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Comparison between Diverging Diamond Interchange and Conventional Diamond Interchange: Case Study in Riyadh City

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Abstract**—**The road users usually suffer from several kinds of congestion and delay especially at intersections. The traffic flow congestion due to increasing traffic volumes can be decreased by implementing some suitable alternative designs of interchanges such as diverging diamond interchange (DDI) and conventional diamond interchange (CDI). In this paper, a comparison between the DDI and CDI in traffic conditions in Riyadh city is conducted. The analysis involved different measures of effectiveness that includes delay, queue length, and number of stops. In this context, each interchange type was evaluated for traffic volumes at certain peak hours using micro-simulation program named as "Synchro". The finding of this study shows that DDI provides a better result when compared with CDI in terms of delay, queue length and number of stops. The control delay for the DDI is approximately one third of the CDI. Also, the queue length for the DDI is about one half of the CDI. Furthermore, the number of stops for the DDI is as one half as the CDI.

Keywords**—**Conventional diamond interchange, diverging diamond interchange, measures of effectiveness, simulation.

I. INTRODUCTION

THE increase in the number of vehicles and travel have affected congestion on many urban areas to the point of desperation. Traffic congestion, especially at peak hour, is a very serious problem. Congestion can be perceived as an unavoidable result of the usage of inadequate transport resources. In the last decades to decrease congestion, the roads were extended to increase the speed and capacity, but the growth of circulation has occurred at a rate higher than expected [1].

The ability to accommodate high traffic volumes safely and efficiently through intersections depends largely on the arrangements presented for handling intersecting traffic [2]. Implementing better designed road junctions is one method that can be used to reduce congestion. Therefore, the interchanges can reduce traffic congestion and improve traffic flow at the same time.

New innovative interchange designs can be developed by engineers to minimize congestion and delays allowing the traffic to move smoothly and safely. an example of such innovative design is the DDI. One of the main goals of the DDI interchange design is to accommodate left-turn movements and therefore eliminate a phase in the signal cycle [3].

The new designs developed, the Synchronized Split-Phasing Intersection and the DDI by [4]. It was observed that the DDI design better than the conventional interchange design.

In the Kingdom of Saudi Arabia, the commonly used type of interchange is CDI. The DDI is somehow an enhanced type of the CDI. CDI consists of four phases of signals, whereas, the DDI has two phases of signals because the through movement is not allowed at the signal, it is already utilized as a free movement through an underpass or bridge. DDI is relatively a new type of design interchanges and it was successfully implemented since 2009 in the United States of America (USA). In 2017, DDI has successfully implemented in two sites in Riyadh city, Saudi Arabia.

The interchange chosen for this case study is DDI at Riyadh city, Saudi Arabia; the first interchange is in the Makkah road with Prince Turki road, and the second interchange in King Khaled road with Prince Saud Ibn Mohammed Ibn Mugrin road. Table I shows the representation for the interchanges of the study site.

TABLE I
REPRESENTATION FOR THE INTERCHANGES OF THE STUDY SITE

Type	Interchange	Notation	
DDI	Makkah road with Prince Turki road	M	M_D
CDI			M_C
DDI	King Khaled road with Prince Saud Ibn Mohammed Ibn Mugrin road	K	K_D
CDI			K_C

II. METHODOLOGY

In order to satisfy the objectives of this paper, the measures of effectiveness such as delay, queue lengths, and number of stops can be used to evaluated and compared between DDI and CDI. The research methodology consists of several stages starting with data collection, preliminary analysis, and validation of the model.

Data were collected from the government departments (Riyadh Municipality, and the High Commission for the Development of Riyadh) and in the field. Field data is comprised of geometric data and traffic data, which is described in detail below.

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A. Geometric Data

Geometric data is related to the detailed dimensions of the roads and interchanges associated with the actual study site. The geometric data consists of a number of lanes and width of lane. Fig. 1 shows the existing geometric design of the interchange MD. The figure illustrates the number of lanes per approach. The width of each lane for the interchange is 3.5 m. The width of Right of Way (ROW) for Prince Turki road in the northern side equal to 60m while in the western side of the road is about 40 m. It is currently controlled by a pre-timed traffic signal and operated with a two-phase traffic signal. Fig. 2 shows the geometric design of interchange M_C before converting it to DDI. The width of each lane for the interchange is 3.5 m. The figure also illustrates the width of ROW for Makkah road and Prince Turki road. It is noted that the width of the ROW for CDI is the same as for DDI. Also, it is controlled by a pre-timed traffic signal and operated with a four-phase traffic signal.

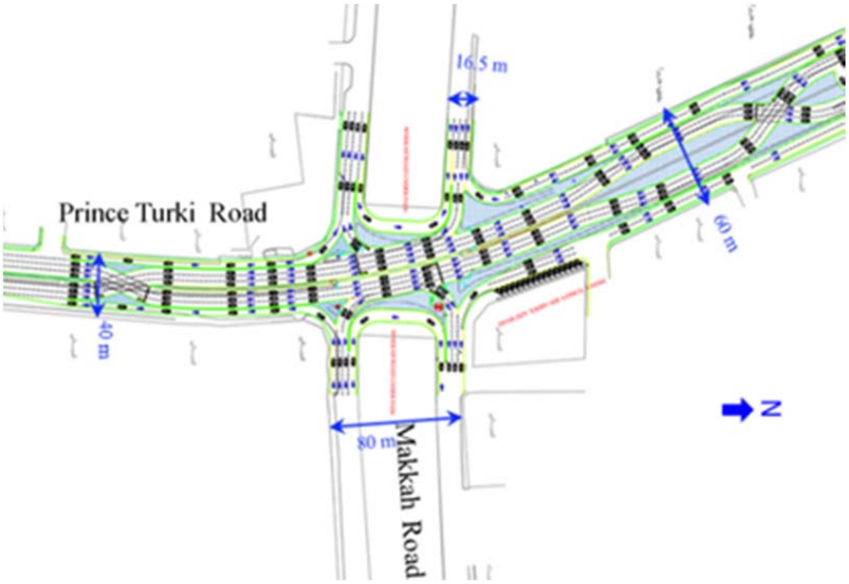

Fig. 1 Existing geometric design of interchange M_D

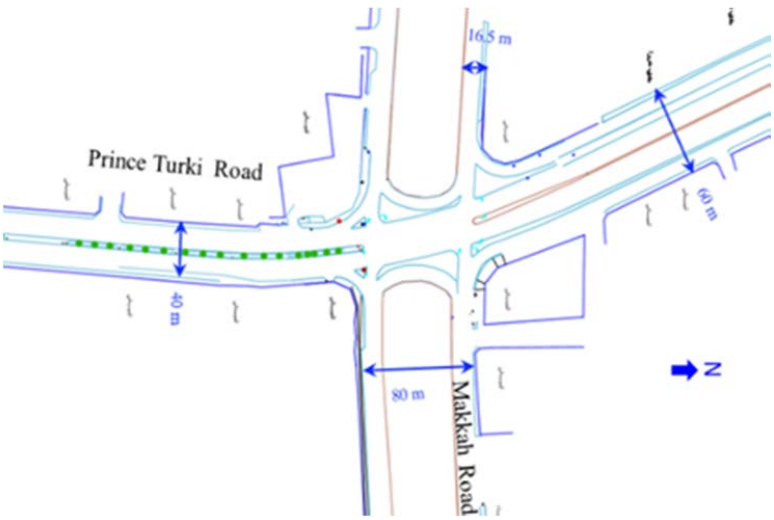

Fig. 2 Geometric design of interchange M_C

Fig. 3 shows the existing geometric design of interchange K_D. The Figure illustrates the number of lanes per approach. The width of each lane for the interchange is 3.5 m. The width of Right of Way (ROW) for the prince Saud Ibn Mohammed Ibn Mugrin road in the eastern side equal to 80 m, while in the western side road about 35 m. It is currently controlled by a pre-timed traffic signal and operated with a two-phase traffic signal. Fig. 4 shows the geometric design of interchange K_C before converting it to DDI. The width of each lane for the interchange is 3.5 m. The figure also shows the width of ROW for King Khaled road with Prince Saud Ibn Mohammed Ibn Mugrin road. It is noted that the width of ROW for CDI is the same as for DDI. It is controlled by a pre-timed traffic signal and operated with a four-phase traffic signal.

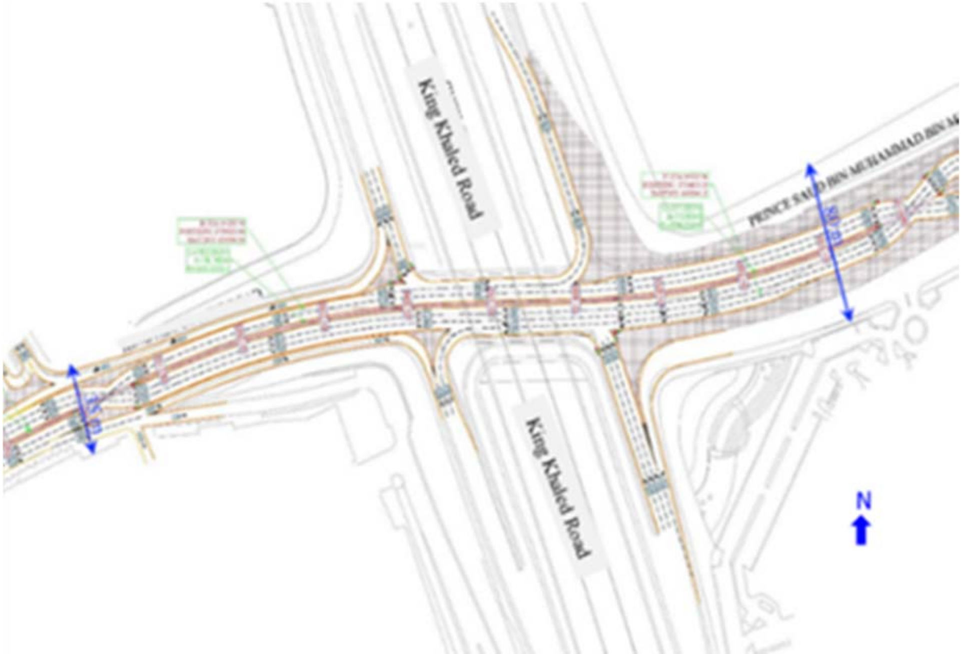

Fig. 3 Existing geometric design of interchange K_D

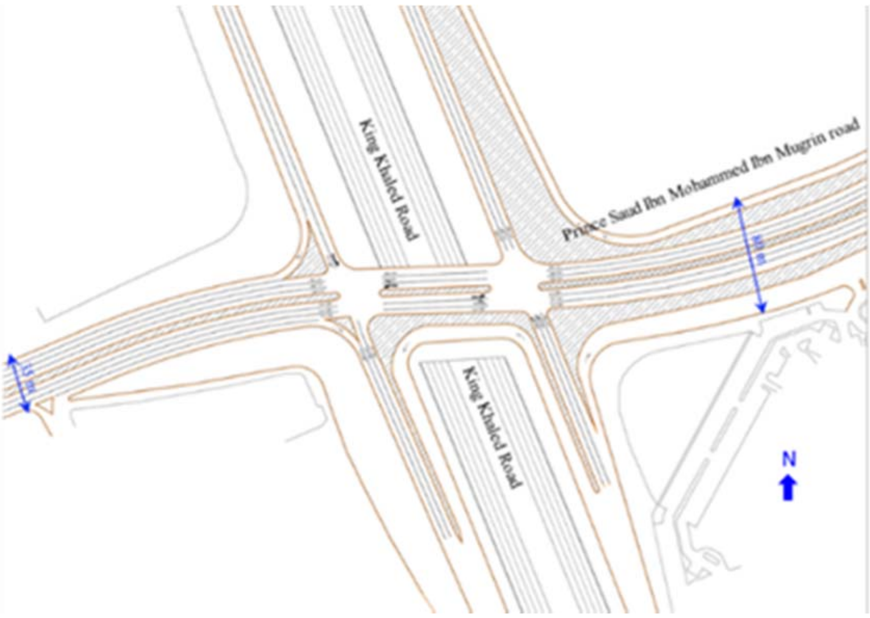

Fig. 1 Geometric design of interchange K_C

B. Traffic Data

The traffic data mainly comprise of the information related to traffic peak hour volume, the percentage of heavy vehicles for traffic movements. This kind of data is further sub-categorized into two groups: (1) off-site data, and (2) on-site data. Off-site data are the traffic regarding previous and existing data which was collected from the responsible government department such as Riyadh Municipality and High Commission for the Development of Riyadh. On the other hand, based on the information from the off-site data, the results of data analysis were used to identify the hourly and daily variations of traffic volume in the study site. Once traffic peak hour was determined, on-site data were collected. The on-site data are detailed information related to traffic movement in each direction of the interchange. Based on the information from the High Commission for the Development of Riyadh, the peak hour for interchange M occurs between 07.00 AM to 08.00 AM.

As soon as the peak hour was identified, the traffic data were collected manually using video cameras which are located on the top of a building near the study site to get a clear view of the interchange movements. Table II shows Peak hour turning movements for M_D. The traffic data related to CDI are obtained from the Riyadh municipality. Peak hour turning movements for interchange M_C are shown in Table III.

TABLE II
PEAK HOUR TURNING MOVEMENT FOR INTERCHANGE M_C

EB				WB			
U	L	S	R	U	L	S	R
472	433	222	76	814	478	241	551
1203				2084			
NB				SB			
U	L	S	R	U	L	S	R
46	229	1092	449	388	1006	499	324
1816				2217			

TABLE III
PEAK HOUR TURNING MOVEMENT FOR INTERCHANGE M_D

EB				WB			
U	L	S	R	U	L	S	R
483	1255	0	73	221	401	0	773
1328				1395			
NB				SB			
U	L	S	R	U	L	S	R
0	386	1426	462	0	1489	589	351
2274				2429			

The peak hour for the interchange K, depending on the information from High Commission for the Development of Riyadh, occurs from 12.00 PM to 01.00 PM. The collection of traffic data was done using video cameras which are located on the top of a building near the study site. Table IV shows Peak hour turning movements for interchange KD. The traffic data for CDI are provided by the High Commission for the Development of Riyadh. Table V shows the peak hour turning movements for interchange KC.

TABLE IV
PEAK HOUR TURNING MOVEMENT FOR INTERCHANGE K_C

EB				WB			
U	L	S	R	U	L	S	R
85	257	279	675	17	376	329	10
1296				732			
NB				SB			
U	L	S	R	U	L	S	R
534	1003	70	738	134	204	46	180
2345				564			

TABLE V
PEAK HOUR TURNING MOVEMENT FOR INTERCHANGE K_D

EB				WB			
U	L	S	R	U	L	S	R
0	355	379	685	0	536	455	200
1419				1191			
NB				SB			
U	L	S	R	U	L	S	R
582	1518	0	624	323	526	0	160
2724				1009			

III. PRELIMINARY ANALYSIS AND VALIDATION OF THE MODEL

The preliminary analysis consists of data related to analysing the measure of effectiveness (traffic delay, queue length, and number of stops), which collected from the field to validate the model. The traffic delay, and 95th queue length, and number of stops were calculated based on the Traffic engineering manual [5]. These data were collected from the field for some approaches for Makkah road with Prince Turki road interchange at peak hour 7.00 AM to 8.00 AM. The summary of the preliminary analysis data was illustrated in Table VI. These data are required to validate the model.

TABLE VI
SUMMARY OF PRELIMINARY ANALYSIS

MOE	NB	SB	WBL
Control delay (sec/veh)	29.9	28.7	21.8
Queue length 95th (m)	156	57	42
Stop/vehicle	0.583	0.500	0.465

The calibration parameter for the Synchro/SimTraffic simulation is already prepared by a previous study [6]. The data used in this study were collected from several pre-timed signalized intersection in Riyadh city. It was observed that the software prediction can be significantly improved by some calibrated parameters namely travel speed, the turning speed, the headway factor and the driver type. The modified parameters were obtained by calibrated travel speed of up to 60 km/h, turning speed to 25 km/h, the headway factor to 0.9 and the driver type towards more aggressive driver population.

In this paper, the validation of the model was conducted using a collected data from study location within the same city which was calibrated by [6] for Riyadh city to check whether the calibrated model parameters are adequate. The purpose of validation is to get confidence in the ability of the model to reasonably reflect real site conditions. The traffic simulation study involves comparisons of simulated results corresponding to field observed data.

As discussed earlier, the selected variables for the validation study were the queue length, delay, and number of stops. There are many statistics of comparisons (e. g., Relative Error (RE), Mean Absolute Percent Error (MAPE), Root Mean Square Error (RMSE), etc.). The Relative Error (RE) criteria was adopted for statistic comparison in this study [7].

The relative error calculates the difference between the observed and the simulated values as a percentage. The RE was determined using (1).

$$APE = \frac{OBS - SIM}{OBS} * 100\% \quad (1)$$

where OBS is observed value, and SIM is simulated value. The observed and simulated values were tabulated for the three MOEs (the 95th queue length, delay, and number of stops). The relative error was calculated for each variable. Finally, the total average relative error was determined as the average of the relative error for the three MOE disregarding the sign (negative or positive). Comparison tables of the measures of effectiveness are shown below in Table VII.

TABLE VII
COMPARISON OF OBSERVED AND SIMULATED VALUE FOR VALIDATION PURPOSES

Approach	Measures of Effectiveness									Total Average RE %
	95th Queue length (m)			Delay (sec)			Number of stop (stop/veh)			
	OBS	SIM	RE %	OBS	SIM	RE %	OBS	SIM	RE %	
NB	156	143	8.3	29.9	27.2	9	0.583	0.53	9	8.8
SB	57	56.1	1.6	28.7	25	12.9	0.500	0.44	12	8.8
WB	42	45.2	-7.6	21.8	19.4	11.1	0.465	0.52	-11.8	10.2

IV. SIMULATION

The micro-simulation modeling was carried out using Synchro program version 10. The base model for the interchanges was coded in Synchro using Figs. 1 and 2 for interchange M, and Figs. 3 and 4 for interchange K. The parameters of Synchro/SimTraffic program which are appropriate for traffic conditions in Riyadh city are used to simulate for CDI and DDI for the selected two study site interchanges (M, and K).

To determine the number of simulation runs, it was required that the variance of a number of performance measures from simulation results be known, which are unknown before simulations. All performance measures of interest are needed to be involved in this calculation and the highest value is the required number of runs. If the current number of runs is already larger than this value, the simulation is ended. Unless, one additional run is performed and then the required number of runs needs to be recalculated. Initially, 10 simulation runs were executed and then the needed number of runs was calculated by using (2) according to the mean and standard deviation of a performance measure of these runs [8].

$$N = \left(t\alpha/2 * \frac{\sigma}{\mu * \epsilon}\right)^2 \quad (2)$$

where μ is the mean and σ is the standard deviation of the performance measures based on the simulation runs which was already conducted; ε is the allowable error specified as a fraction of the mean μ; $t\alpha/2$ is the critical value of the t-distribution at the confidence interval of 1-α. In the calculation process, a 90% confidence interval and a 5% allowable error were used. The initial 10 simulation runs were enough for all the performance measures that were considered. An average of these results was taken into consideration when compared to the performance measures collected in the field.

SimTraffic has an important feature called "Record-Multiple Runs". This feature can record a simulation on multiple runs. A dialog will appear allowing the user to select the number of runs to simulate with every simulation run; the random seed number will change. SimTraffic will provide a statistical average for the multiple simulation runs. This feature was used in this analysis to execute and run the 10 runs with different seed numbers. Ten initial simulation runs for delay per vehicle for the SB approach of Prince Turki road are presented in Table VIII.

From (2) and based on Table VIII, the number of runs can be calculated. For each interchange, five runs were executed for the CDI as well as for each of DDI using different random seeds. Then, the average of the five simulation runs is gained to guarantee the accuracy of the results.

TABLE VIII
TEN INITIAL SIMULATION RUNS DELAY FOR SB APPROACH (PRINCE TURKI ROAD)

c	delay/veh (sec) x	$(x-\bar{x})$	$(x-\bar{x})^2$
1	31.6	-5.09	25.908
2	24.1	2.41	5.808
3	26.4	0.11	0.012
4	23.9	2.61	6.812
5	26.8	-0.29	0.084
6	25.5	1.01	1.020
7	27.0	-0.49	0.240
8	26.6	-0.09	0.008
9	27.4	-0.89	0.792
10	25.8	0.71	0.504
	$\bar{x}$= 26.51		Total =41.189

V. RESULTS AND DISCUSSION

In this section, the results from comparing between CDI and DDI are presented for interchanges M and K. The results of interchange M are exhibited from Figs. 5-7, the figures show that:

The value of control delay per vehicle for DDI is 31.8 seconds, while for the CDI it equals to 84.2 seconds. Accordingly, the control delay for the DDI was about one third of the CDI. As shown in Fig. 5.

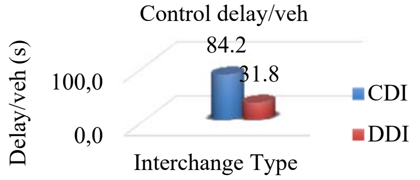

Fig. 2 Control delay per vehicle for interchange M

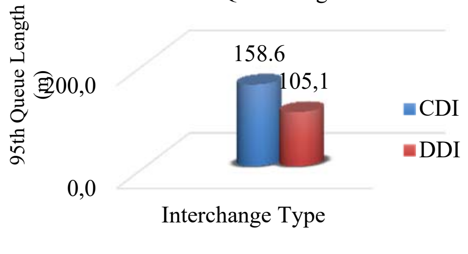

Fig. 3 95th Queue length for interchange M

From Fig. 6, the value of 95th queue length for DDI is 105.1 m, while that of the CDI equals to 158.6 m. The queue length for DDI is approximately one-half of the CDI.

The number of stops for DDI is 0.51, while the conventional diamond gives 1.02. So, the number of stops for the DDI is about one-half of the CDI. As shown the in Fig. 7.

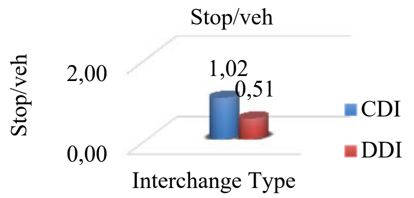

Fig. 4 Number of stops for interchange M

The results of interchange K are shown from Figs. 8-10, the figures show that: From Fig. 8, the control delay per vehicle for DDI is 22.2 s, whilst the value for CDI equals 75 s. It is noted that the control delay for the DDI was approximately one third of the CDI.

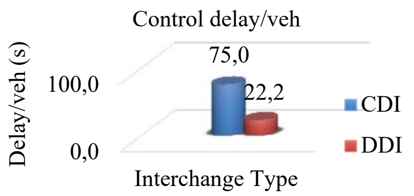

Fig. 5 Control delay per vehicle for interchange K

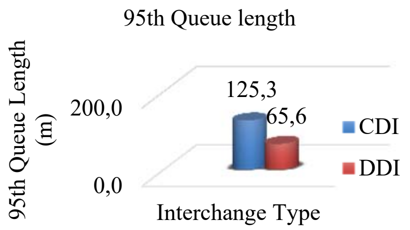

Fig. 6 95th Queue length for interchange K

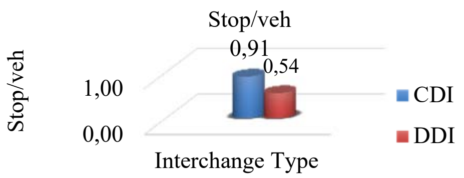

Fig. 7 Number of stops for interchange K

For DDI, the value of 95th queue length is 65.6 m, while the CDI gives 125.3 m. Accordingly, the queue length for DDI is about one-half of the CDI. As shown in Fig. 9.

From Fig. 10, the number of stops for DDI is 0.54, while the DDIs equal to 0.91. Consequently, the number of stops for the DDI is about one-half of the DDI.

VI. CONCLUSIONS AND RECOMMENDATIONS

In this paper, DDI was evaluated and compared to CDI. The following conclusions and recommendations can be made:

- The control delay for the DDI was about one third of the CDI.
- The 95th queue length for DDI is approximately one-half of the CDI.
- The number of stops for the DDI is about one-half of the CDI.
- In general, when viewing the comparisons between the DDI and CDI, the DDI gives a better result when compared with CDI in terms of delay, queue length and number of stops.
- It is recommended the cost-benefit analysis of the CDI vs. DDI. This analysis could show how beneficial and cost-effective each interchange will be.
- Safety analysis is recommended to determine which interchange is the safest alternative.

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