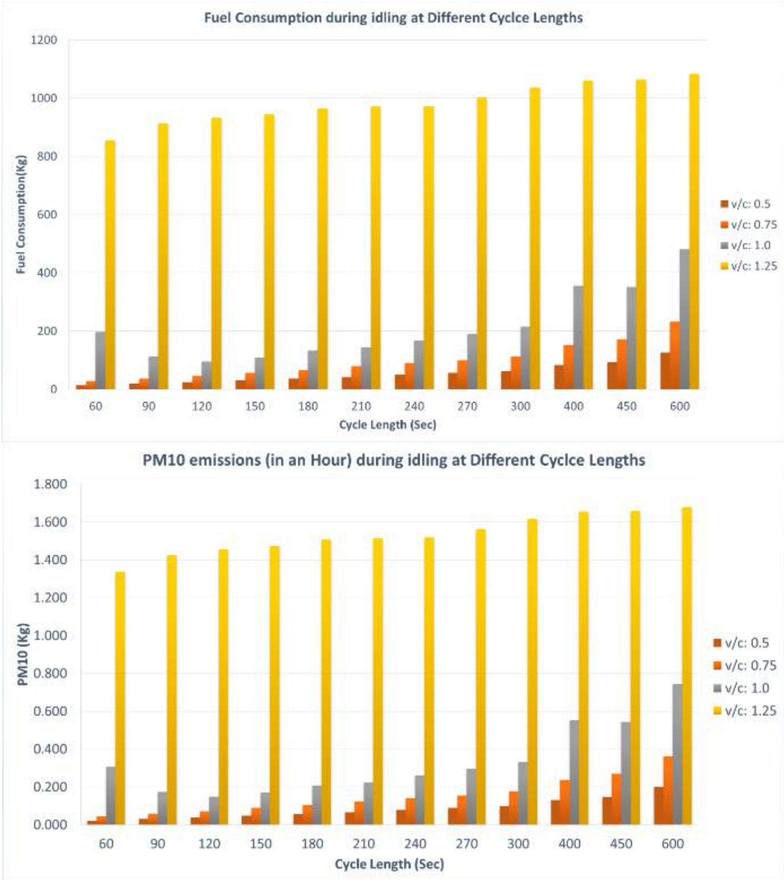


Exhibit 32: Cycle Length Impact on Fuel Consumption and PM10 for Different Volume Levels

Recommendation: Keep cycle length at any intersection between 60 seconds to 150 seconds. This cycle length range leads to lower delays, queue lengths, fuel consumption and emissions.

Q6. On the ground, it feels like longer cycle lengths work better. Why is that?

It is mainly a perception, mostly coming from the fact that no one is measuring the delay or queue lengths in the field. Exhibit 33 and Exhibit 34 clearly show that both the number of stops per vehicle and throughput (number of vehicles discharging from intersection in an hour) are also better at lower cycle lengths for both under saturated (demand less than capacity) and oversaturated (demand greater than capacity) conditions.

In reality, throughput (discharge) from an intersection goes down even further in oversaturated conditions for longer cycle lengths. This is because all the minor junctions that get blocked due to the long reds impact smooth flows, which in turn reduce the throughput.

The other reason traffic police prefer longer cycle lengths is that when they are changing signal indication, it is extremely stressful and difficult to change the indication every 30 to 45 seconds manually. Longer splits also support in traffic police dealing with the violators and provide enforcement while regulating. However, the net impact is greater emissions and fuel consumption.

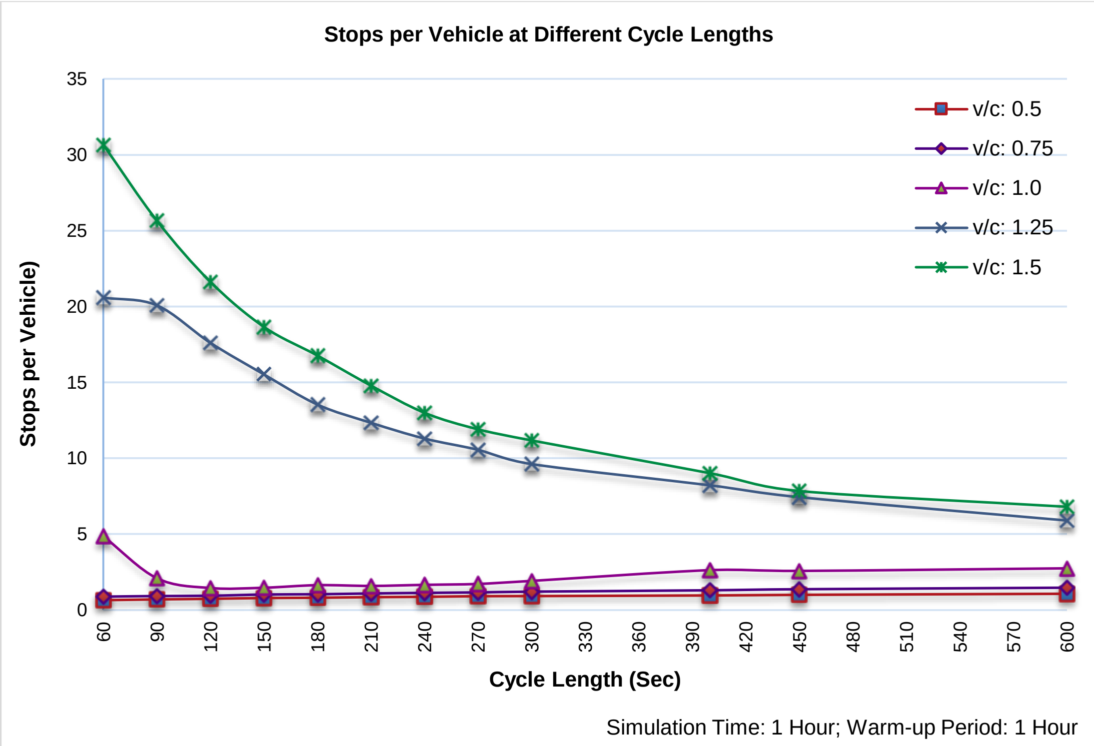


Exhibit 33: Number of Stops per Vehicle

	Cycle Length											
V/C Ratio	**60**	**90**	**120**	**150**	**180**	**210**	**240**	**270**	**300**	**400**	**450**	**600**
0.5	4,498	4,496	4,490	4,490	4,487	4,490	4,492	4,476	4,497	4,491	4,491	4,499
0.75	7,035	7,029	7,025	7,027	7,026	7,090	7,032	7,012	7,031	7,041	7,040	7,025
1	9,216	9,380	9,408	9,399	9,434	9,474	9,439	9,346	9,469	9,416	9,269	9,250
1.25	10,742	10,687	10,708	10,699	10,717	10,630	10,532	10,565	10,461	10,159	10,256	10,138
1.5	10,808	10,766	10,714	10,733	10,554	10,551	10,692	10,571	10,415	10,318	10,404	10,215

Exhibit 34: Throughput (vph) as a Factor of Cycle Length and V/C Ratio

Recommendation: Reality is lower cycle lengths are better in almost all situations. Running a fixed cycle length between 90 seconds and 150 seconds in most situations will lead to lower stops, delays and queue lengths.

Q7. So, what do I look for improving – delay, stops or something else?

The impact measure or commonly known as Measures of Effectiveness that are commonly used for establishing signal timings are given below. A combination of MoEs is also used in certain optimizations.

- Minimise delay
- Maximize progression band (green band that can go through multiple intersections)
- Maximise throughput (volume)
- Minimise fuel consumption

- Minimise pollution (emissions)
- Minimise stops
- Minimise queue length
- Minimise arrival of platoons at red lights

If an optimization software is used, use the default performance indicator in the software. Else, given that there are limitations in collecting data in India here are simple easy to use steps for running the signalized intersection efficiently:

1. At all times ensure that a green is not starved. That is when an approach is green, there should be vehicles feeding the green. We are wasting precious capacity if we are not using the green efficiently.
2. Count the discharge from the given intersection for 5 minutes every 30 to 60 minutes to get an understanding of whether maximum number of vehicles are being discharged during that time. Especially, in oversaturated conditions where queues will keep growing, the principal method to figure out whether one is optimally running the signal is through evaluating throughput/discharge of the intersection.

Recommendation:

1. Ensure that green is used efficiently with no green starvation.

2. Maximize throughput (vehicle discharge) during oversaturated conditions

Q8. How do I decide on intersection cycle length?

As mentioned earlier, cycle length is optimal between the range of 60 seconds to 150 seconds for the most conditions. On occasions where the cycle length is optimized through a software such as Synchro, the value provided by the software can be used. Sixty seconds cycle lengths also work well in non-peak hours, but should be tested properly before applying.

In theory, minimum delay cycle length is determined using a common formula by traffic engineers for isolated intersections. However it is to be noted that this formula is used only for under saturated conditions only.

$$C_O = \frac{1.5L + 5}{1 - \sum_{i=1}^{\#phases} \frac{C_i}{s}}$$

Where:

C_o - Optimal Cycle Length

L – Lost Time = Yellow/Amber + All-Red

C_i - Critical Volume for Phase i

s - Saturation Flow

For coordinated signals, it is important that the cycle length is the same or half/double to support progression. In these situations, an optimization software is preferable since it will look at all combinations for the coordinated signals. As a rule of thumb:

- Signals should be coordinated if they are less than one kilometre. If speeds are uniform, then coordination could be extended up to two kilometres. Beyond two kilometres, platoons dissipate, so there is no great value in trying to achieve progression.
- All coordinated signals should either be on the same cycle length or be half/double of the cycle length.
- Finally, traffic police should not change timings (cycle length, splits), since it will negatively impact the whole system.

Recommendation:
1. Use Webster's minimum delay cycle length formula for determining cycle length
2. Use same cycle length or half/double of the cycle length for coordinated signals
3. Do not any of the coordinated intersections in manual mode if there are no incidents

Q9. How do I decide on green split for each movement?

Webster's methodology is one of the common ways for calculating signalized intersection timings. The methodology prorates the volume to saturation flow of the movement among all movements to determine the green split. As a rule of thumb, here are some simple of ways of achieving the same impact without calculations:

- In undersaturated conditions (demand less than capacity) for isolated intersections, ensure that the queue for each movement is dissipated. The movement goes to red as soon as the queue is dissipated.
- In undersaturated conditions for coordinated arterials, use a signal progression calculator like the one shown at http://www.oregon.gov/ODOT/TD/TP/pages/tools.aspx.
- For oversaturated conditions for both isolated and coordinated intersections, an optimization software (commercial or developed locally) is essential to time the interection. In general, a combination of maximizing throughput of the intersection on a per hour basis and minimizing length of queues for each approach are utilized.

Recommendation: Rule of Thumb for Splits

1. In under-saturated condition for isolated intersection, provide green long enough to discharge the queue formed at the intersection.

2. For coordinated signals in undersatured conditions, use a progression bandwidth model/calculator as shown above.

3. Maximize throughput (vehicle discharge) while minimizing queue lengths during oversaturated conditions. Mostly require a model to provide the split.

Q10. How should the Time-of-Day Plans determined?

Similar volume scenarios require same signal timing plans, generally the total day is divided into number of periods like morning peak , Off-Peak and Peak which are typically called Time of the Day (ToD) Plans. Each ToD Plan has separate signal timings. An analytical approach was developed for India which is available in a worksheet[9] The analytical process is illustrated in Exhibit 35. It mainly consists of:

- Developing optimal number of Transitions (ToD Break Points); and
- Creating timing Program for Each ToD Plan

The analysis procedure helps develop the number of ToD plans appropriate for the selected isolated intersection.

[9] *TOD Plan Development Worksheet, IBI Group, 2015*

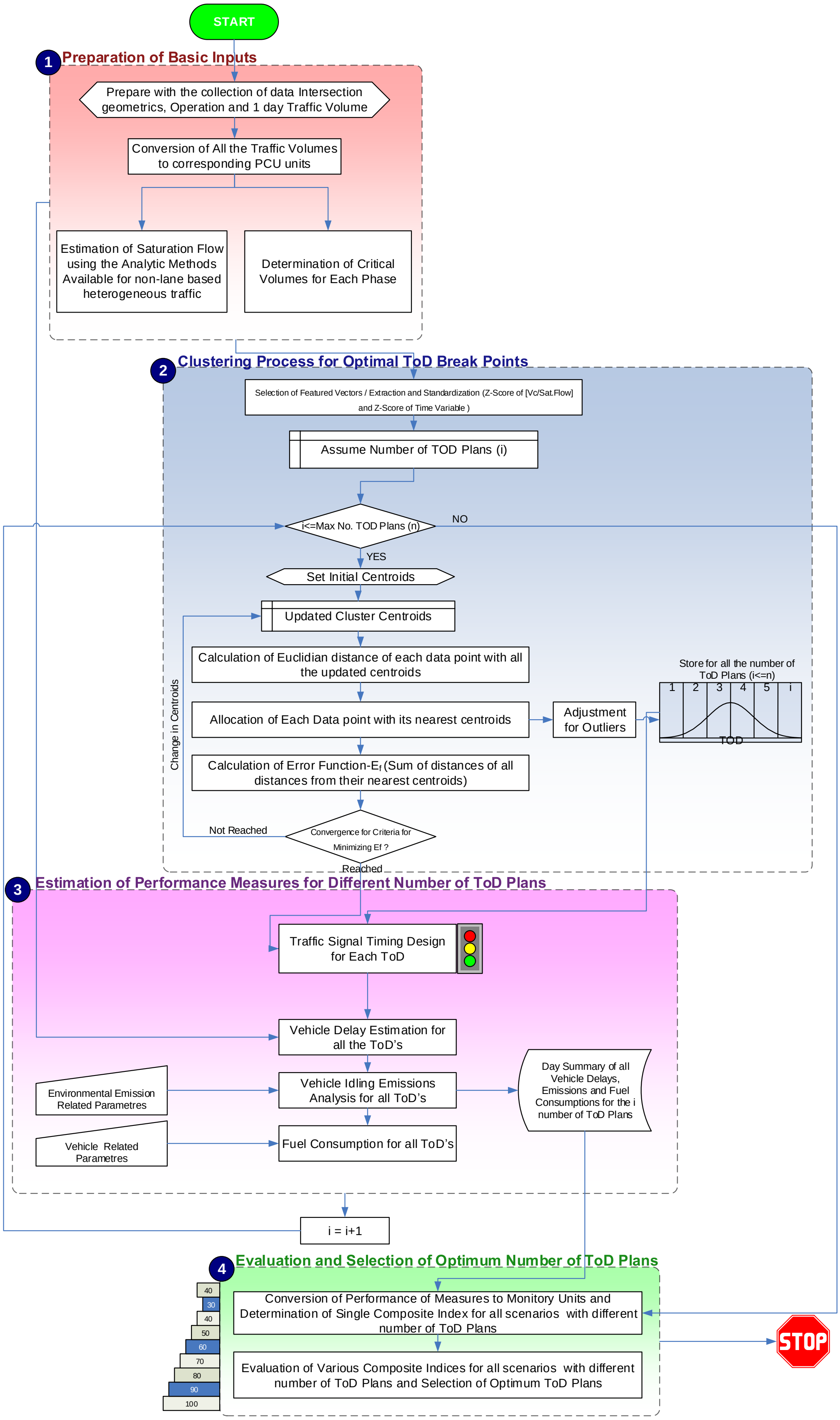


Exhibit 35: ToD Planning Process Developed by IBI Group for India

The typical output is shown in below exhibits for the typical intersection and and 5 of the intersections on AB Road BRT corridor of Indore city.

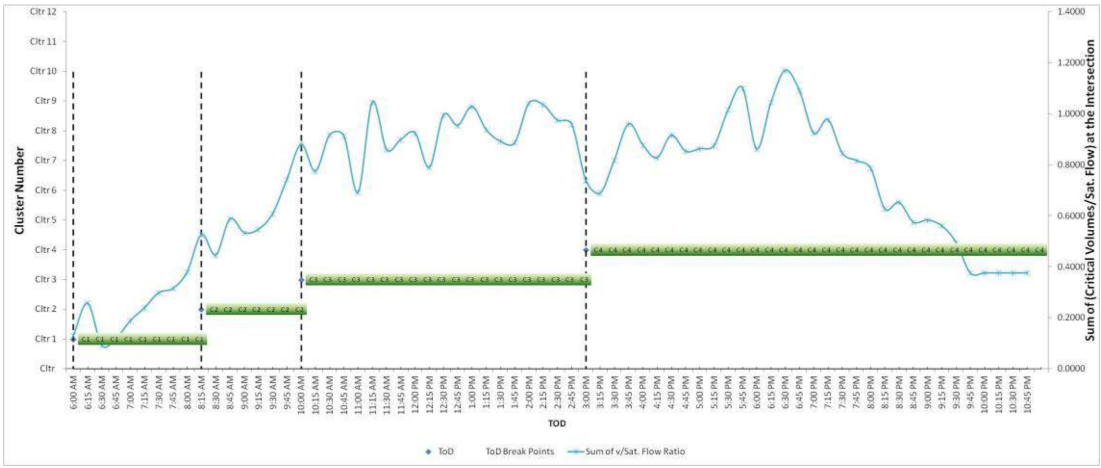


Exhibit 36: Optimal ToD break points for 4 ToD plans (4 transitions) at Geetha Bhavan intersection

Name of the Intersection	Vijaya Nagar		MR 9		LIG		Industry House		New Palasia	
Optimum Number of different ToD Plans	4		4		5		5		4	
Optimum number of Break Points	4		4		5		7		4	
	Transn Points	Timing Plan	Transn Points	Timing Plan.	Transn Points	Timing Plan.	Transn Points	Timing Plan	Transn Points	Timing Plan
Transition Points Cluster numbers	6:00 AM	1	6:00 AM	1	6:00 AM	1	6:00 AM	1	6:00 AM	1
	8:45 AM	2	10:00 AM	2	8:00 AM	2	8:30 AM	2	9:15 AM	2
	1:15 PM	3	2:00 PM	4	9:45 AM	4	9:45 AM	3	11:30 AM	3
	3:45 PM	4	6:00 PM	2	3:15 PM	3	10:45 AM	2	3:30 PM	4
					9:00 PM	5	12:15 PM	3		
							3:45 PM	4		
							7:45 PM	5		

Exhibit 37: Example of ToD Plans from Analysis Worksheet Developed by IBI Group

Recommendation: ToD Plans

1. Sixteen to 24 hour volumes are required for multiple typical days for developing the ToD plans.

2. Detailed analysis will support improving delays through the intersection

3. Higher volume timing plan should be started a bit earlier than required so that congestion onset does not occur.

Q11. Pedestrians keep crossing at all times during the cycle interfering with the vehicular greens and reducing the capacity. What is the solution?

Pedestrians are an essential road user in Indian cities. Behavioural studies showed that pedestrian patience levels start to dip when they start waiting for more than one minute. Hence, it is important:

- Provide safe pedestrian phases in every cycle.
- Create user expectancy that exclusive pedestrian green will be provided in every cycle within 1 to 1.5 minutes. This will allow pedestrians to have better patience.
- Pedestrians are given a higher priority than vehicles while designing signals.

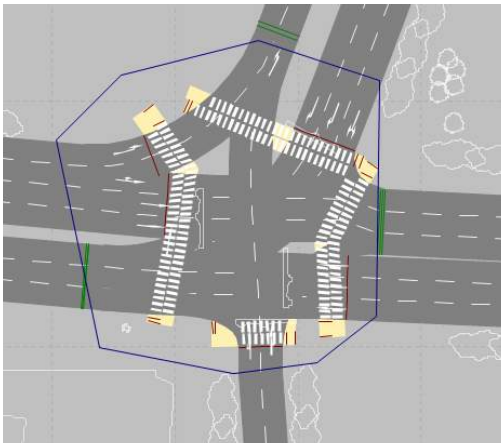


Exhibit 38: Pedestrian Movements Impact on Intersection

The results below show that letting pedestrians cross in the middle of an ongoing green is not beneficial as compared to providing them an exclusive phase or running the pedestrian phase along with the non-conflicting vehicular phase. While not having pedestrians is ideal from a vehicular delay perspective, it also means that people are travelling by private mode and not by mass transport (first and last mile connectivity for transit is through walk). The myth that should be discarded is that pedestrian overpasses (foot-over bridges) are pedestrian infrastructure. All pedestrian overpasses and underpasses are made to improve vehicular flow, and are vehicular infrastructure. Except when pedestrian overpasses are conveniently placed every few hundred meters and connected through convenient escalators (that work all the time), they should not be even considered as an option. It is important that the design person (like design vehicle for pavement construction) for any pedestrian infrastructure should be a person in a wheel chair and a person who is elderly and not particularly healthy.

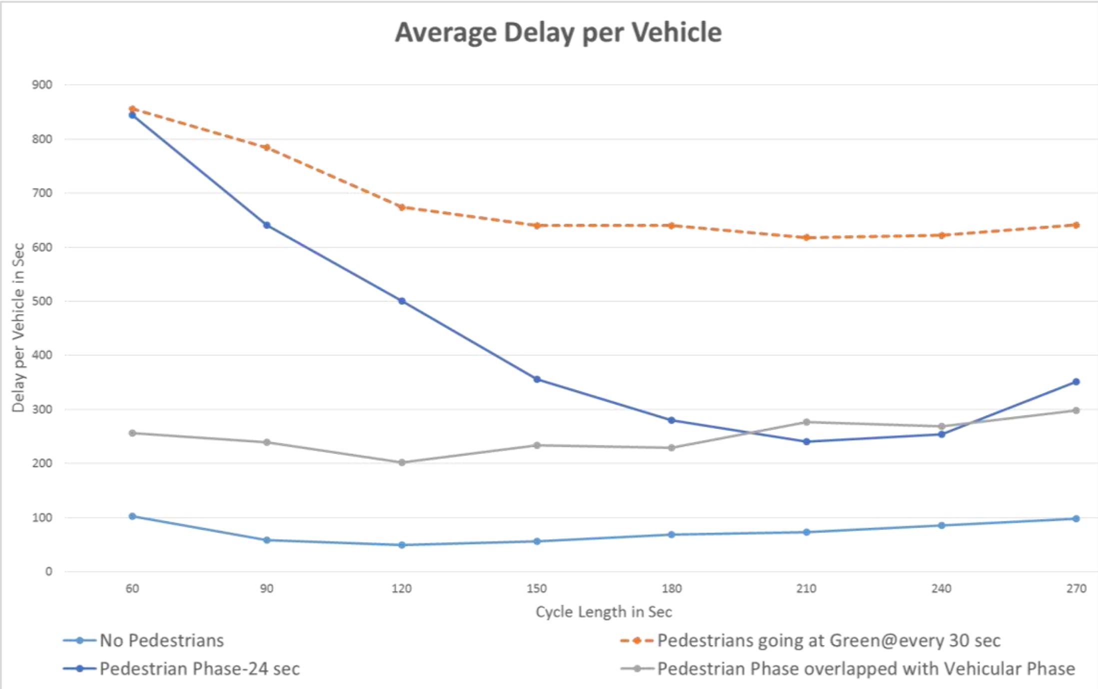


Exhibit 39: Pedestrian Phase vs. Undisciplined Pedestrians Comparison

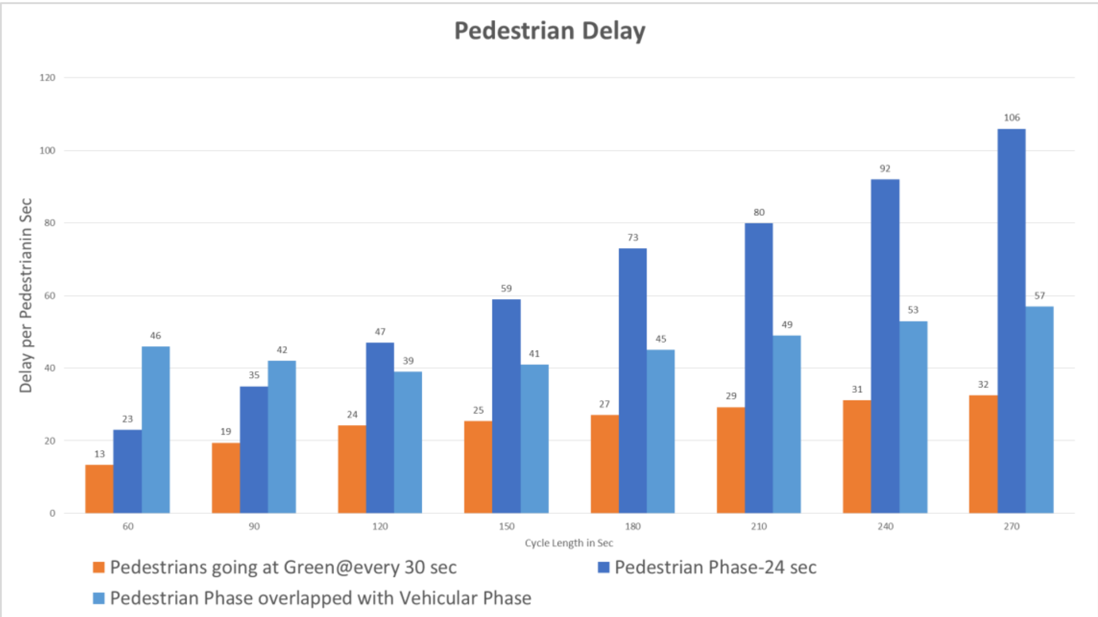


Exhibit 40: Pedestrian Phase vs. Undisciplined Pedestrians Comparison

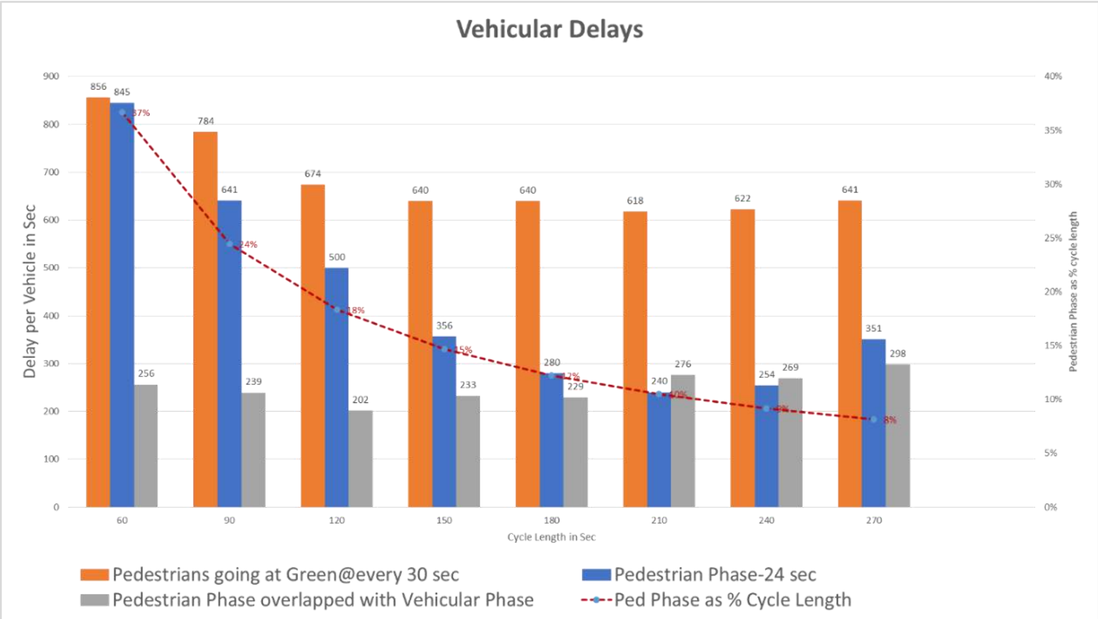


Exhibit 41: Pedestrian Phase vs. Undisciplined Pedestrians Comparison

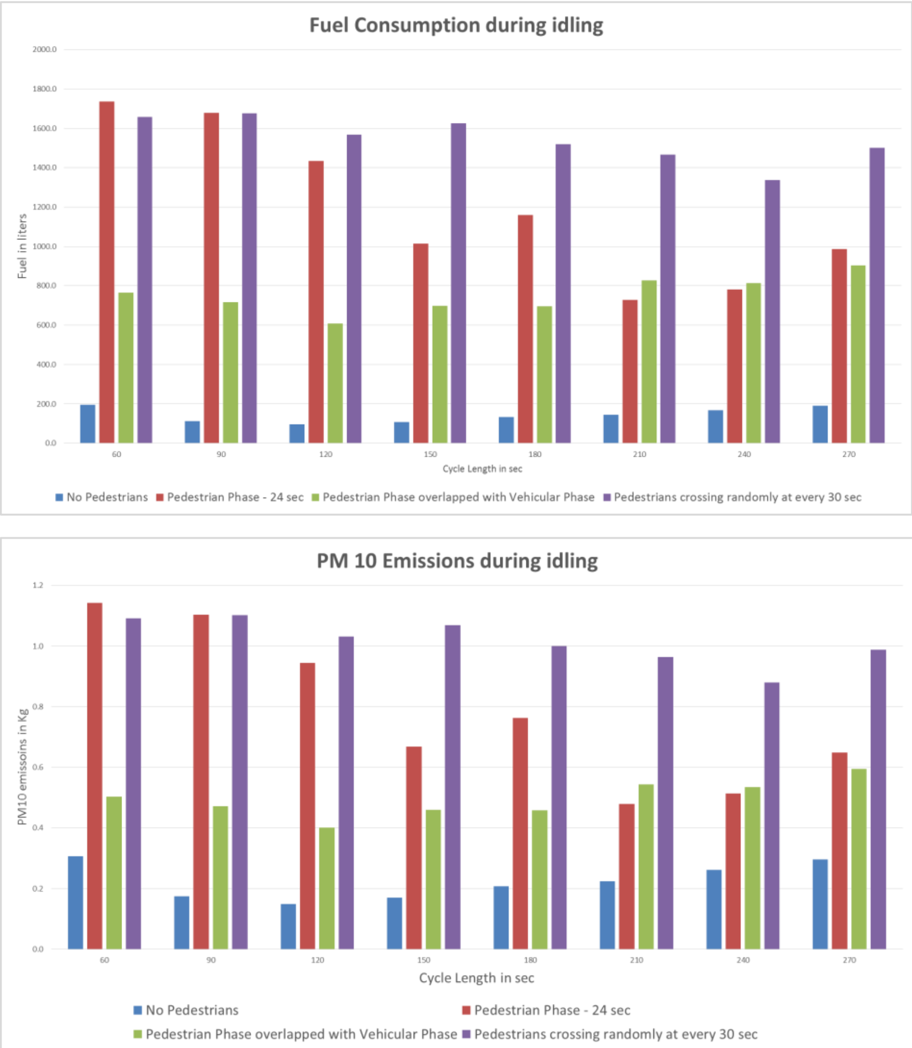


Exhibit 42: Fuel Consumption & Emissions Comparison for Pedestrian Scenarios

Recommendation: Pedestrian Phasing

1. Pedestrian phase that is concurrent with non-conflicting vehicular phase is ideal solution. However, it will require: (1) pedestrians having a higher priority than left-turning vehicles, and (2) having pedestrian refuge islands so that pedestrians can do half crossings.

2. An exclusive pedestrian phase is the next option. The pedestrian delay should be managed so that no pedestrian should wait for more than 60 to 90 seconds.

3. Pedestrian infrastructure should support pedestrians in safely and efficiently crossing the intersection.

4. Pedestrian infrastructure and timing should be designed with wheel chair and elderly persons in mind.

Q12. Are turn-bays (turning lanes) good or bad at intersection?

Turn bays increase the distance required to cross for pedestrians. However, they also help reduce the cycle length by combining the lower volume right-turns together and higher-volume through vehicles together into phases. When right-turn go together at the start as shown in Exhibit 43, it is called lead-lead phasing. When each approach has a separate phase as shown in Exhibit 44, it is called split phasing. As seen below, in most situations the cycle length for split phasing will be more than for phasing with right-turns together (turning volumes are generally lower on arterial streets at most intersections).

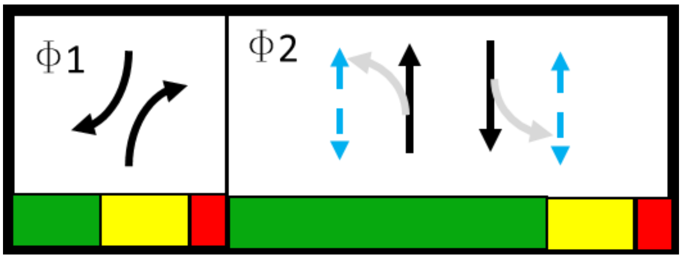


Exhibit 43: Lead-Lead Phasing

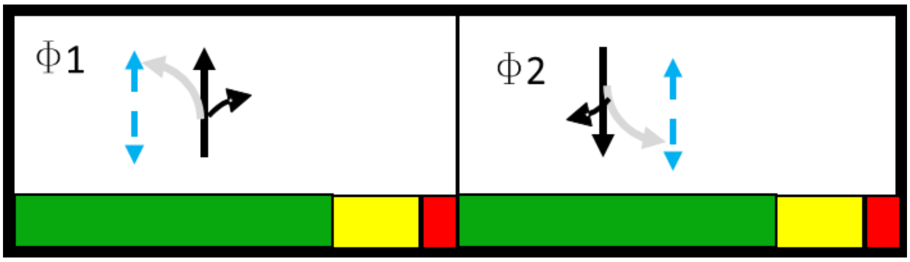


Exhibit 44: Split Phasing

When a storage lane (turn bay) is present, it is possible to optimize the intersection at a lower cycle length which shows great benefit in terms of intersection delays and queue lengths as shown in the exhibits below.

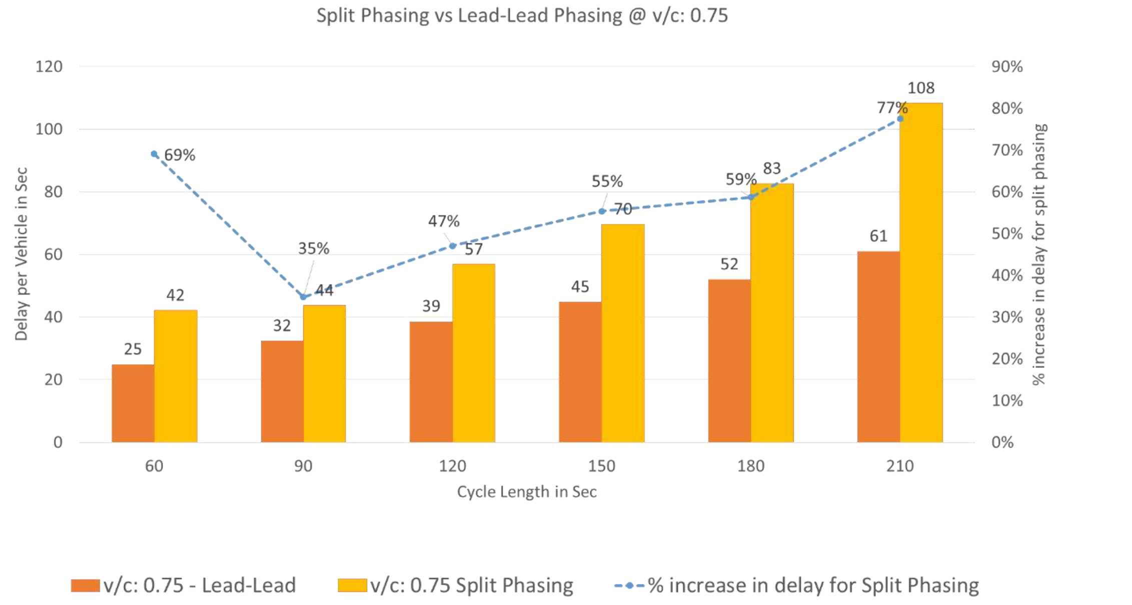


Exhibit 45: Comparison of intersection delay per vehicle for lead-lead and split phasing at v/c of 0.75

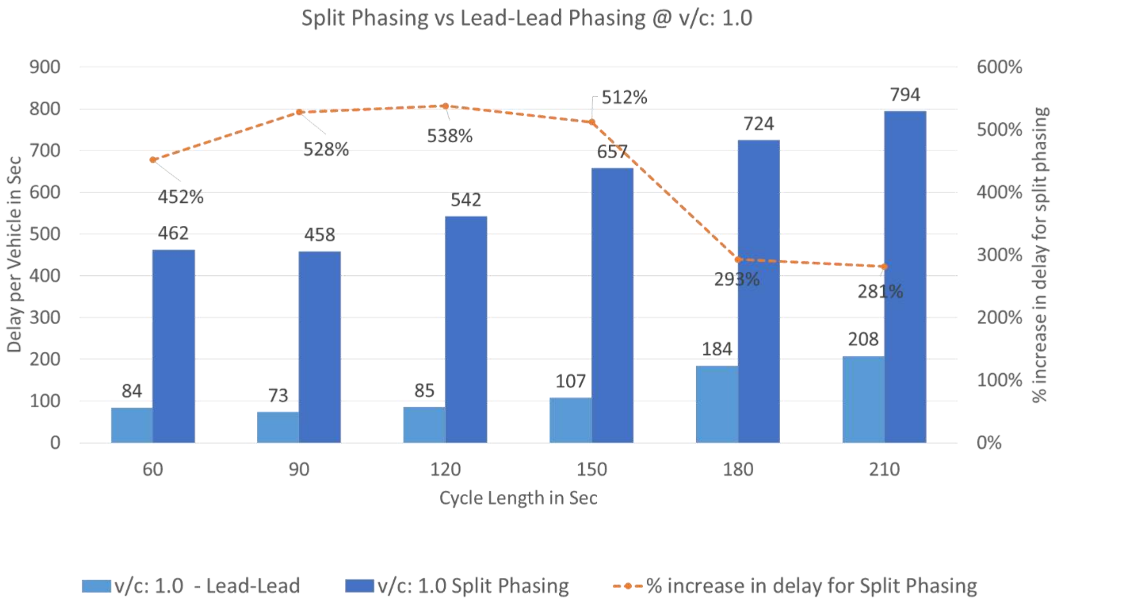


Exhibit 46: Comparison of intersection delay per vehicle for lead-lead and split phasing at v/c of 1.0

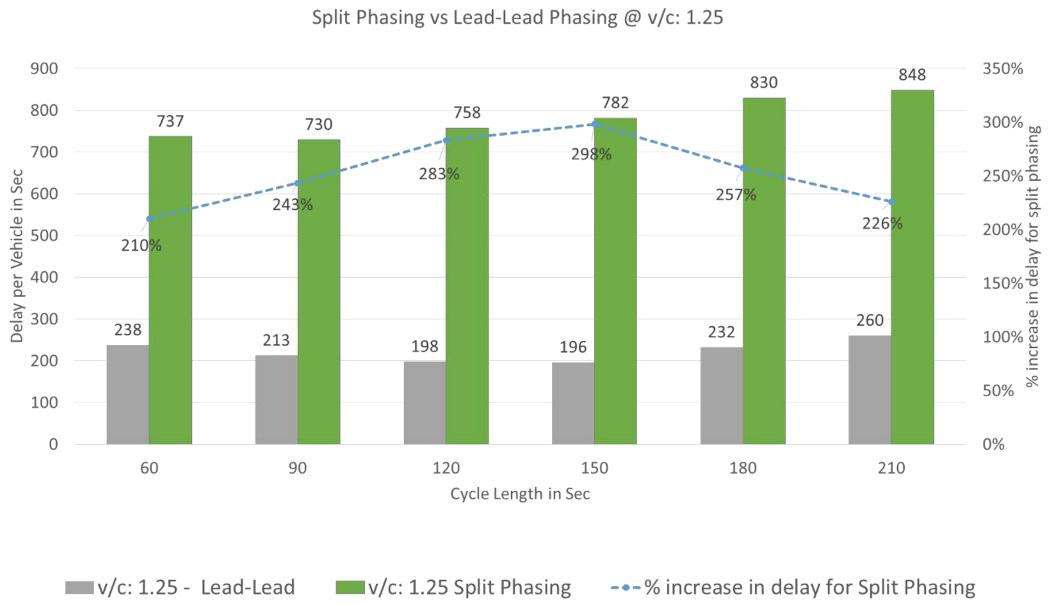


Exhibit 47: Comparison of intersection delay per vehicle for lead-lead and split phasing at v/c of 1.25

Recommendation: Turn Bay and Lead-Lead Phasing

1. When the through and righ-turning vehicles share a lane, split phasing is the natural choice to improve flows.

2. When a long enough right-turn bay is present then right-turn phasing can be separated from through phases.

3. Phasing where right-turns are given a separate phase are more efficient than split phases.

4. Where possible, intersection design should accommodate right-turn bays to improve traffic movement including pedestrian delays.

Q13. Do coordination provide any benefit?

On arterial corridors and networks, signal coordination can provide enormous benefit. Ensuring a platoon (group of vehicles) travel through multiple intersections is also inline with user expectancy. For this to happen, it is preferable to use a progression calculator sheet like the one shown at http://www.oregon.gov/ODOT/TD/TP/pages/tools.aspx or any signal optimization software. The challenge with progression is getting a band to go through multiple intersections in both directions as shown in Exhibit 48**Error! Reference source not found.**. The results are shown below.

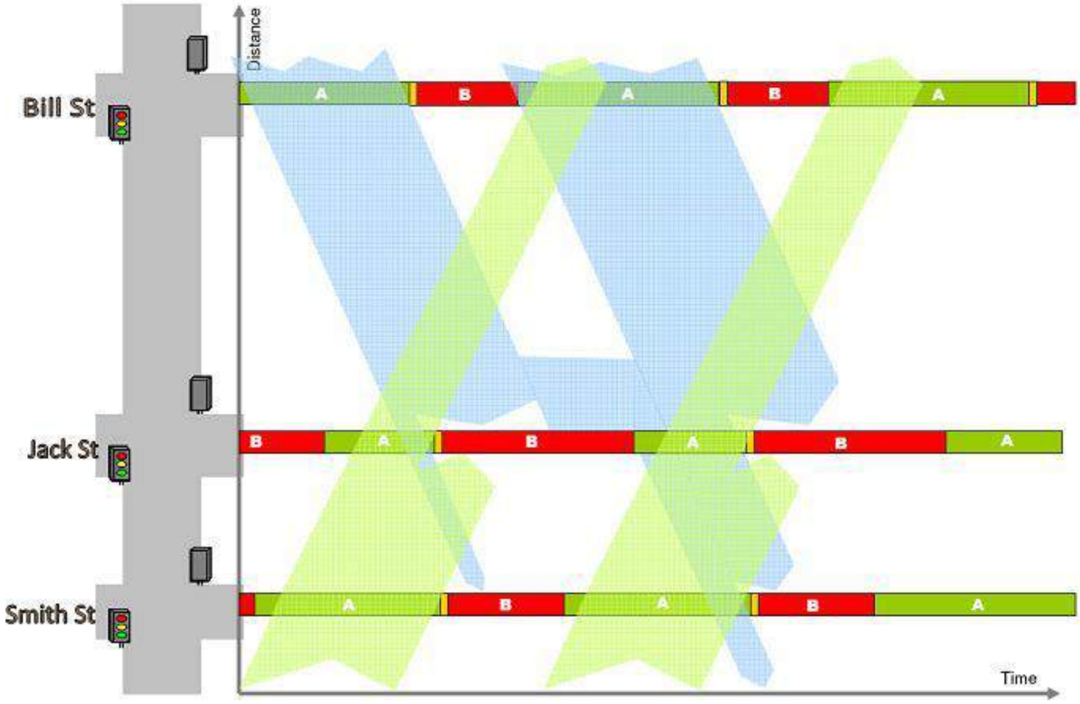


Exhibit 48: Signal Progression showing Bands in Both Direction

Exhibit 49: Arterial Network in VISSIM for Simulating Coordination Impacts

The below Exhibit 50 and Exhibit 51 shows the impact of traffic signal coordination in terms of % reduction in system's or network delay. There is about 30% reduction in delay just by changing the timing parameters and offsets for the case considered.

120 Sec Cycle Length	With Coordination			Without Coordination - Zero sec offset			% Difference		
Intersection	EB Movements	WB Movements	Total Intersection	EB Movements	WB Movements	Total Intersection	EB Movements	WB Movements	Total Intersection
Indira Park I/s	197	30.3	52.6	47	42	238.1	-76%	39%	352%
Ashok Nagar	71.9	45.1	46.7	115.1	92.3	47.3	60%	105%	1%
RTC Cross Roads	69.8	23.9	57.2	60.1	65.3	94.5	-14%	173%	65%
VST	57.1	30.1	235.8	82.8	378	132.0	45%	1156%	-44%
System	98.1			127.9			30%		

Exhibit 50: Coordination Impacts on Delay - Table

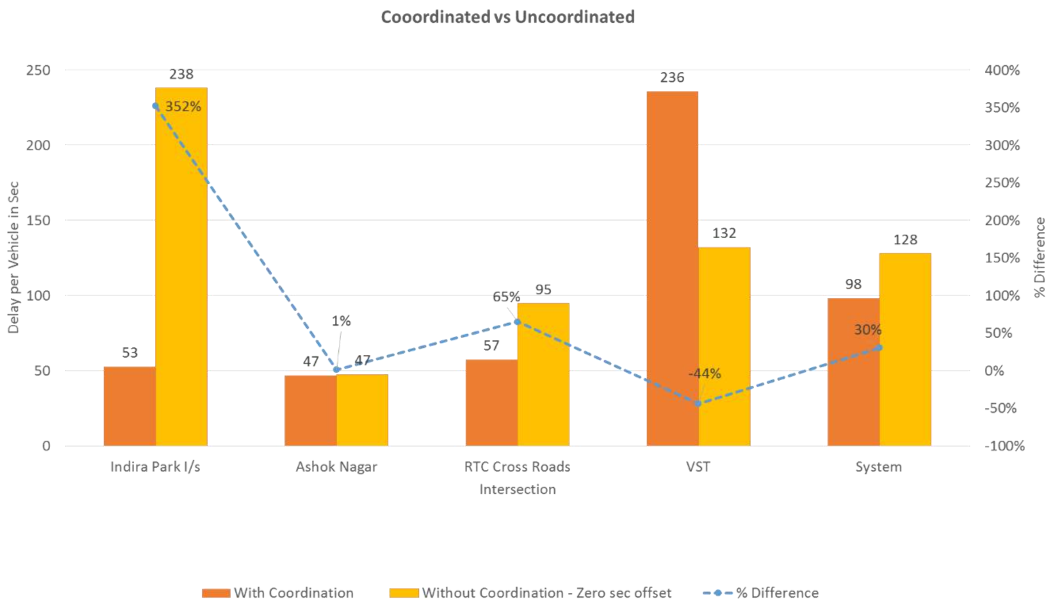


Exhibit 51: Coordination Impacts on Delay

Intersection improvements due to coordination can vary based on the quality of optimization. As seen above, at most junctions even with limited optimization there are substantial improvements in delay.

Recommendation: Signal Coordination

1. Signal coordination improves delays, stops, etc. on an arterial corridor. Where intersections are within one km, signal coordination should be attempted.

2. Signal coordination can be done with a simple bandwidth optimization program.

Q14. Do Sensors/Detectors help reduce traffic congestion

Most modern signalized intersections have detection on some or all movements at signalized intersections. Detectors/sensors ensure that the signalized intersection is providing greens to a given movement only based on the demand. This ensures that the major movement which generally has more demand is getting all the unused green from the minor movements which in-turn allows the intersection to minimize its overall delay.

In fully actuated intersections there is no background cycle, which allows the greens to be provided efficiently to the next movement as soon as there is no demand on the current phase. While in semi-actuated signals, detectors are placed only on minor movements allowing all the unused green from minor movements to be added to the major street green.

Exhibit 54**Error! Reference source not found.** illustrates how detection works on a minor phase. In semi-actuated signals, the minor street phase will have a minimum green split that gets extended based on vehicle actuations (how many vehicles drive over detector). For each actuation, the green split gets extended by a unit amount. It can get extended to the maximum green split set for that movement. If demand is less, then the movement will gap-out allowing the unused green to be moved to the main street.

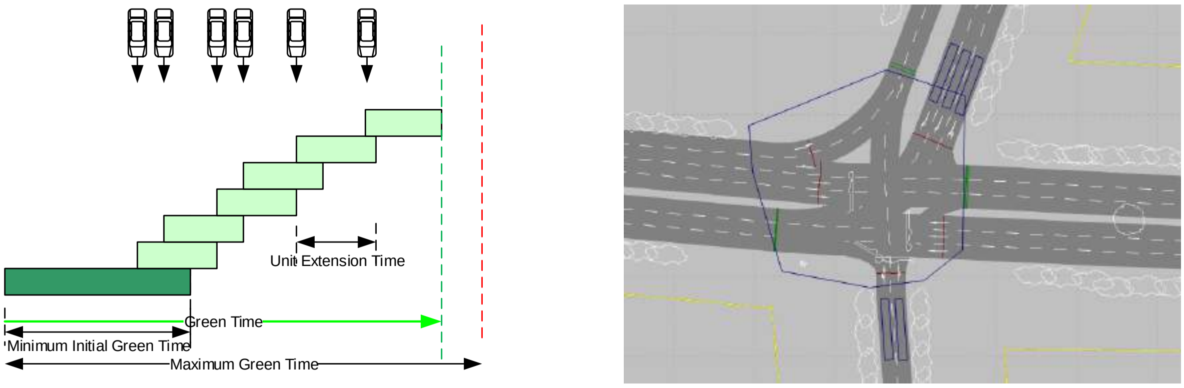
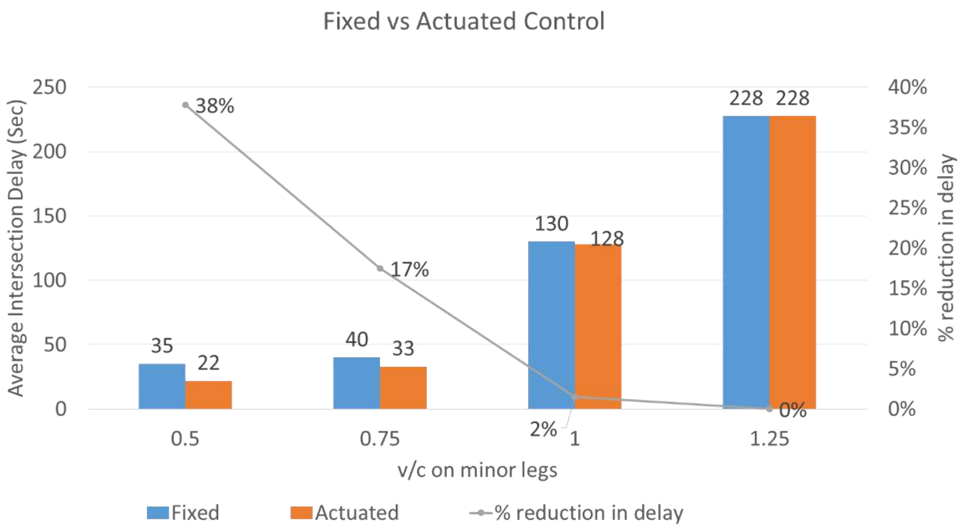


Exhibit 52: Detection for Intersection Movements - Illustration

Exhibit 55, Exhibit 56 and Exhibit 57 show that actuated control on a minor movement is beneficial in under saturated conditions but has no impact in oversaturated conditions. During under saturated conditions, the benefits can be as high as 38% as shown in Exhibit 55 where as in over saturated conditions it is as low as 0%. Hence, the actuated control yields better results during the under-saturaetd conditions of traffic. This is in line with expectations since oversaturation will lead to a phase running on maximum green split.

The reasons why detectors haven't been all that prevalent are due to:

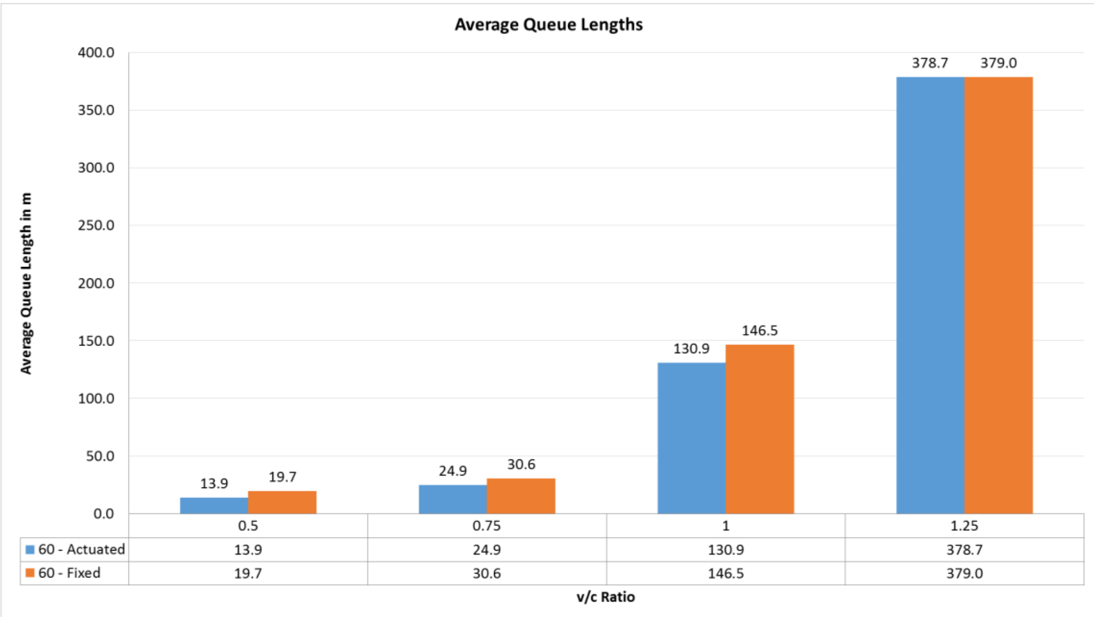
- Loop detectors are most common and cheapest form of detection. However, the uncontrolled road digging that occurs in India results in these loop detectors being dug up.
- Camera based detection with virtual loops is being increasingly used in India. However the cost is substantial for camera based detection. It also requires a lot more fine tuning to make it work.
- Many autos or other vehicles park near the intersection for long stretches of time, which works as constant actuation leading to max green times which completes negates the objective of including detection at the location.



v/c on major legs : **1**

Note: *max greens corresponding to Cycle Length **60 sec** and **v/c** of **1** on minor legs*

Exhibit 53: Fixed vs. Actuated Signals Comparison for Delay



	0.5	0.75	1	1.25
60 - Actuated	13.9	24.9	130.9	378.7
60 - Fixed	19.7	30.6	146.5	379.0

Exhibit 54: Fixed vs. Actuated Signals Comparison for Queue Lengths

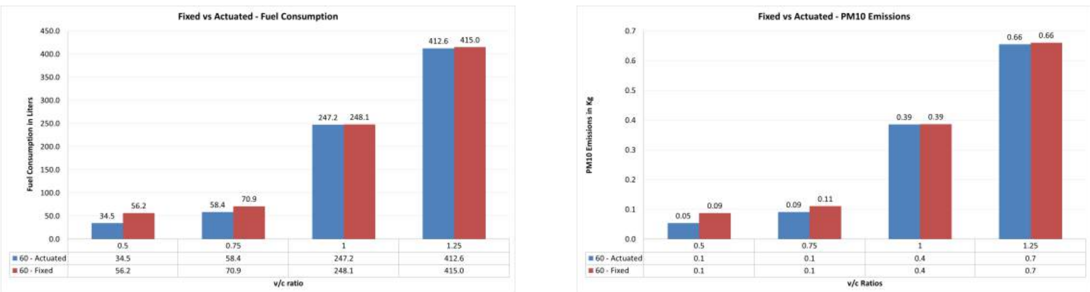


Exhibit 55: Fixed vs. Actuated Signals Comparison for Fuel Consumption & PM10 Emissions

Recommendation: Detection for Signalized Junctions

1. Incorporating detection on minor movements reduces delay during undersaturated conditions on arterial corridors.

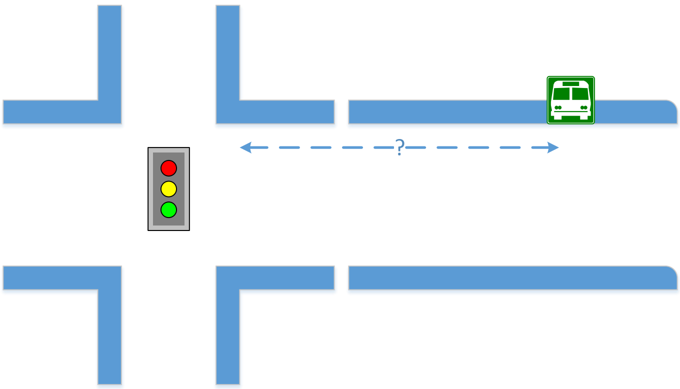
2. Isolated intersections also benefit tremendously during non-peak hours.

3. Camera based detection is recommended for Indian situation where road digging is common place.

4. Stopping and parking restrictions should be strictly enforced where detection is implemented so that parked vehicles do not keep sending constant detector calls.

4.3 Physical Elements

Q15. How far from the intersection should the bus stop be located?



Each bus carries 60 people in the space required for two to four cars. Not needing parking makes buses even more attractive for anyone trying to solve the traffic congestion problem. The challenge for buses when compared to private vehicles is that they do not provide door-to-door service. Having bus stops close to the intersection means that it will allow passenger from three of the four directions to walk the least amount of distance to get to the bus stop. What we know is that people tend to move away from buses and other transit modes to private vehicles when the walking distance is more than 10 minutes or around 400 meters.

We cannot state as recommendation whether bus stop should be upstream or downstream of the intersection without knowing the applicability and traffic conditions. It is important to know advantages and disadvantages of placement of bus stop on upstream and downstream of the intersection on which the decision can be made as per applicability. The disadvantage with upstream bus stop is that there would be more conflicts with left turn traffic in that approach and sufficient sight distance will not available for vehicles behind buses waiting at stops. The capacity gets impacts some times when bus is waiting at stop during green time for the approach as vehicles behind bus gets stuck. The downstream bus stop location (if it is very near) make vehicles spill back on intersection area and impacts the capacity.

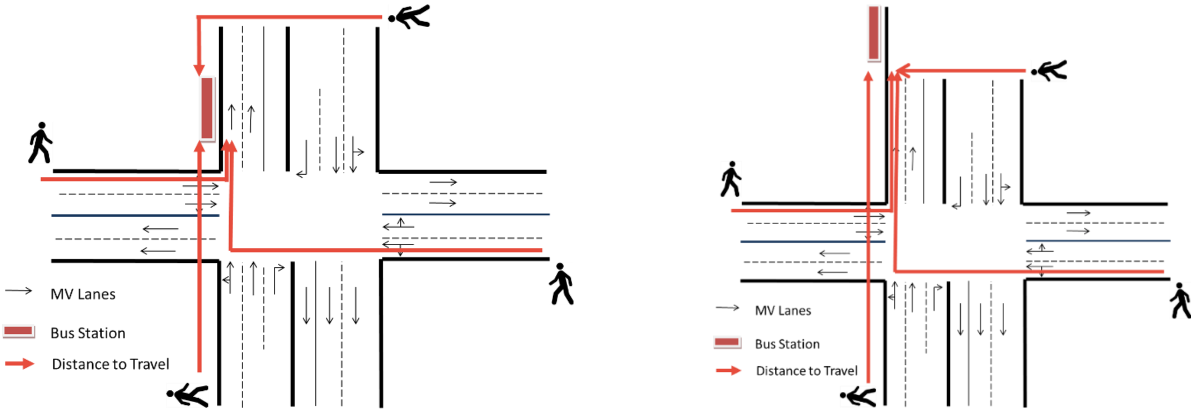
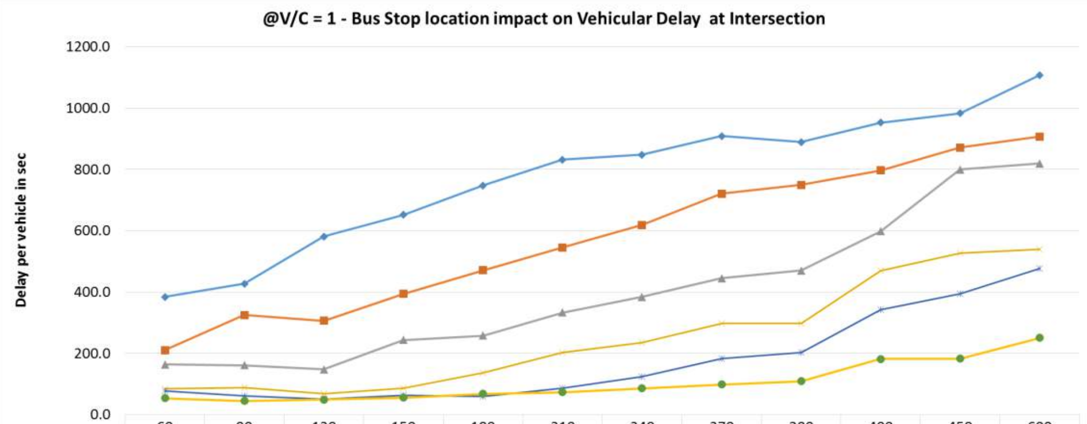


Exhibit 56: An Illustration of Pedestrian Walking Distances Based on Bus Stop Location on down stream

So, the dilemma is how close or far should the bus stop be located to ensure that passengers do not shift to private vehicles while not creating severe vehicular congestion? Keep in mind, that the increase in travel time for buses increases more than other private vehicles during congestion (due to size and stops). So, when buses create vehicular congestion, it has greater impact on bus travel times and consequently reducing the ridership (choice bus users tend not to use bus as much due to increase in travel times).

Exhibit 57, Exhibit 58 and Exhibit 59 provide VISSIM delays for isolated intersection 1, when bus stop is present downstream of intersection between 20 meters to 200 meters, and when no bus stop is present.

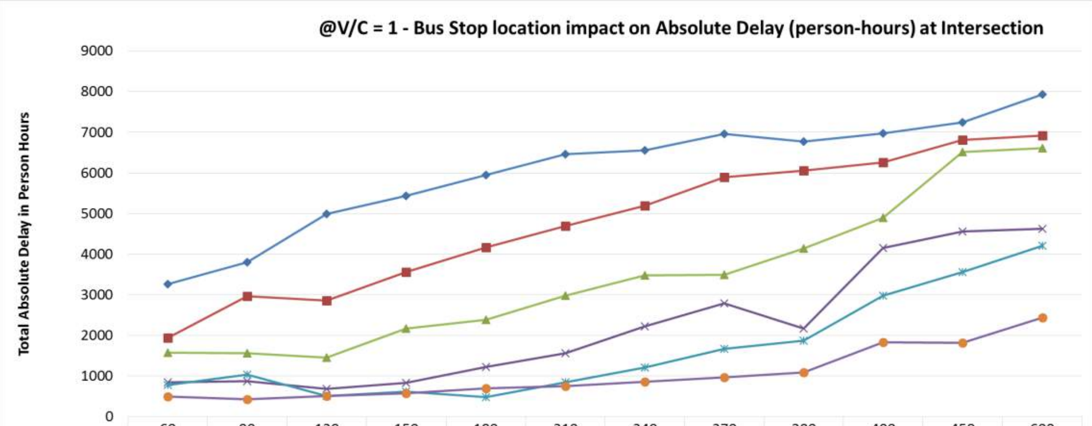
What comes out clearly from the results is that shorter cycle lengths are best from a delay perspective when bus stop is downstream, irrespective of the distance. Naturally, farther downstream the bus stop is positioned the better for smoother traffic movement.



	60	90	120	150	180	210	240	270	300	400	450	600
20	384.1	427.2	581.1	651.8	747.8	831.7	847.9	909.2	889.3	952.8	983.2	1107.3
50	209.9	324.8	305.6	393.5	470.5	545.5	618.9	720.5	749.6	797.2	871.4	907.0
100	163.1	161.3	147.1	243.2	257.5	332.6	384.0	444.9	469.7	598.3	799.3	819.3
150	84.9	87.8	67.3	85.5	136.3	201.7	234.0	298.3	298.2	468.6	526.1	540.2
200	77.9	61.6	50.4	62.6	59.5	86.5	122.8	183.2	202.9	341.9	393.9	475.9
No Bus Stop	53.2	44.6	48.9	55.6	67.9	73.3	85.6	98.0	109.3	181.8	182.7	250.3

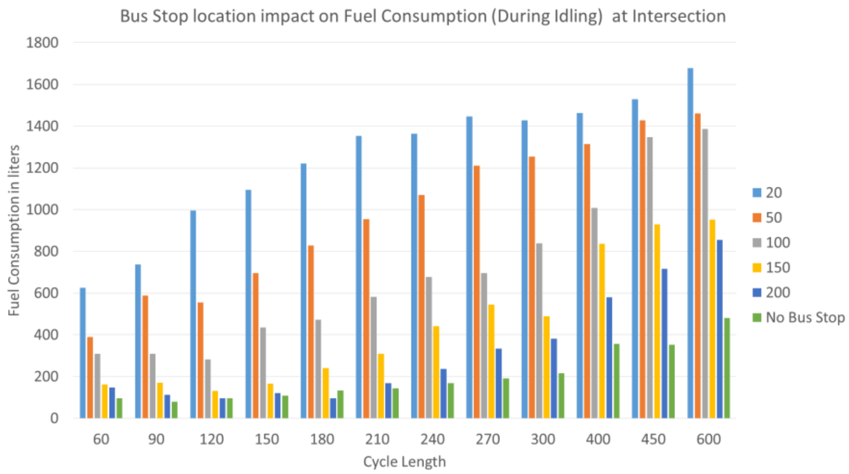
Cycle Lengths

Exhibit 57: Bus Stop Location Impact on Delay per Vehicle



	60	90	120	150	180	210	240	270	300	400	450	600
20	3257	3805	4988	5427	5949	6463	6552	6964	6771	6967	7240	7928
50	1936	2962	2858	3564	4166	4690	5196	5888	6054	6263	6816	6917
100	1573	1558	1446	2166	2384	2971	3475	3494	4144	4892	6519	6604
150	846	868	681	835	1216	1554	2218	2791	2171	4155	4555	4623
200	776	1030	513	610	477	841	1205	1666	1871	2974	3561	4206
No Bus Stop	500	420	501	577	694	754	864	972	1084	1832	1812	2438

Exhibit 58: Bus Stop Location Impact on Total Intersection Delay



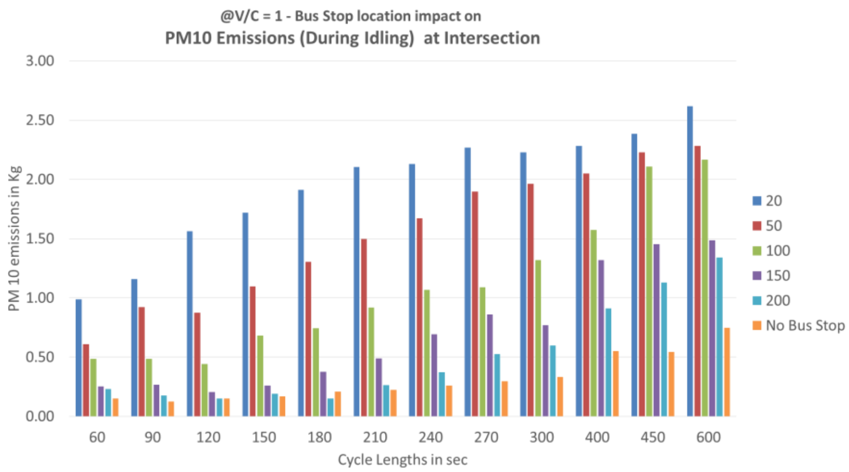


Exhibit 59 Bus Stop Location Impact on Fuel Consumption and PM10 Emissions

The location of the bus stop should be such that it is as close to the intersection without creating spillback (vehicles backing up) into the intersection. For example:

- Assume bus stopping at the stop reduces the downstream capacity by half,
  - If output is 2 veh/ 2 sec, it becomes 1 veh/2sec when bus stops. Hence, queue starts building up from the bus at the rate of 0.5 veh/sec. So, in 30 seconds of upstream green the queue will build up 30 * 0.5 * 4.5 (if all vehicles are cars) = 67.5 meters
- In this scenario, if the green feeding the bus stop approach is 30 seconds, the bus stop should be around 70 meters downstream of the intersection
- then the green split feeding the downstream approach to the bus stop should be less than

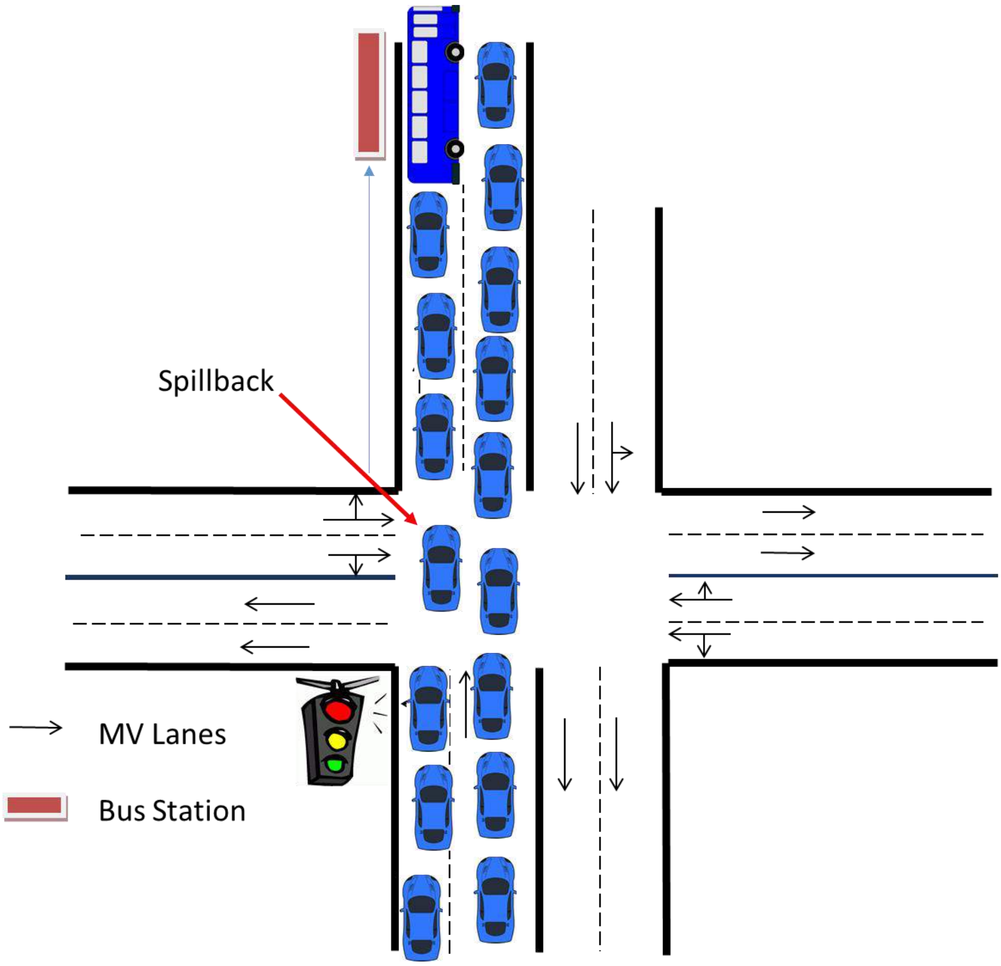


Exhibit 60: An Illustration of Bus Stop Location and Spillback

Recommendation: Bus Stop Location & Cycle Length

1. Shorter cycle lengths support reducing spillback from intersection especially when bus stops are located downstream of the intersection.

2. Even for upstream bus stops, having bus stops close to the intersection will lead to green starvation. Here too, the bus stop location should be far enough upstream that the queue in front of the bus will get dissipated during the green.

3. When a bus is stopped, depending on capacity reduction – the split should be adjusted. Which in-turn should define the cycle length.

4. No stopping (bus or otherwise) should be allowed withi 15 meters of a junction. This distance should increase based on the volumes and geometry at the location.

Q16. What other elements impact congestion?

One of the most disappointing aspects of infrastructure maintenance is the time taken many-a-times to fix potholes. While potholes cause safety issues and should be fixed immediately, another aspect is their impact on delays, queue lengths, throughput, stops, fuel consumption and emissions. Depending on the location, width and depth of a pothole, a pothole can reduce the capacity of an intersection substantially as shown in the plots below.

In general, any geometric (lane reduction, potholes, etc.) or operational element (parked vehicle, etc.) that can result in reducing speeds of an approach should be immediately dealt. The level of damage of road surface also have different impact of delay which is evaluated w.r.t. desired speeds of 10 Kmph and 5 Kmph at potholes. The below exhibit shows the impact of potholes on average intersection delay for the v/c of 1.0 and for cycle lengths from 60 to 150 sec. The exhibits below show that when a speed on a single lane among three lane approach reduces to 5 Kmph, as seen in many places, the overall intersection delay increases almost 400%. The approach with the pothole could have delays that are much higher.

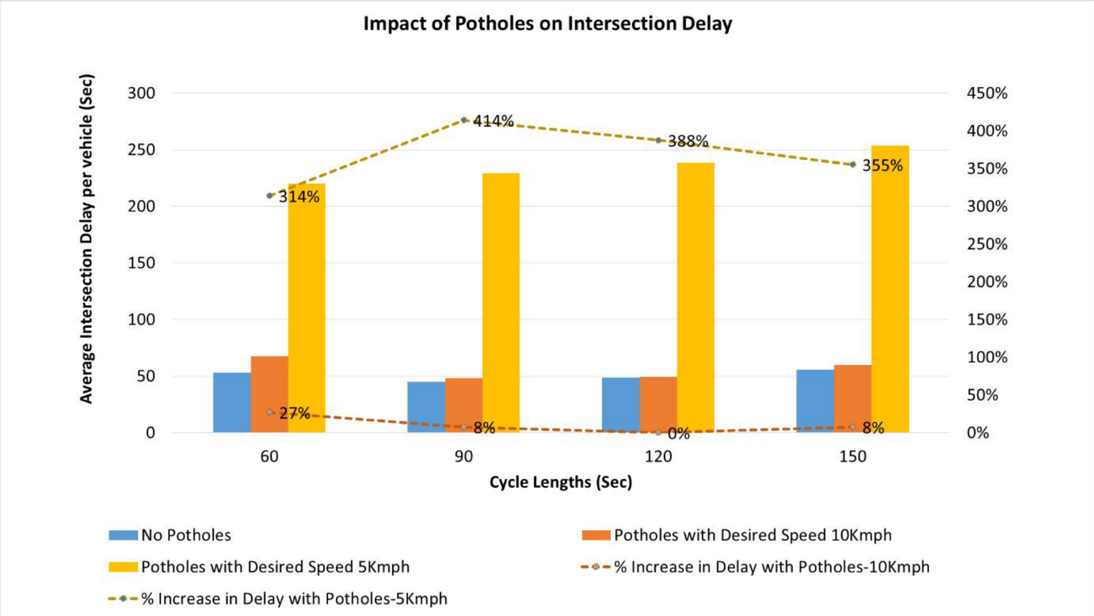


Exhibit 61: Impact of Potholes on Intersection Delay

The below exhibit shows the impact of potholes on average approach delay where the potholes are present for the v/c of 1.0 and for cycle lengths from 60 to 150 sec. The impact is much worse on the approaches as the potholes are present on those approaches. The delays even increased by more than 2000% in case of potholes with desire speed 5 Kmph.

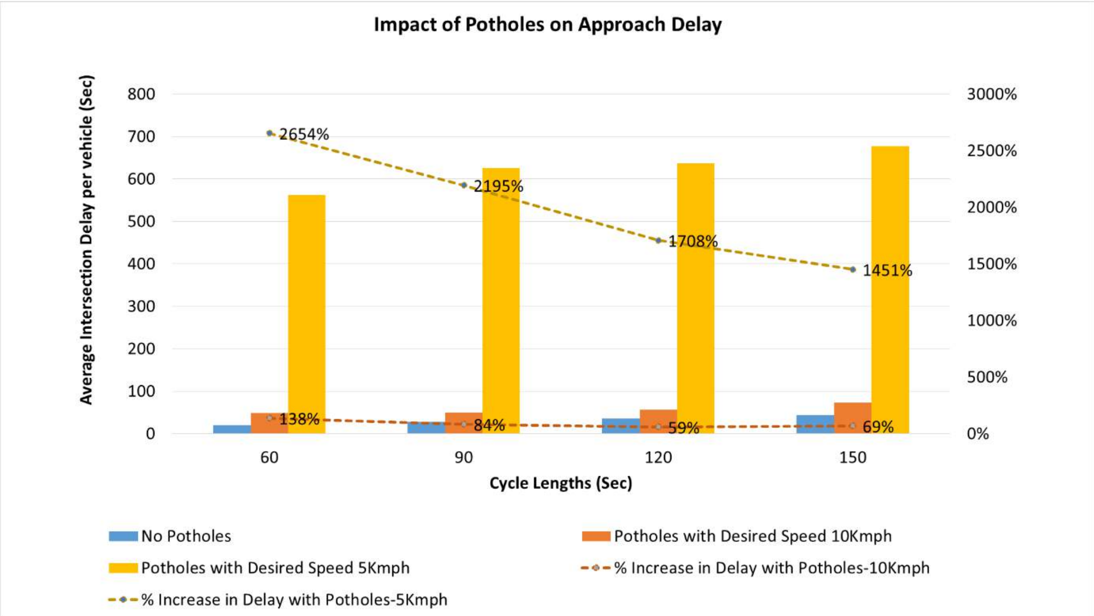


Exhibit 62: Impact of Potholes on Approach Delay

The below exhibits shows the impact of the same potholes on the other measures such as queue lengths, fuel consumption and PM10 emissions.

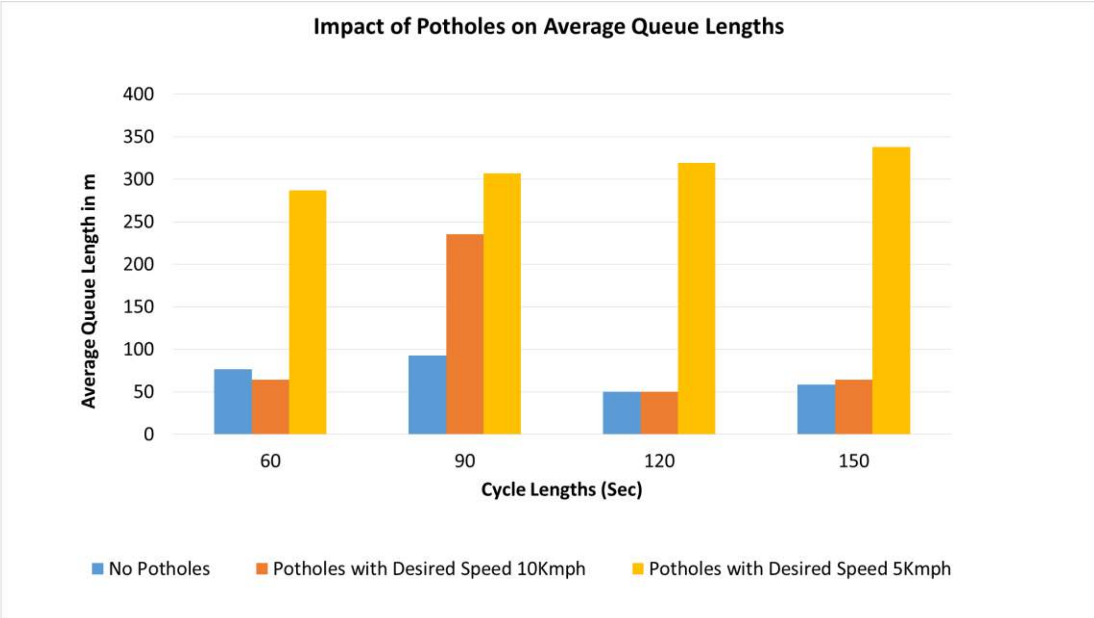


Exhibit 63: Impact of Potholes on Queue Lengths

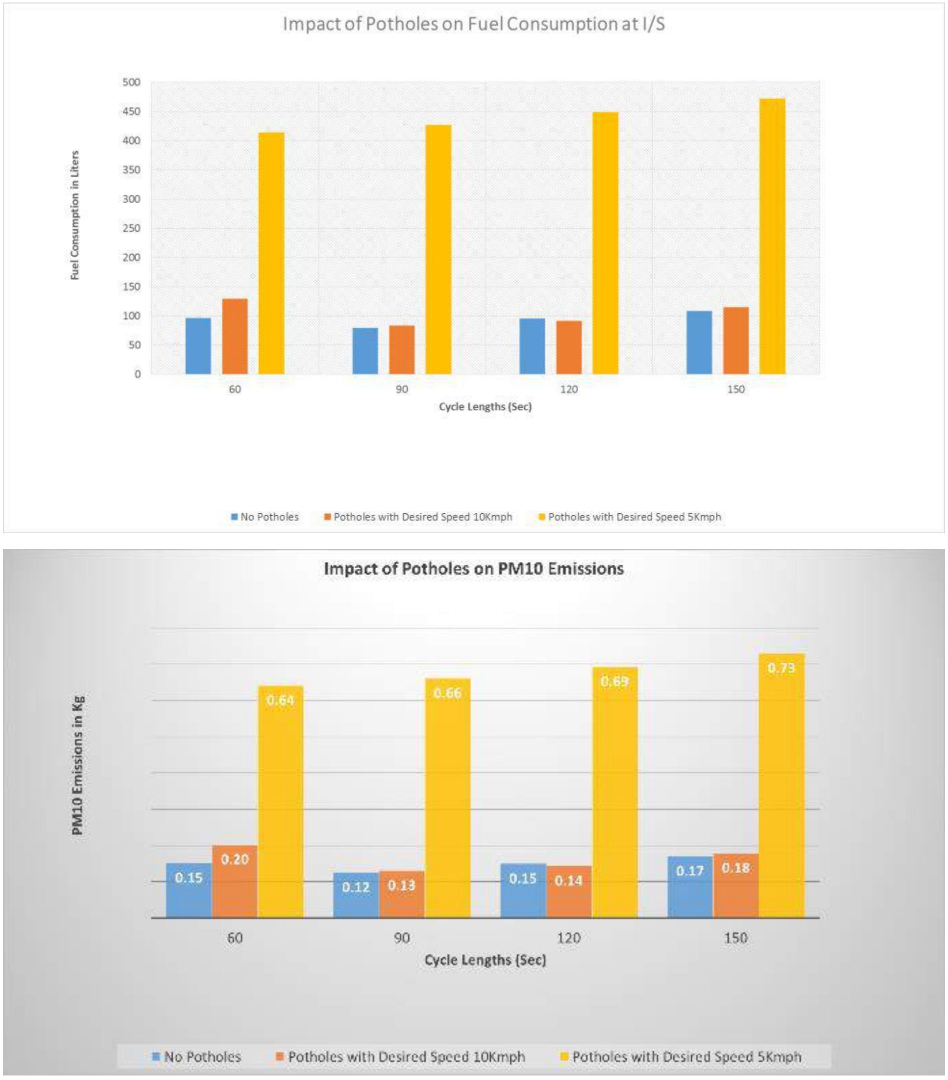


Exhibit 64: Impact of Potholes on Fuel Consumption on Fuel Consumption and PM10 Emissions

Recommendation: Pothole Impact

1. Potholes and other elements that can reduce speeds at an intersection should be immediately dealt.

2. Simulation results show that if the pothole reduces the speed to 5 kmph in a single lane, it can reduce the overall intersection delay by as much as 400%.

Q17. Why lane continuity is important?

It is observed in the field many times that poor geometry exists like lack of continuity in numbers of lanes at upstream and downstream. This kind of lane discontinuity lead to reduction in capacity of the intersection. The same has been demonstrated with the isolated intersection 1 using VISSIM simulation. The isolated intersections with following two cases have been evaluated.

Case A: same number of lanes at upstream and downstream of intersection and

Case B: drop in number of lanes downstream of intersection compared that in upstream

The below exhibit shows the network of isolated intersection with lane discontinuity in EB and WB.

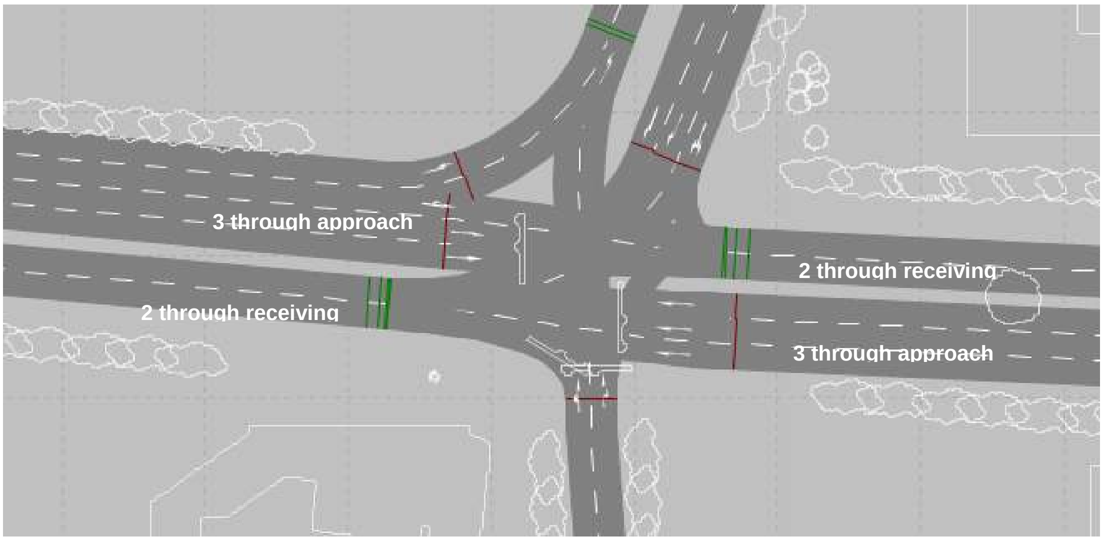


Exhibit 65: Isolated intersection network with lane discontinuity

The results from simulation (as shown in below exhibits) for these two case have shown that there would be an increase of 92% of delay for the above intersection with v/c of 0.75 at 120 sec cycle length.

	With Lane Continuity	With Lane Discontinuity	% of Increase
Intersection Delay per Vehicle (Sec)	35.4	68.0	92%
Average queue length (m)	31.1	112.3	261%
Movement: From Varthur@703.3 - 2: To Marathahalli@4.5			
Number of Lanes on Approach	3	3	-

	With Lane Continuity	With Lane Discontinuity	% of Increase
Number of Lanes on Exit	3	2	-
Movement Delay (Sec/Vehicle)	30.9	64.3	108%
Movement: From Marathahalli@603.3 - 5: To Varthur@6.7			
Number of Lanes on Approach	3	3	-
Number of Lanes on Exit	3	2	-
Movement Delay (Sec/Vehicle)	32.4	72.1	122%

Exhibit 66: Impact of lane discontinuity on intersection delay

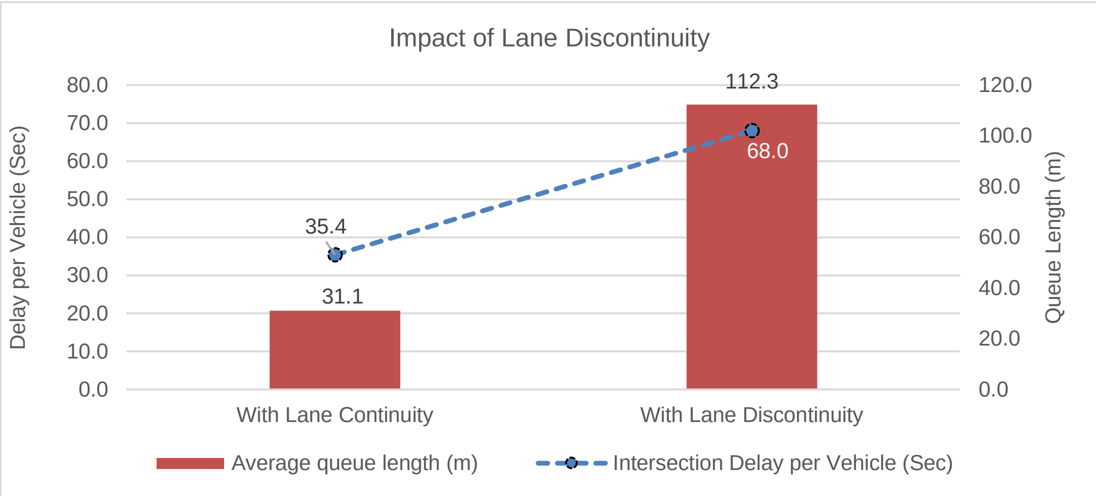


Exhibit 67: Impact of lane discontinuity on intersection delay

Recommendation: Impact of lane discontinuity

1. Lane discontinuity reduces performance of intersection by increasing the delay as high as around 90%. Hence, maintenance of lane continuity is very critical w.r.t. geometry of intersection.

4.4 Subject Area: Education

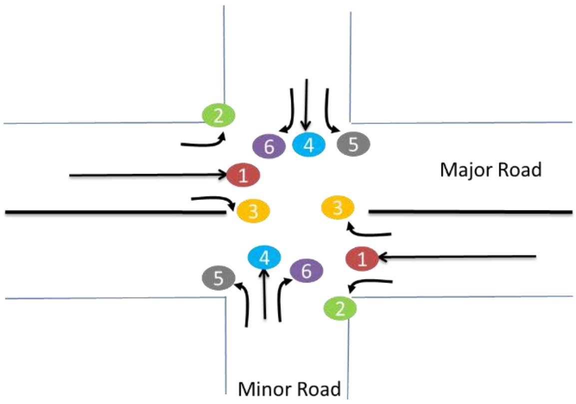
Q18. During non-peak hours, when the intersection in on flashing amber/yellow, who gets priority?

While the lack of discipline remains a serious problem across all Indian cities, the long term solution cannot be the deployment of traffic police at all signalized and un-signalized intersections. Various health professionals including World Health Organization (WHO) have recognized **traffic police are highly vulnerable to several respiratory diseases** due to long term exposure to outdoor air pollution[10].

Considering the health of traffic police and solution that is sustainable over long term, the following steps are recommended:

Education before Enforcement

- Right-of-way rules



- Traffic control
- Setting user expectancy
- Education before enforcement

[10] *http://timesofindia.indiatimes.com/city/nagpur/Traffic-cops-falling-prey-to-lung-diseases/articleshow/47620826.cms*

4.5 Signal Phasing & Bus Rapid Transit

Bus Rapid Transit is finally gaining popularity in India. One of the main challenges for BRT remains the flow of the BRT bus through the signal. Since, median BRT is more efficient than kerb-side BRT; in a typical situation BRT add one or two more phases to an intersection. As stated earlier, the objective at any signalized intersection remains the reduction of phases. This section provides some of the common intersection geometrics and possible turn-restrictions that can be applied to reduce the number of phases and improve the efficiency of BRT. The alternative phasing plans for intersections with BRT are recommended at APPENDIX B.

Junction Type 1: with Shared RT lanes on NB & SB

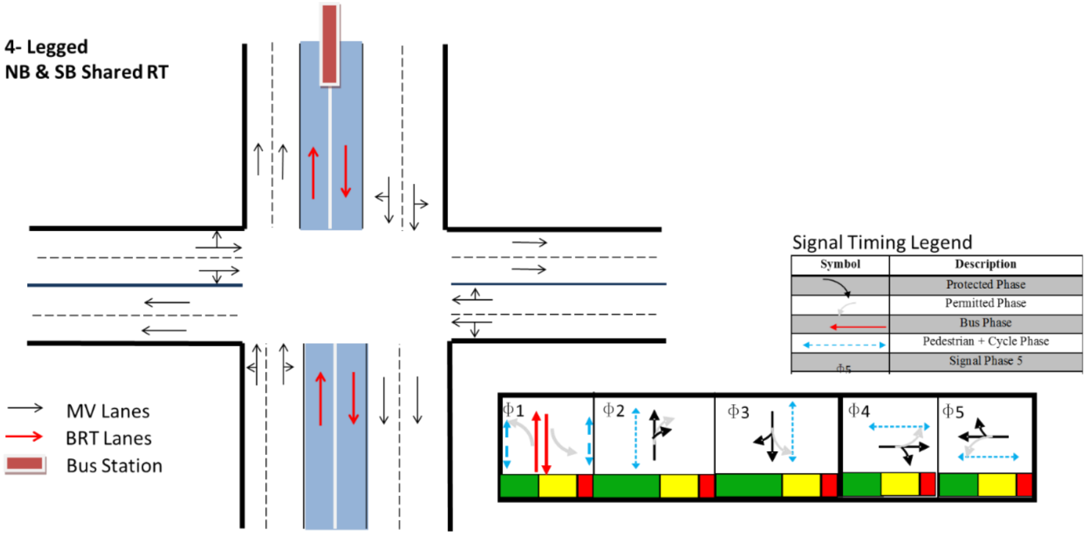


Exhibit 68: Typical phasing option for the 4-legged intersection (with shared lanes) with BRT

The following are the different alternative restriction treatment which need to be applied based on traffic volumes. The corresponding phasing options are also given for the different turn restriction treatments when BRT movements are present at the intersection on Major Street.

Turn Restriction Treatment

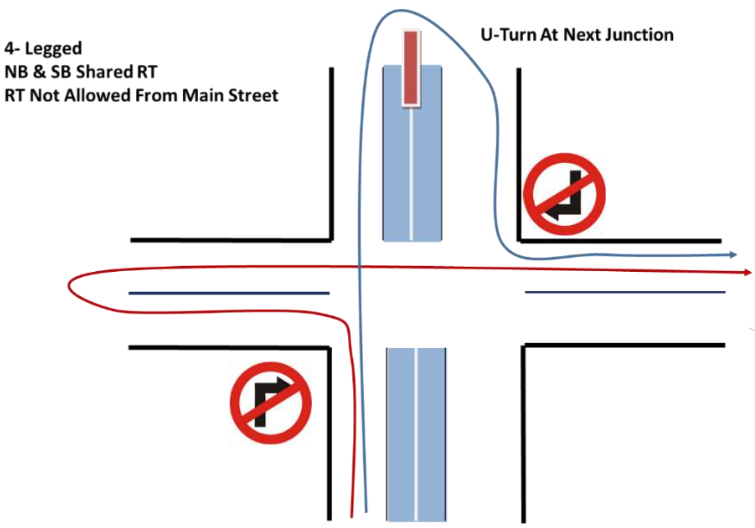


Exhibit 69: Turn restriction (on main street) treatment for the 4-legged intersection (with shared lanes) with BRT

Efficient Phasing for BRT

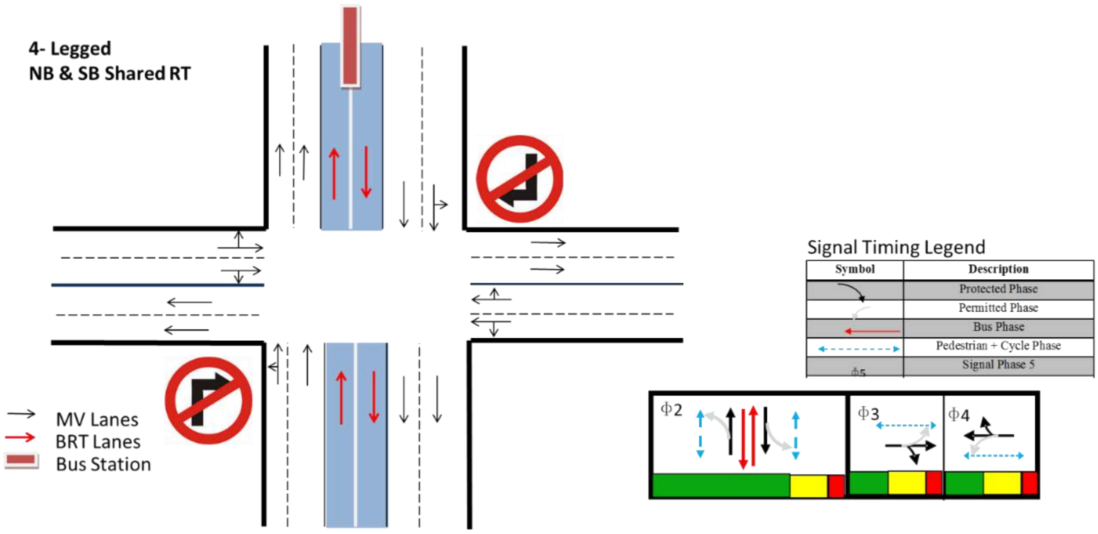


Exhibit 70: Alternative phasing option for the 4-legged intersection (with shared lanes) with BRT after turn restriction (on main street) treatment

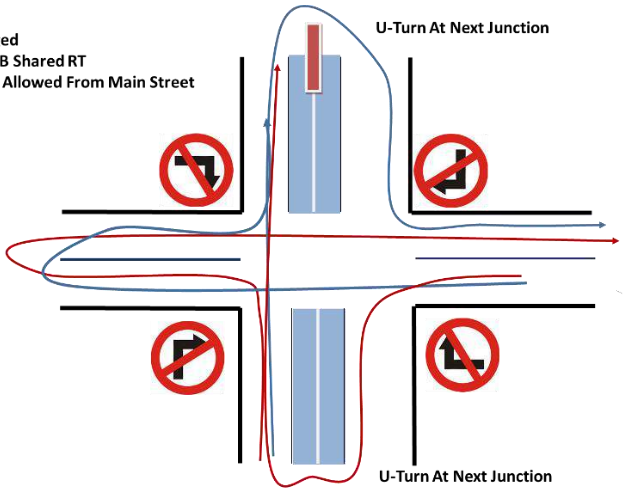


Exhibit 71: Turn restriction (on main & minor street) treatment for the 4-legged intersection (with shared lanes) with BRT

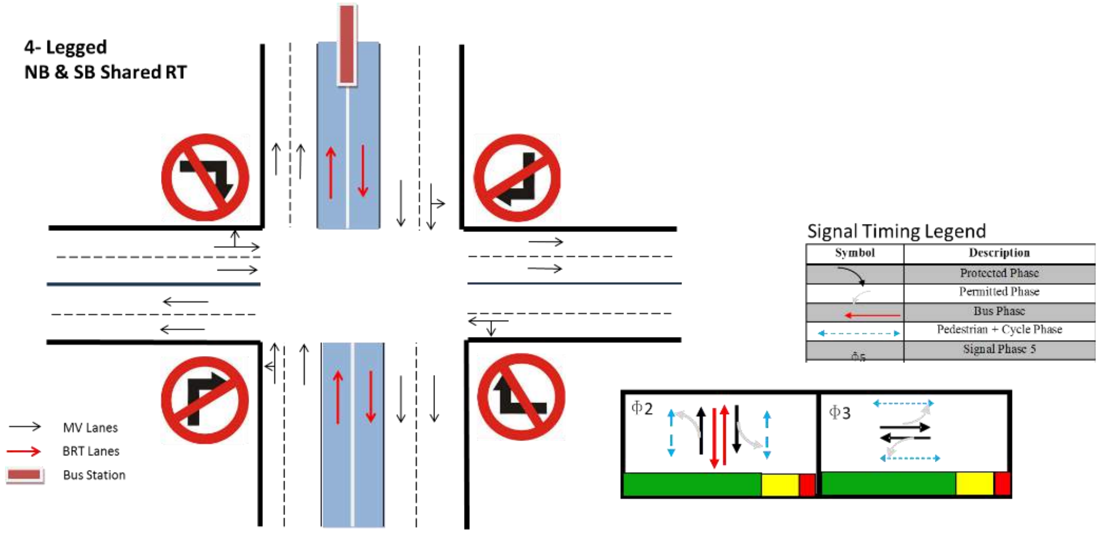


Exhibit 72: Alternative phasing option for the 4-legged intersection (with shared lanes) with BRT after turn restriction (on main and minor street) treatment

Junction Type 2: with exclusive RT lanes on SB and NB

Typical Phasing

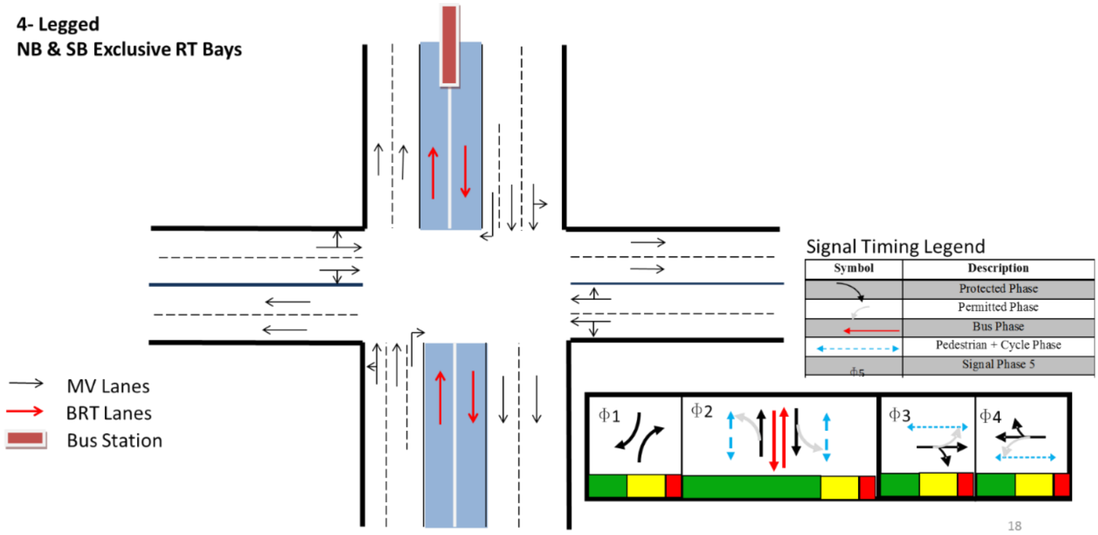


Exhibit 73: Typical phasing option for the 4-legged intersection (with exclusive RT lanes) with BRT

Turn Restriction Treatment

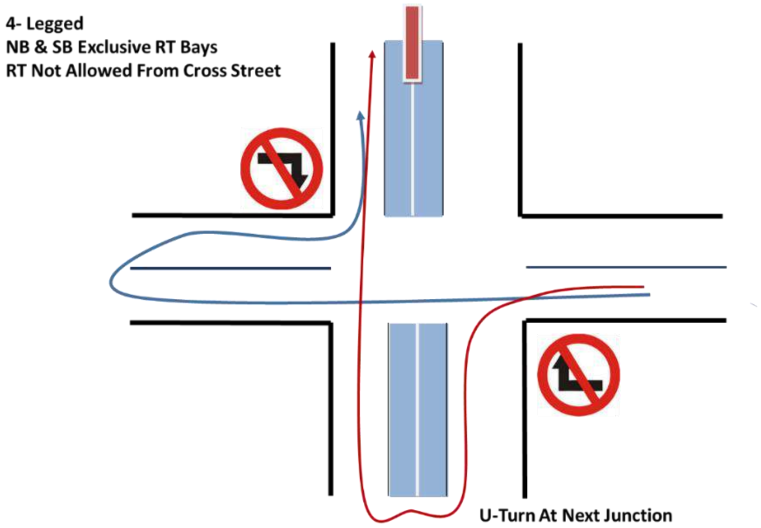


Exhibit 74: Turn restriction (on main street) treatment for the 4-legged intersection (with exclusive RT lanes) with BRT

Efficient Phasing for BRT

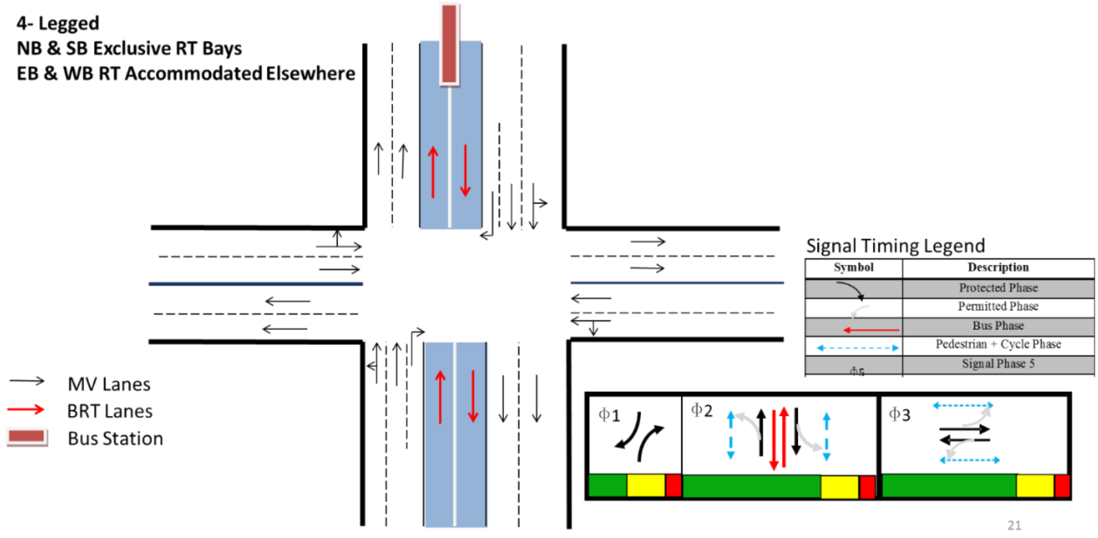


Exhibit 75: Alternative phasing option for the 4-legged intersection (with exclusive RT lanes) with BRT after turn restriction (on main street) treatment

Junction Type 3

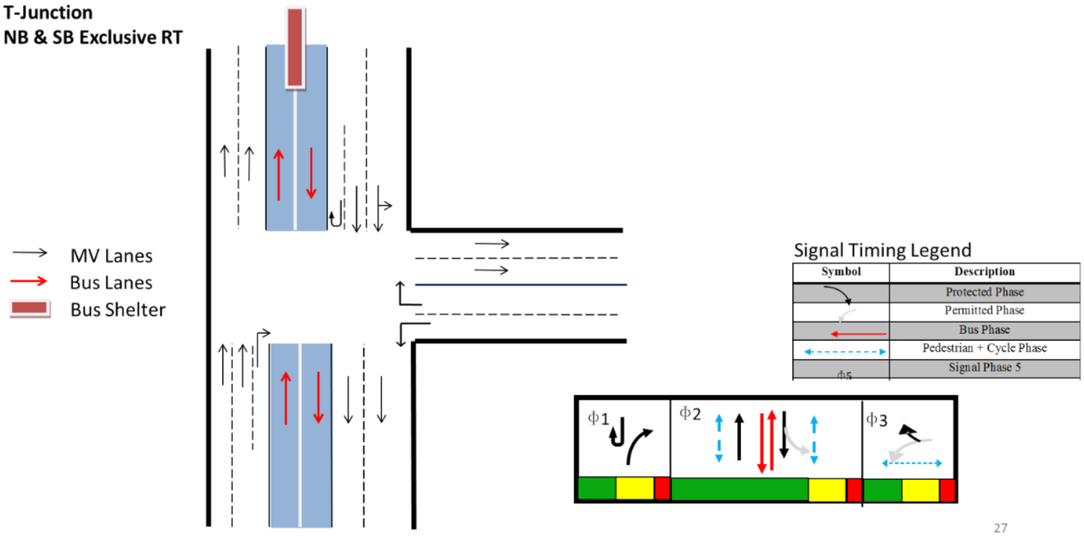


Exhibit 76: Typical phasing option for the 3-legged intersection (with exclusive RT lanes) with BRT

Junction Type 4

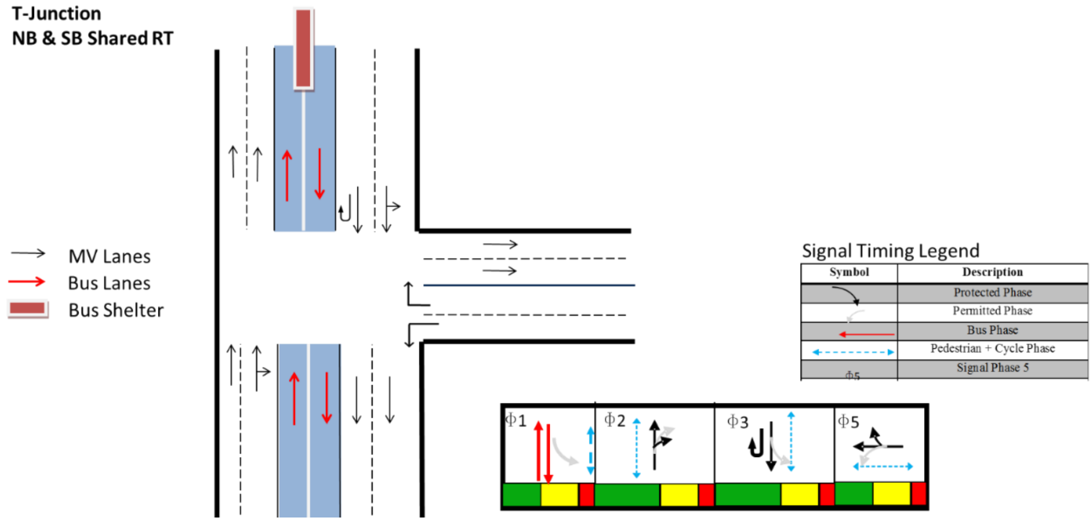


Exhibit 77: Typical phasing option for the 3-legged intersection (with shared RT lanes) with BRT

Turn Restrictions

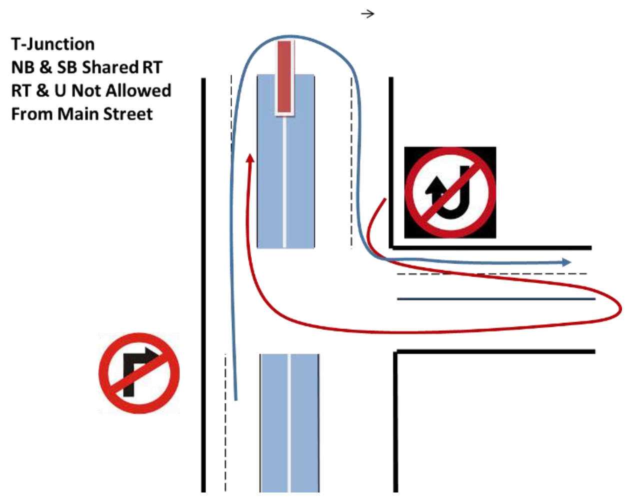


Exhibit 78: Turn restriction (on main street) treatment for the 3-legged intersection (with shared RT lanes) with BRT

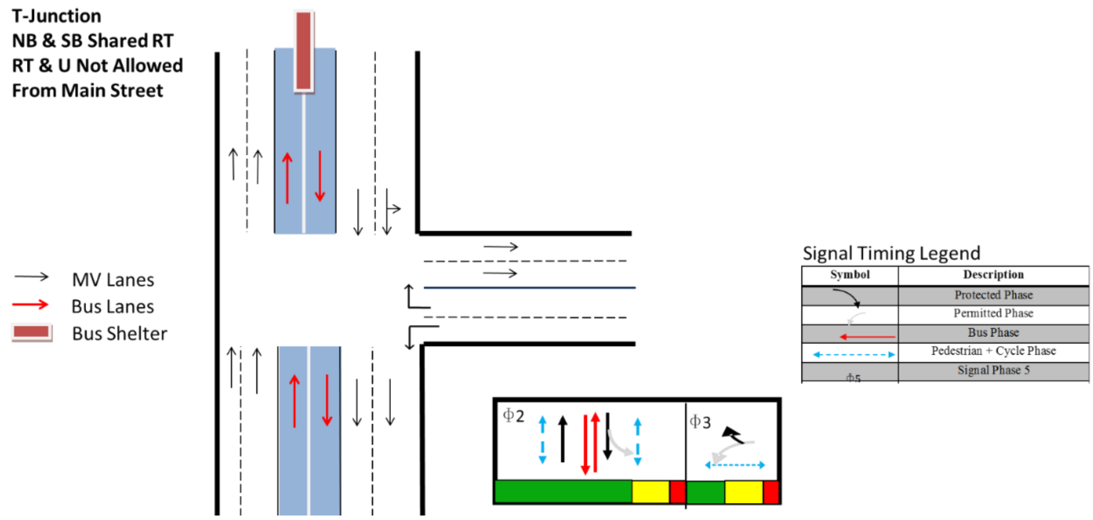


Exhibit 79: Alternative phasing option for the 3-legged intersection (with shared RT lanes) with BRT after turn restriction (on main street) treatment

Appendix A – Adaptive Traffic Signal Control System (ATSC)

5 Adaptive Control Analysis

5.1 Adaptive Traffic Signal Control System (ATSC)

Adaptive Traffic Signal Control (ATSC) has the potential to efficiently alleviate traffic congestion by adjusting the signal timing parameters in response to traffic fluctuations to achieve a certain objective (e.g. to minimize delay); therefore it has a great potential to outperform both pre-timed and actuated controls (McShane et al., 1998). Several ATSC systems have been implemented worldwide. ATSC, in general, evolved through 4 generations of research and development. The basic premise on which ATSC works is illustrated in Exhibit 80.

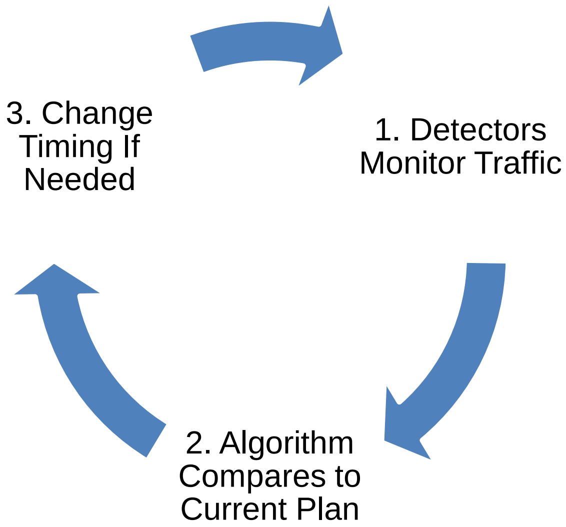


Exhibit 80: ATSC Process

5.1.1 ATSC Benefits

The Key benefits of ATSC include[11]:

- Improved service to road users: since the ATSC algorithm constantly evaluates the current timings and adjusts it, there are improvements in:
  - Congestion
  - Travel Time Reliability
  - Fuel Consumption
- Reduces complexity of management to traffic police and operations personnel by:
  - Reduces Complaints
  - Address variability & unpredictability in demand
- Provides long term value by reducing
  - Retiming costs which is generally required every 3 years
  - Reduces Emissions by reducing stops
  - Enhances Safety by timing as per demand.

[11] *Adaptive Signal Control Technology Overview, Eddie Curtis, FHWA, http://www.nc-ite.org/images/files/Adaptive%20Signal%20Control%20Technology%20Overview%20Presentation.pdf*

The impact of retiming every 3 years vs. having a fine tuned adaptive system is illustrated in Exhibit 81.

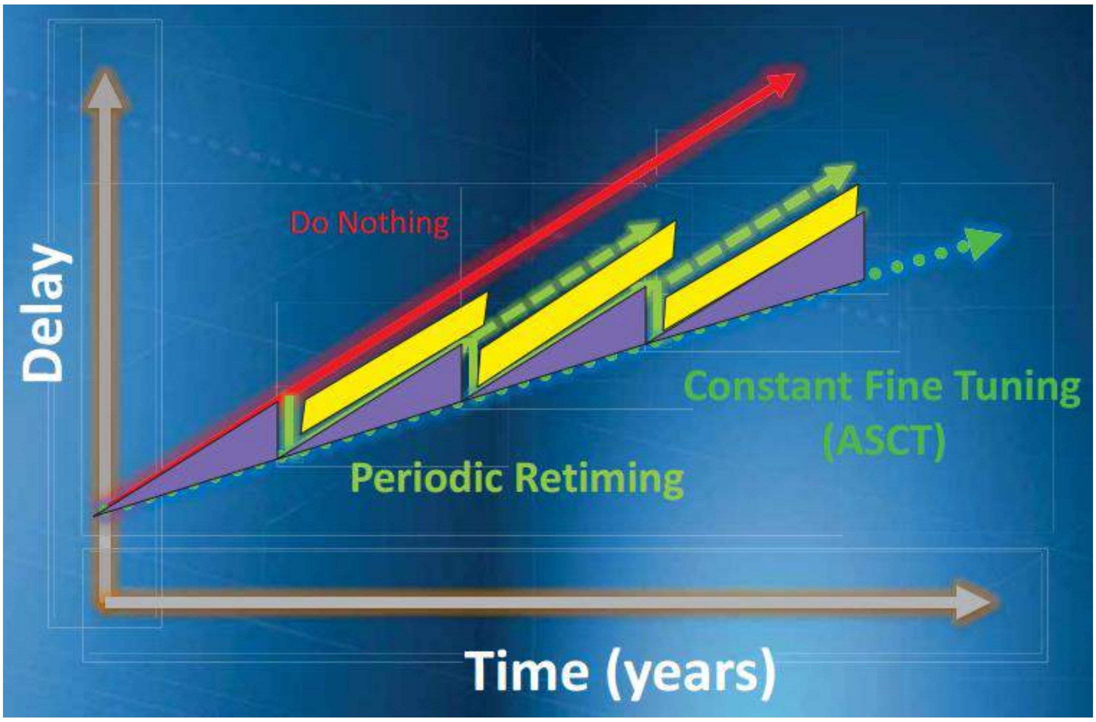


Exhibit 81: Adaptive Signal Control Technology (ASCT) Benefits for Delay[11]

5.2 ATSC Systems

The popular adaptive control systems across the world are listed here with a brief description. Greater detail on the systems used in India is provided in the next section.

S.No.	ATSC System	Description
1	SCOOT[12]	Split Cycle Offset Optimisation Technique (SCOOT) is a leading adaptive traffic control system. It coordinates the operation of all the traffic signals in an area to give good progression to vehicles through the network. In SCOOT, optimization of traffic control in the network is achieved using small, regular changes in signal timings designed to avoid major disturbance of traffic flow. SCOOT systems continually sends data from detection devices to controller for congestion check. With the help of these data, it tries to express traffic demand by making Link Profile Units (LPU), which is a hybrid measure of volume and occupancy. These LPUs are then processed to create Cyclic Flow Profile (CFP) of the platoons. Through CFPs, a model of traffic demand at the stop line (queue on the approach) is predicted.
2	SCATS[13]	Sydney Coordinated Adaptive Traffic System (SCATS) is a fully adaptive urban traffic control system that optimises traffic flow. Its self-calibrating software minimises manual intervention, which can result in substantial operational cost savings. The SCATS system consisting of hardware, software, and a unique traffic control philosophy that operates in real time; adjusting signal timings in response to variations in traffic demand and system capacity as they occur. Rather than changing individual intersections in isolation, SCATS manages groups of intersections that

[12] *http://www.scoot-utc.com/*
[13] *http://www.scats.com.au/*

S.No.	ATSC System	Description
		are called "subsystems," the basic unit of the system.
3	RHODES[14]	Real-time Hierarchical Optimizing Distributed Effective System (RHODES) uses three-level hierarchy for characterizing and managing traffic. It explicitly predicts traffic at these levels utilizing detector and other sensor information. • The highest level is a "dynamic network loading" model that captures the slow-varying characteristics, which pertain to the network geometry and the typical route selection of travelers. • Based on the traffic load on each particular link, RHODES allocate green time for each demand pattern and each phase. These decisions are made at the middle level of the hierarchy, referred as "Network flow control." • Given the approximate green times, the "intersection control" at the third level selects the appropriate phase change epochs based on observed and predicted arrivals of individual vehicles at each intersection. RHODES requires (a) lane traffic data (e.g., through sensors), (b) real-time communication to/from processors, and (c) PC-level computational capability.
4	OPAC	Optimized Policies for Adaptive Control (OPAC) is a distributed real-time traffic signal control system which continuously adapts signal timings to minimize a performance function of total intersection delay + stops over a pre-specified horizon. It can operate as an independent smart controller, or as part of a coordinated system.
5	ACS-LITE[15]	Adaptive Control Software-Lite (ACS Lite) is a reduced-scale version of the adaptive system ACS, which required extensive detection. The system objective was to offer small and medium-sized communities a low-cost traffic control system that operates in real time, adjusts signal timing to accommodate changing traffic patterns, and eases traffic congestion. ACS Lite can be used with new signals or to retrofit existing traffic signals. It is designed for providing cycle-by-cycle control to closed-loop systems, which represents 90% of the traffic signal systems in the United States. The effectiveness of two offset settings at upstream and downstream intersections is measured or quantified by calculating the progressed flow or captured flow. This performance measure is a surrogate for vehicle stops and delay, which cannot be directly measured in the field from point detectors. Specifically, the captured or progressed vehicular flow is the amount of flow (in units of vehicle-seconds of occupancy) arriving at the stop line at a given point in the cycle multiplied by the percent of time the progression phase is green at that time during the cycle. The algorithm evaluates different offsets by calculating the captured flow on each approach and selecting the offset that maximizes the total amount of captured flow.
6	ITACA[16]	Intelligent Traffic Adaptive Control Area (ITACA) offers real-time response to current and future traffic flow demands, and brings 'intelligence' to fixed-time pattern control approaches. It incorporates: (1) an adaptive system, which is used to evolve the best plan at each junction; and (2) an expert system, which can use all the adaptive system's data and predictions to obtain a global solution for the total

[14] *http://ocw.nctu.edu.tw/course/sc011/2012-08-23-1.pdf*
[15] *http://trrjournalonline.trb.org/doi/abs/10.3141/2035-01?journalCode=trr*
[16] *http://trid.trb.org/view.aspx?id=462715*

S.No.	ATSC System	Description
		traffic plan. This solution is communicated to the adaptive system by a sophisticated use of importance (weight) factors. The adaptive system has cycle, split, and offset optimisers, and uses profiles to update the road network model. The model's components include: (1) queue lengths; (2) congestion indicator; (3) load; and (4) saturation flow modifier. The expert system is an optional part of ITACA, which uses the model's current network data and its rules to adjust the weights of each traffic movement. Its most obvious use is to avoid secondary congestion, the blocking of junction exits by downstream queues.
7	InSync[17,18]	The InSync system uses a fundamentally different system of controlling and optimizing signal phases and timings in real- time through an innovative and relatively simple methodology. The InSync methodology can basically be boiled down to three components: • Digital architecture • Global optimization • Local optimization The term "digital architecture" refers to the concept of a finite state machine. A finite state machine has a finite number of states and transitions between those states. As it applies to traffic signals, consider a state to be a pair of non- conflicting phases. There are a finite number of states that are possible. Of these states, there are a finite number of sequences in which those states can be grouped and applied. InSync performs optimization at two levels, the local level and the global level. The global level is focused on creating platoons and moving these platoons through a corridor with the highest level of efficiency possible by focusing on progression. The local intersection is required to serve specific phases associated with the time tunnel based on the global optimizer. This phase may be served by one or more states in a sequence. Outside of the time specified by the global optimizer, each intersection runs its own optimization at the local level. Its optimization algorithm accounts for volume and delay and is based on a modified greedy algorithm. Parameters can be adjusted to give higher priority certain phases, such as when a signal is received from an approaching transit bus.
8	CoSiCoSt	The Composite Signal Control Strategy (CoSiCoSt) developed by CDAC optimizes a weighted combination of delay and number of stops in real-time. CoSiCoSt is designed to cater to the typical Indian driving and traffic conditions such as poor lane discipline and high heterogeneity. CoSiCoSt functions through: • An area being sub-divided into zones or corridors • Corridors operating on common background cycle • Signal timings and Cycle lengths updated dynamically based on real-time demand • Signals synchronized for green-wave • Offset deviation corrected at plan transition • Using stop-line detection with special filters to address poor lane discipline and high heterogeneity

A comparison of features of the US based adaptive control systems is shown in Exhibit 82.

[17] *http://www.westernite.org/annualmeetings/sanfran10/Papers/Session%209_Papers/ITE%20Paper_9A-Siromaskul.pdf*
[18] *http://rhythmtraffic.com/#2*

ATCS Parameter	SCOOT	SCATS	OPAC	RHODES	ACS Lite
Goal	Minimize Performance Index	Minimize Delay and Stops or Maximize Throughput	Minimize Delay and Stops	Minimize Cumulative Delay	Maximize Total Amount of Captured Flow
Detector Layout	Upstream[1]	Stop Bar	Both[4]	Both[5]	Both
Hierarchial Organization	Central	Central, Regional, Local	Synchronization, Coordination, Local	Network Loading, Network Control	Intersection, Regional, Local
Arrival Prediction	Yes	No	Yes	Yes	No
Queue Estimation	Yes	No	Yes	Yes	No
Split Optimization	Yes[2]	Yes	Yes	Yes	Yes
Offset Optimization	Yes3	Yes	Optional	Optional	Yes
Cycle Optimization	Yes	Yes	Optional	Optional	No
Phase Sequence Optimization	No	No	No	No	No
Saturated Condition	Poor	Good	No	No	No

Note:

[1] Detectors deployed at least 300 feet upstream from stop bar.

[2] One third of total split is affected by optimization.

[3] Constraint by sub-area, not affected by congestion.

[4] Upstream detectors deployed at 400-600 feet from stop bar.

[5] Upstream detectors suggested at 325 feet from stop bar.

Exhibit 82: Features of ATSC Systems

5.3 ATSC Systems in India

SCOOT, ITACA and CoSiCoST are the three ATSC systems implemented in India. This section looks at three systems in greater detail along with the strengths and weaknesses.

5.3.1 CoSiCoSt System

CDAC's CoSiCoSt system was developed by CDAC over the past decade and is being improved along with IIT Bombay. The system was implemented in 2007 in Pune at 38 junctions along 6 Corridors in the CBD. While the system improved flows in Pune, it was soon defunct due to the loops being cut. The experiences from Pune and other places made CDAC develop a wireless traffic controller with non-intrusive detection and various other improvements to support actuated and adaptive traffic signal control on Indian roads. CDAC implemented the CoSiCoSt system in Jaipur on 11 signalized intersection on an arterial. The theory behind the distributed network model of CoSiCoSt system is shown in Exhibit 83.

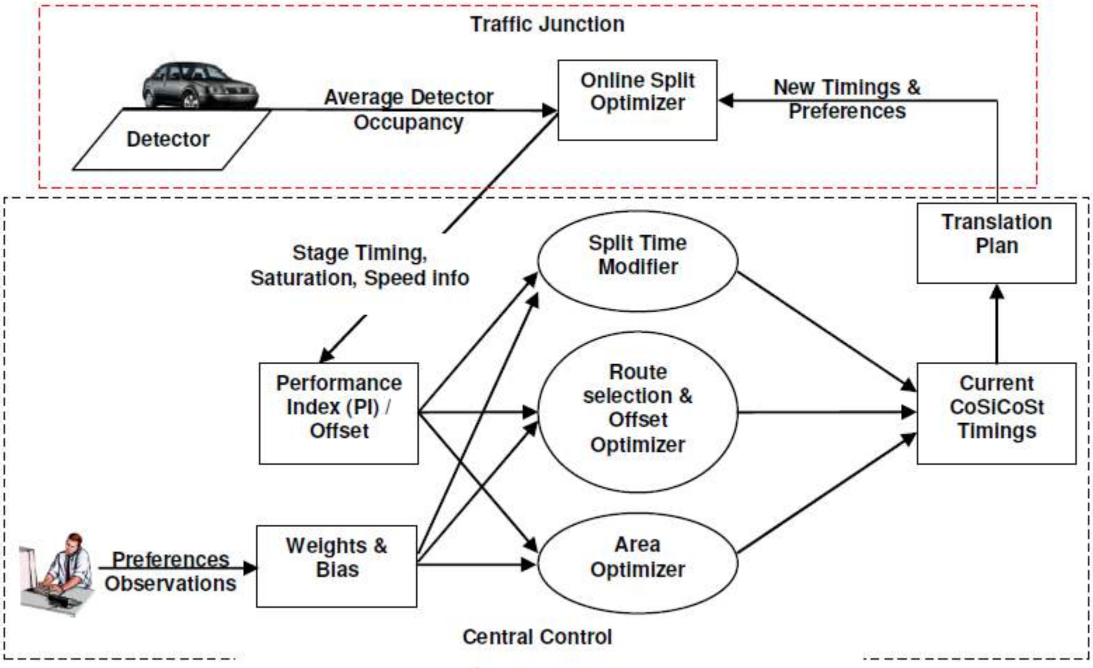


Exhibit 83: CoSiCoSt Network Model (Source: CDAC)

CoSiCoSt addresses the two major issues of existing adaptive control systems for Indian traffic conditions, namely: (1) deriving parameters to address queue service time, and (2) managing the network timing for minimum stops and delays – through a queue exhaustion model built on a Vehicle Actuated (VA) controller. The strengths & weaknesses of the system are as follows:

5.3.2 Strengths

1. CoSiCoSt is the only implemented adaptive control system that has been properly researched in Indian conditions.
2. It integrates theories from other popular adaptive control algorithms like SCOOT and SCATS to ensure that CoSiCoSt system works for the heterogeneous Indian traffic moving without lane discipline. Exhibit 84 shows occupancy in disciplined traffic, while Exhibit 85 shows the same in poor lane discipline. Consideration of these conditions is shown only in CoSiCoSt.

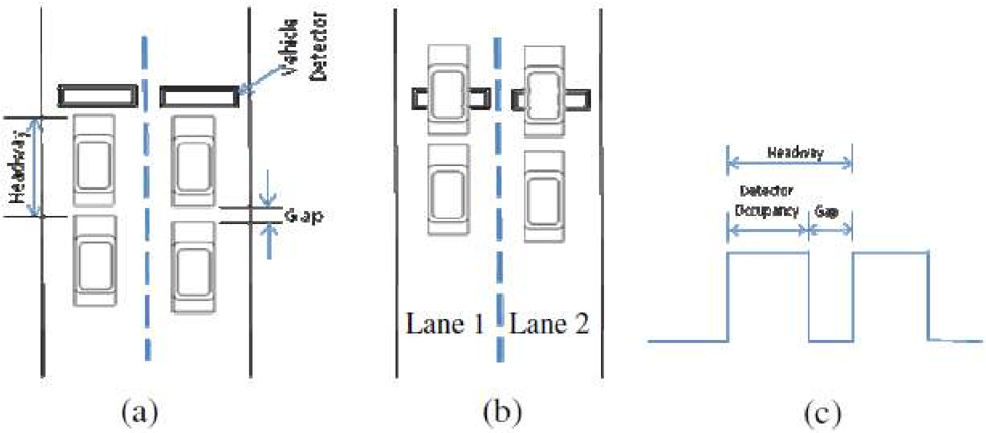


Exhibit 84: Traffic Movement & Detector Output in Disciplined Traffic (Source: CDAC)

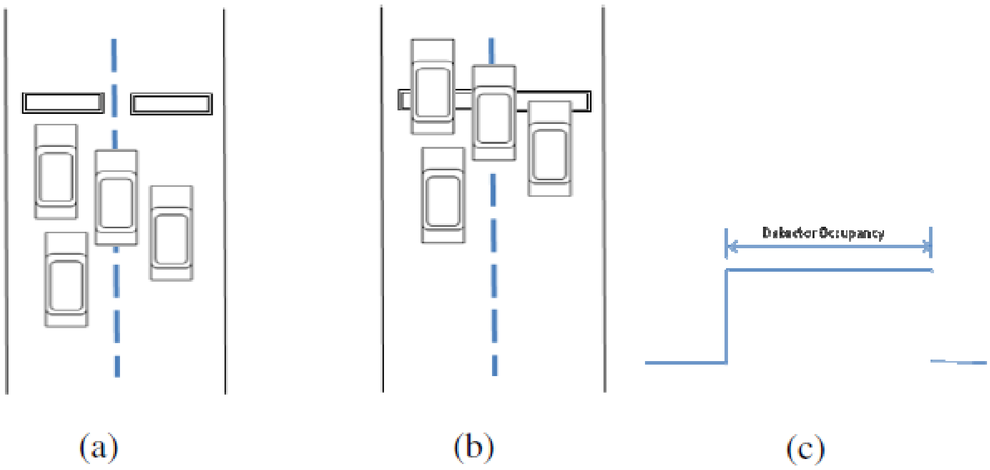


Exhibit 85: Traffic Movement & Detector Output in Poor Lane Discipline (Source: CDAC)

1. Two wheeler traffic is predominant in Indian cities, which is specifically considered in the algorithm development and parameter recommendations, including detector length and location as shown in Exhibit 86.

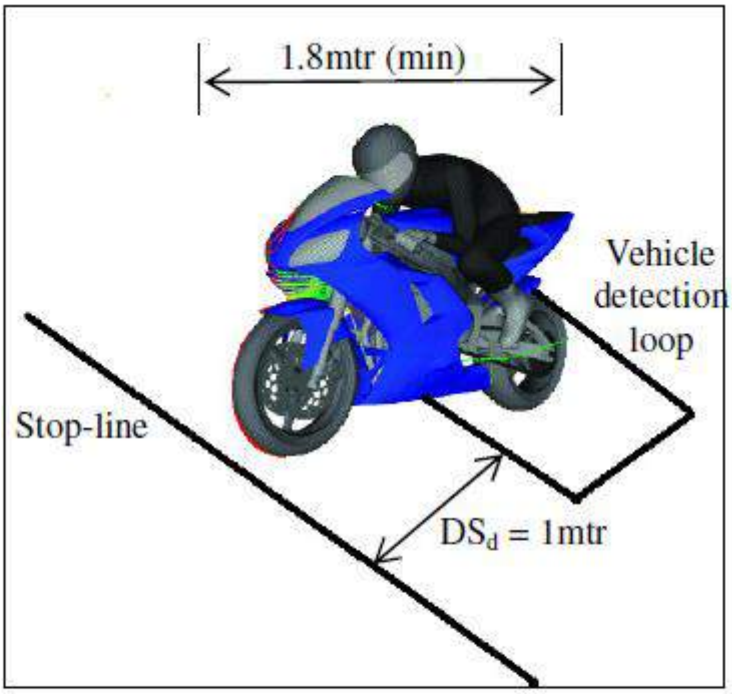


Exhibit 86: Detector Length & Location Recommendations in CoSiCoSt (Source: CDAC)

2. Use of non-intrusive camera detection ensures that the practical problem of cutting of roads does not happen. Improvements were made by CDAC to ensure that detection during twilight hours by camera detection was enhanced.
3. Wireless Controller (WiTraC) is also enhancement provided by CDAC for CoSiCoSt which ensures that no cable needs to run between controller and traffic lights.
4. If central control to the signal is lost (communication failure), the system will run in vehicle actuated (VA) mode which is an improvement over SCOOT, which runs it in fixed mode.

5. Solar power can be used for running the system. CDAC has been successfully running signals using solar power for the past three years in Thiruvananthapuram and almost two years in Pune. They were also running the system in Indore for the past six months on solar power.
6. Seven vendors are available for procurement of the CoSiCoSt system in India.

5.3.3 Weaknesses

1. CoSiCoSt was implemented sparingly in Pune before the detectors were cut by other agencies doing road work. It has only recently been implemented in Jaipur on 11 intersections. Essentially, it is not a fully mature model like SCOOT, SCATS or ITACA which have been implemented for many years in multiple locations across the world.
2. The user interface is not as evolved as SCOOT and ITACA system's interface.
3. The controller available from CDAC is only the WiTrac system (Master and Slave system), which needs to be used even if wired connectivity can be provided at the intersection.

5.4 ITACA System

Televent's (currently Schneider Electric) adaptive control algorithm was implemented at 250 signals in Mumbai. ITACA offers real-time response to current and future traffic flow demands, and brings 'intelligence' to fixed-time pattern control approaches. It incorporates: (1) an adaptive system, which is used to evolve the best plan at each junction; and (2) an expert system, which can use all the adaptive system's data and predictions to obtain a global solution for the total traffic plan. This solution is communicated to the adaptive system by a sophisticated use of importance (weight) factors. The adaptive system has cycle, split, and offset optimizers, and uses profiles to update the road network model. The Mumbai Area Traffic Control System (ATCS) schematic is as shown in Exhibit 87.

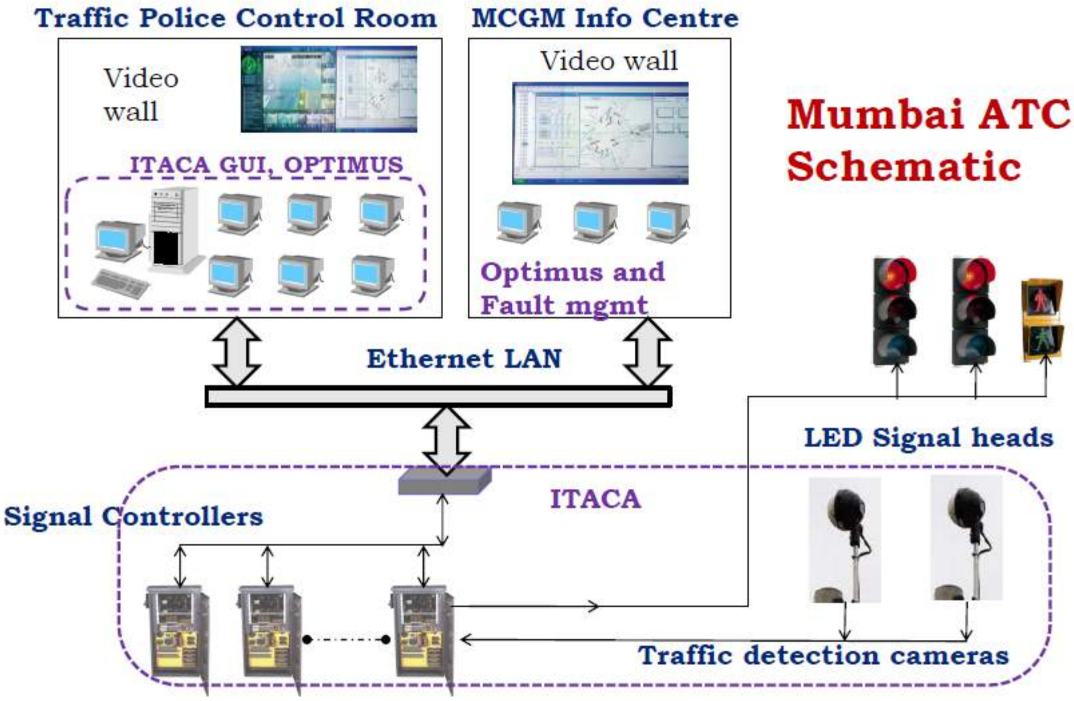


Exhibit 87: Mumbai Area Traffic Control Schematic (Source: MCGM & Schneider Electric)

5.4.1 Strengths:

1. The only adaptive system in India that was applied on such a wide scale of 250 intersections.
2. Algorithm similar to SCOOT, which is a well-established adaptive control software.
3. Extremely robust fault management system that is being leveraged by MCGM to ensure close to 100% availability of traffic signals.
4. MCGM is happy with the system and planning to expand to the rest of the city.
5. The system can fall back to vehicle actuated mode if communication failure occurs from central control.

5.4.2 Weaknesses

1. The system mainly being used as fault management system in Mumbai rather than a Adaptive Control System - as shown in Exhibit 88, very little activity happening on improving the performance of the system for traffic flows.
2. Regular performance monitoring of traffic is not occurring to help take advantage of all the adaptive capabilities of the system. This is felt was due to lack of qualified resources available on the project.
3. The system requires upstream detection, which was a concern since at many locations trees and parking were happening in the Mumbai scenario.
4. Only Schneider Electric provides the ITACA system in India

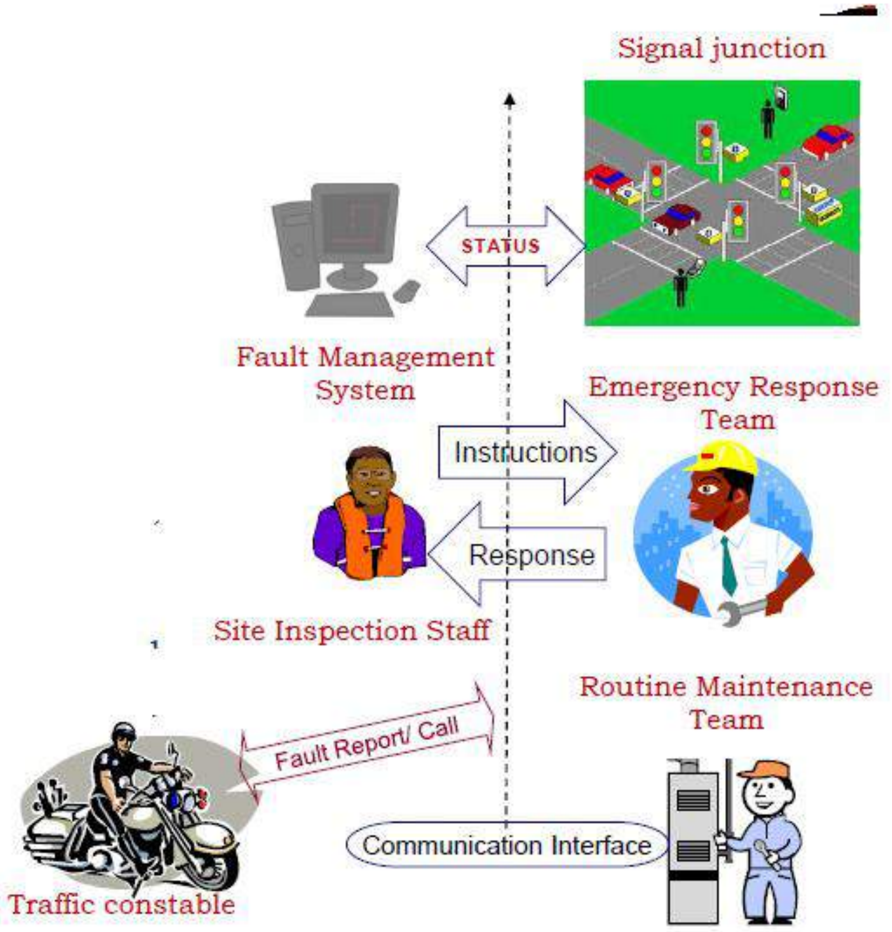


Exhibit 88: Features of MCGM Control Room

5.5 SCOOT System

SCOOT was implemented on the BRT Corridor between Ambedkar Nagar and Moolchand intersections in 2009. It was earlier implemented in Delhi in the CBD area in the 1990s. SCOOT is based on real time application of the popular signal optimization model, TRANSYT. It uses a combination of upstream detection with platoon dispersion to optimize green splits, cycle length and offset. Exhibit 89 illustrates the process.

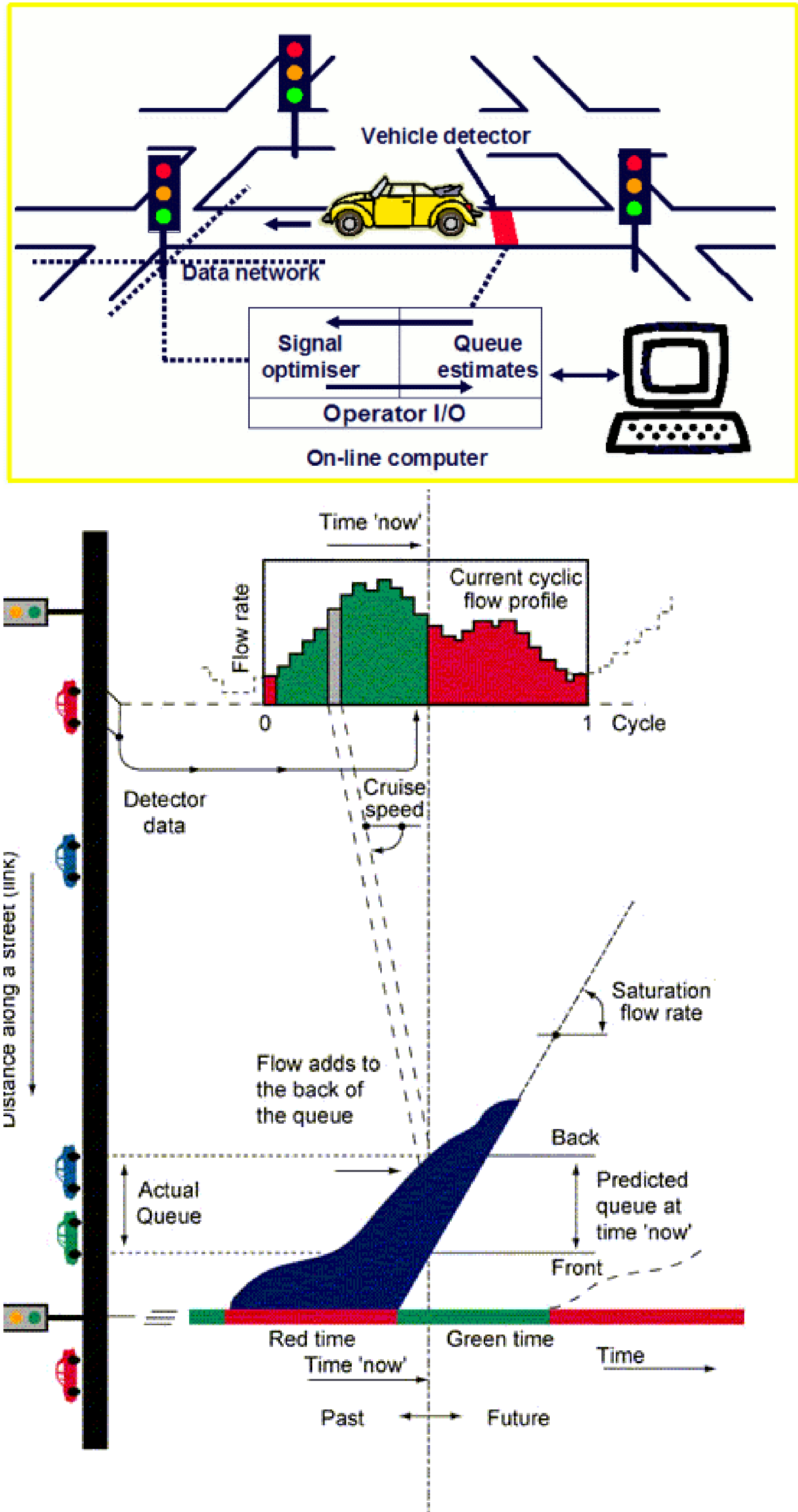


Exhibit 89: How Scoot Works (Source: www.Scoot-utc.com)

5.5.1 Strengths

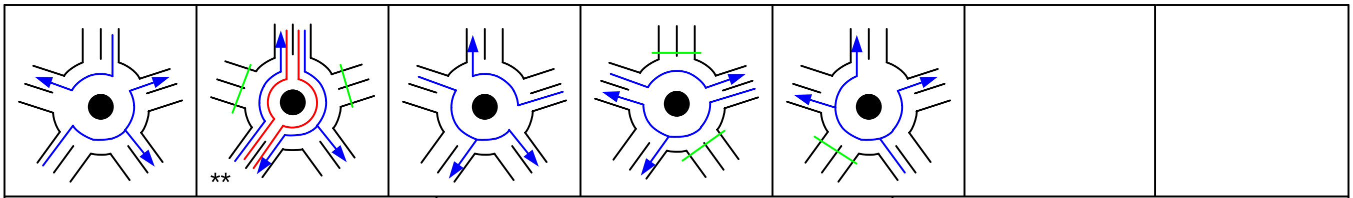
1. SCOOT has by far the most installations in the world boasting of more than 200 installations across the world.
2. It was first installed in 1960s, which makes it a very mature application.
3. SCOOT has proven record of reducing traffic delays of up to 30% compared to Vehicle Actuated signals in many locations across the world.
4. SCOOT's bus priority module is a proven solution.

5.5.2 Weaknesses

1. There were two implementations of SCOOT in Delhi; both of them have not been successful.
2. DIMTS, the latest to implement SCOOT on the Delhi BRTS Corridor mentioned that SCOOT is not appropriate for India due to the need for lane discipline for it to provide optimum results - which does not exist in India.
3. Upstream detection requirements means greater enforcement to ensure no parking happens at the upstream detector locations.
4. SCOOT reverts to fixed time, when communication failures happen.
5. Expertise in traffic engineering is required to operate the system.
6. Only Siemens and Peak provide the SCOOT system.

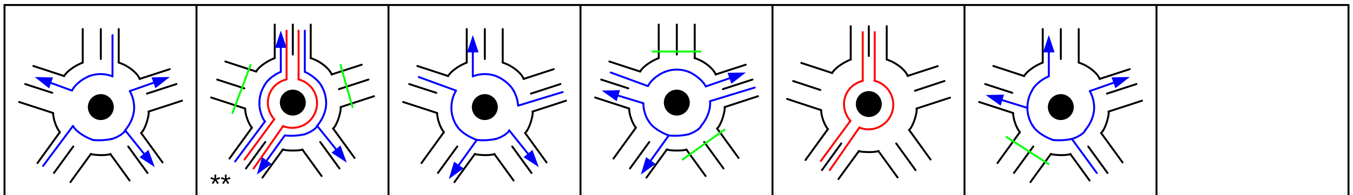
Appendix B – Alternative Phasing Plans for Intersections with BRT

Signalized 5-Leg Roundabout



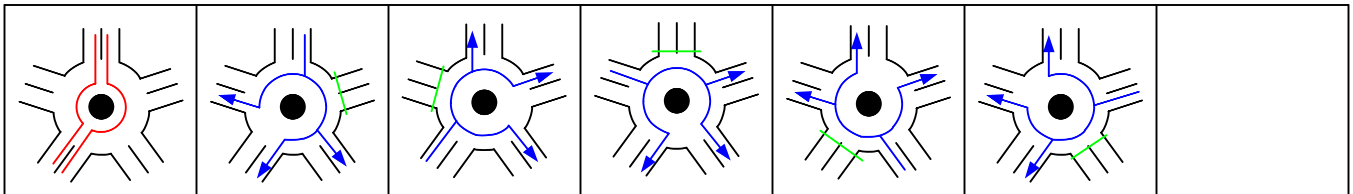
Applicability		Advantages		Disadvantages	
When right turn volumes are balanced	●	Two opportunities to pass BRT vehicles		Increases Cycle Length	
When a right turn volume is higher		BRT delay is reduced		Decreases Overall Capacity	
When overall v/c ratio is low		Minimizes number of stages	●	Allows contra-flow operation	●
When special coordination is needed		Reduces clearance time requirements		Requires dedicated right turn lanes	●
When right turn lanes are not possible		Avoids BRT mixed with general traffic		Long Clearance times	●
** Requires advanced phase for BRT	●	Considers differences on traffic volumes		Increases number of stages	

Comments: BRT vehicles mix with general traffic at roundabouts during the second stage and therefore, BRT vehicles must be provided with a 5-7 seconds advantage over regular traffic.



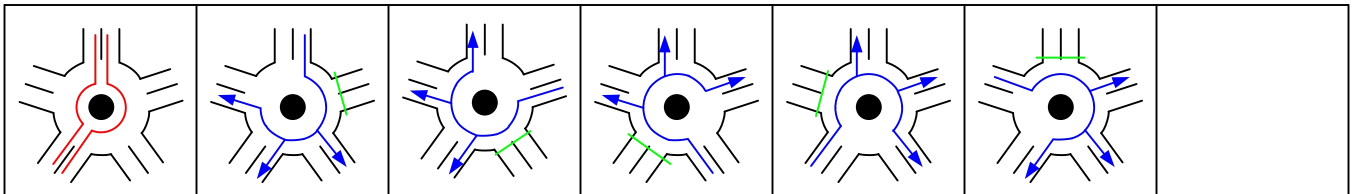
Applicability		Advantages		Disadvantages	
When right turn volumes are balanced	●	Two opportunities to pass BRT vehicles	●	Increases Cycle Length	●
When a right turn volume is higher		BRT delay is reduced	●	Decreases Overall Capacity	●
When overall v/c ratio is low	●	Minimizes number of stages		Allows contra-flow operation	●
When special coordination is needed		Reduces clearance time requirements		Requires dedicated right turn lanes	●
When right turn lanes are not possible		Avoids BRT mixed with general traffic		Long Clearance times	●
** Requires advanced phase for BRT	●	Considers differences on traffic volumes		Increases number of stages	

Comments: BRT vehicles have two opportunities per cycle to cross the intersection. On the second stage, BRT vehicles mix with general traffic at roundabouts. A 5-7 seconds advantage over general traffic must be provided.



Applicability		Advantages		Disadvantages	
When right turn volumes are balanced		Two opportunities to pass BRT vehicles		Increases Cycle Length	●
When a right turn volume is higher		BRT delay is reduced		Decreases Overall Capacity	●
When overall v/c ratio is low		Minimizes number of stages		Allows contra-flow operation	●
When special coordination is needed		Reduces clearance time requirements		Requires dedicated right turn lanes	
When right turn lanes are not possible	●	Avoids BRT mixed with general traffic	●	Long Clearance times	●
** Requires advanced phase for BRT		Considers differences on traffic volumes		Increases number of stages	

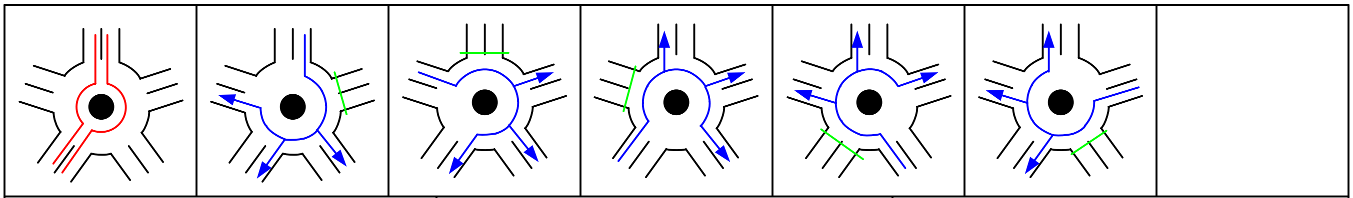
Comments: BRT vehicles cross the intersection on a dedicated phase to avoid mixing with regular traffic. Regular traffic operates on a split mode so the use of dedicated right turn lanes is avoided.



Applicability		Advantages		Disadvantages	
When right turn volumes are balanced		Two opportunities to pass BRT vehicles		Increases Cycle Length	●
When a right turn volume is higher		BRT delay is reduced		Decreases Overall Capacity	●
When overall v/c ratio is low		Minimizes number of stages		Allows contra-flow operation	
When special coordination is needed		Reduces clearance time requirements	●	Requires dedicated right turn lanes	
When right turn lanes are not possible	●	Avoids BRT mixed with general traffic	●	Long Clearance times	
** Requires advanced phase for BRT		Considers differences on traffic volumes		Increases number of stages	

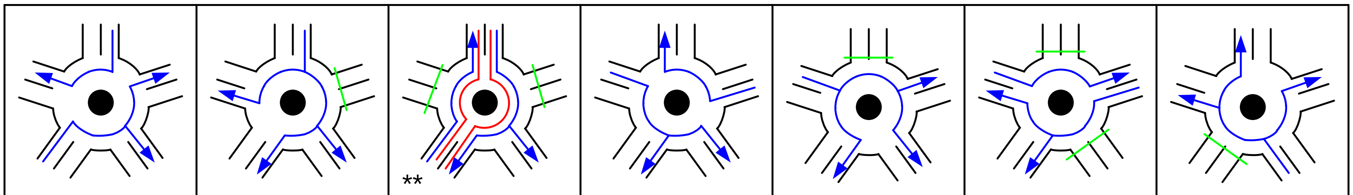
Comments: Similar to previous phasing scheme but approaches are served in a special sequence that allows for shorter clearance times. Contra-flow must not be permitted with this operation.

Signalized 5-Leg Roundabout



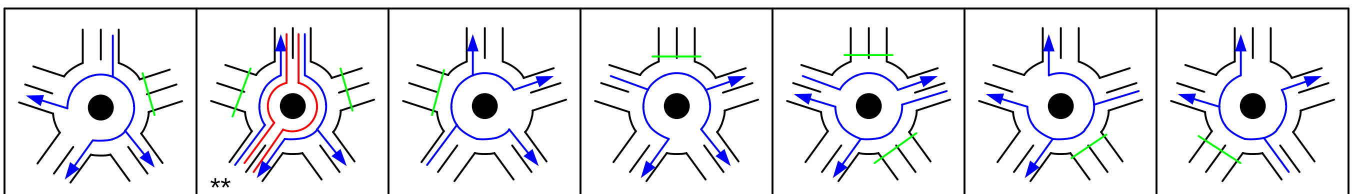
Applicability		Advantages		Disadvantages	
When right turn volumes are balanced		Two opportunities to pass BRT vehicles		Increases Cycle Length	•
When a right turn volume is higher		BRT delay is reduced		Decreases Overall Capacity	•
When overall v/c ratio is low		Minimizes number of stages		Allows contra-flow operation	
When special coordination is needed		Reduces clearance time requirements	•	Requires dedicated right turn lanes	
When right turn lanes are not possible	•	Avoids BRT mixed with general traffic	•	Long Clearance times	
** Requires advanced phase for BRT		Considers differences on traffic volumes		Increases number of stages	

Comments: Similar to previous phasing scheme but the phasing sequence is reversed. This scheme may allow for even shorter clearance times, as long as vehicles do not U-turn at the roundabout.



Applicability		Advantages		Disadvantages	
When right turn volumes are balanced		Two opportunities to pass BRT vehicles		Increases Cycle Length	•
When a right turn volume is higher	•	BRT delay is reduced		Decreases Overall Capacity	
When overall v/c ratio is low		Minimizes number of stages		Allows contra-flow operation	•
When special coordination is needed		Reduces clearance time requirements		Requires dedicated right turn lanes	•
When right turn lanes are not possible		Avoids BRT mixed with general traffic		Long clearance times	•
** Requires advanced phase for BRT	•	Considers differences on traffic volumes	•	Increases number of stages	•

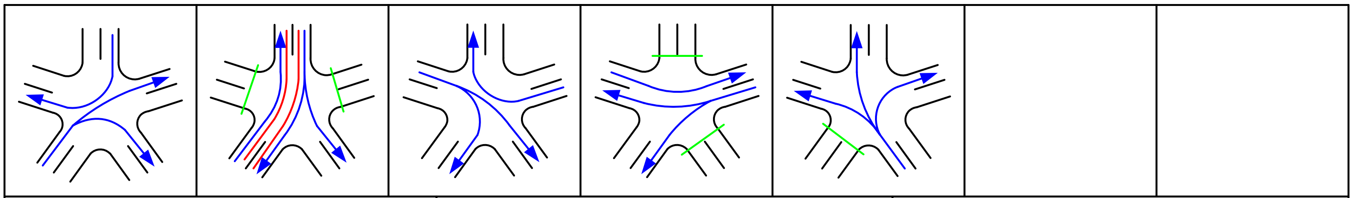
Comments: This phasing scheme is needed when one of the right turn volumes is significantly higher than the opposing right turn volume



Applicability		Advantages		Disadvantages	
When right turn volumes are balanced		Two opportunities to pass BRT vehicles		Increases Cycle Length	•
When a right turn volume is higher		BRT delay is reduced		Decreases Overall Capacity	
When overall v/c ratio is low		Minimizes number of stages		Allows contra-flow operation	•
When special coordination is needed	•	Reduces clearance time requirements		Requires dedicated right turn lanes	•
When right turn lanes are not possible		Avoids BRT mixed with general traffic		Long Clearance times	•
** Requires advanced phase for BRT	•	Considers differences on traffic volumes	•	Increases number of stages	•

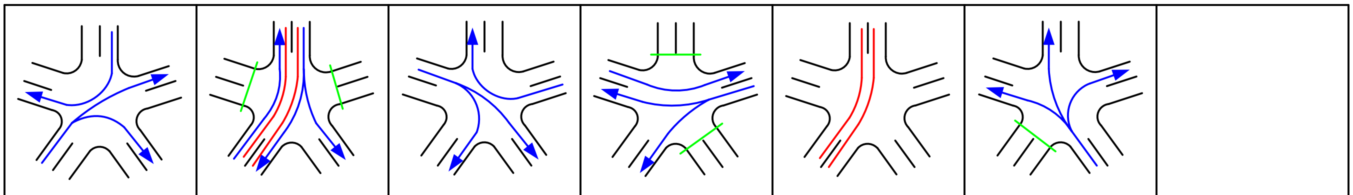
Comments: This phasing scheme is useful for those situations in which platoons from opposing directions arrive on different times. This scheme favours regular traffic coordination, but it does not contribute to the BRT operation.

Signalized 5-Leg Intersection



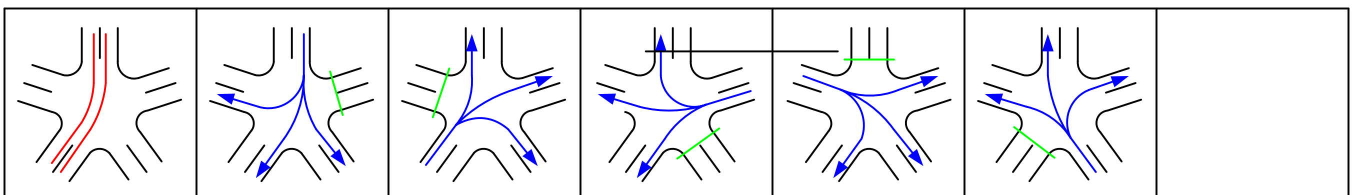
Applicability		Advantages		Disadvantages	
When right turn volumes are balanced	●	Two opportunities to pass BRT vehicles		Increases Cycle Length	
When a right turn volume is higher		BRT delay is reduced		Decreases Overall Capacity	
When overall v/c ratio is low		Minimizes number of stages	●	Requires dedicated right turn lanes	●
When special coordination is needed		Considers differences on traffic volumes		Increases number of stages	
When right turn lanes are not possible		Avoids the need for dedicated right lanes			

Comments: BRT vehicles cross the intersection concurrently with parallel through traffic. This scheme minimizes the number of stages during the cycle.



Applicability		Advantages		Disadvantages	
When right turn volumes are balanced	●	Two opportunities to pass BRT vehicles	●	Increases Cycle Length	●
When a right turn volume is higher		BRT delay is reduced	●	Decreases Overall Capacity	●
When overall v/c ratio is low	●	Minimizes number of stages		Requires dedicated right turn lanes	●
When special coordination is needed		Considers differences on traffic volumes		Increases number of stages	
When right turn lanes are not possible		Avoids the need for dedicated right lanes			

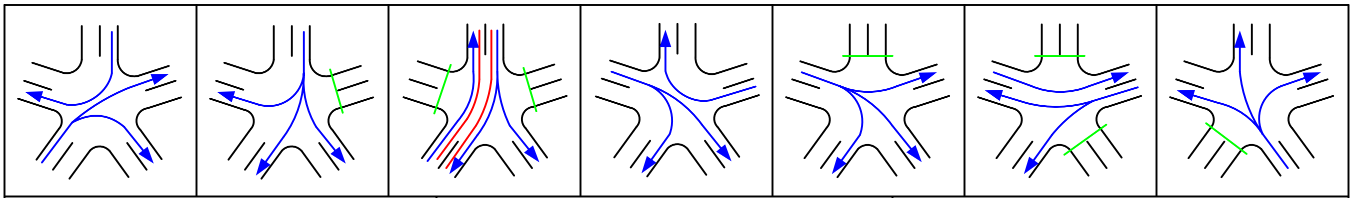
Comments: BRT vehicles have two opportunities per cycle to cross the intersection.



Applicability		Advantages		Disadvantages	
When right turn volumes are balanced		Two opportunities to pass BRT vehicles		Increases Cycle Length	●
When a right turn volume is higher		BRT delay is reduced		Decreases Overall Capacity	●
When overall v/c ratio is low		Minimizes number of stages		Requires dedicated right turn lanes	
When special coordination is needed		Considers differences on traffic volumes		Increases number of stages	
When right turn lanes are not possible	●	Avoids the need for dedicated right lanes	●		

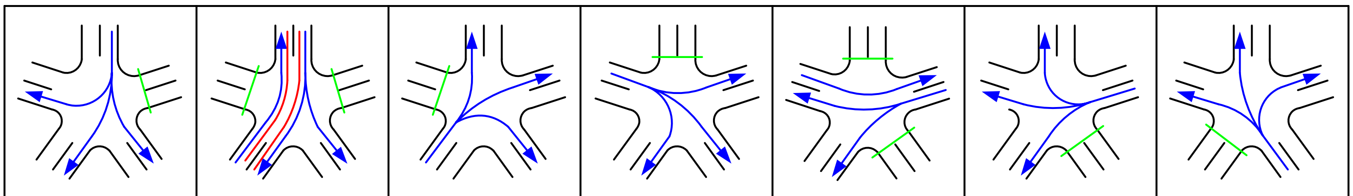
Comments: BRT vehicles cross the intersection on a dedicated phase to avoid mixing with regular traffic. Regular traffic operates on a split mode so the use of dedicated right turn lanes is avoided.

Signalized 5-Leg Intersection



Applicability		Advantages		Disadvantages	
When right turn volumes are balanced		Two opportunities to pass BRT vehicles		Increases Cycle Length	●
When a right turn volume is higher	●	BRT delay is reduced		Decreases Overall Capacity	●
When overall v/c ratio is low		Minimizes number of stages		Requires dedicated right turn lanes	●
When special coordination is needed		Considers differences on traffic volumes	●	Increases number of stages	●
When right turn lanes are not possible		Avoids the need for dedicated right lanes			

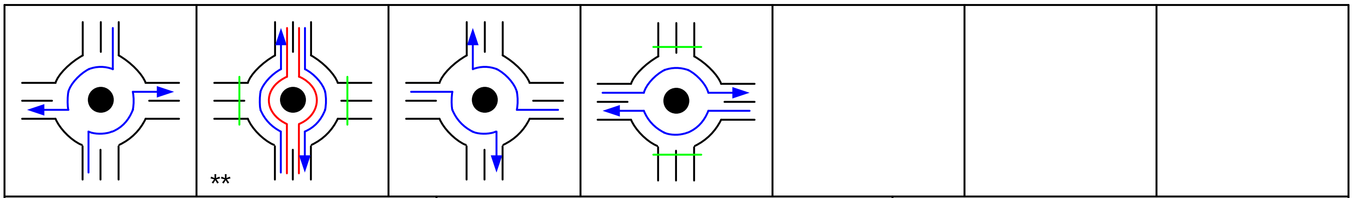
Comments: This phasing scheme is needed when one of the right turn volumes is significantly higher than the opposing right turn volume.



Applicability		Advantages		Disadvantages	
When right turn volumes are balanced		Two opportunities to pass BRT vehicles		Increases Cycle Length	●
When a right turn volume is higher		BRT delay is reduced		Decreases Overall Capacity	●
When overall v/c ratio is low		Minimizes number of stages		Requires dedicated right turn lanes	●
When special coordination is needed	●	Considers differences on traffic volumes		Increases number of stages	●
When right turn lanes are not possible		Avoids the need for dedicated right lanes	●		

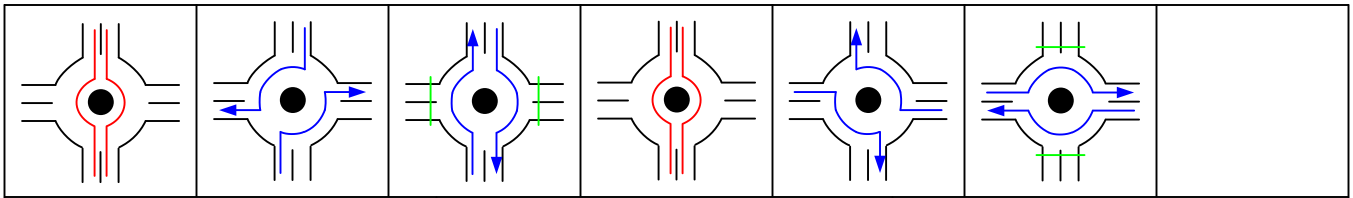
Comments: This phasing scheme is useful for those situations in which platoons from opposing directions arrive on different times. This scheme favours regular traffic coordination, but it does not contribute to the BRT operation.

Signalized 4-Leg Roundabout



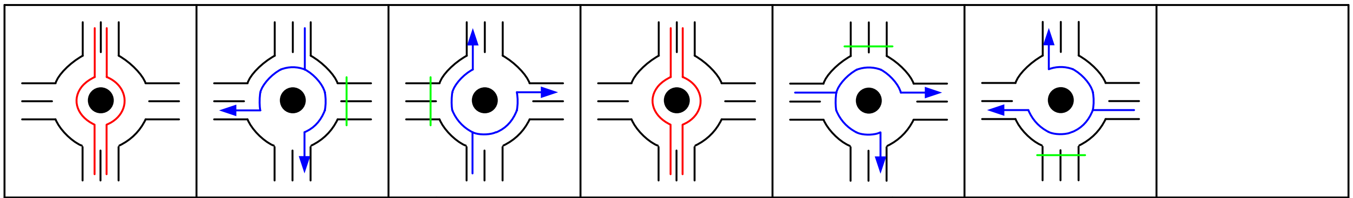
Applicability		Advantages		Disadvantages	
When right turn volumes are balanced	•	Two opportunities to pass BRT vehicles		Increases Cycle Length	
When a right turn volume is higher		BRT delay is reduced		Decreases Overall Capacity	
When overall v/c ratio is low		Minimizes number of stages	•	Allows contra-flow operation	•
When special coordination is needed		Reduces clearance time requirements		Requires dedicated right turn lanes	•
When right turn lanes are not possible		Avoids BRT mixed with general traffic		Long Clearance times	•
** Requires advanced phase for BRT	•	Considers differences on traffic volumes		Increases number of stages	

Comments: BRT vehicles mix with general traffic at roundabouts during the second stage and therefore, BRT vehicles must be provided with a 5-7 seconds advantage over regular traffic.



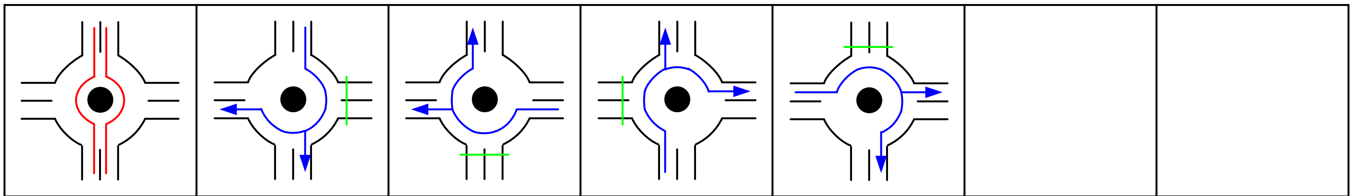
Applicability		Advantages		Disadvantages	
When right turn volumes are balanced	•	Two opportunities to pass BRT vehicles	•	Increases Cycle Length	•
When a right turn volume is higher		BRT delay is reduced		Decreases Overall Capacity	•
When overall v/c ratio is low	•	Minimizes number of stages		Allows contra-flow operation	•
When special coordination is needed		Reduces clearance time requirements		Requires dedicated right turn lanes	•
When right turn lanes are not possible		Avoids BRT mixed with general traffic	•	Long Clearance times	•
** Requires advanced phase for BRT		Considers differences on traffic volumes		Increases number of stages	•

Comments: BRT vehicles have two opportunities per cycle to cross the intersection. This operation avoids BRT vehicles mixing with general traffic.



Applicability		Advantages		Disadvantages	
When right turn volumes are balanced		Two opportunities to pass BRT vehicles	•	Increases Cycle Length	•
When a right turn volume is higher		BRT delay is reduced	•	Decreases Overall Capacity	•
When overall v/c ratio is low	•	Minimizes number of stages		Allows contra-flow operation	•
When special coordination is needed		Reduces clearance time requirements		Requires dedicated right turn lanes	
When right turn lanes are not possible	•	Avoids BRT mixed with general traffic	•	Long Clearance times	•
** Requires advanced phase for BRT		Considers differences on traffic volumes		Increases number of stages	•

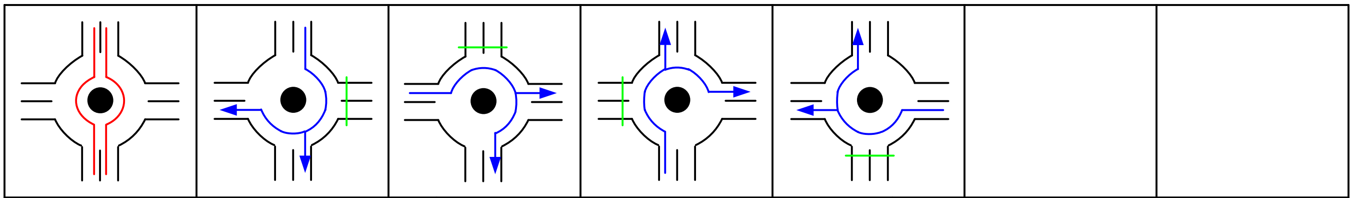
Comments: BRT has two opportunities per cycle to cross the intersection. BRT does not have to mix with general traffic. This operation avoids the need for dedicated right turn lanes



Applicability		Advantages		Disadvantages	
When right turn volumes are balanced		Two opportunities to pass BRT vehicles		Increases Cycle Length	•
When a right turn volume is higher		BRT delay is reduced		Decreases Overall Capacity	•
When overall v/c ratio is low		Minimizes number of stages		Allows contra-flow operation	
When special coordination is needed		Reduces clearance time requirements	•	Requires dedicated right turn lanes	
When right turn lanes are not possible	•	Avoids BRT mixed with general traffic	•	Long Clearance times	
** Requires advanced phase for BRT		Considers differences on traffic volumes		Increases number of stages	

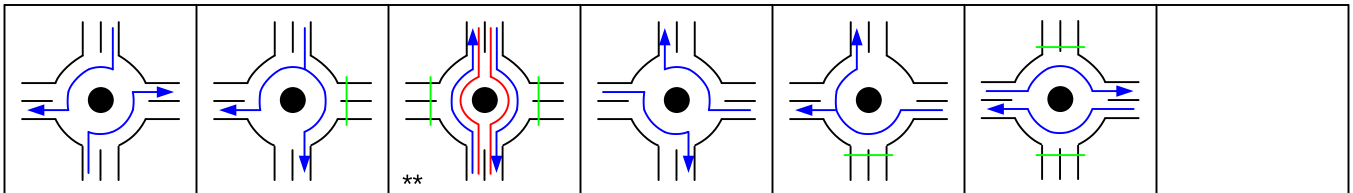
Comments: BRT vehicles cross the intersection on a dedicated phase to avoid mixing with regular traffic. Approaches are served in a special sequence that allows for shorter clearance times. Contra-flow must not be permitted with this operation.

Signalized 4-Leg Roundabout



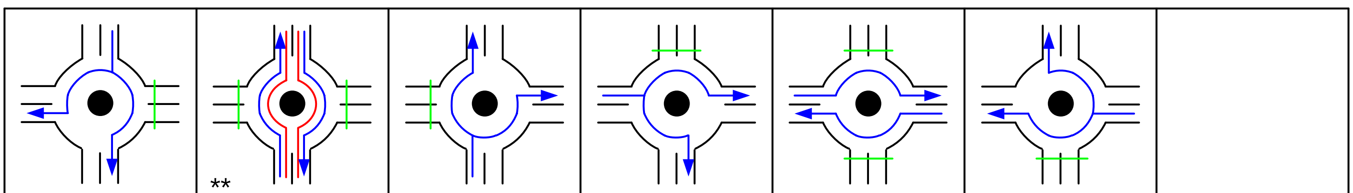
Applicability		Advantages		Disadvantages	
When right turn volumes are balanced		Two opportunities to pass BRT vehicles		Increases Cycle Length	
When a right turn volume is higher		BRT delay is reduced		Decreases Overall Capacity	●
When overall v/c ratio is low		Minimizes number of stages		Allows contra-flow operation	
When special coordination is needed		Reduces clearance time requirements	●	Requires dedicated right turn lanes	
When right turn lanes are not possible	●	Avoids BRT mixed with general traffic	●	Long Clearance times	
** Requires advanced phase for BRT		Considers differences on traffic volumes		Increases number of stages	

Comments: BRT vehicles cross the intersection on a dedicated phase to avoid mixing with regular traffic. Regular traffic operates on a split mode so the use of dedicated right turn lanes is avoided. Approaches are served in a special sequence that allows for shorter clearances times.



Applicability		Advantages		Disadvantages	
When right turn volumes are balanced		Two opportunities to pass BRT vehicles		Increases Cycle Length	●
When a right turn volume is higher	●	BRT delay is reduced		Decreases Overall Capacity	●
When overall v/c ratio is low		Minimizes number of stages		Allows contra-flow operation	●
When special coordination is needed		Reduces clearance time requirements		Requires dedicated right turn lanes	●
When right turn lanes are not possible		Avoids BRT mixed with general traffic		Long Clearance times	●
** Requires advanced phase for BRT	●	Considers differences on traffic volumes	●	Increases number of stages	●

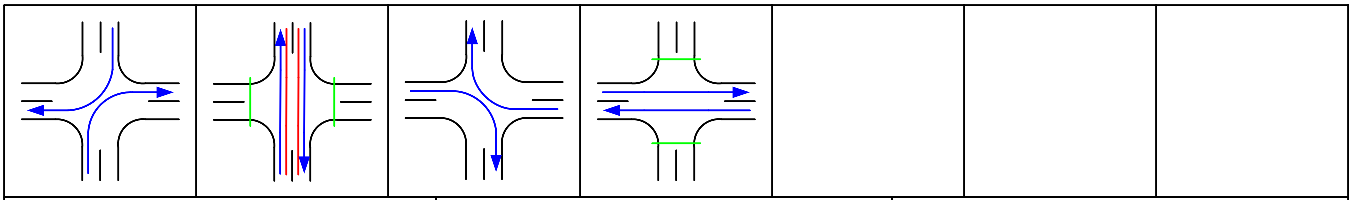
Comments: This phasing scheme is needed when one of the right turn volumes is significantly higher than the opposing right turn volume.



Applicability		Advantages		Disadvantages	
When right turn volumes are balanced		Two opportunities to pass BRT vehicles		Increases Cycle Length	●
When a right turn volume is higher		BRT delay is reduced		Decreases Overall Capacity	●
When overall v/c ratio is low		Minimizes number of stages		Allows contra-flow operation	●
When special coordination is needed	●	Reduces clearance time requirements		Requires dedicated right turn lanes	●
When right turn lanes are not possible		Avoids BRT mixed with general traffic		Long Clearance times	●
** Requires advanced phase for BRT	●	Considers differences on traffic volumes	●	Increases number of stages	●

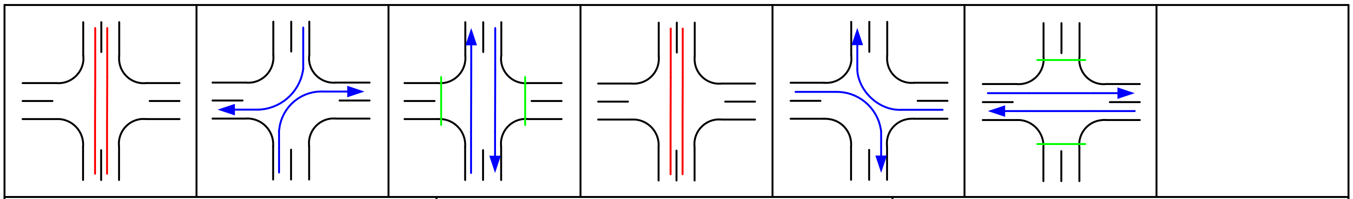
Comments: This phasing scheme is useful for those situations in which platoons from opposing directions arrive on different times. This scheme favours regular traffic coordination, but it does not contribute to the BRT operation

Signalized 4-Leg Intersection



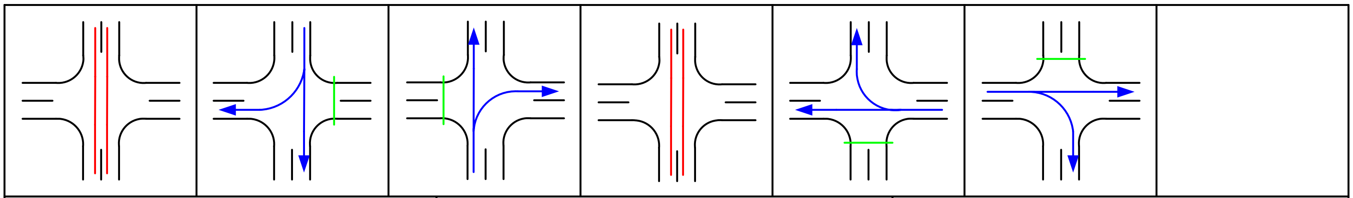
Applicability		Advantages		Disadvantages	
When right turn volumes are balanced	•	Two opportunities to pass BRT vehicles		Increases Cycle Length	
When a right turn volume is higher		BRT delay is reduced		Decreases Overall Capacity	
When overall v/c ratio is low		Minimizes number of stages	•	Requires dedicated right turn lanes	•
When special coordination is needed		Considers differences on traffic volumes		Increases number of stages	
When right turn lanes are not possible		Avoids the need for dedicated right lanes			

Comments: BRT vehicles cross the intersection concurrently with parallel through traffic. This scheme minimizes the number of stages during the cycle.



Applicability		Advantages		Disadvantages	
When right turn volumes are balanced	•	Two opportunities to pass BRT vehicles	•	Increases Cycle Length	•
When a right turn volume is higher		BRT delay is reduced	•	Decreases Overall Capacity	•
When overall v/c ratio is low	•	Minimizes number of stages		Requires dedicated right turn lanes	•
When special coordination is needed		Considers differences on traffic volumes		Increases number of stages	•
When right turn lanes are not possible		Avoids the need for dedicated right lanes			

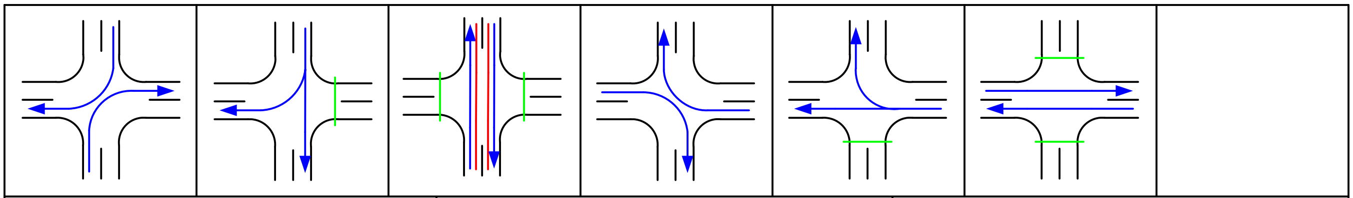
Comments: BRT vehicles have two opportunities per cycle to cross the intersection.



Applicability		Advantages		Disadvantages	
When right turn volumes are balanced		Two opportunities to pass BRT vehicles	•	Increases Cycle Length	•
When a right turn volume is higher		BRT delay is reduced	•	Decreases Overall Capacity	•
When overall v/c ratio is low	•	Minimizes number of stages		Requires dedicated right turn lanes	
When special coordination is needed		Considers differences on traffic volumes		Increases number of stages	•
When right turn lanes are not possible	•	Avoids the need for dedicated right lanes	•		

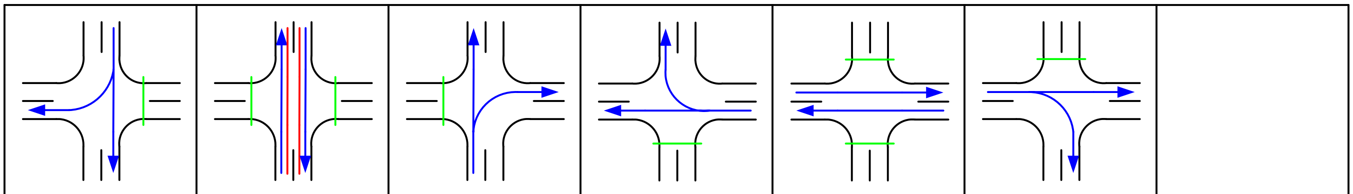
Comments: BRT vehicles have two opportunities per cycle to cross the intersection. Regular traffic operates on a split mode so the use of dedicated right turn lanes is avoided.

Signalized 4-Leg Intersection



Applicability		Advantages		Disadvantages	
When right turn volumes are balanced		Two opportunities to pass BRT vehicles		Increases Cycle Length	•
When a right turn volume is higher	•	BRT delay is reduced		Decreases Overall Capacity	•
When overall v/c ratio is low		Minimizes number of stages		Requires dedicated right turn lanes	•
When special coordination is needed		Considers differences on traffic volumes	•	Increases number of stages	•
When right turn lanes are not possible		Avoids the need for dedicated right lanes			

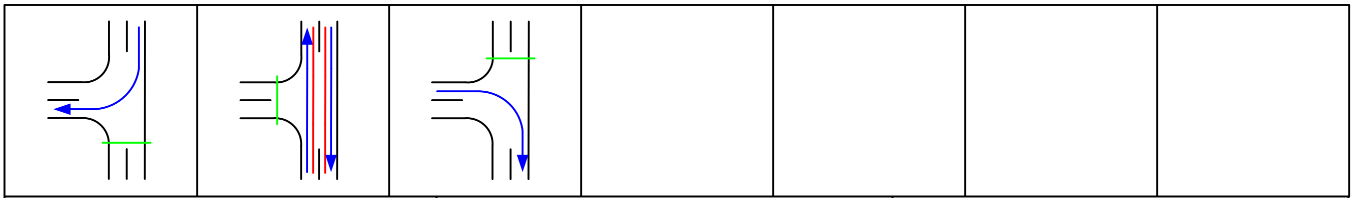
Comments: This phasing scheme is needed when one of the right turn volume is significantly higher than the opposing right turn volume.



Applicability		Advantages		Disadvantages	
When right turn volumes are balanced		Two opportunities to pass BRT vehicles		Increases Cycle Length	•
When a right turn volume is higher		BRT delay is reduced		Decreases Overall Capacity	•
When overall v/c ratio is low		Minimizes number of stages		Requires dedicated right turn lanes	•
When special coordination is needed	•	Considers differences on traffic volumes	•	Increases number of stages	•
When right turn lanes are not possible		Avoids the need for dedicated right lanes			

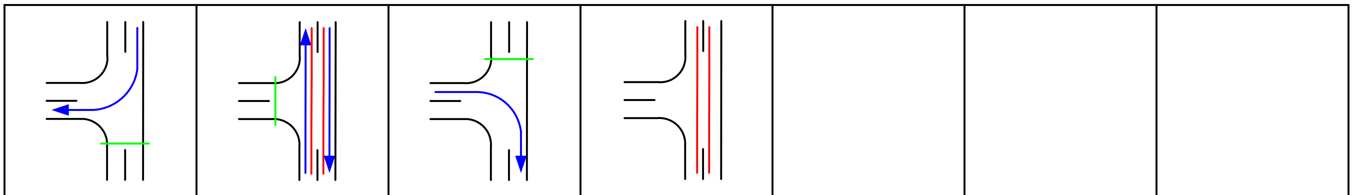
Comments: This phasing scheme is useful for those situations in which platoons from opposing directions arrive on different times. This scheme favours regular traffic coordination, but it does not contribute to the BRT operation.

Signalized 3-Leg Intersection



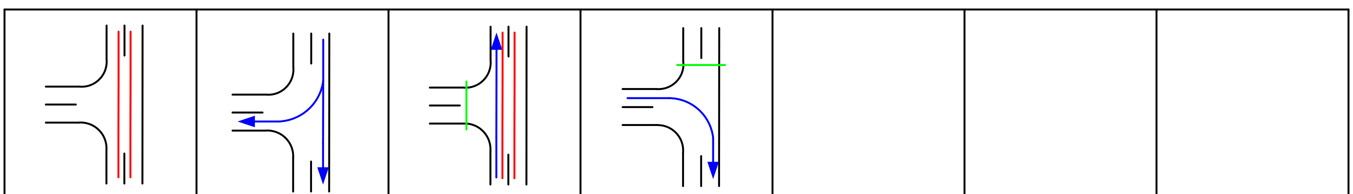
Applicability		Advantages		Disadvantages	
When overall v/c ratio is low		Two opportunities to pass BRT vehicles		Increases Cycle Length	
When overall v/c ratio is high	•	BRT delay is reduced		Decreases Overall Capacity	
When right turn lanes are not possible		Minimizes number of stages	•	Requires dedicated right turn lanes	•
		Avoids the need for dedicated right lanes		Increases number of stages	

Comments: This is a common phasing for a 3-leg intersection. BRT vehicles cross the intersection at the same time than parallel through traffic.



Applicability		Advantages		Disadvantages	
When overall v/c ratio is low	•	Two opportunities to pass BRT vehicles	•	Increases Cycle Length	•
When overall v/c ratio is high		BRT delay is reduced	•	Decreases Overall Capacity	•
When right turn lanes are not possible		Minimizes number of stages		Requires dedicated right turn lanes	•
		Avoids the need for dedicated right lanes		Increases number of stages	•

Comments: This phasing allows for smaller delays on BRT vehicles since they have the opportunity to cross the intersection twice per cycle.



Applicability		Advantages		Disadvantages	
When overall v/c ratio is low	•	Two opportunities to pass BRT vehicles	•	Increases Cycle Length	•
When overall v/c ratio is high		BRT delay is reduced	•	Decreases Overall Capacity	•
When right turn lanes are not possible	•	Minimizes number of stages		Requires dedicated right turn lanes	
		Avoids the need for dedicated right lanes	•	Increases number of stages	•
				Crosswalk on south leg must be closed	•

Comments: This phasing is useful when dedicated right turn lanes are not possible. Crosswalk on the south leg must be closed to allow for this operation.