Economic design volume for isolated traffic signals in saturated flow conditions

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ABSTRACT: Design of isolated signals depends on traffic flows at the approaches. Since flows vary along the day, it is important to select an economic design flow. In situations where two peaks occur, the design volume is the average off peak. Such design would not optimize delay during peaks but it would be appropriate for other hours. The problem prevails in congested networks of cities in the developing world is different. More than two peaks occur. This raises the question of the need to use saturated flows for design but is it economically feasible? The paper addresses this question.. Using measured hourly flows at selected congested intersections in Cairo, comparison are made between signal design at peak, average off peak and each hour volumes. The consequences of these designs economically evaluated based on delays, lost time on the network and fuel consumption. Recommendations will be presented.

RÉSUMÉ : La Conception de signaux isolés dépend des flux de trafic dans les approches. Dans la mesure où les flux varient tout au long de la journée, il est important de choisir un flux de conception économique. Dans des situations où deux heures de pointe ont lieu, le volume de conception est la moyenne en dehors des heures de pointe. Une telle conception n'optimiserait pas le retard pendant les heures de pointe mais elle serait appropriée aux autres heures. Le problème qui règne dans les réseaux encombrés des villes des pays en voie de développement est différent. Il y a plus de deux heures de pointe. Cela soulève la question du besoin d'utiliser des flux saturés pour la conception mais est-ce économiquement faisable ? La communication pose cette question. En utilisant des flux horaires mesurés à certaines intersections encombrées au Caire, la comparaison est faite entre la conception de signal à l'heure de pointe, la moyenne en dehors des heures de pointe sommet et chaque volume d'heure. Les conséquences de ces conceptions économiquement évaluées de manière économique sont basées sur les retards, le temps perdu sur le réseau et la consommation de carburant. Des recommandations seront présentées.

1 INTRODUCTION

The objectives of the current research is to define the proper traffic flow rate for optimum signal timing design at pre timed isolated intersections in saturated flow conditions where the peak period is dominated for more than one hour during the day, with application to Cairo. This flow rate is selected based on quantitative evaluation in terms of the generated traffic delay and fuel consumption and on qualitative evaluation in terms of the intersection Performance Index. First, a special survey was carried out to study the traffic fluctuation during the day and to identify the peak volume, peak period and the design volume. Optimum cycle length and the associated evaluation measures are defined for the volume of each hour. Emphasis is given for the analysis results of both the peak volume and the design volume. The traffic simulation software "Synchro (1)" is used. Different cycle lengths are applied for the volume of each hour to investigate the evaluation measures. A trade off between the associated evaluation' measures resulted due to the application of the signal design that suits each of three different cases is established. These three cases are the application of the signal design of each hour actual volume, the peak volume and the average off peak volume. The totals of these measures are calculated over the measuring period (7 a.m. to 9 p.m.). The differences between these volumes help in the identification of the economic traffic volume that can be applied over the day. This evaluation helps also in selecting the best signal design technique to be applied such as pre-timed and traffic actuated techniques. The differences between these totals are monetary evaluated over a hypothetical number of operational years to assess the benefits of the application of the economic volume.

2 BACKGROUND

Traffic signals may defined as power operated signal displays used to regulate or worn traffic (Synchro 4, 1999). In a broad sense, traffic signals include displays for intersection control, flashing beacons, lane directional signals, and ramp metering signals. When traffic signals are installed and properly operated, they can provide specific advantages in traffic control and safety. Signal installations, however, also have certain disadvantages that may or may not apply at a particular location. The objectives of traffic signals are many, such as they reducing the frequency of certain types of accidents, increasing traffic handling capacity of the intersection, bring bout considerable economy over manual control at intersections where alternate assignment of right of way is required and finally, promoting driver confidence by assigning right of way. On the other hand, signal installation at intersections increases the intersection total delay and fuel consumption and Performance Index especially during the off peak periods. The Performance Index PI is function of the intersection percentile delay D in sec, the queue penalty QP and the vehicle stops St. The function is given in equation 1.

$$PI = (D * 1 + St * 10 + QP * 100) / 3600 \quad (1)$$

Signal installation may be associated with probable increase in certain types of accident such as rear/ end collisions. Improper signal timing may cause excessive delay, increasing driver irritation (1).

Signals may be designed as pre-timed or traffic actuated. Actuated controller can be further defined as semi-actuated (coordinated or non-coordinated) and fully actuated. Under the pre-timed signal conditions, the signal assigns right-of-way at an intersection according to a predetermined schedule. The sequence of right-of-way (phases and splits), and the length of the time interval for each signal indication in the cycle is fixed, based on the historic traffic patterns. The major elements of pre-timed control are fixed cycle length and fixed phase length. Timing of pre-timed signals is easily adjusted in the field and under certain conditions can be programmed to handle peak periods. However the pre-time signals have these advantages,, it does not recognize or accommodate short term fluctuations in traffic demand and can cause excessive delay to vehicles and pedestrian during off-peak periods ((Synchro 4 , 1999), (Homburger, Kell & Perkins, 1992), (Messer , 1998) , (TRB, 1994) & (Gerlough & Huber, 1975))

3 PROPOSED METHODOLOGY

A comparison between traffic actuated and pre-timed signal design techniques is carried in order to be able to recommend the best technique and the economic volume. Since the design of the pre-timed signals needs a volume to be based on, each “different” hourly volume is used and evaluated using the quantitative measures such as (delay and fuel consumption and PI The steps of the proposed methodology of this research are as listed below:

- Make a selection of an example intersection with typical geometric and performance features.
- Establish a special directional traffic count survey by different hours of the day covering both peak and off peak conditions.
- Draw The traffic fluctuation to define the key volumes such as peak volume, average volume and average off peak volume.
- Use the average off peak volume in signal design and estimate the evaluation measures (Delay D_d, Fuel Consumption FC_d, and overall PI).
- Use results of signal design using the design volume with actual volume throughout the 14 hours and estimate the evaluation measures individually and compute the overall value of these measures.
- Use the peak volume as signal design volume and estimate the corresponding evaluation measures (Delay D_p, Fuel Consumption FC_p, and the overall PI)
- Repeat step number 5 using the results of using the peak volume as signal design volumes as well as the corresponding total evaluation measures.
- Identify each hour’s volume and use these volumes as design volume for signal timing, estimate and study the signal design features.
- Apply the design features produced from step 8 over other hourly volume.
- Evaluate the performance measures due to using each one of these volumes for signal design.
- A trade off between the volume used for signal design and the overall value of the evaluation measures is made then the economic design volume could be identified and recommended.
- Economic assessment of the, resulting savings in delay and fuel consumption due to application of the economic design volume for signal design over different hours of the day is estimated.

4 DATA COLLECTION

A typical isolated four leg intersection is selected based on the common features of the street network in Cairo. The traffic count was carried out for 14 hours (7 am. to 9 pm.). The location of this intersection practices 13 directions of movements in its four approaches. Table 1 provides the traffic hourly volume for each approach.

5 SIGNAL DESIGN ANALYSIS

5.1 Traffic volume fluctuation and peak and average off peak volumes identification

Figure 1 shows the fluctuation of traffic volume for all directions throughout the survey fourteen hours. This fluctuation is studied to identify the peak hour, the average off peak volumes and other key volumes. Table 1 gives traffic volume by hour as values and as percentages of each of the peak and the average off peak volumes.

From the Figure and Table, it can be noticed that the peak volume is 5428 veh/hr and volumes within 95% of the peak volume are dominated for 50% of the counting period. The average off peak volume is estimated as 4916 veh/hr.. The minimum traffic volume represents about 85% of the peak volume. This observation emphasizes the necessity of the current research since the peak hour volume does not last only for one hour and consequently this affects the value of the signal design volume. The average of hourly volumes excluding peak volumes is calculated This percentage is found for 7 other hours during the counting hours.

Table 1. Traffic Volumes at Typical four Leg Intersection, Percentage from Peak Volume and Average off Peak Volume

Hour	Direction				Total
	A	B	C	D	
7-8am	978	107	1401	1185	4591
8-9	1362	1154	1495	1108	5119
9-10	1404	1012	1332	900	4648
10-11	1280	1384	1164	1116	4944
11-12	1372	1456	1272	1036	5136
12-1pm	1432	1336	1212	980	4960
1-2	1416	1408	1268	1040	5132
2-3	1371	1479	1299	960	5109
3-4	1912	1292	1180	1148	5232
4-5	1528	1480	1252	1168	5428
5-6	1372	1440	1200	1132	5144
6-7	1252	1404	1212	1176	5044
7-8	1380	1544	1284	1144	5352
8-9	1484	1456	1260	1176	5376

Table 1. Traffic Volumes at Typical Four Leg Intersection, Percentage from Peak Volume and Average off Peak Volume (Cont.)

Hour	Total	% PV	%Average off peak
7-8 am	4591	85	93
8-9	5119	94	104
9-10	4648	86	95
10-11	4944	91	101
11-12	5136	95	104
12-1 pm	4960	91	101
1-2	5132	95	104
2-3	5109	94	104
3-4	5232	96	106
4-5	5428	100	110
5-6	5144	95	105
6-7	5044	93	103
7-8	5352	99	109
8-9	5376	99	109

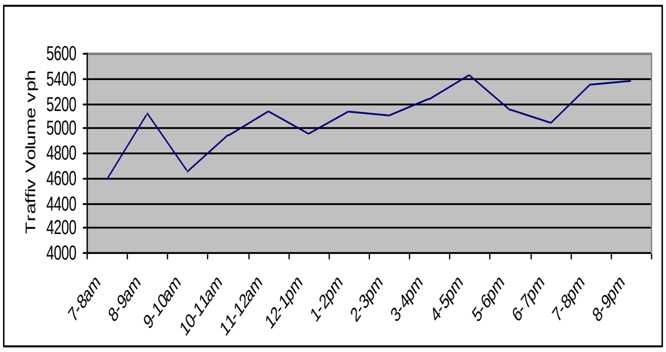

Figure 1. Hourly Fluctuation of Traffic Volume

5.2 Signal design using peak and average off peak volumes

Optimum signal timing for the intersection is investigated when using the peak volume (5428 veh/hr). The optimum cycle length is 43 sec. and the actual effective greens is 18 sec. with an intersection total delay of 201 hr. The fuel consumption is 822 liters. The PI is calculated using equation (1) and equals 250.

The optimum signal timing for the intersection is designed based on the average off peak volume (4916 veh/hr) also. The optimum cycle length is also 43 sec. and the actual effective greens is 17 sec. with an intersection total delay of 147 hr. The fuel consumption is 637 liters. The PI equals 184.

5.3 *Signal design using each hour traffic volume*

The optimum signal designs for each hour using that hour traffic volumes are estimated. The design is provided with all evaluation measures including the PI, delays, and the consumption. Table 2 provides the results of the design. It is concluded from the Table that the optimum cycle length varies from 43 sec. to 65 sec. for all hours. The hourly delay values vary from 129 to 196 hrs. with total value of 2366 hrs. and hourly mean value of 169 hrs., with coefficient of variation equals 0.13.. The hourly fuel consumption varies from 565 to 801 liters with total value of 9885 liters , hourly mean value of 706 liters and with coefficient of variation of 0.109. Finally the PI varies from 155 to 244 with mean value of 207 and coefficient of variation of 0.136.

Table 2. Optimum Signal Design and Associated Evaluation Measures Based on Each Hour Traffic Volume

Volume	C (Sec.)*	D (hr.)*	FC (L)*	PI*
4591	50	129	565	158
5119	50	167	716	209
4648	65	130	569	155
4944	43	152	651	191
5136	50	173	717	211
4960	50	156	661	191
5132	50	173	710	211
5109	50	171	707	200
5232	43	182	759	226
5428	43	201	822	250
5144	43	172	719	215
5044	50	167	692	203
5352	50	197	795	240
5376	43	196	802	244
Total		2366	9885	-
Average		169	706	208

* C is the cycle length, D is the total delay, FC is the fuel consumption, and PI is the PI.

6 EVALUATION OF USING HOURLY TRAFFIC VOLUME ON SIGNAL DESIGN

6.1 Application of peak and average off peak volumes signal design

Since the optimum cycle length associated with both the peak and the average off peak volumes is the same, it is necessary to evaluate the application of this signal design with all other hourly volumes and assess the corresponding benefits and/or losses. Table 3 gives the results of this application. From the Table it can be noticed that the total delay during the measuring period is 2362 hrs. and the total fuel consumption is 9863 liters and the corresponding average PI is 208.2.

From Tables 2 and 3, it is observed that application of optimum signal design of the peak volume and the average off peak volumes over all other hours of the day instead of using each hour actual optimum signal features causes improvement in total fuel consumption, reducing it from 9885 to 9863 liters. In addition, the total delay slightly decreases (from 2366 to 2362 hrs.) while the PI remains constant at 208. It should be mentioned here that the cycle length of 43 sec. doest not fit only the peak volume and the average off peak volume but also fits a group of volumes their mean value equals 5224 veh/hr.

6.2 Application of the signal design features based on the volume of each hour

Bearing in mind the analysis of the optimum signal timing design during the hours of the delay in the example intersection, it is noticed that only 3 different values of optimum cycle lengths are dominated. These values are the length associated with the peak and the design volumes (43 sec.) and 2 other values which are 50 and 65 sec. Table (3) gives the results of application of each of these values as a pre-timed signal design to all hours of the day to enable the evaluation and selection of the economic design volume. The selection process is based on the comparison between the total delay, total fuel consumption and the performance index. The Table shows that the application of cycle length of 43 sec. is more efficient than the other 2 values. This cycle length fits more the hour of traffic volume of 4591 and 4648 veh/hr. and provides the minimum of all delays, fuel consumption and PI. It is worth mentioning that the second optimum cycle length for the peak volume (5428 veh/hr) is 50 sec. which is associated with the same PI of 250 but only more by 5 hrs in delay (from 201 to 206 hrs.) and 6 units in fuel consumption (from 822 to 828 liters).

Table(3). Evaluation Measures Due to Application of Repeated Optimum Cycle Length (C=43, 50, 65)

Hourly Volume	D at 43	FC at 43	PI at 43	D at 50	FC at 50	PI at 50
4591	126	562	158	129	565	158
5119	167	713	209	171	716	209
4648	126	570	158	127	569	156
4944	152	651	191	156	657	191
5136	196	713	211	173	717	211
4960	153	658	191	156	661	191
5132	169	714	211	173	718	211
5109	167	705	208	171	709	208
5232	182	759	226	186	764	227
5428	201	822	250	206	828	250
5144	172	719	215	176	724	215
5044	163	686	204	167	692	203
5352	192	789	240	197	785	240
5376	196	802	244	200	808	244
Total	2362	9863	-	2388	9913	-
Average	168.7	704.5	208.3	171	708	208

Table(3). Evaluation Measures Due to Application of Repeated Optimum Cycle Length (C=43, 50, 65) (cont.)

Hourly Volume	D at 65	FC at 65	PI at 65
4591	135	575	160
5119	182	738	214
4648	130	569	155
4944	165	676	195

5136	183	739	216
4960	165	680	195
5132	183	740	216
5109	179	726	211
5232	196	785	231
5428	217	849	254
5144	185	744	218
5044	176	712	208
5352	207	816	244
5376	211	829	242
Total	2514	10178	-
Average	180	727	211

Figures 2 shows the variation of the PI which takes into considerations the total delay, queue penalty and vehicle stops, at different possible design cycle lengths (C = from 40 to 70 sec.) throughout the 14 hours of the counting period. Table 4 gives the average of each evaluation measure at the above cycle lengths. The Table and Figure indicate that the application of cycle length of 43 sec. and 50 sec. is associated with minimum value of all considered evaluation measures for different volumes.

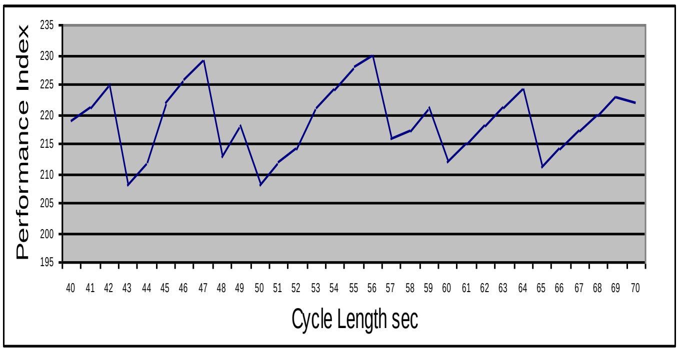

Figure 2. Variation in PI at Different Possible Cycle Length

Table 4. Evaluation Measures Associated with Application of Different Cycle Length over the Day

CL	PI	FC	D	CL	PI	FC	D
40	219	727	173	55	228	762	189
41	221	734	176	56	230	769	192
42	225	746	180	57	216	729	179
43	208	705	169	58	217	737	182
44	212	716	171	59	221	745	185
45	222	741	179	60	212	726	178
46	226	751	183	61	215	735	182
47	229	761	187	62	218	742	185
48	213	725	175	63	221	750	187
49	218	734	179	64	224	758	190
50	208	708	171	65	211	727	180
51	212	720	174	66	214	733	182
52	214	727	177	67	217	742	185
53	221	744	182	68	220	748	188
54	224	751	185	69	223	757	190
55	228	762	189	70	222	756	191

7 ECONOMIC DESIGN VOLUME

Based on the above results, it is clear that the dominant cycle length equals 50 sec. and lasts as optimum value for eight hours (7-9 am, 12-3 pm, 6-8 pm). The average of these volumes is 5055 veh/hr. which represents 93% of the peak volume and 102% of the average off peak volume. The second optimum cycle length is 43 sec.. This cycle length is dominated for five hours. These hours are distributed throughout the day as 10-11 am, 3-6 pm, and 8-9 pm. The average volume of these hours is 5224 veh/hr. This presents 96% of the peak volume or 106% of the average off peak volumes. It is worth mentioning that the average volume 5224 veh/hr includes the effect of the peak volume that equals 5428 veh/hr.

It is shown that differences in all the evaluation measures due to the application of the signal design of the peak volume as the design volume or the application of the traffic actuated signal design is minimal. This is due to practicing uniform volume during different hours of the day that varies from 85% to 100% of the peak volume. However, a procedure is set out in this research to investigate the economic design volume. This procedure starts with the calculation of the average volume that has the same value of the optimum cycle length. Only 3 values of cycle length are determined (43, 50 and 65 sec) as mentioned earlier. These values are applied over the whole day and the corresponding total values of the evaluation measures are calculated. The results of this application are obtained from Tables 2, 3, and 4 and summarized in Table 5. The table shows that the differences in evaluation measures between the actuated condition and the group of the peak volume are 4 hrs saving in delay (from 2366 to 2362 hrs) and about 22 liter saving in fuel consumption (from 9885 to 9863 liters).

Table 5. Example Average Volume with Corresponding Evaluation Measures Observed

Average Volume	Cycle Lengths	Total Delay	Total FC	PI
5224	43	2362	9863	208
5055	50	2388	9913	211
4648	65	2514	10178	207
5086	actuated	2366	9885	208
5428	peak	2362	9863	208

Regression relationships between the average volume and each evaluation measure are calibrated to study the sensitivity of each measure due to volume changes. The parameters of these models depend on the local operation features. Justification of these relations to fit different locations is out of the scope of this research. The importance of these regression models is in their capabilities to reflect the variability between the involved variables. The application of the fitted relations resulted the estimated values of the measures that provided in Table 6.

Table 6. Example Average Volume with Corresponding Evaluation Measures (estimated)

Average Volume	Cycle Lengths	Total Delay	Total FC	PI
5224	43	2348	9823	207
5055	50	2394	9919	208
4648	65	2505	10152	210
5086	actuated	2385	9902	208
5428	43	2292	9707	206

For evaluation purposes, the average values of each traffic volumes group and the associated evaluation measures using the calibrated models are used. When the peak volume is used, the estimated delay associated with the peak volume group is 2292 hrs, fuel consumption is 9707 liters and the PI is 206. On the other hand, when the group that includes the actual traffic volumes is used, the estimated delay equals 2385 hrs, the fuel consumption equals 9902 liters, and the average PI equals 208. Consequently, the application of the peak volume signal design (43sec.) uniformly over different hours saves around 195 liters of fuel (from 9902 to 9707 liters) and reduces delay by 93 hours (from 2385 to 2292 hrs). As a result, a volume of from 96% to 100% of the peak volume can be defined as the "economic design volume" since it is associated with best performance over all hours of the day. These results show that the application of "pre timed " signal design using signal design associated with the peak volume is more efficient than using "traffic actuated" signal design technique.

8 MONETARY VALUATION OF THE IMPACT OF ECONOMIC DESIGN VOLUME APPLICATION FOR SIGNAL DESIGN

This research shows that the selection of the signal design associated with the peak volume as pre-timed signal design is the best. This selection gives the minimum values of the evaluation measures such as delay and fuel consumption. The differences if the evaluation measures between the case of the traffic actuated signal performance and the application of the signal design of the peak volume are calculated. These differences are considered as savings when calculated in money.

The estimation of these savings' money values are necessary to enable the analyst to assess the benefits due to the optimum choice for signal design volume. The evaluation measures used for this analysis are the delay and the fuel consumption. The evaluation takes into consideration a hypothetical operation period of 10 years with 340 days of annual normal performance. The necessary information for this evaluation includes the fuel price per liter, the value of persons travel time in Egyptian urban areas and the price consumer index for 2003. The literature and the information available about the existing situation help in identifying these requirements. Consequently, the value of persons' travel time in Egyptian urban transport studies is reviewed and found as 2.617 LE/vehicle•hr of volume in 1987 prices (Abdel_Nasser,1987) . Estimation of this value in 2003 price needs the price consumer indices for years 1987 and 2003. Available references give the price consumer index for 1998 (= 389.9) referred to 1987 index(= 100). Complementary references give the price consumer index for 2003 (= 132.2) referred to that for 1996 (=100). Based on this information and additional calculations concluded that the price consumer index for 2003 is 445.7. ((Census Report, 1997 & (Central Agency for Public Mobilization and Statistics ,2003)).

The calculations indicate that the total savings due fuel equals 662,796 LE per intersection and the savings due to time savings equal 3,698,589LE per intersection. Consequently, the total savings approaches 4,361,384.8 LE for one intersection based on the estimated data from the models. According the urban road network size and geometric features similarities between intersections, the economic value of these savings of the network can be assessed.

9 SUMMARY

In this research, the choice procedures of the economic design traffic volume for isolated signal design in saturated flow conditions are investigated. Typical intersection is selected to establish the field work and consequently the analysis. This intersection is selected as four-leg intersection in Cairo CBD area. A traffic count survey was carried out for continuous 14 hours in under normal operation conditions. Volumes were measured by approach and direction and consequently, the traffic fluctuation was obtained and the peak volume and the average off peak volumes were determined. It was investigated that the minimum traffic volume presents 85% of the peak volume. This observation with other features of the locations (i.e. road width, saturation flow) emphasized the continuous over saturation of the intersection over the measuring period. The intersection signal was designed by different pre defined and experimental volumes to enable the choice of the economic volume over the different hours of the day. The computer software "Synchro" was used in this research for signal design. First, each hour volume , including the peak volume, was applied to the intersection as the signal design volume and the associated evaluation measures were estimated. These evaluation measures are total delay, fuel consumption and PI. The PI takes into consideration, in addition to the delay, the queue penalty and vehicle stops. The range of the best cycle length in seconds during the day was identified (40 to 70 sec.). Each value of the cycle length in this range with one sec. increment including the dominated values of optimum cycle lengths (43, 50 and 65 sec) were tested and applied one at a time over the 14 hours of the counting period and the corresponding evaluation measures were assessed. Simple regression relations between traffic volume and the corresponding evaluation measures are drawn to help in testing this approach versus any traffic volume. This analysis showed that the application of the signal timing resulted from using the peak volume as pre timed signal is more beneficial than application of each hour volume as traffic actuated technique. The assessment of the evaluation measures helps in this conclusion. The economic values of the savings in delay and fuel consumption in monetary values were assessed for a hypothetical period of 10 years. If only one intersection were considered, savings in fuel reaches about 662,796 LE and in delay savings reaches 3,698,589 LE with total amount of approximately 4.36 million LE. The size of the urban road network and number of intersections should be considered in the total economic evaluation.

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RESUME

La conception des signaux routiers isolés en espace urbain dépend des flux de trafic mesurés à distance amont sur chacune des rues en direction du carrefour. Puisque les flux sont variables selon les heures de la journée, l’expert doit choisir un contexte économique d’étude pour des signaux isolés. Quand il n’y a que 2 pointes caractéristiques de trafic (le matin et le soir), on retient habituellement l’heure de référence, qui est le résultat de la moyenne des autres heures de la journée. Bien qu’une telle étude n’optimise pas les délais d’attente pendant les deux heures de pointes, cependant elle est bien appropriée pour les autres plages horaires de la journée. Les problèmes essentiels pour les réseaux congestionnés de nombreuses villes dans les pays en voie de développement sont cependant différents. Il y a plus de 2 pointes et Cette réalité soulève la question d’avoir à utiliser les flux maximums pour la conception, mais est-ce encore économiquement raisonnable d’appliquer la conception des situations saturées ?

Ce document traite ce problème de conception et tente de trouver la réponse adéquate à la question posée. A partir de flux mesurés par heure à certains carrefours congestionnés du Caire, des comparaisons seront faites entre la conception du signal dans heures de pointes et la moyenne des autres heures de la journée et chaque heure de reference Les conséquences de ces conceptions seront économiquement évaluées en se basant sur le résultat calculé sur les retards globaux et pertes d’heures/véhicules estimés et la consommation d’essence des véhicules retardés. Des recommandations seront présentées.