Intersection Capacity Utilization

Evaluation Procedures for Intersections and Interchanges

2003 EDITION

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Trafficware®

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Table of Contents

List of Figures

List of Tables

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Chapter 1 – Introduction

The Intersection Capacity Utilization (ICU) method is a simple yet powerful tool for measuring an intersection's capacity. The ICU can be calculated using a single page worksheet, that is both easy to generate and easy to review. The ICU is the perfect tool for planning applications such as roadway design and traffic impact studies.

The method sums the amount of time required to serve all movements at saturation for a given cycle length and divides by that reference cycle length. This method is similar to taking a sum of critical volume to saturation flow ratios (v/s), yet allows minimum timings to be considered. The ICU tells how much reserve capacity is available or how much the intersection is overcapacity. The ICU does not predict delay, but it can be used to predict how often an intersection will experience congestion.

The ICU is timing plan independent, yet has rules to insure that minimum timing constraints are taken into account. This removes the choice of timing plan from the capacity results. The ICU can also be used on unsignalized intersections to determine the capacity utilization if the intersection were to be signalized.

ICU is an ideal solution for traffic planning purposes. Its intended applications are for traffic impact studies, future roadway design, and congestion management programs. The ICU is not intended for operations or signal timing design. The primary output from ICU is similar to the intersection volume to capacity ratio. Some of the benefits to using ICU over delay-based methods include greater accuracy, and a clear image of the intersection's volume to capacity ratio.

The ICU has not been designed for operations and signal timing design. Delay based methods and simulation such as the Highway Capacity Manual (HCM), Synchro, and SimTraffic should be used for operations and signal timing design.

ICU 2003 includes new procedures for analyzing Diamond Interchanges and Single Point Urban Interchanges (SPUI). The Diamond method includes procedures recognizing the special timing needs of a diamond interchange to prevent spillback.

ICU and the HCM

Currently, the most popular method for analyzing capacity is the HCM. The HCM method is based on estimating delay for the intersection.

The ICU 2003 is designed to be compatible with the HCM and can be used in conjunction with the HCM and other methods. The default saturated flow rates and volume adjustments are the same as those recommended by the HCM. In most circumstances, the volume to saturated flow rates in ICU 2003 (v/s) will be the same as those in the HCM. When an agency requires an acceptable HCM Level of Service (LOS), an acceptable ICU Level of Service will insure that the HCM LOS is met.

An acceptable ICU LOS guarantees that a timing plan exists that will meet all of the following:

- Acceptable HCM LOS.
- All minimum timing requirements.
- Acceptable volume to capacity (v/c) ratios for all movements.
- All movement volumes can have their volume increased by the inverse of the ICU and be at saturation.

If the intersection has an ICU LOS of E or better, a timing plan exists that will give LOS E or better with the HCM. With an ICU of F, the intersection will be over capacity for the peak 15-minutes. However, it may be possible to get an acceptable HCM LOS when the intersection is over capacity by using a timing plan favoring the highest volume movements.

Table 1-1 compares ICU to delay based calculations such as the HCM and simulation for a typical project.

Table 1-1 ICU Comparison to HCM and Simulation

	ICU	HCM and Delay Based	Simulation
Measure of Effectiveness	Volume to Capacity	Delay	Delay, Stops, Queues
Best Applications	Planning, Impact Studies, Roadway Design	Operations, Signal Timing	Unusual Situations, Closely Spaced Intersections
Secondary Applications		Planning, Impact Studies, Roadway Design	Operations, Signal Timing, Planning, Impact Studies, Roadway Design
Pages of Input	0.3	2	4
Pages of Output	0.7	5	12
Expected Accuracy	10%	30%	30%
Dependent on signal timing	No	Yes	Yes

Changes in ICU 2003

ICU was originally proposed by Robert Crommelin in 1974 in a paper entitled

"Employing Intersection Capacity Utilization Values to Estimate Overall Level of Service". The ICU method is used in Southern California for the congestion management programs and is used in traffic impact studies. A similar method called the Critical Lane Volume (CLV) method is used in Maryland for similar applications.

The ICU 2000 extended and improved upon the original ICU method. The changes to ICU 2000 over the original ICU and CLV include the following:

- Uses the same saturated flow rates, lost time, and volume adjustments as the HCM 1997 and the HCM 2000 thus generating comparable results to the HCM.
- Instructions and procedures for modeling permitted left turns and shared left-through lanes. These intersections were not specifically addressed in the original ICU.
- Consideration of minimum green times, pedestrian timing requirements, and pedestrian interference.
- Improved logic for right turns. ICU 2000 accounts for free rights, overlapping right turn phases, and right turns on red.

The ICU 2003 includes several changes from ICU 2000. These include:

- Volumes entered are 60-minute volumes, rather than peak 15-minute volumes. No Peak Hour Factor is used. The LOS cutoff points are revised to reflect 60-minute counts rather than 15-minute counts.
- New method for permitted left turns from a shared lane. This new 5-step method is based on simulation research performed by Trafficware. The ICU 2003 will give better capacities for single lane approaches, and permitted left turns from a shared lane.
- New method for analyzing diamond interchanges.
- New worksheet customized for analyzing single point urban interchanges.

Chapter 2 – Level of Service

The ICU Level of Service (LOS) gives insight into how an intersection is functioning and how much extra capacity is available to handle traffic fluctuations and incidents. ICU is not a value that can be measured with a stopwatch, but it does give a good reading on the conditions that can be expected at the intersection.

The ICU is the sum of time required to serve all movements at saturation given a reference cycle length, divided by the reference cycle length.

$ICU = (\max(tMin, v/s_i) * CL + tL_i) / CL$ = Intersection Capacity Utilization

CL = Reference Cycle Length

tL_i = Lost time for critical movement i

v/s_i = volume to saturation flow rate, critical movement i

$tMin$ = minimum green time, critical movement i

The ICU LOS should not be confused with delay-based levels of service such as the HCM. Both are providing information about the performance of an intersection; but are measuring a different objective function. The ICU LOS reports on the amount of reserve capacity or capacity deficit. The delay based LOS reports on the average delay experienced by motorists.

New in ICU 2003

The ICU 2003 uses one-hour volume counts with no adjustment for Peak Hour Factor. Older versions of the ICU used one-hour volume counts with a peak hour adjustment factor (with a default of 0.90). The scale has been adjusted to reflect this change while still providing the same LOS.

The ratio between the old to new LOS is 0.91, not the 0.90 one might expect. The difference is because time consumes part of the available cycle. The ratio was calculated by comparing some typical intersections under both the old and new methods.

Table 2-1 Revised Peak Hour Adjustment Factor

LOS	Old ICU	New ICU
A	<60%	≤55.0%*
B	60% to 70%	>55% to 64.0%
C	70% to 80%	>64% to 73.0%
D	80%to 90%	>73% to 82.0%
E	90% to 100%	>82% to 91.0%
F	100% to 110%	>91% to 100.0%
G	110% to 120%	>100% to 109.0%
H	>120%	>109%

* Note: An ICU value equal to 55.0% would be LOS A, while an ICU of 55.1 % is LOS B.

A brief description of the conditions expected for each ICU LOS follows:

LOS A, ICU ≤55%: The intersection has no congestion. A cycle length of 80 seconds or less will move traffic efficiently. All traffic should be served on the first cycle. Traffic fluctuations, accidents, and lane closures can be handled with minimal congestion. This intersection can accommodate up to 40% more traffic on all movements.

LOS B, >55% to 64%: The intersection has very little congestion. Almost all traffic will be served on the first cycle. A cycle length of 90 seconds or less will move traffic efficiently. Traffic fluctuations, accidents, and lane closures can be handled with minimal congestion. This intersection can accommodate up to 30% more traffic on all movements

LOS C, >64% to73%: The intersection has no major congestion. The majority of traffic should be served on the first cycle. A cycle length of 100 seconds or less will move traffic efficiently. Traffic fluctuations, accidents, and lane closures may cause some congestion. This intersection can accommodate up to 20% more traffic on all movements.

LOS D, >73% to 82%: The intersection normally has no congestion. Most of the traffic should be served on the first cycle. A cycle length of 110 seconds or less will move traffic efficiently. Traffic fluctuations, accidents, and lane closures can cause significant congestion. Sub optimal signal timings can cause congestion. This intersection can accommodate up to 10% more traffic on all movements.

LOS E, >82% to 91%: The intersection is right on the verge of congested conditions. Many vehicles are not served on the first cycle. A cycle length of 120 seconds is required to move all traffic. Minor traffic fluctuations, accidents, and lane closures can cause significant congestion. Sub-optimal signal timings can cause significant congestion. This intersection has less than 10% reserve capacity available.

LOS F, >91% to 100%. The intersection is over capacity and likely experiences congestion periods of 15 to 60 consecutive minutes. Residual queues at the end of green are common. A cycle length over 120 seconds is required to move all traffic. Minor traffic fluctuations, accidents, and lane closures can cause increased congestion. Sub-optimal signal timings can cause increased congestion.

LOS G, >100% to 109%: The intersection is up to 9% over capacity and likely experiences congestion periods of 60 to 120 consecutive minutes. Long queues are common. A cycle length over 120 seconds is required to move all traffic. Motorists may be choosing alternate routes, if they exist, or making fewer trips during the peak hour. Signal timings can be used to distribute capacity to the priority movements.

LOS H, >109%: The intersection is 9% or greater over capacity and could experience congestion periods of over 120 minutes per day. Long queues are common. A cycle length over 120 seconds is required to move all traffic. Motorists may be choosing alternate routes, if they exist, or make fewer trips during the peak hour. Signal timings can be used to distribute capacity to the priority movements.

The above cycle lengths assume that the sum of minimum timing requirements is less than 70 seconds.

The length of the congested period is heavily dependent on the source of traffic and the availability of alternate routes. If traffic is generated by a single factory shift change, the congested period may be shorter. However, a shopping mall could cause congestion for several hours. If alternate routes exist, motorists may know to avoid the congested intersections during the peak hour and this reduces congestion.

If intersections have LOS E to LOS G, queues between intersections can lead to blocking problems. Signal timing plans should be analyzed with microscopic simulation to insure that spillback is not causing additional problems.

ICU LOS and HCM Level of Service

The ICU 2003 is designed to be compatible with the HCM. The default saturated flow rates and volume adjustments are the same as those recommended by the HCM. The two methods are closely interrelated. If the intersection has an ICU LOS of E or better, a timing plan exists that will give LOS E or better with the HCM. With an ICU of F, the intersection will be over capacity for the peak 15-minutes. It may possible to get an acceptable HCM LOS when the intersection is over capacity by using a timing plan favoring the highest volume movements.

Table 2-2 ICU vs. HCM LOS Compatibility

Given an ICU LOS	Resulting HCM LOS
F or worse	F normally D or E possible with special timings
E or better	E or better
D or better	D or better (depends on cycle length) v/c ratios < 0.80

Chapter 3 – Overview of Calculations

Overview of Calculation

The primary calculation for ICU 2003 is to compute an Adjusted Reference Time for each movement. The Reference Time is the amount of time required for each movement at 100% capacity. The Reference Time is volume divided by Saturated Flow rate multiplied by the Reference Cycle Length.

tRef = vC/s * CL = reference time

vC = adjusted volume combined for lane group

s = saturation flow rate for lane group

CL = reference cycle length

The Reference Time must be greater than the Minimum Green time and is added to the Lost Time to give the Adjusted Reference Time. The ICU is the sum of the critical Adjusted Reference Times divided by the Reference Cycle Length. The Reference Cycle Length is a fixed input value; the default is 120 seconds.

tAdj = max(tRef, tMin) + tL = adjusted reference time

tMin = minimum green time

tL = lost time

There are further adjustments to account for pedestrian time and pedestrian interference.

The reference times for the critical movements are added together to get the combined time required.

Protected, Permitted, or Split Phasing

Only one critical movement has control of the intersection at a time. **Figure 3-1** illustrates the sequence. This is the protected sequence. The combined reference time for Northbound (NB) and Southbound (SB) approaches is:

tNSprot = max(tAdjNBL + tAdjSBT, tAdjSBL + tAdjNBT) = north south combined protected time

tAdjxx = adjusted reference time for movement xx

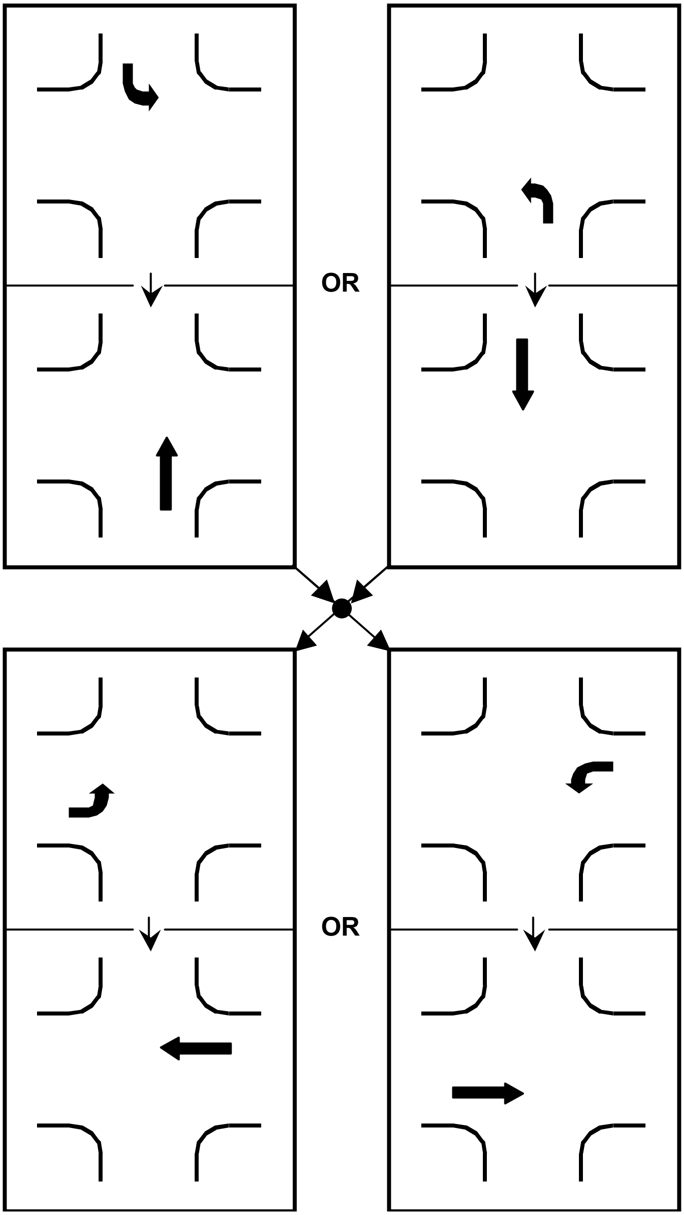

Figure 3-1 One Critical Movement Controls Intersection

Protected phasing cannot be used when there is a shared left-through lane. In this case, the split option or permitted option can be used. **Figure 3-2** shows the intersection control sequence for split phasing. The combined time for northbound and southbound split approaches is the maximum of the northbound reference times plus the maximum of the southbound reference times.

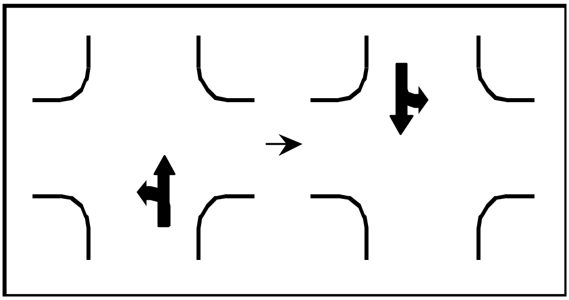

Figure 3-2 Split Phasing

tNS split = max(tAdjNBL, tAdjNBT) + max(tAdjSBL, tAdjSBT) = north south combined split

tAdjxx = adjusted reference time for movement xx

Permitted phasing may be the most efficient phasing when there is a relatively low volume of left turns, a single lane oncoming approach, or low volume of oncoming traffic. **Figure 3-3** shows intersection control for permitted phasing. The combined time for northbound and southbound permitted approaches is the maximum of the northbound and southbound permitted reference times. The permitted reference time calculation is a bit more complex and described in Chapter 5.

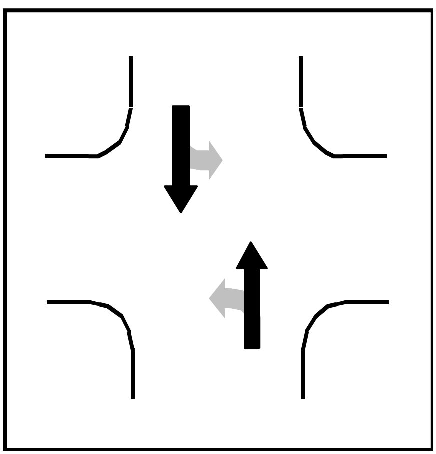

Figure 3-3 Permitted Phasing

tNS perm= max(tAdjNBLpm, tAdjNBTpm, tAdjSBLpm, tAdjSBTpm) = north south combined permitted

tAdjXXpm = adjusted permitted reference time for movement XX

When there are separate lanes for left and through traffic, the protected option should always be the most efficient and give the lowest sum of reference times. The permitted and split options may be more efficient when there is a shared lane. A more complete discussion on permitted lefts and shared lanes is available in Chapter 8.

Figure 3-4 shows how reference times are added up for the protected, permitted, and split options. In this example NBL + SBT is greater than SBL + NBT and is used for the protected option. The permitted and split options are greater than the protected option, so the protected option is used.

Permitted Plus Protected Phasing

There is no option for permitted plus protected phasing. Although this option may be best operationally, it is not the most optimal for evaluating capacity. With exclusive left turn lanes, the protected option will require less reference time than a comparable permitted plus protected option.

With a shared left-through lane, the permitted option will work for low volume situations. At higher left turn volumes, the left lane will become a de facto left turn lane and the intersection can be evaluated using protected phasing converting the left lane to left only.

Permitted plus protected phasing is often thought of incorrectly as a strategy for increasing capacity. This type of phasing is able to reduce delays and improve operations in many, cases but it doesn't increase the capacity of the intersection. A vehicle turning left requires about 2.2 seconds; it can take 2.2 seconds from a protected left turn phase, or from a gap in oncoming traffic during a permitted phase. If there are gaps in oncoming traffic, the oncoming through phase has extra green time that could be reassigned to the left turn phase.

There are three exceptions to the above discussion.

- If there is a shared left-through lane, it is possible that permitted plus protected phasing could add to the capacity. The calculations are very complex just as the in street operation is very complex and prone to safety problems. Shared left-through lanes in conjunction with permitted plus protected phasing should be avoided if possible.

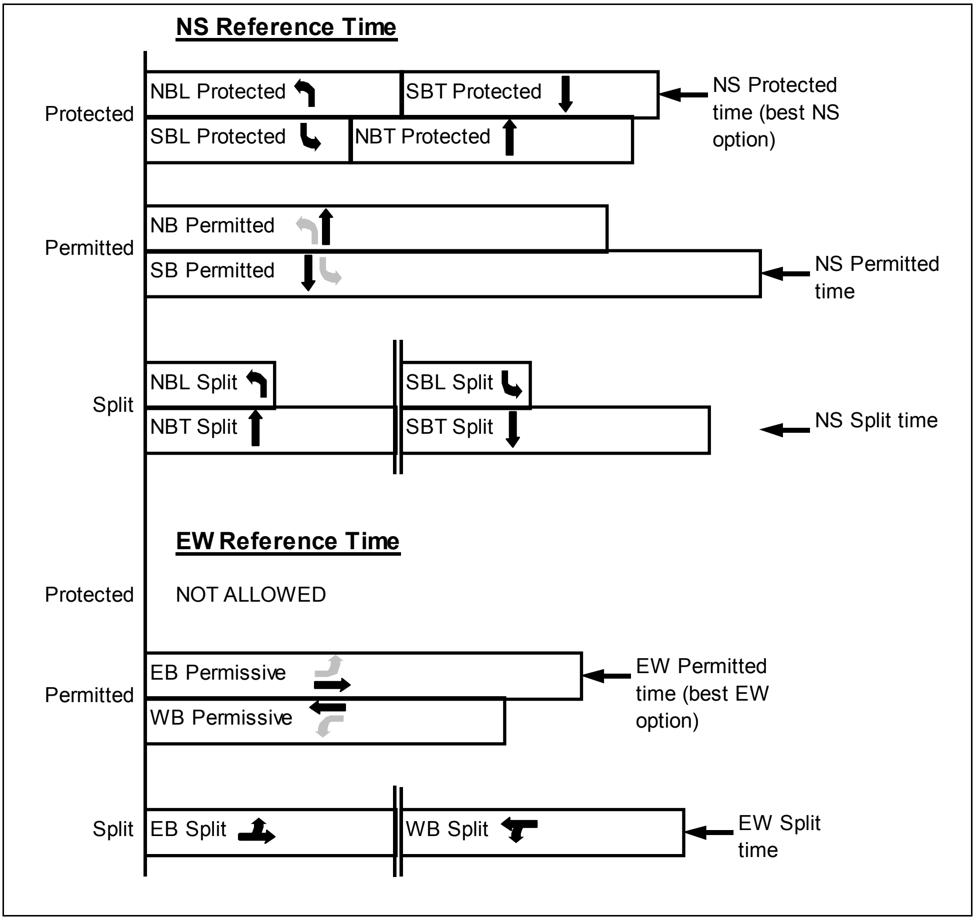

Figure 3-4 Sum of Reference Times

- Permitted plus protected phasing allows for two sneakers at the end of green that can add some "free" capacity for left turns. These left turns in effect are using the lost time of the phase change to get in some extra capacity. These left turns may in add to the lost time of the next phase, especially if the sneakers are trucks.
- If the oncoming through phase must be held green for pedestrians, this time can be used by left turns. Using an actuated pedestrian phase will cause the oncoming phase to only time when there are pedestrians present.

The ICU tries to accommodate these issues to some extent. The permitted option is available for low volume intersections, this option can account for all three of the above phenomenon.

Right Turns

A separate check is made for right turns when there is an exclusive right turn lane. When the right turn is free and has an acceleration lane, the right turn will not conflict with any movement. The adjusted reference time for the right turn is an alternate maximum for the intersection.

Right turns normally conflict with only two movements, the oncoming left turns, and the through traffic from the left (see **Figure 3-5**). The adjusted reference times for the right turns and these other movements are added to find an alternate maximum reference time for the intersection. **Figure 3-6** illustrates how reference times are added with EBR and WBR. In this example, the WBR is the critical movement and its sum is higher than the intersection total. The sum of WBR, EBL and NBT is used for the intersection ICU calculation.

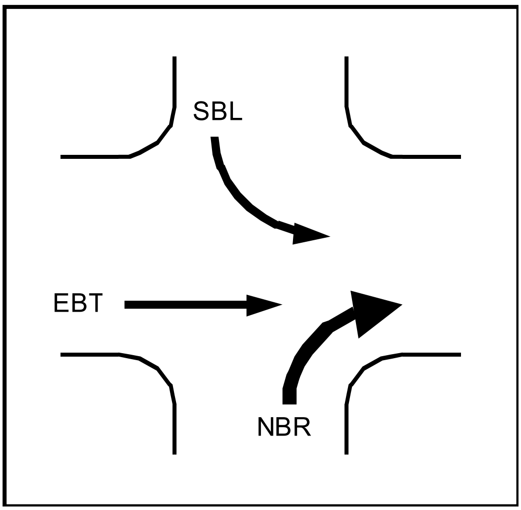

Figure 3-5 Movements Conflicting with Right Turns

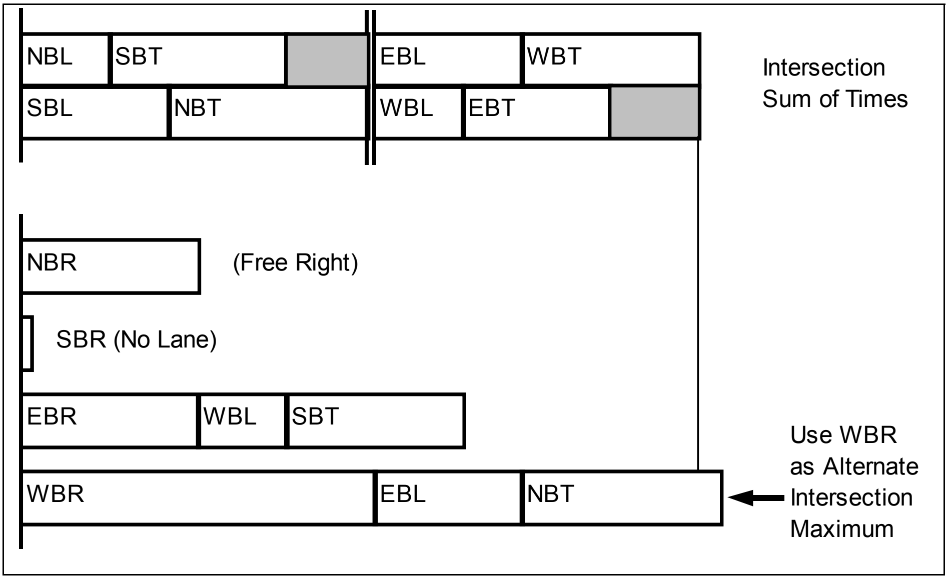

Figure 3-6 Alternate Max Right Turns

When the right turns share a through lane, they are included in the combined volume for the through lane and no special right turn check is needed.

Reference Times Versus Sum of v/s Ratios

The traditional intersection capacity calculation used by the HCM and older ICU is to take the sum of critical v/s ratios (volume to saturated flow rate) and adjust for the lost time.

$$IntVC = (v/s_i) * CL / (CL - (tL_i)) = \text{Traditional Intersection v/c}$$

v/s_i = volume to sat flow ratio for critical lane group i

tL_i = lost time for critical lane group i

CL = cycle length

The new ICU uses a sum of reference times. The relevant formula is:

$$ICU = (v/s_i * CL + tL_i) / CL$$

These resulting values are very close but not exact. If one assumes that all L_i are equal, the ICU formula can be manipulated as follows:

$$ICU = (v/s_i * CL + tL) / CL = (v/s_i) * CL/CL + (tL) / CL$$

$$ICU = (v/s_i) + (tL)/CL$$

Table 3-1 compares the calculation for ICU with the HCM intersection v/c calculation for a range of sum (v/s), cycle lengths and lost times. When the sum(v/s) is in the range 0.9 to 1.1, the two calculations compare to within 2%.

For less saturated intersections, the ICU method will generate a number up to 10% higher than the HCM value. The reason for this difference at lower saturations is that lost time requirements make up a bigger part of the total time required; with the HCM method, the lost time adjustment is always a fixed ratio.

Table 3-1 ICU Compared with HCM Intersection v/c Calculation

			ICU	HCM v/c	
Σ(v/s)	C	L	Σ(v/s)+L/C	Σ(v/s)*C/(C-L)	Difference
0.5	120	16	0.63	0.58	-9.8%
0.7	120	16	0.83	0.81	-3.2%
0.9	120	16	1.03	1.04	0.5%
1.0	120	16	1.13	1.15	1.8%
1.1	120	12	1.20	1.22	1.8%
0.5	200	20	0.60	0.56	-8.0%
0.7	200	20	0.80	0.78	-2.9%
0.9	200	20	1.00	1.00	0.0%
1.0	200	20	1.10	1.11	1.0%
1.1	200	20	1.20	1.22	1.8%
0.5	90	12	0.63	0.58	-9.8%
0.7	90	12	0.83	0.81	-3.2%
0.9	90	12	1.03	1.04	0.5%
1.0	90	12	1.13	1.15	1.8%
1.1	90	12	1.23	1.27	2.8%

where:

C = cycle length

L = sum of lost time

Why does the ICU use sum of reference times rather than the traditional sum of v/s ratios?

The HCM and traditional ICU calculation is a theoretical calculation with no units and is not based on any actual timing plan. There is no provision to insure that minimum times are met.

The sum of reference times is based on time units and represents an actual value. It is the time required to serve all movements at saturation divided by the time available. Using the sum of reference times allows the method to include timing requirements for minimum green times and pedestrians. This method allows for the inclusion of pedestrian only phases, phases serving low volume movements and special timings for things such as transit priority. An ICU <100% guarantees that there is a real timing plan available that can service the input traffic.

Chapter 4 – Data Collection

This chapter discusses the data needed to perform an intersection capacity utilization analysis.

Traffic Counts

Volumes

The most important data for ICU is the turning movement counts for the peak hour. Normally the ICU uses a 60-minute count.

Data can be collected by hand or sometimes automatically with detectors. It is necessary that each intersection movement is counted. Usually data is collected in 15-minute increments. The peak hour is determined by finding the 4 sequential 15-minute periods with the highest total intersection traffic volume.

Older versions of ICU and other methods of intersection analysis use a 15-minute period. 60-minute counts are converted to 15-minute counts using a peak hour factor (PHF). The ICU 2003 eliminates the PHF conversion. The resulting LOS scale has been adjusted to balance out this change in analysis methodology.

It is assumed that the peak 15-minute period will experience traffic that is about 11% higher than the peak 60-minute period. If there is some event that causes a higher spike in 15-minute traffic, it may be necessary to use a 15-minute count. A shift change at a nearby large employer might cause this spike in traffic. To convert the 15-minute count to a 60-minute count multiply by 3.6 or 0.9 * 4. The 0.9 is to take out the normal peak hour factor adjustment and 4 is the four periods.

Volume Fluctuations

Traffic volumes can vary greatly throughout the day, by day of week, by time of year, and even by 5-minute intervals during the peak hour. Traffic volumes can also experience additional fluctuations due to accidents, special events, or weather and will also change over time as cities grow.

The following three figures illustrate how traffic can fluctuate by day of the week, hour of the day, and over 5-minute intervals in the peak hour. In many areas, it is common for Friday afternoon traffic to be 10% to 20% higher than other weekdays due to recreational weekend traffic.

Normally traffic studies are performed using the average weekday peak hour traffic counts. For a normal commute route there will be a morning and an afternoon peak.

For shopping areas, the busiest traffic usually occurs on Saturday afternoon and traffic may be heavy for many hours.

When performing traffic studies it is necessary to be aware of the peak trip times, and perform analysis for these times. Collecting data for multiple days is preferable to a single day.

Remember that traffic does fluctuate and there is no single correct answer for when to collect traffic volume data. For locations with higher levels of traffic fluctuation, a lower ICU LOS is advised. Note that a delay-based analysis such as HCM will not be able to predict whether the facility is able to handle higher traffic volumes due to fluctuations.

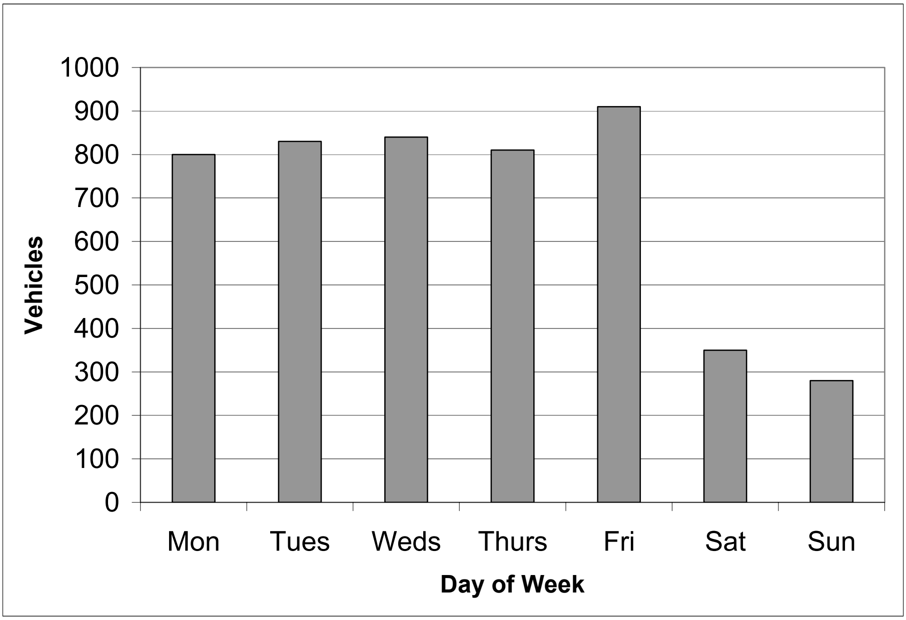

Figure 4-1 Volume Fluctuations by Day of Week

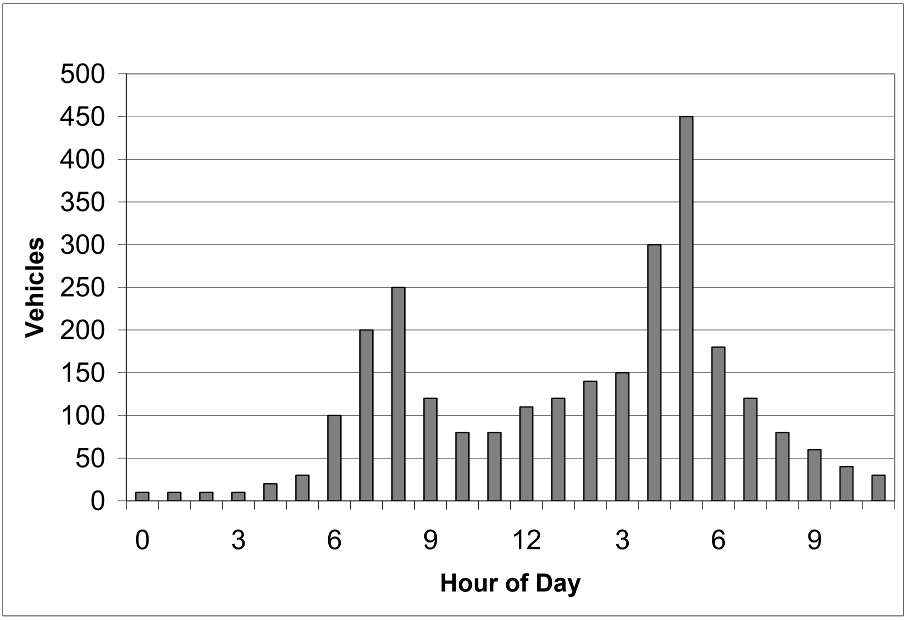

Figure 4-2 Volume Fluctuations by Hour of Day

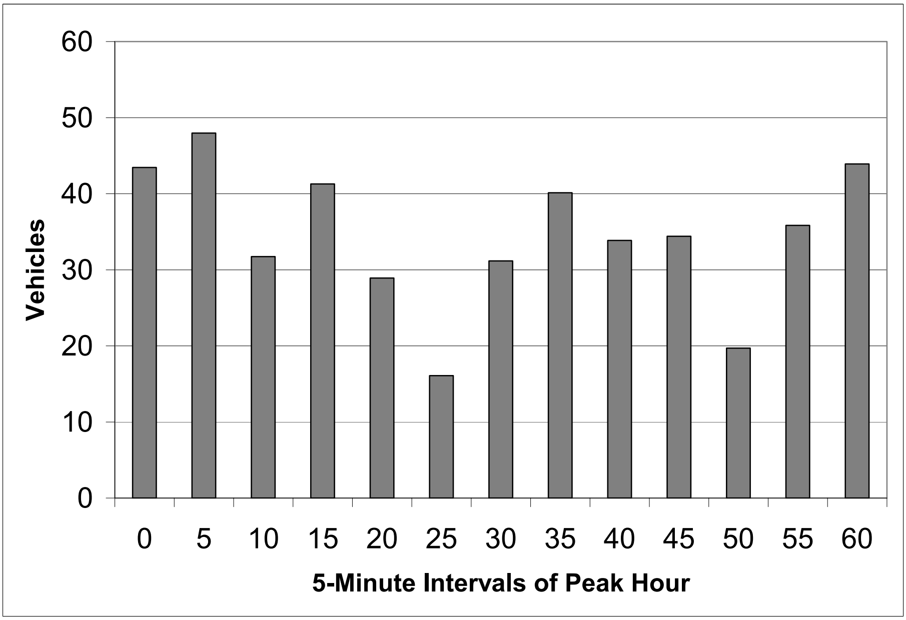

Figure 4-3 Volume Fluctuations by 5-Minute Intervals of Peak Hour

Pedestrians

The number of pedestrians is needed to determine their interference with right turning traffic and to estimate how frequent pedestrian phases are called.

Exact figures for this data aren't strictly required; a guess to within ±50% is usually adequate.

Less than five pedestrians per hour will have the minimum effect.

Pedestrians over 100 per hour will have the maximum effect.

Number of Lanes

For an existing intersection, simply record the number of lanes and the allowed movements for each lane.

For a future scenario, it may be necessary to try several alternatives. The ICU spreadsheet allows alternate lane numbers and assignments to be tried while giving instant feedback to their effects on capacity.

Saturated Flow Rates

The Ideal Saturated Flow rates are inputted in the ICU method. By default, the ideal saturated flow rates are 1900 vehicle per hour per lane (vphpl) for intersections and 2000 vphpl for interchanges. These are the default values used in the HCM 2000. Actual measurements of saturated flow rates have found a variation between 1700 and 2200 vphpl.

The ideal saturated flow rates entered will be adjusted for turning factors (0.95 for left turns and 0.85 for right turns), lane utilization, and permitted left turns.

In general, higher speed facilities will have higher saturated flow rates. Here is a guide for saturation flow rates to use:

1700 vphpl	Central Business District with slow speeds, short block spacing, transit, and parking activity
1900 vphpl	Medium density areas with speeds of 25 to 35 mph.
2000 vphpl	Interchanges and other limited access intersections with speeds of 35 to 50 mph
2100 vphpl	High-speed intersections on limited access roadways (a saturated flow rate study should be used to justify)

It is recommended to use local data if available. To collect saturated flow rate data, count the number of vehicles crossing the stop bar while there is a queue, starting at the beginning of green.

s' = N/(t-2.5)*3600 = observed sat flow rate

N = number of vehicles crossing stop bar

t = time until queue is cleared

2.5 = start up lost time

Remember to convert collected data into to ideal rates by dividing out turning factors and lane utilization factors.

Signal Timings

One huge benefit to using ICU is that it is not necessary to know or estimate the traffic signal timings. The method generates a capacity analysis that is independent of any signal timing plan. Reference times are generated by the method.

However, it is still necessary to know some timing parameters as discussed below.

Reference Cycle Length

The Reference Cycle Length is the longest desired cycle length. The default is 120 seconds.

The value entered should be the maximum cycle length used by the agency during the peak hour. Suggested values are:

120 s	suburban arterial
200 s	expressway with high speeds, long block spacing and adequate storage lengths
90 s	central business district with short block spacing, small intersections, and permitted left turns

Lost Time

The total Lost Time is equal to the Startup Lost Time plus the Clearance interval (yellow and all-red time, less the extension of effective green, see **Figure 4-4**).

The startup lost time is typically 2 seconds. The extension of effective green is typically 2 seconds. This yields a lost time equal to the yellow + all-red time.

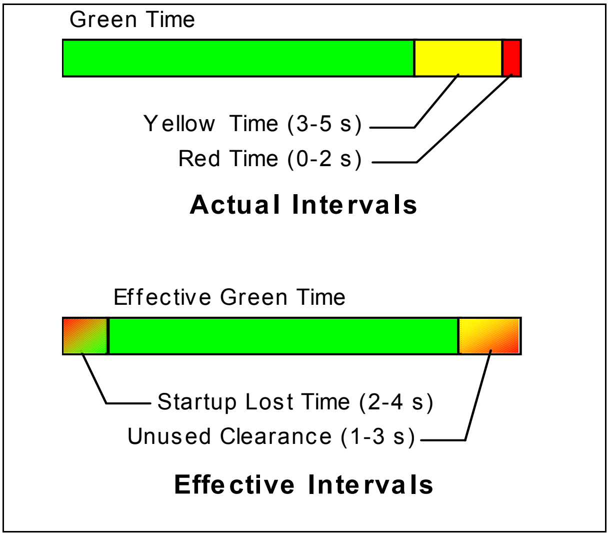

Figure 4-4 Total Lost Time

For normal intersections with speeds of 35 mph or less, a lost time of 4 seconds can be used. For higher speeds and larger width intersections, a larger lost time is recommended. However, the lost time should normally equal the yellow plus all red time.

An alternative minimum for the lost time is to use the travel time through the intersection plus 2 seconds. Remember, turning traffic moves slower, perhaps at 15 mph for left turns. This calculation will be significant for turning paths through large intersections. Single point urban interchanges require longer lost times.

tL = min (4s, 2s + D/sp, Y+AR) = lost time

Y+AR = yellow plus all-red time

D = distance though intersections

sp = speed through intersection, 15 mph for left turns

Pedestrian crossing times

The pedestrian crossing times are used to determine the timing requirements for pedestrians. Traditionally a time of 4 ft/s is used for pedestrian flashing don't walk crossing times plus a minimum of 4 seconds for the walk time. If the study area is in an area with many seniors, a slower speed should be considered. Newer studies recommend using 3.5 ft/s to determine pedestrian flashing don't walk times.

The street width is also needed for this calculation.

The lost time is added to the pedestrian time so there will be an extra 4 seconds available for pedestrians.

If the signal is actuated and a pedestrian button is available, the pedestrian time will only be required for some of the cycles.

Chapter 5 – Intersection Calculation

Overview

Step by Step

This section contains line-by-line instructions for filling out the worksheet. **Figure 5-1** shows the Intersection Capacity Utilization worksheet.

Symbols

Table 5-1 defines the symbols used in the calculations along with the section they appear in, their line number and their units.

The L, T, and R suffixes can be used to indicate left, through, or right. A full movement name such as "NBL" can be used as a suffix to specify a specific movement (i.e., Northbound Left).

Intersection Capacity Utilization Worksheet

Intersection Location:		**City:**	
Analyzed by:		**Alternative:**	
Date and Time of Data:		**Project:**	

1	**Movement**	**EBL**	**EBT**	**EBR**	**WBL**	**WBT**	**WBR**	**NBL**	**NBT**	**NBR**	**SBL**	**SBT**	**SBR**
2	Lanes												
3	Shared LT Lane (y/n)	☐ Yes			☐ Yes			☐ Yes			☐ Yes		
4	Volume												
5	Pedestrians												
6	Ped Button (y/n)		☐ Yes			☐ Yes			☐ Yes			☐ Yes	
7	Pedestrian Timing Required												
8	Free Right (y/n)			☐ Yes			☐ Yes			☐ Yes			☐ Yes
9	Ideal Flow												
10	Lost Time												
11	Minimum Green												
12	Reference Cycle Length												
13	Volume Combined												
14	Volume Separate Left												
15	Lane Utilization Factor												
16	Turning Factor Adjust												
17	Saturated Flow Combined												
18	Saturated Flow Separate												
19	Pedestrian Interference Time												
20	Pedestrian Frequency												
21	**Protected Option Allowed**												
22	Reference Time												
23	Adjusted Reference Time												
	Permitted Option												
24	Proportion Lefts												
25	Volume Left Lane												
26	Proportion Lefts Left												
27	Left-turn Equivalents												
28	Left-turn Factor												
29	Permitted Sat Flow												
30	Reference Time A												
31	Adjusted Saturation B												
32	Reference Time B												
33	Reference Time Lefts												
34	Reference Time												
35	Adjusted Reference Time												
	Split Timing												
36	Ref Time Combined												
37	Ref Time By Movement												
38	Reference Time												
39	Adjusted Reference Time												

	Summary	**East West**	**North South**
40	Protected Option		
41	Permitted Option		
42	Split Option		
43	Minimum		
44	Combined		

	Right Turns	**EBR**	**WBR**	**NBR**	**SBR**
45	Adjusted Reference Time				
46	Cross Through Direction				
47	Cross Through Adj Ref Time				
48	Oncoming Left Direction				
49	Oncoming Left Adj Ref Time				
50	Combined				

51	**Intersection Capacity Utilization**	
52	**Level Of Service**	

Revision 2003.0

Figure 5-1 Intersection Capacity Utilization Worksheet

Table 5-1 Intersection Capacity Utilization Worksheet Key

Section	Line #	Symbol	Units	Description
Input	2	n	number	Lanes
Input	4	v	vph	Volume
Input	5	ped	pph	Pedestrians
Input	7	tPed	s	Pedestrian Timing Required
Input	9	i	s	Ideal Flow
Input	10	tL	s	Lost Time
Input	11	tMin	s	Minimum Green
Input	12	CL	s	Reference Cycle Length
Calculations	13	vC	vph	Volume Combined
Calculations	14	vS	vph	Volume Separate Left
Calculations	15	fLU	factor	Lane Utilization Factor
Calculations	16	fT	factor	Turning Factor Adjust
Calculations	17	S	vph	Saturated Flow Combined
Calculations	18	sC	vph	Saturated Flow Separate
Calculations	19	intf	s	Pedestrian Interference Time
Calculations	20	freq	factor	Pedestrian Frequency
Protected	22	tRef	s	Reference Time
Protected	23	tAdj	s	Adjusted Reference Time
Permitted	24	pL	factor	Proportion Lefts
Permitted	25	EL	number	Left-turn Equivalents
Permitted	26	fLT	factor	Left-turn Factor
Permitted	27	sA	vph	Permitted Sat Flow
Permitted	30	tRefA	s	Reference Time A
Permitted	31	sB	vph	Adjusted Saturation B
Permitted	32	tRefB	s	Reference Time B
Permitted	33	tRefBL	s	Reference Time Lefts
Permitted	34	tRefPerm	s	Reference Time
Permitted	35	tAdjPerm	s	Adjusted Reference Time
Split	36	tRefC	s	Ref Time Combined
Split	37	tSefS	s	Ref Time By Movement
Split	38	tRefSplit	s	Reference Time
Split	39	tAdjSplit	s	Adjusted Reference Time
Summary	40	tProtxx	s	Protected Option
Summary	41	tPermxx	s	Permitted Option
Summary	42	tsSplitxx	s	Split Option
Summary	44	tCombined	s	Combined
Right Turns	45	tAdj	s	Adjusted Reference Time
Right Turns	47	tAdjMinT	s	Cross Through Adj Ref Time
Right Turns	49	tAdjMinL	s	Oncoming Left Adj Ref Time
ICU	51	ICU	factor	Intersection Capacity Utilization
ICU	52	LOS	letter	Level Of Service

Inputs

Rows 1 to 12 represent input data. Refer to Chapter 4 for a detailed discussion about data collection and input parameters.

1. **Movement names:** 1 column for each of the 12 basic directions. NBL is northbound left. EBR is eastbound right, etc.
2. **Number of Lanes:** (n) Enter the number of lanes for each movement. Any type of shared lane counts as a through lane. For example, if the lane geometry is L LT T TR, enter 1 left, 3 through, and 0 right lanes. A LR lane should be entered as a through lane.
3. **Shared Left Through Lane:** Enter a "y" if there is a shared left-through lane.
4. **Volume:** (v) Enter the number of vehicles per hour for each movement. Refer to Chapter 4 for instructions about using 15-minute counts.
5. **Pedestrians**: (ped) Enter the number of pedestrians per hour. Enter the number of pedestrians on the link to the right of the movement. These pedestrians will conflict with right turns and walk on the phase associated with this leg's through movement. Refer to Chapter 4 for instructions about collecting or estimating pedestrian data.
6. **Pedestrian Button:** Enter "y" if this signal is actuated and there is a push button for these pedestrians.
7. **Pedestrian Timing Required:** (tPed) Enter the time required for pedestrians to cross the leg to the right. This time includes walk and flashing-don't-walk, but not yellow or all-red time. Enter zero if pedestrians are prohibited for this movement or this is an area with no pedestrians.
8. **Free Right:** Enter "y" if there is a right turn lane and right turns can move at all times into their own departure lane.
9. **Ideal Flow:** (i) This is the ideal saturated flow rate of vehicles. The value used may vary between 1700 and 2200 vphpl. The default is 1900 vphpl. Refer to Chapter 4 for a discussion about which saturated flow rates to use.
10. **Lost Time:** (tL) This is the total lost time for the movement including start-up lost time and clearance interval lost time. The minimum lost time is 4 seconds. If this is a very large intersection, such as a single-point urban interchange, use a larger value for lost time. Lost time must be greater than or equal to the travel time through the intersection. Turning traffic may have a longer travel time due to their slower turning speeds.
11. **Minimum Green Time:** (tMin) This is the minimum time a signal can show green. Enter 4 seconds for all movements (longer in some jurisdictions).

Reference Cycle Length: (CL) This is an input value with a default of 120 seconds. An agency may decide to use an alternate value based on local conditions. Refer to Chapter 4 for a discussion about which cycle length is appropriate to use.

This is the end of the data inputs. If using the spreadsheet, you are now finished and the remaining items are calculated automatically.

Calculations

Lines 13 to 52 are used for calculations. Normally these are performed automatically with a spreadsheet or software. These instructions give a step-by-step reference to the ICU 2003 methods. These instructions also explain some of the reasons behind the method.

12. **Volume Combined:** (vC) This is the volume assigned to each lane group.

    vCT = vT + vR* + vL**

    vCL = vL**

    vCR = vR*

    *vR is added to vCT when nR = 0, otherwise vR is added to vCR.

    ** vL is added to vCT when there is a left-through lane (Line 3 = yes), otherwise vL is added to vCL.

13. **Volume Separate Left:** (vS) This is the volume assigned to lane groups, except that left traffic is kept in the left lane group. This value is used for the Permitted "B" calculation and Split Timing calculation.

    vST = vT + vR*

    vSL = vL

    vSR = vR*

    *vR is added to vCT when nR = 0, otherwise vR is added to vCR.

14. **Lane Utilization Factor:** (fLU) This factor adjusts the saturated flow rate when there are 2 or more lanes. This adjustment accounts for the unequal use of lanes.

Table 5-2 Lane Utilization Factor

Number of Lanes	Left	Through	Right
1	1.0	1.0	1.0
2	0.971	0.952	0.885
3 or more	0.971	0.908	0.885

15. **Turning Factor Adjustment:** (fT) This factor adjusts for the number of right or left turners in the lane group.

fTL = 0.95

fTR = 0.85

fTT = (1 - 0.15 * (vR - vCR)/vCT) * (1 - 0.05 * (vL - vCL)/vCT)

16. **Saturated Flow Rate Combined:** (s) This is the adjusted saturated flow rate.

s = i * n * fLU * fT

If there is a shared Left-Through lane (line 3), count the left lanes in the through group and then leave the left saturated flow rate blank.

sT = i * (nT + nL) * fLU * fT

sL = 0

17. **Saturated Flow Rate Separate :** (sC) This is used with a shared left-through lane. This value is used for the Permitted "B" calculation and Split Timing calculation.

sC = i * n * fLU * fT

If there is a shared Left-Through lane (line 3), add one to the number of left lanes. Also include the shared lane in the through flow rate.

sCT = i * nT * fLU * (1 - 0.15 * (vR - vSR) / vST)

sCL = i * (nL + 1) * fLU * fT

18. **Pedestrian Interference Time:** (intf) This is the time that traffic will be blocked by pedestrians. For right turns use the formula:

intfR = 24 - 8 * e^(-ped/2*(CL-8)/3600) - 16 * e^(-ped/2*4/3600)

For through movements with no right lanes, use the formula:

intfT = [24 - 8 * e^(-ped/2*(CL-8)/3600) - 16 * e^(-ped/2*4/3600)] * vR/vC

Otherwise, Pedestrian Interference time is zero. Pedestrians can cause up to 24 seconds of delay per cycle. Four seconds each for pedestrians starting immediately from the near and far sides or 8 seconds total; up to 16 seconds for pedestrians starting within the first 8 seconds of green time in either direction.

The 8 * e^(-ped/2*112/3600) term represents the pedestrians starting immediately. Pedestrians are divided by 2 for two directions. 112/3600 represents 112 seconds of pedestrians, the reference cycle less the first 8 seconds. The 8 represents 4 seconds of interference per direction times two directions.

The 16 * e^(-ped/2*4/3600) term represents the pedestrians starting during the first 8 seconds, but not immediately. Pedestrians are divided by 2 for two directions. 4/3600 represents 4 seconds of pedestrians. The 16 represents 4 seconds of interference per direction multiplied by two directions multiplied by two-4 second intervals. This term will be less than 1 second when ped is less than 120.

20. **Pedestrian Frequency:** (freq) This is the probability of a pedestrian activating the pedestrian timings on any cycle. If pedestrians are 0 (line 6), enter 0. If there is no push button (line 7), enter 1. Otherwise use this formula:

    freq = 1 - e^(-ped*CL/3600)

Protected Option

Lines 21 to 23 calculate the ICU using protected phasing. This option is not available if a shared left-through lane is present in either of the opposing directions. If your intersection has a left-through lane, you might try reclassifying it as an exclusive left lane and/or an exclusive through lane to evaluate the intersection using protected phasing. The protected phasing will usually be the most efficient operation, except at low volume intersections.

21. **Protected Option Allowed:** The protected option is allowed for a movement (NS or EW) when that movement has no shared left-through lanes. The protected option is allowed for eastbound and westbound, when neither of these movements has a shared left-through lane (line 3). Mark Yes or No for the north-south movements and then the east-west movements. Leave lines 22 and 23 blank for the movements where protected phasing is not allowed.

22. **Reference Time:** (tRef) This is the time required to serve the adjusted volume at 100% saturation.

    tRef = vC / s * CL + intf

    If there is no volume for this movement, leave this entry and row 23 blank.

23. **Adjusted Reference Time:** (tAdj) This is the reference time adjusted for minimums, pedestrians, and lost time. For through movements, use the formula:

    tAdj = tLost + max(tMin, tRef) * (1 - freq) + max(tMin, tRef, tPed) * freq

    Pedestrian times are not needed for exclusive left and right movements. Use this formula for left and right movements:

    tAdj = tLost + max(tMin, tRef)

    If the movement has 0 capacity and 0 volume, such as a one-way street or prohibited left; enter 0.

Permitted Option

Lines 24 to 35 calculate the ICU using a permitted left turn option. Traditionally the ICU method did not allow for permitted left turns because it is taking a sum of conflicting movements. However using the protected option requires a dedicated left lane. Many intersections in urban areas have shared left-through lanes that are analyzed too conservatively with the protected or split options. Intersections with single lane approaches may operate more efficiently using permitted left turns because left turns on opposing approaches create gaps for each other.

Chapter 8 contains more discussion about permitted left turns, shared lanes, and single lane approaches. Trafficware performed some research using simulation to determine the maximum theoretical capacity for a full range of single lane approaches and the results are explained there.

The ICU 2003 contains two options for treating permitted left turns. Option "A" assumes that there are relatively few left turners. These left turners will be accommodated as sneakers at the end of a green or when there is a left turn on an oncoming single lane approach. Option "A" should only be used when the left turn volume is less than 60 vph or the oncoming approach is a single lane with some left turn traffic.

Option "B" assumes that the oncoming traffic is relatively light and that oncoming traffic will only block the left turns for the first 8 seconds of green. Option "B" is only available when the oncoming traffic is less than 120 vph.

If the volume exceeds the requirements for both Options "A" and "B", it is considered that the intersection would operate as efficiently using protected or split phasing. It may be necessary to reclassify a left-through lane as a left only lane for the analysis. More information about permitted left turns is available in Chapter 8.

24. **Proportion of Lefts:** (pL) This is the proportion of left turn traffic in the lane group. This will be 1 for the left group and 0 for a through group without a shared lane.

    pL = vL / vC, for shared left-through lane

25. **Volume Left Lane:** (vLL) This is the traffic in the left lane for a multi-lane lane group. The formula assumes that for the purposes of lane selection, a left turn will count the equivalent of 5 vehicles. The volume in the left lane will be at least equal to the left turn volume.

    vLL = vC * max(pL, (pL*4+1)/n - pL*4)

    For a left lane group: vLL = vC / n

26. **Proportion of Lefts in Left Lane:** (pLL) This is the proportion of left turning traffic in the left lane. For a single-lane lane group this will be the same as pL.

    pLL = pL * vC/vLL

    For a left lane group: pLL = 1

27. **Left Turn Equivalents:** (EL) This represents the number of vehicle equivalents each left turner represents. It is equal to the time a left turner will take divided by the 2 seconds that a through vehicle will use.

$EL = (0.5 + 0.8 * pLL - 0.3 * pLL^2) / [2* (1 + pLL)/CL + vLO / vCO]$

vLO = volume of oncoming left turns. Only use vLO term when oncoming is a single lane with left traffic, otherwise this term is zero.

vCO = combined volume of oncoming traffic in single lane

This formula was derived by research performed by Trafficware simulating permitted left turns at shared lanes. More information about permitted left turns can be found in Chapter 8.

The denominator determines the opportunities for left turns to go. The first term represents 2 seconds for each sneaker, 2nd sneaker is proportion of left; the entire term is multiplied by two because the left turns will block for 1/2 the cycle on average.

The second denominator term accounts for left turns in the oncoming traffic stream.

28. **Left Turn Factor:** (fLT) The left turn factor is multiplied by the saturated flow rate to determine an adjusted capacity.

    $fLT = 1 / [1 + pLL * (EL – 1)]$

29. **Adjusted Saturation A:** (sA) This is the saturation flow rate adjusted for permitted lefts for the left lane only.

    $sA = s * fLT / n$

30. **Reference Time A:** (tRefA) This is the reference time for a permitted movement adjusted for permitted left equivalents.

    $tRefA = max(vLL * CL / sA + intf, vC * CL/ s)$

    The alternate maximum for volume combined is to handle the case where left turns are unimpeded, the left lane with the vLL assignment would have less time requirements than the other lanes.

31. **Adjusted Saturation B:** (sB) This is the saturated flow rate of the through lanes without the shared lane. If there is a shared left-through lane, enter:

    $sBT = sT * (nT - 1) / nT$.

    With no shared lane: $sBT = sT$

32. **Reference Time B:** (tRefB) If oncoming through traffic is greater than 120 vph, enter "NA". Otherwise enter:

    $tRefB = 8 + (vST - 8 * sBT / CL) * CL / sS + intf$

    This formula assumes that the left lane will be blocked for 8 seconds to account for the oncoming traffic of up to 120 vph.

33. **Reference Time Lefts:** (tRefBL) If oncoming through traffic is greater than 120 vph, enter "NA". Otherwise enter:

    tRefBL = 8 + vSL * CL / sS

    8 seconds are added to account for the oncoming traffic of up to 120 vph.

34. **Reference Time:** (tRefPerm) Use the minimum of the maximum of (Reference Time A left and Reference Time A through) and the maximum of (Reference Time B and Reference Line Lefts).

    tRefPerm = min(max(tRefAL, tRefAT), max(tRefBL, tRefB))

35. **Adjusted Reference Time:** (tAdjPerm) This is the reference time adjusted for minimums, pedestrians, and lost time. Use the formula:

    tAdjPerm = tLost + max(tMin, tRefPerm) * (1 - freq) + max(tMin, tRefPerm, tPed) * freq

Split Option

Lines 36 to 39 calculate the ICU using split phasing. The split option is always allowed, in some cases the split option is the only option allowed. The split option analyzes the combined lane group and also checks the left and through traffic independently.

36. **Reference Time Combined:** (tRefC) Use the formula:

    tRefC = vC / s * CL + intf

37. **Reference Time By Movement:** (tRefS) Use the formula:

    tRefS = vS / sS * CL + intf

38. **Reference Time:** (tRefSplit) Use the maximum of Reference Time Combined and the two Reference Times by Movement.

    tRefSplit = max (tRefC, tRefST, tRefSL)

39. **Adjusted Reference Time:** (tAdjSplit) This is the reference time adjusted for minimums, pedestrians, and lost time. Use the formula:

    tAdjSplit = tLost + max(tMin, tRefSplit) * (1 - freq) + max(tMin, tRefSplit, tPed) * freq

    If the movement has 0 volume and 0 capacity, such as a one-way street or unused leg at T; enter 0.

Summary

This section summarizes and combines the required times for left and through traffic by approach pairs. The best solution is found for each approach pair and combined.

40. **Protected Option:** (tProt) Add the Adjusted Reference Times from line 23, if computed.

    tProtNS = max(tAdjNBL + tAdjSBT, tAdjSBL + tAdjNBT)

    tProtEW = max(tAdjEBL + tAdjWBT, tAdjWBL + tAdjEBT)

41. **Permitted Option:** (tPerm) Take the maximum Adjusted Reference Times from line 35, if computed.

    tPermNS = max(tAdjPermNBT, tAdjPermSBT)

    tPermEW = max(tAdjPermEBT, tAdjPermWBT)

    Enter NA, if permitted is not allowed for the approach pair.

42. **Split Option:** (tSplit) Take the sum of the Adjusted Reference Times from line 39.

    tSplitNS = tAdjSplitNBT + tAdjSplitSBT

    tSplitEW = tAdjSplitEBT + tAdjSplitWBT

43. **Minimum:** For each approach pair, take the minimum combined adjusted reference time. For each column, take the minimum value from lines 40 to 42.

44. **Combined:** (tCombined) Add the two columns from line 43

Right Turns

Right turns from exclusive lanes are calculated by a separate calculation. This accounts for free rights, overlapping right turn phases, and right turns on red.

45. **Adjusted Reference Time:** (tAdj) Copy the Adjusted Reference Times for right turns from line 23. For approaches with 0 exclusive right lanes, this value will be 0.

46. **Cross Through Direction:** This is the direction from the left side that will merge with the right turns. Enter SBT, NBT, EBT, WBT for EBR, WBR, NBR, and SBR., respectively.

47. **Cross Through Adjusted Reference Time:** (tAdjMinT) Enter the minimum Adjusted Reference Times for the cross through movement from lines 23, 35, and 39.

    tAdjMinT = min(tAdj, tAdjPerm, tAdjSplit)

48. **Oncoming Left Direction:** This is the oncoming direction from which left traffic will merge with the right turns. Enter WBL, EBL, SBL, and NBL for EBR, WBR, NBR, and SBR.

49. **Oncoming Adjusted Left Reference Time:** (tAdjMinL) Enter the minimum Adjusted Reference Times for the cross left movement from lines 23, and 39. Do not include the permitted time for oncoming left. The split reference time for left movements should be the same as for through movements.

tAdjMinL = min(tAdj, tAdjSplit)

50. **Combined:** If this movement is a free right, copy line 45. Otherwise add lines 45, 47, and 49.

Final Calculations

51. **Intersection Capacity Utilization:** (ICU) Use line 44 or the sum of values on line 50, whichever is the maximum, and divide by the Reference Cycle Length. This is the Intersection Capacity Utilization. It is similar to, but not exactly the same as the intersection volume to capacity ratio. A value less than 1 indicates that the intersection has extra capacity. A value greater than 1 indicates the intersection is over capacity.

52. **Level of Service:** Enter a letter A to H based on **Table 5-3** and Line 51. Note that the ICU 2003 includes additional levels past F to further differentiate congested operation. The ICU table has been adjusted to account for volumes not being adjusted for PHF.

    A complete discussion of LOS can be found in Chapter 2.

Table 5-3 Level of Service

LOS	New ICU
A	≤55.0%*
B	>55% to 64.0%
C	>64% to 73.0%
D	>73% to 82.0%
E	>82% to 91.0%
F	>91% to 100.0%
G	>100% to 109.0%
H	>109%

* Note: An ICU value equal to 55.0% would be LOS A, while an ICU of 55.1 % is LOS B.

Discussion

The ICU method is designed to give the ICU results comparable to the intersection volume to capacity ratio determined by the HCM 2000 methods. In some cases, the results may vary due to differences in calculation and the philosophy behind the calculations. The following sections discuss some of these differences.

Reference Cycle Length

One criticism of using ICU and intersection v/c ratios is that they vary depending on the cycle length. The percentage of lost time is directly related to the cycle length, using a longer cycle length can reduce the lost time and improve the ICU and v/c ratio.

The ICU 2003 requires the use of a fixed Reference Cycle Length. All analysis is performed using this cycle length insuring that the amount of lost time is consistent for all evaluations. By default, the Reference Cycle Length is 120 seconds. It is possible for an agency to specify another Reference Cycle Length to match their desired maximum cycle length. However, the agency must consistently use the same Reference Cycle Length for all intersection analyses to provide consistency.

The use of a Reference Cycle Length does not imply that the intersections should operate at this cycle. The ICU is to be used for measuring capacity and is not to be used for operations or designing timing plans.

Conclusion

The ICU 2003 method is presented as an accurate, easy to use method for determining intersection level-of-service. The method is intended to provide an alternative to the HCM intersection methods for the applications of planning, roadway design, and traffic impact studies.

The method does not optimize or use an actual timing plan and it does not calculate delays. The method is not appropriate for signal timing design or operations. The ICU method is intended for use in conjunction with other analysis methods such as Synchro and the HCM.

The ICU gives a clear, accurate comparison of an intersection's current volume to its ultimate capacity.

Chapter 6 – Diamond Interchanges

A diamond interchange is the most common type of freeway interchange. An example of a diamond interchange layout is shown in **Figure 6-1**.

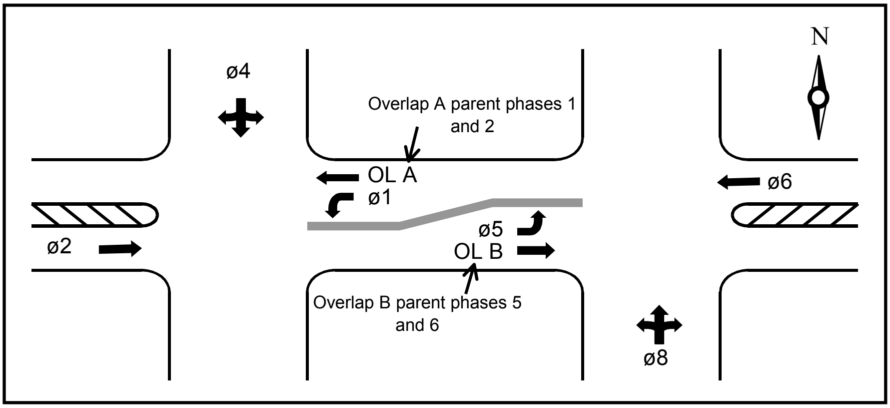

Figure 6-1 Example Diamond Interchange Layout

The signal timing for a diamond interchange can be tricky because the short distance between the intersections can lead to spillback and blocking. The six movements through an interchange that are subject to spillback are shown in **Figure 6-2** and **Figure 6-3**. Note that there are 4 interlocking left turn movements, no two of which can be served simultaneously. The on-ramp left turns are typically the most critical because of the limited left turn storage space between the intersections.

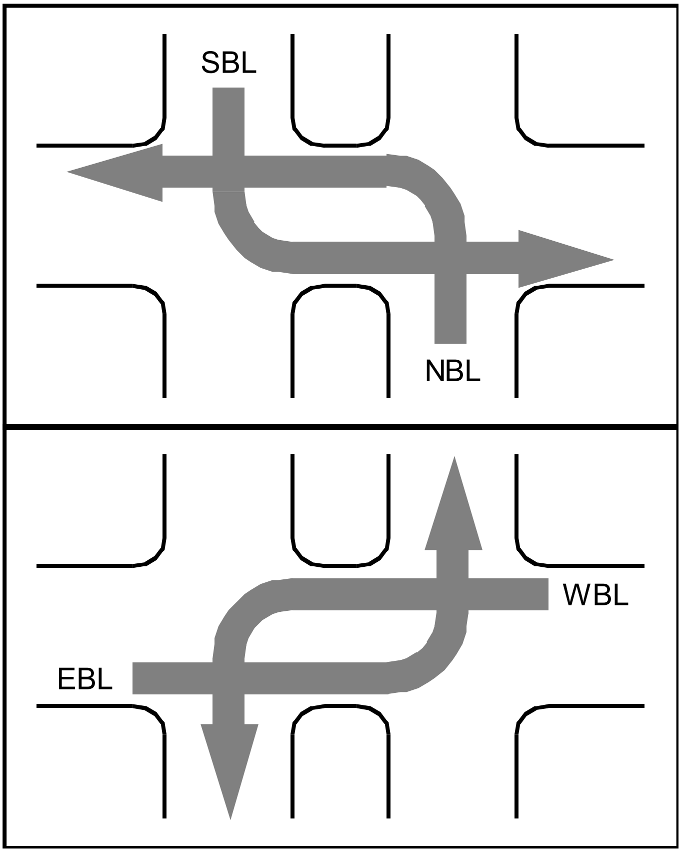

Figure 6-2 Movements Subject to Spillback –1

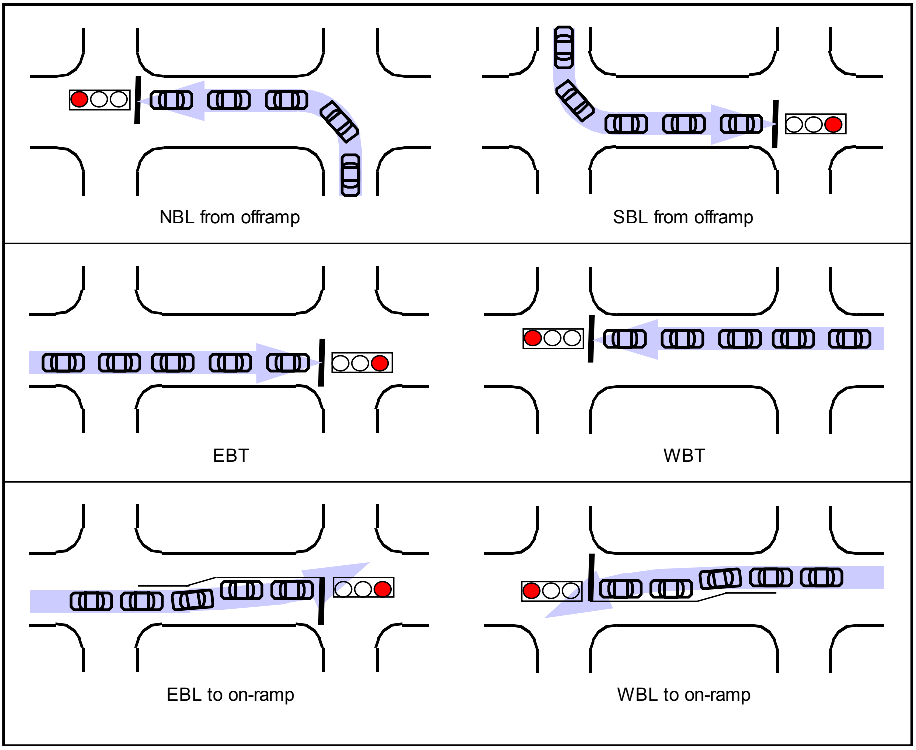

Figure 6-3 Movements Subject to Spillback –2

Some special considerations for ICU diamond interchanges include:

- Special timing plans are required to prevent spillback
- Checks are required to insure adequate storage space
- All left turns are protected
- No option for permitted left turns
- No option for shared left-though lanes on arterial
- Higher Ideal Saturated Flow rates

It is possible to use permitted or permitted plus protected phasing at a diamond interchange. This procedure is focused on high volume interchanges with exclusive left turn lanes. Permitted and shared lanes are not considered.

Storage Space

A timing plan with a phase that serves half of a spillback movement can only be used if there is sufficient storage space to store the traffic for that movement. **Figure 6-4** shows how to determine the storage space for the spillback movements. For the through (EBT/WBT) movements and the off ramp left turns, the storage space is equal to the internal distance between the intersections multiplied by the number of through lanes.

For the on ramp through movements, the storage space is equal to the space in the turning bay, plus any lanes that reach back for the entire internal distance. If no left lanes extend back, one lane of through traffic can be counted as storage upstream of the left turn bay.

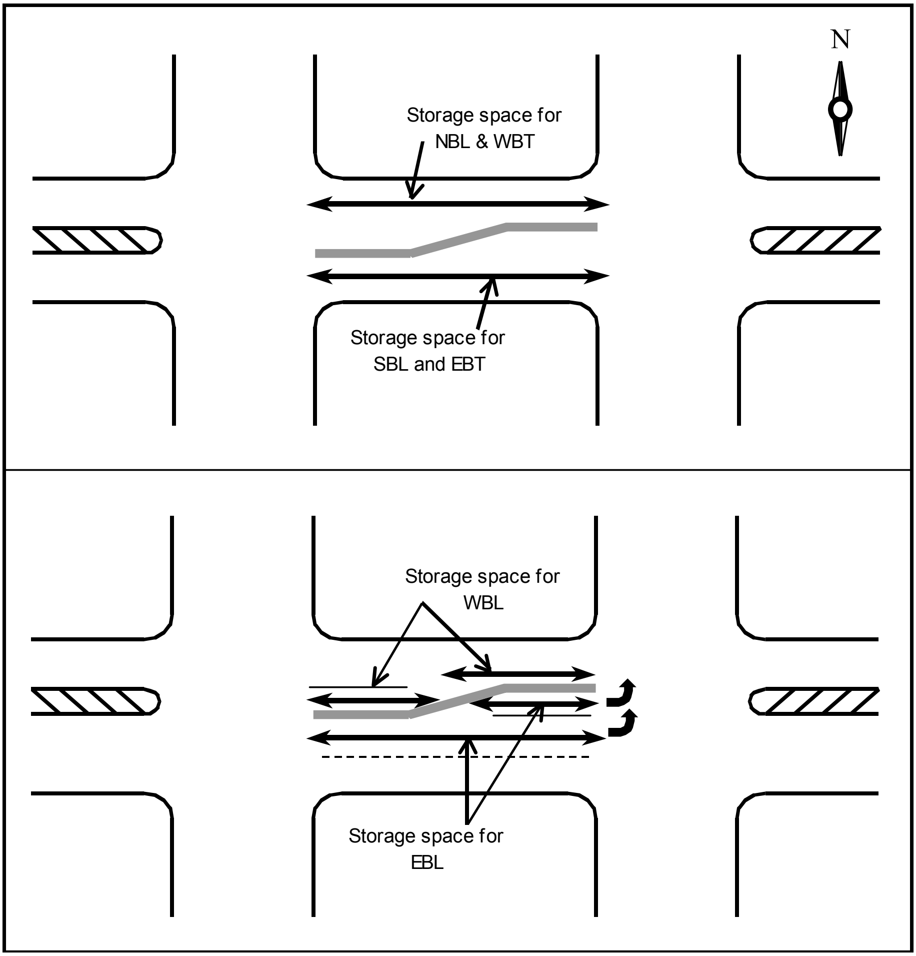

Figure 6-4 Diamond Interchange Storage Space

Some timing plans require traffic to be stored between the intersections. The procedure has a check to compare the 90th percentile traffic per cycle to the available storage space.

vCy = vC * CL/3600 = volume per cycle

vCy90 = vCy + sqrt(vCy) * 1.28 = 90th percentile volume per cycle

The standard deviation for the number of a discrete event is the square root of the number of discrete events. In this case, the discrete event is the number of vehicle arrivals in a cycle.

Timing plans that cannot serve a movement with both sides of the interchange can not be used unless there is adequate storage space. This occurs when the 90th percentile volume per cycle is less than the available storage space;

Timing Options

There are a number of timing plans commonly used for diamond interchanges.

Independent Operation

The simplest timing is to use fully actuated timings with the two intersections operating independently. This timing plan should only be used if there is sufficient storage to store a complete cycle of traffic for all six spillback movements. This occurs with low volume interchanges or when the internal distance between the intersections is large.

Leading Alternating

The Leading Alternating plan is often called "four phase with overlaps". Trafficware discourages this name since the timing plan actually uses 8 or more phases. This timing plan is shown in **Figure 6-5** and continues in **Figure 6-6**. The benefits of this timing plan are that all spillback movements can be served as long as needed without spillback. The plan also allows for some "overlap" time where two movements can be served for a short time period allowing for an increase in efficiency. This timing plan works well with limited storage space, and short distances between the intersections.

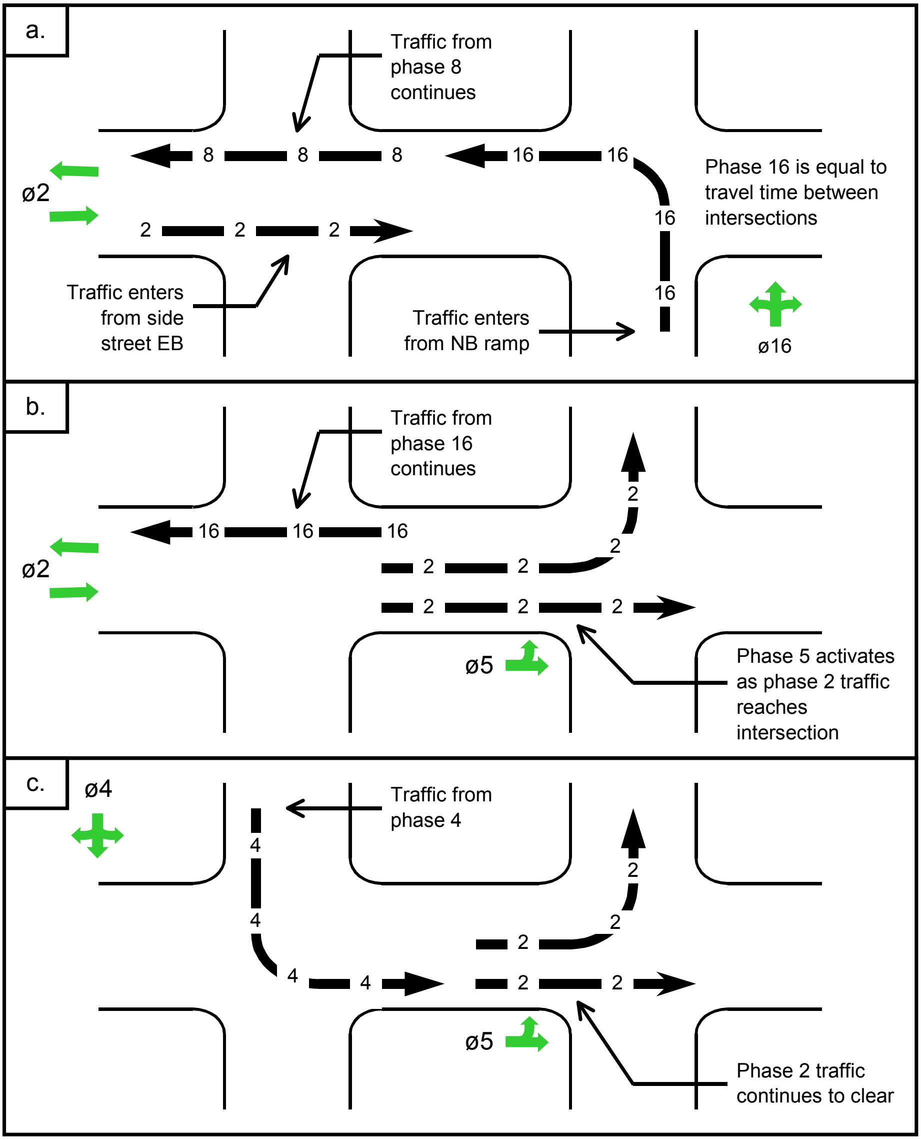

Figure 6-5 Diamond Leading Alternating Operation –1

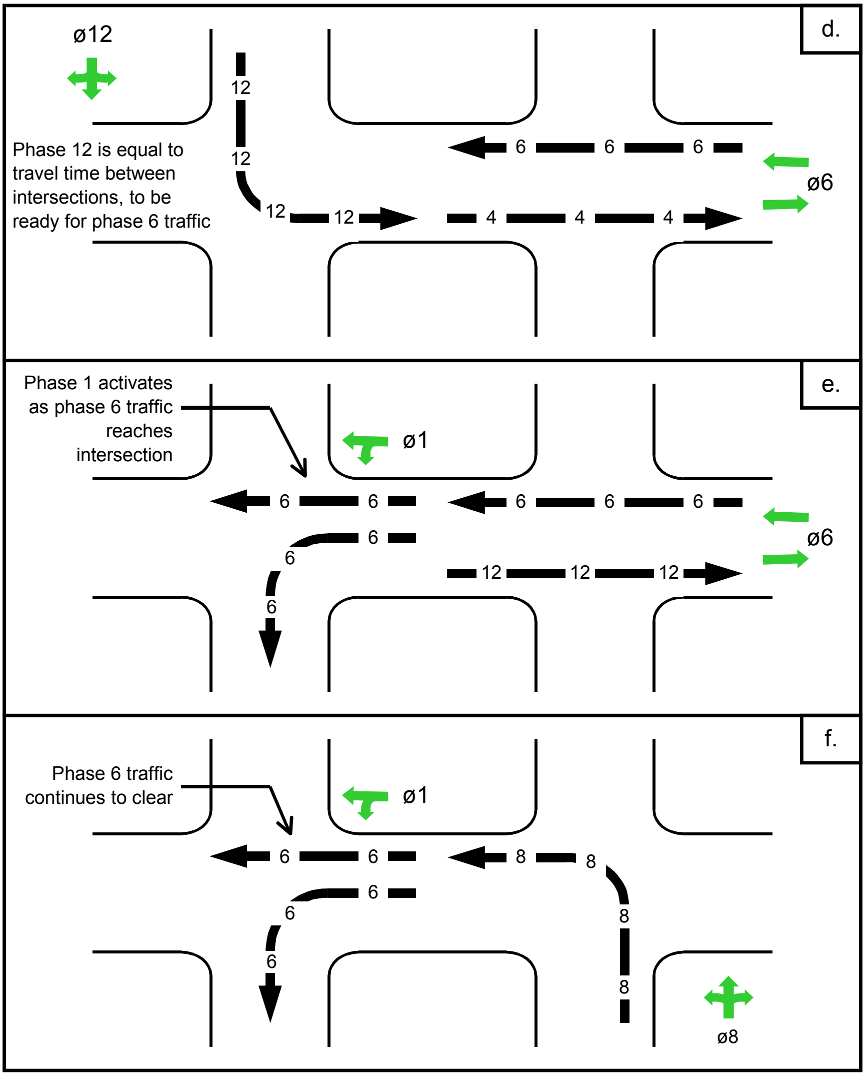

Figure 6-6 Diamond Leading Alternating Operation –2

The primary drawback to the Leading Alternating timing plan is that the two through directions are not served simultaneously. This timing plan may not be as efficient when the majority of traffic is through on the arterial.

Figure 6-7 illustrates the situation that each left turn movement has its own stage that allows continuous flow for all movements for as long as needed. Two intervals are limited by the travel time between the intersections. This timing plan is evaluated with the Leading Option.

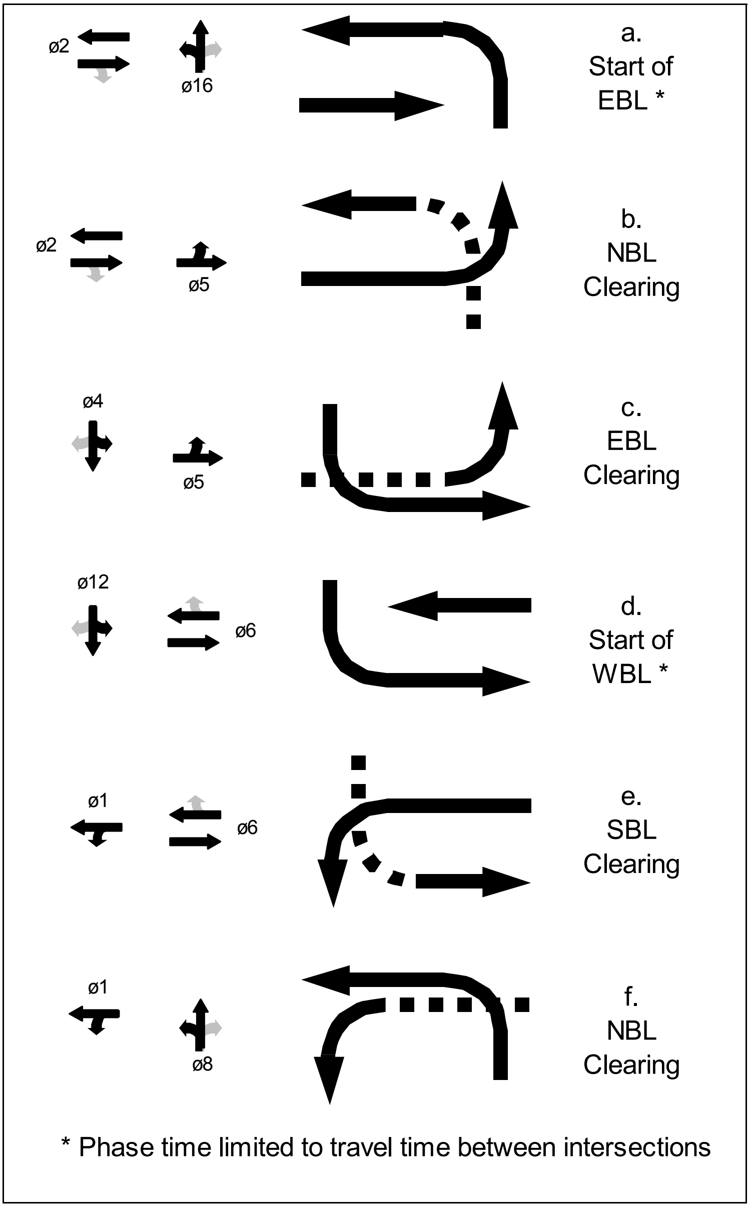

Figure 6-7 Leading Alternating Timing Plan

Lagging

The lagging timing plan is often called "three phase lagging". Trafficware discourages this name since the timing plan actually uses 6 or more phases. This timing operation is shown in **Figure 6-8**, and the plan is shown in **Figure 6-9**.

The benefit of this timing plan are:

- Good coordination for all movements.
- Allows the two through movements to move simultaneously.
- Works well with large amounts of storage space, and longer distances between the intersections.
- Allows for long green times to through traffic on the arterial.

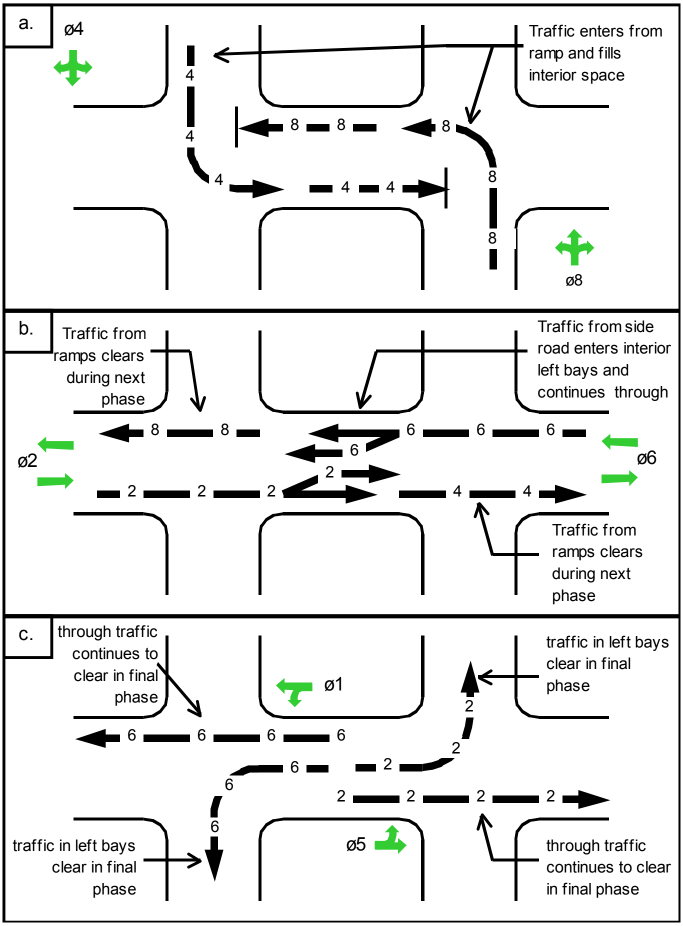

Figure 6-8 Diamond Lagging Operation

The drawback to the Lagging timing plan is that there must be sufficient storage space for all four left turn movements. None of the four left movements has continuous flow phases.

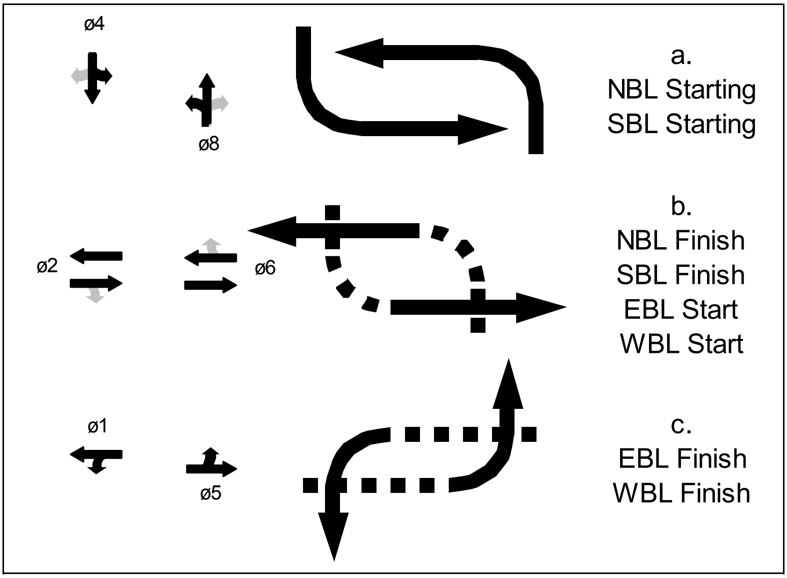

Figure 6-9 Diamond Lagging Timing Plan

Lead-Lag Timing Plan

The lead-lag timing operation (**Figure 6-10**) and lead-lag timing plan shown in **Figure 6-11** can provide service to the on ramp left turn movements along with good coordination for the through arterial. This timing plan provides continuous flow for the on ramp left turns and the arterial through movements. The off ramp left turns will need sufficient storage space to handle one cycle of their traffic. This timing plan works well when there is a medium amount of storage space and coordination along the arterial is important.

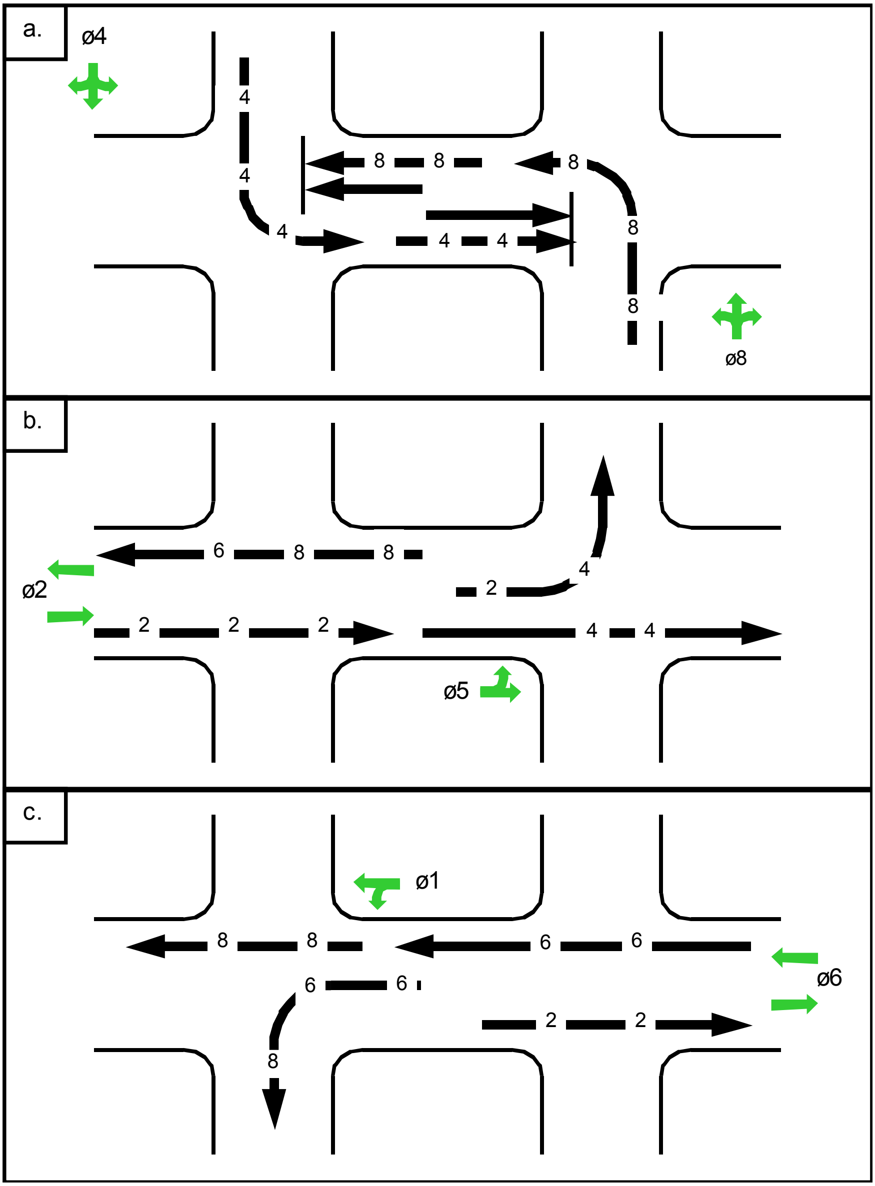

Figure 6-10 Diamond Lead-Lag Operation

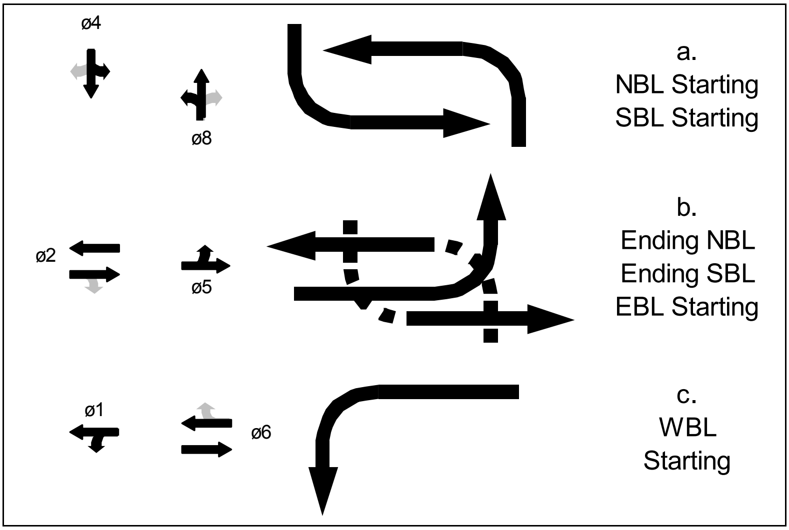

Figure 6-11 Diamond Lead-Lag Timing Plan

Summary

The diamond ICU calculation compares the 90th percentile volume per cycle to the amount of storage space available. Some of the timing plans are not allowed when this ratio exceeds one for some of the movements.

Table 6-1 Timing Plans allowing Continuous Flow

Timing Option	Off ramp lefts	On ramp lefts
Leading	Yes	Yes
Lagging	No	No
Lead-Lag	No	Yes

Diamond Interchange Capacity Utilization Calculation

Figure 6-12 shows the Diamond Interchange Capacity Utilization worksheet. This section contains line-by-line instructions for filling out the worksheet.

Unless noted, the symbols and calculations are the same as those in the single intersection worksheet.

Diamond Interchange Capacity Utilization Worksheet
East-West Arterial

Intersection Location:	________________	**City:**	________________
Analyzed by:	________________	**Alternative:**	________________
Date and Time of Data:	________________	**Project:**	________________

	Intersection	West							East						
1	**Movement**	EBT	EBR	WBL	WBT	SBL	SBT	SBR	WBT	WBR	EBL	EBT	NBL	NBT	NBR
2	Lanes														
3	Shared Lane (y/n)		☐ Yes			☐ Yes		☐ Yes		☐ Yes			☐ Yes		☑ Yes
4	Volume														
5	Pedestrians														
6	Ped Button (y/n)		☐ Yes					☐ Yes		☐ Yes					☐ Yes
7	Pedestrian Timing Required														
8	Free Right (y/n)		☐ Yes					☐ Yes		☐ Yes					☐ Yes
9	Ideal Flow														
10	Storage Space														
11	Lost Time														
12	Minimum Green														
13	Reference Cycle Length														
14	Travel Time														
15	Lanes Available														
16	Volume Combined														
17	Lane Utilization Factor														
18	Turning Factor Adjust														
19	Saturated Flow Combined														
20	Pedestrian Interference Time														
21	Pedestrian Frequency														
22	Reference Time														
23	Adjusted Reference Time														
24	Interchange Reference Time														
25	Volume per Cycle														
26	Volume per Cycle, 90th														
27	Volume to Storage														
	Timing Options														
28	Isolated Time 1														
29	Isolated Alternate Check														
30	Isolated Combined														
31	Overlap times														
32	Leading Alternating Option														
33	Lagging Time	Option Allowed													
34	Lead-Lag Time	Option Allowed													
35	Best Alternative														
36	**Intersection Capacity Utilization**														
37	**Level Of Service**														

Revision 2003.1

Figure 6-12 Diamond Interchange Capacity Utilization Worksheet

Symbols

The **Table 6-2** defines the symbols used in the calculations along with the section they appear in, their line number and their units.

Table 6-2 Diamond Interchange Capacity Utilization Worksheet Key

Section	Line #	Symbol	Units	Description
Input	2	n	number	Lanes
Input	4	v	vph	Volume
Input	5	ped	vph	Pedestrians
Input	7	tPed`	s	Pedestrian Timing Required
Input	9	I	s	Ideal Flow
Input	10	L	vehicles	Storage Space
Input	11	tL	s	Lost Time
Input	12	tMin	s	Minimum Green
Input	13	CL	s	Reference Cycle Length
Input	14	tT	s	Travel Time
Calculations	15	n'	number	Lanes Available
Calculations	16	vC	vph	Volume Combined
Calculations	17	fLU	factor	Lane Utilization Factor
Calculations	18	fT	factor	Turning Factor Adjust
Calculations	19	s	vph	Saturated Flow Combined
Calculations	20	Intf	s	Pedestrian Interference Time
Calculations	21	freq	factor	Pedestrian Frequency
Calculations	22	tRef	s	Reference Time
Calculations	23	tAdj	s	Adjusted Reference Time
Calculations	24	tIC	s	Interchange Reference Time
Calculations	25	vCy	s	Volume per Cycle
Calculations	26	vCy90	s	Volume per Cycle, 90th
Calculations	27	vLRatio	factor	Volume to Storage ratio
Timings	27	tI1	s	Isolated Time 1
Timings	27	tI2	s	Isolated Alternate
Timings	28	tI	s	Isolated Combined
Timings	29	tO	s	Overlap times
Timings	30	tLA	s	Leading Option
Timings	31	lLR	s	Leading Option, Right overlaps
Timings	32	tLG	s	Lagging Time
Timings	33	tLL	s	Lead Lag Time
Timings	34	tB	s	Best Alternative
ICU	28	ICU	factor	Intersection Capacity Utilization
ICU	29	LOS	letter	Level Of Service

The L, T, and R suffixes can be used to indicate left, through, or right. A full movement name such as "NBL" can be used as a suffix to specify a specific movement.

Inputs

Rows 1 to 14 represent input data. Refer to Chapter 4 for detailed discussion about data collection and input parameters.

1. **Movement names:** 1 column for each of the 12 basic directions. NBL is northbound left. EBR is eastbound right.

2. **Shared Lane:** Select Yes if this movement is allowed in the adjacent lane group. For example; if there is a TR lane, code 1 through lane, 0 right lane, and Yes for Right Shared Lane.

   For a L LTR R lane configuration, code 1 left lane, 1 through lane, 1 right lane, Yes for Left Shared Lane, and Yes for Right shared lane.

3. **Number of Lanes:** (n) Enter the number of lanes for each movement. Any type of shared lane counts as a through lane. If the lane geometry is L LT T TR, enter 1 left, 3 through, and 0 right lanes.

4. **Volume:** (v) Enter the number of vehicles per hour for each movement. Refer to Chapter 4 for instructions about using 15-minute counts.

5. **Pedestrians:** (ped) Enter the number of pedestrians per hour. Enter the number of pedestrians on the link to the right of the movement. These pedestrians will conflict with right turns and walk on the phase associated with this leg's through movement. Refer to Chapter 4 for instructions about collecting or estimating pedestrian data.

6. **Pedestrian Button:** Enter "y" if this signal is actuated and there is a push button for these pedestrians.

7. **Pedestrian Timing Required:** (tPed) Enter the time required for pedestrians to cross the leg to the right. This time includes walk and flashing-don't-walk, but not yellow or all-red time. Enter zero if pedestrians are prohibited for this movement or this is an area with no pedestrians.

8. **Free Right:** Enter "y" if there is a right turn lane and right turns can move at all times into their own departure lane.

9. **Ideal Flow:** (i) This is the ideal saturated flow rate of vehicles. The value used may vary between 1700 and 2200 vphpl. The default for a freeway interchange is 2000 vphpl. Refer to Chapter 4 for a discussion about which saturated flow rates to use.

10. **Storage Space:** (L) This is the storage space in passenger vehicles that can fit between the two intersections. Refer to **Figure 6-4** for which space is included.

    For the internal left turn movements, count the space in the storage bay. Also, include the leftmost through lane above the storage when no left lanes extend to the upstream intersection. Use 25ft for the default average vehicle length when no local data is available. Be sure to multiple by the number of lanes available.

11. **Lost Time:** (tL) The minimum lost time is 8 seconds for left turns and 6 seconds for other movements. Larger lost times need to be used because an urban interchange features long paths through the intersection. Lost time must be greater or equal to the travel time through the intersection. Turning traffic may have a longer travel time due to their slower turning speeds.

12. **Minimum Green Time:** (tMin) This is the minimum time a signal can show green. Enter 4 seconds for all movements.

13. **Reference Cycle Length:** (CL) This is an input value, the default value is 120 s. An agency may decide to use an alternate value based on local conditions. Refer to Chapter 4 for a discussion about which cycle length is appropriate to use.

14. **Travel Time:** (tT) This is the travel time between the two intersections in seconds. This value will be used for the leading alternating timing plan

This is the end of the data inputs. If using the spreadsheet, you are now finished and the remaining items are calculated automatically.

Calculations

Lines 15 to 36 represent calculations. Normally these are performed automatically with a spreadsheet or software. These instructions give a step-by-step reference to the Diamond Interchange ICU 2003 methods. These instructions also explain some of the reasons behind the method.

15. **Lanes Available:** (n’) This is the number of lanes available including shared lanes for each movement. This value is used to assign traffic to lane groups for volume combined. A shared lane counts as ½ a lane.

    Except as noted:

    $n' = n$

    For left movements add 0.5 when there is a shared lane in the through lane group

    For right movements add 0.5 when there is a shared lane in the through or left lane group

16. **Volume Combined:** (vC) This is the volume assigned to lane groups.

    $vCT = vT + vR * (nR' - nR)/nR' + vL * (nL' - nL)/nL'$

    $vCR = vR*nR/nR'$

    vR is added to vCT when there is a through lane, otherwise it is added to vCL.

17. **Lane Utilization Factor:** (fLU) This factor adjusts the saturated flow rate when there are 2 or more lanes. This adjustment accounts for the unequal use of lanes.

Table 6-3 Lane Utilization Factor Table

Number of Lanes	Left	Through	Right
1	1.0	1.0	1.0
2	0.971	0.952	0.885
3 or more	0.971	0.908	0.885

18. **Turning Factor Adjustment:** (fT) This factor adjusts for the number of right or left turners in the lane group.

    fTL = 0.95 – 0.10 * pR

    fTR = 0.85

    fTT = 1 - 0.15 pR – 0.05 * pL

    pR is the proportion of right traffic in lane group

    pL is the proportion of left traffic in lane group

19. **Saturated Flow Rate Combined:** (s) This is the adjusted saturated flow rate.

    s = i * n * fLU * fT

20. **Pedestrian Interference Time:** (intf) This is the time that traffic will be blocked by pedestrians. For right turns use the formula:

    intfR = 24 - 8 * e^(-ped/2*(CL-8)/3600) - 16 * e^(-ped/2*4/3600)

    For through and left movements with shared right traffic, use the formula:

    intfT = [24 - 8 * e^(-ped/2*(CL-8)/3600) - 16 * e^(-ped/2*4/3600)] * pR

    Otherwise, Pedestrian Interference time is zero.

    Pedestrians can cause up to 24 seconds of delay per cycle: Four seconds each for pedestrians starting immediately from the near and far sides or 8 seconds total, and up to 16 seconds for pedestrians starting within the first 8 seconds of green time in either direction.

    The 8 * e^(-ped/2*112/3600) term represents the pedestrians starting immediately. Pedestrians are divided by 2 for two directions. 112/3600 represents 112 seconds of pedestrians; the reference cycle less the first 8 seconds. The 8 represents 4 seconds of interference per direction times two directions.

    The 16 * e^(-ped/2*4/3600) term represents the pedestrians starting during the first 8 seconds, but not immediately. Pedestrians are divided by 2 for two directions. 4/3600 represents 4 seconds of pedestrians. The 16 represents 4 seconds of interference per direction multiplied by two directions multiplied by two-4 second intervals. This term will be less than 1 second when ped is less than 120.

21. **Pedestrian Frequency:** (freq) This is the probability of a pedestrian activating the pedestrian timings on any cycle. If pedestrian is 0 (line 6), enter 0. If there is no push button (line 7), enter 1. Otherwise use this formula:

    freq = 1 - e^(-ped*CL/3600)

    Lines 21 to 23 calculate the ICU using protected phasing. This option is not available if a shared left-through lane is present in either of the opposing directions. If your intersection has a left-through lane, you might try reclassifying it as an exclusive left lane and/or an exclusive through lane to evaluate the intersection using protected phasing. The protected phasing will usually be the most efficient operation, except at low volume intersections.

22. **Reference Time:** (tRef) This is the time required to serve the adjusted volume at 100% saturation.

    tRef = vC / s * CL + intf

    If there is no volume for this movement, leave this entry and row 23 blank.

23. **Adjusted Reference Time:** (tAdj) This is the reference time adjusted for minimums, pedestrians, and lost time. For through movements, use the formula:

    tAdj = tLost + max(tMin, tRef) * (1 - freq) + max(tMin, tRef, tPed) * freq

    Pedestrian times are not needed for left and right movements. Use this formula for left and right movements:

    tAdj = tLost + max(tMin, tRef)

    If the movement has 0 capacity and 0 volume, such as a one-way street or prohibited left; enter 0.

24. **Interchange Reference Time:** (tIC) This is the time required by the interchange. The is the Adjusted Reference Time, except for free right movements.

    tIC = tAdj, all movements except free rights

    tIC = 0, free right movements

25. **Volume per Cycle:** (vCy) This is the volume per cycle length for the lane group.

    vCy = vC * CL/3600

26. **Volume per Cycle, 90^{th}:** (vCy90) This is the 90^{th} percentile volume for the lane group.

    vCy90 = vCy + sqrt(vCy) * 1.28

Vehicle arrivals are a discrete event, thus the standard deviation is the square root of the number of events. To get the 90th percentile volume per cycle, add the square root multiplied by a Z value of 1.28.

27. **Volume to Storage Ratio:** (vLRatio) This is the volume to storage ratio for one cycle of traffic at 90th percentile volumes.

    vLRatio = vCy90 / L

    For the off ramp left turn movements, use the through storage space between the intersections. The Volume to Storage ratio will be used to test whether certain timing plans are allowed.

Timing Options

This section summarizes and combines the required times for left and through traffic by approach pairs. The best solution is found for each approach pair and combined.

28. **Isolated Time 1:** (tI1) Add the Interchange Reference Times from line 24, if computed. Isolated Time 1 uses the internal left and the arterial external through movements.

    For an EW arterial at the west intersection:

    tI1 = max(tICEBT, tICEBR) + tICWBL + max(tICSBL, tICSBT)

    For an EW arterial at the east intersection:

    tI1 = max(tICWBT, tICWBR) + tICEBL + max(tICNBL, tICNBT)

29. **Isolated Alternate Check:** (tI2) Add the Interchange Reference Times from line 24, if computed. Isolated Alternate Check uses the internal through movements.

    For an EW arterial at the west intersection:

    tI2 = tICWBT + max(tICSBL, tICSBT, tICSBR)

    For an EW arterial at the east intersection:

    tI2 = tICEBT + max(tICNBL, tICNBT, tICNBR)

30. **Isolated Combined:** (tI) Take the maximum of tI1 and tI2.

    tI = max(tI1, tI2)

31. **Overlap Times:** (tO) This is used to calculate the timings for a leading alternate timing plan. The overlaps times are the minimum of the travel time and the timings needed for the arterial through traffic at the external entries.

    For an EW arterial, tO for the west intersection is:

    tOW = min(tT, max(tICEBT. tICEBR))

    For an EW arterial, tO for the east intersection is:

tOE = min(tT, max(tICWBT. tICWBR))

32. **Leading Alternate Option:** (tLA) This is the required timing for the leading alternate option. The calculation is a bit tricky because of the overlaps involved. See **Table 6-4**.

Table 6-4 Required Timing for Leading Alternate Option

Step	Take Maximum	Notes
Add	tICEBT, tICEBR	EB phase
Add	tICSBL, tICSBT, tICSBR, tT*2	SB phase
Subtract	tOE	Overlap WB and SB
Add	tICWBT, tICWBR	WB phase
Add	tICNBL, tICNBT, tICNBR, tT*2	NB phase
Subtract	tOW	Overlap EB and NB

The NB and the SB phases must be held for at least two times the travel time to accommodate the overlaps. The overlap time is limited by the minimum of the travel time or the external through timing requirement.

33. **Lagging Time:** (tLG) This is the maximum of the two isolated times, tI. The lagging option is only allowed when vLRatio is less then 1 for the four left turn movements. If there is insufficient storage for any of the left turn movements, this timing plan is subject to spillback.

34. **Lead-Lag Time:** (tLL) This is the maximum of the two isolated times, tI. The lead-lag option is only allowed when vLRatio is less then 1 for the two off ramp left turn movements. Otherwise this timing plan is subject to spillback.

35. **Best Alternative:** Take the minimum of the Leading Alternative option (tLA), the lagging option if allowed (tLG), and the lead-lag option if allowed (tLL).

Final Calculations

36. **Intersection Capacity Utilization:** (ICU) Take the maximum of line 21 and all the values on line 28 and divide by the Reference Cycle Length. This is the Intersection Capacity Utilization. It is similar to, but not exactly the same as the intersection volume to capacity ratio. A value less than 1 indicates that the intersection has extra capacity. A value greater than 1 indicates the intersection is over capacity.

37. **Level of Service:** Enter a letter A to H based on the table and Line 28. Note that the ICU 2003 includes additional levels past F to further differentiate congested operation. The ICU table has been adjusted to account for volumes not being adjusted for PHF.

    A complete discussion of LOS can be found in Chapter 2.

Table 6-5 Level of Service

LOS	New ICU
A	≤55.0%*
B	>55% to 64.0%
C	>64% to 73.0%
D	>73% to 82.0%
E	>82% to 91.0%
F	>91% to 100.0%
G	>100% to 109.0%
H	>109%

* Note: An ICU value equal to 55.0% would be LOS A, while an ICU of 55.1 % is LOS B.

Chapter 7 – Single Point Urban Interchanges

A Single Point Urban Interchange is a special type of freeway interchange. The intersection is designed with a special structure so that all four left turn movements cross in the center at a single point. An urban interchange requires special longer overpasses to allow for the left turn approaches at the intersection. **Figure 7-1** shows an urban interchange with an overpass over the freeway. **Figure 7-2** shows an urban interchange with an underpass under the freeway.

Figure 7-1 Urban Interchange with Overpass

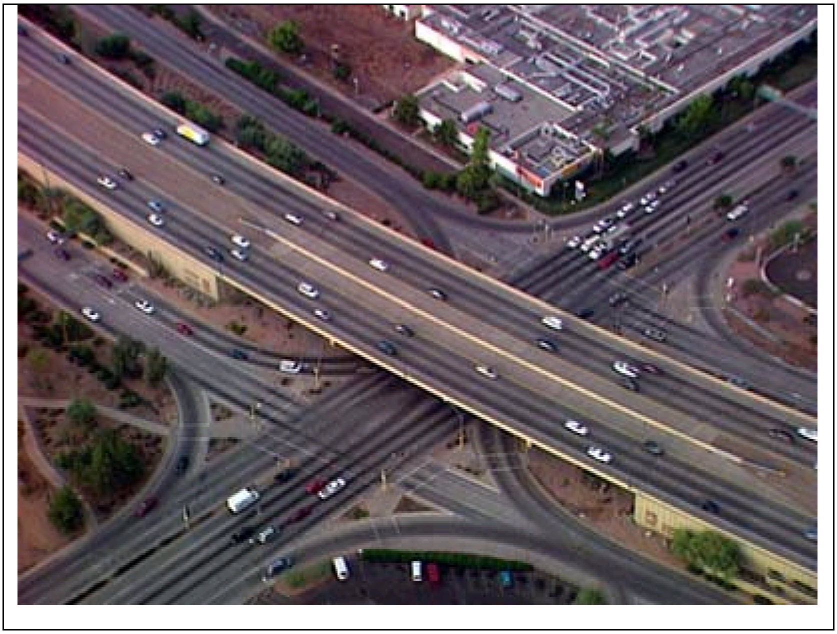

Figure 7-2 Urban Interchange with Underpass

The primary benefit to using an urban interchange over a diamond interchange is that oncoming left turn movements can go simultaneously without any risk of spillback. **Figure 7-3** shows a typical timing plan for an urban interchange. Urban interchanges are popular in urban areas because they use less space than a wide diamond, a cloverleaf, or a partial cloverleaf interchange configuration.

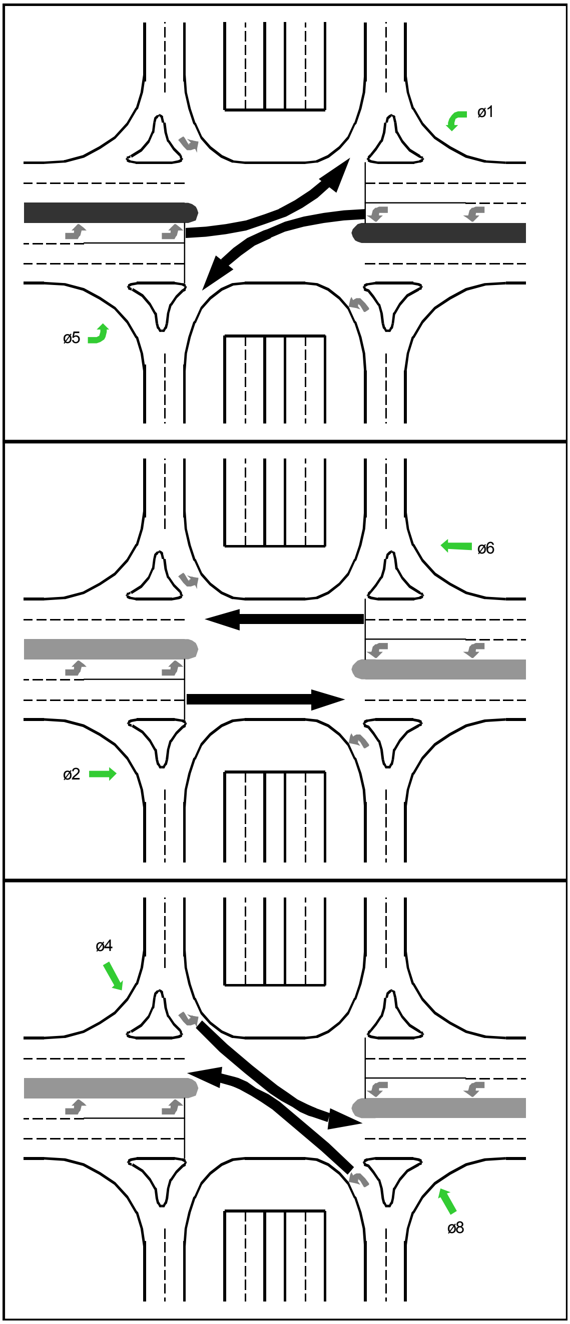

Figure 7-3 Typical Timing Plan for Urban Interchange

The ICU manual includes special worksheets for analyzing urban interchanges so that they can be compared side by side with a diamond interchange.

In most aspects, an urban interchange is analyzed in the same way as a standard single intersection except for the following special parameters.

- Longer lost times, especially for left turns
- All left turns are protected
- No option for permitted left turns
- No option for shared left-though lanes
- No option for split phasing
- Data input for side street through traffic is grayed out
- Higher Ideal Saturated Flow rates

It is possible to use the Intersection spreadsheet for analyzing urban intersections. However, the Urban Interchange worksheet provides a convenient subset of the intersection worksheet with parameters setup for an urban interchange.

Special Considerations

The most important change for analyzing an urban interchange is to use longer than normal lost times, especially for the left turn movements. An urban interchange typically has left turn paths through the intersection of 160 feet or more. It can take a truck, moving at 15 mph, 9 seconds to clear this path. This compares with 120 feet for a large sized right angle intersection. The default lost times are 8 seconds for left turn movements and 6 seconds for through and right turn movements. See Chapter 4 about collecting data for determining the appropriate lost times.

The default ideal saturated flow is 2000 vphpl versus 1900 for intersections. Studies have shown that interchanges have a higher flow rate than other intersections. See Chapter 4 for discussion about the appropriate saturated flow rates.

Most urban interchanges don't allow through traffic across the arterial. There may be a special case where frontage road traffic is allowed to move through. The data fields for the cross street through is grayed out, but they can be used if needed.

This model assumes all left turns are protected. Most urban interchanges feature long left turn paths in conjunction with high speeds. Permitted left turns would not be appropriate.

Calculations

Figure 7-4 shows the Urban Interchange Capacity Utilization worksheet. This section contains line-by-line instructions for filling out the worksheet.

Unless noted, the symbols and calculations are the same as those in the single intersection worksheet.

Urban Interchange Capacity Utilization Worksheet
East-West Arterial

Intersection Location:		**City:**	
Analyzed by:		**Alternative:**	
Date and Time of Data:		**Project:**	

		EBL	EBT	EBR	WBL	WBT	WBR	NBL	NBT	NBR	SBL	SBT	SBR
1	**Movement**												
2	Lanes												
3	Volume												
4	Pedestrians												
5	Ped Button (y/n)		☐ Yes			☐ Yes			☐ Yes			☐ Yes	
6	Pedestrian Timing Required												
7	Free Right (y/n)			☐ Yes			☐ Yes			☐ Yes			☐ Yes
8	Ideal Flow												
9	Lost Time												
10	Minimum Green												
11	Reference Cycle Length												
12	Volume Combined												
13	Lane Utilization Factor												
14	Turning Factor Adjust												
15	Saturated Flow Combined												
16	Pedestrian Interference Time												
17	Pedestrian Frequency												
	Protected Option												
18	Reference Time												
19	Adjusted Reference Time												

	Summary	**East West**	**North South**
20	Protected Option		
21	Combined		

	Right Turns	**EBR**	**WBR**	**NBR**	**SBR**
22	Adjusted Reference Time				
23	Cross Through Direction				
24	Cross Through Adj Ref Time				
25	Oncoming Left Direction				
26	Oncoming Left Adj Ref Time				
27	Combined				

28	**Intersection Capacity Utilization**	
29	**Level Of Service**	

Revision 2003.0

Figure 7-4 Urban Interchange Capacity Utilization worksheet

Symbols

The **Table 7-1** defines the symbols used in the calculations along with the section they appear in, their line number and their units.

Table 7-1 Urban Interchange Capacity Utilization Worksheet Key

Section	Line #	Symbol	Units	Description
Input	2	n	number	Lanes
Input	3	v	vph	Volume
Input	4	ped	vph	Pedestrians
Input	6	tPed	s	Pedestrian Timing Required
Input	8	i	s	Ideal Flow
Input	9	tL	s	Lost Time
Calculations	10	tMin	s	Minimum Green
Input	11	CL	s	Reference Cycle Length
Calculations	12	vC	vph	Volume Combined
Calculations	13	fLU	factor	Lane Utilization Factor
Calculations	14	fT	factor	Turning Factor Adjust
Calculations	15	s	vph	Saturated Flow Combined
Calculations	16	intf	s	Pedestrian Interference Time
Calculations	17	freq	factor	Pedestrian Frequency
Protected	18	tRef	s	Reference Time
Protected	19	tAdj	s	Adjusted Reference Time
Summary	20	tProtxx	s	Protected Option
Summary	21	tCombined	s	Combined
Right Turns	22	tAdj	s	Adjusted Reference Time
Right Turns	24	tAdjMinT	s	Cross Through Adj Ref Time
Right Turns	26	tAdjMinL	s	Oncoming Left Adj Ref Time
ICU	28	ICU	factor	Intersection Capacity Utilization
ICU	29	LOS	letter	Level Of Service

The L, T, and R suffixes can be used to indicate left, through, or right. A full movement name such as "NBL" can be used as a suffix to specify a specific movement.

Inputs

Rows 1 to 10 represent input data. Refer to Chapter 4 for detailed discussion about data collection and input parameters.

1. **Movement Names:** 1 column for each of the 12 basic directions. NBL is northbound left. EBR is eastbound right.
2. **Number of Lanes**: (n) Enter the number of lanes for each movement. Any type of shared lane counts as a through lane. If the lane geometry is L LT T TR, enter 1 left, 3 through, and 0 right lanes. A LR lane should be entered as a through lane.
3. **Volume:** (v) Enter the number of vehicles per hour for each movement. Refer to Chapter 4 for instructions about using 15-minute counts.

4. **Pedestrians:** (ped) Enter the number of pedestrians per hour. Enter the number of pedestrians on the link to the right of the movement. These pedestrians will conflict with right turns and walk on the phase associated with this leg's through movement. Refer to Chapter 4 for instructions about collecting or estimating pedestrian data.
5. **Pedestrian Button:** Enter "y" if this signal is actuated and there is a push button for these pedestrians.
6. **Pedestrian Timing Required:** (tPed) Enter the time required for pedestrians to cross the leg to the right. This time includes walk and flashing-don't-walk, but not yellow or all-red time. Enter zero if pedestrians are prohibited for this movement or this is an area with no pedestrians.
7. **Free Right:** Enter "y" if there is a right turn lane and right turns can move at all times into their own departure lane.
8. **Ideal Flow:** (i) This is the ideal saturated flow rate of vehicles. The value used may vary between 1700 and 2200 vphpl. The default for a freeway interchange is 2000 vphpl. Refer to Chapter 4 for a discussion about which saturated flow rates to use.
9. **Lost Time:** (tL) The minimum lost time is 8 seconds for left turns and 6 seconds for other movements. Larger lost times need to be used because an urban interchange features long paths through the intersection. Lost time must be greater or equal to the travel time through the intersection. Turning traffic may have a longer travel time due to their slower turning speeds.
10. **Minimum Green Time:** (tMin) This is the minimum time a signal can show green. Enter 4 seconds for all movements.

Reference Cycle Length: (CL) This is an input value, the default value is 120 s. An agency may decide to use an alternate value based on local conditions. Refer to Chapter 4 for a discussion about which cycle length is appropriate to use.

This is the end of the data inputs. If using the spreadsheet, you are now finished and the remaining items are calculated automatically.

Calculations

Lines 11 to 29 represent calculations. Normally these are performed automatically with a spreadsheet or software. These instructions give a step-by-step reference to the Urban Interchange ICU 2003 methods. These instructions also explain some of the reasons behind the method.

11. **Volume Combined:** (vC) This is the volume assigned to lane groups.

    vCT = vT + vR* + vL**

    vCL = vL**

    vCR = vR*

    *vR is added to vCT when nR = 0, otherwise vR is added to vCR.

** vL is added to vCT when there is a left-through lane (Line 3 = yes), otherwise vL is added to vCL.

12. **Lane Utilization Factor:** (fLU) This factor adjusts the saturated flow rate when there are 2 or more lanes. This adjustment accounts for the unequal use of lanes.

Table 7-2 Lane Utilization Factor

Number of Lanes	Left	Through	Right
1	1.0	1.0	1.0
2	0.971	0.952	0.885
3 or more	0.971	0.908	0.885

13. **Turning Factor Adjustment:** (fT) This factor adjusts for the number of right or left turners in the lane group.

    fTL = 0.95

    fTR = 0.85

    fTT = (1 - 0.15 * (vR - vCR)/vCT) * (1 - 0.05 * (vL - vCL)/vCT)

14. **Saturated Flow Rate Combined:** (s) This is the adjusted saturated flow rate.

    s = i * n * fLU * fT

    If there is a shared Left-Through lane (line 3), count the left lanes in the through group and the leave the left saturated flow rate blank.

    sT = i * (nT + nL) * fLU * fT

    sL = 0

15. **Pedestrian Interference Time:** (intf) This is the time that traffic will be blocked by pedestrians. For right turns use the formula:

    intfR = 24 - 8 * e^(-ped/2*(CL-8)/3600) - 16 * e^(-ped/2*4/3600)

    For through movements with no right lanes, use the formula:

    intfT = [24 - 8 * e^(-ped/2*(CL-8)/3600) - 16 * e^(-ped/2*4/3600)] * vR/vC

    Otherwise, Pedestrian Interference time is zero.

    Pedestrians can cause up to 24 seconds of delay per cycle. Four seconds each for pedestrians starting immediately from the near and far sides or 8 seconds total, and up to 16 seconds for pedestrians starting within the first 8 seconds of green time in either direction.

    The 8 * e^(-ped/2*112/3600) term represents the pedestrians starting immediately. Pedestrians are divided by 2 for two directions. 112/3600 represents 112 seconds of pedestrians, the reference cycle less the first 8 seconds. The 8 represents 4 seconds of interference per direction times two directions.

The 16 * e^(-ped/2*4/3600) term represents the pedestrians starting during the first 8 seconds, but not immediately. Pedestrians are divided by 2 for two directions. 4/3600 represents 4 seconds of pedestrians. The 16 represents 4 seconds of interference per direction multiplied by two directions multiplied by two-4 second intervals. This term will be less than 1 second when ped is less than 120.

16. **Pedestrian Frequency:** (freq) This is the probability of a pedestrian activating the pedestrian timings on any cycle. If pedestrians are 0 (line 6), enter 0. If there is no push button (line 7), enter 1. Otherwise use this formula:

    freq = 1 - e^(-ped*CL/3600)

Protected Option

Lines 21 to 23 calculate the ICU using protected phasing. This option is not available if a shared left-through lane is present in either of the opposing directions. If your intersection has a left-through lane, you might try reclassifying it as a exclusive left lane and/or an exclusive through lane to evaluate the intersection using protected phasing. The protected phasing will usually be the most efficient operation, except at low volume intersections.

17. **Reference Time:** (tRef) This is the time required to serve the adjusted volume at 100% saturation.

    tRef = vC / s * CL + intf

    If there is no volume for this movement, leave this entry and row 23 blank.

18. **Adjusted Reference Time:** (tAdj) This is the reference time adjusted for minimums, pedestrians, and lost time. For through movements, use the formula:

    tAdj = tLost + max(tMin, tRef) * (1 - freq) + max(tMin, tRef, tPed) * freq

    Pedestrian times are not needed for left and right movements. Use this formula for left and right movements:

    tAdj = tLost + max(tMin, tRef)

    If the movement has 0 capacity and 0 volume, such as a one-way street or prohibited left; enter 0.

Summary

This section summarizes and combines the required times for left and through traffic by approach pairs. The best solution is found for each approach pair and combined.

19. **Protected Option:** (tProt) Add the Adjusted Reference Times from line 19, if computed.

    tProtNS = max(tAdjNBL + tAdjSBT, tAdjSBL + tAdjNBT)

tProtEW = max(tAdjEBL + tAdjWBT, tAdjWBL + tAdjEBT)

20. **Combined:** (tCombined) Add the two columns from line 20.

Right Turns

Right turns from exclusive lanes are calculated by a separate calculation. This accounts for free rights, overlapping right turn phases, and right turns on red.

22. **Adjusted Reference Time:** (tAdj) Copy the Adjusted Reference Times for right turns from line 19. For approaches with 0 exclusive right lanes, this value will be 0.
23. **Cross Through Direction:** This is the direction from the left side that will merge with the right turns. Enter SBT, NBT, EBT, WBT for EBR, WBR, NBR, and SBR.
24. **Cross Through Adjusted Reference Time:** (tAdjMinT) Enter the Adjusted Reference Times for the cross through movement from line 19.
25. **Oncoming Left Direction:** This is the oncoming direction from which left traffic will merge with the right turns. Enter WBL, EBL, SBL, and NBL for EBR, WBR, NBR, and SBR.
26. **Oncoming Adjusted Left Reference Time:** (tAdjMinL) Enter the Adjusted Reference Times for the cross left movement from line 19.
27. **Combined:** If this movement is a free right, copy line 22. Otherwise, add lines 22, 24, and 26.

Final Calculations

28. **Intersection Capacity Utilization:** (ICU) Take the maximum of line 21 and all the values on line 27 and divide by the Reference Cycle Length. This is the Intersection Capacity Utilization. It is similar to, but not exactly the same as the intersection volume to capacity ratio. A value less than 100% indicates that the intersection has extra capacity. A value greater than 100% indicates the intersection is over capacity.
29. **Level of Service:** Enter a letter A to H based on the **Table 7-3** and Line 28. Note that the ICU 2003 includes additional levels past F to further differentiate congested operation. The ICU table has been adjusted to account for volumes not being adjusted for PHF.

A complete discussion of LOS can be found in Chapter 2.

Table 7-3 Urban Interchange Capacity Level of Service

LOS	New ICU
A	≤55.0%*
B	>55% to 64.0%
C	>64% to 73.0%
D	>73% to 82.0%
E	>82% to 91.0%
F	>91% to 100.0%
G	>100% to 109.0%
H	>109%

* Note: An ICU value equal to 55.0% would be LOS A, while an ICU of 55.1 % is LOS B.

Chapter 8 – Permitted Lefts and Shared Lanes

The modeling of permitted left turns, particularly for shared lanes is problematic in the ICU methodology. This is especially a problem for single lane approaches.

The ICU method requires a movement to be protected to determine its timing requirements based of the v/s ratio (volume to saturated flow ratio). If there is no left turn lane, protected phasing cannot be used. The two options available are to use Split phasing or to assume a de-facto left turn lane. For modest left turn volumes, neither of these solutions is satisfactory because a large proportion of the time there will be no left turn vehicles and the lanes will function as though they were normal through lanes.

Permitted left turns will be able to go under three conditions:

1. A gap in oncoming traffic due to low oncoming traffic volumes
2. Sneakers at the end of green
3. A gap in oncoming traffic caused by a left turn from a single lane approach.

The HCM's solution to modeling this situation is to calculate an fLT that takes into account the above behavior. This solution generates a reasonable saturated flow rate that can be used to calculate the capacity and delay of the movement in question. However, this solution is not appropriate for determining the capacity of the entire intersection because the capacity of one movement is dependent on the volume of the oncoming movement. In order to determine the intersection capacity it is necessary for the ultimate capacity to be determined independently of any other movement's volume.

The ICU method provides two alternate methods for determining the capacity of permitted left turns. Method "A" looks at gaps in oncoming traffic when the oncoming approach has very low volume <120 vph. This takes care of the condition (1) above. This method is dependent on the oncoming traffic volume but is only used when the oncoming volume is relatively light.

Method "B" looks at the gaps created by sneakers and gaps from an oncoming single lane approach. This takes care of conditions (2) and (3) above. Method B does not consider the oncoming volume, only the timing plan and the proportion of left turns in this stream and an oncoming single lane. Trafficware performed some research modeling 'permitted left turns' using simulation to determine the capacity of permitted left turns with these gaps. This research is described below.

Using Methods "A" and "B" together generates a permitted and shared lane model that considers the primary causes of gaps, while being independent of the oncoming volume, thus creating a method that can calculate the "true" capacity of an intersection.

General Notes

Some general notes about permitted left turns for shared lanes. This lane geometry is very difficult to model. Our simulation results showed the capacity varying with a standard deviation of 10 to 15%. The only randomness was the sequence in which left and through traffic arrived at the stop bar. Any capacity or delay prediction in this circumstance will experience huge fluctuations from observed field conditions.

This type of lane configuration has many safety problems. Many of the uncertainties in modeling these lanes also create uncertainties for motorists driving in these lanes. Some safety problems include:

- Rear end collisions with through vehicles hitting waiting left turn vehicles.
- Lane change accidents with through vehicles making last minute lane changes to avoid stopped left turners.
- Head on collisions, left turners nose into the intersection to allow through traffic to pass around them.
- Bicycle accidents, through vehicles swerve around left turners don't notice bicycles in the right lane or shoulder

Whenever there is any significant left turn traffic, left turn lanes are highly desirable to improve safety, to improve capacity, and to create a more predictable experience for motorists.

Split phasing can also be used to provide the benefits of protected left turns where there is no right of way to create left turn lanes.

Method "A"

The ICU A Method of modeling permitted left turns assumes that the oncoming traffic in the through lane group is less than 120 vph. This method assumes the oncoming traffic will block any lane with left turns for 8 seconds at the beginning of green, after which the traffic can flow with relatively little impedance. In this methodology, 8 seconds is added to the reference time of any lane group with left turn traffic.

Note that if there was an exclusive left turn lane, the addition of this 8 seconds is the same amount of time added with an additional protected phase. That is 4 seconds minimum green plus 4 seconds of lost time.

Method "B"

Method B models the effect of gaps in traffic due to sneakers and oncoming lefts from a single lane approach.

Trafficware conducted research using simulation to determine the average amount of green time a left turner spends at the stop bar. The simulations were performed for a complete range of left turn proportions for the subject approach and a complete range of left turn proportions for the oncoming approach. If the oncoming approach has multiple lanes, the behavior assumed to be equivalent to zero oncoming left turns.

A software program was written to simulate vehicle arrivals and departures at the stop bar. Vehicles were randomly generated as left or through in the proportions specified for the subject and oncoming approaches. At each 2-second time slice, a through vehicle would be able to depart except at the end of green. A left vehicle would be able to depart if the oncoming approach also had a left vehicle or on the last four seconds of green. fLT values were calculated to compare the actual vehicles served to the number served at full capacity using through vehicles only.

Note: The simulated capacity for permitted shared lanes was found to have standard deviations of 10 to 15%. The capacity of permitted-shared lanes is difficult to predict and any model will have limited accuracy.

One interesting result of this research is that the simulated capacity for permitted shared lanes was found to have standard deviations of 10 to 15% based on simulating repeated 15-minute intervals. The only changed variable was the sequence in which left and through vehicles arrived. The implication is that the capacity of permitted-shared lanes is difficult to predict and any model will have limited accuracy. Another implication is that any facility designed with permitted shared left lanes needs extra capacity to accommodate the wide swings in actual capacity.

Some of the resulting fLT values are shown in the table below.

Table 8-1 Calculated Left Turn Factors (fLT)

	pLOp								
pL	**0**	**1**	**5**	**10**	**20**	**40**	**50**	**75**	**100**
0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1	0.882	0.907	0.96	0.971	0.993	0.999	0.999	1.0	1.001
5	0.556	0.618	0.778	0.87	0.95	0.989	0.997	1.001	1.002
10	0.383	0.425	0.593	0.751	0.882	0.966	0.983	0.999	1.004
15	0.266	0.322	0.458	0.621	0.794	0.942	0.966	0.997	1.007
20	0.211	0.24	0.387	0.55	0.733	0.909	0.947	0.991	1.009
30	0.156	0.187	0.282	0.412	0.611	0.836	0.907	0.98	1.013
40	0.127	0.149	0.24	0.318	0.504	0.758	0.842	0.967	1.021
50	0.107	0.123	0.191	0.295	0.445	0.699	0.788	0.941	1.026
75	0.083	0.095	0.149	0.212	0.328	0.56	0.659	0.881	1.047
100	0.071	0.082	0.119	0.169	0.264	0.448	0.56	0.812	1.071

The following formulas were developed to fit the results of the simulation:

EL = (0.5 + 0.8 * pL - 0.3 * pL^2) / [(4* (1 + pL)/CL + pLO] = through vehicle equivalents for left turns

pLO = proportions of oncoming left turns from single lane, zero if oncoming approach is multilane

pL = proportion of left turns in lane group

CL = cycle length

fLT = 1 / [1 + pL * (EL-1)] = left turn factor

The resulting calculation gives fLT values that match the simulation results to within 4% for all values in the table.

Chapter 9 – Comparison to HCM and Delay Based Methods

ICU 2003 Compared to the HCM Method

Currently the most popular method for analyzing intersection capacity is the HCM. The HCM method is based on estimating delay for the intersection.

The ICU 2003 is designed to be compatible with the HCM and can be used in conjunction with the HCM and other methods. The default saturated flow rates and volume adjustments are the same as those recommended by the HCM. In most circumstances, the volume to saturated flow rates in ICU 2003 (v/s), will be the same as those in the HCM.

An acceptable ICU LOS guarantees that a timing plan exists that will meet all of the following:

- Acceptable HCM LOS
- All minimum timing requirements are met
- All movements have acceptable v/c ratios
- All movement volumes can have their volume increased by the reciprocal of the ICU and be at or below saturation.

With an acceptable HCM LOS, the following is guaranteed:

- Average delays are less than the amount for that LOS
- The majority of traffic has acceptable v/c ratios or short red time

For some applications, ICU 2003 provides a better methodology than the HCM signalized intersection methods. The primary benefits of the ICU are that it is easy to calculate and provides answers with a higher degree of certainty. The ICU gives a clear picture of how much additional capacity an intersection has. A summary of both methods is shown in **Table 9-1**.

The HCM's primary Measure of Effectiveness (MOE) is delay. Delay based models are appropriate for designing signal timing plans and for evaluating operations. Delay is a value that can be measured and explained to the public.

Table 9-1 HCM Comparison to ICU 2003

	HCM	ICU 2003
Primary MOE	Delay	Volume to Capacity
Applications, primary	Operations, Signal Timing	Planning, Impact Studies, Roadway Design
Applications, secondary	Planning, Impact Studies, Roadway Design	
Pages of Worksheets	8	1
Available as spreadsheet	No	Yes
Can be calculated by hand	Lengthy	Yes
Single Correct Answer	No	Yes
Considers Pedestrian Timing	No	Yes
Typical Accuracy	±30%	±10%
Requires Optimized Timing	Yes	No
Requires Optimized Phasing	Yes	No
Requires Estimating Actuated Signal operation	Yes	No
Requires Estimating Effects of Coordination	Yes	No
True Measure of Maximum Capacity	No	Yes
Accounts for Minimum Green Times	No	Yes

One major advantage of the ICU is simplicity. The HCM signalized operations method requires up to 10 worksheets and the chapters related to signals contain over 170 pages. A longer procedure requires more time to use and more time to review. The longer procedure also opens the possibility for more mistakes and less chance of finding these mistakes during review. The longer procedure is also more difficult to implement in software. A simpler methodology will lead to more accurate software implementations.

Another advantage of the ICU is that it is simple enough to be used by hand or with a spreadsheet. This allows free and easy access to the methods and their underlying calculations.

The ICU explicitly accounts for pedestrians both through interference adjustments and through required timings. The HCM does not explicitly require that timing plans contain enough time for pedestrians.

The HCM method requires the user to estimate the actuated green times and the platoon factors. Small changes to these input values can make a significant difference to the results. A skilled HCM user can manipulate these input values to give the desired result.

The HCM uses a single methodology for multiple applications: to measure capacity and to evaluate timing plans. In many cases, an optimal timing plan can mask a capacity deficiency. It is possible to get HCM LOS D with an intersection v/c ratio or ICU of 1.1 or higher.

One criticism of the ICU is that the resulting timing plans are inefficient, and a timing plan optimized for delay is more efficient. The ICU is not intended for operations or timing plan design. The Reference Times are not intended to be used as timing plans, but only as an aid in calculating ICU at a predetermined Reference Cycle Length.

There are advantages to not calculating the actual timing plan. It is not necessary to optimize timing and phase sequence. It is also not necessary to have a long, complicated, permitted left turn procedure.

Notes on HCM Volume to Capacity Ratio

Proponents of the HCM point out that the HCM does have a calculation for determining intersection volume to capacity (v/c) ratio as a secondary MOE. The Intersection v/c ratio is similar to but not the same as the ICU.

The HCM Intersection v/c has a number of limitations that are addressed by the ICU. These include:

- Capacity is double counted for permitted lefts. The HCM uses a permitted left turn factor that considers the gaps in oncoming through traffic. The capacity of the lefts is thus dependent on the oncoming traffic. If the intersection v/c ratio is 0.9 for example, it is not possible to increase all traffic by 1/ 0.9 because the increase in oncoming through traffic will reduce the capacity for permitted lefts.
- Does not consider minimum timing requirements. The adjustment for lost time is:

  $C/(C - L)$

  C = cycle length

  L = sum of lost time

  This assumes that all movements are going to use all of their green time at the same degree of saturation. Some lower volume movements will need a longer green to accommodate the pedestrian crossing times or even the minimum green requirements. Most agencies will not display a green light for less than 4 to 8 seconds. The ICU accommodates minimum times by using a reference time for each movement.

- Problems with permitted plus protected phasing. The HCM Intersection v/c calculation has some problems with permitted plus protected phasing. The method is to sum the v/s ratio for the critical lane group in each interval. A left turn might be critical in both its permitted and protected intervals. It might even be critical in three intervals. Its volume is allocated among these intervals based to get the v/s ratios. There are cases when the interval timings are not optimum and the summed v/s ratios are higher than would be the case with optimal timings. Further, the v/c calculation is undefined with overlapping clearance intervals. This is when the yellow intervals on each side of the barrier partially overlap. For example, the green time for NBL is 10 s and SBL is 12 s, the yellow time is 4 s. About 10% of all 8 phase controllers will have timing plans with overlapping clearance intervals.

Accuracy and Precision

This section contains a short discussion about accuracy and precision. The uncertainties in the inputs are analyzed along with their effects on the resulting values. A simplified method is presented to show how uncertainties in input values propagate to uncertainties in results.

Table 9-2 lists the primary inputs for an ICU calculation, and an intersection delay calculation along with typical uncertainties.

The general volume to capacity ratios can be calculated with more accuracy than delay. The following illustrates how inaccuracies can compound in an ICU or delay analysis:

Table 9-2 ICU Primary Inputs and Typical Uncertainties

Value	Typical	Uncertainty	Percent
Volume	500	50	10%
Saturated Flow	2000	100	5%
Lane Utilization	0.9	0.05	6%
Lost Time	4	0.5	13%
Permitted Left Factor	0.3	0.03	10%
Green Time	40	2	5%
Platoon Factor	1	0.3	30%

Table 9-3 shows how these certainties combine to effect the overall uncertainty in the resulting ICU. The ICU effect was calculated using a spreadsheet. The relevant input variable was increased 1% and the resulting ICU for a typical intersection was compared to the baseline ICU. A value of 0.88 indicates that a 1% increase in volume increases the ICU by 0.88%. Each input value's percent uncertainty is multiplied by the effect factor and squared. The root of the sum of the squares is the combined uncertainty for all input uncertainties. For this example, the ICU has an uncertainty of 10.6%.

If the ICU had been calculated without permitted left turns, the resulting ICU uncertainty would be 9%. Most ICU calculations do not use permitted left turns.

Table 9-3 Overall Uncertainty in Resulting ICU Calculations

Value	u_i	m_i (ICU)	$(u_i * m_i)^2$
Volume	7%	0.88	0.0036
Saturated Flow	5%	-0.87	0.0019
Lane Utilization	6%	-0.87	0.0023
Lost Time	13%	0.12	0.0002
Permitted Left Factor	10%	-0.57	0.0032
Green Time	5%	na	
Platoon Factor	30%	na	
Sum			0.0113
Combined Uncertainty (CU)			10.6%

CU = Combined Uncertainty = $[\Sigma(u_i * m_i)^2]^{0.5}$

u_i = Uncertainty for input i

m_i = Multiplier effect (A 1% change in i causes a m% change in the output.)

Table 9-4 examines the same uncertainties effect on HCM delay. Two cases are considered, the first has a v/c of 0.75 and the second has a v/c of 1.0. Note that uncertainty in volume and capacity has a multiplying effect of over 3 at capacity, but only about 1 at lower v/c ratios.

Table 9-4 Uncertainties Effect On HCM Delay

Value	u_i	m_i (HCM 0.75)	$(u_i * m_i)^2$	m_i (HCM 1.00)	$(u_i * m_i)^2$
Volume	7%	0.92	0.0039	3.33	0.0517
Saturated Flow	5%	-1.04	0.0027	-3.60	0.0325
Lane Utilization	6%	-1.04	0.0033	-3.60	0.0401
Lost Time	13%	-0.16	0.0004	-0.40	0.0025
Permitted Left Factor	10%	-1.04	0.0108	-3.60	0.1299
Green Time	5%	-1.59	0.0063	-3.87	0.0375
Platoon Factor	30%	0.82	0.0611	0.53	0.0257
Sum			0.0886		0.3199
Combined Uncertainty (Sum of Squares)			30%		57%

If the intersection is assumed to be uncoordinated and uses protected lefts, the platoon factor and permitted left turn factor contributions are removed and the resulting uncertainties are 13% and 41% for the 0.75 and 1.0 cases, respectively.

Table 9-5 summarizes the amount of uncertainty that can be expected from ICU and HCM methods for various scenarios. The uncertainty for ICU is relatively low and constant for all options. The uncertainty for HCM is acceptably low when v/c is under capacity, left turns are protected, and the approach is uncoordinated. The HCM and delay based calculations become very uncertain when v/c approaches 1 because small changes to input values have a 3x effect on the resulting delay. The HCM relies on estimates of platoon factor to account for the effects of coordination. This adds greatly to the effects of uncertainty in the HCM delay values.

Table 9-5 Combined Uncertainty in ICU and HCM for Various Scenarios

	ICU	HCM
Protected Lefts, Uncoordinated, v/c = 0.75	9%	11%
Protected Lefts, Uncoordinated, v/c = 1	9%	41%
Protected Lefts, Coordinated, v/c = 0.75	9%	28%
Protected Lefts, Coordinated, v/c = 1	9%	44%
Permitted Lefts, Uncoordinated, v/c = 0.75	11%	17%
Permitted Lefts, Uncoordinated, v/c = 1	11%	54%
Permitted Lefts, Coordinated, v/c = 0.75	11%	30%
Permitted Lefts, Coordinated, v/c = 1	11%	57%

The ICU is inherently more precise because the delay equation is unstable near capacity. The calculation of delay requires an estimate for the effects of coordination, which adds greatly to the resulting uncertainty.

One consequence of the high range of uncertainties is that it makes the method easy to manipulate. In some cases, it is possible to get a 20% reduction in delay or two Levels of Service by increasing capacity 5% and reducing volume 5%.

The following graph illustrates how delay is related to volume. Note that delay increases significantly once capacity is reached. This steepness of the graph illustrates how small changes to volume or capacity can make a significant difference in delay. The v/c ratio increases linearly and also provides information about when the delay slope will start to increase.

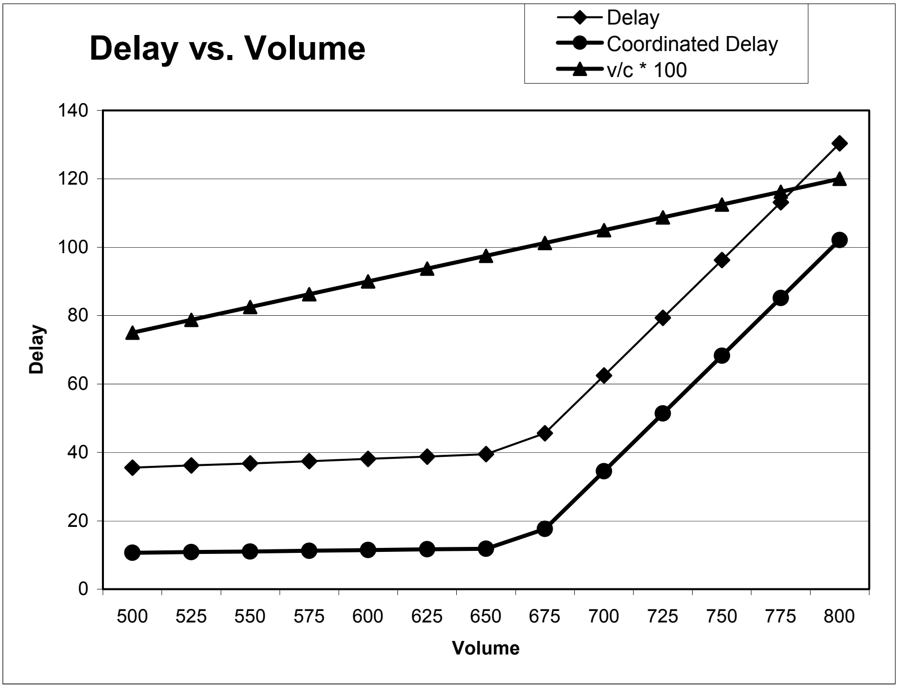

Figure 9-1 LOS Example – Delay vs. Volume

Traffic volumes fluctuate as discussed in Chapter 4. Volume will change by day of week, hour of the day, by time of year, and even within the peak hour. Volume will also change due to special events, accidents, and bad weather.

Some days can experience peak hour volumes 10% above average. The delay for these days can be 30% higher and the LOS two levels worse. The ICU for these days will only be 10% higher and one level worse. The ICU does a better job of predicting reserve capacity.

Chapter 10 – Example Problems

Example Problem 1 Multi-Lane Intersection

The intersection of 1st (NB/SB) and Main Street (EB/WB) is located in an outlying area of the city. Intersection geometry and flow characteristics are shown in **Figure 10-1**. This is an example of a multi-lane roadway (Main Street) crossed by a single lane roadway (1st Street).

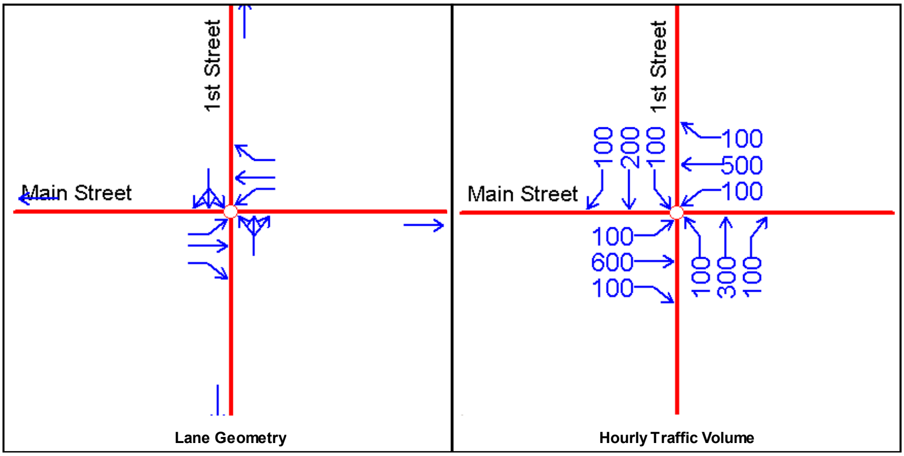

Figure 10-1 Example 1 Multi-Lane Intersection Geometry

In addition, the following information is provided for this example:

- Pedestrian volumes are zero during this analysis period
- Pedestrian push buttons are not present
- Pedestrian timing should be considered in the case that a pedestrian arrives (walk = 5 seconds, flashing don't walk = 11 seconds)
- The right turns are not free movements
- The Ideal Saturation Flow is 1,900 vphpl
- The Minimum Green time for each movement should be 4.0 seconds
- The Lost Time for each movement is 4.0 seconds

Computational Steps

The following computational steps use the Intersection Capacity Utilization worksheet as shown in **Figure 5-1**

1-12	Data Inputs	See Figure 10-2
13.	Volume Combined (vC)	vCT = vT + vR + vL vCT (NB) = 100 + 300 + 100 = 500
14.	Volume Separate Left (vS)	vST = vT + vR vST (NB) = 300 + 100 = 400
15.	Lane Utilization Factor (fLU)	Use Table 5-2. fLU (NB) = 1.000
16.	Turning Factor Adjustment (fT)	fTT = (1 - 0.15 * (vR - vCR)/vCT) * (1 - 0.05 * (vL - vCL)/vCT) fTT (NB) = (1 - 0.15 * (100 - 0)/500) * (1 - 0.05 * (100 - 0)/500) = 0.960
17.	Saturated Flow Rate Combined (s)	sT = i * (nT + nL) * fLU * fT sT (NB) = 1900 * (1 + 0) * 1.0 * 0.960 = 1824.6
18.	Saturated Flow Rate Separate (sC)	sCT = i * nT * fLU * (1 - 0.15 * (vR - vSR) / vST) sCT (NB) = 1900 * 1 * 1 * (1 - 0.15 * (100 - 0) / 400) = 1828.8
19.	Pedestrian Interference Time (intf)	No pedestrians, use zero
20.	Pedestrian Frequency (freq)	No pedestrians, use zero
Protected Option		
21.	Protected Option Allowed	Only allowed when there is a separate left turn lane. NB Protected Option Allowed = False
22.	Reference Time (tRef)	Not allowed for NB tRef (NB) = Not Applicable (no separate left lane)
23.	Adjusted Reference Time	Not allowed for NB

	(tAdj)	tAdj (NB) = Not Applicable (no separate left lane)
Permitted Option		
24.	Proportion of Lefts (pL)	pL = vL / vC, for shared left-through lane pL (NB) = 100 / 500 = 0.20
25.	Volume Left Lane (vLL)	vLL = vC * max(pL, (pL*4+1)/n - pL*4) vLL (NB) = 500 * max(0.20, (0.20*4+1)/1 - 0.20*4) = 500
26.	Proportion of Lefts in Left Lane (pLL)	pLL = pL * vC/vLL pLL (NB) = 0.2 * 500/500 = 0.20
27.	Left Turn Equivalents (EL)	EL = (0.5 + 0.8 * pLL - 0.3 * pLL^2) / [4* (1 + pLL)/CL + vLO / (vCO)] EL (NB) = (0.5 + 0.8 * 0.20 - 0.3 *0.20^2) / [4* (1 + 0.20)/120 + 100 / (400)] = 2.23
28.	Left Turn Factor (fLT)	fLT = 1 / [1 + pLL * (EL - 1)] fLT (NB) = 1 / [1 + 0.20 * (2.23 - 1)] = 0.803
29.	Adjusted Saturation A (sA)	sA = s * fLT / n sA (NB) = 1824.6 * 0.803 / 1 = 1463
30.	Reference Time A (tRefA)	tRefA = max(vLL * CL / sA + intf, vC * CL/ s) tRefA (NB) = max(500 * 120 / 1463 + 0, 500 * 120/ 1824) = 41.0
31.	Adjusted Saturation B (sB)	sBT = sT * (nT - 1) / nT sBT (NB) = 1829 * (1 - 1) / 1 = 0
32.	Reference Time B (tRefB)	Oncoming through traffic > 120, NA
33.	Reference Time Lefts (tRefBL)	Oncoming through traffic > 120, NA

34. Reference Time (tRefPerm)	tRefPerm = min(max(tRefAL, tRefAT), max(tRefBL, tRefB)) tRefPerm (NB) = min(max(0, 41.0), max(NA, NA)) = 41.0
35. Adjusted Reference Time (tAdjPerm)	tAdjPerm = tLost + max(tMin, tRefPerm) * (1 - freq) + max(tMin, tRefPerm, tPed) * freq tAdjPerm (NB) = 4 + max(4, 41) * (1 - 0) + max(4, 41, 16) * 0 = 45.0
Split Option	
36. Reference Time Combined (tRefC)	tRefC = vC / s * CL + intf tRefC (NB) = 500 / 1824.6 * 120 + 0 = 32.9
37. Reference Time By Movement (tRefS)	tRefS = vS / sS * CL + intf tRefS (NB) = 400 / 1828.8 * 120 + 0 = 26.2
38. Reference Time (tRefSplit)	tRefSplit = max (tRefC, tRefST, tRefSL) tRefSplit (NB) = max (32.9, 26.2, 6.6) = 32.9
39. Adjusted Reference Time (tAdjSplit)	tAdjSplit = tLost + max(tMin, tRefSplit) * (1 - freq) + max(tMin, tRefSplit, tPed) * freq tAdjSplit = 4 + max(4, 32.9) * (1 - 0) + max(4, 32.9, 15) * 0 = 36.9
Summary	
40. Protected Option (tProt)	tProtNS = max(tAdjNBL + tAdjSBT, tAdjSBL + tAdjNBT) tProtNS = NA
41. Permitted Option,(tPerm)	tPermNS = max(tAdjPermNBT, tAdjPermSBT) tPermNS = max(45.0, 42.7) = 45.0
42. Split Option (tSplit)	tSplitNS = tAdjSplitNBT + tAdjSplitSBT tSplitNS = 36.9 + 30.6 = 67.5
43. Minimum	Min(tProt, tPerm, tSplit) Min(NA, 45.0, 67.5) = 45.0
44. Combined (tCombined)	Sum of two columns in row 43 52.5 + 45.0 = 97.5

Right Turns	
45. Adjusted Reference Time (tAdj)	From line 23, NBR = 0.0
46. Cross Through Direction	From left side of movement, NBR cross direction is EBT
47. Cross Through Adjusted Reference Time (tAdjMinT)	tAdjMinT = min(tAdj, tAdjPerm, tAdjSplit) tAdjMinT (NBR) = min(41.9, 103.7, 41.9) = 41.9
48. Oncoming Left Direction	For the NBR direction, the oncoming left direction is SBL
49. Oncoming Adjusted Left Reference Time (tAdjMinL)	tAdjMinL = min(tAdj, tAdjSplit) tAdjMinL (NBR) = min(NA, 30.6) = 30.6
50. Combined	0.0 + 41.9 + 30.6 = 72.5
Final Calculations	
51. Intersection Capacity Utilization (ICU)	ICU = Max(97.5, 52.7, 59.0, 72.5, 72.5)/120 ICU = 97.5/120 = 0.813 or 81.3%
52. Level of Service	Enter a letter A to H based on **Table 5-3** and Line 51. ICU LOS = D

Intersection Capacity Utilization Worksheet

Intersection Location:	1st Street & Main Street	**City:**	Anytown
Analyzed by:	Trafficware	**Alternative:**	Existing
Date and Time of Data:	June, 2003	**Project:**	Example 1

		EBL	EBT	EBR	WBL	WBT	WBR	NBL	NBT	NBR	SBL	SBT	SBR
1	**Movement**	**EBL**	**EBT**	**EBR**	**WBL**	**WBT**	**WBR**	**NBL**	**NBT**	**NBR**	**SBL**	**SBT**	**SBR**
2	Lanes	1	1	1	1	1	1	0	1	0	0	1	0
3	Shared LT Lane (y/n)	☐ Yes			☐ Yes			☑ Yes			☑ Yes		
4	Volume	100	600	100	100	500	100	100	300	100	100	200	100
5	Pedestrians			0			0			0			0
6	Ped Button (y/n)		☐ Yes			☐ Yes			☐ Yes			☐ Yes	
7	Pedestrian Timing Required		16			16			16			16	
8	Free Right (y/n)			☐ Yes			☐ Yes			☐ Yes			☐ Yes
9	Ideal Flow	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900
10	Lost Time	4	4	4	4	4	4	4	4	4	4	4	4
11	Minimum Green	4	4	4	4	4	4	4	4	4	4	4	4
12	Reference Cycle Length	120											
13	Volume Combined	100.0	600.0	100.0	100.0	500.0	100.0	0.0	500.0	0.0	0.0	400.0	0.0
14	Volume Separate Left	100.0	600.0		100.0	500.0		100.0	400.0		100.0	300.0	
15	Lane Utilization Factor	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
16	Turning Factor Adjust	0.950	1.000	0.850	0.950	1.000	0.850	0.950	0.960	0.850	0.950	0.950	0.850
17	Saturated Flow Combined	1805.0	1900.0	1615.0	1805.0	1900.0	1615.0	0.0	1824.6	0.0	0.0	1805.9	0.0
18	Saturated Flow Separate	1805.0	1900.0		1805.0	1900.0		1805.0	1828.8		1805.0	1805.0	
19	Pedestrian Interference Time		0.0	0.0		0.0	0.0		0.0	0.0		0.0	0.0
20	Pedestrian Frequency		0.0%			0.0%			0.0%			0.0%	
21	**Protected Option Allowed**		TRUE			TRUE			FALSE			FALSE	
22	Reference Time	6.6	37.9	7.4	6.6	31.6	7.4	NA	NA	0.0	NA	NA	0.0
23	Adjusted Reference Time	10.6	41.9	11.4	10.6	35.6	11.4	NA	NA	0.0	NA	NA	0.0
	Permitted Option												
24	Proportion Lefts	1	0.00		1	0.00		1	0.20		1	0.25	
25	Volume Left Lane	100	600		100	500		0	500		0	400	
26	Proportion Lefts Left	1	0.00		1	0.00		1	0.20		1	0.25	
27	Left turn Equivalents	15.0	15.0		15.0	15.0		3.2	2.2		3.8	2.8	
28	Left turn Factor	0.07	1.00		0.07	1.00		0.32	0.80		0.27	0.69	
29	Permitted Sat Flow	120.3	1900.0		120.3	1900.0		0.0	1463.3		0.0	1241.4	
30	Reference Time A	99.7	37.9		99.7	31.6		0.0	41.0		0.0	38.7	
31	Adjusted Saturation B		1900.0			1900.0			0.0			0.0	
32	Reference Time B		NA			NA			NA			NA	
33	Reference Time Lefts	NA			NA			NA			NA		
34	Reference Time		99.7			99.7			41.0			38.7	
35	Adjusted Reference Time		103.7			103.7			45.0			42.7	
	Split Timing												
36	Ref Time Combined		37.9			31.6			32.9			26.6	
37	Ref Time By Movement	6.6	37.9		6.6	31.6		6.6	26.2		6.6	19.9	
38	Reference Time		37.9			31.6			32.9			26.6	
39	Adjusted Reference Time	41.9	41.9		35.6	35.6		36.9	36.9		30.6	30.6	

	Summary	**East West**	**North South**
40	Protected Option	52.5	NA
41	Permitted Option	103.7	45.0
42	Split Option	77.5	67.5
43	Minimum	52.5	45.0
44	Combined	97.5	

	Right Turns	**EBR**	**WBR**	**NBR**	**SBR**
45	Adjusted Reference Time	11.4	11.4	0.0	0.0
46	Cross Through Direction	SBT	NBT	EBT	WBT
47	Cross Through Adj Ref Time	30.6	36.9	41.9	35.6
48	Oncoming Left Direction	WBL	EBL	SBL	NBL
49	Oncoming Left Adj Ref Time	10.6	10.6	30.6	36.9
50	Combined	52.7	59.0	72.5	72.5

51	**Intersection Capacity Utilization**	**81.3%**
52	**Level Of Service**	**D**

Revision 2003.1

Figure 10-2 Example 1 ICU Worksheet

Example Problem 2 Multi-Lane Intersection Geometry

The intersection of 2nd Street (NB/SB) and Main Street (EB/WB) is located in an outlying area of the city. Intersection geometry and flow characteristics are shown in **Figure 10-3**. This is an example of a multi-lane roadway (Main Street) crossed by a multi- lane roadway (2nd Street).

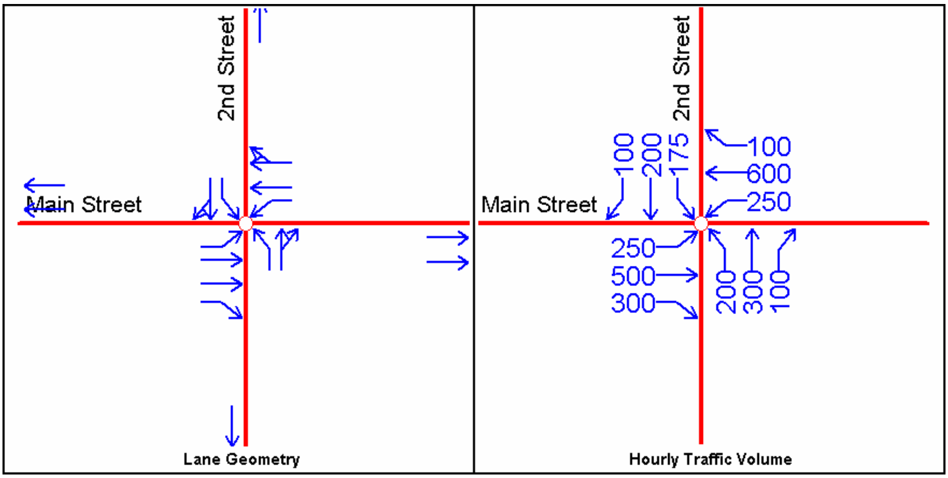

Figure 10-3 Example 2 Multi Lane Intersection Geometry

In addition, the following information is given for this example:

- Twenty (20) Pedestrian conflict with all right turns during this analysis period
- Pedestrian push buttons are present
- Pedestrian timing should be considered in the case that a pedestrian arrives (walk = 5 seconds, flashing don't walk = 11 seconds)
- The right turns are not free movements
- The Ideal Saturation Flow is 1,900 vphpl
- The Minimum Green time for each movement should be 4.0 seconds
- The Lost Time for each movement is 4.0 seconds

Computational Steps

The following computational steps use the Intersection Capacity Utilization worksheet as shown in **Figure 5-1**.

1-12.	Data Inputs	See **Figure 10-4**
13.	Volume Combined (vC)	vCT = vT vCT (EB) = 500
14.	Volume Separate Left (vS)	vST = vT vST (EB) = 500
15.	Lane Utilization Factor, (fLU)	Use **Table 5-2** fLU (EB) = 0.952
16.	Turning Factor Adjustment (fT)	fTT = (1 - 0.15 * (vR - vCR)/vCT) * (1 - 0.05 * (vL - vCL)/vCT) fTT (EB) = (1 - 0.15 * (300 - 300)/500) * (1 - 0.05 * (250 - 250)/500) = 1.0
17.	Saturated Flow Rate Combined (s)	sT = i * n * fLU * fT sT (EB) = 1900 * 2 * 0.952 * 1.0 = 3617.6
18.	Saturated Flow Rate Separate (sC)	sT = i * n * fLU * fT sT (EB) = 1900 * 2 * 0.952 * 1.0 = 3617.6
19.	Pedestrian Interference Time (intf)	Use zero for EBT.
20.	Pedestrian Frequency (freq)	freq = 1 - e^(-ped*CL/3600) freq (EB) = 1 - e^(-20*120/3600) = 0.487
Protected Option		
21.	Protected Option Allowed	Only allowed when there is a separate left turn lane. EB Protected Option Allowed = True
22.	Reference Time (tRef)	tRef = vC / s * CL + intf tRef (EB) = 500 / 3617.6 * 120 + 0 = 16.6
23.	Adjusted Reference Time (tAdj)	tAdj = tLost + max(tMin, tRef) * (1 - freq) + max(tMin, tRef, tPed) * freq

	tAdj (EB) = 4 + max(4, 16.6) * (1 - 0.487) + max(4, 16.6, 16) * 0.487 = 20.6
Permitted Option	
24. Proportion of Lefts (pL)	pL = vL / vC, for shared left-through lane pL (EB) = 0 for through lane group
25. Volume Left Lane (vLL)	vLL = vC / n vLL (EB) = 250 / 1 = 250
26. Proportion of Lefts in Left Lane (pLL)	Exclusive left, use pLL = 1.0 for EBL and pLL = 0.0 for EBT.
27. Left Turn Equivalents (EL)	EL = (0.5 + 0.8 * pLL - 0.3 * pLL^2) / [4* (1 + pLL)/CL + vLO / (vCO)] EL (EB) = (0.5 + 0.8 * 1.0 - 0.3 *1.0^2) / [4* (1 + 1.0)/120 + 0 / (700)] = 15.0 Note: vLO = 0 since oncoming traffic is not in a single lane.
28. Left Turn Factor (fLT)	fLT = 1 / [1 + pLL * (EL - 1)] fLT (EB) = 1 / [1 + 0.0 * (15 - 1)] = 1.0
29. Adjusted Saturation A (sA)	sA = s * fLT / n sA (EB) = 3617.6 * 1.0 / 2 = 1808.8
30. Reference Time A (tRefA)	tRefA = max(vLL * CL / sA + intf, vC * CL/ s) tRefA (EB) = max(250 * 120 / 1808.8 + 0, 500 * 120/ 3617.6) = 16.6
31. Adjusted Saturation B (sB)	No shared lane, sBT = sT sBT (EB) = 3617.6
32. Reference Time B (tRefB)	Oncoming through traffic > 120, NA
33. Reference Time Lefts (tRefBL)	Oncoming through traffic > 120, NA
34. Reference Time (tRefPerm)	tRefPerm = min(max(tRefAL, tRefAT), max(tRefBL, tRefB)) tRefPerm (EB) = min(max(249.3, 16.6), max(NA, NA)) = 249.3
35. Adjusted Reference Time (tAdjPerm)	tAdjPerm = tLost + max(tMin, tRefPerm) * (1 - freq) + max(tMin, tRefPerm, tPed) * freq

	tAdjPerm (EB) = 4 + max(4, 249.3) * (1 - 0) + max(4, 249.3, 16) * 0 = 253.3
Split Option	
36. Reference Time Combined (tRefC)	tRefC = vC / s * CL + intf tRefC (EB) = 500 / 3617.6 * 120 + 0 = 16.6
37. Reference Time By Movement (tRefS)	tRefS = vS / sS * CL + intf tRefS (EB) = 500 / 3617.6 * 120 + 0 = 16.6
38. Reference Time (tRefSplit)	tRefSplit = max (tRefC, tRefST, tRefSL) tRefSplit (EB) = max (16.6, 16.6, 16.6) = 16.6
39. Adjusted Reference Time (tAdjSplit)	tAdjSplit = tLost + max(tMin, tRefSplit) * (1 - freq) + max(tMin, tRefSplit, tPed) * freq tAdjSplit (EB) = 4 + max(4, 16.6) * (1 - 0) + max(4, 16.6, 16) * 0 = 20.6
Summary	
40. Protected Option (tProt)	tProtEW = max(tAdjEBL + tAdjWBT, tAdjWBL + tAdjEBT) tProtNS = max(20.6 + 28.1, 20.6 + 20.6) = 48.7
41. Permitted Option,(tPerm)	tPermEW = max(tAdjPermEBT, tAdjPermWBT) tPermEW = max(253.3, 253.3) = 253.3
42. Split Option (tSplit)	tSplitEW = tAdjSplitEBT + tAdjSplitWBT tSplitEW = 20.6 + 28.1 = 48.7
43. Minimum	Min(tProt, tPerm, tSplit) Min (EW) = Min(48.7, 253.3, 48.7) = 48.7
44. Combined (tCombined)	Sum of two columns in row 43 48.7 + 46.5 = 95.1
Right Turns	
45. Adjusted Reference Time (tAdj)	From line 23, EBR = 26.3
46. Cross Through Direction	From left side of movement, EBR cross direction is SBT

47.	Cross Through Adjusted Reference Time (tAdjMinT)	tAdjMinT = min(tAdj, tAdjPerm, tAdjSplit) tAdjMinT (EBR) = min(24.7, 178.5, 24.7) = 24.7
48.	Oncoming Left Direction	For the EBR direction, the oncoming left direction is WBL
49.	Oncoming Adjusted Left Reference Time (tAdjMinL)	tAdjMinL = min(tAdj, tAdjSplit) tAdjMinL (EBR) = min(20.6, 28.6) = 20.6
50.	Combined	26.3 + 24.7 + 20.6 = 71.6
Final Calculations		
51.	Intersection Capacity Utilization (ICU)	ICU = Max(71.6, 51.4, 36.2, 45.4, 95.1)/120 ICU = 95.1/120 = 0.793 or 79.3%
52.	Level of Service	Enter a letter A to H based on **Table 5-3** and Line 51. ICU LOS = D

Intersection Capacity Utilization Worksheet

Intersection Location:	2nd Street & Main Street	**City:**	Anytown
Analyzed by:	Trafficware	**Alternative:**	Existing
Date and Time of Data:	June, 2003	**Project:**	Example 2

1	**Movement**	EBL	EBT	EBR	WBL	WBT	WBR	NBL	NBT	NBR	SBL	SBT	SBR
2	Lanes	1	2	1	1	2	0	1	1	0	1	1	0
3	Shared LT Lane (y/n)	☐ Yes			☐ Yes			☐ Yes			☐ Yes		
4	Volume	250	500	300	250	600	100	200	300	100	175	200	100
5	Pedestrians			20			20			20			20
6	Ped Button (y/n)		☑ Yes			☑ Yes			☑ Yes			☑ Yes	
7	Pedestrian Timing Required		16			16			16			16	
8	Free Right (y/n)			☐ Yes			☐ Yes			☐ Yes			☐ Yes
9	Ideal Flow	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900
10	Lost Time	4	4	4	4	4	4	4	4	4	4	4	4
11	Minimum Green	4	4	4	4	4	4	4	4	4	4	4	4
12	Reference Cycle Length	120											
13	Volume Combined	250.0	500.0	300.0	250.0	700.0	0.0	200.0	400.0	0.0	175.0	300.0	0.0
14	Volume Separate Left	250.0	500.0		250.0	700.0		200.0	400.0		175.0	300.0	
15	Lane Utilization Factor	1.000	0.952	1.000	1.000	0.952	1.000	1.000	1.000	1.000	1.000	1.000	1.000
16	Turning Factor Adjust	0.950	1.000	0.850	0.950	0.979	0.850	0.950	0.963	0.850	0.950	0.950	0.850
17	Saturated Flow Combined	1805.0	3617.6	1615.0	1805.0	3540.1	0.0	1805.0	1828.8	0.0	1805.0	1805.0	0.0
18	Saturated Flow Separate	1805.0	3617.6		1805.0	3540.1		1805.0	1828.8		1805.0	1805.0	
19	Pedestrian Interference Time		0.0	2.3		0.3	2.3		0.6	2.3		0.8	2.3
20	Pedestrian Frequency		48.7%			48.7%			48.7%			48.7%	
21	**Protected Option Allowed**		TRUE			TRUE			TRUE			TRUE	
22	Reference Time	16.6	16.6	24.6	16.6	24.1	0.0	13.3	26.8	0.0	11.6	20.7	0.0
23	Adjusted Reference Time	20.6	20.6	28.6	20.6	28.1	0.0	17.3	30.8	0.0	15.6	24.7	0.0
	Permitted Option												
24	Proportion Lefts	1	0.00		1	0.00		1	0.00		1	0.00	
25	Volume Left Lane	250	250		250	350		200	400		175	300	
26	Proportion Lefts Left	1	0.00		1	0.00		1	0.00		1	0.00	
27	Left turn Equivalents	15.0	15.0		15.0	15.0		15.0	15.0		15.0	15.0	
28	Left turn Factor	0.07	1.00		0.07	1.00		0.07	1.00		0.07	1.00	
29	Permitted Sat Flow	120.3	1808.8		120.3	1770.0		120.3	1828.8		120.3	1805.0	
30	Reference Time A	249.3	16.6		249.3	24.1		199.4	26.8		174.5	20.7	
31	Adjusted Saturation B		3617.6			3540.1			1828.8			1805.0	
32	Reference Time B		NA			NA			NA			NA	
33	Reference Time Lefts	NA			NA			NA			NA		
34	Reference Time		249.3			249.3			199.4			174.5	
35	Adjusted Reference Time		253.3			253.3			203.4			178.5	
	Split Timing												
36	Ref Time Combined		16.6			24.1			26.8			20.7	
37	Ref Time By Movement	16.6	16.6		16.6	24.1		13.3	26.8		11.6	20.7	
38	Reference Time		16.6			24.1			26.8			20.7	
39	Adjusted Reference Time	20.6	20.6		28.1	28.1		30.8	30.8		24.7	24.7	

	Summary	**East West**	**North South**
40	Protected Option	48.7	46.5
41	Permitted Option	253.3	203.4
42	Split Option	48.7	55.5
43	Minimum	48.7	46.5
44	Combined	95.1	

	Right Turns	**EBR**	**WBR**	**NBR**	**SBR**
45	Adjusted Reference Time	28.6	0.0	0.0	0.0
46	Cross Through Direction	SBT	NBT	EBT	WBT
47	Cross Through Adj Ref Time	24.7	30.8	20.6	28.1
48	Oncoming Left Direction	WBL	EBL	SBL	NBL
49	Oncoming Left Adj Ref Time	20.6	20.6	15.6	17.3
50	Combined	73.9	51.4	36.2	45.4

51	**Intersection Capacity Utilization**	**79.3%**
52	**Level Of Service**	**D**

Revision 2003.1

Figure 10-4 Example 2 ICU Worksheet

Example Problem 3 Diamond Interchange

Main Street and Interstate 99 is located on the west side of Anytown. A diamond interchange exists and the geometry and flow characteristics are shown in **Figure 10-5**.

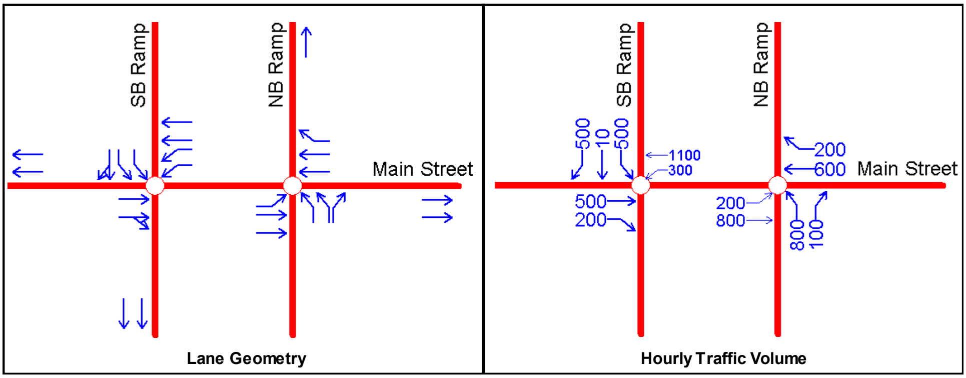

Figure 10-5 Example 3 Diamond Interchange Intersection Geometry

In addition, the following information is given for this example:

- Pedestrian volumes are zero during this analysis period
- Pedestrian push buttons are not present
- The WB right turn at the NB Ramp is a free movement
- The Ideal Saturation Flow is 2,000 vphpl
- The Minimum Green time for each movement should be 4.0 seconds
- The Lost Time for each movement is 4.0 seconds

Computational Steps

The following computational steps use the Intersection Capacity Utilization worksheet as shown in **Figure 6-12**.

1–9.	Data Inputs	See **Figure 10-6**
10.	Storage Space (L)	Refer to **Figure 6-4** for how space is included. L (WBL) = [(150’ * 2) + 414’ - 80’ - 150’] / 25’ = 19.4 80’ is the internal distance of the intersections taken out.
11.	Lost Time (tL)	
12.	Minimum Green Time (tMin)	Enter 4 seconds
13.	Reference Cycle Length (CL)	Enter 120 seconds
14.	Travel Time (tT).	Travel time between intersections tT = 414’ / (40 mph * 1.467) = 7.1 seconds
15.	Lanes Available (n’)	n' = n n' (WBL) = 2.0
16.	Volume Combined (vC)	vCL = vL * nL/nL’ + vR * (nR’ – nR)/nR’ vCL (WBL) = 300 * 2/2 + 0 = 300
17.	Lane Utilization Factor (fLU)	Use **Table 6-3** fLU (WBL) = 0.971
18.	Turning Factor Adjustment (fT)	fTL = 0.95 – 0.10 * pR fTL (WBL) = 0.95 – 0.10 * 0 = 0.95
19.	Saturated Flow Rate Combined (s)	s = i * n * fLU * fT s (WBL) = 2000 * 2 * 0.971 * 0.95 = 3689.8
20.	Pedestrian Interference Time (intf)	No pedestrians, use zero
21.	Pedestrian Frequency (freq)	No pedestrians, use zero
22.	Reference Time (tRef)	tRef = vC / s * CL + intf

	tRef (WBL) = 300 / 3689.8 * 120 + 0 = 9.8
23. Adjusted Reference Time (tAdj)	tAdj = tLost + max(tMin, tRef) tAdj (WBL) = 4 + max(4, 9.8) = 13.8
24. Interchange Reference Time (tIC)	tIC = tAdj, all movements except free rights tIC (WBL) = 13.8
25. Volume per Cycle (vCy)	vCy = vC * CL/3600 vCy (WBL) = 300 * 120/3600 = 10.0
26. vCy90 = vCy + sqrt(vCy) * 1.28	vCy90 = vCy + sqrt(vCy) * 1.28 vCy90 (WBL) = 10 + sqrt(10) * 1.28 = 14.0
27. Volume to Storage Ratio (vLRatio)	vLRatio = vCy90 / L vLRatio (WBL) = 14 / 19.4 = 0.7
28. Isolated Time 1 (tI1)	tI1 = max(tICEBT, tICEBR) + tICWBL + max(tICSBL, tICSBT) tI1 (west intersection) = max(27.0, 0) + 13.8 + max(20.3, 39.9) = 80.7
29. Isolated Alternate Check (tI2)	tI2 = tICWBT + max(tICSBL, tICSBT, tICSBR) tI2 (west intersection) = 38.7 + max(20.3, 39.9, 0.0) = 78.5
30. Isolated Combined (tI)	tI = max(tI1, tI2) tI = max(80.7, 78.5) = 80.7
31. Overlap Times (tO)	tOW = min(tT, max(tICEBT. tICEBR)) tOW (west intersection) = min(7.1, max(27.0. 0)) = 7.1
32. Leading Alternate Option (tLA)	= max(tICEBT, tICEBR) + max(tICSBL, tICSBT, tICSBR, tT*2) + max(tICWBT, tICWBR) + max(tICNBL, tICNBT, tICNBR, tT*2) - tOE – tOW = max(27.0, 0.0) + max(20.3, 39.9, 0.0, 7.1*2) + max(22.9, 0.9) + max(30.0, 0.0, 11.1, 7.1*2) - 7.1 - 7.1 = 105.6
33. Lagging Time (tLG)	vLRatio > 1.0 for NBL, not allowed
34. Lead-Lag Time (tLL)	vLRatio > 1.0 for NBL, not allowed

35. Best Alternative	Min (tLA, tLG, tLL) Min (105.6, NA, NA) = 105.6
36. Intersection Capacity Utilization (ICU)	ICU = 105.6/ 120 = 0.88 or 88%
37. Level of Service	Enter a letter A to H based on **Table 6-5** and Line 51. ICU LOS = E

Diamond Interchange Capacity Utilization Worksheet
East-West Arterial

Intersection Location: Main Street & I-99 **City:** Anytown
Analyzed by: Trafficware **Alternative:** Existing
Date and Time of Data: July, 2003 **Project:** Example 3

	Intersection	West							East						
1	**Movement**	EBT	EBR	WBL	WBT	SBL	SBT	SBR	WBT	WBR	EBL	EBT	NBL	NBT	NBR
2	Lanes	2		2	2	2	1	0	2	1	1	2	2	0	1
3	Shared Lane (y/n)		☑ Yes			☐ Yes		☑ Yes		☐ Yes			☐ Yes		☐ Yes
4	Volume	500	200	300	1100	500	10	500	600	200	200	800	800	0	100
5	Pedestrians							0							
6	Ped Button (y/n)		☐ Yes					☐ Yes		☐ Yes					☐ Yes
7	Pedestrian Timing Required		0					16			0				0
8	Free Right (y/n)		☐ Yes					☐ Yes		☑ Yes					☐ Yes
9	Ideal Flow	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
10	Storage Space			19.4	26.7						19.4	26.7			
11	Lost Time	4	4	4	4	4	4	4	4	4	4	4	4	4	4
12	Minimum Green	4	4	4	4	4	4	4	4	4	4	4	4	4	4
13	Reference Cycle Length	120													
14	Travel Time	7.1													
15	Lanes Available	2.0	0.5	2.0	2.0	2.0	1.0	0.5	2.0	1.0	1.0	2.0	2.0	0.0	1.0
16	Volume Combined	700.0	0.0	300.0	1100.0	500.0	510.0	0.0	600.0	200.0	200.0	800.0	800.0	0.0	100.0
17	Lane Utilization Factor	0.952	1.000	0.971	0.952	0.971	1.000	1.000	0.952	1.000	1.000	0.952	0.971	1.000	1.000
18	Turning Factor Adjust	0.957	0.850	0.950	1.000	0.950	0.853	0.850	1.000	0.850	0.950	1.000	0.950	1.000	0.850
19	Saturated Flow Combined	3644.8	0.0	3689.8	3808.0	3689.8	1705.9	0.0	3808.0	1700.0	1900.0	3808.0	3689.8		1700.0
20	Pedestrian Interference Time	0.0	0.0				0.0	0.0	0.0	0.0			0.0	0.0	0.0
21	Pedestrian Frequency		0.0%					0.0%		0.0%					0.0
22	Reference Time	23.0	0.0	9.8	34.7	16.3	35.9	0.0	18.9	14.1	12.6	25.2	26.0	0.0	7.1
23	Adjusted Reference Time	27.0	0.0	13.8	38.7	20.3	39.9	0.0	22.9	18.1	16.6	29.2	30.0	0.0	11.1
24	Interchange Reference Time	27.0	0.0	13.8	38.7	20.3	39.9	0.0	22.9	0.0	16.6	29.2	30.0	0.0	11.1
25	Volume per Cycle			10.0	36.7	16.7					6.7	26.7	26.7		
26	Volume per Cycle, 90th			14.0	44.4	21.9					10.0	33.3	33.3		
27	Volume to Storage			0.7	1.7	0.8					0.5	1.2	1.2		
	Timing Options														
28	Isolated Time 1							80.7							69.6
29	Isolated Alternate Check							78.5							59.2
30	Isolated Combined							80.7							69.6
31	Overlap times							7.1							7.1
32	Leading Alternating Option							105.6							
33	Lagging Time	Option Allowed			FALSE			80.7							
34	Lead-Lag Time	Option Allowed			FALSE			80.7							
35	Best Alternative							105.6							
36	**Intersection Capacity Utilization**		**88.0%**												
37	**Level Of Service**		**E**												

Revision 2003.1

Figure 10-6 Example 3 ICU Worksheet

Example Problem 4 Single Point Urban Interchange

Main Street and Interstate 499 is located on the west side of Anytown. A single point urban interchange exists and the geometry and flow characteristics are shown in **Figure 10-7**

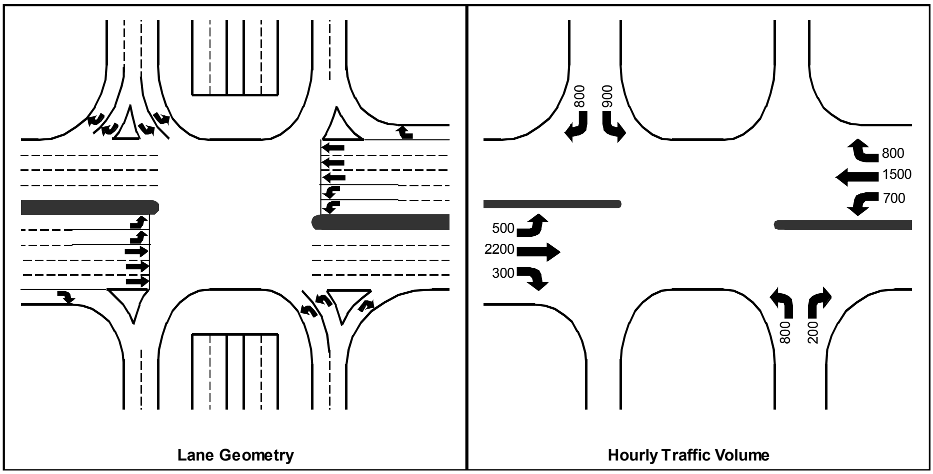

Figure 10-7 Example 4 Single Point Urban Intersection Geometry

In addition, the following information is given for this example:

- Pedestrian volumes are zero during this analysis period
- Pedestrian push buttons are not present
- Pedestrian timing should be considered in the case that a pedestrian arrives (walk = 5 seconds, flashing don't walk = 11 seconds)
- The right turns are not free movements
- The Ideal Saturation Flow is 1,900 vphpl
- The Minimum Green time for each movement should be 4.0 seconds
- The Lost Time for each movement is 4.0 seconds

Computational Steps

The following computational steps use the Intersection Capacity Utilization worksheet as shown in **Figure 7-4**.

1–11.	Data Inputs	See **Figure 10-8**
12.	Volume Combined (vC)	vCT = vT + vR* + vL** vCT (EB) = 2200
13.	Lane Utilization Factor (fLU)	Use **Table 7-2** fLU (EB) = 0.908
14.	Turning Factor Adjustment (fT)	fTT = (1 - 0.15 * (vR - vCR)/vCT) * (1 - 0.05 * (vL - vCL)/vCT) fTT (EB) = (1 - 0.15 * (0 - 0)/2200) * (1 - 0.05 * (0 - 0)/2200) = 1.00
15.	Saturated Flow Rate Combined (s)	sT = i * (nT + nL) * fLU * fT sT (EB) = 2000 * (3 + 0) * 0.908 * 1.00 = 5448.0
16.	Pedestrian Interference Time (intf)	Exclusive right for EB, use zero for EBT
17.	Pedestrian Frequency (freq)	Exclusive right for EB, use zero for EBT
Protected Option		
18.	Reference Time (tRef)	tRef = vC / s * CL + intf tRef (EB) = 2200 / 5448.0 * 120 + 0 = 48.5
19.	Adjusted Reference Time (tAdj)	tAdj = tLost + max(tMin, tRef) * (1 - freq) + max(tMin, tRef, tPed) * freq tAdj (EB) = 6 + max(8, 48.5) * (1 - 0.0) + max(8, 48.5, 24) * 0 = 54.5
Summary		
20.	Protected Option (tProt)	tProtEW = max(tAdjEBL + tAdjWBT, tAdjWBL + tAdjEBT) tProtES = max(24.3 + 39.0, 30.8 + 54.5) = 85.2
21.	Combined (tCombined)	Sum of two columns in row 20

	85.2 + 37.3 = 122.5
Right Turns	
22. Adjusted Reference Time (tAdj)	From line 19, EBR = 27.2
23. Cross Through Direction	From left side of movement, EBR cross direction is SBT
24. Cross Through Adjusted Reference Time (tAdjMinT)	tAdjMinT is SBT value from line 19 tAdjMinT (EBR) = 0.0
25. Oncoming Left Direction	For the EBR direction, the oncoming left direction is WBL
26. Oncoming Adjusted Left Reference Time (tAdjMinL)	tAdjMinL WBL value from line 19 tAdjMinL (EBR) = 30.8
27. Combined	Movement is a free right, copy line 22, 27.2
Final Calculations	
28. Intersection Capacity Utilization (ICU)	ICU = Max(122.5, 27.2, 86.7, 111.8, 37.9)/120 ICU = 122.5/120 = 1.021 or 102.1%
29. Level of Service	Enter a letter A to H based on **Table 7-3** and Line 28. ICU LOS = G

Urban Interchange Capacity Utilization Worksheet
East-West Arterial

Intersection Location:	1st Street & I-99	**City:**	Anytown
Analyzed by:	Trafficware	**Alternative:**	Existing
Date and Time of Data:	July, 2003	**Project:**	Example 4

1	**Movement**	**EBL**	**EBT**	**EBR**	**WBL**	**WBT**	**WBR**	**NBL**	**NBT**	**NBR**	**SBL**	**SBT**	**SBR**
2	Lanes	2	3	1	2	3	1	2	0	1	2	0	2
3	Volume	500	2200	300	700	1500	800	800	0	200	900	0	800
4	Pedestrians			12			0			0			0
5	Ped Button (y/n)		☑ Yes			☑ Yes			☐ Yes			☐ Yes	
6	Pedestrian Timing Required		24			24			20			20	
7	Free Right (y/n)			☑ Yes			☑ Yes			☑ Yes			☑ Yes
8	Ideal Flow	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
9	Lost Time	8	6	6	8	6	6	8	6	6	8	6	6
10	Minimum Green	8	8	8	8	8	8	8	8	8	8	8	8
11	Reference Cycle Length	120											
12	Volume Combined	500.0	2200.0	300.0	700.0	1500.0	800.0	800.0	0.0	200.0	900.0	0.0	800.0
13	Lane Utilization Factor	0.971	0.908	1.000	0.971	0.908	1.000	0.971	1.000	1.000	0.971	1.000	0.885
14	Turning Factor Adjust	0.950	1.000	0.850	0.950	1.000	0.850	0.950	1.000	0.850	0.950	1.000	0.850
15	Saturated Flow Combined	3689.8	5448.0	1700.0	3689.8	5448.0	1700.0	3689.8	0.0	1700.0	3689.8	0.0	3009.0
16	Pedestrian Interference Time		0.0	1.5		0.0	0.0		0.0	0.0		0.0	0.0
17	Pedestrian Frequency		33.0%			0.0%			0.0%			0.0%	
	Protected Option												
18	Reference Time	16.3	48.5	21.2	22.8	33.0	56.5	26.0	0.0	14.1	29.3	0.0	31.9
19	Adjusted Reference Time	24.3	54.5	27.2	30.8	39.0	62.5	34.0	0.0	20.1	37.3	0.0	37.9

	Summary	**East West**	**North South**
20	Protected Option	85.2	37.3
21	Combined	122.5	

	Right Turns	**EBR**	**WBR**	**NBR**	**SBR**
22	Adjusted Reference Time	27.2	62.5	20.1	37.9
23	Cross Through Direction	SBT	NBT	EBT	WBT
24	Cross Through Adj Ref Time	0.0	0.0	54.5	39.0
25	Oncoming Left Direction	WBL	EBL	SBL	NBL
26	Oncoming Left Adj Ref Time	30.8	24.3	37.3	34.0
27	Combined	27.2	86.7	111.8	37.9

28	**Intersection Capacity Utilization**	**102.1%**
29	**Level Of Service**	**G**

Revision 2003.0

Figure 10-8 Example 4 ICU Worksheet

Index

R

S

T

V