Interrupted Flow

1. Concepts

This section presents concepts and methods for interrupted flow facilities. Interrupted flow refers to travel on elements of the highway system, on which traffic flow is interrupted through traffic control devices at at-grade intersections. Interrupted flow thus encompasses traffic signals, modern roundabouts, stop-controlled intersections, and various variations of these intersection forms. Interrupted flow also occurs along the arterial street of a freeway interchange, which often features one or more intersections. This section presents basic concepts and methods of analysis for interrupted flow, which are in some ways similar to the uninterrupted flow material presented in the last section, but in other ways distinctly different in terms of the methods used to calculate capacity, delay, and other performance measures.

Interrupted flow occurs at at-grade intersections, which are locations where two or more roads intersect and vehicles on different approaches can cross paths with other vehicles as they progress through the intersection.

The location where vehicle paths cross is known as a conflict point. At a typical intersection of two streets, there are 32 conflict points to consider, while a roundabout can have as little as 8 conflict points for a four-legged intersection. This is illustrated in Figure below.

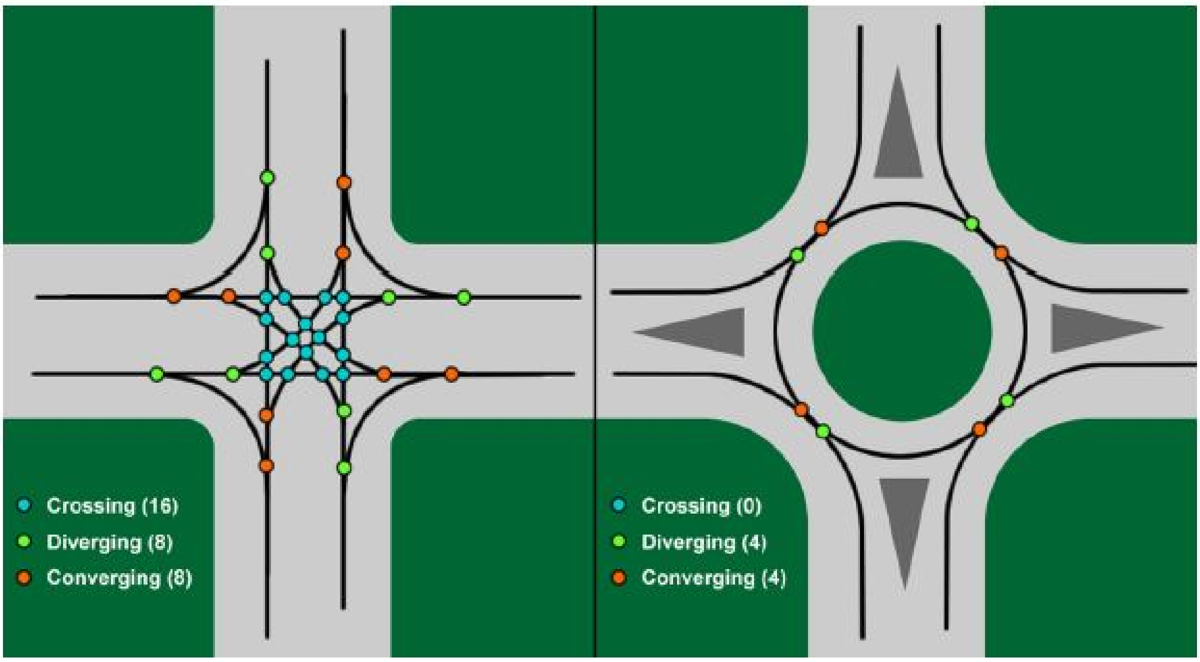


Figure: Conflict points at signalized intersection and modern roundabout.

The purpose of traffic control devices is to control the interaction of conflicting vehicle streams at these conflict points, by introducing rules and a hierarchy of movements that govern the interaction of these traffic streams.
Traffic control devices are used to reduce the potential for collisions by assigning the right of way to proceed through the intersection to specific movements and in specific order, and in some cases significantly reducing the number of conflict points. Traffic control devices primarily include traffic signals, yield signs (including those used at entry points to modern roundabouts), and stop signs, but can also include various forms of flashing beacons to alert drivers, pedestrians, or cyclists to the intersection and potential conflicts.

Some countries further have completely unsigned intersections, where the interaction and priority of movements is governed by other rules established in the applicable driving manuals or motor vehicle codes.
Examples here include the right-before-left rule, which gives priority to the movement to the right. If all approaches of an intersection have vehicles, drivers often communicate through eye contact and hand signals to decide who goes first. This, however, is rare, as many right-before-left intersections are used at very low-volume junctions within residential areas or neighborhoods.

There are even some examples of completely uncontrolled intersections, in which case there are no signs, traffic lights, or other traffic control devices, and drivers are left to figure out priority on their own.
But independent of the type of traffic control used, interrupted flow facilities principally differ from uninterrupted flow in that the hourly capacity of each lane is divided up in time, and only a portion of the theoretical hourly capacity remains for the approach under study. So while the capacity of an uninterrupted flow freeway segment is, say, 2000 vehicles/h per lane, the capacity of a traffic signal is the theoretical hourly rate (say, 1800 vehicles/h per lane) multiplied by the fraction of the hour that is actually assigned to that movement. A large focus in interrupted flow analysis is to decide how much time (capacity) to allocate to which movement to safely and efficiently operate the intersection.

2. <u>Types of Traffic Control at Intersections</u>

Some examples of types of traffic control are shown in the following intersections. The most common forms include two-way stop-controlled intersections (TWSC, Figure below)

Figure: Two-way stop-controlled intersection (T-intersection).

, all-way stop-controlled intersections (AWSC, Figure below),

Figure: All-way stop-controlled intersection. Photo by Daniel Findley.

yield-controlled intersections, including modern roundabouts (Figure below),

Figure: Yield-controlled intersection (modern roundabout).

and finally signalized intersections (Figure below).

Figure: Signalized intersection.

Signals are most commonly installed either for operational reasons (too high delays without the traffic control device) or for safety reasons (with the goal of eliminating specific crash patterns through signalization).
Signals are commonly thought of as controlling the flow of vehicular traffic, but they are also commonly used to accommodate pedestrians and cyclists, or to control the interaction between vehicular traffic and various forms of transit (bus, light rail, heavy rail, etc.).

In the United States, the Manual on Uniform Traffic Control Devices (MUTCD) (FHWA, 2009) provides warrants to evaluate the viability of a signal at an intersection, which are evaluated through an engineering study and used to determine if a signal is appropriate at a given location.
Suppose the decision has already been made to install a traffic signal at an intersection. The question now becomes, "What kind of traffic signal is needed at this intersection?"

<u>Traffic signals (or controllers) are generally categorized as one of three types:</u>

- Pretimed: All operations of the signal remain the same from cycle to cycle and throughout the day or specific times during a day (like am peak or pm peak). This is the way the first signal controllers operated, and can imply some inefficiencies as the traffic signal does not have the ability to react to fluctuations in traffic demand. However, pretimed signals are still quite common and can be very useful in, for example, downtown grid systems, to allow progression of movements in multiple directions.
- Actuated-coordinated: In this scheme, referred to sometimes as semiactuated, it is typical that the mainline movement is allocated a specific green time (as well as starting and end points) to facilitate progression of platoons of vehicles along the arterial. In other words, the green "windows" at successive signals are timed such that traffic leaving an upstream intersection in green is likely to be able to proceed through one or multiple downstream intersections in green without stopping. In an actuated-coordinated signal, the side street traffic triggers the signal through various traffic detection technologies to allocate some green time when vehicles are waiting on the side street to proceed through the intersection. In the absence of a "call" on the side-street detectors, that movement may not be given any green time, and unused time reverts to the major movement.
- Fully-actuated: In this scheme, the major street and the side street traffic both trigger the signal to request green time (between a minimum and a maximum amount) to proceed through the intersection. Fully actuated signals are common in isolated locations, where there are not adjacent signals that would be coordinated with one another. Often agencies also run fully actuated control during nighttime or extremely low-volume conditions to provide fast service to any vehicle wanting to enter the intersection (as opposed to having to wait for a pretimed or coordinated phase to elapse).

In many cases, the signal controller is set to change timing patterns throughout the day as demand dictates. Thus, there may exist one or more “timing plans” such as an am peak hour timing plan, a pm peak hour timing plan, an off-peak weekday timing plan, and a weekend timing plan. There may be timing plans for weekend traffic near a major shopping mall, or special event plans for sporting/concert events for a street network adjacent to an arena. The point here is that signal controllers can respond to a wide variety of traffic patterns on highways and streets. An example of traffic pattern changing over the course of a day, and resulting in alternating timing plans is shown in Figure below. In the example, a total of four timing plans are shown:
15free-running, 25low-volume off peak, 35am peak, and 45pm peak plans.

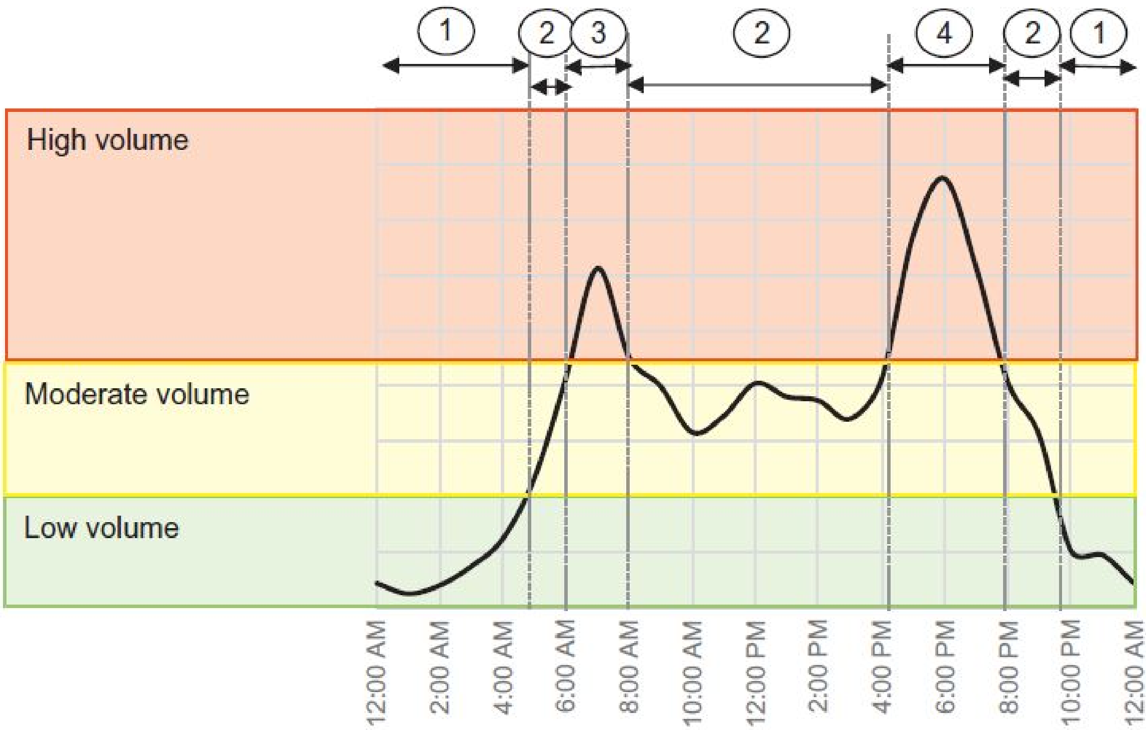


Figure: Timing plan changes based on traffic patterns.

Typical signalized intersections can provide up to eight protected movements that can be shown in various combinations. These phases include four through movements and four left turns, with the four right turns typically being processed concurrently with the adjacent through traffic. In addition, pedestrians are included to be shown in the movement sequence, with bicycles typically being served either as a vehicle (if on street) or as a pedestrian (if on sidewalk).
The 12 vehicular movements (4 through, 4 left, and 4 right) are assigned to different phases within the signal control logic. Each phase is assigned a specific time (typically with a minimum and maximum limit for actuated control), and a specific placement in the sequence of phases shown. A full sequence of all phases at an intersection is referred to as a cycle. The cycle length refers to the total time (in seconds) allocated to complete one sequence of all phases, in which each phase is assigned a split time.

While a typical signalized intersections can have eight protected movements, with each allocated to a separate phase, only six movement combinations can take place in a given cycle. Often, an actuated controller provides different variations of this sequence, and these variations are triggered by the demands of traffic on each approach.

Consider the conceptual diagram provided in Figure below. It shows a typical timing sequence separating movements for the east_west direction (left) and north_south direction (right). The sequence first processes (protected) left turns, followed by the through movements. If moving along the center path in the figure, the sequence in a cycle may consist of only four phases: east_west left turns, east_west through, north_south left turns, and north_south through.

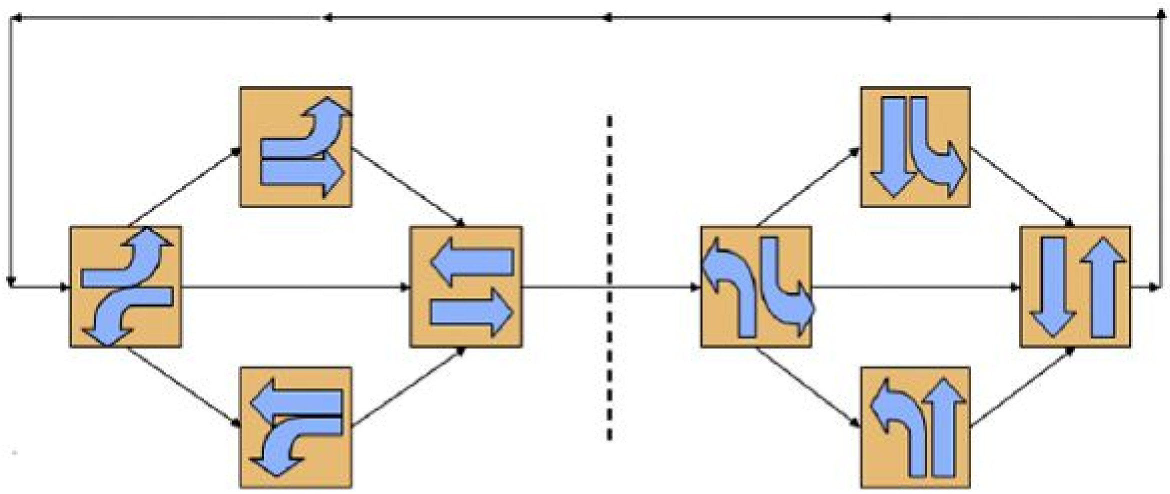


Figure: Conceptual understanding of an 8-phase intersection.

However, the figure also shows options to, for example, allow the west-to-north left turn (also called westbound left) to continue longer than the eastbound left, presumably due to higher demand levels. If the eastbound left was higher than the westbound left, the bottom sequence may be used, allowing the eastbound through to begin processing traffic after all westbound left vehicles have been processed. The same options can exist for the north_south movements. The example in Figure above is, of course, just one example for a timing sequence, and many other combinations exist to optimize operations depending on intersection geometry, volume levels, and other considerations.

3. Signal Terminology

Traffic engineers, signal technicians, and controller designers all need to talk the same language. As such, signalized intersection control uses very specific terminology, as given in the following list and used to describe an intersection movement and timing diagram such as the one shown in Figure below. The example shows a four-legged intersection with protected and leading left turns on the east_west mainline. The side street is shown with what is known as split phasing, which means that the side street is split between giving green to first the southbound movement and then the northbound movement.

- Interval: an amount of time allocated within a phase where signal indications do not change (e.g., green, yellow, red, green arrow, yellow arrow, pedestrian indicators as well).
- Phase split (φ): an amount of time within the cycle where one or more traffic movements are allowed to move through the intersection. (Note: You could have a pedestrian phase where no vehicular movements were allowed.) It is typically the sum of the green, yellow and red intervals associated with a particular movement.
- Cycle (C): the total amount of time of all phases that do not overlap whereby one complete sequence of signal indications is achieved.
- Lane group: One or more lanes on an approach that operate together under the same phase.
- Saturation flow (s): The maximum number of vehicles that can move past the stop bar in one lane group per unit of time, usually per hour (veh/h).
- Lane group capacity: The maximum vehicular flow (veh/h) that can be accommodated by a particular lane group under given signal timings.
- Volume-to-capacity ratio, v/c (X): The ratio of lane group volume to lane group capacity.
- Lost time: Wasted time, when no vehicles are moving through the intersection. Lost time per phase is l; lost time per cycle is L.
- Effective green (g): Usable phase time, or total phase time minus lost time per phase.
- Critical lane group: Of all the lane groups moving during a phase, this one has the highest volume-to-saturation flow (v/s) ratio.
- Overlap: A movement allowed during more than one phase.
- Permissive movement: A movement allowed only after opposing movements or pedestrians have cleared, indicated by a green ball signal.
- Protected movement: A movement that has the right of way. Protected turns are indicated with green arrow signals.
- Protected/permissive movement: A movement made under protected and permissive conditions during different times of the signal cycle.
- Leading sequence: When the green arrow appears before the green ball for a particular approach.
- Lagging sequence: When the green ball appears before the green arrow for a particular approach.

4. <u>Roundabouts and Unsignalized Control</u>

Signalized intersections represent just one form of intersection control. While many may think of signals as the “standard” form of intersection, the reality is that there are many more unsignalized intersections across most countries. Just think of the multitude of neighborhood intersections that, in most cases, do not have traffic signals. Similarly, many lowvolume intersections can operate just fine under all-way stop-control (AWSC), a common treatment in the United States, or even no formal control in the form of signs or signals, as is common in many European countries (e.g., Germany’s “right before left” rule). Similarly, many junctions of major roadways and minor roads can be stop or yield controlled on the minor approaches, a strategy that works up to certain volume levels where the delays on side streets become too large.

A special form of unsignalized intersection is the modern roundabout, which will be discussed in detail in a later section. The roundabout has become a very popular alternative to signalized intersection in many countries (e.g., France, which has more than 20,000 roundabouts). The popularity of roundabouts is largely due to their improved safety performance over signals and two-way stop-controlled intersections, as well as their ability to adapt well to ever-changing traffic patterns and volume levels throughout the day without the need to retime any traffic signals. Roundabouts also have an aesthetic appeal, offering landscaping opportunities, and can provide a safe environment for pedestrians and cyclists largely due to low operating speeds of vehicular traffic. In terms of safety performance, a recent comprehensive study in the United States showed that for a conversion from signalized intersections, roundabouts result in a 48% reduction in total crashes, and, more importantly, a 78% reduction in injury crashes for rural and 60% for urban roundabouts. Similar safety benefits have been documented for roundabouts converted from TWSC intersections.

The safety benefits of roundabouts are largely attributed to the slower speeds at which collisions occur (TRB, 2007), as well as the reduced number of conflict points relative to a signalized intersection, as was shown in Figure below.

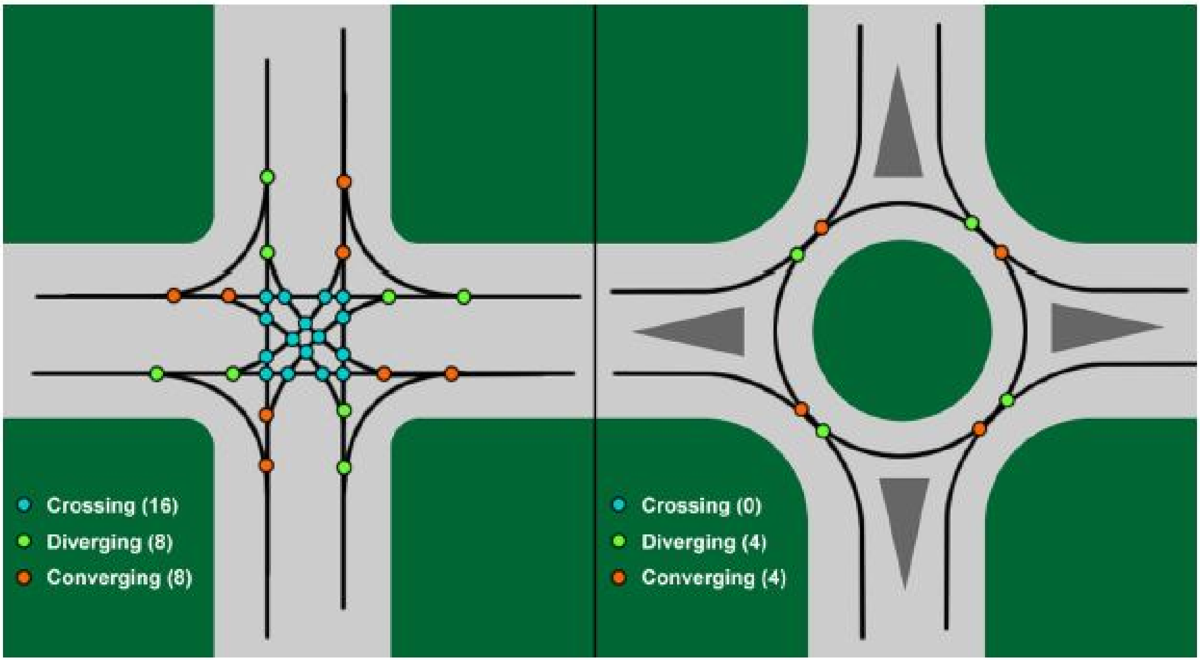


Figure: Conflict points at signalized intersection and modern roundabout.

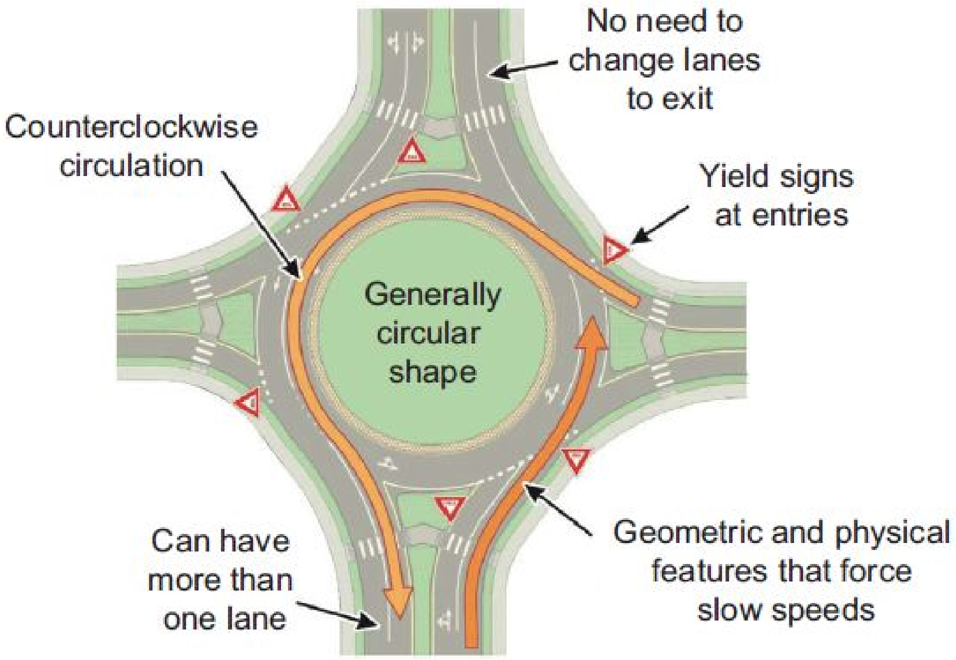
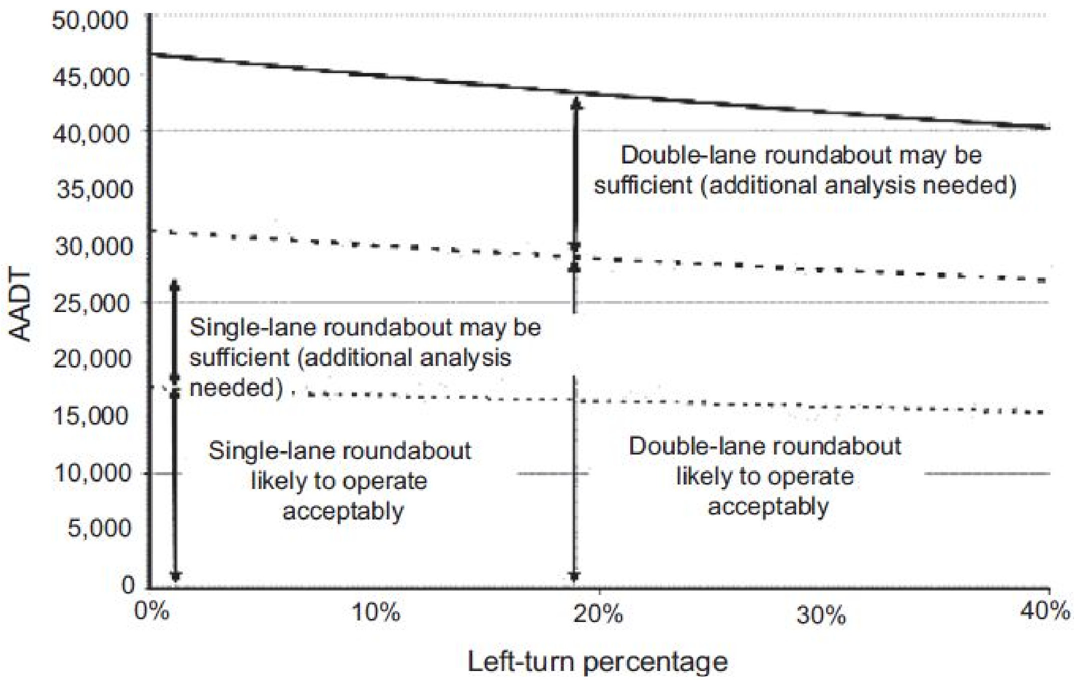


Figure: Roundabout design features. Source: NCHRP Report 672.

Figure above shows typical design features of modern roundabouts, including yield signs at entry, counterclockwise circulation, geometric and physical features that result in slow vehicle speeds, and a lane assignment that eliminates the need for lane changes in the circle and after exit for multilane roundabouts.

Roundabouts can have application even for elevated volume levels, but may require multiple lanes to adequately process the traffic. Figure below shows the feasibility of a modern roundabout as a function of the average annual daily traffic (AADT) summed across both intersecting roadways, and the percentage of left turns. The various regimes identify where single-lane and double-lane roundabouts are likely to operate acceptably, and where additional analysis is needed to confirm operations of roundabouts are appropriate.
As a result of the safety benefits and operational performance of roundabouts, many states have adopted policies to explicitly consider roundabouts as an alternative for new intersection designs, and even some that have implemented so-called “roundabouts first” policies. These require analysis of roundabouts as the preferred alternative over other intersection forms, and only allow construction of, say, a signalized intersection if a roundabout was shown to be infeasible for the location under study.



<u>Figure:</u> Planning-level assessment of roundabouts Source: Rodegerdts et al., 2010. http://safety.fhwa.dot.gov/intersection/roundabouts/fhwasa10006/ppt/.

5. <u>Critical Movement Analysis</u>

An operational analysis of intersections can be quite complicated, especially in the case of a signalized intersection with actuated timings. In practice, systems of intersections are typically analyzed using software, to automate complex (and at time iterative) computations. Fortunately, a straightforward planning-level methodology exists for the assessment of intersection capacity, which can typically be completed by hand in as little as 15 min as a true “back of the envelope” calculation. The critical movement analysis (CMA) was formalized by TRB Circular 212: Interim Materials on Highway Capacity in 1980 (TRB, 1980), but dates back even before that time. Today, CMA is sometimes ignored as a “dated” and “simplistic” approach, which is unfortunate as the straightforward and simple approach is invaluable in developing an understanding of intersection capacity relationships, and in performing quick estimation performance checks of intersection operations.

The basic principle underlying the CMA is that two vehicles cannot be in the same place at the same time, and that within an hour there is thus a limit to the number of vehicles that can be processed through any one point.
microscopic characteristics of traffic flow has already introduced the concept of minimum headway between successive vehicles (say, 2 s per vehicle) and how this translates to a maximum flow rate of 1800 vehicles per hour of continuous green in each lane. CMA adapts this concept, though further restraining the maximum hourly flow rate to account for lost time, which is time needed to safely transition from one vehicle stream to another. Accounting for lost time, a reasonable hourly “point capacity per lane” is 1400 veh/h, which gives a conservative estimate of intersection operations with a lost time of roughly 20% over the maximum flow rate. In reality, the lost time depends on the number of critical phases,

and intersections with fewer phases will also result in lower lost time (and thus higher capacities). But the estimate of 1400 veh/h is a reasonable initial estimate for a planning level, quick estimation of intersection performance.
In application of the critical movement analysis method, the basic task then involves identifying conflicting movements, estimating the associated traffic streams, and comparing the resulting flow rates across each conflict point to the capacity. The availability of multiple lanes increases the capacity, as well as allows demand to be distributed across multiple lanes.

The only required inputs for applying the CMA are turning movement volumes and approach geometry. Potential applications of the CMA include:
• Planning-level or quick estimation capacity analysis.
• Evaluating adequacy of approach geometry (number of lanes).
• Development of initial signal phasing plans and green times.
• Conducting reasonableness checks on software calculations.
• Performing quick and efficient alternative evaluation.

Critical Movement Analysis Step-by Step

The following basic steps are used in a critical movement analysis of an intersection:

- **Step 1** Identify movements and hourly volumes per lane: The analyst reviews the approach geometry (number of lanes) for each approach to the intersection, and needs to obtain the traffic volumes in vehicles per hour (adjusted to peak 15 min as desired). The volumes are then converted to a per-lane basis for analysis for all movements.
- **Step 2** Assign movements to phase sequence: A traffic signal allows certain phases to run concurrently, while others are run sequentially. The analyst needs to have a sense of what phasing scheme is used or make some assumptions. Consideration is given to the treatments of left turns as either protected or permissive.
- **Step 3** Determine critical volume pair in each interval: For each conflicting movement pair in each interval, the analyst calculates the sum of volumes on a per-lane basis. The highest movement pair (volume across a point) is identified as the critical volume pair.
- **Step 4** Sum critical volumes for phase sequence: The critical volumes for all intervals are summed for the overall phase sequence.
- **Step 5** Identify maximum critical volume: This is the theoretical total volume past a point. Earlier, it was recommended to use a conservative volume of 1400 veh/h, which is based on the 1985 HCM. This value considers varying effects of lost time, heavy vehicles, grades, unfamiliar drivers, turn geometry, and pedestrians. The 1400 veh/h value gives a conservative estimate of capacity, which is deemed appropriate for planning-level analyses. But higher values can be adopted by agencies as desired. For more detailed analysis, the lost time and maximum volume (capacity) can be estimated using the methodology described in the next section.
- **Step 6** Calculate critical v/c ratio and determine intersection status: The critical v/c or volume-to-capacity ratio is calculated by dividing the sum of critical volumes from step 4 by the maximum critical volume from step 5. Thresholds for interpreting the resulting v/c ratio are given in Table below.

In application of the CMA, it is noted that the steps just listed are readily combined as needed, but were specifically separated out here to fully describe the method. It is also noted that the HCM has adopted a slightly different quick estimation method that modified the CMA approach described here to work more explicitly within the context of the HCM operational context. The reader is encouraged to refer to that method as needed, but it is believed that the basic CMA presented here provides a straightforward and more easily understood approach.

6. Signalized Intersection Operational Analysis

The operational analysis of signalized intersections can be very complex. As was discussed earlier, some intersections are pretimed, while others (more commonly) are running in actuated or actuated-coordination operations. The challenge for the operational analysis of the more common actuated coordination signal system, is that phase durations depend on the arriving traffic volume, which triggers a detector to call or extend different phases. At the same time, the traffic volume, or more specifically the arrival patterns, at the next downstream intersection depend on the phase durations of the upstream intersection. To make this really tricky, consider that arterial streets have traffic moving in two directions, essentially reversing what is upstream and downstream when moving in the opposite direction. In other words, signal phase durations and thereby signal capacity and operations depend on arrivals from the upstream signals, which in turn impacts how much traffic the signal discharges to that same adjacent signal in the opposite direction.

This complication of actuated controllers makes the analysis process iterative for the case of actuated-coordinated controllers, a process that is described in great detail in the HCM. This discussion focuses on pretimed signal control as a more straightforward and simplified analysis approach.
It is true that almost all signal installations done today rely on actuated control for one or more of the approaches. This achieves the most flexibility in accommodating fluctuating traffic demand throughout the day.
However, during the peak hour, traffic demand may be at high-enough volumes for the controller to receive the maximum green time for all approaches. If this happens, the controller is essentially functioning like a pretimed controller. Therefore, we can use timing calculation procedures appropriate for this kind of operation for simplified analysis and in the absence of using software for the more complicated analyses.

6.1 Methodology
The HCM signalized intersection procedure is illustrated in Figure below, where it is summarized in seven steps. All steps are described in detail in the following.

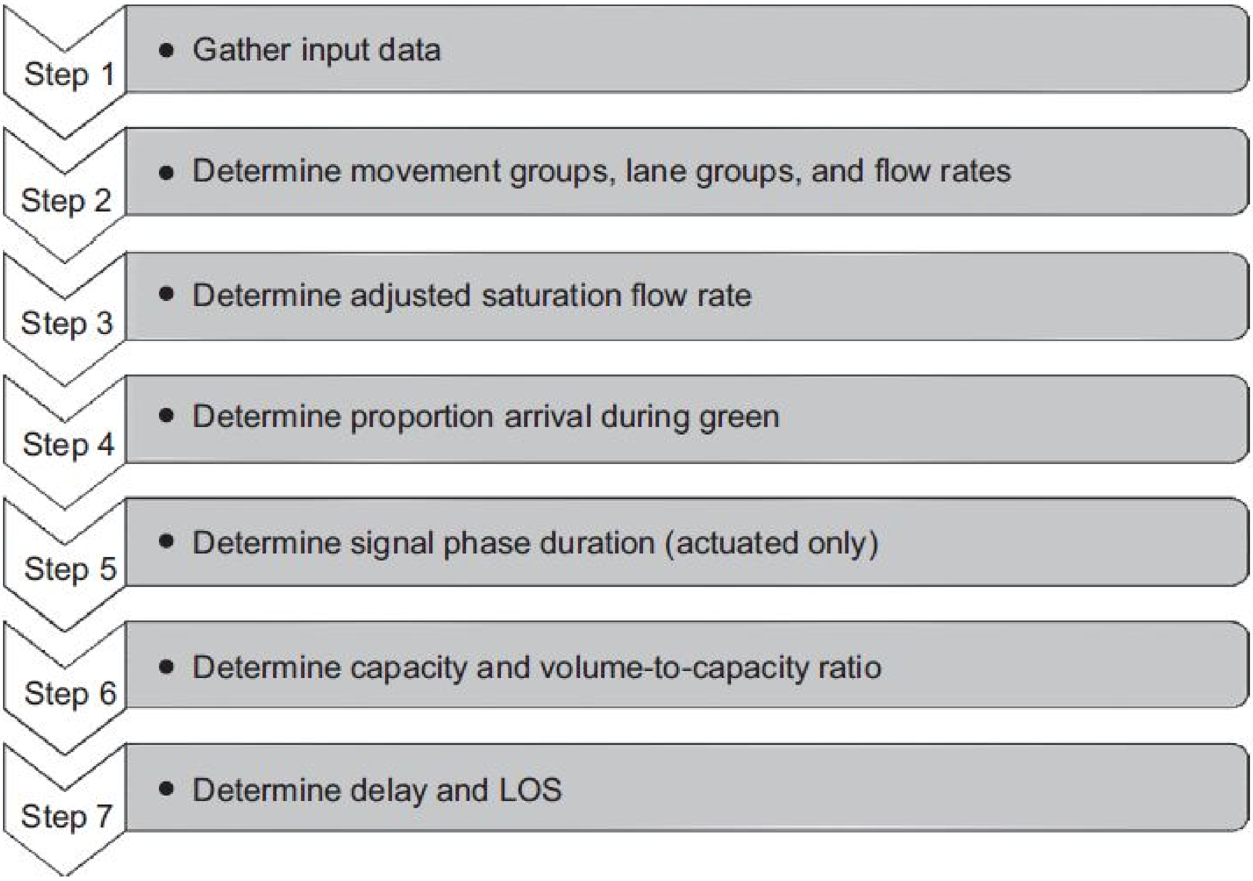


Figure: Methodology steps for signals analysis.

Step 1: Gather Input Data

The first step in the analysis is to gather input data. This includes the demand or volume data in the form of turning movement counts, including a percentage of heavy vehicles for each movement. Data needs also include geometric data about the intersection, including number of lanes, turn pocket details, lane widths, and intersection widths. Finally, the input data includes signal timing data.

Step 2: Determine Movement Groups, Lane Groups, and Flow Rates

As a second step, each intersection approach is divided into movement groups and lane groups. Movement groups generally refer to movements that are progressed together on one approach during a signal phase, while lane groups refer to the smallest capacity analysis unit. Often, movement groups and lane groups are identical, for example, in the case of exclusive left-turn lanes. The difference comes into play for shared lanes.

Take, for example, an intersection approach with one exclusive through lane and one shared through-right lane. Clearly the two lanes move during the same signal through phase. But for capacity analysis purposes, the two lanes are different as the shared through/right lane may experience impedance from slower turning vehicles and pedestrians or cyclists when making a turn. As such, the capacity of the shared lane is likely to be less than the capacity of the exclusive (unimpeded) lane, justifying separate analyses for the two.

Table below shows some examples of lane configurations, movement groups, and lane groups. As a rule of thumb, any exclusive turn lanes are separated into their own movement groups, and any shared lanes are then separated out into their own lane group.

<u>Table</u>: Illustrating movements, movement groups, and lane groups.

Number of lanes	Movements by lanes	Movement groups (MG)	Lane groups (LG)
1	Left, through & right:	MG 1:	LG 1:
2	Exclusive left:	MG 1:	LG 1:
	Thru. & right:	MG 2:	LG 2:
2	Left & thru:	MG 1:	LG 1:
	Thru. & right:		LG 2:
3	Exclusive left:	MG 1:	LG 1:
	Exclusive left:		
	Through:	MG 2:	LG 2:
	Through:		
	Thru. & right:		LG 3 :

Source: TRB, 2015.

The total approach volume is assigned to each movement group, which typically emerges naturally from the turning movement patterns. For example, all left-turn demand is assigned to the left-turn movement group, and so forth. Estimating flow rates for lane groups (the smallest analysis unit in the HCM) can be a bit more challenging for multilane groups with one or more shared lanes. The analyst may use judgment to decide on the relative distribution of flows, or may turn to a detailed procedure given in the HCM.

<u>Step 3: Determine Adjusted Saturation Flow Rate</u>

Next, the analysis estimates the saturation flow rate for each lane group. The saturation flow rate is one of the most critical parameters describing lane group capacity. Saturation flow rate is defined as the maximum throughput in a lane per hour of continuous green (the second important factor in signal capacity is what proportion of that hour is actually available to the movement, which is estimated later).

The saturation flow rate is a function of a base saturation flow rate, and a whole series of adjustment factors accounting for lane width, heavy vehicles, lane utilization, and several other parameters, as shown in Eq. below:

$$s = s_o f_w f_{HVg} f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb} f_{wz} f_{ms} f_{sp}$$

where:
s=adjusted saturation flow rate (veh/h per lane).
s_o =base saturation flow rate (passenger cars/h per lane).
f_w =adjustment factor for lane width.
f_{HVg} =adjustment factor for heavy vehicles and grade.
f_p =adjustment factor for existence of a parking lane and parking activity adjacent to lane group.
f_{bb} =adjustment factor for blocking effect of local buses that stop within intersection area.
f_a =adjustment factor for area type.
f_{LU} =adjustment factor for lane utilization.
f_{LT} =adjustment factor for left-turn vehicle presence in a lane group.
f_{RT} =adjustment factor for right-turn vehicle presence in a lane group.
f_{Lpb} =pedestrian adjustment factor for left-turn groups.
f_{Rpb} = pedestrian-bicycle adjustment factor for right-turn groups.
f_{wz} =adjustment factor for work zone presence at the intersection.
f_{ms} =adjustment factor for downstream lane blockage.
f_{sp} =adjustment factor for sustained spillback.

In the HCM, the base saturation flow rate, s_o, is equal to 1900 passenger cars/h per lane for large metropolitan areas with a population of more than 250,000, and a default of 1750 passenger cars/h per lane for smaller communities.
However, many agencies have performed local studies and developed their own defaults based on local driver characteristics. This practice is strongly encouraged, and details on how to conduct saturation flow (or headway) studies are described in the ITE Manual of Transportation Engineering Studies (Schroeder et al., 2010).

For the various adjustments to saturation flow rate, a factor of 1.0 corresponds to standard or ideal conditions, with nonstandard conditions resulting in an adjustment typically below 1.0 to reduce the saturation flow. Some of the more common saturation flow adjustments are summarized in Table below.
In the table, the more common and straightforward adjustments are given directly. For some more complicated adjustments the reader is referred to the HCM or additional details. If these special conditions (e.g., work zones, lane closures, or spillback) are not present, the adjustment factor default for all conditions is 1.0.

Table: Saturation flow rate adjustments.

Factor	Condition	Factor	Comments
Lane width (ft), f_W	<10.0	0.96	n/a
	≥10.0–12.9	1.00	
	>12.9	1.04	
Heavy vehicles and grade, f_{HVg}	Downhill	$\frac{100-0.79P_{HV}-2.07P_g}{100}$	P_{HV} = % heavy veh P_g = % grade
	Level or uphill	$\frac{100-0.78P_{HV}-0.31P_g}{100}$	
Parking, f_p	Parking present	$\frac{N-0.1-\frac{18\times N_m}{3600}}{N}$	N = # of lanes N_m = # parking maneuvers per hour $f_p >= 0.050$
Bus blockage, f_{bb}	Buses and bus parking present	$N-\frac{14.4N_b}{3600}/N$	N_b = Bus stopping rate per hour $f_{bb} \geq 0.050$
Area type, f_a	Central business district (CBD)	0.90	Use judgment before applying
Lane utilization, f_{LU}	Imbalanced utilization	Custom	Special applications in *HCM*
Right turns, f_{RT}	Right turn	$1/E_R$	E_R = right-turn equivalency (=1.18)
Left turns, f_{RT}	Left turn	$1/E_L$	E_L = left-turn equivalency (=1.05)
Pedestrian or bike, f_{pb}	Pedestrians and bikes present	Custom	Special application in *HCM*
Work zone, f_{WZ}	Work zone present	Custom	Special application in *HCM*
Downstream lane blocks, f_{ms}	Downstream lane closure	Custom	Special application in *HCM*
Spillback, f_{sp}	Queue spillback	Custom	Special application in *HCM*

Step 4: Determine Proportion Arrival on Green

The procedure next estimates the proportion of arrivals during green. A signal generally runs more efficiently with a greater percentage of arrivals on green, as vehicles can proceed through the signals (and the corridor) without stopping. On the other hand, if arrivals in green is low (and arrivals in red high) the intersection intuitively incurs more delay.

The proportion arrivals in green is estimated from a term called the platoon ratio (R_p) and the proportion of the cycle that is green for a movement, which is the g/C ratio (effective green to cycle length ratio).

$$P = R_p \frac{g}{C}$$

The value for the platoon ratio can be estimated using a detailed iterative procedure for arrival flow prediction available in the HCM. For the purpose of this discussion, Table below provides guidance for estimating the platoon ratio as the function of the arrival type at the signal. Arrival type is a value from 1 to 6, which describes how well a signal is coordinated relative to its upstream neighbour. Arrival type 1 in this case is poor, while arrival type 6 is ideal or (near) perfect progression. Arrival type 3 refers to essentially random arrivals.

Table: Arrival types and platoon ratio

Arrival type	Typical signal spacing (ft)	Progression quality	Description of coordination patterns	Platoon ratio
1	≤ 1600	Very poor	Predominant arrivals on red, which can occur on a coordinated two-way street where the nonpeak direction does not receive good progression	0.33
2	>1600–3200	Unfavorable	A less extreme version of arrival type 1	0.67
3	>3200	Random arrivals	Essentially random arrivals at isolated signals or widely spaced coordinated signals	1.00
4	>1600–3200	Favorable	Coordinated operation on a two-way street where the subject direction receives good progression	1.33
5	≤ 1600	Highly favorable	Coordinated operation on a two-way street where the subject direction receives good progression	1.67
6	≤ 800	Exceptionally favorable	Coordinated operation on a one-way street in dense networks and central business districts	2.00

Step 5: Determine Signal Phase Duration (Actuated Only)

For an actuated controller, this step is where the phase duration would be estimated based on the arrival flow profiles and the signal timing parameters (min green, max green, extension times, etc.). As discussed earlier, the phase duration at one intersection impacts arrivals at the downstream intersection, the arrivals at the downstream intersection impact its phase duration, those phase durations in turn impact the arrivals at the first intersection for traffic in the opposite direction, which in turn impact its phase durations, and so forth. This makes the procedure iterative, and in the case of an arterial street with multiple intersections, quite complicated.

But for the purpose of a pretimed intersection, or a congested actuated signal with most phases extended to their maximum times, this step can be skipped in this discussion. The reader is, however, encouraged to refer to the HCM for a more detailed discussion of this method, and to use software to perform the more complicated actuated computations.

Step 6: Determine Capacity and Volume-to-Capacity Ratios

The capacity of each lane group at a signalized intersection is estimated from Eq. below.

$$c = N \times s \times \frac{g}{C}$$

where

c=capacity (veh/h).

N=number of lanes in the lane group.

s=saturation flow rate (veh/h per lane).

g=effective green time for group (s).

C=cycle length (s).

The equation applies to all protected movement, with the capacity estimation for permitted movements being more complicated due to gap acceptance processes. For details on the capacity of permitted movements, the reader is referred to the HCM.

The volume-to-capacity ratio, X, for the lane group is estimated simply by dividing the lane group flow rate by the previously calculated capacity as shown in Eq. below.

$$X = \frac{v}{c}$$

where:

X=volume-to-capacity ratio.

v=demand flow rate (veh/h).

c=capacity (veh/h).

Step 7: Determine Delay and LOS

As the final step, performance measures for each lane group are calculated, including control delay, LOS, and queue storage ratio. The control delay for a signalized intersection is the sum of three delay terms: uniform delay, incremental delay, and initial queue delay. Only the uniform delay is (the incremental and initial queue delays are described in detail in the HCM).

$$d = d_1 + d_2 + d_3$$

where:

d=control delay (s/veh).

d1=uniform delay (s/veh).

d2=incremental delay (s/veh).

d3=initial queue delay (s/veh).

Conceptually, the uniform delay considers the effect of the traffic signal only, without any impacts from adjacent intersections. The incremental delay adds a time-dependent delay component, which considers the effects of other vehicles, signal type, presence of upstream signal, and signal capacity effects. The initial queue delay is added for signals at which a queue is present at the beginning of a signal cycle that impacts the operations. The uniform delay is calculated as shown in Eqs. below:

$$d_1 = PF\frac{0.5C\left(1-g/C\right)^2}{1-\left[min(1,X)g/C\right]}$$

$$PF = \frac{1-P}{1-g/C} \times \frac{1-y}{1-min(1,X)P} \times \left[1+y\frac{1-PC/g}{1-g/C}\right]$$

<u>where:</u>
PF=progression adjustment factor.
y=flow ratio, y=min(1,X)g/C.
P=proportion of vehicles arriving during the green indication (decimal)
g=effective green time (s)
C=cycle length (s)
(all other variables are as previously defined)

The incremental delay and the initial queue delay require advanced computations of non random arrivals, queue spillback, and oversaturated cycles, which are beyond the scope of this text. The reader is referred to the HCM for details on those computations.
With the lane group delays calculated, delays can be aggregated to the approach level by calculating the weighted average control delay across all lane groups for that approach. The weighting is done by the lane group flow rates. Similarly, the intersection control delay is obtained through a weighted average of the individual approach delays.
Level of service (LOS) is defined based on the average control delay at the lane group, approach, or intersection level. The thresholds for LOS are shown in Table below.

<u>Table:</u> LOS threshold for signalized intersections.

LOS	Control delay (s/veh)
A	≤10
B	>10–20
C	>20–35
D	>35–50
E	>50–80
F	>80 or v/c ratio > 1.0