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RESEARCH PAPER

Coordination of Traffic Signals on Arterial Streets in Duhok City

Dilshad Ali Mohammed 1, Aso Faiz Saeed Talabany*,2
[1] Department of Civil Engineering, College of Engineering, Duhok University, Kurdistan Region, Iraq
[2] Department of Civil Engineering, College of Engineering, Salahaddin University-Erbil, Kurdistan Region, Iraq

A B S T R A C T:
Duhok City lies in the north of Iraq and it has mountainous terrain. The poor road infrastructure of the city and also the daily increasing number of vehicles had left no choice other than applying traffic control systems to solve congestion problems in the city streets. Traffic control signal coordination which is one of efficient method of traffic control system that can improve the traffic operation and safety for series of signalized intersections along the arterials in the city. In this study the benefit of actuating traffic signal coordination was evaluated, and comparison in control delay against the same signalized intersection in case of being isolated was made. To achieve this four successive signalized intersections on Barzani street and three successive signalized intersections on Zakho street which are two major arterials in Duhok City were chosen. Traffic data (traffic volumes, vehicle link and approach speeds, and passenger car equivalent) during peak hours were collected. Also, geometric data and signalization data were collected using different methods, such as video recording technique, moving vehicle method and manual methods. To check the coordination attainability, the coupling index and key intersection was determined, then time-space diagrams were constructed representing one-way coordination for the intersections on Barzani and Zakho Streets, and others represented two-way coordination for the intersections on Zakho Street with acceptable progression bandwidth efficiency. The results of this study showed that a progression bandwidth of 54 seconds for east direction coordination and 17 seconds for west direction coordination on Barzani Street under suggested controlled speed of 60 kph pleasant with the present data. For Zakho Street, the progression bandwidth is 19 seconds for east direction coordination and 18 seconds for west direction coordination under suggested controlled speed of 40 kph. The results show that traffic signal coordination had led to high reduction in intersection control delays. On Barzani arterial street the reduction was between 16.2% and 51.8%, while for Zakho arterial street the reduction ranges between 16.93% and 26.11%.

KEY WORDS: Traffic Signal; Signal Coordination; Arterial Coordination
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1.INTRODUCTION :

The increased usage of vehicles has led to congestion, not only in urban metropolitan areas, but also in rural small and mid-size cities. In most areas, the networks operate at capacity or near capacity, during the morning and evening peak hours (Zaher Khatib, et al, 2001).

When traffic signals are located in close proximity, the presence of the upstream traffic signals alters the arrival pattern of traffic at the downstream traffic signals from random arrivals to arrivals in platoons.

This means that improved traffic flow can be achieved if the green signal at the downstream traffic signal is arranged to coincide with the arrival of the platoon. To achieve this, traffic signals are coordinated, sometimes called “linked”. This improves the level of service on a road network where the spacing of traffic signals is such that isolated operation causes excessive delays (Luk, J.Y.K. and Sims, A.G., 1982).

Traffic signal coordination can be applied when two or more traffic signals are working together so that cars moving through a group of traffic signals will make the least number of stops possible. In order to perform such process, each traffic signal in the group of signals must allow

*** Corresponding Author:**
Aso Faiz Saeed Talabany
e-mail: aso.talabany@su.edu.krd
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for a green light for desired directions of travel during the correct fixed time period. However, traffic signal coordination does not mean that drivers will never have to stop for red light because of some reasons which affect the amount of time available for green light in that direction. Those reasons are pedestrian crossings, cross traffic, left turn signals, two-way traffic flow and off-peak traffic periods (City of Kent Development assistance brochure, 2001).

Advantages of signal coordination include the following (Martin Rogers, 2003):

1- Reduced energy and fuel consumption
2- Reduced vehicle emissions
3- Bolstered local economies
4- Eliminated or delayed street widening needs
5- Improved emergency response
6- Reduced motorist frustration and road rage
7- Increased control of travel speeds
8- Reduced diversionary flows in neighbourhoods
9- Real-time traffic monitoring
10 Advanced equipment monitoring

The main disadvantage of signal coordination is that side street traffic typically experiences a longer wait time.

The objective of this research is to apply coordination of traffic signals for sets of successive isolated intersections on two arterial streets in Duhok City in order to get best progress and greatest number of vehicles through a corridor with the fewest stops in the safest and most efficient manner; hence, reducing delay and optimizing the capacity of these intersections in the direction of progression.

William A. Stimpson and Gerald M. Takasaki (1982) developed a study (Coordinating vehicle-actuated traffic signals to reduce vehicular fuel consumption) in Britain. They stated that: Test car fuel consumption was reduced through signal retiming and co-ordination by greater percentage than was travel time; indeed, over the full 29-link route, reductions in morning fuel use were accompanied by increases in travel time. This phenomenon resulted from reductions in stop frequency coupled with increases in stopping time. It appears that changes in signal timing are not related simply to corresponding changes in travel time.

Masaki Koshi (1989) showed fundamental relationships between the cycle time and delay as well as number of stops of a signalized corridor based on some assumptions with the field experiment results. The study showed that cycle time can be optimized through on-line feedback techniques and demonstration of results of experiments made by the author.

Chang, E C and Koothrappally, J (1994) studied the effect of actuated traffic signals used on isolated intersections in Kingsville, Texas. The purpose of the study was to develop an analytical methodology for improving the overall design and operation of actuated controllers, determining the best way to use the added flexibility of actuated control in a coordinated system, and generate feasible coordination parameters for arterial progression. The field examination of the coordinated, actuated operations of a real arterial traffic signal system in Kingsville, Texas, is described. The validity of the simulation study was proven. Signal system improvements of semi-actuated coordinated timing was compared with that of either fully actuated or pretimed coordinated timing plan was used.

Wei Li and Andrew P. Tarko (2007) used Synchro and SimTraffic software package to optimize signal coordination. The research outcome is expected to help traffic systems engineers reach reasonable signal settings in a shorter time. The final part of the research was the investigation of the robustness of the arterial signal coordination procedure. In current practice, signals are optimized to traffic volumes that represent a single time interval. In spite of the randomness of traffic, these plans are executed for a long period of time until obvious insufficiencies of the signal timings are noticed and re-timing is necessary.

Hirsh Muhammad Majid and Aso Faiz Talabany (2007) studied number of adjacent intersections in Sulaimani City-Kurdistan-Iraq. The attainability of coordinating these intersections by calculating the coupling index as a treatment of some traffic problems which exist in these intersections, like congestion, delay and traffic jam due to heavy traffic volume, and poor timing of traffic signals. The coordination between mamostayan and yakgirten intersections (Mamostayan2) and between palace, aqare and engineering intersections (Salm1 and Salm2 respectively) is studied. For each intersection in this study data were collected by various methods such as video camera, manual method or by moving vehicle method for finding the elements which are necessary to obtain the coordination goal. The elements are peak hour volume, passenger car equivalent, saturation flow, link speed, spot speed approach and intersection stopped and approach delays and intersection control delay before coordination and after coordination. In addition, the authors checked the two-way coordination availability for application by calculating the attainability factor and finding its efficiency. It was found by the researchers that the coordination between these intersections give good results, moreover, the coordination between Palace and Aqare intersection (Salm1), in one-way or two-way progression, gives the best results.

2. METHODOLOGY

The methodology to achieve the of this research, includes the main methods and equations which was used to obtain the necessary elements for the data collection and data analysis.

2.1 Passenger Car Equivalent (PCE)

HCM 2000 tables were used to find Passenger Car Equivalent for trucks and buses as it reports PCEs according to percent and length of grade and proportion of heavy vehicles.
The terrain in the studied segments is a combination of horizontal and vertical alignment permits heavy vehicles to maintain approximately the same speed as passenger cars. Therefore, the terrain is assumed to be level terrain, and the value of PCE is equal to 1.5 for trucks and buses.

2.2 Link Speeds

Moving vehicle method was used to obtain average link travel speeds between intersections on the arterial streets. For reliable results a minimum of six test runs were performed in each direction under comparable conditions (Pignataro, L. J., 1973).

Also spot speed study at selected locations were used to determine the Mid-Link spot speed, a sample size of at least 50 and preferably 100 vehicles are usually obtained. The spot speed data are collected using the stopwatch.

2.3 Traffic Volume

Traffic volume studies are conducted to determine the number, type of movements, and classification of vehicles at study locations using Moving vehicle method to obtain link volume on arterial streets and video recording technique for the determination of intersection volumes at peak hours dividing the period of data collection into 5-minute intervals to obtain PHF

2.4 Saturation Flow Rate

HCM2000 method was used for the determination of saturation flow which is used for the computation of both cycle time and traffic control delay for the signalized intersections.

2.5 Coordination of Traffic Signals

The Intersection Control Strategy was determined for each intersection. The relationship between each signalized intersection's location and the adjacent signalized intersections was determined using the coupling index (Alexandar Skabardonis, 1998).

The Coupling Index is a simple methodology to determine the potential benefit of coordinating operation of two signalized intersections. The theory is based on Newton's law of gravitation, which states that the attraction between two bodies is proportional to the size of the two bodies (traffic volume) and inversely proportional to the distance squared. In equation form, the Coupling Index is:

$$Ic = V / d_L^2 \quad \text{…………………… …………. (1)}$$

Where:

- I_C = Coupling Index
- V = Two-way total traffic volume peak hour (vph)
- d_L = Distance between signals (meters)

When Ic is greater than 0.5, signal progression is recommended. As the link volume increases, so the need to provide signal progression is essential. Based on the coupling index, the signal is classified as an isolated, arterial, crossing arterial, or dense network intersection as follows:

Isolated	Ic ≤ 0.5 for all directions
Arterial	Ic > 0.5 for major street only
Crossing arterial	Ic > 0.5 for major street, and at least one side street link
Dense network	Ic > 0.5 for both the major street and minor street links

The Measure of Effectiveness (MOEs) associated with the green bands in the Time-Space Diagram (TSD) are Bandwidth Efficiency and Bandwidth attainability (Minnesota Department of Transportation, 2005).

Bandwidth Efficiency which is simply the proportion of the cycle that is included in through green bands, extending the entire length of the system. A simple Time-Space Diagram showing perfect time-space progression illustrates the concept. Mathematically, efficiency is calculated as (Minnesota Department of Transportation):

$$E = \frac{B_f + B_r}{2C} \;\ldots\ldots \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \; (7)$$

Where:

B_f, B_r Bandwidths in the forward (f) and reverse (r) directions with respect to the arterial orientation (sec).

C Cycle time, sec.

E Bandwidth efficiency

Bandwidth attainability as a measure of how much of the maximum available green is used for through progression was calculated. The bandwidth attainability is the ratio of the total bandwidths to critical phase lengths for each of the directions on the arterial and is computed as (Minnesota Department of Transportation):

$$A = \frac{B_f + B_r}{G_f + G_r} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; (8)$$

Where:

A Bandwidth attainability

Gf, Gr The critical (or minimum) green periods (including change periods) in the two directions.

In this study the following types of coordination was applied:

1. One-way street: - The simplest form of coordinating signals is along a one-way street or to favor one direction of traffic on a two-way street that contains highly directional traffic flows. Essentially, the mathematical relationship between the progression speed S and the offset L can be described as (Minnesota Department of Transportation):

$$S(mph) = D(ft)/1.47L$$

$$\text{or } S(kph) = D(m)/0.278L \;\ldots\ldots \; (9)$$

Where: D Spacing of signals (m or ft)

2. Two-way street: For a two-way movement, many modes of operation are possible, the relative efficiency of any of these modes is dependent on the distances between signalized intersections, the speed of traffic, the cycle length, the roadway capacity, the amount of friction caused by turning vehicles, and parking and unparking maneuvers (Institute of Traffic Engineers, 1978).

2.6 Traffic Delay

Delay estimate measures reflect the driver discomfort, frustration, fuel consumption and lost travel time. The (HCM) approach control delay equation was used for the determination of control delay for each lane group, approach and the whole intersection. Then the Level of Service (LOS) was determined from a predefined range of average control delay values.

3. SELECTION OF STUDY AREA

Two arterial streets were selected for the purpose of this study, Barzani and Zakho Streets. While the studied links on Barzani Street are 6 - lane sub urban, arterial dual carriageway road, the studied links on Zakho Street are 4 - lane urban, arterial divided road. The lengths of the links on both arterial streets are measured using mechanical distance meter, as shown in Tables (1) and (2).

Table (1) Link Speed and Volume Data on Barzani Street

Link	Link length (m)	Travel speed (km/h)	Running speed (km/h)	Mid-Link Spot Speed			Volume (vph)	% of Directional Distribution
				Sample size (N)	Mean (km/h)	Standard Deviation		
SRS-SIL	1.05	35.46	44.80	116	71.7	10.65	3125	50.8
SIL-SRS	1.05	38.10	44.27	111	62.2	10.10	3019	49.2
SIL-R	0.305	13.76	28.75	105	48.4	9.33	2913	49.0
R-SIL	0.305	27.61	27.61	101	64.7	11.65	3024	51.0
R-SK	1.10	42.20	47.96	109	78.2	11.24	2747	49.6
SK-R	1.10	28.43	43.72	104	77.7	11.63	2782	50.4

Table (2) Zakho Street Links Speed and Volume Data

Lin k	k len	spe ed (k	spe ed	Mid-Link Spot Speed	um e (	ona l

				Sample size (N)	Mean (km/h)	S.D		
K-A	425	16.33	28.51	105	50.2	8.21	905	41.90
A-K	425	14.44	28.35	103	42.8	7.44	1254	58.10
A-D	416	19.12	30.65	106	63.3	7.56	1369	44.50
D-A	416	16.88	28.62	104	54.9	8.00	1710	55.50

Four successive intersections on Barzani street were studied: Sarsink (SRS), Silav (SIL), Raza (R) and Sarok (SK) Intersections. These intersections have approximately the same geometry they are three-leg three approach actuated signalized intersections. Also three successive signalized intersections on Zakho Street were studied they are: Kawa (K), Azadi (A) and Daristan (D) intersections. These intersections also have approximately the same geometry they are three-leg three approach actuated signalized intersections except Azadi intersection which is four leg actuated intersection. The arterials and intersections are shown in Figures (1) through (9).

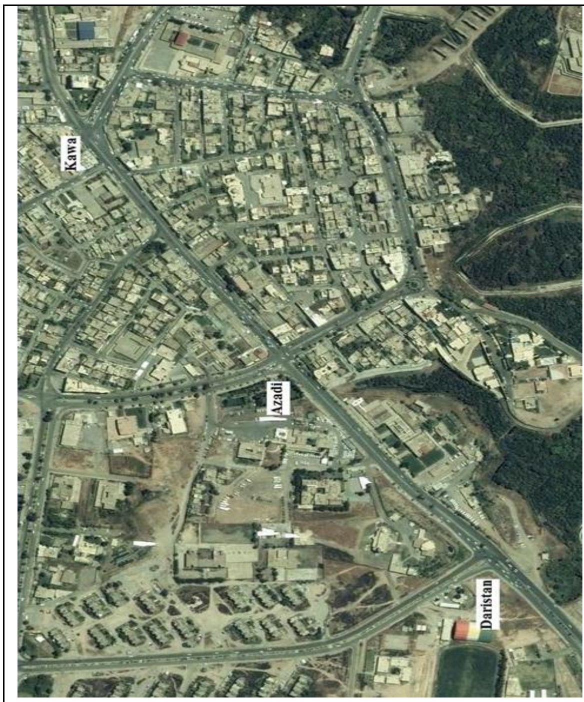

Figure (6) Google image of Zakho street showing the three studied intersecions (Directorate of Traffic, Traffic Engineering Department, Duhok City, 2009)

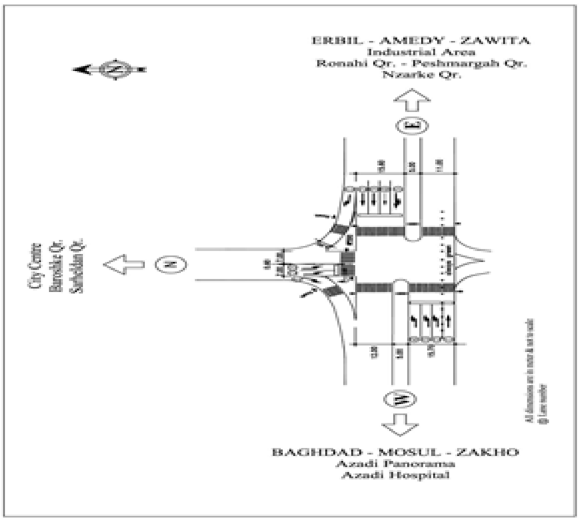

Figure (2): Sarsink Intersection (SRS) Plan (Directorate of Traffic, Duhok City, 2009)

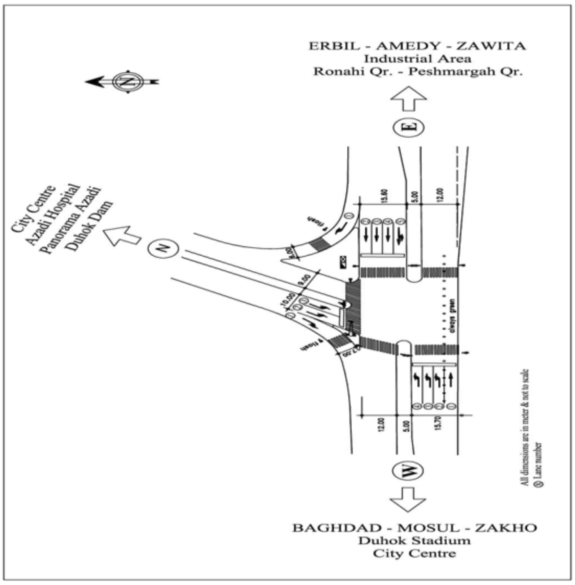

Figure (3): Silav Intersection (SIL) Plan (Directorate of Traffic, Duhok City, 2009)

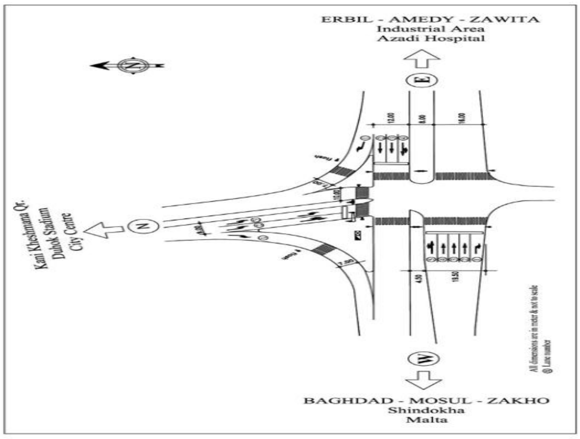

Figure (4): Raza Intersection (R) Plan (Directorate of Traffic, Traffic Engineering Department, Duhok City, 2009)

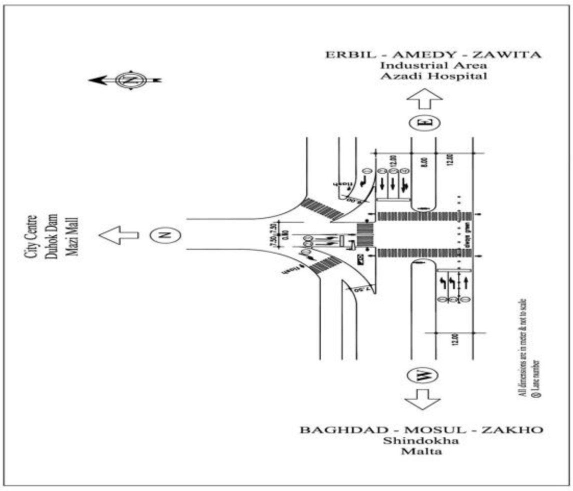

Figure (5): Sarok Intersection (SK) Plan (Directorate of Traffic, Traffic Engineering Department, Duhok City, 2009)

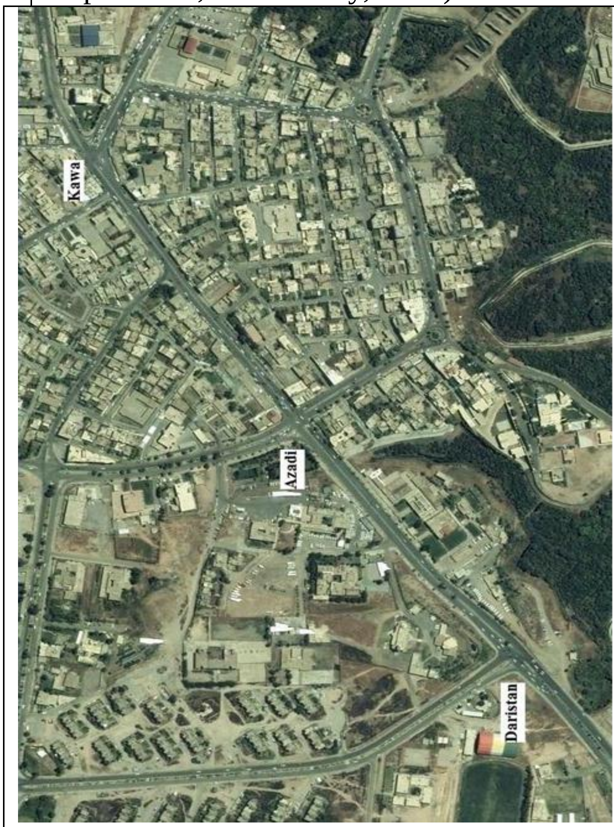

Figure (6) Google image of Zakho street showing the three studied intersecions (Directorate of Traffic, Traffic Engineering Department, Duhok City, 2009)

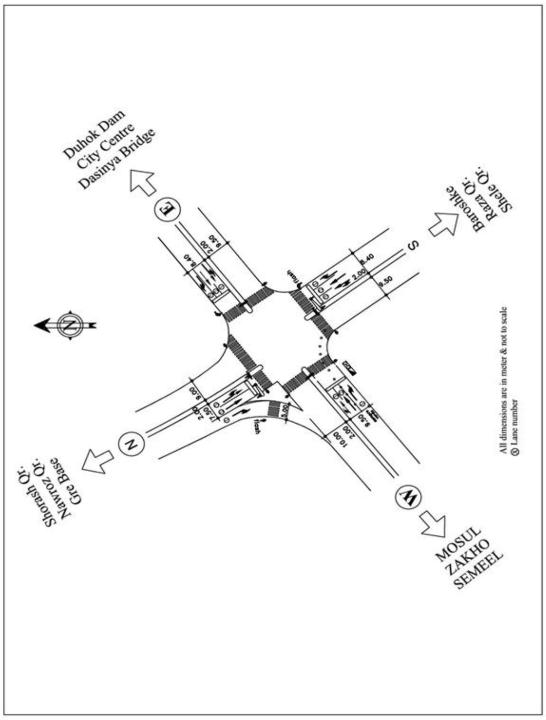

Figure (7): Azadi Intersection (A) Plan (Directorate of Traffic, Traffic Engineering Department, Duhok City, 2009)

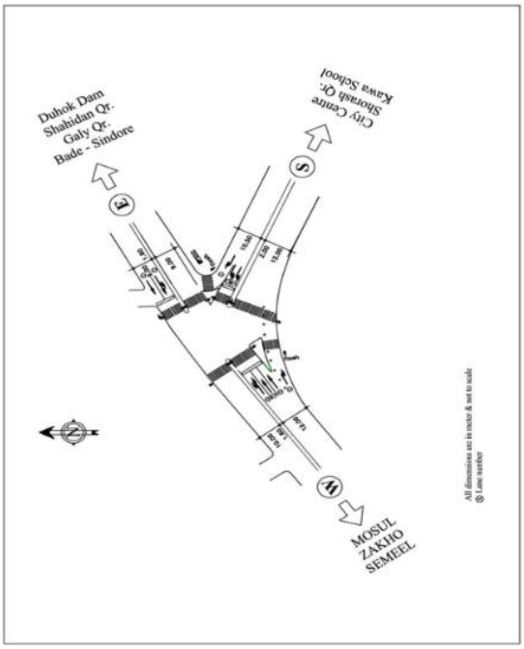

Figure (8): Kawa Intersection (K) Plan (Directorate of Traffic, Traffic Engineering Department, Duhok City, 2009)

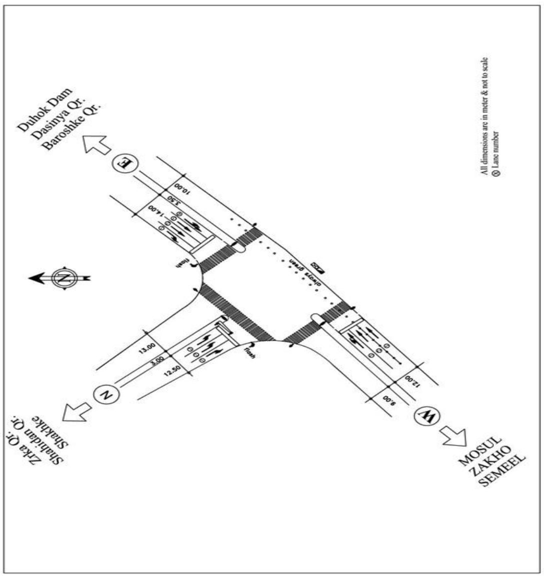

Figure (9): Daristan Intersection (D) Plan (Directorate of Traffic, Traffic Engineering Department, Duhok City, 2009)

4. DATA COLLECTION

To achieve the objective of this study, data was collected on intersections and links geometry, approach counts, AM and PM peak hour counts, posted speed on all links and approaches, percent of heavy vehicles. Morever, all the data required for field studies such as travel time and approach delay, signal timing and phasing data was collected

The determination of time period for data collection has its own importance in satisfying statistical evaluation for traffic activities. For this purpose, data collection was made by choosing different time periods from 7:30 AM to 7:30 PM according to the traffic activity. The study had avoided collecting data during weekends and other holidays as they don't represent the actual traffic activity and finding the peak periods.

Different methods of data collection were used in this study. The manual method was used to collect the intersection geometry, detectors measurements, approach speed and mid link spot speed. Moving vehicle method was used to collect the speed and volume data for the links between the studied intersections, while video camera technique was used to collect all other necessary data, which were not collected manually or by moving vehicle. The video camera data was abstracted using a computer program named EVENT (Al-Neami, A.H.K., 1995).

5. DATA ANALYSIS

5.1 Link Speeds and Volumes

It can be realized that there is a big difference between Mid-link average spot speed and link average running speed, (1.5-2) times the running speed. This may be due to the acceleration and deceleration near approaches to intersections and uncontrolled crossing walk for pedestrian in the link. Therefore, this was not used in the traffic signal coordination.

The spot speed data for mid-links on both streets were statistically analyzed using SPSS version (17) software. The chi-square test (Pignataro, L. J.,, 1973) showed that these speeds may be considered to be normally distributed at 95% confidence level.

The posted speed limit is 60 km/h for Barzani street. Mid-link spot speed and average travel and running speeds for all studied links on this street were obtained. The running speed values are approximately equal for studied links, because the link geometric conditions are not much different except (SIL-R or R-SIL) link which has a shorter length causing the vehicle to move at speed less than the speed of other links. These speed values can be combined to an average running speed (Barzani street running speed) to use it as progression speed in the coordinated system. Table (1) shows the results of spot speed and link running and travel speeds for the studied links on Barzani street.

On Zakho street, the speed limit is 40 km/h. Mid-link spot speed and average travel and running speeds for all studied links on this street were also obtained. For the links on Zakho Street, the running speed values are very close to each other as the geometric conditions of the links are similar. Therefore, these speeds also can be combined to an average running speed (Zakho street running speed) to use it as progression speed in the coordinated system. Table (2) shows the results of spot speed and link running and travel speeds for the studied links on Zakho street.

The links volumes and the directional distribution for studied links on both streets were observed. Tables (3) and (4) show results of peak hour volumes and saturation flow rate for the intersections.

5.2 Coordination of Traffic Signals on Barzani Street Intersections

Lane groups, design cycle time, green splits, yellow time, all-red time and red time for all the studied intersection on both Barzani and Zakho

Streets for isolated intersection plan strategy are shown in Tables (5) and (6) respectively.

It can be noticed that Raza Intersection has the maximum value of cycle time of 118 seconds among the other intersections on Barzani Street. While Azadi Intersection has a cycle time of 88 seconds which is the maximum cycle time value for the intersections on Zakho Street.

For coordinated plan, it should be noted that all signals within the same signal system must generally have the same cycle length, to make it possible for the pattern of timings to repeat every cycle.

Table (3) Design hourly volume and saturation flows for intersections on Barzani street (pcph)

Inter`.	Parameter		Approach								
			E			W			N		
			L	T	R	L	T	R	L	T	R
SRS	Volume (vph)	Total	0	2693	57	361	1888	0	26	0	85
		Bus%	0	4	0	0	1	0	0	0	0
		Truck%	0	3	0	0	2	0	0	0	0
	PHF			0	0.913	0.712	0.727	0.959	0	0.722	0
	Saturation Flow pcphgpl) *		1604			1721			1459		
SIL	Volume (vph)	Total	0	2085	1012	669	1417	0	763	0	408
		Bus%	0	4	2	0	5	0	1	0	1
		Truck%	0	3	1	0	4	0	2	0	1
	PHF			0	0.899	0.937	0.785	0.921	0	0.827	0
	Saturation Flow pcphgpl) *		1396			1465			1708		
R	Volume (vph)	Total	193	1644	620	334	1081	47	600	125	387
		Bus%	0	2	0	0	4	0	0	0	0
		Truck%	0	4	0	0	5	0	0	0	0
	PHF			0.782	0.851	0.771	0.705	0.932	0.734	0.787	0.744
	Saturation Flow pcphgpl) *		1568			1293			1734		
SK	Volume (vph)	Total	0	1790	372	361	1074	0	397	0	350
		Bus%	0	3	1	1	4	0	2	0	1
		Truck%	0	5	2	2	6	0	2	0	1
	PHF			0	0.883	0.721	0.737	0.962	0	0.735	0
	Saturation Flow pcphgpl) *		1595			1436			1470		

- Determined using HCM method

Table (4) Design hourly volume and saturation flows for intersections on Zakho Street

Inter.	Parameter		Approach											
			E			S			W			N		
			L	T	R	L	T	R	L	T	R	L	T	R
K	Volume (vph)	Total	406	481	0	983	0	305	0	540	706	0	0	0
		Bus%	0	0	0	0	0	0	0	0	0	0	0	0
		Truck%	0	0	0	0	0	0	0	0	0	0	0	0
	PHF		0.914	0.868	0	0.826	0	0.794	0	0.854	0.828	0	0	0
	Saturation Flow pcphgpl)		1864			1806			1627			-----		
A	Volume (vph)	Total	226	473	59	521	313	121	75	464	596	323	319	50
		Bus%	0	0	0	0	0	0	0	0	0	0	0	0
		Truck%	0	0	0	0	0	0	0	0	0	0	0	0
	PHF		0.871	0.949	0.912	0.956	0.932	0.843	0.821	0.945	0.932	0.873	0.891	0.912
	Saturation Flow pcphgpl)		1615			1590			1515			1728		
D	Volume (vph)	Total	0	887	243	0	0	0	330	763	0	461	0	199
		Bus%	0	0	0	0	0	0	0	0	0	0	0	0
		Truck%	0	0	0	0	0	0	0	0	0	0	0	0
	PHF		0	0.811	0.883	0	0	0	0.871	0.922	0	0.883	0	0.781
	Saturation Flow (pcphgpl)		1527			-----			1619			1853		

The suggested values of, green, yellow and all-red times as well as cycle time for all the studied intersections on both Barzani and Zakho Streets are shown in Tables (7) and (8) respectively. The maximum cycle time of Raza intersection (118 seconds) was used for the system. The green times for other intersections was extended proportionally so that the cycle time equals to 118 seconds.

Table (5) Signal Timing for Isolated Intersections on Barzani Street

Int.	Phase No.	Lane Group	ee n (s	o w (s	R ed (s	ti m e
SRS	I	$T_E+T_E+T_E+(T_E+L_E)$	62	4	2	99
	II	$L_W+L_W+L_W$	10	4	2	99
	III	LN+LN	9	4	2	99
SIL	I	$T_E+T_E+T_E+(T_E+L_E)$	48	4	2	97
	II	$L_W+L_W+L_W$	12	4	2	97
	III	L_N+L_N	19	4	2	97
R	I	$T_E+T_E+(T_E+L_E)$	54	4	2	118
	II	$T_W+T_W+T_W+(L_W+T_W)$	28	4	2	118
	III	$(T_N+L_N)+L_N$	18	4	2	118
SK	I	$T_E+T_E+(T_E+L_E)$	47	4	2	87
	II	L_W+L_W	9	4	2	87
	III	L_N+L_N	13	4	2	87

Table (6) Signal Timing for Intersections on Zakho Street (Isolated Plan)

Int.	Phase No.	Lane Group	Green (sec)	Yellow (sec)	All-Red (sec)	Cycle time (sec)
K	I	$T_E+(T_E+L_E)$	14	4	2	71
	II	$T_W+T_W+(T_W+L_W)$	24	4	2	71
	III	L_S+L_S	15	4	2	71
A	I	$R_E+T_E+(T_E+L_E)$	15	4	2	88
	II	$T_N+(T_N+L_N)$	21	4	2	88
	III	$T_W+(T_W+L_W)$	14	4	2	88
	IV	$R_S+T_S+(T_S+L_S)$	14	4	2	88
D	I	T_E+(TE+LE)	15	4	2	55
	II	$T_W+T_W+(T_W+L_W)$	10	4	2	55
	III	L_S+L_S	12	4	2	55

Table (7) Signal Timing for Coordinated Intersections on Barzani Street

Int.	Phase No.	Lane Group	Green (sec)	Yellow (sec)	All Red (sec)	Cycle time (sec)
SRS	I	E	75	4	2	118
	II	W	13	4	2	118
	III	N	12	4	2	118
SIL	I	E	60	4	2	118
	II	W	16	4	2	118
	III	N	24	4	2	118
R	I	E	54	4	2	118
	II	W	28	4	2	118
	III	N	18	4	2	118
SK	I	E	66	4	2	118
	II	W	14	4	2	118
	III	N	20	4	2	118

Table (8) Signal Timing for Intersections on Zakho Street (Coordinated Plan)

Int.	Phase No.	Lane Group	Green (sec)	Yellow (sec)	All-Red (sec)	Red (sec)	Cycle time (sec)
K	I	E	19	4	2	65	88
	II	S	31	4	2	53	88
	III	W	20	4	2	64	88
A	I	E	15	4	2	69	88
	II	S	21	4	2	63	88
	III	W	14	4	2	70	88
	IV	N	14	4	2	70	88
D	I	E	28	4	2	56	88
	II	W	20	4	2	64	88
	III	WN	23	4	2	61	88

The coordination application on the arterial streets should be checked in order to achieve excellent results before starting the work. Coupling index for each link on Barzani and Zakho streets are calculated from two-way peak hour volumes and link length to determine the need of providing signal progression. The coupling index is greater than 0.5 for all links as shown in Tables (9) and (10) therefore, signal progression is recommended for all intersections on both Arterials.

Table (9) Coupling Index for Links on Barzani Street

Link	Link Volume veh/h	Length (m)	Coupling Index $Ic=V/d_L$
SRS-SIL	3125	1050	5.85
SIL-SRS	3019		
SIL-R	2913	305	19.47
R-SIL	3024		
R-SK	2747	1100	5.03
SK-R	2782		

Table (10) Coupling Index for Links on Zakho Street

Link	Link Volume veh/h	Length (m)	Coupling Index $Ic=V/d_L$
K-A	905	425	5.08
A-K	1254		
A-D	1369	416	7.40
D-A	1710		

5.2.1 One Direction Coordination Under Prevailing Conditions

In this case, the prevailing traffic conditions was used in the analysis without improvements. The running speeds, calculated from the moving car method, were used in the analysis. One direction coordination of traffic signals has more flexibility in dealing with bandwidth values. By using this way, a greater value of bandwidth could be achieved.

The time-space diagram for the one direction coordination of traffic signals for all the intersections located on Barzani Street under prevailing conditions are shown in Figure (10). This Figure shows the coordination of the east approach of an intersection with the east approach of the next intersection along the arterial which represents the east direction coordination. Table (11) shows offsets and bandwidths resulted from the coordination operation. The offsets are 84 – 4 - 87 seconds while the band width is 54 seconds.

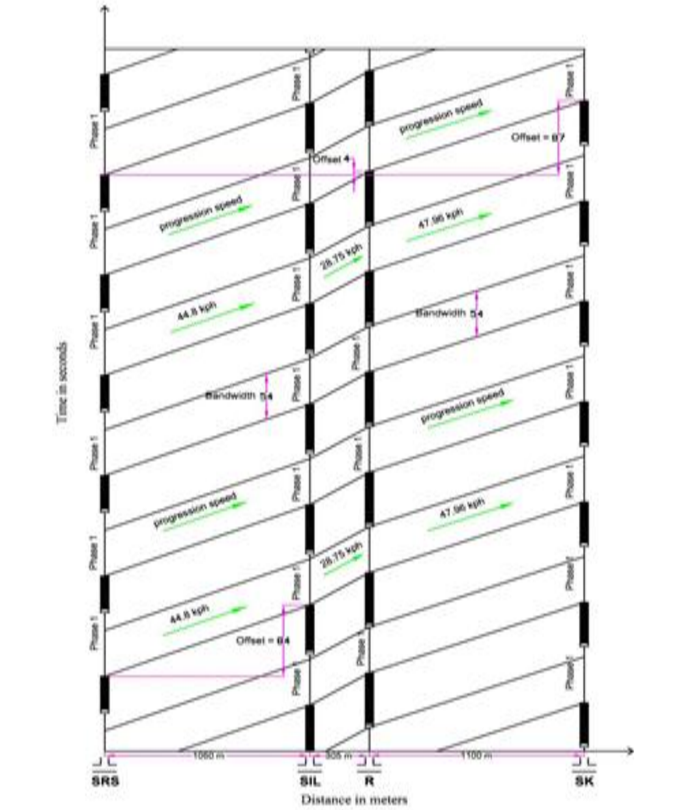

Figure (10) Time-Space Diagram for East Direction Coordination of Traffic Signals on Barzani Street under Prevailing Conditions

Table (11) Offsets & Bandwidths for One Direction Coordination of Traffic Signals on Barzani Street

Coordination Direction	Offsets (sec)	Bandwidth (sec)	Figure
East (prevailing)	84 - 4 – 87	54	(10)
East (constant speed)	84 - 4 – 87	50	(11)
East (controlled)	63 – 81 – 29.3	54	(12)

The coordination for other approaches on Barzani street are not significant, as there is already an always-green lane for the West Approach of all intersections except Raza Intersection, and also most of the vehicles during the green time move to the left direction except few vehicles that move straight and continue moving to the next intersection.

5.2.2 One Direction Coordination Using Street Average Speed (Constant Speed)

As mentioned, one running speed which was obtained by equalizing the speeds into Barzani street average speed (constant speed) was used in order to improve the coordination performance as shown in Figure (11). Table (11) shows offsets and bandwidths resulted from the coordination operation. Kell method resulted in a lower value of bandwidth therefore, it was not used in this study. The offsets are 84 – 4 - 87 seconds while the band width is 50 seconds. This means that the offsets remain the same while the band width decreased. Again, the coordination for other approaches are not significant for the same reason.

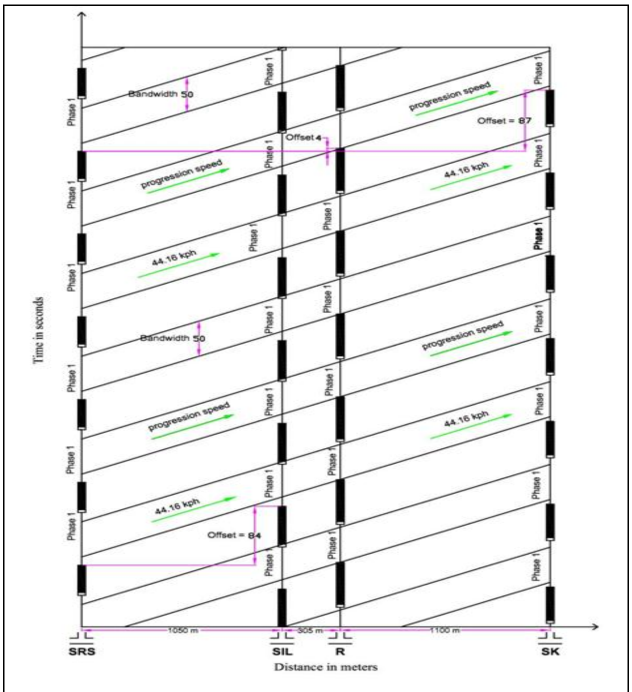

Figure (11) Time-Space Diagram for East Direction Coordination of Traffic Signals on Barzani Street under a Constant Speed

5.2.3 One Direction Coordination of Traffic Signals Under Controlled Conditions

To increase the efficiency and attainability of the traffic signals in the two studied Arterials, some improvements are recommended. One of these suggested improvements is increasing the running speed by preventing pedestrians from crossing the roadway, except at crossing areas and using traffic signs and enforcement to assure the posted speed limit.

For the speeds on Barzani Street, the constant speed of the East Direction Coordination was changed from 44.16 km/h to the posted limit speed of this street which is 60 km/h. The controlled conditions give a greater bandwidth than the prevailing conditions as shown in Figure (12). Table (11) shows offsets and bandwidths resulted from the coordination operation.

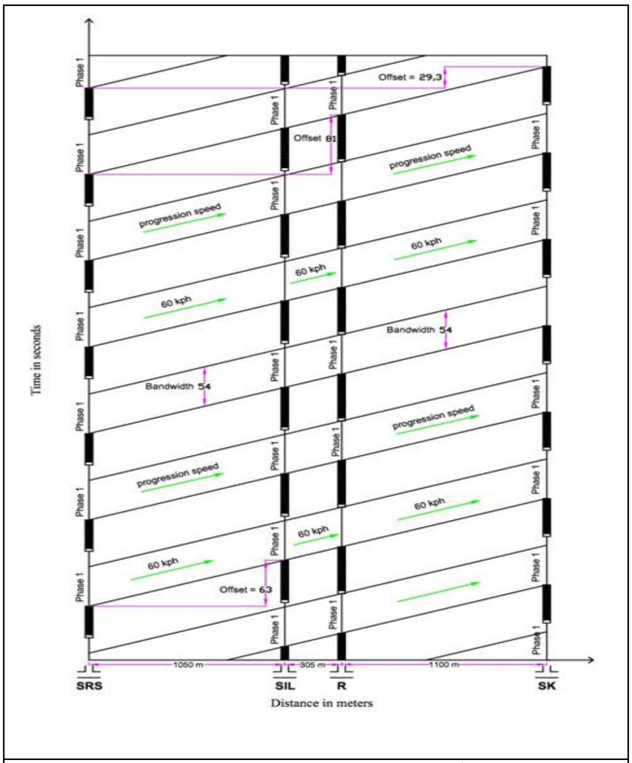

Figure (12) Time-Space Diagram for East Direction Coordination of Traffic Signals on Barzani Street under Controlled Conditions

It can be noticed that, the offsets changed to 63 – 81 – 29.7 seconds, while the bandwidth increased to a value of 54 seconds under a posted speed limit of 60 km/h. This value could also be increased to 58 seconds if the yellow time added to the green time to insure greater bandwidth (FHWA, 2008). Bandwidth of 54 seconds is adopted since the 54 seconds are sufficient for the platoon to move through all intersections.

5.2.4 Two Direction Coordination

The two-direction coordination for the traffic signals on Barzani street is not applicable and may be impossible to be executed. This is because of the left turn that is existing on the West Approach of each intersection that couldn't be ignored. Therefore, one direction coordination is more preferable for this arterial as there is always-green lane for all intersections except Raza Intersection, which helps the west direction to act as a coordinated direction all over the time.

5.3 Coordination of Traffic Signals on Zakho Street Intersections

5.3.1 One Direction Coordination Under Prevailing Conditions

The time-space diagram was drawn to show one direction coordination of traffic signals for the intersections located on Zakho Street under prevailing conditions or east and west directions respectively. The offsets are 54 – 15 seconds and 53 – 19 seonds for east and west approaches respectively, while the band widths 19 seconds and 18 seconds. The time space diagram, offsets and bandwidths from the coordination operation are shown in Figures (13) and (14) and Table (12).

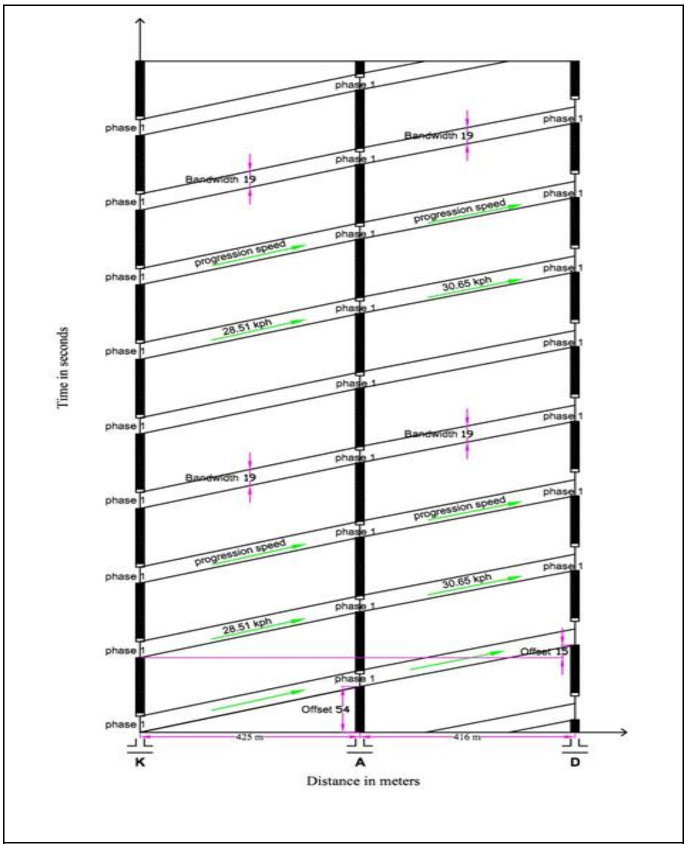

Figure (13) Time-Space Diagram for East Direction Coordination of Traffic Signals on Zakho Street under Prevailing Conditions

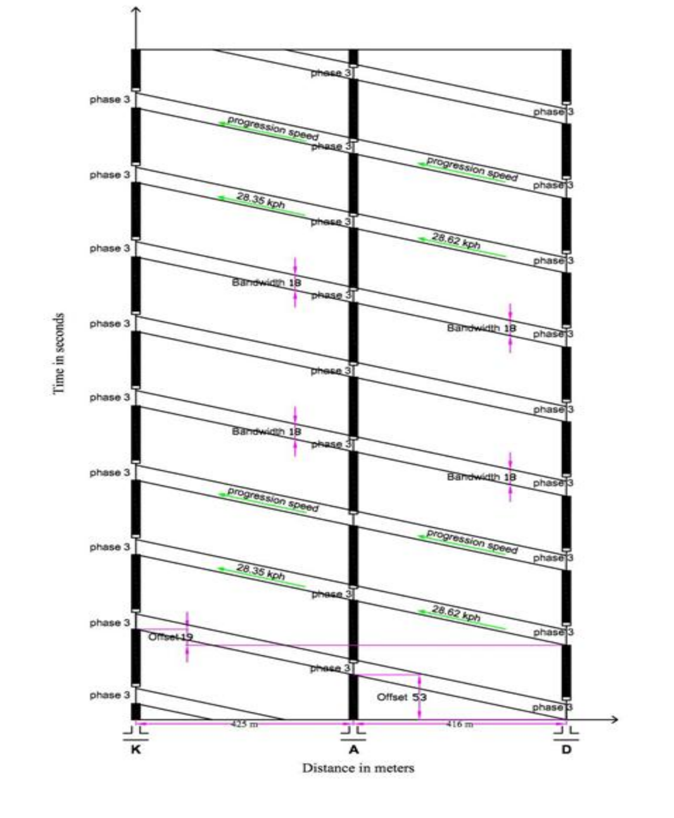

Figure (14) Time-Space Diagram for West Direction Coordination of Traffic Signals on Zakho Street under Prevailing Conditions

Table (12) Offsets & Bandwidths for One Direction Coordination of Traffic Signals on Zakho Street under Prevailing Conditions			
Coordination Direction	Offsets (sec)	Bandwidth (sec)	Figure
East (prevailing)	54 – 15	19	(13)
West (prevailing)	53 – 19	18	(14)
East (constant speed)	54 – 15	19	(15)
West (constant speed)	53 – 19	18	(16)
East (controlled)	38.2 – 75.7	19	(17)
West (controlled)	37.5 – 75.7	18	(18)

5.3.2 One Direction Coordination Using Street Average Speed (Constant Speed)

It can be seen that there is no difference in bandwidths because coordination – through band – is restricted by the smaller (green plus yellow) time for both of east and west approaches of Azadi intersection. The offsets and band widths for east and west approaches are equal to that of prevailing speed and not changed. The time space diagram, offsets and bandwidths from the coordination operation are shown in Figures (15) and (16) and Table (12).

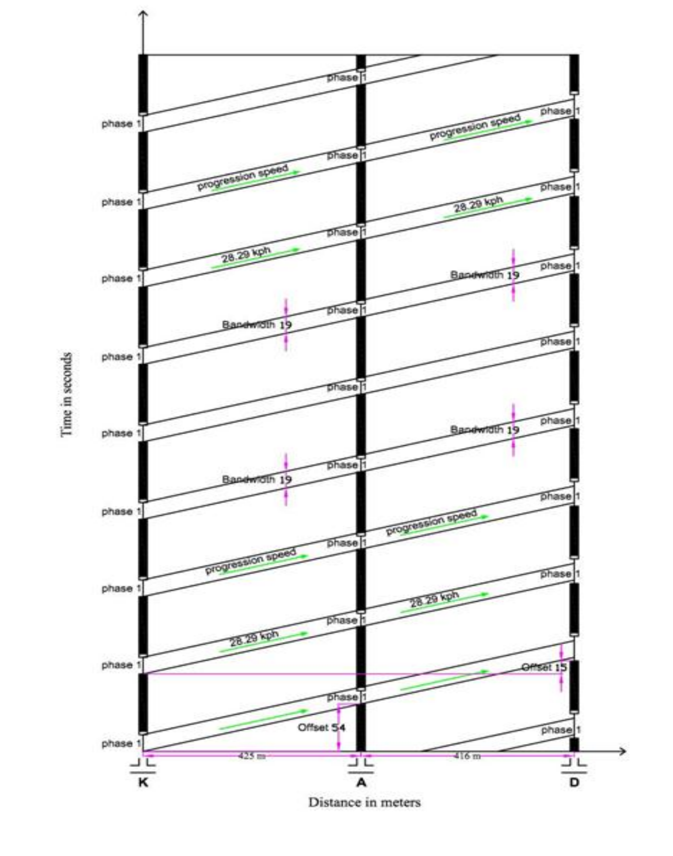

Figure (15) Time-Space Diagram for East Direction Coordination of Traffic Signals on Zakho Street under a Constant Speed

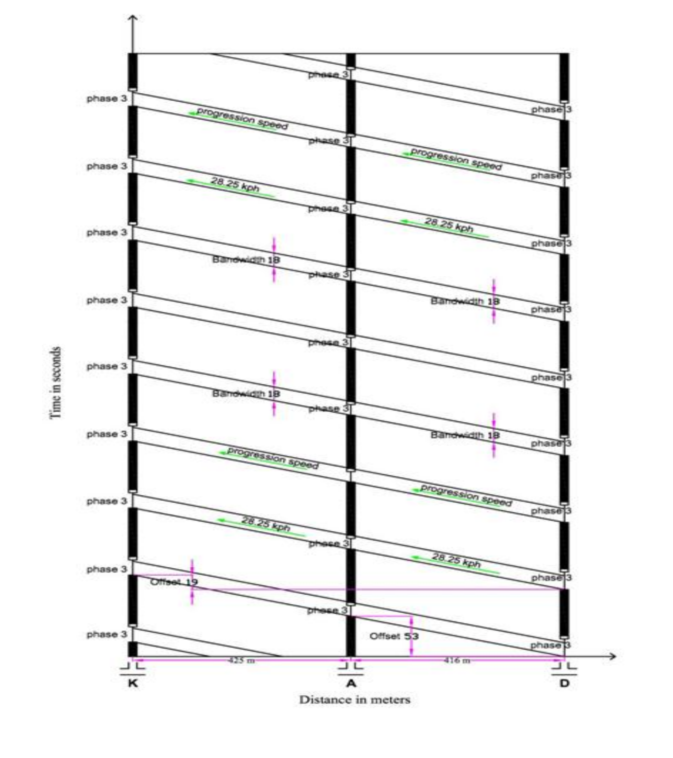

Figure (16) Time-Space Diagram for West Direction Coordination of Traffic Signals on Zakho Street under a Constant Speed

5.3.3 One Direction Coordination of Traffic Signals Under Controlled Conditions

For Zakho Street, the constant speeds of both east and west direction coordination was changed from 28.29 km/h and 28.25 km/h to the posted limit speed of this arterial which is 40 km/h the offsets and the bandwidths under controlled conditions.

The offsets are 38.2 – 75.7 seconds and 37.5 – 75.7 seconds for east and west approaches respectively, while no difference in bandwidths can be noticed after controlling the speed on Zakho Street, because coordination –through band– is again restricted by the smaller (green plus yellow) time for both of east and west approaches of Azadi Intersection, while the band widths remain as 19 seconds and 18 seconds for east and west approaches respectively. The time space diagram, offsets and bandwidths from the coordination operation are shown in Figure (17) and (18) and Table (12).

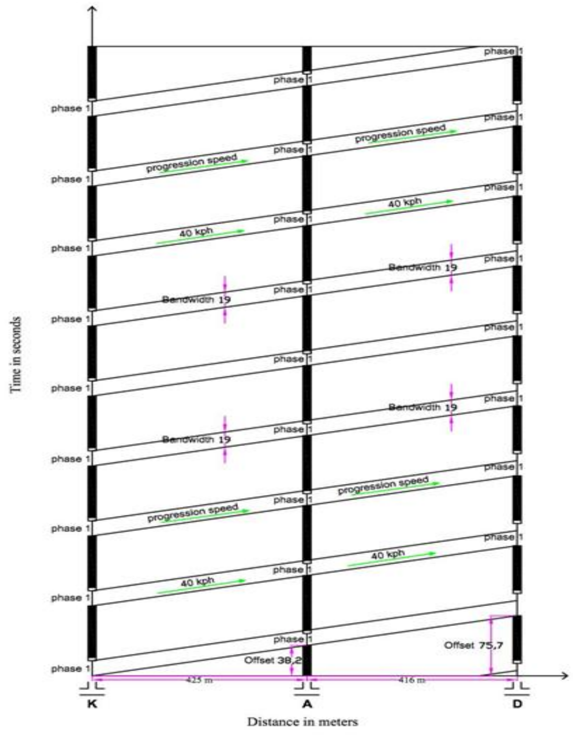

Figure (17) Time-Space Diagram for East Direction Coordination of Traffic Signals on Zakho Street under Controlled Conditions

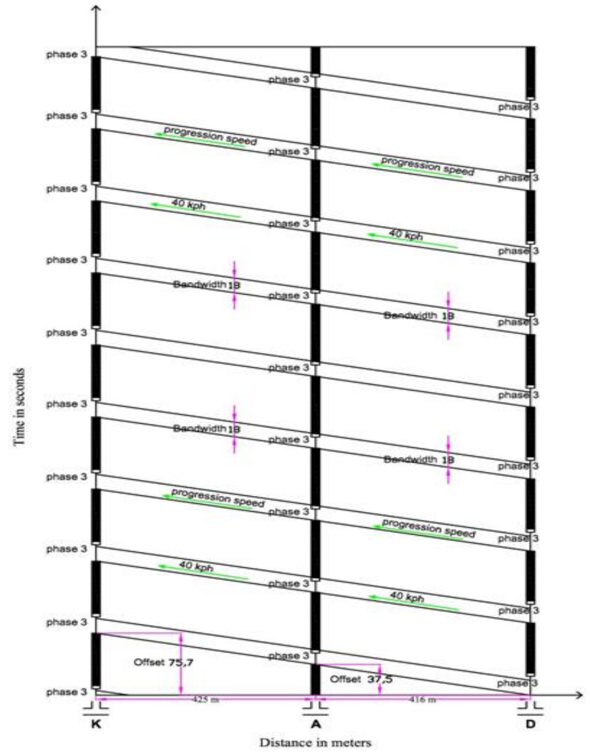

Figure (18) Time-Space Diagram for West Direction Coordination of Traffic Signals on Zakho Street under Controlled Conditions

5.3.4 Two Direction Coordination

The two-direction coordination can be designed for the traffic signals on Zakho Street, resulting in smaller value of bandwidth than one direction coordination. The design of the two-direction coordination was executed under controlled conditions as it's difficult to give good results under prevailing conditions. The offsets are 57 – 3.92 seconds and 42.08 – 87.08 seconds for east and west approaches respectively, while the band widths for both approaches are 16 seconds. The time space diagram, offsets and bandwidths from the coordination operation are shown in Figure (19) and Table (13).

The results show a higher value of bandwidth efficiency when applying coordination for two traffic signals, while coordination of three traffic signals gives less efficiency. Table (14) shows results of bandwidth efficiency which were obtained.

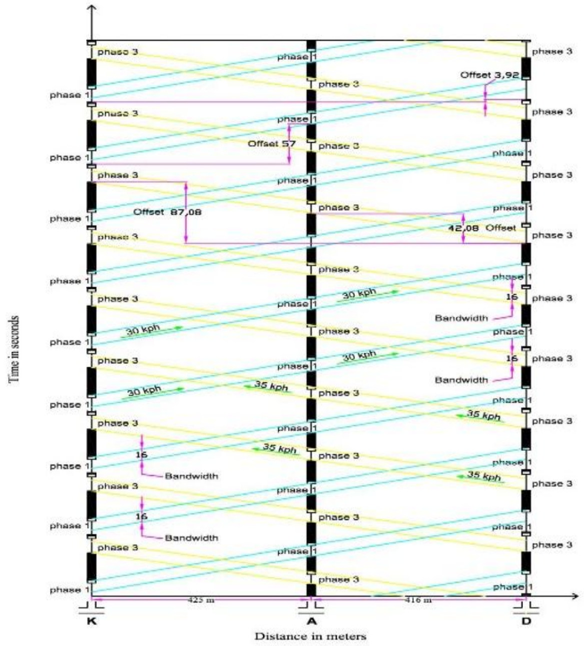

Figure (19) Time-Space Diagram for Two Direction Coordination (East-West) of Traffic Signals on Zakho Street under Controlled Conditions

Table (13) Offsets & Bandwidths for Two Direction Coordination of Traffic Signals on Zakho Street under Controlled Conditions

Coordination Direction	Offsets (sec)	Bandwidth (sec)
East (controlled)	57 – 3.92	16
West (controlled)	42.08 – 87.08	16

Table (14) Bandwidth Efficiencies for Two Direction Coordination on Zakho Street under Controlled Conditions

Link	Coordination type	B_f (sec)	B_r (sec)	Bandwidth Efficiency
K-A	Two-Way	18	18	20 %
A-D	Two-Way	18	18	20 %
K-A-D	Two-Way	16	16	18 %

It can be seen that the bandwidth attainability for coordination of two traffic signals is higher than the attainability for coordination of three traffic signals. Table (15) shows results of bandwidth attainability which was obtained.

Table (15) Bandwidth Attainability for Two Direction Coordination on Zakho Street

Link	Coordination type	B_f (sec)	B_r (sec)	G_f (sec)	G_r (sec)	Bandwidth Attainability
K-A	Two-Way	18	18	19	19	95 %
A-D	Two-Way	18	18	19	19	95 %
K-A-D	Two-Way	16	16	19	19	84 %

5.4 Control Delay

5.4.1 Approach Control Delay

Table (16) shows a comparison between approach control delays for the intersections on Barzani street before and after coordination. The Table also shows the percentage of improvement was obtained by decreasing delays for all the approaches.

Table (16) Approach Control Delays on Barzani Street before and after coordination

Int.	App.	Control Delay (sec/veh)		% Reduced Delay
		Before Coordination	After Coordination	
SRS	E	21.23	6.57	69.05
	W	54.81	51.95	5.21
	N	48.82	48.35	0.97
SIL	E	30.62	17.93	41.43
	W	99.14	71.16	28.23
	N	82.05	64.26	21.69
R	E	37.24	24.72	33.63
	W	77.50	68.79	11.25
	N	115.88	106.04	8.49
SK	E	26.75	12.51	53.23
	W	59.70	52.72	11.70
	N	63.43	51.40	18.97

It can be noticed that the best improvement was made in the east approach of Sarsink intersection with 69.05% reduction in delay. While the lowest improvement noticed on the north approach of the same intersection with 0.97% reduction in delay. Table (17) shows the comparison between approach control delays before and after coordination on Zakho Street. The best improvement was made in the east approach of Kawa intersection with 33.38% reduction in delay. While the lowest improvement was noticed on the west approach of the same intersection with 8.19% reduction in delay.

5.4.2 Intersection Control Delay

the comparison between intersection control delays before and after coordination on Barzani street was made to show the percent improvements. The highest improvement was made in Sarsink intersection with 51.79% reduction in delay. While the lowest improvement can be seen in Raza intersection with 16.21% reduction in delay. Table (18) shows the percentage of improvement obtained by decreasing the intersection control delay for intersections on Barzani street.

Table (17) Approach Control Delays on Zakho Street before and after coordination

Int.	App.	Control Delay (sec/veh)		% Reduced Delay
		Before Coordination	After Coordination	
K	E	77.32	51.52	33.38
	S	32.40	25.41	21.57
	W	36.60	33.61	8.19
A	E	89.63	78.86	12.02
	S	62.76	49.94	20.44
	W	72.79	57.62	20.85
	N	76.97	64.15	16.65
D	E	31.59	25.18	20.29
	W	33.86	29.55	12.73
	N	31.90	27.52	13.72

Table (18) Intersection Control Delay Before and After Coordination on Barzani Street

Int.	Control Delay (sec/veh)		% Reduced Delay
	Before Coordination	After Coordination	
SRS	25.40	12.24	51.79
SIL	55.00	38.26	30.43
R	65.90	55.22	16.21
SK	37.13	24.26	34.65

For Zakho street, the highest improvement was made in Kawa Intersection with 26.11% reduction in delay. While the lowest improvement can be seen in Daristan intersection with 16.93% reduction in delay.
Table (19) shows the comparison between intersection control delays before and after coordination on Zakho Street.

As a result, the highest reduction in control delay value is for Sarsink intersection on Barzani Street, and for Kawa intersection on Zakho street.

Table (19) Intersection Control Delay Before and After Coordination on Zakho Street

Int.	Control Delay (sec/veh)		% Reduced Delay
	Before Coordination	After Coordination	
K	49.88	36.85	26.11
A	75.04	62.27	17.01
D	32.12	26.68	16.93

6. CONCLUSIONS & RECOMMENDATIONS

6.1 Conclusions

The following conclusions can be drawn based on the results of this study:

1. Intersections on Barzani Street have evening peak hour in the range between (5:30 to 6:30) PM in winter, while intersections on Zakho Street have evening peak hour in the range between (6:00-7:00) PM in spring.
2. The range of observed flow for intersections on Barzani Street was between 111 veh/h on North Approach of Sarsink Intersection, and 3070 veh/h on East Approach of Silav Intersection. While the range of observed flow for the intersections on Zakho Street was between 660 veh/h on North Approach of Daristan Intersection, and 1288 veh/h on South Approach of Kawa Intersection.
3. The range of saturation flow for intersections on Barzani Street was between 1293 pcphpl on West Approach of Raza Intersection, and 1734 pcphpl on North Approach of the same intersection. While for intersections on Zakho Street the range of saturation flow was between 1515 pcphpl on West Approach of Azadi Intersection, and 1864 pcphpl on East Approach of Kawa Intersection.
4. The coupling index values for the all links on Barzani and Zakho Arterial Streets were more than 0.5 which means that the coordination of traffic signal on both Arterials is applicable.
5. The average travel and running speeds are nearly equal for the links of both Barzani and Zakho Street as these links have approximately the same length and geometry on each street.
6. The coordination results under prevailing and controlled traffic conditions for both Barzani and Zakho Streets show an increase in bandwidths by controlling the progression speeds.
7. The intersection control delay and level of service values after coordination for the intersections on Barzani and Zakho Streets are improved.

6.2 Recommendations

1. Installing permanent video recording camera on streets and intersections for traffic volume counting and measuring speed of vehicles, this will simplify the process of data collection and data analysis for future studies.

2. Continuous maintenance for all the streets and intersections is needed including new marking lines and lightings.
3. Providing speed humps at the middle of the links that have long distances in order to avoid the probability of platoon dispersion. This mechanism is used to force the drivers to reduce their speeds at the point where the speed hump was installed, and then recollecting the platoon again so as to arrive together to the next intersection.
4. Offering a proposal for executing the east direction coordination on Barzani Street and the two-way coordination on Zakho Street as it gives the best results in this study.
5. As the coordination under controlled speed gives best results therefore, it is necessary to provide speed limit dynamic signs to show the speed required to reach the next intersection without interruption.

6.3 Further Research

Future research in this area will be aimed at:

1. Studies required to be made on networks in Duhok city and for Kurdistan Region wide.
2. Fuel consumption and Carbon Monoxide Emission studies for the coordinated traffic signals.

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