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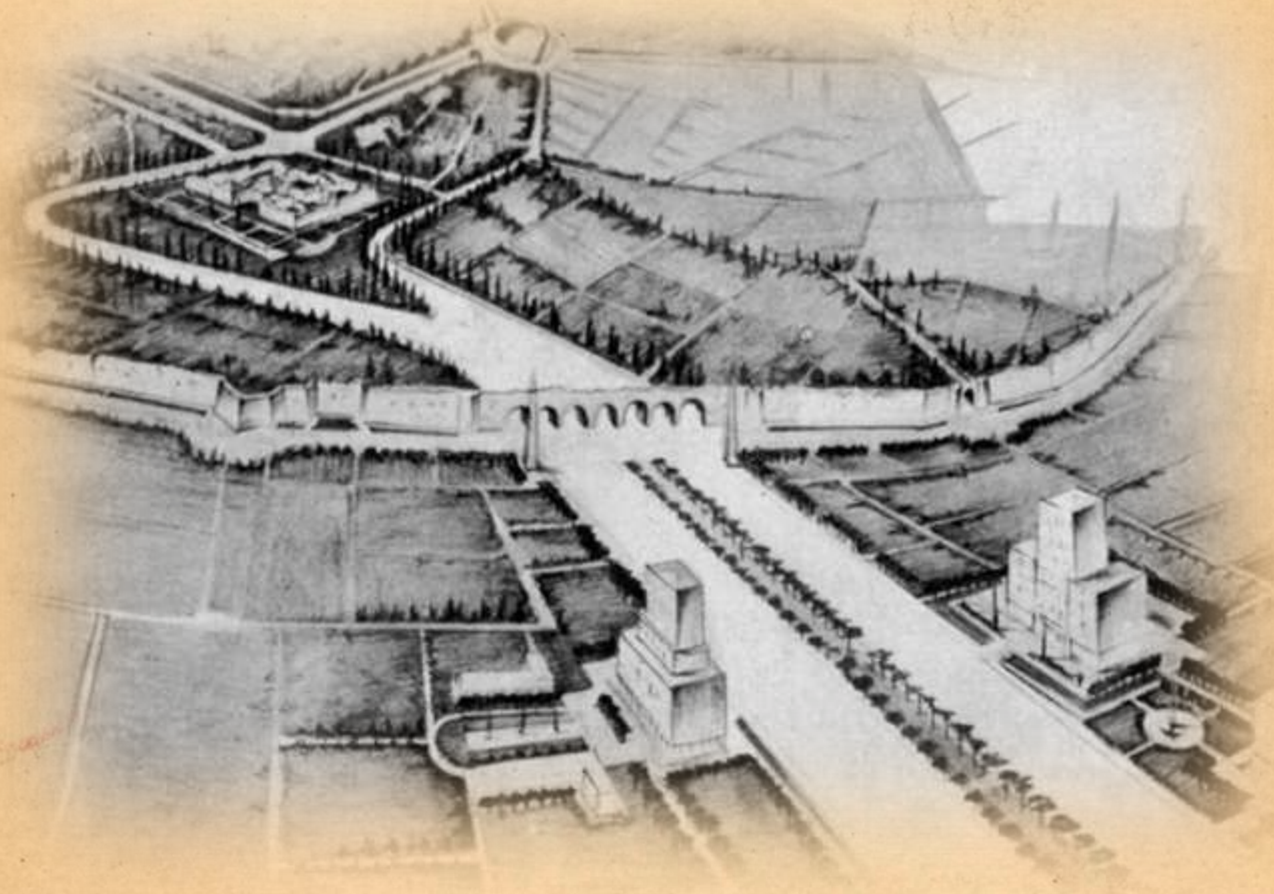

Traffic Signal Setting Design

Via Cristoforo Colombo

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The short history as introduction…

Being a part of big plan related to the Universal Exposition of Rome, the road Via Cristoforo Colombo (that time Via Imperiale, ed.) was designed in 1937 by Giuseppe Nicolosi, Aldo ed Edmondo del Bufalo and Carlo Roccatelli [1]. The main goal was to expand Rome towards to sea, therefore the subject of the road was to connect center of the Ancient Rome with Exposition. The street was characterized by a huge central avenue, 20 meters wide, and two counter avenues, 8 meters wide, flanked by rows of pine trees. The route was characterized by long straights, the first stretch started from Porta Capena, crossing "la Passeggiata Archeologica" [2], then a large curve led to Porta Ardeatina, along the Aurelian Walls, in which four large arches were created. From here another straight led to the Piazza delle Legioni Romane, today Piazza dei Navigatori, a curve to the west led to the large Piazza del Lavoro , on which Viale Marconi would have joined, then the road monumentally crossed the center of the Exposition, curved near Decima towards the west and came straight to the sea, making a small correspondence of the Royal Estate of Castel Porziano, which was thus not affected by the expropriations to build the road.

The construction works of the artery continued until 1941, after which they were abandoned due to the war, the great viaduct that crossed the railway tracks shortly after the Ostiense station was also left incomplete.

In 1948 the road was renamed to Cristoforo Colombo, the works resumed later and ended in 1954.

This short history was introduced for readers to show how much were proud four young analysts of the University of Rome Sapienza that they were honored to analyze and prepare the traffic project related to the part of Via Cristoforo Colombo. As an additional information, it could be interesting to know that Via Cristoforo Colombo is the longest Italian road among those included within the borders of a single municipality and, in several stretches, the largest in Italy. According to the local laws, it is characterized as "Strada a scorrimento veloce" [3] (SSV, ed.)

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[1] Source - https://www.rerumromanarum.com/2020/09/via-cristoforo-colombo.html (ed.)

[2] via delle Terme di Caracalla (ed.)

[3] Fast Road

Study Area.

The part of Via Cristoforo Colombo considered under the analysis of this paper is composed by 8 junctions, starting from Viale di Porta Adreatina until Via Accademia degli Agiati with the total distance of 2616 m.

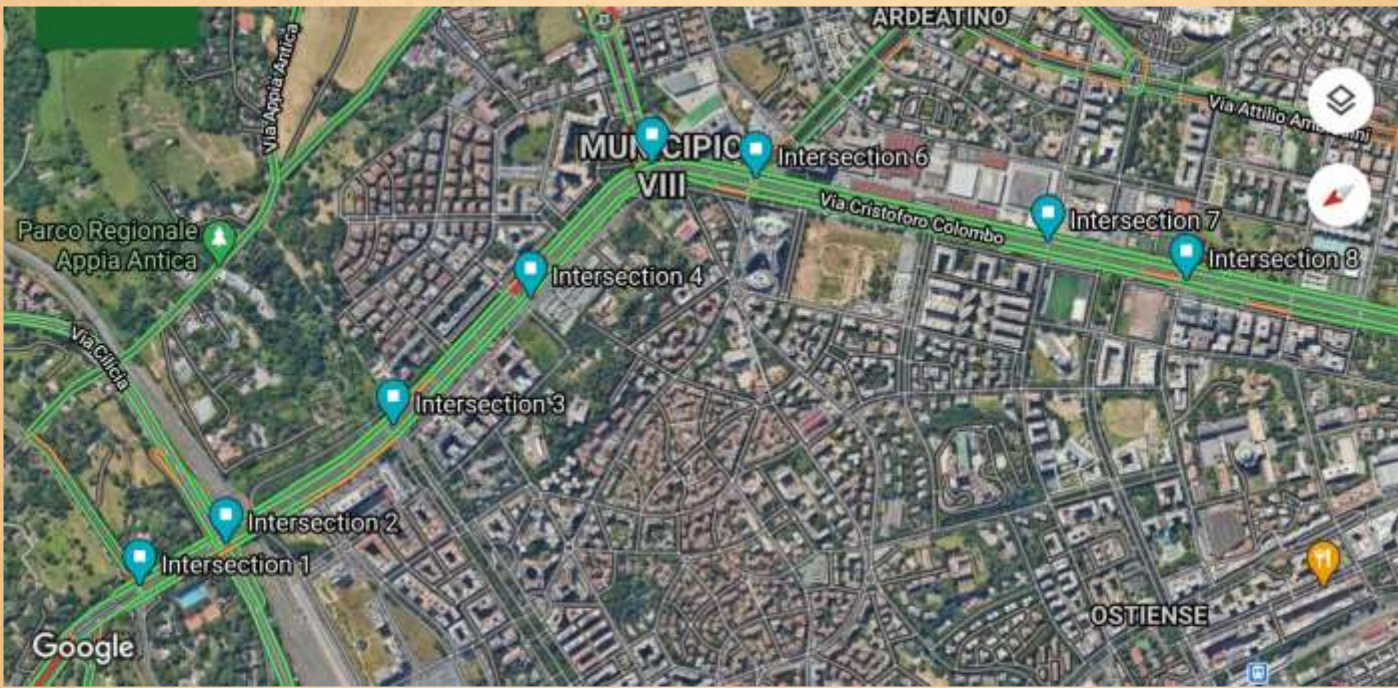


Figure 1 : Intersections analyzed on the Via Cristoforo Colombo.

As can be seen from the Fig. 1 and as observed by the analysts, this area cannot be considered as central business district (CBD), what was reflected on the volume adjustment steps for preliminary research of the current levels of service (LOS) later in this project. In the tables below is given general information about geometry and topography of the artery:

Intersection	EB	WB	SB	NB
1	Viale di Porta Adreatina	Viale di Porta Adreatina	Via Cristoforo Colombo	Via Cristoforo Colombo
2	Via Odoardo Beccari	*	Via Cristoforo Colombo	Via Cristoforo Colombo
3	Largo Angelo Fochetti	*	Via Cristoforo Colombo	Via Cristoforo Colombo
4	Via Padre Semeria	*	Via Cristoforo Colombo	Via Cristoforo Colombo
5	*	Via delle Sette Chiese	Via Cristoforo Colombo	Via Cristoforo Colombo
6	Via Giovanni Genocchi	Piazza Elio Rufino	Via Cristoforo Colombo	Via Cristoforo Colombo
7	Via Constantino	*	Via Cristoforo Colombo	Via Cristoforo Colombo
8	*	Via Accademia degli Agiati	Via Cristoforo Colombo	Via Cristoforo Colombo

Table 1. All junctions with related street names.

Junctions	Distance between	Progressive distance
1 to 2	190	190
2 to 3	451	641
3 to 4	414	1055
4 to 5	375	1430
5 to 6	257	1687
6 to 7	652	2339
7 to 8	277	2616

Table 2. Progressive and paired distances.

Methodology of the analysis and optimization.

1. Data Collection.

Overall analysis and data collection for the current project is done under the instructions of Highway Capacity Manual (2000 edition)[4] :

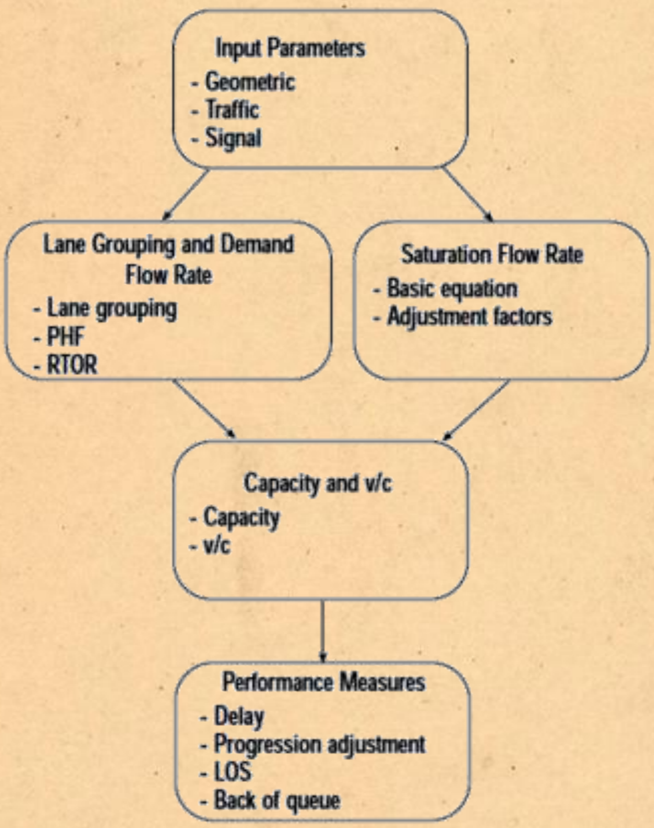


Figure 2: HCM Methodology for Signalized Intersection

[4] The Highway Capacity Manual (HCM) is a publication of the Transportation Research Board of the National Academies of Science in the United States (ed.)

According to the related article of this publication namely Chapter 16, there are several inputs needed for the future calculations of LOS for signalized intersections. The types of the inputs are shown in the table below:

EXHIBIT 16-3. INPUT DATA NEEDS FOR EACH ANALYSIS LANE GROUP	
Type of condition	**Parameter**
Geometric conditions	Area type Number of lanes, N Average lane width, W (m) Grade, G (%) Existence of exclusive LT or RT lanes Length of storage bay, LT or RT lane, Ls (m) Parking
Traffic conditions	Demand volume by movement, V (veh/h) Base saturation flow rate, so (pc/h/ln) Peak-hour factor, PHF Percent heavy vehicles, HV (%) Approach pedestrian flow rate, vped (p/h) Local buses stopping at intersection, NB (buses/h) Parking activity, Nm (maneuvers/h) Arrival type, AT Proportion of vehicles arriving on green, P Approach speed, SA (km/h)
Signalization conditions	Cycle length, C (s) Green time, G (s) Yellow-plus-all-red change-and-clearance interval (intergreen), Y (s) Actuated or pretimed operation Pedestrian push-button Minimum pedestrian green, Gp (s) Phase plan Analysis period, T (h)

Table 3. Summary of all data that should be collected for the analysis of LOS.

2. Current demand determination and disaggregation.

Determination of the flow rate can be executed by different approaches, however only one is chosen and used in this paper. The main difference of this approach is collection of the traffic data in 15 minutes analysis period in peak-hour period of the day. According to HCM:

" *A difficulty with considering only one 15-min period is that a queue may be left at the end of the analysis period because of demand in excess of capacity. In such cases it is possible that the queue carried over to the next period will result in delay to vehicles that arrive in that period beyond that which would have resulted had there not been a queue carryover.* "

Different study approaches are shown in the Figure 3:

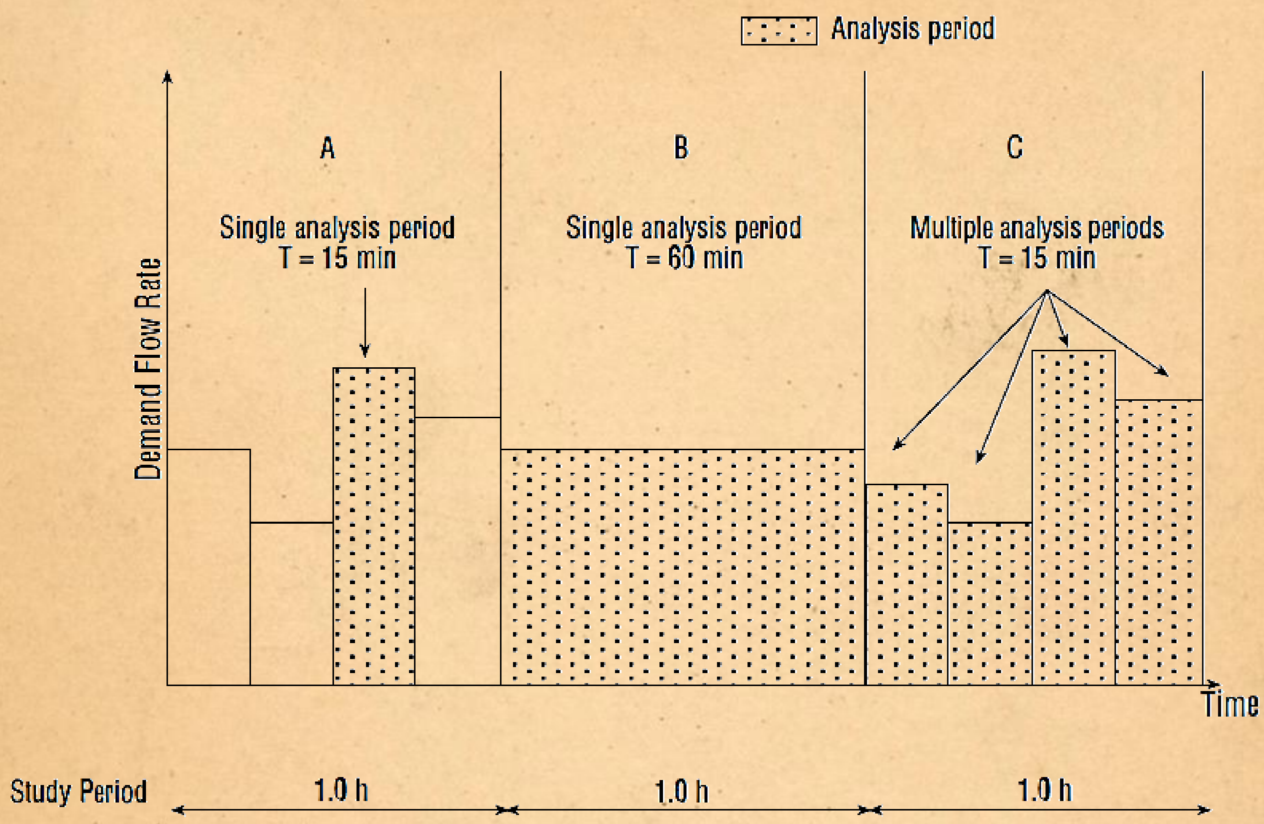


Figure 3: Three alternative study approaches.

In order to derive peak 15 min. flow rate the Peak Hour Factor (PHF) is used. For the current study PHF = 0.90.

$$v_p = \frac{V}{PHF}$$

where:

- Vp=flow rate during peak -15- min period (veh/h)
- V= hourly volume (veh/h)
- PHF= peak-hour factor

Demand by itself disaggregated not only on the different approaches (North Bound, East Bound, etc.), but also on different lane groups. Well, the determination of the lane group is quite simple and based on the natural characteristics, such as geometric conditions or traffic distribution. For example, the lane which is observed as the exclusive right turn cannot be treated the same as the lane, where vehicles passing only through. Later we will see for each intersection its own grouping, based on analysts observations and conclusions. Figure 4 giving a general idea about the lane grouping:

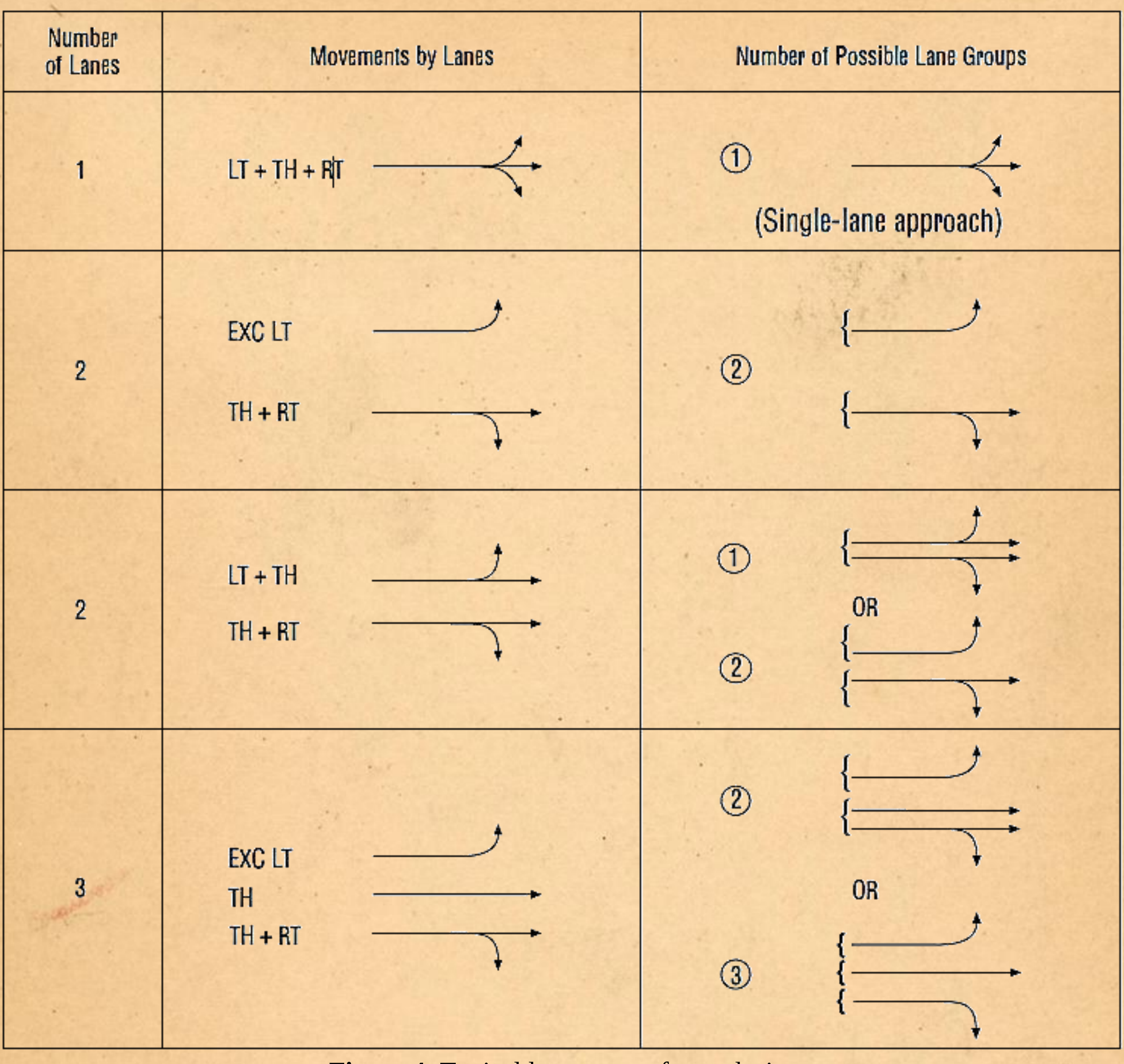


Figure 4: Typical lane groups for analysis

3. Lane group actual capacity for signalized intersection.

When we come to the term of capacity, it is visible without diving too much into the theory that actual supply constrained by so many factors. Indeed, the bus stopping not far from the junction or vehicles reducing the speed before turning right are causing delays and therefore constrain the ability of the intersection to accommodate higher demand. All those factors cannot be passed without the attention of analysts and therefore considered into the two main steps. The first step is determination of the actual capacity without the consideration of the green time border – it is so called saturation flow rate determination:

$$s = s_0\, N\, f_w\, f_{HV}\, f_g\, f_p\, f_{bb}\, f_a\, f_{LU}\, f_{LT}\, f_{RT}\, f_{Lpb}\, f_{Rpb}$$

where:

s	=	saturation flow rate for subject lane group, expressed as a total for all lanes in lane group (veh/h);
s_o	=	base saturation flow rate per lane (pc/h/ln);
N	=	number of lanes in lane group;
f_w	=	adjustment factor for lane width;
f_{HV}	=	adjustment factor for heavy vehicles in traffic stream;
f_g	=	adjustment factor for approach grade;
f_p	=	adjustment factor for existence of a parking lane and parking activity adjacent to lane group;
f_{bb}	=	adjustment factor for blocking effect of local buses that stop within intersection area;
f_a	=	adjustment factor for area type;
f_{LU}	=	adjustment factor for lane utilization;
f_{LT}	=	adjustment factor for left turns in lane group;
f_{RT}	=	adjustment factor for right turns in lane group;
f_{Lpb}	=	pedestrian adjustment factor for left-turn movements; and
f_{Rpb}	=	pedestrian-bicycle adjustment factor for right-turn movements.

The value of 2100 veh/h/lane is estimated as the base saturation flow. Some of these adjustment factors will be better observed on the actual intersections later in the following sections. It should be also commented that demand value of the vehicles turning right on the red were excluded in the analysis, since these vehicles has not real effect on the delays and therefore on level of service.

After determination of the saturation flows for every lane group, another constrain should be applied to get the final lane group real capacity – green time, because the vehicles will be able to pass the intersection only at the green signal.

$$c_i = s_i \frac{g_i}{C}$$

Where:

c_i=capacity of lane group I (veh/h)

s_i= saturation flow rate for lane group I (veh/h)

g_i/C=effective green ratio for lane group I

4. Final calculations and Level of Service determination.

After adjusting the capacity to the actual factors, it is a time to identify Level of Service. One of the important values as the input for the delays determination is the volume to capacity ratio (*X*), which is also referred as degree of saturation.

$$X_i = (\frac{v}{c})_i = \frac{v_i}{s_i(\frac{g_i}{C})} = \frac{v_i C}{s_i g_i}$$

where *i* is the current lane group.

The term Level of Service is basically intersection quality representation based on the average delay per vehicle.

LOS	Control Delay per Vehicle (s/veh)
A	≤ 10
B	$> 10 - 20$
C	$> 20 - 35$
D	$> 35 - 55$
E	$> 55 - 80$
F	> 80

Table 4. Level of Service (LOS) criteria for signalized intersections.

This criterion requires identification of the intersection delay, which can be defined from approaches delays, whose result is obtained from related lane group delays. Control delay of the vehicle is represented by the three type of the delays.

$$d = d_1(PF) + d_2 + d_3$$

Where:

d = control delay per vehicle (s/veh);
d_1 = uniform control delay assuming uniform arrivals (s/veh);
PF = uniform delay progression adjustment factor, which accounts for effects of signal progression;
d_2 = incremental delay to account for effect of random arrivals and oversaturation queues, adjusted for duration of analysis period and type of signal control; this delay component assumes that there is no initial queue for lane group at start of analysis period (s/veh); and
d_3 = initial queue delay, which accounts for delay to all vehicles in analysis period due to initial queue at start of analysis period (s/veh) (detailed in Appendix F of this chapter).

PF may be computed from measured values of P using the given values for f-PA. Alternatively, exhibit 16-12 may be used to determine PF as a function of the arrival type based on the default values for P (i.e., Rpgi/C) and f-PA associated with each arrival type. If PF is estimated by Equation, its calculated value may exceed 1.0 for Arrival Type 4 with extremely low values of g/C. As a practical matter, PF should be assigned a maximum value of 1.0 for Arrival Type 4. When delay is estimated for future situations involving coordination, particularly in the analysis of alternatives, it is advisable to assume Arrival Type 4 as a base condition for coordinated lane groups (except left turns). Arrival Type 3 should be assumed for all uncoordinated lane groups.

$$PF = \frac{(1-P)f_{PA}}{1-\left(\frac{g}{C}\right)}$$

where:

PF = progression adjustment factor,
P = proportion of vehicles arriving on green,
g/C = proportion of green time available, and
f_{PA} = supplemental adjustment factor for platoon arriving during green.

Arrival Type	Range of Platoon Ratio (R_p)	Default Value (R_p)	Progression Quality
1	≤ 0.50	0.333	Very poor
2	> 0.50–0.85	0.667	Unfavorable
3	> 0.85–1.15	1.000	Random arrivals
4	> 1.15–1.50	1.333	Favorable
5	> 1.50–2.00	1.667	Highly favorable
6	> 2.00	2.000	Exceptional

EXHIBIT 16-12. PROGRESSION ADJUSTMENT FACTOR FOR UNIFORM DELAY CALCULATION

Green Ratio (g/C)	Arrival Type (AT)					
	AT 1	AT 2	AT 3	AT 4	AT 5	AT 6
0.20	1.167	1.007	1.000	1.000	0.833	0.750
0.30	1.286	1.063	1.000	0.986	0.714	0.571
0.40	1.445	1.136	1.000	0.895	0.555	0.333
0.50	1.667	1.240	1.000	0.767	0.333	0.000
0.60	2.001	1.395	1.000	0.576	0.000	0.000
0.70	2.556	1.653	1.000	0.256	0.000	0.000
f_{PA}	1.00	0.93	1.00	1.15	1.00	1.00
Default, R_p	0.333	0.667	1.000	1.333	1.667	2.000

Notes:
$PF = (1 - P)f_{PA}/(1 - g/C)$.
Tabulation is based on default values of f_{PA} and R_p.
$P = R_p * g/C$ (may not exceed 1.0).
PF may not exceed 1.0 for AT 3 through AT 6.

Table 5: Default values for the PF.

Uniform delay is taken under the estimation of uniform arrivals, stable flow, and no initial queue. It is based on the first term of Webster's delay formulation and is widely accepted as an accurate depiction of delay for the idealized case of uniform arrivals.

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

where:

d_1 = uniform control delay assuming uniform arrivals (s/veh);
C = cycle length (s); cycle length used in pretimed signal control, or average cycle length for actuated control (see Appendix B for signal timing estimation of actuated control parameters);
g = effective green time for lane group (s); green time used in pretimed signal control, or average lane group effective green time for actuated control (see Appendix B for signal timing estimation of actuated control parameters); and
X = v/c ratio or degree of saturation for lane group.

Due to nonuniform arrivals and temporary cycle failures (random delay) as well as delay caused by sustained periods of oversaturation, incremental delay must be taken into the account:

$$d_2 = 900T\left[(X-1)+\sqrt{(X-1)^2+\frac{8kIX}{cT}}\right]$$

where:

d_2 = incremental delay to account for effect of random and oversaturation queues, adjusted for duration of analysis period and type of signal control (s/veh); this delay component assumes that there is no initial queue for lane group at start of analysis period;
T = duration of analysis period (h);
k = incremental delay factor that is dependent on controller settings;
I = upstream filtering/metering adjustment factor;
c = lane group capacity (veh/h); and
X = lane group v/c ratio or degree of saturation.

Since in the current designed all intersections' signals are considered as pretimed, the incremental delay factor k = 0.5 .

$d3$ = initial queue delay, which accounts for delay to all vehicles in analysis period due to initial queue at start of analysis period (s/veh) (considered zero in this project: no queue at the beginning of the observation period).

Finally, the delay for an approach is computed using equation below:

$$d_A = \frac{\sum d_i v_i}{\sum v_i}$$

where:

d_A = delay for Approach A (s/veh),
d_i = delay for lane group i (on Approach A) (s/veh), and
v_i = adjusted flow for lane group i (veh/h).

The same calculation based on the weighting delays by flows is done for the intersection average control delay:

$$d_I = \frac{\sum d_A v_A}{\sum v_A}$$

Current situation analysis.

Junction 1.

The first junction is four-arm signalized intersection formed by main artery Via Cristoforo Colombo and Viale di Porta Ardeatina. Satellite view on this intersection and layout are shown in the figures below:

Figure 5: First intersection view (SB at North)

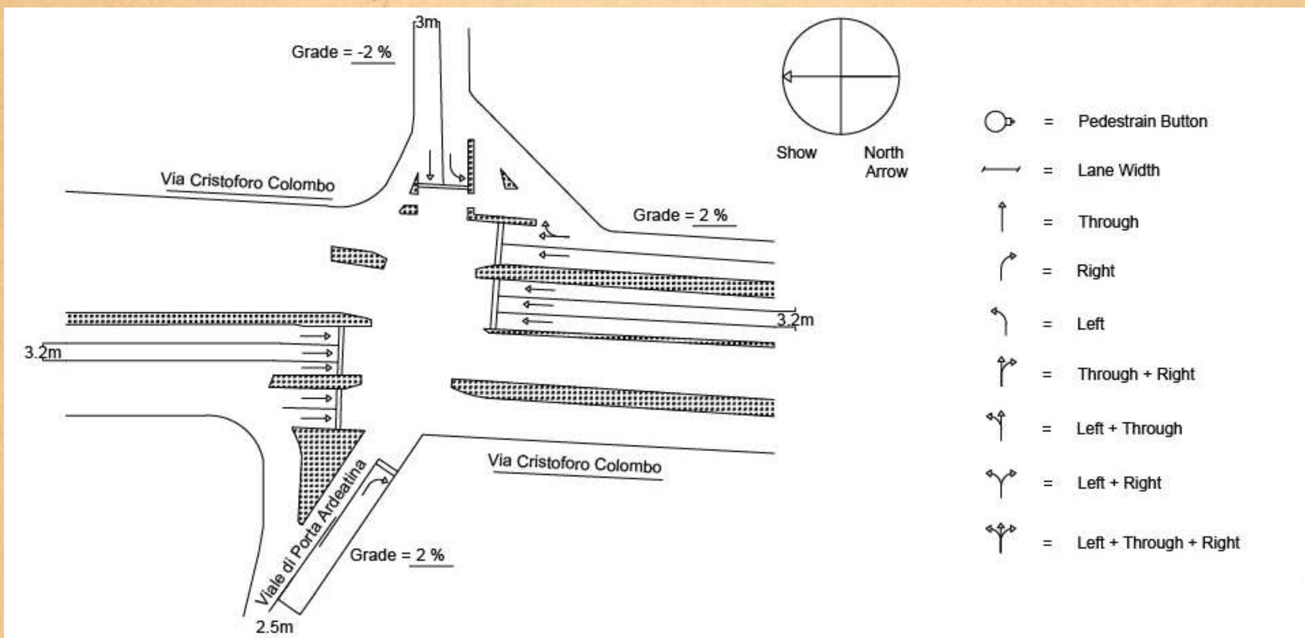


Figure 6: First intersection's layout

Next information provides an overall view to different properties of the intersection used for the following analysis.

	Intersection	EB	WB	NB	SB
	1	Viale di Porta Ardeatina	Viale di Porta Ardeatina	Via Cristoforo Colombo	Via Cristoforo Colombo
Number of lanes	1	1	2	5	5
Lane width	1	3,00	2,50	3,20	3,20
Effective Crosswalk length	1	4	4	0	4
Crosswalk length	1	10	17	0	44
Pedestrian Speed	1	1,2	1,2	1,2	1,2
Grade	1	2	-2	2	-1
Phases	1	Phase 2		Phase 1	
Green	1	57		74	
Yellow	1	4		4	
Red	1	78		61	
Cycle length	1	139			
Distance to Bus stops (m)	1	-	-	90	85

Table 6: General information about geometry and cycle time for the 1st Intersection.

Since in the South Bound the Right Turn is protected from pedestrians by island, it was not affected by the appropriate adjustment factor. Also, as it can be observed from the Table 6, the distances between bus stops and intersections are high enough and therefore do not reduce the saturation flow of the SB and NB approaches. The absence of the throughout flow from the EB is saving left turn flow from WB from being disturbed by the opposite flow. And the absence of the crosswalk on NB allows LT flow of WB freely propagate without any critical points.

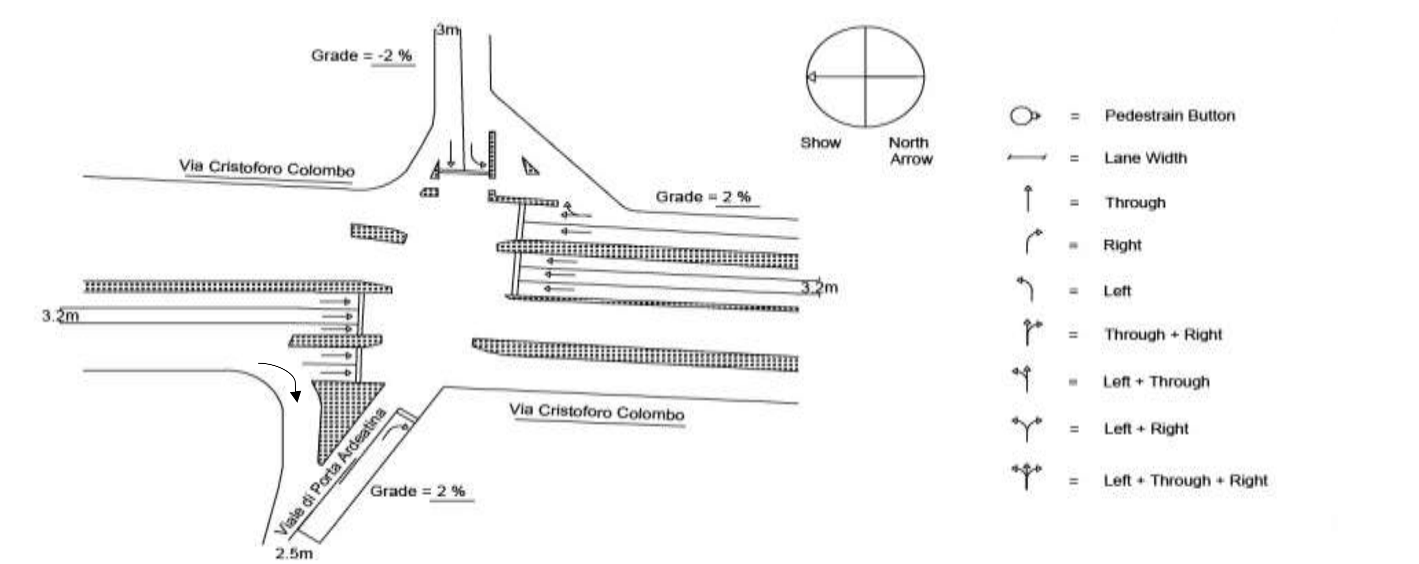
Signal is pretimed and has two phases. Significant flows from SB and NB require higher green times, therefore we will not observe higher green times for WB and EB in the following intersections too. First phase in this and all following analysis is always considered for the SN and NB.

Next table is classical Input Worksheet, that contains already seen inputs and some additional information.

INPUT WORKSHEET

General Information	Site Information
Analyst : Arif huseynov	Intersection: Viale di Porta Ardeatina/Via Cristoforo Colombo
Agency or Company: Sapienza Univesity	Area Type CBD ● Other
Date Performed : 23/05/2019	Jurisdiction
Analysis Time Period : 9:30 - 11:30	Analysis Year : 2019

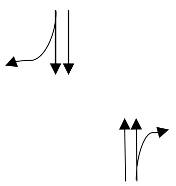
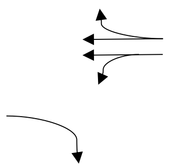
Intersection Geometry



Volume and Timing Input

	EB			WB			NB			SB		
	LT	TH	RT	LT	TH	RT	LT	TH	RT	LT	TH	RT[1]
Volume, V (veh/h)	0	0	33	228	233	101		2055	308		2292	55
% Heavy Vehicles, % HV	0,00%			0,00%			5%			12%		
Peak-hour factor, PHF	0,9			0,9			0,9			0,9		
Pretimed (P) or actuated (A)	P			P			P			P		
Start-up lost time, I1 (s)	2,5			2,5			2,5			2,5		
Extension of effective green time, e (s)	1			1			1			1		
Arrival type, AT	5			4			4			4		
Approach pedestrian volume[2], v_{ped} (p/h)	0			24			0			10		
Approach bicycle volume[2], v_{bic} (bicycles/h)	0			0			0			0		
Parking (Y or N)	Y			N			N			N		
Parking maneuvers, NM (maneuvers/h)	12			0			0			0		
Bus stopping, NB (buses/h)	0			0			0			0		
Min. timing for pedestrian[3], Gp (s)	12			23			4			42		

Signal Phasing Plan

	Ø1			Ø2			Ø3			Ø4			Ø5		
DIAGRAM															
Timing	G =	74	sec	G =	57	sec	G =			G =			G =		
	Y =	4	sec	Y =	4	sec	Y =			Y =			Y =		
										Cycle length			C=	139	Sec

Notes

1 - RTOR is excluded from the Analysis

Table 7: Input Worksheet of the 1st Intersection.

Table 7 contains the traffic count data which is gathered in the field observation. In the current analysis and in the following descriptions for other intersections every 3 motorbikes are considered as one car and one heavy vehicle is considered as 2 cars. The peak hour factor is 0.9 since the data is gathered based on 15 minutes of observation and these 15 minutes may not be necessary during the peak hour. The start-up and clearance loss time are assumed to be 2.5sec and 3sec, respectively, which gives us a total lost time of 5.5 seconds. The arrival type for this junction, based on Exhibit 16-4 of Highway Capacity Manual, is assumed AT 3 for the WB which is for random arrivals and in which the main platoon contains less than 40 percent of lane group volume and AT 4 for NB and SB which is for moderately dense platoon arriving in the middle of the green phase. The area type of this intersection is not considered as CBD because as per HCM, area type is considered as CBD if characteristics like narrow street right-of-way, frequent parking maneuvers, vehicle blockage, small radius turns, limited use of exclusive turn lanes, high pedestrian activity etc. are present. As per our field observation, our road did not meet the above-mentioned characteristics and hence, the intersection is not considered as CBD and the area type adjustment factor is considered as 1 as per HCM.

Table 7 also includes information regarding bicycle and pedestrian volume. Based on this volume, the volume of the pedestrian/bicycle per cycle and then the minimum effective green for pedestrian can be computed using Exhibit 16-2 in Highway Capacity Manual.

Having all this initial data, in the Volume adjustment and saturation flow rate worksheet, the adjustment factors can be computed to be applied for the calculation of the saturation flow. Table 8 contains the worksheet of the Highway Capacity Manual to compute the adjustment factors and the saturation flow. At the top part of this worksheet, the adjusted flow rates and the lane groups are defined. The adjusted flow rate is obtained by dividing the real flow over the Peak Hour Factor.

The second part of this worksheet is for the calculation of adjustment factors and it is shown in the Table 8. In regards with parking maneuvers observed on the field on the EB, appropriate adjustment is applied. Table 9 contains the process of Pedestrian\Bicycle adjustment factor calculation.

Finally, in the Table 10 is given actual Level of Service computation.

Notes.

- Lost time can be counted as the sum between initial lost time l_1 and subtraction result of the extension of effective green time from yellow time, or as a sum between l_1 and l_2 (initial queue clearance time). Since the signal is pretimed and therefore extension of the green time is the constant value, both kind of calculations in this paper are similar and right.

VOLUME ADJUSTMENT AND SATURATION FLOW RATE WORKSHEET

General Information

Project Description : Viale di Porta Ardeatina - Via Cristoforo Colombo

Volume Adjustment

	EB			WB			NB			SB		
	LT	TH	RT	LT	TH	RT	LT	TH	RT	LT	TH	RT
Volume, V (veh/h)			33	228	233	101		2055	308		2292	55
Peak-hour factor, PHF		0,9			0,9			0,9			0,9	
Adjusted flow rate, Vp = V/PHF (veh/h)			38	254	260	113		2283	342		2547	61
Lane Group												
Adjusted flow rate in lane group, v (veh/h)		38			627			2625			2608	
Proportion of LT or RT (P_LT or P_RT)			1	0,41		0,18			0,13			0,02
Saturation Flow Rate (see Exhibit 16-7 to determine adjustment factors)												
Base Saturation flow, Sp (pc/h/ln)		2100			2100			2100			2100	
Number of lanes, N		1			2			5			5	
Lane width adjustment factor, fw		0,93			0,88			0,96			0,96	
Heavy-vehicle adjustment factor, f_HV		1,00			1,00			0,95			0,89	
Grade adjustment factor, fp		0,99			1,01			0,99			1,01	
Parking adjustment factor, fp		0,84			1,00			1,00			1,00	
Bus blockage adjustment factor, f_bb		1,00			1,00			1,00			1,00	
Area type adjustment factor, f_a		1,00			1,00			1,00			1,00	
Lane utilization adjustment factor, f_LU		1,00			0,84			0,75			0,61	
Left-turn adjustment factor, f_LT		1,00			0,98			1,00			1,00	
Right-turn adjustment factor, f_RT		0,85			0,97			0,98			1,00	
Left-turn ped/bike adjustment factor, f_Lpb		1,00			1,00			1,00			1	
Right-Turn ped/bike adjustment factor, f_Rpb		1,00			0,998			0,997			1	
Adjusted saturation flow, s (veh/h) $s = s_0 N f_w f_{HV} f_a f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb}$		1385			2979			6919			5461	

Notes

Table 8: Volume Adjustment Worksheet of the 1st Intersection.

SUPPLEMENTAL WORKSHEET FOR PEDESTRIAN-BICYCLE EFFECTS ON PERMITTED LEFT TURNS AND RIGHT TURNS

General Infromation				
Project Description : Viale di Porta Ardeatina - Via Cristoforo Colombo				
Permited Left Turns				
	EB	WB	NB	SB
Effective pedestrian green time, gp (s)				
Conflicting pedestrian volume, Vped (p/h)				
Vpedg = Vped (C/gp)				
OCCpedg = Vpedg/2000 if (Vped≤1000) OCCpedg=0.4+Vpedg/10000 if (1000<Vpedg≤5000)				
Opposing queue clearing green, gq (s)				
Effective pedestrian green consumed by opposing vehicle queue, gq/gp: if gq≥gp then fLPb = 1				
OCCpedu = OCCpedg [1-0.5(gq/gp)]				
Opposing flow rate, Vo (veh/h)				
OCCr = OCCpedu $[e^{-\left(\frac{5}{3600}\right)Vo}]$				
Number of cross-street receiving lanes, Nrec				
Number of turning lanes, Nturn				
ApbT = 1 - OCCr if Nrec = Nturn ApbT = 1 - 0.6(OCCr) if Nrec > Nturn				
Proportion of left turns, P-LT				
Proportion of left turns using protected phase, P-LTA				
f_{Lpb} = 1.0 - P_{LT}(1 - A_{pbT})(1-P_{LTA})				
Permitted Right Turns				
Effective pedestrian green time, gp (s)		57	74	
Conflicting pedestrian volume, Vped (p/h)		10	24	
Conflicting bicycle volume, Vbic (bicycles/h)		0	0	
Vpedg = Vped (C/gp)		24,39	45,08	
OCCpedg = Vpedg/2000 if (Vped≤1000) OCCpedg=0.4+Vpedg/10000 if (1000<Vpedg≤5000)		0,01	0,02	
Effective green, g (s)		57	74	
Vbicg = Vbic (C/g)		0	0	
OCCbicg = 0.02 + Vbicg/2700		0	0	
OCCr=OCCpedg+OCCbicg-(OCCpedg)(OCCbicg)		0,01	0,02	
Number of cross-street receiving lanes, Nrec		1	1	
Number of turning lanes, Nturn		1	1	
ApbT = 1 - OCCr if Nrec = Nturn ApbT = 1 - 0.6(OCCr) if Nrec > Nturn		0,99	0,98	
Proportion of right turns, P-RT		0,1802	0,1303	
Proportion of right turns using protected phase, P-RTA		0	0	
f_{Rpb} = 1.0 - P_{RT}(1 - A_{pbT})(1-P_{RTA})		0,998	0,997	
Notes				

Table 9: Supplemental worksheet for pedestrian-bicycle effects

CAPACITY AND LOS WORKSHEET				
General Information				
Project Description : Viale di Porta Ardeatina - Via Cristoforo Colombo				
Capacity Analysis				
Phase Number	1	1	2	2
Phase Type	P	P	P	P
Lane Group				
Adjusted flow rate, v (veh/h)	38	627	2625	2608
Saturation flow rate, s (veh/h)	1385	2979	6919	5461
Lost time, t_L = I1 + Y - e	5,5	5,5	5,5	5,5
Effective green time, g (s), g = G + Y - t_L	55,5	55,5	72,5	72,5
Green ratio, g/C	0,40	0,40	0,52	0,52
Lane group capacity, c = s(g/C), (veh/h)	553	1189	3609	2849
v/c ratio, X = v/c	0,07	0,53	0,73	0,92
Flow ratio, v/s	0,03	0,21	0,38	0,48
Critical lane group/phase (√)	-	√	-	√
Sum of flow ratios for critical lane groups, Yc = ∑ (critical lane groups, v/s)	0,688			
Total lost time per cycle, L (s)	11,0			
Critical flow rate to capacity ratio, Xc Xc = (Yc) (C)/(C - L)	0,747			
Lane Group Capacity, Control Delay, and LOS Determination				
	EB	WB	NB	SB
Lane group				
Adjusted flow rate, v (veh/h)	38	627	2625	2608
Lane group capacity, c (veh/h)	553	1189	3609	2849
v/c ratio, X = v/c	0,07	0,53	0,73	0,92
Total green ratio, g/C	0,40	0,40	0,52	0,52
Uniform delay, $d_1 = \frac{0.50\,C\,[1-(\frac{g}{C})]^2}{1-[\frac{\min(1,X)\,g}{C}]}$ (s/veh)	26	32	26	30
Incremental delay calibration, k	0,50	0,50	0,50	0,50
Incremental delay, d_2=900T[(X-1)+$\sqrt{(X-1)^2+\frac{8kIX}{cT}}$] (s/veh)	0,24	1,67	1,32	5,93
Initial queue delay, d3 (s/veh)	0,0	0,0	0,0	0,0
Progression adjustment factor, PF	1,000	1,000	0,767	0,767
Delay, d = d1(PF) + d2 + d3 (s/veh)	26	33	21	29
LOS by lane group	C	C	C	C
Delay by approach, $d_A = \frac{\sum(d)(v)}{\sum v}$ (s/veh)	26	33	21	29
LOS by approach	C	C	C	C
Approach flow rate, (veh/h) V_A	38	627	2625	2608
Intersection delay, $d_I = \frac{\sum(d_A)(V_A)}{\sum V_A}$ (s/veh)	26	Intersection LOS		C
Notes				

Table 10: Capacity and LOS Worksheet of 1st Intersection

Junction 2.

This is so-called T-type junction because it is composed only by three arms – our main artery and one street Via Odoardo Beccari. The satellite view and layout of this intersection are given in the figures below.

Figure 7: Satellite view of 2nd Intersection.

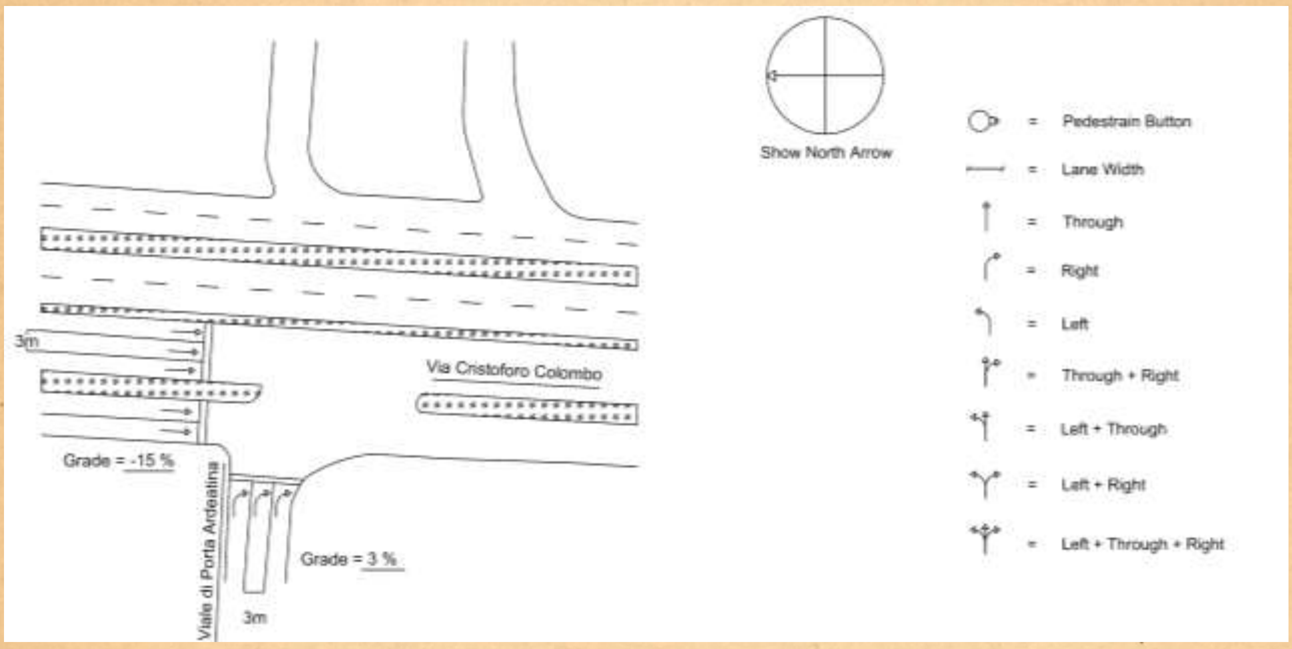


Figure 8: 2nd Intersection's layout.

Next information provides an overall view to different properties of the intersection used for the following analysis.

	Intersection	EB	SB
	2	Viale di Porta Ardeatina	Via Cristoforo Colombo
Number of lanes	2	3	5
Lane width	2	3,00	3,00
Effective Crosswalk width	2	-	-
Crosswalk length	2	-	-
Pedestrian Speed	2	-	-
Grade	2	3	-15
Phases	2	Phase 2	Phase 1
Green	2	55	84
Yellow	2	4	4
Red	2	88	59
Cycle length	2	147	
Distance to Bus stops (m)	2	-	>75

Table 11: General information about geometry and cycle time for the 2nd Intersection.

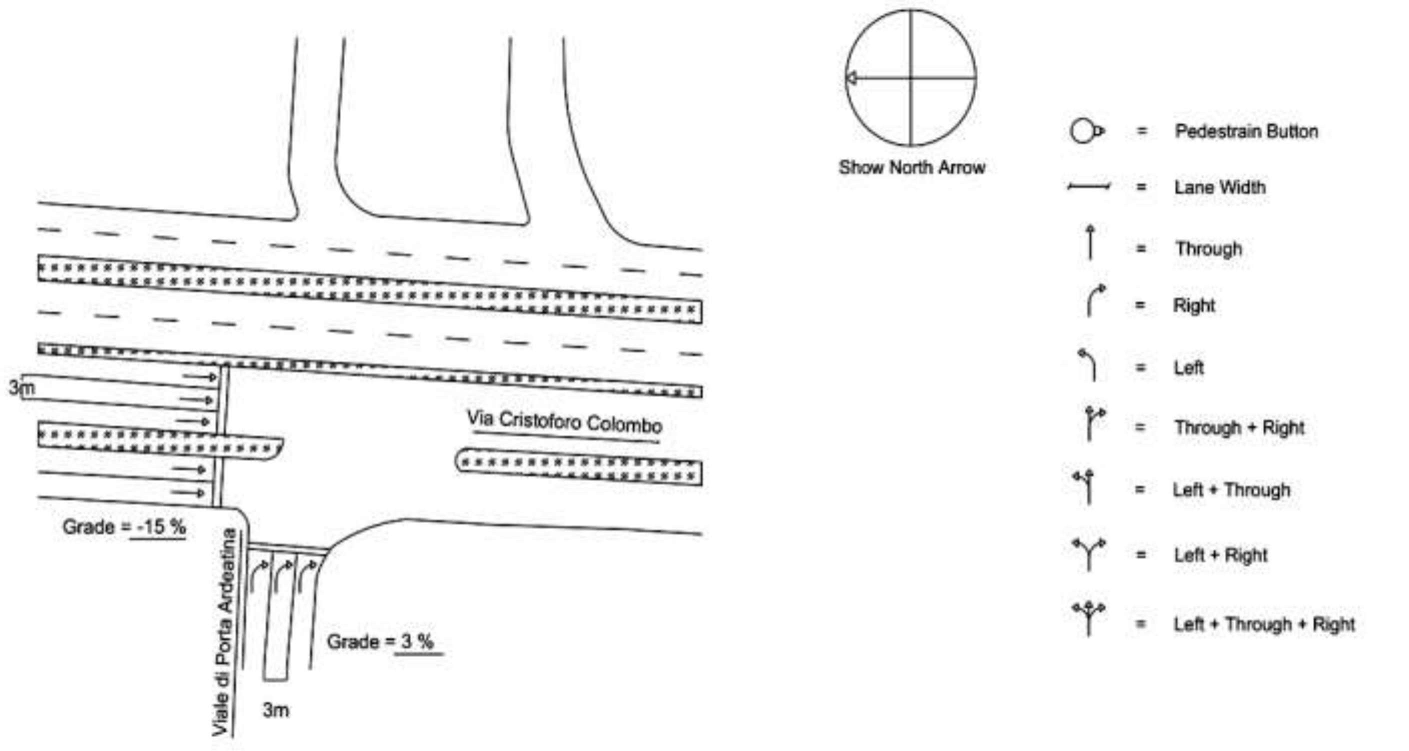
There is another road downstream from SB that is exiting from Viale Marco Polo and feeding Cristoforo Colombo, however this junction is not controlled by the signal and therefore is not considered under the analysis.

Signal is pretimed and has two phases. As before AT for the SB is equal to 4, EB – to 3. In the following pages HCM worksheets contains all information about this intersection and current situation.

INPUT WORKSHEET

General Information	Site Information
Analyst : Arif huseynov	Intersection: Via Odoardo Beccari / Via Cristoforo Colombo
Agency or Company: Sapienza University	Area Type CBD • Other
Date Performed : 23/05/2019	Jurisdiction
Analysis Time Period : 9:30 - 11:30	Analysis Year : 2019

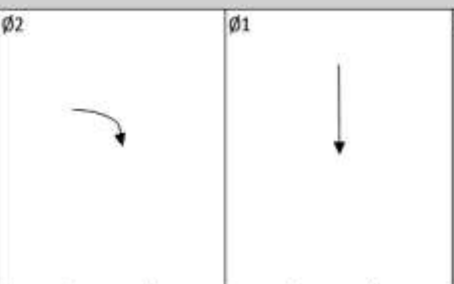
Intersection Geometry



Volume and Timing Input

	EB			SB		
	LT	TH	RT	LT	TH	RT
Volume, V (veh/h)	-	-	885	-	2373	-
% Heavy Vehicles, %HV	3,61%			7,08%		
Peak-hour factor, PHF	0,9			0,9		
Pretimed (P) or actuated (A)	P			P		
Start-up lost time, l1 (s)	2,5			2,5		
Extension of effective green time, e (s)	1			1		
Arrival type, AT	3			4		
Approach pedestrian volume[2], v_{ped} (p/h)	0			0		
Approach bicycle volume[2], v_{bic} (bicycles/h)	0			0		
Parking (Y or N)	N			N		
Parking maneuvers, NM (maneuvers/h)	0			0		
Bus stopping, NB (buses/h)	0			0		
Min. timing for pedestrian[3], Gp (s)	0			0		

Signal Phasing Plan



	Ø2			Ø1			Ø3	Ø4	Ø5
DIAGRAM									
Timing	G =	55	sec	G =	84	sec			
	Y =	4	sec	Y =	4	sec			
							Cycle length	C= 147	Sec

Notes

Table 12: 2nd Intersection's Input Worksheet

VOLUME ADJUSTMENT AND SATURATION FLOW RATE WORKSHEET

General Information												
Project Description : Via Odoardo Beccari / Via Cristoforo Colombo												
Volume Adjustment												
	EB			SB								
	LT	TH	RT	LT	TH	RT						
Volume, V (veh/h)			885	-	2373	-						
Peak-hour factor, PHF		0,9			0,9							
Adjusted flow rate, Vp = V/PHF (veh/h)			984		2638							
Lane Group												
Adjusted flow rate in lane group, v (veh/h)		984			2638							
Proportion of LT or RT (P_LT or P_RT)			1									
Saturation Flow Rate (see Exhibit 16-7 to determine adjustment factors)												
Base Saturation flow, Sp (pc/h/ln)		2100			2100							
Number of lanes, N		3			5							
Lane width adjustment factor, fw		0,93			0,93							
Heavy-vehicle adjustment factor, f_HV		0,97			0,93							
Grade adjustment factor, fp		0,98			1,08							
Parking adjustment factor, fp		1,00			1,00							
Bus blockage adjustment factor, f_bb		1,00			1,00							
Area type adjustment factor, f_a		1,00			1,00							
Lane utilization adjustment factor, f_LU		0,92			0,84							
Left-turn adjustment factor, f_LT		1,00			1,00							
Right-turn adjustment factor, f_RT		0,85			1,00							
Left-turn ped/bike adjustment factor, f_Lpb		1,00			1,00							
Right-Turn ped/bike adjustment factor, f_Rpb		1,00			1,00							
Adjusted saturation flow, s (veh/h) $s = s_0 N f_w f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb}$		4361			8280							
Notes												

Table 13: Volume Adjustment Worksheet for the 2nd Intersection.

CAPACITY AND LOS WORKSHEET		
General Information		
Project Description : Via Odoardo Beccari / Via Cristoforo Colombo		
Capacity Analysis		
Phase Number	2	1
Phase Type	P	P
Lane Group		
Adjusted flow rate, v (veh/h)	984	2638
Saturation flow rate, s (veh/h)	4361	8280
Lost time, t_L = I1 + Y - e	5,5	5,5
Effective green time, g (s), g = G + Y - t_L	54	83
Green ratio, g/C	0,4	0,6
Lane group capacity, c = s(g/C), (veh/h)	1587	4647
v/c ratio, X = v/c	0,62	0,57
Flow ratio, v/s	0,23	0,32
Critical lane group/phase (√)		√
Sum of flow ratios for critical lane groups, Yc = ∑ (critical lane groups, v/s)	0,544	
Total lost time per cycle, L (s)	11	
Critical flow rate to capacity ratio, Xc Xc = (Yc) (C)/(C - L)	0,588	
Lane Group Capacity, Control Delay, and LOS Determination		
	EB	SB
Lane group		
Adjusted flow rate, v (veh/h)	984	2638
Lane group capacity, c (veh/h)	1587	4647
v/c ratio, X = v/c	0,62	0,57
Total green ratio, g/C	0,36	0,56
Uniform delay, $d_1 = \frac{0.50\, C\, [1-(\frac{g}{C})]^2}{1-[\frac{\min(1,X)\, g}{C}]}$ (s/veh)	38	21
Incremental delay calibration, k	0,50	0,50
Incremental delay, d_2=900T[(X-1)+$\sqrt{(X-1)^2+\frac{8kIX}{cT}}$] (s/veh)	1,83	0,51
Initial queue delay, d3 (s/veh)	0,0	0,0
Progression adjustment factor, PF	1,000	0,576
Delay, d = d1(PF) + d2 + d3 (s/veh)	40	12
LOS by lane group	D	B
Delay by approach, $d_A = \frac{\sum(d)(v)}{\sum v}$ (s/veh)	40	12
LOS by approach	D	B
Approach flow rate, (veh/h) V_A	984	2638
Intersection delay, $d_I = \frac{\sum(d_A)(V_A)}{\sum V_A}$ (s/veh)	20	C
Notes		

Table 14: Capacity and LOS for 2nd Intersection

Junction 3.

The 3rd intersection connects via Cristoforo Colombo with Largo Angelo Fochetti. As it is shown in the figure below, it is T junction. The main street, via Cristoforo Colombo has 10 lanes, each direction having 5. Largo Angelo Fochetti has 2 lanes which merge to the major lane

Geographical representation is illustrated in figure below.

Figure 9: 3rd Junction's satellite view

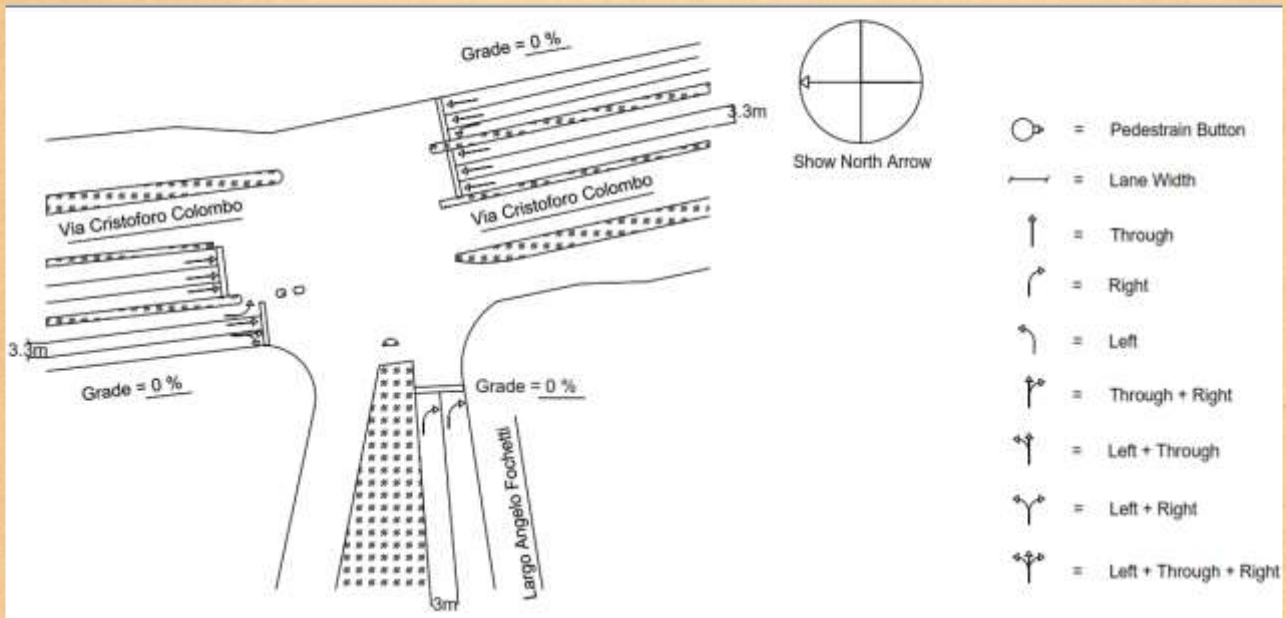


Figure 10: 3rd Junction's layout.

The characteristics of different approaches are represented in table below:

Approach	street	Number of lanes	Lane Width	Grade (%)
NB	Via Cristoforo Colombo	5	3.3	0
SB	Via Cristoforo Colombo	5	3.3	0
EB	Largo Angelo Fochetti	2	3	0

Table 15: Characteristics of each approach in 3rd Junction.

Since the arrival of cars are random, the arrival type of vehicle coming to east bound is assumed 3. For the major lanes moderately dense platoon arriving in the middle of the green phase so arrival type should consider as 4.

Consider the lane width of all approaches are less than the standard lane width (3.6 m), so the lane width adjustment factor should consider. The lane width adjustment factor f_w accounts for the negative impact of narrow lanes on saturation flow rate and allows for an increased flow rate on wide lanes.

In this intersection major flow is on north south direction. Since Largo Angelo Fochetti is T road, there is now EB-R maneuver which is joining to the mainstream SB and there is only one lane group present. In major stream SB having 2 lane group, one is through movement plus right turn and another one is exclusive left otherwise can be called as U-turn. Out of 5 lanes in SB, 4 lanes dedicated for through plus right movement and 1 for exclusive left turn, NB also having two lane group, a total of 5 lanes in which 4 lanes for through only movement and one for exclusive left.

There is a bus stop within 75 m of the stop line (downstream) in the NB and SB which considered as a bus blockage adjustment factor. The buses which are not stopping there can be considered as heavy vehicle.

This junction has 2 phases with cycle length of 144 seconds. The first and the most important one is regulated for NB-SB approach with green split of 78 sec. The second phase belongs to EB having a green split of 58 sec is allocated to this approach.

Volume and timing output table also contains the traffic count data which is gathered in the field observation. As it was explained in methodology, in this observation, every 3 motor bikes are considered as one car. As it is shown in the table 6, the peak hour factor is 0.9 since the data is gathered based on 15 minutes of observation and these 15 minutes may not be necessarily during the peak hour. Since the setting is pre timed, there is no extension of effective green time. The lane utilization adjustment factor FLU accounts for the unequal distribution of traffic among the lanes in a lane group with more than one lane. Here in EB having two lanes in one lane group with unequal distribution so the lane utilization adjustment factor based on the HCM is 0.952. However major lanes (NB &SB) Even though having more than one lane in a lane group, we can see a uniform traffic distribution along all lanes so lane utilization can be assumed as 1.

Volume and timing output table also includes information regarding bicycle and pedestrian volume. This volume has been assumed as the maximum value of pedestrian/bicycle volume for each side of the intersection in NB/SB or EB approaches. Based on this volume, the volume of the pedestrian/bicycle per cycle and then the minimum effective green for pedestrian can be computed using Exhibit 16-2 in Highway Capacity Manual. This data is shown in the last row of the input worksheet. This table also provides data regarding the parking and bus stopping within the 75 meters distance from the stop line. This data will be later applied for computing the adjustment factors. In NB we have a separate lane for buses, just before the intersection so for buses and taxies no need to wait on intersection. As it is shown in input table, there is no bus stop within 75-meter distance from the stop line for EB. For SB/NB approaches parking is not allowed. For EB approach, parking is allowed, 8 parking maneuvers was observed during the observation.

The third intersection situated in a broad area with less parking maneuvers and comparatively less pedestrians so it cannot be considered as central business district (CBD) so factor for area type is one. All pedestrians and bicycle movements are protected with signal setting, hence factors for that may considered as 1.

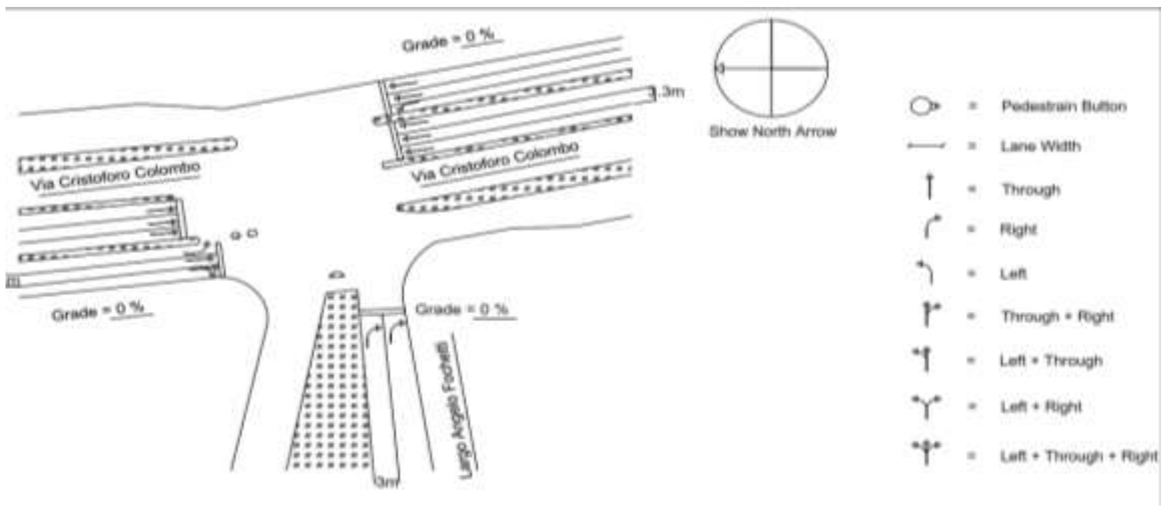
The pedestrians whose crossing EB is making conflicting zone with the right turn vehicles from SB. A flowchart in Exhibit D16-3 illustrates a step-by-step procedure for computation, and a supplemental worksheet is also provided to compute pedestrian-bicycle saturation flow rate adjustment factors. The right turn adjustment factor for the EB approach which has exclusive lanes with protected right turn, has the value of 0.85. The left turn adjustment factor for NB & SB approach has protected exclusive lanes for left so the factor could be 0.95.

Tables below are related to HCM Worksheets and contains all information about the current traffic conditions and LOS of the intersection.

INPUT WORKSHEET

General Information	Site Information
Analyst :AKHILASH VIJAYAKUMAR	Intersection:Junction: Via Cristoforo Colombo - Largo Angelo Fochetti
Agency or Company SAPIENZA UNIVERSITY	Area Type CBD ● Other
Date Performed : 23/05/2019	Jurisdiction
Analysis Time Period : 9:30 - 11:30 A.M	Analysis Year : 2019

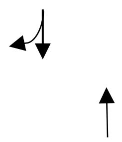
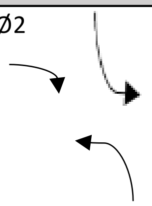
Intersection Geometry



Volume and Timing Input

	EB		NB		SB	
	EX. RT		EX.LT	TH-R	THR+R	EX.LT
Volume, V (veh/h)	339		470	3200	3245	160
% Heavy Vehicles, % HV	0		0	4	4	0
Peak-hour factor, PHF	0,9		0,9		0,9	
Pretimed (P) or actuated (A)	P		P		P	
Start-up lost time, l1 (s)	2,5		2,5		2,5	
clearence lost time (s)	3		3		3	
Arrival type, AT	3		4		4	
Approach pedestrian volume, 2 vped (p/h)	60		0		400	
Approach bicycle volume, 2 vbic (bicycles/h)	10		37		40	
Parking (Y or N)	Y		N		N	
Parking maneuvers, NM (maneuvers/h)	8		0		0	
Bus stopping, NB (buses/h)	0		28		28	
Min. timing for pedestrian, 3 Gp (s)	9		40		48	

Signal Phasing Plan

	Ø1			Ø2			Ø3			Ø4			Ø5		
DIAGRAM															
Timing	G =	78	sec	G =	58	sec	G =			G =			G =		
	Y =	4	sec	Y =	4	sec	Y =			Y =			Y =		
										Cycle length			C=	144	Sec

NOTES:

1.TH-R=Through movement
2.EX.LT= Exclusive left turn
3.TH+R= Through movement plus right turn
4.Red for phase 1 : 62 s
5.Red for phase 2: 82 s

Table 16: 3rd Intersection's Input Worksheet

VOLUME ADJUSTMENT AND SATURATION FLOW RATE WORKSHEET						
General Information						
Project Description : Via Cristoforo Colombo -Largo Angelo Fochetti						
Volume Adjustment						
	EB		NB		SB	
	EX.RT		EX.LT	THR	THR+RT	EX.LT
Volume, V (veh/h)	339		470	3200	3245	160
Peak-hour factor, PHF	0,9		0,9		0,9	
Adjusted flow rate, Vp = V/PHF (veh/h)	377		523	3556	3606	178
Lane Group	1		1	1	1	1
Adjusted flow rate in lane group, v (veh/h)	377		523	3556	3606	178
Proportion of LT or RT (P_LT or R_RT)	1		1	1	0,14	1
Saturation Flow Rate (see Exhibit 16-7 to determine adjustment factors)						
Base Saturation flow, Sp (pc/h/ln)	2100		2100		2100	
Number of lanes, N	2		1	4	4	1
Lane width adjustment factor, fw	0,93		0,97	0,97	0,97	0,97
Heavy-vehicle adjustment factor, f_HV	1,00		1,00	0,96	0,96	1,00
Grade adjustment factor, fp	1,00		1,00	1,00	1,00	1,00
Parking adjustment factor, fp	0,93		1,00	1,00	1,00	1,00
Bus blockage adjustment factor, f_bb	1,00		1,00	0,97	0,97	1,00
Area type adjustment factor, f_a	1,00		1,00	1,00	1,00	1,00
Lane utilization adjustment factor, f_LU	0,95		1,00	1,00	1,00	1,00
Left-turn adjustment factor, f_LT	1,00		0,95	1,00	1,00	0,95
Right-turn adjustment factor, f_RT	0,85		1,000	1,000	0,979	1,000
Left-turn ped/bike adjustment factor, f_Lpb	1,00		1,000	1,000	1,000	1,000
Right-Turn ped/bike adjustment factor, f_Rpb	1,00		1,000	1,000	0,986	1,000
Adjusted saturation flow, s (veh/h) $s = s_0 N f_w f_{HV} f_a f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb}$	2944		1929	7589	7327	1929
Notes						

Table 17: Volume Adjustment Worksheet for the 3rd Intersection.

SUPPLEMENTAL WORKSHEET FOR PEDESTRIAN-BICYCLE EFFECTS ON PERMITTED RIGHT TURNS	
General Infromation	
Project Description : Via Cristoforo Colombo-Via Largo Angelo Fochetti	
Permitted Right Turns	
Approach	SB
Effective pedestrian green time, gp (s)	56,5
Conflicting pedestrian volume, Vped (p/h)	60
Conflicting bicycle volume, Vbic (bicycles/h)	10
Vpedg = Vped (C/gp)	153
OCCpedg = Vpedg/2000 if (Vped≤1000) OCCpedg=0.4+Vpedg/10000 if (1000<Vpedg≤5000)	0,076
Effective green, g (s)	76,5
Vbicg = Vbic (C/g)	19
OCCbicg = 0.02 + Vbicg/2700	0,027
OCCr=OCCpedg+OCCbicg-(OCCpedg)(OCCbicg)	0,101
Number of cross-street receiving lanes, Nre	1
Number of turning lanes, Nturn	1
ApbT = 1 - OCCr if Nrec = Nturn ApbT = 1 - 0.6(OCCr) if Nrec > Nturn	0,899
Proportion of right turns, P-RT	0,1387
Proportion of right turns using protected phase, P-RTA	0
f_{Rpb} = 1.0 - $P_{RT}(1 - A_{pbT})(1\text{-}P_{RTA})$	0,986
Notes	

Table 18: Supplemental Worksheet for pedestrian-bicycle effects on permitted right turns for 3rd Int.

Having all initial data, the adjustment factors can be computed to be applied for calculation of the saturation flow. Like the previous junction, the base saturation flow is considered equal to 2100 vehicle/hour, Table above contains the worksheet of Highway Capacity Manual to compute the adjustment factors and the saturation flow. At the top part of this worksheet, the adjusted flow rates and the lane groups are defined. Adjusted flow rate is obtained by dividing the real flow over the Peak Hour Factor.

Having the saturation flow and the adjusted flow rate for each lane group as the result of table, the computation for defining the level of service on each lane group, on each approach and for the entire intersection can be done. These computations are summarized in next table. In upper part of the table, capacity analysis is made. To do so, by multiplying the saturation flow to the green share of each lane group, the capacity of lane group is defined. Then, having the capacity of each lane group, the volume over capacity of each lane group can be defined and then the critical lane group (which has the highest v/c among all lane group in the same phase) for each phase is identified. This critical lane group v/c for each phase can be applied for computing the minimum green requirements. Then by knowing the critical lane group in each phase, and using the summation of v/s ratio for those lane groups and the total lost time of the intersection, XC which is critical v/c ratio for the whole intersection can be computed using equation 16-8 of Highway Capacity Manual. This indicator is useful in evaluating the overall intersection with respect to the geometric and total cycle length and in estimating signal timings when they are not known.

CAPACITY AND LOS WORKSHEET

General Information

Project Description : Via Cristoforo Colombo -Largo Angelo Fochetti

Capacity Analysis

Phase Number	1	1	2	2	2							
Phase Type	P	P	P	P	P							
Lane Group												
Adjusted flow rate, v (veh/h)	3556	3606	377	470	160							
Saturation flow rate, s (veh/h)	7589	7327	2944	1929	1929							
Lost time, t_	5,5	5,5	5,5	5,5	5,5							
Effective green time, g (s), g = G + Y - t_L	76,5	76,5	56,5	56,5	56,5							
Green ratio, g/C	0,5	0,5	0,4	0,4	0,4							
Lane group capacity, c = s(g/C), (veh/h)	4032	3893	1155	757	757							
v/c ratio, v/s	0,88	0,93	0,33	0,62	0,21							
Flow ratio, v/s	0,47	0,49	0,13	0,24	0,08							
Critical lane group/phase (√)		√		√								
Sum of flow ratios for critical lane groups, Yc Yc = ∑ (critical lane groups, v/s)	0,736											
Total lost time per cycle, L (s)	11											
Critical flow rate to capacity ratio, Xc Xc = (Yc) (C)/(C - L)	0,797											

Lane Group Capacity, Control Delay, and LOS Determination

	EB	WB	NB			SB		
Lane group								
Adjusted flow rate, v (veh/h)	377		523	3556		3606	160	
Lane group capacity, c (veh/h)	1155		757	4032		3893	757	
v/c ratio, X = v/c	0,33		0,69	0,88		0,93	0,21	
Total green ratio, g/C	0,39		0,39	0,53		0,53	0,39	
Uniform delay, $d_1 = \frac{0.50\,C\,[1-(\frac{g}{C})]^2}{1-[\min(1,X)\frac{g}{C}]}$ (s/veh)	30		36	30		31	29	
Incremental delay calibration, k	0,50		0,50	0,50		0,50	0,50	
Incremental delay, d2 (s/veh) $d_2=900T[(X-1)+\sqrt{(X-1)^2+\frac{8kIX}{cT}}]$	1		5	3		5	0,6	
Initial queue delay, d3 (s/veh)	0,0		0,0	0,0		0,0	0,0	
Progression adjustment factor, PF	1		0,77	0,77		0,77	0,77	
Delay, d = d1(PF) + d2 + d3 (s/veh)	31		33	26		29	23	
LOS by lane group	C		C	C		C	C	
Delay by approach $d_A = \frac{\sum(d)(v)}{\sum v}$ (s/veh)	31		27			29		
LOS by approach	C		C			C		
Approach flow rate, V_A (veh/h)	377		4079			3766		
Intersection delay, $d_I = \frac{\sum(d_A)(V_A)}{\sum V_A}$ (s/veh)	28	Intersection LOS				C		

Notes

Table 19: Capacity and LOS Worksheet of 3rd Intersection.

The second part of capacity and level of service table is related to defining the level of service. To do so, first the delay for each lane group should be calculated using equation 16-9 of Highway Capacity Manual. This formula has 3 elements. As explained before in methodology, these elements can be calculated using equations 16-11 and 16-12 of Highway Capacity Manual. Since no initial queue is observed in the survey, the third component, d3, is considered 0. Since the arrival type is 3 for EB, the progression factor (PF) is assumed equal to 1. For NB&SB the arrival type is 4 and the progression adjustment factor can be found with respect to the green ratio according to Exhibit 16-12 of Highway capacity Manual which is shown in methodology.

In the computation of the second term of the delay, incremental delay, to determine the value of k, the incremental delay factor, the Exhibit 16-13 of Highway Capacity Manual can be applied which is shown in Figure 11 in methodology. Since in this intersection the controller setting is pre timed, then the value of k is equal to 0.5. Another element in equation 16-12 is I which is upstream filtering/metering adjustment factor. Based on the guidance of Highway Capacity Manual, for a signal analysis of an isolated junction, a value of 1 for I is used

After computing the uniform delay and incremental delay and by applying the equation 16-9, the total delay for each lane group can be defined. Then the average delay for each approach can be computed by applying the weighted average of the delay of all lane groups in each approach, considering the flow of each lane group as its weight based on equation 16-13 of Highway Capacity Manual. Finally, the average delay of the whole intersection can be calculated by using the weighted average of all lane groups of the intersection using equation 16-14 of Highway Capacity Manual.

The final step is to define the level of service for each lane group, then each approach and at last for the whole intersection. As explained in methodology, the level of service can be defined using the Exhibit 16-12 of Highway Capacity Manual which is represented in the methodology part of this report.

It is seen in Table 19 that all the lane groups have LOS equal to C. Hence the entire intersection has the level of service of C based in the delay equal to 28 seconds.

Junction 4.

The 4th intersection connects via Cristoforo Colombo with Via Padre Semeria and via Cesare Federici. As it is shown in the figure it is four-arm intersection. The main street, via Cristoforo Colombo has 10 lanes, each direction having 5 lanes. Apart from that we have via Padre Semeria street which going towards both sides of via Cristoforo Colombo and via Cesare Federici. The geographical features of this junction are provided in the figure below.

Figure 11: Satellite view of the 4th Junction.

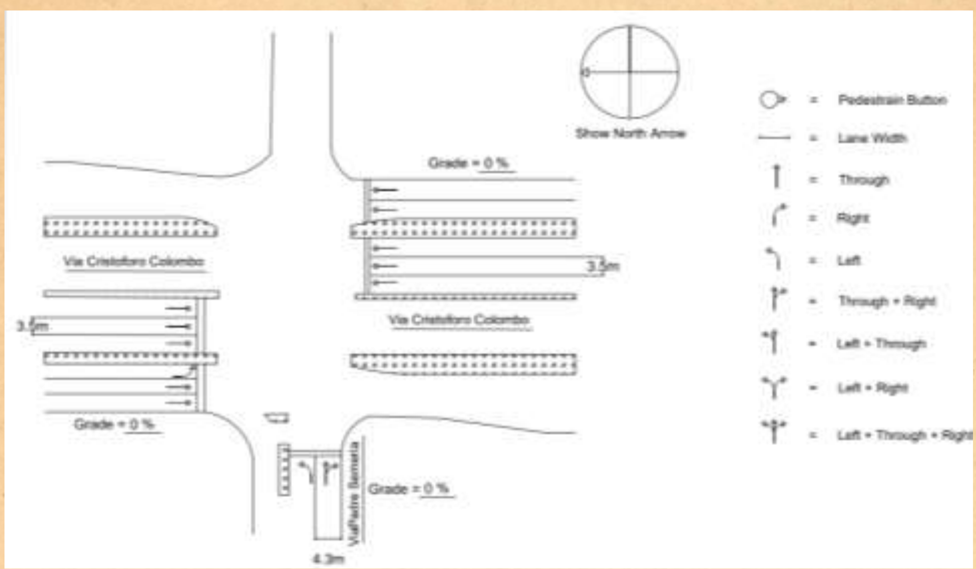


Figure 12: Layout of the 4th Junction.

In this intersection major flow is on north-south direction (Via Cristoforo Colombo), Vehicles from the street via Padre Semeria is going straight to Via Cesare Federici, which is a one-way, right to via Cristoforo Colombo SB & left for Cristoforo Colombo NB. Since the arrival of cars are random, the arrival type of vehicle coming to east bound is assumed 3. For the major lanes moderately dense platoon arriving in the middle of the green phase so arrival type should consider as 4.

In major stream SB having 2 lane group one is through movement and another one is exclusive left which can be called as U-turn. Out of 5 lanes in SB, 4 lanes dedicated for through movement and 1 for exclusive left turn. NB having 5 lanes which are only dedicated to through movements. EB having two lane group each having one lane. One is exclusive left and other is through plus right.

Just before the EB signal, there is another parallel road which makes a percentage of right turning vehicles to go right parallelly without making conflict with pedestrians who crossing the NB and eventually merging to the mainstream. Hence in EB right turning vehicles having negligible chances of confronting pedestrians whose crossing major stream. So that right turn can be considered as protected one without any disturbances. In addition to that there is a crosswalk in EB and that is completely protected with signal phasing. Hence no need of considering supplementary worksheet for left and right pedestrian and bicycle factor for saturation flow.

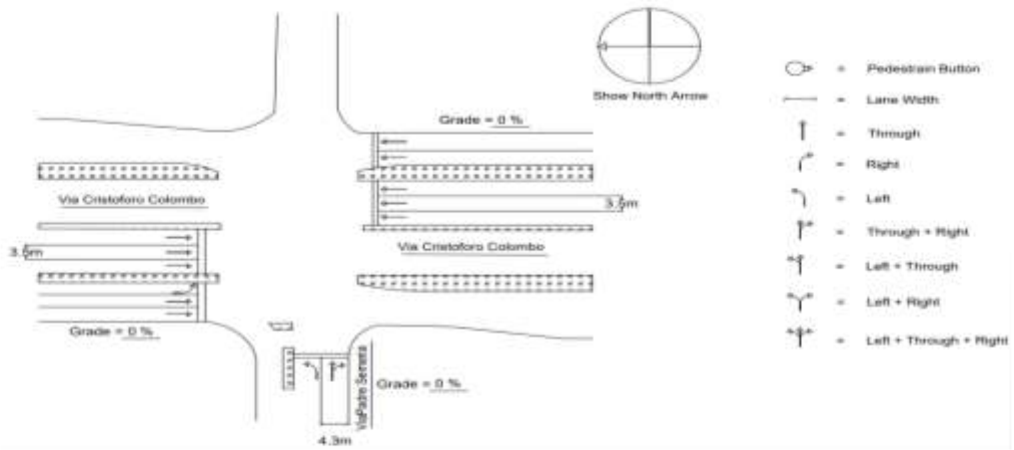
There is a bus stop within 75 m of the stop line (downstream) in the NB and SB which considered as a bus blockage adjustment factor. The buses which are not stopping there can be considered as heavy vehicle.

This junction has 2 phases with cycle length of 144 seconds. The first and the most important one is regulated for NB-SB approach with green split of 80 sec. The second phase belongs to EB having a green split of 56 sec is allocated to this approach.

INPUT WORKSHEET

General Information	Site Information
Analyst :AKHILASH VIJAYAKUMAR	Intersection:Via Cristoforo Colombo-Via Padre Semeria - Via Cesare Federici
Agency or Company SAPIENZA UNIVERSITY	Area Type CBD ● Other
Date Performed : 23/05/2019	Jurisdiction
Analysis Time Period : 9:30 - 11:30 A.M	Analysis Year : 2019

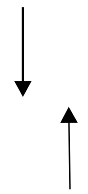
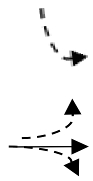
Intersection Geometry



Volume and Timing Input

	EB			NB	SB	
	LT	TH+RT		TH-R	EX.LT	TH-R
Volume, V (veh/h)	135	202		3958	420	3498
% Heavy Vehicles, % HV	0	0		3	3	3
Peak-hour factor, PHF	0,9			0,9	0,9	
Pretimed (P) or actuated (A)	P			P	P	
Start-up lost time, l1 (s)	2,5			2,5	2,5	
clearence lost time	3			3	3	
Arrival type, AT	3			4	4	
Approach pedestrian volume, 2 vped (	50			450	0	
Approach bicycle volume, 2 vbic (bicy	0			25	0	
Parking (Y or N)	Y			N	N	
Parking maneuvers, NM (maneuvers/h	12			0	0	
Bus stopping, NB (buses/h)	3			12	0	
Min. timing for pedestrian, 3 Gp (s)	11			36	33	

Signal Phasing Plan

	Ø1	Ø2	Ø3	Ø4	Ø5
D I A G R A M					
Timing	G = 80 sec	G = 56 sec	G =	G =	G =
	Y = 4 sec	Y = 4 sec	Y =	Y =	Y =
				Cycle length	C= 144 Sec

Notes

1.TH-R=Through movement
2.EX.LT= Exclusive left turn
3.Red for phase 1 : 60 s
4.Red for phase 2: 84 s

Table 20: Input Worksheet for 4th Intersection.

Volume and timing output table also contains the traffic count data which is gathered in the field observation. As it was explained in methodology, in this observation, every 3 motor bikes are considered as one car. As it is shown in the table 6, the peak hour factor is 0.9 since the data is gathered based on 15 minutes of observation and these 15 minutes may not be necessarily during the peak hour. Since the setting is pre timed, there is no extension of effective green time. The lane utilization adjustment factor FLU accounts for the unequal distribution of traffic among the lanes in a lane group with more than one lane. Here in EB having two lane groups with unequal distribution so the lane utilization adjustment factor based on the HCM is 0.952. However major lanes (NB &SB) Even though having more than one lane in a lane group, we can see a uniform traffic distribution along all lanes so lane utilization can be assumed as 1.

Volume and timing output table also includes information regarding bicycle and pedestrian volume. This volume has been assumed as the maximum value of pedestrian/bicycle volume for each side of the intersection in NB/SB or EB approaches. Based on this volume, the volume of the pedestrian/bicycle per cycle and then the minimum effective green for pedestrian can be computed using Exhibit 16-2 in Highway Capacity Manual. This data is shown in the last row of the input worksheet. This table also provides data regarding the parking and bus stopping within the 75 meters distance from the stop line. This data will be later applied for computing the adjustment factors. As it is shown in input table SB/NB approaches parking is not allowed but ins EB twelve parking manoeuvres observed.

The 4th intersection situated in a broad area with less parking maneuvers and comparatively less pedestrians so it cannot be considered as central business district (CBD) so factor for area type is one. All pedestrians and bicycle movements are protected with signal setting, hence factors for that may considered as 1.

In EB there is an exclusive permitted left turn present with an opposing flow of SB single lane exclusive left turn. When permitted left turns exist, either from shared lanes or from exclusive lanes, their impact on intersection operations is complex. Here both lane groups are exclusive left turns.

When the case of a single-lane approach opposed by another single-lane approach has a number of unique features that must be reflected in the model. The most critical of these is the effect of opposing left turns. An opposing left-turning vehicle in effect creates a gap in the opposing flow through which a subject left turn may be made. This gap can occur during the clearance of the opposing queue as well as during the unsaturated portion of the green phase.

Calculation of left turn adjustment factors shown in this supplemental worksheet.

VOLUME ADJUSTMENT AND SATURATION FLOW RATE WORKSHEET

General Information						
Project Description : :Via Cristoforo Colombo-Via Padre Semeria - Via Cesare Federici						
Volume Adjustment						
	EB		WB	NB	SB	
	EX.LT	TH+RT		TH-R	EX.LT	TH-R
Volume, V (veh/h)	135	202		3958	420	3498
Peak-hour factor, PHF	0,9			0,9	0,9	
Adjusted flow rate, Vp = V/PHF (veh/h)	150	225		4398	467	3887
Lane Group	1	1		1	1	1
Adjusted flow rate in lane group, v (veh/h)	150	225		4398	467	3887
Proportion of LT or RT (P_LT or R_RT)	1	0,11			1	1
Saturation Flow Rate (see Exhibit 16-7 to determine adjustment factors)						
Base Saturation flow, Sp (pc/h/ln)	2100	2100		2100	2100	
Number of lanes, N	1	1		5	1	4
Lane width adjustment factor, fw	1,078	1,078		0,989	0,989	0,989
Heavy-vehicle adjustment factor, f_HV	1,000	1,000		0,971	0,971	0,971
Grade adjustment factor, fp	1,000	1,000		1,000	1,000	1,000
Parking adjustment factor, fp	0,840	0,840		1,000	1,000	1,000
Bus blockage adjustment factor, f_bb	0,988	0,988		0,990	1,000	0,987
Area type adjustment factor, f_a	1,000	1,000		1,000	1,000	1,000
Lane utilization adjustment factor, f_LU	0,950	0,950		1,000	1,000	1,000
Left-turn adjustment factor, f_LT	0,646	1,000		1,000	0,950	1,000
Right-turn adjustment factor, f_RT	1,000	0,983		1,000	1,000	1,000
Left-turn ped/bike adjustment factor, f_Lpb	1,000	1,000		1,000	1,000	1,000
Right-Turn ped/bike adjustment factor, f_Rpb	1,000	1,000		1,000	1,000	1,000
Adjusted saturation flow, s (veh/h) $s = s_0 N f_w f_{HV} f_a f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb}$	1153	1755		9984	1915	7960
Notes						

Table 21: Volume Adjustment Worksheet for 4th Intersection.

SUPPLEMENTAL WORKSHEET FOR PERMITTED LEFT TURNS OPPOSED BY SINGLE LANE APPROACH				
General Information				
Project Description : Via Cristoforo Colombo-Via Padre Semeria - Via Cesare Federici				
Input				
	EB	WB	NB	SB
Cycle length, C (s)	144			
Total actual green time for LT lane group, G (s)	56			
Effective permitted green time for LT lane group, g (	54,5			
Opposing effective green time, g_o (s)	54,5			
Number of lanes in LT lane group, N	1			
Number of lanes in opposing approach, N_o	1			
Adjusted LT flow rate, VLT (veh/h)	150			
Proportion of LT volume in LT lane group, PLT	1			
Adjusted flow rate for opposing approach, V_o (veh/h	467			
Lost time for LT lane group, t_L	3			
Computation				
LT volume per cycle, LTC = VLT*C/3600	6,00			
Opposing lane utilization factor, fLU_o (refer to Volume Adjustment and Saturation Flow Rate Worksheet)	1			
Opposing flow per lane, per cycle $V_{olc} = \frac{V_o C}{3600 N_o f LU_o}$ (veh/h/ln)	18,7			
$g_f = G\left[e^{-0.882(LTC^{0.717})}\right] - t_L \; g_f \leq g$ (except for exclusive left-turn lanes)	0,94			
Opposing platoon ratio, Rp_o (refer to Exhibit 6-11)	1,33			
Oppsoing queue ratio, qr_o = max[1-Rp_o(g_o/C),0]	0,50			
gq = 4.943volc0.762 qro1.061 – tL when 0 ≤ gq ≤ g	18,89			
$g_u = g - g_q$ when $g_q \geq g_f$ $g_u = g - g_f$ when $g_q < g_f$	35,61			
EL1 (refer to Exhibit C16-3)	2,034			
$P_L = P_{LT} = 1.0.$	1			
$E_{L2} = \frac{(1 - P_{THo}^n)}{P_{LTo}}$	1			
F_{LT} $f_{LT} = \left(\frac{g_f}{g}\right) + \left(\frac{g_{diff}}{g}\right)\left[\frac{1}{1+P_{LT}(E_{L2}-1)}\right] + \left(\frac{g_u}{g}\right)\left[\frac{1}{1+P_{LT}(E_{L1}-1)}\right]$ (C16-9)	0,646			
Notes				

Table 22: Supplemental Worksheet for permitted left turns opposed by single lane approach (4th Int).

CAPACITY AND LOS WORKSHEET

General Information												
Project Description : Via Cristoforo Colombo-Via Padre Semeria - Via Cesare Federici												
Capacity Analysis												
Phase Number	1			1	2		2	2				
Phase Type	P			P	P		P	P				
Lane Group												
Adjusted flow rate, v (veh/h)	4398			3887	467		225	150				
Saturation flow rate, s (veh/h)	9984			7960	1915		1755	1153				
Lost time, t_L = l1+l2	5,5			5,5	5,5		5,5	5,5				
Effective green time, g (s), g = G + Y - t_L	78,50			78,5	54,5		54,5	54,5				
Green ratio, g/C	0,55			0,55	0,38		0,38	0,38				
Lane group capacity, c = s(g/C), (veh/h)	5443			4339	724,9		664,1	421,6				
v/c ratio,	0,808			0,896	0,644		0,339	0,356				
Flow ratio, v/s	0,44			0,488	0,244		0,128	0,13				
Critical lane group/phase (√)				√	√							
Sum of flow ratios for critical lane groups, Yc Yc = ∑ (critical lane groups, v/s)	0,732											
Total lost time per cycle, L (s)	11											
Critical flow rate to capacity ratio, Xc Xc = (Yc) (C)/(C - L)	0,793											

Lane Group Capacity, Control Delay, and LOS Determination						
	EB		WB	NB	SB	
Lane group						
Adjusted flow rate, v (veh/h)	225	150		4398	467	3887
Lane group capacity, c (veh/h)	664	422		5443	725	4339
v/c ratio, X = v/c	0,34	0,36		0,81	0,64	0,90
Total green ratio, g/C	0,38	0,38		0,55	0,38	0,55
Uniform delay, $d_1 = \dfrac{0.50\,C\,[1-(\frac{g}{C})]^2}{1-[\min(1,X)\frac{g}{C}]}$ (s/veh)	32	32		27	37	29
Incremental delay calibration, k	0,50	0,50		0,50	0,50	0,50
Incremental delay, d2 (s/veh) $d_2=900T[(X-1)+\sqrt{(X-1)^2+\frac{8kIX}{cT}}]$	1	2		1	4	3,3
Initial queue delay, d3 (s/veh)	0,0	0,0		0,0	0,0	0,0
Progression adjustment factor, PF	1	1		0,77	0,77	0,77
Delay, d = d1(PF) + d2 + d3 (s/veh)	33	35		22	33	26
LOS by lane group	C	D		C	C	C
Delay by approach, $d_A = \dfrac{\sum(d)(v)}{\sum v}$ (s/veh)	34			22	26	
LOS by approach	C			C	C	
Approach flow rate, V_A (veh/h)	375			4398	4354	
Intersection delay, $d_I = \dfrac{\sum(d_A)(V_A)}{\sum V_A}$ (s/veh)	24,500		Intersection LOS		C	
Notes						

Table 23: Capacity and LOS Worksheet for 4th Intersection.

Junction 5.

This junction is composed of two streets, Via Cristoforo Colombo, and Via delle Sette Chiese. The geographical representation of this junction is shown in Figure 13.

Figure 13: Satellite view of the 5th Intersection.

This intersection is a typical T-intersection. The layout and geometry of the intersection are shown in Figure 14.

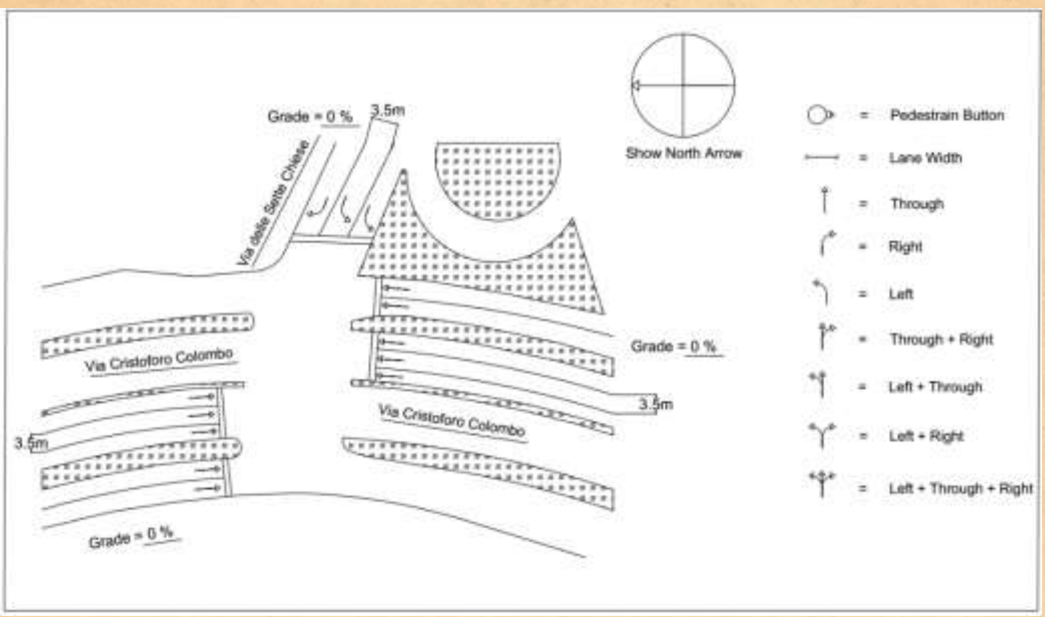


Figure 14: Geometric Properties of the 5th Intersection

Figure 14 illustrates the geometric properties of the intersection such as the width of the lanes and the grade of each approach. It also represents all possible maneuvers in this junction. These characteristics are summarized in Table 24.

Approach	Street	Number of lanes	Lane Width [m]	Grade [%]	Possible Movements
NB	Via Cristoforo Colombo	5	3.5	0	TH
SB	Via Cristoforo Colombo	5	3.5	0	TH
WB	Via delle Sette Chiese	3	3.5	0	LT+RT

Table 24: Characteristics of each Approach in 5th Junction.

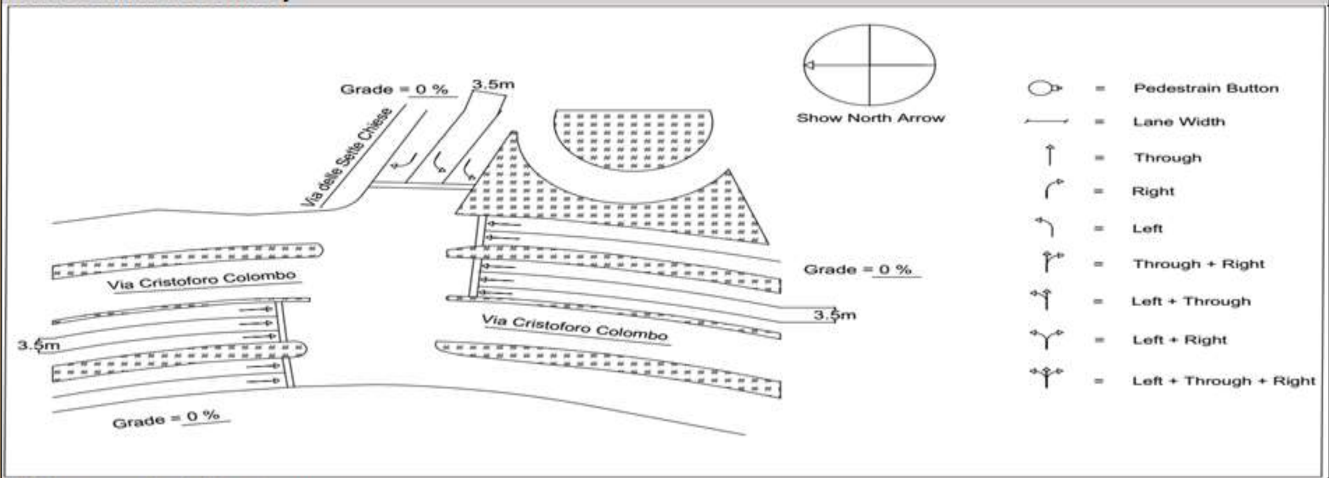
This is a 2-phase intersection. The first phase belongs to the NB and SB approach, which has a green time of 82 seconds since the flow in these approaches are high compared to WB and the second phase belongs to WB, where only left and right movements are present.

Since the EB flows are in the second phase, there is no opposing flow for the left and right turns. Hence, they are considered as protected left and right turns. The input worksheet for the operational analysis in the format given by the HCM is shown in Table 25.

INPUT WORKSHEET

General Information	Site Information
Analyst :KEN KOSHY VARGHESE	Intersection:Via Cristoforo Colombo-Via delle Sette Chiese
Agency or Company SAPIENZA UNIVERSITY	Area Type CBD ● Other
Date Performed : 23/05/2019	Jurisdiction
Analysis Time Period : 9:30 - 11:30 A.M	Analysis Year : 2019

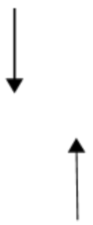
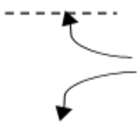
Intersection Geometry



Volume and Timing Input

	WB				NB	SB
	LT		RT		TH	TH
Volume, V (veh/h)	708		304		4184	3156
% Heavy Vehicles, % HV	1		11		4	7
Peak-hour factor, PHF	0.9				0.9	0.9
Pretimed (P) or actuated (A)	P				P	P
Start-up lost time, l1 (s)	2.5				2.5	2.5
Clearence lost time,l2 (s)	3				3	3
Arrival type, AT	3				4	4
Approach pedestrian volume, 2 vped (p	24				0	88
Approach bicycle volume, 2 vbic (bicyc	4				0	4
Parking (Y or N)	N				N	N
Parking maneuvers, NM (maneuvers/h	0				0	0
Bus stopping, NB (buses/h)	0				14	17
Min. timing for pedestrian, 3 Gp (s)	18				33	34

Signal Phasing Plan

	Ø1			Ø2			Ø3			Ø4			Ø5		
DIAGRAM															
Timing	G =	82	sec	G =	50	sec	G =		sec	G =			G =		
	Y =	4	sec	Y =	4	sec	Y =		sec	Y =			Y =		
										Cycle length			C=	140	Sec

Notes

1-TH=Through
2. LT and RT = Left and Right Turn
3-Red for Phase 1 is 54 (sec)
4-Red for Phase 2 is 86 (sec)

Table 25: Input Worksheet of 5th Intersection.

Table 25 contains the traffic count data which is gathered in the field observation. As it was explained in methodology, in this observation, every 3 motorbikes are considered as one car and one heavy vehicle is considered as 2 cars. As it is shown in Table 6, the peak hour factor is 0.9 since the data is gathered based on 15 minutes of observation and these 15 minutes may not be necessary during the peak hour. The start-up and clearance loss time are assumed to be 2.5sec and 3sec, respectively, which gives us a total lost time of 5.5 seconds. The arrival type for this junction, based on Exhibit 16-4 of Highway Capacity Manual, is assumed AT 3 for the WB which is for random arrivals and in which the main platoon contains less than 40 percent of lane group volume and AT 4 for NB and SB which is for moderately dense platoon arriving in the middle of the green phase. The area type of this intersection is not considered as CBD because as per HCM, area type is considered as CBD if characteristics like narrow street right-of-way, frequent parking maneuvers, vehicle blockage, small radius turns, limited use of exclusive turn lanes, high pedestrian activity etc. are present. As per our field observation, our road did not meet the above-mentioned characteristics and hence, the intersection is not considered as CBD and the area type adjustment factor is considered as 1 as per HCM.

Table 25 also includes information regarding bicycle and pedestrian volume. Based on this volume, the volume of the pedestrian/bicycle per cycle and then the minimum effective green for pedestrian can be computed using Exhibit 16-2 in Highway Capacity Manual. This table also provides data regarding the parking and bus stops within the 75 meters distance from the stop line. This data will be later applied for computing the adjustment factors.

Having all this initial data, in the Volume adjustment and saturation flow rate worksheet, the adjustment factors can be computed to be applied for the calculation of the saturation flow. Table 26 contains the worksheet of the Highway Capacity Manual to compute the adjustment factors and the saturation flow. At the top part of this worksheet, the adjusted flow rates and the lane groups are defined. The adjusted flow rate is obtained by dividing the real flow over the Peak Hour Factor. The NB and SB have only through movements, they contain only one lane group. For WB, since there are only left and right turns and it uses separate lanes, they are considered as two different lane groups. So, there is a total of 4 lane groups for this intersection.

The second part of this worksheet is for the calculation of adjustment factors. For what concerns Lane Utilization Factor, since no specific data about the volume of each lane, was gathered during the observation, HCM suggests chapter 10 for the calculation, but since I was not able to find the chapter in the provided HCM, I choose an average value of 0.95 for lane groups having more than one land and a value of 1 for exclusive lane, which I obtained from one of the example problems of the highway capacity manual. The base saturation of 2100 pc/h/ln is used for all the intersections of this road. The grade and parking adjustment factor for all approach is 1 since there the grade of each approach is zero and there were no parking maneuvers. The left-turn and right turn adjustment factors are taken as 0.952 and 0.85 since the act as exclusive lanes and for all the other approach it is 1 since there are no left and right-turn movements.

VOLUME ADJUSTMENT AND SATURATION FLOW RATE WORKSHEET

General Information						
Project Description : Via Cristoforo Colombo-Via delle Sette Chiese						
Volume Adjustment						
	WB				NB	SB
	LT		RT		TH	TH
Volume, V (veh/h)	708		304		4184	3156
Peak-hour factor, PHF	0.9				0.9	0.9
Adjusted flow rate, Vp = V/PHF (veh/h)	787		338		4649	3507
Lane Group	1		1		1	1
Adjusted flow rate in lane group, v (veh/h	787		338		4649	3507
Proportion of LT or RT (P_LT or R_RT)	1		1		1	1
Saturation Flow Rate (see Exhibit 16-7 to determine adjustment factors)						
Base Saturation flow, Sp (pc/h/ln)	2100				2100	2100
Number of lanes, N	2		1		5	5
Lane width adjustment factor, fw	0.989				0.989	0.989
Heavy-vehicle adjustment factor, f_HV	0.989		1.118		0.965	0.936
Grade adjustment factor, fp	1.000				1.000	1.000
Parking adjustment factor, fp	1.000				1.000	1.000
Bus blockage adjustment factor, f_bb	1.000		1.000		0.989	0.986
Area type adjustment factor, f_a	1.000				1.000	1.000
Lane utilization adjustment factor, f_LU	0.950		1.000		0.950	0.950
Left-turn adjustment factor, f_LT	0.952		1.000		1.000	1.000
Right-turn adjustment factor, f_RT	1.000		0.850		1.000	1.000
Left-turn ped/bike adjustment factor, f_L	1.000		1.000		1.000	1.000
Right-Turn ped/bike adjustment factor, f_	1.000		0.913		1.000	1.000
Adjusted saturation flow, s (veh/h) $s = s_0 N f_w f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb}$	3716		1801		9412	8651
Notes						

Table 26: Volume Adjustment Worksheet for 5th Intersection.

The right turn pedestrian/bicycle adjustment factor should be calculated using a separate supplemental worksheet which is shown in Table 27 since there is a conflict between pedestrians crossing NB and vehicles turning right from WB. All the other adjustment factors can be directly computed by applying the formulas in Exhibit 16-7 of the Highway Capacity Manual which are also in methodology in this report. The result of Table 26 is the value of saturation flow for each lane group.

SUPPLEMENTAL WORKSHEET FOR PEDESTRIAN-BICYCLE EFFECTS ON PERMITTED LEFT TURNS AND RIGHT TURNS				
General Infromation				
Project Description :Via Cristoforo Colombo-Via delle Sette Chiese				
Permitted Right Turns				
	EB	WB	NB	SB
Effective pedestrian green time, gp (s)		50		
Conflicting pedestrian volume, Vped (p/h)		88		
Conflicting bicycle volume, Vbic (bicycles/h)		4		
Vpedg = Vped (C/gp)		247		
OCCpedg = Vpedg/2000 if (Vped≤1000) OCCpedg=0.4+Vpedg/10000 if (1000<Vpedg≤5000)		0.124		
Effective green, g (s)		50		
Vbicg = Vbic (C/g)		10		
OCCbicg = 0.02 + Vbicg/2700		0.024		
OCCr=OCCpedg+OCCbicg-(OCCpedg)(OCCbicg)		0.145		
Number of cross-street receiving lanes, Nrec		2		
Number of turning lanes, Nturn		1		
ApbT = 1 - OCCr if Nrec = Nturn ApbT = 1 - 0.6(OCCr) if Nrec > Nturn		0.913		
Proportion of right turns, P-RT		1.000		
Proportion of right turns using protected phase, P-RTA		0		
$f_{Rpb} = 1.0 - P_{RT}(1 - A_{pbT})(1-P_{RTA})$		0.913		
Notes				

Table 27: Supplemental Worksheet for permitted left turns opposed by single lane approach (5th Int)

Having the saturation flow and the adjusted flow rate for each lane group as the result of Table 26, the computation for defining the level of service on each lane group, on each approach and for the entire intersection can be done. These computations are summarized in Table 28. In upper part of Table 28, capacity analysis is made. To do so, by multiplying the saturation flow to the green share of each lane group, the capacity of the lane group is defined. Then, having the capacity of each lane group, the volume by the capacity of each lane group can be defined and then the critical lane group (which has the highest v/c among all lane group in the same phase) for each phase is identified. This critical lane group v/c for each phase can be applied for computing the minimum green requirements. Then by knowing the critical lane group in each phase and using the summation of v/s ratio for those lane groups and the total lost time of the intersection, Xc which is the critical v/c ratio for the whole intersection can be computed using equation 16-8 of Highway Capacity

Manual. This indicator is useful in evaluating the overall intersection with respect to the geometric and total cycle length and in estimating signal timings when they are not known.

The second part of Table 28 is related to defining the level of service. To do so, first the delay for each lane group should be calculated using equation 16-9 of the Highway Capacity Manual. This the formula has 3 elements. As explained before in methodology, these elements can be calculated using equations 16-11 and 16-12 of Highway Capacity Manual. Since no initial queue is observed in the survey, the third component, d3, is considered as 0. Since the arrival type for WB is AT 3, the progression factor (PF) is assumed equal to 1 according to Exhibit 16-12 of Highway Capacity Manual and the PF for the NB and SB are computed by the equation 16-10 in HCM by considering a range of platoon ratio (Rp) and supplemental adjustment factor for platoon arriving during green (fpa) as 1.333 and 1.15, respectively, according to Exhibit 16-12 for AT 4.

In the computation of the second term of the delay, incremental delay, to determine the value of ‘k’, the incremental delay factor, the Exhibit 16-13 of Highway Capacity Manual can be applied.

Since in this intersection the controller setting is pre-timed, then the value of ‘k’ is equal to 0.5. Another element in equation 16-12 is ‘I’ which is the upstream filtering/metering adjustment factor. Based on the guidance of the Highway Capacity Manual, for signal analysis of an isolated junction, a value of 1 for ‘I’ is used.

After computing the uniform delay and incremental delay and by applying the equation 16-9, the total delay for each lane group can be defined. Then the average delay for each approach can be computed by applying the weighted average of the delay of all lane groups in each approach, considering the flow of each lane group as its weight based on equation 16-13 of Highway Capacity Manual. Finally, the average delay of the whole intersection can be calculated by using the weighted average of all lane groups of the intersection using equation 16-14 of Highway Capacity Manual. The final step is to define the level of service for each lane group, then each approach and at last for the whole intersection. As explained in methodology, the level of service can be defined using Exhibit 16-2 of Highway Capacity Manual. It is seen in Table 9 that due to a significant difference in flow between NB and SB compared to WB, the values for delay and LOS are significantly different for the approaches. This is also understood when we compare the green ratios of the approaches. The NB and SB are given a ratio of 0.58 while WB has only 0.35. Hence, the entire intersection has the level of service of ‘B’ based on the delay which equals 19.16 seconds.

CAPACITY AND LOS WORKSHEET

General Information										
Project Description : Via Cristoforo Colombo-Via delle Sette Chiese										
Capacity Analysis										
Phase Number	1	1	2	2						
Phase Type	P	P	P	P						
Lane Group	↑	↓	↙	↖						
Adjusted flow rate, v (veh/h)	4649	3507	787	338						
Saturation flow rate, s (veh/h)	9412	8651	3716	1801						
Lost time, t_L = l1 + l2	5.5	5.5	5.5	5.5						
Effective green time, g (s), g = G + Y - t_L	80.5	80.5	48.5	48.5						
Green ratio, g/C	0.6	0.6	0.346	0.346						
Lane group capacity, c = s(g/C), (veh/h)	5412	4975	1287	624						
v/c ratio, X	0.859	0.705	0.61	0.54						
Flow ratio, v/s	0.494	0.405	0.21	0.19						
Critical lane group/phase (√)	√		√							
Sum of flow ratios for critical lane groups, Yc Yc = ∑ (critical lane groups, v/s)	0.706									
Total lost time per cycle, L (s)	11									
Critical flow rate to capacity ratio, Xc Xc = (Yc) (C)/(C - L)	0.766									

Lane Group Capacity, Control Delay, and LOS Determination						
	WB				NB	SB
Lane group	↙		↖		↑	↓
Adjusted flow rate, v (veh/h)	787		338		4649	3507
Lane group capacity, c (veh/h)	1287		624		5412	4975
v/c ratio, X = v/c	0.61		0.54		0.86	0.70
Total green ratio, g/C	0.35		0.35		0.58	0.58
Uniform delay, $d_1 = \frac{0.50\,C\,[1-(\frac{g}{c})]^2}{1-[\frac{\min(1,X)\,g}{C}]}$ (s/veh)	38		37		25	21
Incremental delay calibration, k	0.50		0.50		0.50	0.50
Incremental delay, d2 (s/veh) d_2=900T[(X-1)+$\sqrt{(X-1)^2+\frac{8kIX}{cT}}$]	2		3		2	0.9
Initial queue delay, d3 (s/veh)	0.0		0.0		0.0	0.0
Progression adjustment factor, PF	1		1		0.63	0.63
Delay, d = d1(PF) + d2 + d3 (s/veh)	40		40		18	14
LOS by lane group	D		D		B	B
Delay by approach, $d_A = \frac{\sum(d)(v)}{\sum v}$ (s/veh)	40				18	14
LOS by approach	D				B	B
Approach flow rate, V_A (veh/h)	1125				4649	3507
Intersection delay, $d_I = \frac{\sum(d_A)(V_A)}{\sum V_A}$ (s/veh)	19.159			Intersection LOS		B
Notes						

Table 28: Capacity and LOS Worksheet for 5th Intersection.

Junction 6.

This junction is composed of 3 streets, Via Cristoforo Colombo-Via Giovanni Genocchi-Piazza Elio Rufino. The geographical representation of this junction is shown in Figure 15.

Figure 15: Satellite view of 6th Junction.

As it is shown in Figure 15, this intersection can be modelled as a typical 4-armed intersection. Some geometric properties of the intersection such as the width of the lanes and also the grade of each approach and the possible maneuvers are shown in Figure 16.

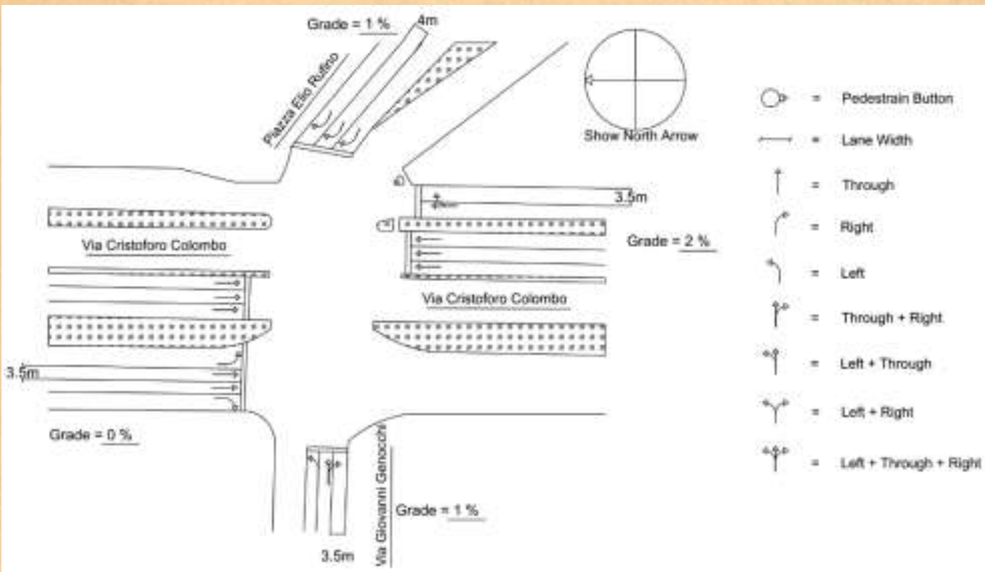


Figure 16: Geometric Properties of the 6th Intersection.

Figure 16 illustrates the geometric properties of the intersection such as the width of the lanes and the grade of each approach. It also represents all possible maneuvers in this junction. These characteristics are summarized in Table 29.

Approach	Street	Number of lanes	Lane Width [m]	Grade [%]
NB	Via Cristoforo Colombo	5	3.5	2
SB	Via Cristoforo Colombo	7	3.5	0
WB	Piazza Elio Rufino	3	4	1
EB	Via Giovanni Genocchi	4	3.5	1

Table 29: Characteristics of each Approach in 6th Junction.

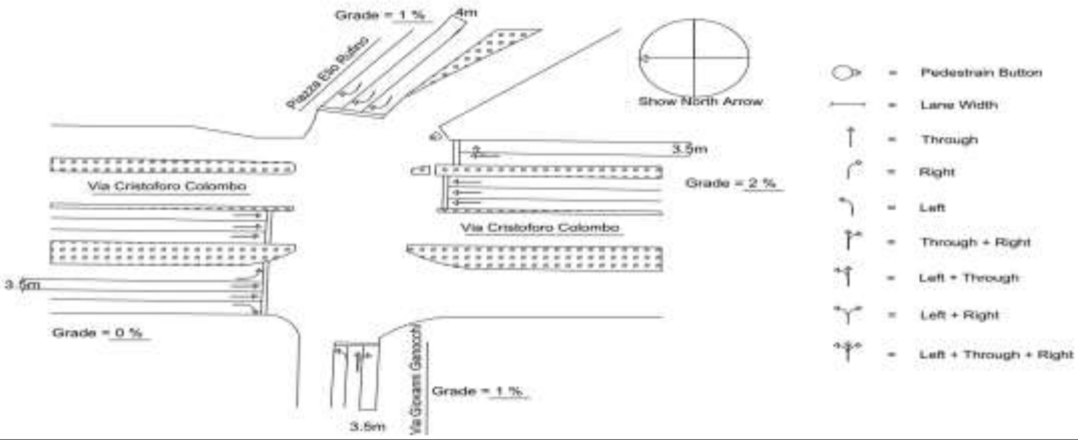
This is a 3-phase intersection. The first phase belongs to the NB and SB approach, which has a green time of 72 seconds since the flow in these approaches is high compared to other approaches and the second phase belongs to EB, with a green time of 30 seconds and the third phase contains the left turn of SB and right turn movements of WB, with a green time of 30s.

Since the EB flows are in the second phase, there is no opposing flow for the left turn and also in the third phase, the left turn of SB and the right turn of WB doesn't have conflict points. Hence, they are considered as protected left and right turns. The input worksheet for the operational analysis in the format given by the HCM is shown in Table 30.

INPUT WORKSHEET

General Information	Site Information
Analyst :KEN KOSHY VARGHESE	Intersection:Via Cristoforo Colombo-Via Giovanni Genocchi-Piazza Elio Rufino
Agency or Company : SAPIENZA UNIVERSITY	Area Type CBD ● Other
Date Performed : 23/05/2019	Jurisdiction
Analysis Time Period : 9:30 - 11:30 A.M	Analysis Year : 2019

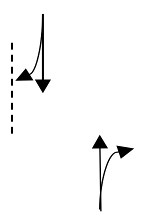
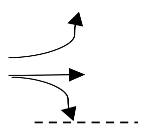
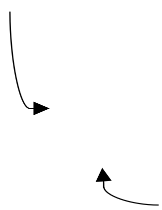
Intersection Geometry



Volume and Timing Input

	EB		WB	NB	SB		
	LT	TH+RT	EX-RT	TH+TH-RT	EX-LT	TH-R	EX-RT
Volume, V (veh/h)	278	594	273	3620	296	3395	425
% Heavy Vehicles, % HV	3		0	3	3	5	2
Peak-hour factor, PHF	0.9		0.9	0.9	0.9		
Pretimed (P) or actuated (A)	P		P	P	P		
Start-up lost time, l1 (s)	2.5		2.5	2.5	2.5		
Clearence lost time,l2 (s)	3		3	3	3		
Arrival type, AT	3		3	4	4		
Approach pedestrian volume, 2 vped (p	50		80	150	0		
Approach bicycle volume, 2 vbic (bicycl	4		8	12	0		
Parking (Y or N)	N		N	N	N		
Parking maneuvers, NM (maneuvers/h	0		0	0	0		
Bus stopping, NB (buses/h)	0		11	13	0		
Min. timing for pedestrian, 3 Gp (s)	16		21	40	39		

Signal Phasing Plan

	Ø1			Ø2			Ø3			Ø4			Ø5		
DIAGRAM															
Timing	G =	72	sec	G =	30	sec	G =	30	sec	G =			G =		
	Y =	4	sec	Y =	4	sec	Y =	4	sec	Y =			Y =		
										Cycle length			C=	144	Sec

Notes

1-TH-RT=Through and Right Turn
2-EX-RT/EX-LT = Exclusive Right/Exclusive Left
3-TH-R=Through Reserved Lane
4-Red for Phase 1 is 68 (sec)
5-Red for Phase 2 is 110 (sec)
6-Red for Phase 3 is 110 (sec)

Table 30: Input Worksheet for 6th Intersection.

Table 30 contains the traffic count data which is gathered in the field observation. All the assumptions regarding the peak hour factor, arrival type and how to aggregate the number of motorbikes and vehicles are like the previous intersection. The start-up and clearance loss time are assumed to be 2.5sec and 3sec, respectively, which gives us a total lost time of 5.5 seconds. The arrival type for this junction, based on Exhibit 16-4 of Highway Capacity Manual, is assumed AT 3 for the WB and EB which is for random arrivals and in which the main platoon contains less than 40 percent of lane group volume and AT 4 for NB and SB which is for moderately dense platoon arriving in the middle of the green phase. The area type of this intersection is not considered as CBD because as per HCM, area type is considered as CBD if characteristics like narrow street right-of-way, frequent parking maneuvers, vehicle blockage, small radius turns, limited use of exclusive turn lanes, high pedestrian activity etc. are present. As per our field observation, our road did not meet the above-mentioned characteristics and hence, the intersection is not considered as CBD and the area type adjustment factor is considered as 1 as per HCM.

Table 30 also includes information regarding bicycle and pedestrian volume. Based on this volume, the volume of the pedestrian/bicycle per cycle and then the minimum effective green for pedestrian can be computed using Exhibit 16-2 in Highway Capacity Manual. This table also provides data regarding the parking and bus stops within the 75 meters distance from the stop line which is observed for NB and WB only. This data will be later applied for computing the adjustment factors.

Having all this initial data, in the Volume adjustment and saturation flow rate worksheet, the adjustment factors can be computed to be applied for the calculation of the saturation flow. Table 31 contains the worksheet of the Highway Capacity Manual to compute the adjustment factors and the saturation flow. At the top part of this worksheet, the adjusted flow rates and the lane groups are defined. The adjusted flow rate is obtained by dividing the real flow over the Peak Hour Factor. The SB contains 2 lane groups since the left turn of this approach is exclusive and also is in the third phase, it is considered separate. The EB also has 2 lane groups because the left turn is an exclusive turn and has a significant amount of flow through this lane. The NB and WB have only 1 lane groups each. So, there is a total of 6 lane groups for this intersection.

The second part of this worksheet is for the calculation of adjustment factors. For what concerns Lane Utilization Factor, since no specific data about the volume of each lane, was gathered during the observation, HCM suggests chapter 10 for the calculation, but since I was not able to find the chapter in the provided HCM, I choose an average value of 0.95 for lane groups having more than one lane and a value of 1 for exclusive lanes, which I obtained from one of the example problems of the highway capacity manual. The base saturation of 2100 pc/h/ln is used for all the intersections of this road. The grade adjustment factor is calculated using the equation in Exhibit 16-7 and the grade of each approach are calculated with the help of google earth by taking the elevation of two points in the approach which are 100m apart. The parking adjustment factor for all approach is 1 since there were no parking maneuvers. The left-turn and right turn adjustment factors are taken as 0.952 and 0.85 for exclusive lanes and for EB since the right turn is in the shared lane, the right turn adjustment factor is calculated by considering the proportion of right-turning vehicles.

VOLUME ADJUSTMENT AND SATURATION FLOW RATE WORKSHEET

General Information							
Project Description : Via Cristoforo Colombo-Via Giovanni Genocchi-Piazza Elio Rufino							
Volume Adjustment							
	EB		WB	NB	SB		
	LT	TH+RT	EX-RT	TH+TH-RT	EX-LT	TH-R	EX-RT
Volume, V (veh/h)	278	594	273	3620	296	3395	425
Peak-hour factor, PHF	0.9		0.9	0.9	0.9		
Adjusted flow rate, Vp = V/PHF (veh/h)	309	660	304	4023	329	3773	473
Lane Group	1	1	1	1	1	1	1
Adjusted flow rate in lane group, v (veh/h	309	660	304	4023	329	3773	473
Proportion of LT or RT (P_LT or R_RT)	1	0.2155		0.0166	1		1
Saturation Flow Rate (see Exhibit 16-7 to determine adjustment factors)							
Base Saturation flow, Sp (pc/h/ln)	2100		2100	2100	2100		
Number of lanes, N	1	2	3	5	1	5	1
Lane width adjustment factor, fw	0.989		1.044	0.989	0.989		
Heavy-vehicle adjustment factor, f_HV	0.971	1.031	1.000	0.973	0.974	0.954	0.977
Grade adjustment factor, fp	0.995		0.995	0.990	1.000	1.000	1.000
Parking adjustment factor, fp	1.000		1.000	1.000	1.000	1.000	1.000
Bus blockage adjustment factor, f_bb	1.000	0.990	0.985	0.990	1.000	0.990	1.000
Area type adjustment factor, f_a	1.000		1.000	1.000	1.000	0.900	0.900
Lane utilization adjustment factor, f_LU	1.000	0.950	0.950	0.950	1.000	0.950	1.000
Left-turn adjustment factor, f_LT	0.952	1.000	1.000	1.000	0.950	1.000	1.000
Right-turn adjustment factor, f_RT	1.000	0.968	0.850	0.998	1.000	1.000	0.850
Left-turn ped/bike adjustment factor, f_Lp	1.000	1.000	1.000	1.000 / 1.000 / 1.000	1.000	1.000	1.000
Right-Turn ped/bike adjustment factor, f_	1.000	0.950	1.000	1.000 / 1.000 / 1.000	1.000	1.000	0.928
Adjusted saturation flow, s (veh/h) $s = s_0 N f_w f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb}$	1911	3684	5209	9376	1921	9319	1600
Notes							

Table 31: Volume Adjustment Worksheet for 6th Intersection.

The right turn pedestrian/bicycle adjustment factor should be calculated using a separate supplemental worksheet which is shown in Table 32 since there is a conflict between pedestrians crossing EB and vehicles turning right from SB and pedestrians crossing NB and vehicle turning right from EB. There was a conflict point between pedestrians crossing EB and right-turning vehicles of NB but since this right turning proportion is very less and no conflict was observed in the field observation, this factor is considered as 1. All the other adjustment factors can be directly computed by applying the formulas in Exhibit 16-7 of the Highway Capacity Manual which are also in methodology in this report. The result of Table 31 is the value of saturation flow for each lane group.

SUPPLEMENTAL WORKSHEET FOR PEDESTRIAN-BICYCLE EFFECTS ON PERMITTED LEFT TURNS AND RIGHT TURNS				
General Infromation				
Project Description : Via Cristoforo Colombo-Via Giovanni Genocchi-Piazza Elio Rufino				
Permitted Right Turns				
	EB			**SB**
Effective pedestrian green time, gp (s)	30			72
Conflicting pedestrian volume, Vped (p/h)	150			50
Conflicting bicycle volume, Vbic (bicycles/h)	12			4
Vpedg = Vped (C/gp)	720			100
OCCpedg = Vpedg/2000 if (Vped≤1000) OCCpedg=0.4+Vpedg/10000 if (1000<Vpedg≤5000)	0.360			0.05
Effective green, g (s)	30			72
Vbicg = Vbic (C/g)	48			7
OCCbicg = 0.02 + Vbicg/2700	0.038			0.023
OCCr=OCCpedg+OCCbicg-(OCCpedg)(OCCbicg)	0.384			0.072
Number of cross-street receiving lanes, Nrec	2			1
Number of turning lanes, Nturn	1			1
ApbT = 1 - OCCr if Nrec = Nturn ApbT = 1 - 0.6(OCCr) if Nrec > Nturn	0.77			0.928
Proportion of right turns, P-RT	0.215			1.000
Proportion of right turns using protected phase, P-RTA	0			0
$f_{Rpb} = 1.0 - P_{RT}(1 - A_{pbT})(1 - P_{RTA})$	0.95			0.928
Notes				

Table 32: Supplemental Table for Pedestrian-Bicycle effects on Permitted Right Turn of the 6th junction.

Having the saturation flow and the adjusted flow rate for each lane group as the result of Table 31, the computation for defining the level of service on each lane group, on each approach and for the entire intersection can be done. These computations are summarized in Table 33. In upper part of Table 33, capacity analysis is made. To do so, by multiplying the saturation flow to the green share of each lane group, the capacity of the lane group is defined. Then, having the capacity of each lane group, the volume by the capacity of each lane group can be defined and then the critical lane group (which has the highest v/c among all lane group in the same phase) for each phase is identified. This critical lane group v/c for each phase can be applied for computing the minimum green requirements. Then by knowing the critical lane group in each phase and using the summation of v/s ratio for those lane groups and the total lost time of the intersection, Xc which is the critical v/c ratio for the whole intersection can be computed using equation 16-8 of Highway Capacity Manual. This indicator is useful in evaluating the overall intersection with respect to the geometric and total cycle length and in estimating signal timings when they are not known.

The second part of Table 33 is related to defining the level of service. To do so, first the delay for each lane group should be calculated using equation 16-9 of the Highway Capacity Manual. This the formula has 3 elements. As explained before in methodology, these elements can be calculated using equations 16-11 and 16-12 of the Highway Capacity Manual. Since no initial queue is observed in the survey, the third component, d3, is considered as 0. Since the arrival type for WB and EB is AT 3, the progression factor (PF) is assumed equal to 1 according to Exhibit 16-12 of Highway Capacity Manual and the PF for the NB and SB are computed by the equation 16-10 in HCM by considering a range of platoon ratio (Rp) and supplemental adjustment factor for platoon arriving during green (fpa) as 1.333 and 1.15, respectively, according to Exhibit 16-12 for AT 4.

In the computation of the second term of the delay, incremental delay, to determine the value of ‘k’, the incremental delay factor, the Exhibit 16-13 of Highway Capacity Manual can be applied. Since in this intersection the controller setting is pre-timed, then the value of ‘k’ is equal to 0.5. Another element in equation 16-12 is ‘I’ which is the upstream filtering/metering adjustment factor. Based on the guidance of the Highway Capacity Manual, for signal analysis of an isolated junction, a value of 1 for ‘I’ is used.

After computing the uniform delay and incremental delay and by applying the equation 16-9, the total delay for each lane group can be defined. Then the average delay for each approach can be computed by applying the weighted average of the delay of all lane groups in each approach, considering the flow of each lane group as its weight based on equation 16-13 of Highway Capacity Manual. Finally, the average delay of the whole intersection can be calculated by using the weighted average of all lane groups of the intersection using equation 16-14 of Highway Capacity Manual.

The final step is to define the level of service for each lane group, then each approach and at last for the whole intersection. As explained in methodology, the level of service can be defined using Exhibit 16-2 of Highway Capacity Manual. It is seen in Table 33 that due to a significant difference in flow between NB and SB compared to EB, the values for delay and LOS are significantly different for these approaches. Therefore, the delay for the vehicles in the third phase is high compared to other approaches and have a LOS of ‘E’. However, the entire intersection has the level of service of ‘C’ based on the delay which equals 34.183 seconds.

CAPACITY AND LOS WORKSHEET

General Information										
Project Description : Via Cristoforo Colombo-Via Giovanni Genocchi-Piazza Elio Rufino										
Capacity Analysis										
Phase Number	1	1	1	2	2	3	3			
Phase Type	P	P	P	P	P	P	P			
Lane Group										
Adjusted flow rate, v (veh/h)	4023	3773	473	660	309	304	329			
Saturation flow rate, s (veh/h)	9376	9319	1600	3684	1911	5209	1921			
Lost time, t_L = l1 + l2	5.5	5.5	5.5	5.5	5.5	5.5	5.5			
Effective green time, g (s), g = G + Y - t_L	70.5	70.5	70.5	28.5	28.5	28.5	28.5			
Green ratio, g/C	0.5	0.5	0.5	0.198	0.198	0.198	0.2			
Lane group capacity, c = s(g/C), (veh/h)	4590	4563	784	729	378	1031	380			
v/c ratio, X	0.876	0.83	0.6	0.91	0.82	0.29	0.87			
Flow ratio, v/s	0.429	0.4	0.3	0.18	0.16	0.06	0.17			
Critical lane group/phase (√)	√			√			√			
Sum of flow ratios for critical lane groups, Yc Yc = ∑ (critical lane groups, v/s)	0.780									
Total lost time per cycle, L (s)	16.5									
Critical flow rate to capacity ratio, Xc Xc = (Yc) (C)/(C - L)	0.880									

Lane Group Capacity, Control Delay, and LOS Determination							
	EB		WB	NB	SB		
Lane group							
Adjusted flow rate, v (veh/h)	309	660	304	4023	329	3773	473
Lane group capacity, c (veh/h)	378	729	1031	4590	380	4563	784
v/c ratio, X = v/c	0.82	0.91	0.29	0.88	0.87	0.83	0.60
Total green ratio, g/C	0.20	0.20	0.20	0.49	0.20	0.49	0.49
Uniform delay, $d_1 = \frac{0.50\,C\,[1-(\frac{g}{C})]^2}{1-[\min(1,X)\frac{g}{C}]}$ (s/veh)	55	56	49	33	56	32	27
Incremental delay calibration, k	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Incremental delay, d2 (s/veh) $d_2=900T[(X-1)+\sqrt{(X-1)^2+\frac{8kIX}{cT}}]$	18	17	1	3	22	1.8	3.4
Initial queue delay, d3 (s/veh)	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Progression adjustment factor, PF	1	1	1	0.78	1.00	0.78	0.78
Delay, d = d1(PF) + d2 + d3 (s/veh)	73	73	50	28	78	27	24
LOS by lane group	E	E	D	C	E	C	C
Delay by approach, $d_A = \frac{\sum(d)(v)}{\sum v}$ (s/veh)	73		50	28	30		
LOS by approach	E		D	C	C		
Approach flow rate, V_A (veh/h)	969		304	4023	4575		
Intersection delay, $d_I = \frac{\sum(d_A)(V_A)}{\sum V_A}$ (s/veh)	34.183		Intersection LOS		C		
Notes							

Table 33: Capacity and LOS Worksheet of 6th Junction.

Junction 7.

The 7th intersection connects Via Cristoforo Colombo and Via Constantino as shown in fig 17. The main street Via Cristoforo Colombo has 10 lanes of 3.5 M wide, each direction having 5 lanes. Via Constantino having 2 lanes with a width of 4.8 m which connects to Via Cristoforo Colombo.

Figure 17: Satellite view of 7th Junction.

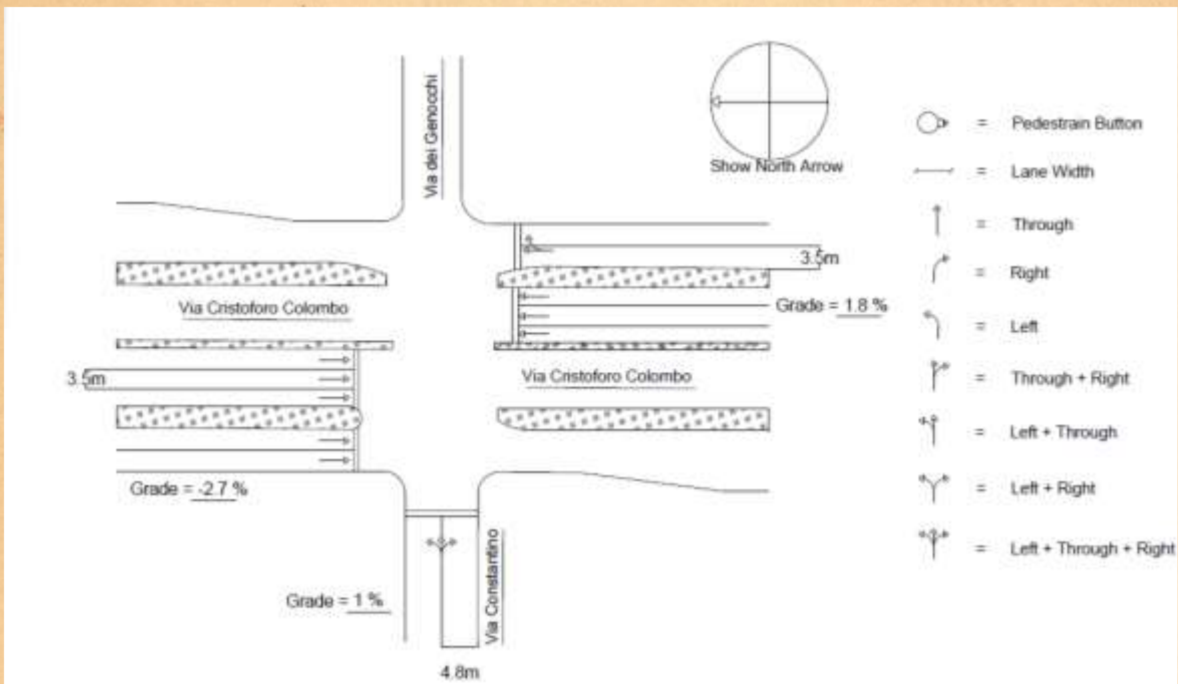


Figure 18: Layout of 7th Intersection.

The characteristics of different approaches are represented in table below:

Approach	Street	Number of lanes	Lane Width [m]	Grade [%]
NB	Via Cristoforo Colombo	5	3.5	1.8
SB	Via Cristoforo Colombo	5	3.5	-2.7
WB				
EB	Via Constantino	2	4.8	2

Table 34: Geometric properties of the Intersection.

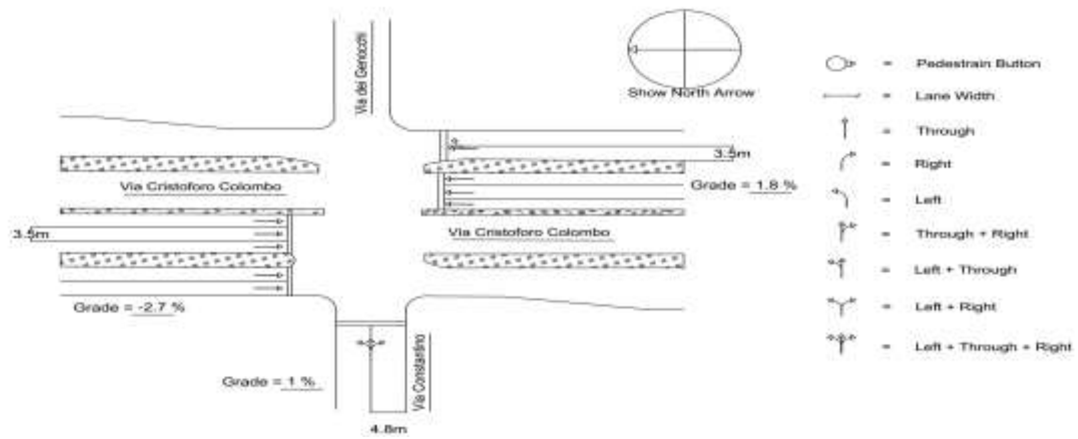
Since the arrival of cars is random, the arrival type of vehicle in eastbound is assumed 3. For the major lanes moderately dense platoon arriving in the middle of the green phase so arrival type should consider as 4. Considering the different lanes widths of 3.5 and 4.8 the lane width adjustment factor is calculated. Lane width adjustment factor, f_w, account for the negative impact of narrow lanes on saturation flow rate and allows for an increased flow rate on wide lanes.

This is a 2-phase intersection. The first phase belongs to the NB and SB approach, which has a green time of 84 seconds since the flow in these approaches are high compared to WB and the second phase belongs to WB.

INPUT WORKSHEET

General Information	Site Information
Analyst : PUSHKAR	Via Cristoforo Colombo/Via Constantino
Agency or Company: SAPIENZA UNIVERSITY	Area Type CBD ● Other
Date Performed : 23/05/2019	Jurisdiction
Analysis Time Period : 9:30 - 11:30 A.M	Analysis Year : 2019

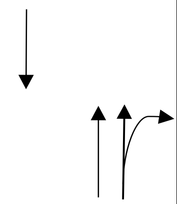
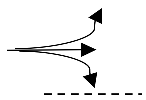
Intersection Geometry



Volume and Timing Input

	EB				NB			SB
	LT+TH+RT					TH-R	TH-RT	TH-R
Volume, V (veh/h)	544				-	2486	1631	4101
% Heavy Vehicles, % HV	3				-	0	7	6
Peak-hour factor, PHF	0.9					0.9		0.9
Pretimed (P) or actuated (A)	P					P		P
Start-up lost time, l1 (s)	2.5					2.5		2.5
Clearence lost time, l2(s)	3					3		3
Arrival type, AT	3					3		3
Approach pedestrian volume, 2 vped (p	72					168		0
Approach bicycle volume, 2 vbic (bicycl	4					0		0
Parking (Y or N)	N					N		N
Parking maneuvers, NM (maneuvers/h	0					0		0
Bus stopping, NB (buses/h)	0				0	0	12	16
Min. timing for pedestrian, 3 Gp (s)	12					34		33

Signal Phasing Plan

	Ø1			Ø2			Ø3			Ø4			Ø5		
DIAGRAM															
Timing	G =	84	sec	G =	52	sec	G =			G =			G =		
	Y =	4	sec	Y =	4	sec	Y =			Y =			Y =		
											Cycle length		C=	144	Sec

Notes

1-TH-RT=Through and Right Turn
2- TH-R=Through Reserved Lane
3-Red for Phase 1 is 56 (sec)
4-Red for Phase 2 is 88 (sec)

Table 35: Input Worksheet of 7th Intersection.

The start-up and clearance loss time are assumed to be 2.5 sec and 3 sec, the arrival type for this junction, based on Exhibit 16-4 of Highway Capacity Manual, is assumed AT 3 for the EB which is for random arrivals and in which the main platoon contains less than 40 per cent of lane group volume and AT 4 for NB and SB which is for moderately dense platoon arriving in the middle of the green phase. The area type of this intersection is not considered as CBD because as per HCM, area type is considered as CBD if characteristics like narrow street right-of-way, frequent parking maneuvers, vehicle blockage, small radius turns, limited use of exclusive turn lanes, high pedestrian activity etc. are present. As per our field observation, our road did not meet the above-mentioned characteristics and hence, the intersection is not considered as CBD and the area type adjustment factor is considered as 1 as per HCM.

The pedestrian volume for the NB approach is high so there exists a conflict with the right turning vehicles from the EB. It is also observed that bus stop is found only on NB and SB which are within 75m, therefore the bus adjustment factor should be calculated based on Exhibit 16-7 of HCM.

Having all this initial data, in the Volume adjustment and saturation flow rate worksheet, the adjustment factors can be computed to be applied for the calculation of the saturation flow. At the top part of this worksheet, the adjusted flow rates and the lane groups are defined. The adjusted flow rate is obtained by dividing the real flow over the Peak Hour Factor. The SB have only through movements, they contain only one lane group and the NB is split into 2 lane groups, one reserved for through movements and the other for through-right movements. For EB, since there is only one lane group where left, through and right movements are included in one lane group. So, there is a total of 4 lane groups for this intersection.

The second part of this worksheet is for the calculation of adjustment factors. For what concerns Lane Utilization Factor, as explained in the previous intersection, I choose an average value of 0.95 for lane groups having more than one lane and a value of 1 for an exclusive lane. The base saturation of 2100 pc/h/ln is used for all the intersections of this road. The parking adjustment factor for all approach is 1 since there were no parking maneuvers. The left-turn and right turn adjustment factors are calculated based on the proportion of left and right turning vehicles and for all the other lane groups it is 1 since there are no left and right-turn movements.

VOLUME ADJUSTMENT AND SATURATION FLOW RATE WORKSHEET

General Information										
Project Description : Via Cristoforo Colombo/Via Constantino										
Volume Adjustment										
	EB			WB			NB			SB
	LT+TH+RT			LT	TH	RT		TH-R	TH-RT	TH-R
Volume, V (veh/h)	544						-	2486	1631	4101
Peak-hour factor, PHF	0.9						0.9			0.9
Adjusted flow rate, Vp = V/PHF (veh/h)	605							2763	1813	4557
Lane Group	1							1	1	1
Adjusted flow rate in lane group, v (veh/h	605							2763	1813	4557
Proportion of LT or RT (P_LT or R_RT)	0.238		0.2182						0.1169	1
Saturation Flow Rate (see Exhibit 16-7 to determine adjustment factors)										
Base Saturation flow, Sp (pc/h/ln)	2100						2100			2100
Number of lanes, N	2						5			5
Lane width adjustment factor, fw	1.133							0.989	0.989	0.989
Heavy-vehicle adjustment factor, f_HV	0.971							1.000	0.935	0.943
Grade adjustment factor, fp	0.995							0.991	0.991	1.014
Parking adjustment factor, fp	1.000							1.000	1.000	1.000
Bus blockage adjustment factor, f_bb	1.000							1.000	0.976	0.987
Area type adjustment factor, f_a	1.000							1.000	1.000	1.000
Lane utilization adjustment factor, f_LU	0.952							1.000	0.952	0.952
Left-turn adjustment factor, f_LT	0.988							1.000	1.000	1.000
Right-turn adjustment factor, f_RT	0.967							1.000	0.982	1.000
Left-turn ped/bike adjustment factor, f_Lp	1.000							1.000	1.000	1.000
Right-Turn ped/bike adjustment factor, f_	0.967							1.000	1.000	1.000
Adjusted saturation flow, s (veh/h) $s = s_0 N f_w f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb}$	4049							6174	3511	9328
Notes										

Table 36: Volume Adjustment Worksheet of the 7th Intersection.

The right turn pedestrian/bicycle adjustment factor should be calculated using a separate supplemental worksheet, there is a conflict between pedestrians crossing NB and vehicles turning right from EB which is shown in Table 37. All the other adjustment factors can be directly computed by applying the formulas in Exhibit 16-7 of the Highway Capacity Manual which are also in methodology in this report. The result of Table 36 is the value of saturation flow for each lane group.

SUPPLEMENTAL WORKSHEET FOR PEDESTRIAN-BICYCLE EFFECTS ON PERMITTED LEFT TURNS AND RIGHT TURNS				
General Infromation				
Project Description : Via Cristoforo Colombo/Via Constantino				
Permitted Right Turns				
Effective pedestrian green time, gp (s)	52			
Conflicting pedestrian volume, Vped (p/h)	168			
Conflicting bicycle volume, Vbic (bicycles/h)	0			
Vpedg = Vped (C/gp)	465			
OCCpedg = Vpedg/2000 if (Vped≤1000) OCCpedg=0.4+Vpedg/10000 if (1000<Vpedg≤5000)	0.233			
Effective green, g (s)	52			
Vbicg = Vbic (C/g)	0			
OCCbicg = 0.02 + Vbicg/2700	0.02			
OCCr=OCCpedg+OCCbicg-(OCCpedg)(OCCbicg)	0.248			
Number of cross-street receiving lanes, Nrec	2			
Number of turning lanes, Nturn	1			
ApbT = 1 - OCCr if Nrec = Nturn ApbT = 1 - 0.6(OCCr) if Nrec > Nturn	0.851			
Proportion of right turns, P-RT	0.218			
Proportion of right turns using protected phase, P-RTA	0			
$f_{Rpb} = 1.0 - P_{RT}(1 - A_{pbT})(1-P_{RTA})$	0.967			
Notes				

Table 37: Supplemental Worksheet for pedestrian-bicycle effects on permitted right turns for 7th Int.

Having the saturation flow and the adjusted flow rate for each lane group as the result of Table 36, the computation for the delay and defining the level of service on each lane group, on each approach and for the entire intersection can be done. These computations are summarized in Table 38. the arrival type for WB is AT 3, the progression factor (PF) is assumed equal to 1 according to Exhibit 16-12 of Highway Capacity Manual and the PF for the NB and SB are computed by the equation 16-10 in HCM by considering a range of platoon ratio (Rp) and supplemental adjustment factor for platoon arriving during green (fpa) as 1.333 and 1.15, respectively, according to Exhibit 16-12 for AT 4. The values for 'k' and 'I' are taken as 0.5 and 1 respectively, for the calculation of incremental delay. After computing the uniform delay and incremental delay, the average delay for each approach and overall intersection delay is computed. Based on these delays, corresponding LOS is also found and are summarized in Table 38. As explained in the previous intersections, since the flow in NB and SB are comparatively high, more importance is given to these approaches leading to a LOS of B and LOS of D to EB. However, the overall intersection delay is 20.21 sec which gives an overall LOS of C for this intersection.

CAPACITY AND LOS WORKSHEET

General Information
Project Description : Via Cristoforo Colombo/Via Constantino

Capacity Analysis

Phase Number		1	1	1	2							
Phase Type		P	P	P	P							
Lane Group												
Adjusted flow rate, v (veh/h)		2763	1813	4557	605							
Saturation flow rate, s (veh/h)		6174	3511	9328	4049							
Lost time, t_L = I1 + I2		5.5	5.5	5.5	5.5							
Effective green time, g (s), g = G + Y - t_L		82.5	82.5	82.5	50.5							
Green ratio, g/C		0.57	0.57	0.57	0.351							
Lane group capacity, c = s(g/C), (veh/h)		3537	2012	5344	1420							
v/c ratio, X		0.78	0.901	0.85	0.43							
Flow ratio, v/s		0.45	0.52	0.49	0.15							
Critical lane group/phase (√)			√		√							
Sum of flow ratios for critical lane groups, Yc Yc = ∑ (critical lane groups, v/s)	0.666											
Total lost time per cycle, L (s)	11											
Critical flow rate to capacity ratio, Xc Xc = (Yc) (C)/(C - L)	0.721											

Lane Group Capacity, Control Delay, and LOS Determination

	EB	WB	NB			SB
Lane group						
Adjusted flow rate, v (veh/h)	605			2763	1813	4557
Lane group capacity, c (veh/h)	1420			3537	2012	5344
v/c ratio, X = v/c	0.43			0.78	0.90	0.85
Total green ratio, g/C	0.35			0.57	0.57	0.57
Uniform delay, $d_1 = \frac{0.50\,C\,[1-(\frac{g}{C})]^2}{1-[\min(1,X)\frac{g}{C}]}$ (s/veh)	36			24	27	26
Incremental delay calibration, k	0.50			0.50	0.50	0.50
Incremental delay, d2 (s/veh) $d_2=900T[(X-1)+\sqrt{(X-1)^2+\frac{8kIX}{cT}}]$	1			2	7.0	1.9
Initial queue delay, d3 (s/veh)	0.0			0.0	0.0	0.0
Progression adjustment factor, PF	1			0.64	0.64	0.64
Delay, d = d1(PF) + d2 + d3 (s/veh)	37			17	24	18
LOS by lane group	D			B	C	B
Delay by approach, $d_A = \frac{\sum(d)(v)}{\sum v}$ (s/veh)	37		19.9			18.3
LOS by approach	D		B			B
Approach flow rate, V_A (veh/h)	605		4576			4557
Intersection delay, $d_I = \frac{\sum(d_A)(V_A)}{\sum V_A}$ (s/veh)	20.221	Intersection LOS				C

Notes

Table 38: Capacity and LOS of 7th Intersection.

Junction 8.

This junction is composed of 2 streets, Via Cristoforo Colombo - Via Accademia degli Agiati. The geographical representation of this junction is shown in figure below.

Figure 19: Satellite view on the 8th Junction.

As it is shown in this intersection can be modelled as a typical 4-armed intersection. The main flow in NB&SB direction having one lane group each. SB having a through plus right and NB having through movement only. Minor flow in WB consisting one lane group, that's through plus left turn. Some geometric properties of the intersection such as the width of the lanes and also the grade of each approach and the possible maneuvers are shown in figure below.

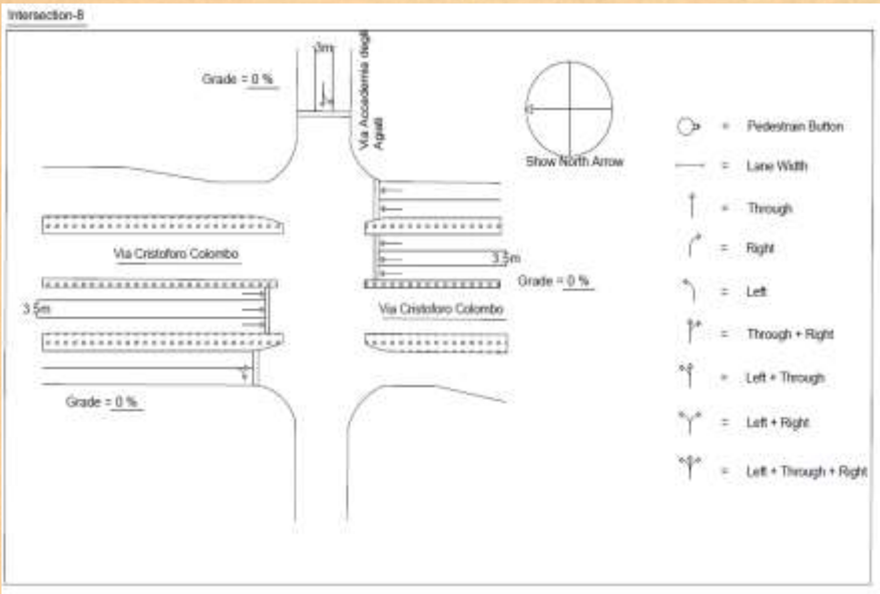
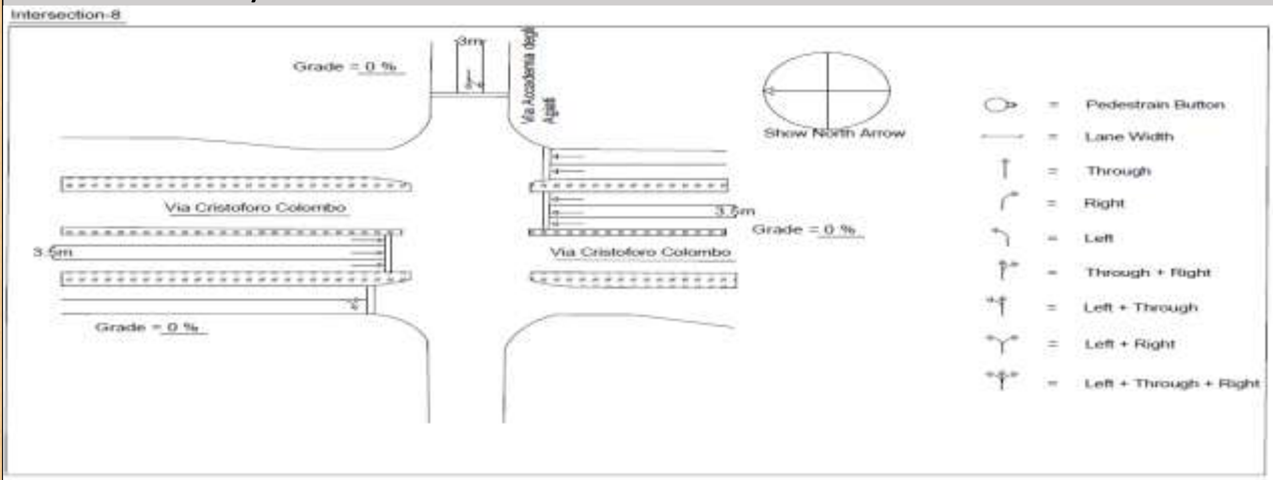


Figure 20: Layout of the 8th Intersection.

INPUT WORKSHEET

General Information	Site Information
Analyst :PUSHKAR	Intersection:Via Cristoforo Colombo - Via Accademia degli Agiati.
Agency or Company SAPIENZA UNIVERSITY	Area Type CBD ● Other
Date Performed : 23/05/2019	Jurisdiction
Analysis Time Period : 9:30 - 11:30 A.M	Analysis Year : 2019

Intersection Geometry



Volume and Timing Input

	EB	WB	NB	SB
		TH+LT	TH	TH+RT
Volume, V (veh/h)		1075	3566	3875
% Heavy Vehicles, % HV		0	2	3
Peak-hour factor, PHF		0.9	0.9	0.9
Pretimed (P) or actuated (A)		P	P	P
Start-up lost time, I1 (s)		2.5	2.5	2.5
Clerance lost time		3	3	3
Arrival type, AT		3	4	4
Approach pedestrian volume, 2 vped (p/h)		60	0	200
Approach bicycle volume, 2 vbic (bicycles/h)		12	24	36
Parking (Y or N)		N	N	N
Parking maneuvers, NM (maneuvers/h)		0	0	0
Bus stopping, NB (buses/h)		0	12	16
Min. timing for pedestrian, 3 Gp (s)		9	33	34

Signal Phasing Plan

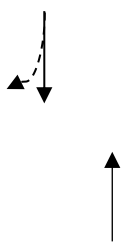
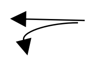
	Ø1			Ø2			Ø3			Ø4			Ø5		
DIAGRAM															
Timing	G =	78	sec	G =	60	sec	G =			G =			G =		
	Y =	4	sec	Y =	4	sec	Y =			Y =			Y =		
										Cycle length			C=	146	Sec

Table 39: Input Worksheet of 8th Intersection.

Volume and timing output table also contains the traffic count data which is gathered in the field observation. As it was explained in methodology, in this observation, every 3 motor bikes are considered as one car. As it is shown in the table 6, the peak hour factor is 0.9 since the data is gathered based on 15 minutes of observation and these 15 minutes may not be necessarily during the peak hour. Since the setting is pre timed, there is no extension of effective green time. The lane utilization adjustment factor FLU accounts for the unequal distribution of traffic among the lanes in a lane group with more than one lane. Here in WB having three lanes in one lane group with unequal distribution so the lane utilization adjustment factor based on the HCM is 0.952. However major lanes (NB &SB) Even though having more than one lane in a lane group, we can see a uniform traffic distribution along all lanes so lane utilization can be assumed as 1.

Volume and timing output table also includes information regarding bicycle and pedestrian volume. This volume has been assumed as the maximum value of pedestrian/bicycle volume for each side of the intersection in NB/SB or WB approaches. Based on this volume, the volume of the pedestrian/bicycle per cycle and then the minimum effective green for pedestrian can be computed using Exhibit 16-2 in Highway Capacity Manual. This data is shown in the last row of the input worksheet. This table also provides data regarding the parking and bus stopping within the 75 meters distance from the stop line. This data will be later applied for computing the adjustment factors. For SB/NB &WB approaches parking is not allowed.

The 8th intersection situated in a broad area with less parking maneuvers and comparatively less pedestrians so it cannot be considered as central business district (CBD) so factor for area type is one. All pedestrians and bicycle movements are protected with signal setting, hence factors for that may considered as 1.

When considering SB right turning, very less pedestrians & bicycles conflicting are observed so it can be considered as protected right turning. We fill find the proportion of right turning vehicles and compute the right turning adjustment factor and apply in SB saturation flow.

As like same in the WB direction there is one lane group and will find the proportion of left turning vehicles and left turn adjustment factors can be computed and applied to WB saturation flow.

Pedestrian’s & bicycles crossing in WB is completely protected.

VOLUME ADJUSTMENT AND SATURATION FLOW RATE WORKSHEET

General Information				
Project Description : Via Cristoforo Colombo - Via Accademia degli Agiat				
Volume Adjustment				
		WB	NB	SB
		TH+LT	TH	TH+RT
Volume, V (veh/h)		1075	3566	3875
Peak-hour factor, PHF		0.9	0.9	0.9
Adjusted flow rate, Vp = V/PHF (veh/h)		1195	3963	4306
Lane Group		1	1	1
Adjusted flow rate in lane group, v (veh/h)		1195	3963	4306
Proportion of LT or RT (P_LT or R_RT)		0.251046025	1	0
Saturation Flow Rate (see Exhibit 16-7 to determine adjustment factors)				
Base Saturation flow, Sp (pc/h/ln)		2100	2100	2100
Number of lanes, N		3	5	5
Lane width adjustment factor, fw		0.933	0.989	0.989
Heavy-vehicle adjustment factor, f_HV		1.000	0.980	0.971
Grade adjustment factor, fp		1.000	1.000	1.000
Parking adjustment factor, fp		1.000	1.000	1.000
Bus blockage adjustment factor, f_bb		1.000	0.990	0.987
Area type adjustment factor, f_a		1.000	1.000	1.000
Lane utilization adjustment factor, f_LU		0.950	1.000	1.000
Left-turn adjustment factor, f_LT		0.987	1.000	1.000
Right-turn adjustment factor, f_RT		1.000	1.000	0.985
Left-turn ped/bike adjustment factor, f_Lpb		1.000	1.000	1.000
Right-Turn ped/bike adjustment factor, f_Rpb		1.000	1.000	1.000
Adjusted saturation flow, s (veh/h) s=s_0 N f_w 〖f〗_HV 〖f〗_g 〖f〗_p 〖f〗_bb 〖f〗_(		5513	10082	9803
Notes				

Table 40: Volume Adjustment Worksheet of 8th Intersection.

CAPACITY AND LOS WORKSHEET

General Information												
Project Description : Via Cristoforo Colombo - Via Accademia degli Agiat												
Capacity Analysis												
Phase Number	1			1				2				
Phase Type	P			P				P				
Lane Group												
Adjusted flow rate, v (veh/h)	3963			4306				1195				
Saturation flow rate, s (veh/h)	10082			9803				5513				
Lost time, t_L = I1 + Y - e	5.5			5.5				5.5				
Effective green time, g (s), g = G + Y - t_L	76.5			76.5				58.5				
Green ratio, g/C	0.5			0.5				0.401				
Lane group capacity, c = s(g/C), (veh/h)	5282.7			5136				2209				
v/c ratio, v/s	0.75018			0.838				0.54				
Flow ratio, v/s	0.39308			0.439				0.22				
Critical lane group/phase (√)				√				√				
Sum of flow ratios for critical lane groups, Yc Yc = ∑ (critical lane groups, v/s)	0.656											
Total lost time per cycle, L (s)	11											
Critical flow rate to capacity ratio, Xc Xc = (Yc) (C)/(C - L)	0.709											

Lane Group Capacity, Control Delay, and LOS Determination				
	EB	WB	NB	SB
Lane group				
Adjusted flow rate, v (veh/h)		1195	3963	4306
Lane group capacity, c (veh/h)		2209	5283	5136
v/c ratio, X = v/c		0.54	0.8	0.84
Total green ratio, g/C		0.40	0.52	0.52
Uniform delay, $d\_1=(0.50\ C〖[1-(g/c)]〗$ (s/veh)		33	27	29
Incremental delay calibration, k		0.50	0.50	0.50
Incremental delay, d2 (s/veh) d_2=900T[(X-1)+√(〖(X−1)〗^2+8k		1	1	2
Initial queue delay, d3 (s/veh)		0.0	0.0	0.0
Progression adjustment factor, PF		1	0.58	0.58
Delay, d = d1(PF) + d2 + d3 (s/veh)		34	17	19
LOS by lane group		C	B	B
Delay by approach, $d\_A=(\sum(d)(v)$ (s/veh)		34	17	19
LOS by approach		C	B	B
Approach flow rate, V_A(veh/h)		1195	3963	4306
Intersection delay, $d\_I=(\sum(d\_A)(V\_$ (s/veh)	20	Intersection LOS		B
Notes				

Table 41: Capacity and LOS worksheet of 8th Intersection.

Optimization of LOS.

Optimization is finding an alternative with the most cost effective or highest achievable performance under the given constraints, by maximizing desired factors and minimizing undesired ones. In this case, after the computation through the HCM method of the delays for each intersection, our purpose is to minimize that delay achieving better performances, higher level of services (LOS).

There are three different kind of cycle times considered in this paper for comparison: Minimum cycle, Webster's optimum cycle and cycle obtained from Enumerative Approach.

Minimum cycle.

Minimum cycle is the smallest value of Cycle length that satisfies all the capacity constraints, it is computed once known the values of flow ratios and it's obtainable through the following equation:

$$C_{min} = \frac{\sum_i l_i}{1 - \sum_i y_i}$$

Where:

l_i = lost time for lane group ***i***

y_i = critical flow ratio for lane group ***i***

Once calculated the value of the Minimum Cycle is possible to compute the minimum effective green times, obtained multiplying the minimum cycle and the critical flow ratio:

$$g_i = C_{min}\, y_i$$

Optimum Cycle.

Optimum Cycle is obtained from Webster assumptions, reconducting the original problem to a one with a single variable, the cycle length, which is computed by assuming the delay model of stationary queue with casual arrivals that overlaps to uniform arrivals that is equal to the average value of flow, the optimum cycle can be obtained from the equation:

$$C_{opt} = \frac{\left(1.5 \sum_i \ l_i\right) + 5}{1 - \sum_i \ y_i}$$

Once computed the optimal cycle is possible to obtain the values for the minimum effective green times with the equation:

$$g_i = \frac{y_i}{\sum_i \ y_i} \left(C_{opt} - \sum_i l_i \right)$$

Enumerative method.

The enumerative approach is considered as most effective way to find optimum cycle length with minimum intersection's delay. It is applied by use of Python language through Jupyter Lab environment[5] and its integration with Excel Worksheets. Before diving into the code, it would be immensely helpful to explain general approach used in the enumerative search of the optimum point.

General idea behind this approach is based on the visiting every meaningful cycle length and green ratio's values for the minimum delay search. Well, the word 'meaningful' here is used because that would be incorrect to start the search with cycle time less that minimum cycle time, or with such green ratio, where the effective green for most critical phase is given very less compared to other. Therefore, we must define the meaningful range of Cycle times, and once we visit some cycle time – meaningful range of green's ratios. Honestly, sometimes for better representation of the 3D Figure (x = cycle length, y = green's ratios, z = intersection delay) we were adjusting the cycle times or green's ratio ranges to show on the plot clearly the point of optimum. Although this method is a bit longer in terms of computation, it is much more precise, and we exactly reach the minimum point.

The general representation of the Optimization Code is shown in the figure below. In the cells with three dots appropriate codes are hidden. This kind of view is for making our code more user friendly and avoid some changes the cells.

[5] JupyterLab is a web-based interactive development environment for Jupyter notebooks, code, and data.

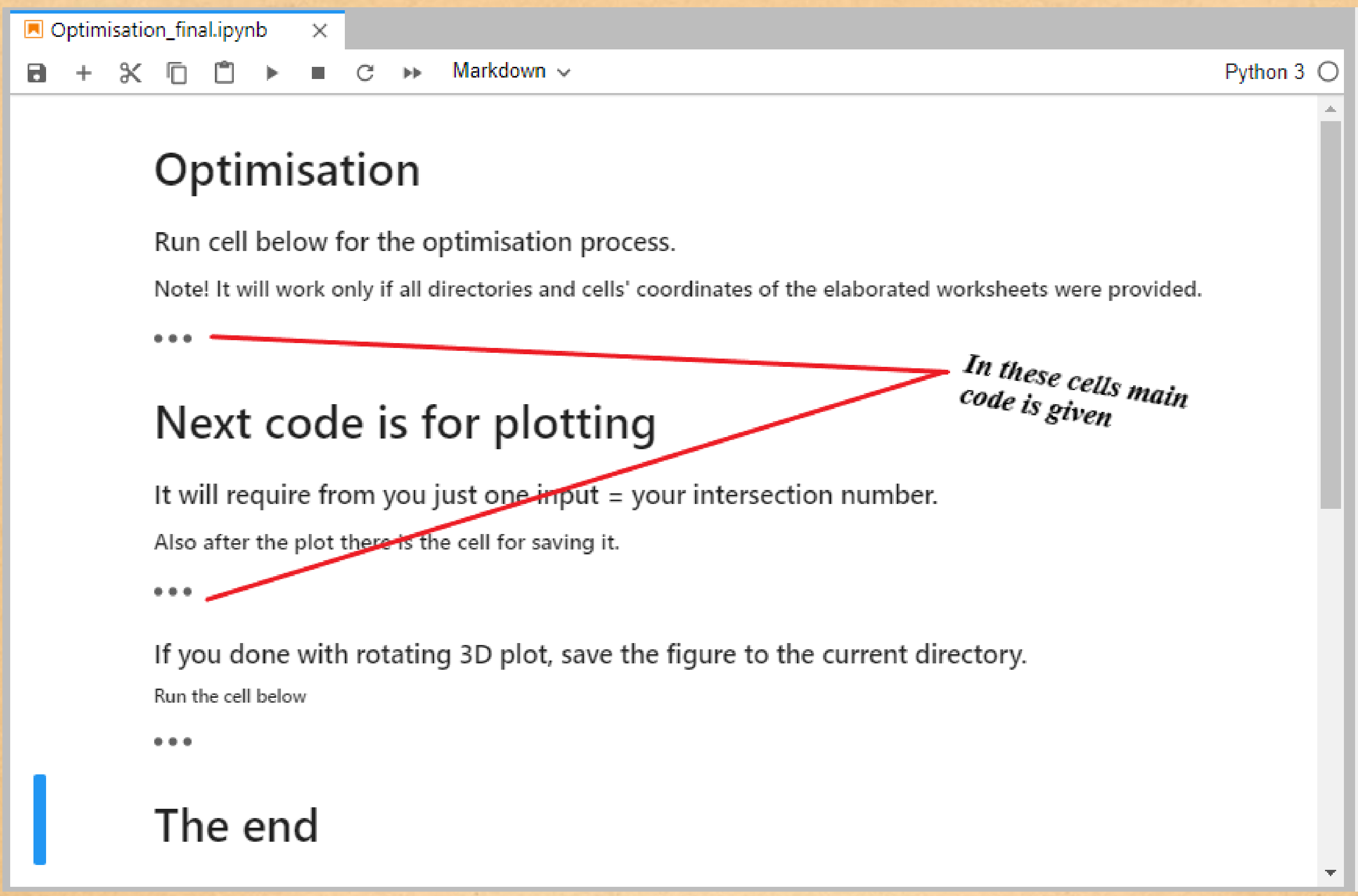


Figure 21: General view of the Optimization Code.

The ***xlwings*** library helped us to integrate optimization with excel. The first cell contains following main code represented in the figure below. First, we define coordinates of the cell, that contains inputs for the algorithm. Then we are creating the range with different cycle times, which starts from minimum cycle time and ends with Cmin *4 (or less, depends on the representation in 3D plot). The we need to define minimum and maximum values for green's ratios, and to do this we can apply the same capacity constraints based on critical flow ratio of every approach of the current intersection. Thus, we will obtain following formulas for extremum ratios for 2 Phase Intersection:

$$u_{min} = \frac{y_1}{1 - y_1 - \frac{t_l}{C}}$$

$$u_{max} = \frac{1 - y_2 - \frac{t_l}{C}}{y_2}$$

And for 3-Phase Intersection:

$$u_{min} = \frac{2y_2}{1 - 2y_2 - \frac{t_l}{C}}$$

$$u_{max} = \frac{1 - 2y_2 - \frac{t_l}{C}}{2y_2}$$

As we can see in the case of 3-Phase Intersection the formulas for $\boldsymbol{u_{min}}$ is a bit unexpected, since we are using y_2 instead of y_1, but the range between those extremum points only gave us appropriate right optimum as we will see later in 3D plots.

The algorithms start with visiting one by one every given value for a cycle. In every such visit it is creating a new range of green's ratios and within this range at each iteration applying current green values for the appropriate cells in excel worksheet, taking the value of the resulting intersection delay and storing it. Thus, we will have a matrix of delays for every cycle time and different green's ratios. Also, we will have the matrix in the same size for green times. In the end our algorithm will compare all results and will choose best green pairs with related global minimum delay of the current intersection.

One important notice – instead of using effective green times we made direct transformations on capital green time. Thus, we are directly getting all new properties for signal timing of the current intersection.

```python
import matplotlib.pyplot as plt
import numpy as np
import pandas as pd

import xlwings as xw


filename = 'Optimisation_int_4.xlsx'             #    change all filenames to your

wb = xw.Book(filename)
optimisation = wb.sheets['Green_times']     # change the sheet name to your own, it
                                            # giving different values of green for c

cell_green_1 = 'A2'
cell_green_2 = 'B2'          #  these are cell coordinates for corresponding values
delay_value = 'B5'           # in my optimisation sheet, called 'Green_times'
minumum_cycle_value = 'B13'

minimum_cycle = int(optimisation.range('B13').value)   #give your own value of minim


cycles_list = np.linspace(minimum_cycle*1.2, minimum_cycle*1.8, 100)

sat_degree_1 = optimisation.range('B10').value
sat_degree_2 = optimisation.range('B11').value
total_lost_time = optimisation.range('B12').value


cycles_delay=[]
greens_matrix = []
for C in cycles_list:
    min_coef = sat_degree_1/(1-sat_degree_1-total_lost_time/C)
    max_coef = (1-sat_degree_2-(total_lost_time/C))/sat_degree_2
    u = np.linspace(1.2*min_coef, 1.1*max_coef, 50)
    delays_list = []
    greens_list = []
    for i in u:
        Green_2=(C-8)/(1+i)
        Green_1= C - 8 - Green_2
        greens_list.append([Green_1, Green_2])
        optimisation.range(cell_green_1).value = Green_1
        optimisation.range(cell_green_2).value = Green_2
        delays_list.append(optimisation.range(delay_value).value)
    cycles_delay.append(delays_list)
    greens_matrix.append(greens_list)


minimums = []
indexes = []
for i in range(len(cycles_delay)):
    index = cycles_delay[i].index(min(cycles_delay[i]))
    minimums.append(min(cycles_delay[i]))
    indexes.append(index)
best_delay = min(minimums)

index_1 = minimums.index(min(minimums))
index_2 = indexes[index_1]

best_greens = greens_matrix[index_1][index_2]

print('Best Green Values are:')
print(f'Phase 1: {best_greens[0]}')
print(f'Phase 2: {best_greens[1]}')
print(f'Best delay is {best_delay}')

optimisation.range(cell_green_1).value = best_greens[0]
optimisation.range(cell_green_2).value = best_greens[1]
```

Figure 22: Main code contains the ‘engine’ of the enumerative optimization.

Finally, thanks for already created matrixes, we can make some transformations and plot different graphs to see whether we really reached the minimum, and if our algorithm working properly or not. This is done by following piece of code:

Figure 23 ***(given below):***

The code for plotting 3 kind of plots.

```
%matplotlib widget
import os
from matplotlib import gridspec

current_intersection =input('Please type the number of intersection: ')

fig = plt.figure(figsize=(7, 13))
fig.suptitle(f'Optimisation process from different perspectives \n for the Intersent
gs = gridspec.GridSpec(2, 6, height_ratios=[1, 3])

ax1 = fig.add_subplot(gs[0:3])
ax2 = fig.add_subplot(gs[3:6])
ax3 = fig.add_subplot(gs[6:12], projection = '3d')



##################################################################################


cycles_greens_ratio = pd.DataFrame(greens_matrix, index = cycles_list)
cycles_greens_ratio = cycles_greens_ratio.transpose()

cycles_delay_df = pd.DataFrame(cycles_delay, index = cycles_list)
cycles_delay_df = cycles_delay_df.transpose()


for i in cycles_greens_ratio.columns:
    for y in range(len(cycles_greens_ratio[cycles_greens_ratio.columns[0]])):
        cycles_greens_ratio[i][y]=cycles_greens_ratio[i][y][0]/cycles_greens_ratio[i

i = 7
list_for_legend = []
while i<31:
    ax1.plot(cycles_greens_ratio.iloc[:, i], cycles_delay[i], label = f'Cycle = {rou
    i = i + 10


ax1.set_title('\n \n \n Changes in the intersection delay with respect to \n green r
ax1.set_xlabel('Green ratio', fontsize = 9, family = 'cursive', fontname = 'Arial')
ax1.set_ylabel('Delay', fontsize = 9, family = 'cursive', fontname = 'Arial')
ax1.tick_params('both', labelsize = 8)
ax1.locator_params('x', nbins = 8)
ax1.legend(loc='upper right', shadow=True,  prop={'size': 6})
```

```
ax1.grid(True)
##########################################################################################



i = 5
while i<=30:
    ax2.plot(cycles_list, cycles_delay_df.iloc[i, :], label = f'Coeff. # {i}')
    i = i + 10



ax2.set_title('\n \n \n Changes in the intersection delay with respect to \n cycle l
ax2.set_xlabel('Cycle Length', fontsize = 9, family = 'cursive', fontname = 'Arial')
ax2.set_ylabel('Delay', fontsize = 9, family = 'cursive', fontname = 'Arial')
ax2.tick_params('both', labelsize = 8)
ax2.locator_params('x', nbins = 10)
ax2.legend(loc='upper center', shadow=True, prop={'size': 6})
ax2.grid(True)

##########################################################################################

X = cycles_greens_ratio
Y = cycles_list
ylen = len(Y)
x = cycles_greens_ratio.iloc[:, 0]
Y, x = np.meshgrid(Y, x)
Z = cycles_delay_df

# Plot the surface.
xlen = len(cycles_greens_ratio.iloc[:, 0])
colortuple = ('y', 'm')
colors = np.empty(X.shape, dtype=str)
for y in range(ylen):
    for x in range(xlen):
        colors[x, y] = colortuple[(x + y) % len(colortuple)]

ax3.plot_surface(X, Y, Z, facecolors=colors, linewidth=0, antialiased=False)

ax3.set_title("\n Representation of the convex optimisation through \n 3-dimensional
ax3.set_xlabel('Green ratios', fontsize = 9, family = 'cursive', fontname = 'Arial')
ax3.set_ylabel('Cycle length', fontsize = 9, family = 'cursive', fontname = 'Arial')
ax3.set_zlabel('Delay', fontsize = 9, family = 'cursive', fontname = 'Arial')
ax3.tick_params(axis = 'both', labelsize = 8)

fig.subplots_adjust(left  = 0.08, right = 0.92,  wspace = 2)
#fig.tight_layout(pad=0.5, w_pad=0.5, h_pad=1.0)
```

Results of optimization.

The tables below are representing different delay values obtained from Minimum Cycle, Webster Optimum Cycle and Optimum Cycle of Enumerative Approach for each Intersection. After every table three kinds of plot are given: delay as the function of cycle length with constant ratio, delay as the function of green's ratio with constant cycle length, 3-dimensional plot with x = cycle length, y = green's ratio, z = intersection delay.

Table 42: Results of optimization process for different intersections.

Junction 1					
	Cycle Length	**Green 1**	**Green 2**	**Intersection Delay**	**LOS**
Current Situation	139	74	57	26	C
Minimum Cycle	35	18,5	8,5	21,34	C
Webster Optimum Cycle	69	41,7	19,3	14,55	B
Optimum Cycle of EA	57,16	34,23	14,93	13,92	B

Junction 2					
	Cycle Length	**Green 1**	**Green 2**	**Intersection Delay**	**LOS**
Current Situation	147	84	55	20	C
Minimum Cycle	24	9,5	6,5	30,16	C
Webster Optimum Cycle	47,2	22,7	16,5	13,2	B
Optimum Cycle of EA	35,2	15,47	11,73	12,82	B

Junction 3					
	Cycle Length	**Green 1**	**Green 2**	**Intersection Delay**	**LOS**
Current Situation	144	78	58	28	C
Minimum Cycle	42	22,5	11,5	21,65	C
Webster Optimum Cycle	81,39	48,58	24,81	15,72	B
Optimum Cycle of EA	67,58	39,57	20,01	15,3	B

Junction 4					
	Cycle Length	**Green 1**	**Green 2**	**Intersection Delay**	**LOS**
Current Situation	144	80	56	24,5	C
Minimum Cycle	41,01	21,52	11,49	25,83	C
Webster Optimum Cycle	80,27	47,7	24,57	14,3	B
Optimum Cycle of EA	81,54	50,68	22,86	13,91	B

Junction 5					
	Cycle Length	Green 1	Green 2	Intersection Delay	LOS
Current Situation	140	82	50	19,1	B
Minimum Cycle	37	20	9	18,03	B
Webster Optimum Cycle	73	45	20	10,8	B
Optimum Cycle of EA	75,61	48,49	19,12	10,43	B

Junction 6					
	Cycle Length	Green 1	Green 2/ Green 3	Intersection Delay	LOS
Current Situation	144	72	30	33,76	C
Minimum Cycle	74	34	14	30,36	C
Webster Optimum Cycle	134	68	27	31,45	C
Optimum Cycle of EA	92	46	17	27,6	C

Junction 7					
	Cycle Length	Green 1	Green 2	Intersection Delay	LOS
Current Situation	144	84	52	20,22	C
Minimum Cycle	33	19	6	16,36	B
Webster Optimum Cycle	64	43	13	10,55	B
Optimum Cycle of EA	62,86	43,21	11,65	10,22	B

Junction 8					
	Cycle Length	Green 1	Green 2	Intersection Delay	LOS
Current Situation	146	78	60	21	C
Minimum Cycle	45	21,5	15,5	17,48	B
Webster Optimum Cycle	87	45,5	35,5	14,8	B
Optimum Cycle of EA	64,55	33,1	23,45	13,56	B

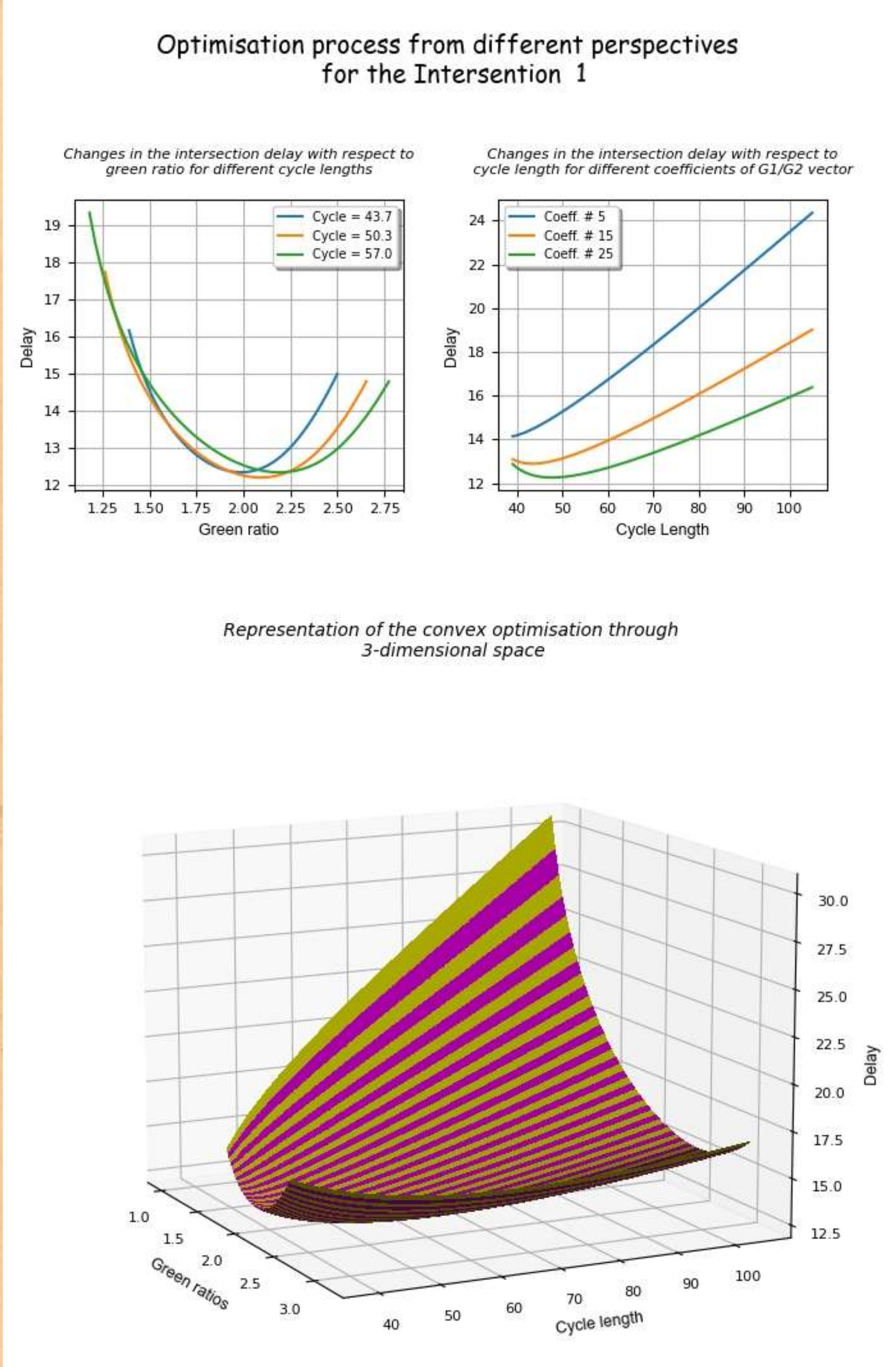


Figure 24: 1st Intersection's Optimization process.

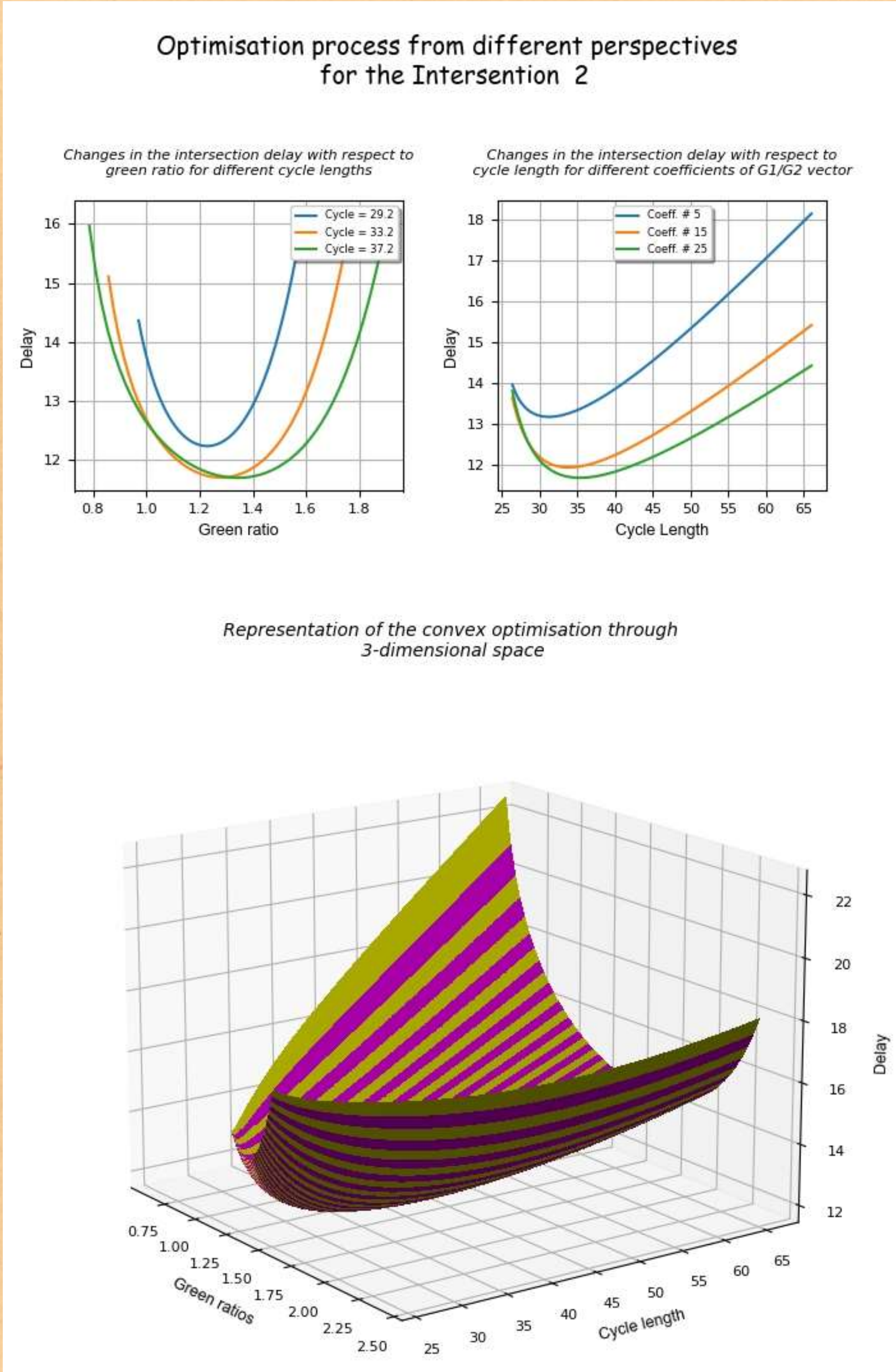


Figure 25: 2nd Intersection's Optimization process.

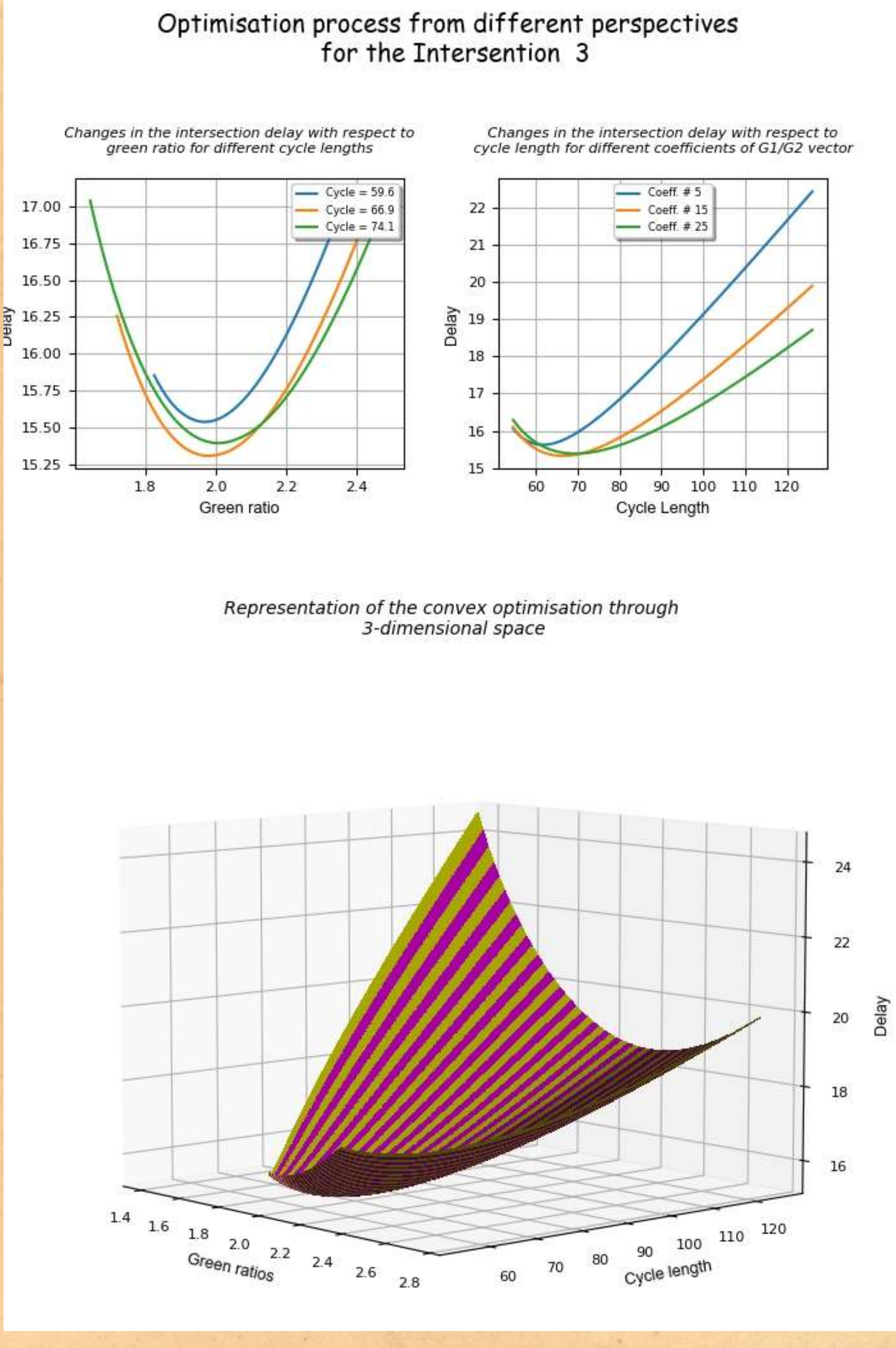


Figure 26: 3rd Intersection's Optimization process.

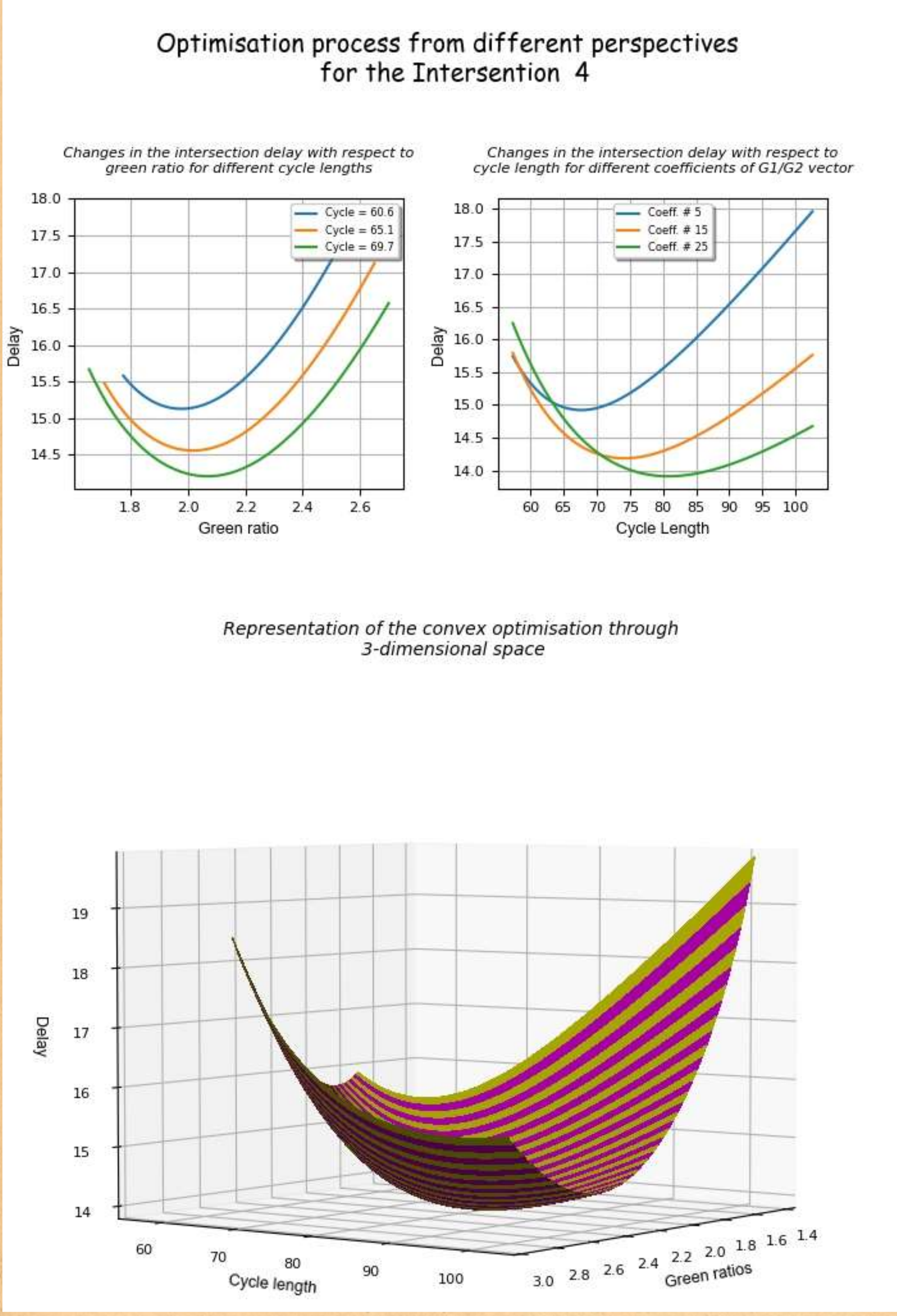


Figure 27: 4th Intersection's Optimization process.

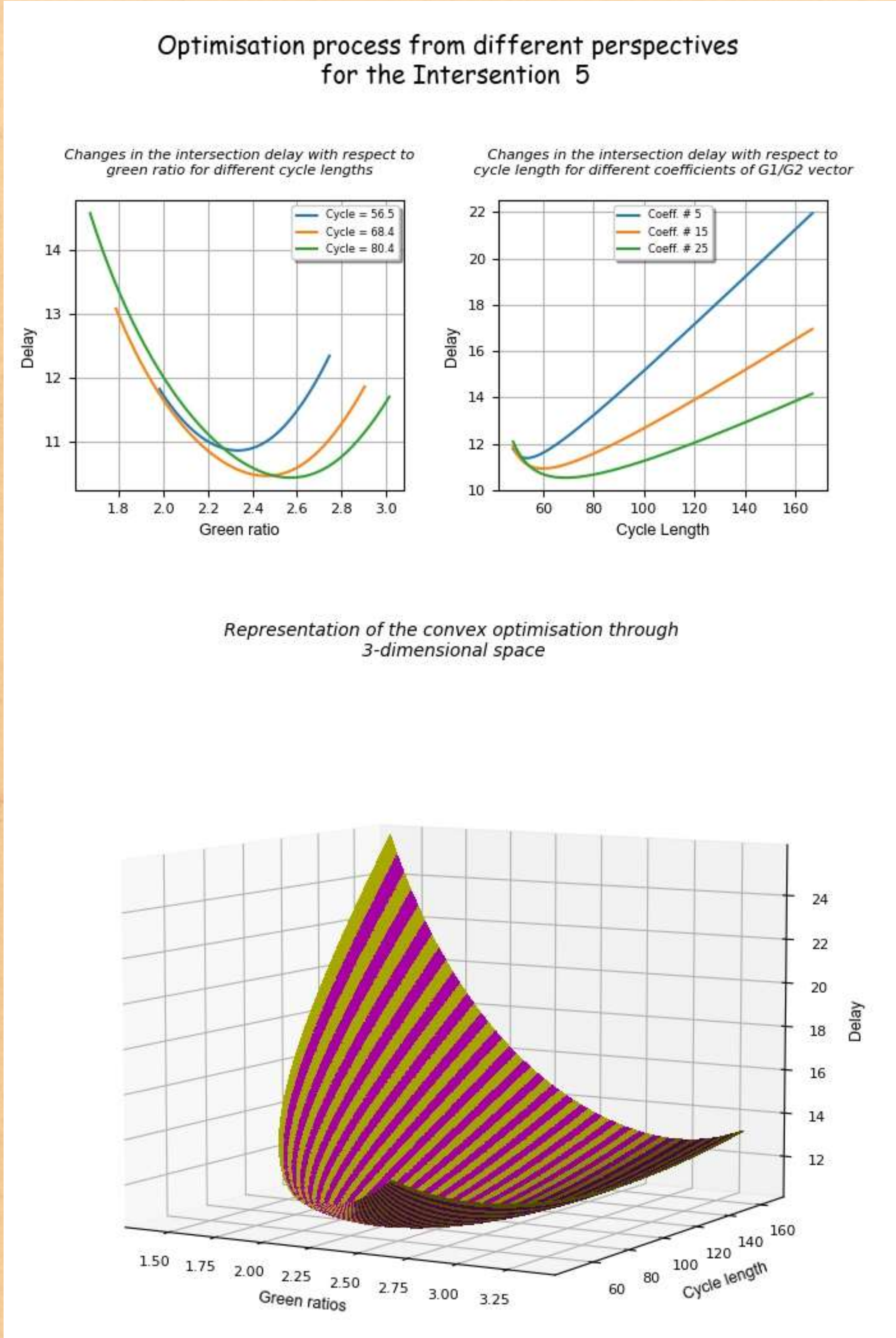


Figure 28: 5th Intersection's Optimization process.

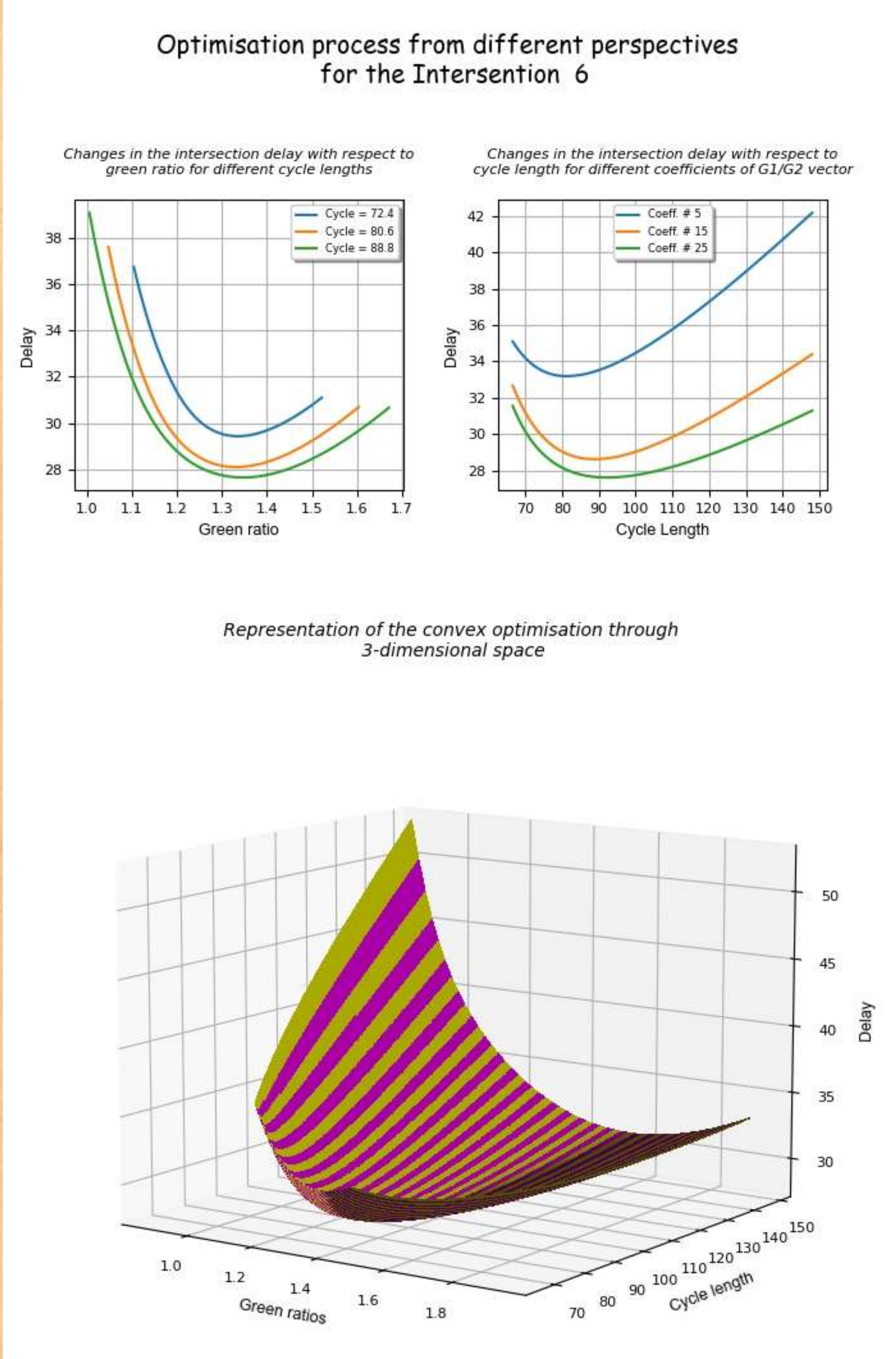


Figure 29: 6th Intersection's Optimization process.

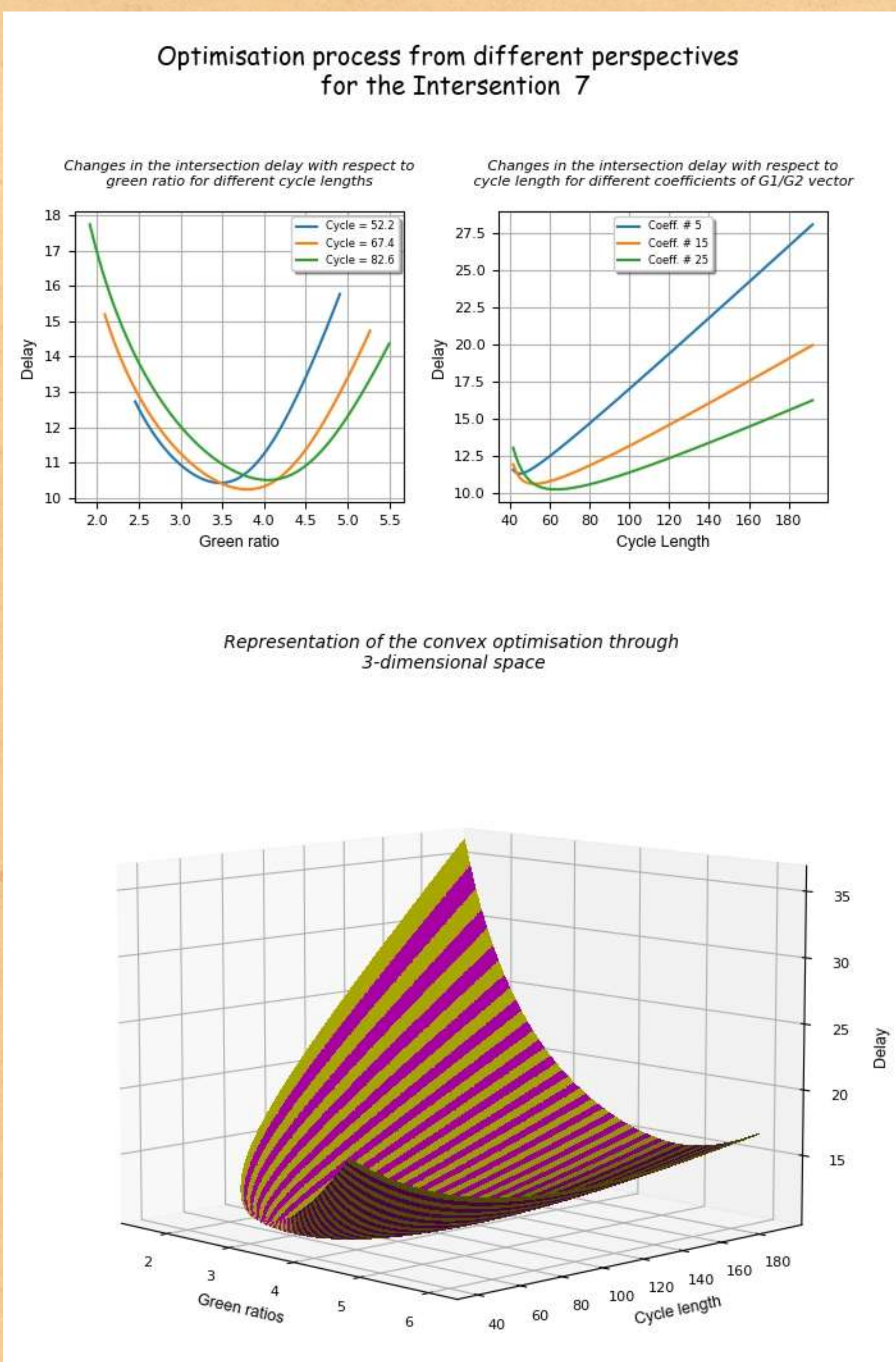


Figure 30: 7th Intersection's Optimization process.

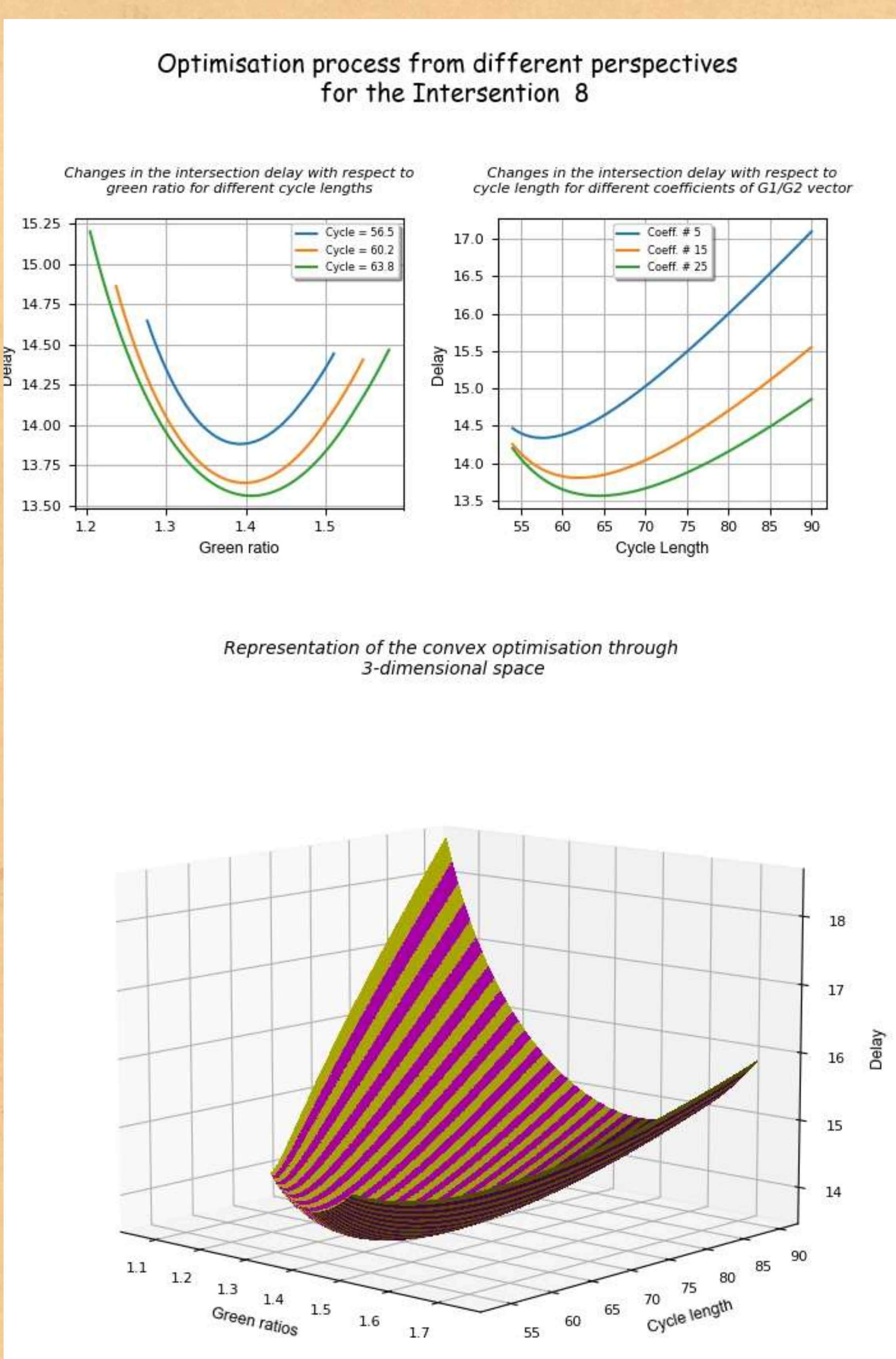


Figure 31: 8th Intersection's Optimization process.

Synchronization.

In the previous part, optimization is done based on the assumption that intersections are isolated which means that there is no interaction among junctions. However, synchronization is done by considering interaction among all the intersection. Therefore, the objective of this part is to compute an appropriate offset between the junctions so that delay of all intersections is minimized. This minimization problem is not convex so for solving this problem, another optimization method can be which is maximum bandwidth problem.

The inputs of this method are as followings:

- An identical cycle length for all the junctions
- Green share of each junction along Via Cristoforo Colombo
- Synchronization speed
- The distances between the intersections

An identical cycle length for all the junction is taken as the maximum cycle length among all intersections after optimization because it can be seen in almost all the optimization graphs, the slope of the function on the right side of the minimum is much lower than the slope of the function in the right side. It means that even if a cycle length for a generic junction is increased with respect to its optimal cycle length, the delay will not increase dramatically. However, if the chosen cycle length is lower than the optimal one, the delay will increase more dramatically.

After choosing the cycle length, the enumerative method is used to find the green times of each intersection by keeping this cycle length as fixed and changing the green ratios and the one with the minimum delay is chosen. Results of this procedure are shown in the Table below:

Synchronization					
ntersectio	Cycle [sec]	g1 [sec]	g2 [sec]	Delay [sec/veh]	LOS
1	92	61	23	15,5	B
2	92	56	28	18	B
3	92	57	27	16,1	B
4	92	59	25	14,08	B
5	92	61	23	10,78	B
6	92	46	17	28,76	C
7	92	67	17	11,16	B
8	92	51	33	15	B

Table 43: Results of optimization with constant cycle length = 92 sec.

A value between the minimum and maximum speed is chosen as the synchronization speed for via Cristoforo Colombo. Since the maximum speed of the road is 50 km/h, a synchronization speed of 12 m/s is taken which is equal to 43.2 km/h.

All the input data for the synchronization problem have been summarized in Table 44.

	INPUTS		
C [s]	92		
v [m/s]	12		
Intersection	**Abscissa (m)**	**Green (s)**	**g/C**
1	0	61	0.66
2	190	56	0.61
3	641	57	0.62
4	1055	59	0.64
5	1430	61	0.66
6	1687	46	0.50
7	2339	67	0.73
8	2616	51	0.55

Table 44: Input data for the synchronization.

Using these input data, the parameter A can be computed which is the distance between two ideal nodes:

$$A = \frac{Cv}{2} = \frac{92 * 12}{2} = 552\, m$$

Firstly, the 1st and 2nd intersections are taken and the value of maximum bandwidth with respect to the two intersections are computed and the location of the ideal node based on this intersection is computed. For the calculating the bandwidth, there are two cases depending on the distance between the intersections and A:

Case 1:

$$if\ \ l_{ij} < \frac{A}{2} \quad or \quad l_{ij} > \frac{3A}{2} \quad then$$

$$\theta_{ij} = 0$$

$$b_{ij} = \frac{1}{2}\left(g_i + g_j - \frac{l_{ij}}{A}\right)$$

$$x_0 = x_j + A\left(b_{ij} - g_j\right)$$

Case 2:

$$if\ \ \frac{A}{2} < l_{ij} < \frac{3A}{2} \quad then$$

$$\theta_{ij} = 0.5$$

$$b_{ij} = \frac{1}{2}\left(g_i + g_j - 1 + \frac{l_{ij}}{A}\right)$$

$$x_0 = x_j - A\left(b_{ij} - g_j + 1\right)$$

Using the formulas above, the location of the first ideal node which is representative of the first two junctions is found. Then the 3rd junction can be synchronized with respect to the ideal node of the first 2 junctions and the new green bandwidth and the new position of ideal nodes are computed, and this procedure is going on until the last junction. In synchronization of each new junction with the ideal node of the previous junctions, based on the distance between two junctions (which is the difference between the position of the new intersection form abscissa 0 and the position of the previous ideal node from abscissa 0) there are 2 cases:

Case 1:

$$if\ 0 \leq mantissa\left(\frac{x_r - x_0(i,j)}{A}\right) < 0.5 \quad then$$

$$\theta_{ij} = 0$$

$$b_{ij} = \frac{1}{2}\left(g_r + b_{ij} - mantissa\left[\frac{x_r - x_0(i,j)}{A}\right]\right)$$

$$x_0 = x_j + A\left(b_{ij} - g_j\right)$$

Case 2:

$$if\ 0.5 \leq mantissa\left(\frac{x_r - x_0(i,j)}{A}\right) < 0.1 \quad then$$

$$\theta_{ij} = 0.5$$

$$b_{ij} = \frac{1}{2}\left(g_r + b_{ij} - 1 + mantissa\left[\frac{x_r - x_0(i,j)}{A}\right]\right)$$

$$x_0 = x_j - A\left(b_{ij} - g_j + 1\right)$$

In the synchronization procedure, when a new junction is added to previously synchronized junctions, if the computed bandwidth is greater than the previously computed bandwidths, the bandwidth and the locations of ideals nodes should not be updated. However, if the new bandwidth is smaller than the previous bandwidths, both the bandwidth and the locations of the ideal nodes must be updated. Using the formulas above and starting from the first junction and continuing till the last junction, the following results are obtained which are shown in Table 45.

1st and 2nd Junctions	Node		Distance [m]	b_{ij}	Updated Abscissa [m]
	1	2	190	0.464	110
Remaining 6 Junctions	**Node**		$Man\left[\frac{(X_j - X_0)}{A}\right]$	**b_{ij}**	**Updated Abscissa of ideal node [m]**
	i	j			
	1,2	3	0.962	0.464	-
	1,2,3	4	0.712	0.409	632
	1,2,3,4	5	0.447	0.313	1237
	1,2,3,4,5	6	0.816	0.313	-
	1,2,3,4,5,6	7	0.997	0.313	-
	1,2,3,4,5,6,7	8	0.499	0.184	2412

Table 45: Synchronization Procedure

The final output of the optimization procedure which are the offsets between intersections and the maximum bandwidth is summarized in Table 89. The graphical representation of the result including the maximum bandwidth, locations of ideal nodes and real intersection locations are shown in Figure 32.

Final Outputs of Synchronizations							
Intersections	1 & 2	2 & 3	3 & 4	4 & 5	5 & 6	6 & 7	7 & 8
Offsets	0	0.5	0.5	0	0.5	0.5	0
Maximum Bandwidth	**16.92 s**						

Table 46: Results of synchronization.

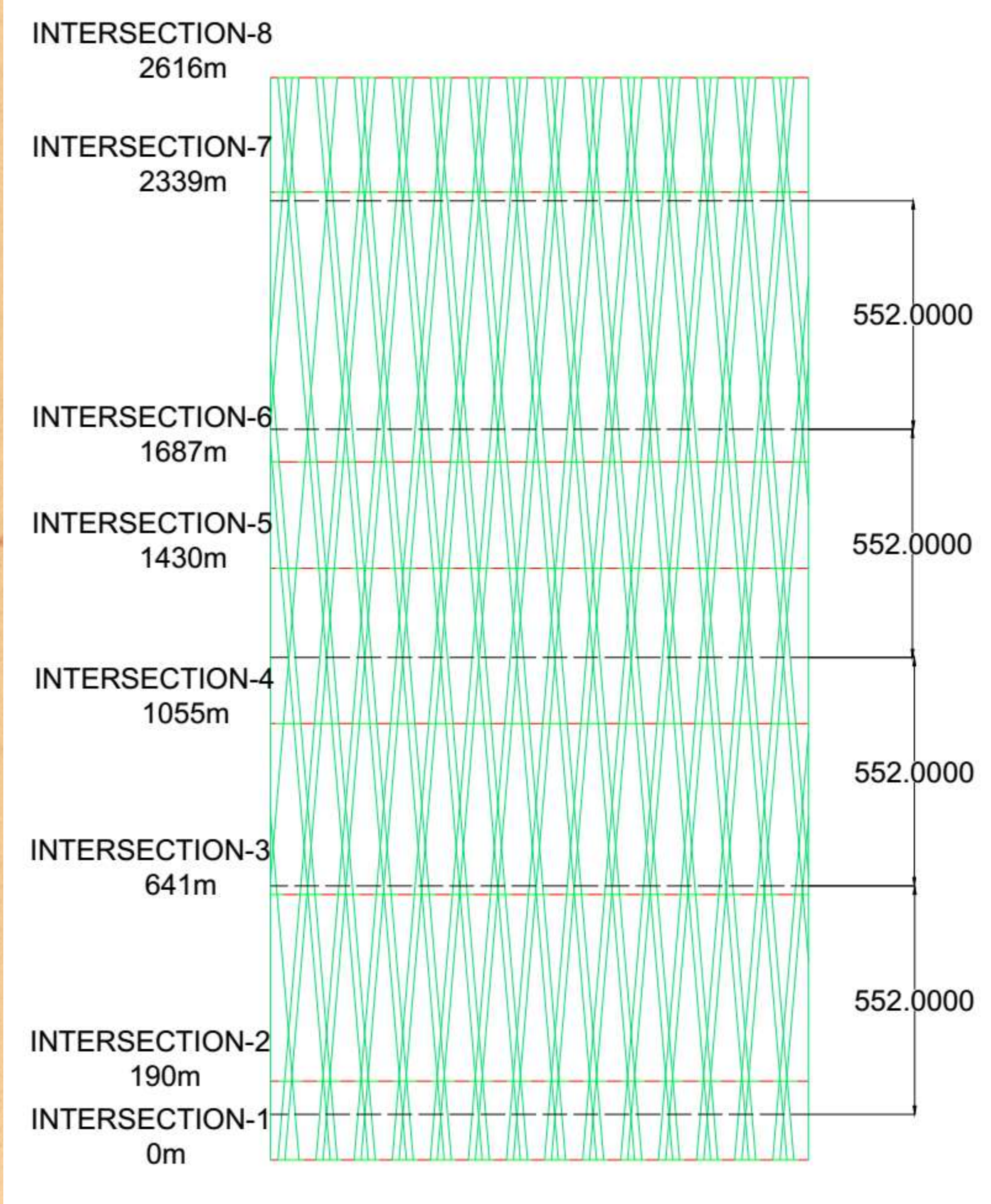


Figure 32: Results of synchronization.

Conclusion.

To conclude, the main goal of this project was to reduce the delay of all intersections and improve the level of service of each and these improvements can happen by fine-tuning the signal setting.

The following chart indicates the comparison between delay in the current situation and then the delay in the optimum situation and finally in the synchronized situation, for all 8 intersections. It is obvious that after redesigning the intersections, the delay of all intersections reduces and gets better value. However, after synchronization since all the intersection from an isolated assumption changed to joined junction assumption, the delay increases a little bit.

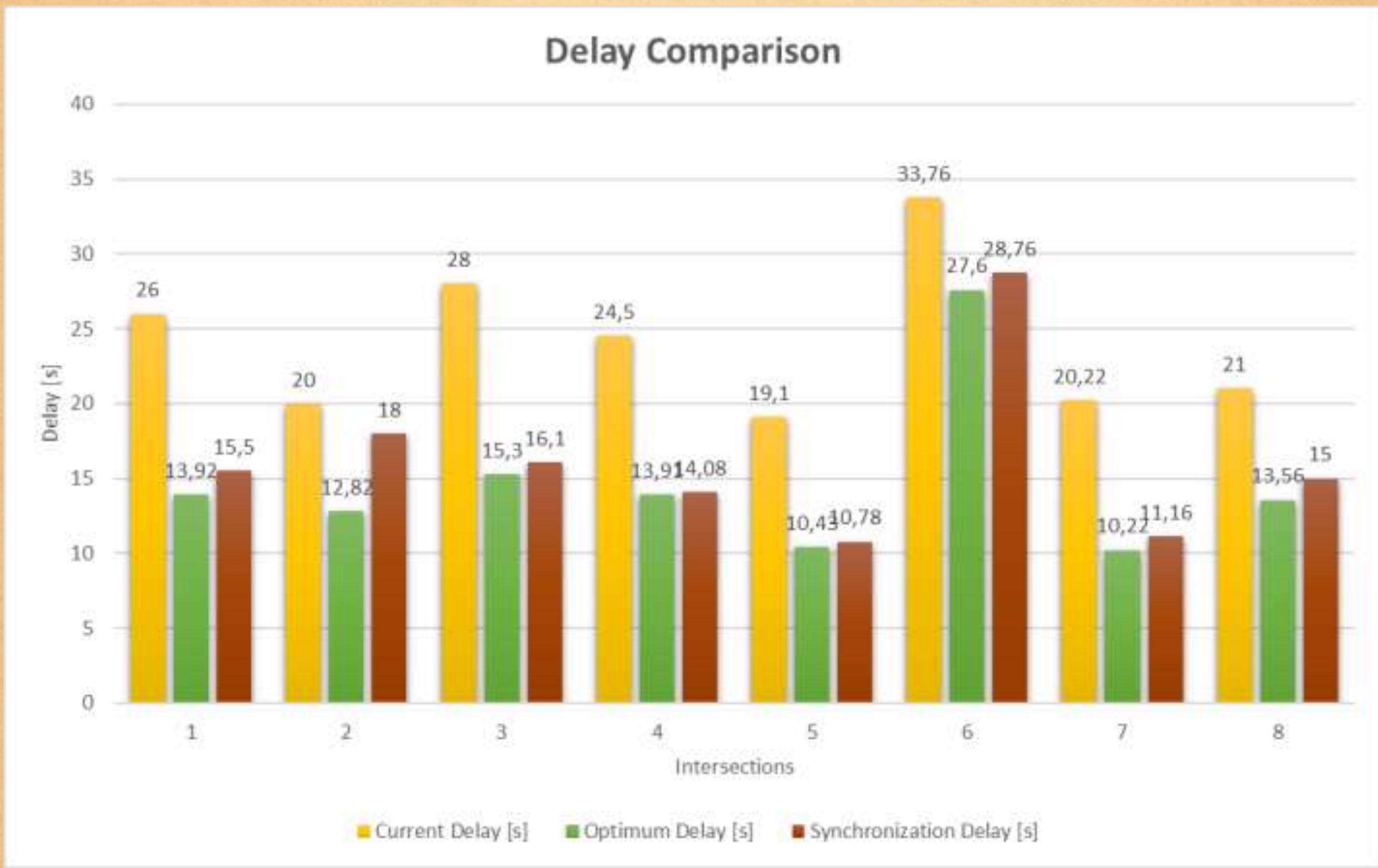


Figure 33: Delay comparison of all the 8 intersections.