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Transit Signal Priority Algorithm for Urban Corridors

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ملخص البحث

تعانى محافظة القاهرة بجمهورية مصر العربية من العديد من المشاكل المرورية المتمثلة فى الإزدحام المرورى الشديد خاصة فى أوقات الذروة، وقلة مستوى الخدمة للنقل العام؛ مما يؤدى إلى تجنب مستخدمى الطريق الإعتماد علي النقل العام واللجوء الى الميكروباصات وسيارات الأجرة، وقد تناول هذا البحث دراسة إستخدام نظام الحارة الخاصة للحافلات فقط، ودراسة إعطاء هذه الحافلات الأولوية. إن الهدف الرئيسى لهذا البحث هو تطوير وتقييم نظام فعال لإعطاء أولوية المرور للنقل العام يستجيب للظروف البيئية والمرورية في مدينة القاهرة، وذلك من خلال مقارنة كفاءة استخدام هذا النظام و مدى تأثيره على مستوى الخدمة لعدة تقاطعات بمحور مصطفى النحاس الرئيسى الواقع بمنطقة مدينة نصر بالقاهرة الكبرى؛ والذى قد تم اختياره ليكون محلا للدراسة ؛وذلك نظرا لتطبيق نظام الحارة الخاصة بسير الحافلات به.

لقد تم تجميع العديد من البيانات اللازمة للبحث لأربعة تقاطعات رئيسية فى هذا المحور والتى تتمثل فى التقاطعات مع كلاً من :شارع مكرم عبيد، شارع عباس العقاد، شارع الطيران، وأخيرا شارع يوسف عباس. وشمل هذا البحث تحسين استخدام برامج الإشارات الضوئية إلى أقصى درجة ممكنة من خلال استخدام البيانات السابقة ببرنامج Synchro® وذلك لنموذجين أحدهما فى حالة وجود الحارة الخاصة بالحافلات والآخر فى حالة عدم وجودها، و من ثم المقارنة بينهم واستنتاج أفضل برنامج للإشارات الضوئية بكل تقاطع وذلك فى كلا الحالتين. بالاستعانة بنتائج برنامج Synchro®، فقد تم إدخالها على النموذج المُعد لمحور الدراسة ببرنامج المحاكاة VISSIM المقدم من شركة PTV GROUP و مقارنة النتائج فى حالة إستخدام الحارة الخاصة للحافلة أو عدم استخدامها وإستنتاج النظام الأفضل. ومن ثم تم برمجة نظام لإعطاء الأولوية للحافلات باستخدام برنامج © VisVAP 2.16 والذى تم برمجته على إعطاء الأولوية للحافلات فى حالة مرورها على الكاشف الإلكترونى، ولكن بعد مراجعة الزمن الأحمر لجميع الطرق المؤدية للتقاطع بحيث لا يتعدى زمن دورة كاملة، وبمقارنة نتائج مقاييس الفعالية لبرنامج المحاكاة، يمكن استنتاج أفضل نظام للإشارات الضوئية المستخدمة عند التقاطعات، والذى يكون مناسباً لمحور رئيسى مزدحم بالقاهرة الكبرى؛ ويعطى أفضل مستوى خدمة لمستخدمى الطريق.

Abstract:

This research developed actuated signal plans for bus priority using green split optimization and the boundary conditions for cycle lengths done through Synchro® signal optimization tool. A case study was applied on a corridor's segment that consists of four consecutive intersections on Mostafa El Nahas Corridor at Nasr City, Cairo. This corridor besides being one of the most congested corridors in Cairo, has also one of the deployments of exclusive bus lanes in an urban corridor in Cairo, Egypt. Pre-timed signal optimization was carried out using Synchro®. 8.0 for two different corridor geometric configurations: first configuration including exclusive bus lanes in the middle, and the other configuration removing the bus lanes and increasing the capacity by adding one lane in each direction (mixed traffic lanes). The optimization was carried out for split signal phasing plans for AM peak period. This optimization resulted in optimized cycle lengths for each intersection as well as the optimized signal plans for the two optimized scenarios based upon split phasing plans.

PTV Vissim 7.0 traffic micro-simulation tool was used in order to simulate the optimized signal plans for different scenarios: exclusive bus lanes configurations for split signal phasing, and *Transit Signal Priority* (TSP) scenarios, mixed traffic lanes configurations for split signal phasing, TSP, TSP with U-turns. The simulations results

were used to compare the effectiveness of TSP and non-TSP scenarios on the test corridor.
Before analyzing the various TSP scenarios, a sensitivity analysis was carried out in order to decide the best cycle length for the four intersections on the corridor by using the green splits percentages from the optimized signal timings. A tailored bus priority algorithm was created using VisVAP 2.16 © simulation language. Buses were provided priority in the intersection after checking that each red time in each other approach in the intersection is not exceeding the maximum red time.
The developed TSP algorithm used mainly red truncation, green extension, phase insertion, and/or phase rotation according to bus arrival pattern. On the basis of MOEs for TSP and non-TSP scenarios, it was found out that transit signal priority strategy with mixed traffic scenario that includes U-turns and prohibiting left turn movements at intersections was the recommended strategy to use for accommodating bus flows in congested urban corridors.

Keywords: Actuated Signal Plans, Bus Priority Measures, Exclusive bus lanes, Signal Optimization, Transit Signal Priority (TSP).

1. Introduction

Nowadays, most major urban cities worldwide, including Cairo, suffer from severe traffic congestion problems. Deficiencies in roads' design, traffic control devices, random pedestrian crossings, unplanned public transport, cruising for parking spaces, drivers' behavior, and many other factors contributed to the problem leading to a significant deterioration of the network level of service.

Traffic congestion on urban roads is forcing governmental authorities to adopt innovative transportation solutions. One of these solutions is to mitigate traffic congestion through the promotion of public transit via modern technology so that more car users are encouraged to use transit. Exclusive/dedicated bus lanes are internationally recognized as an effective mean to reduce travel delay and as a result, improve the service quality of transit systems.

With exclusive bus lanes, a bus generally can avoid congestion in the normal traffic lanes, thereby reducing its travel times and its variability. *Transit Signal Priority* (TSP) is another strategy to give priority to transit vehicles at signalized intersections and hence, reduce their travel times. The strategy has been used for a long time and it has shown that it could reduce the travel times of buses with only minor negative impacts on conflicting traffic. Through proper evaluation and implementation, TSP can be integrated into existing systems at relatively low costs, (Neves and Pedro, 2006).

1.1 Problem Definition

In Egypt, the traffic environment is very hard. This environment is impacting the traffic stream, causing delay, congestion, high emissions' rates, noise, non-reliability, and lack of pedestrian safety. Therefore, it impacts the movement of public transport causing the buses to have a low LOS as well.

The trend that goes nowadays in Cairo is that people use their cars and microbuses instead of using buses. The world bank Cairo transport 2010 statistics show that the comparison of modal splits in 2010 and 2005 indicates that the share of passenger cars remains the highest and has generally increased since 2005, while the share of microbuses, minibusses and taxis has moderately increased, see figure (1).

On the other hand, the large bus share has dropped (Nakat and Herrera, 2010). The microbuses are used in Egypt more often than buses. The reason for this is that microbuses could easily move around, maneuvering to get to their destinations faster and also loading and unloading faster, the thing that makes people prefer using microbuses more than buses. Therefore, microbuses have a higher Level Of Service (LOS) than buses.

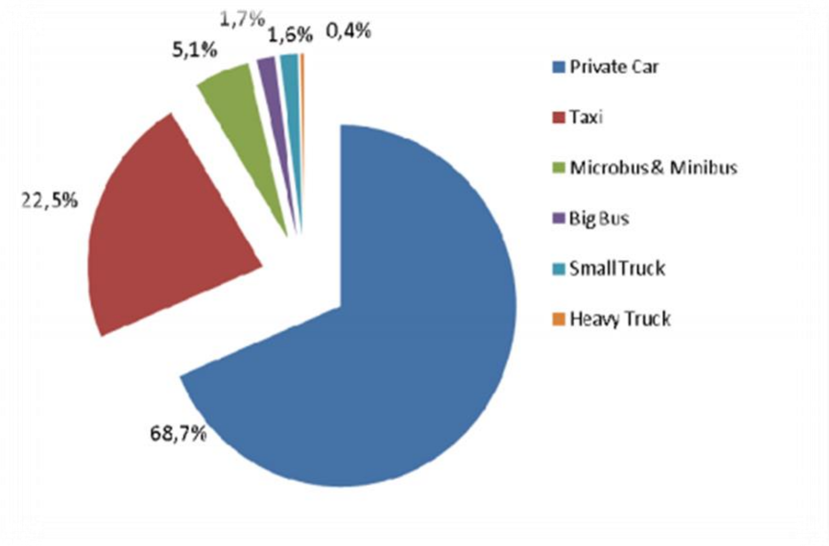

Figure (1): Modal Split in urban corridors in Cairo – (World Bank Cairo Transport 2010)

1.2 Objective

The main objective is to develop and assess effective transit signal priority measurements that are responding to Cairo environmental conditions through developing a robust algorithm.

1.3 Literature Review

TSP is one of the signal control strategies used for intersections. It facilitates the movement of certain vehicles' types (buses, trams…etc.,) across a corridor by making them pass through the traffic signalized intersections with a full or partial priority (Smith et al., 2005).

The objectives of TSP control system are as follow, (An Overview of Transit Signal Priority, 2002):

- To reduce the travel time and the delay of the type of a certain vehicle (e.g. buses).
- To make it more reliable.
- To minimize the impacts of this priority on corridor users (cross street vehicles and pedestrian).

There are three different strategies to implement TSP including passive, active and adaptive signal priority schemes, (Christofa and Skabardonis, 2010). The following figure (2) shows the types of TSP strategies.

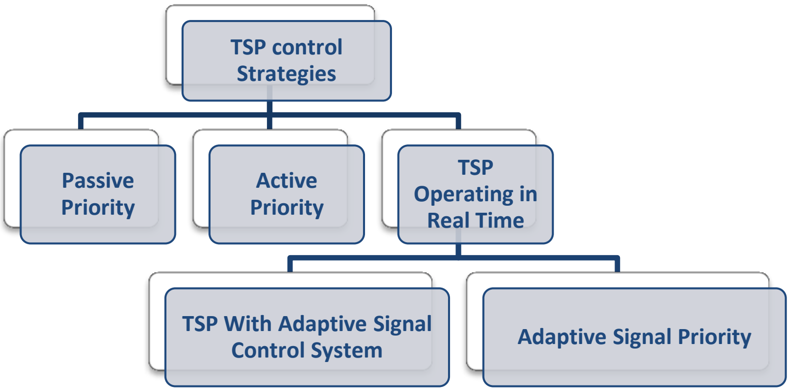

Figure (2): TSP control strategies

Passive priority is a priority which operates with the transit according to a pre-timed schedule and a predictable transit operation with a consistent dwell time. Whether the transit is present or not, it just operates as a pre-timed signal control system with a priority for transit according to the previously gathered data and information for the network. It doesn't require any detection or software system for generating the transit priority system. It works very effectively with high transit frequencies and low traffic volumes (Zeng et al., 2014).

The active priority is a TSP system which is activated only when the detector detects a transit (Stewart and Corby, 2006). Therefore, it generates the transit priority system by changing the signal timing using different strategies such as green extension, red truncation, and/or extra phase insertion, according to the bus arrival pattern.

(El Esawey et al., 2009) compared classic and dynamic TSP strategies by using VAP for TSP algorithm development. The classic TSP strategy includes check in and check out detectors at the intersections, using the green extension and red truncation strategies. The algorithms were run on the model five times for each. The result was that the dynamic TSP strategy outperformed the classic one.

The study of (Vlachou et al., 2010) examined the usage of TSP algorithm in small and medium cities. They evaluated two different scenarios; one with a ten-second green extension and the other with a ten-second green extension in addition to a 15-minute bus headway. The study analysis results in improvement in the overall bus travel time in both routes. No significant delay occurred for the buses in the opposed directions which do not have a priority because of using the green extension TSP system. (Davol, 2001) had used in his research MITSIMLab, a microscopic traffic simulation laboratory which was developed for ITS design and evaluation for simulation. He also used an active signal priority strategy named PRIBUSS "Prioritization of Buses in a Coordinated Signal System" that was developed for use in the city of Stockholm, Sweden. A comparison between the network's travel time without transit signal priority and with signal priority in both 100% AM peak traffic demand and 115% AM peak traffic demand were carried out. There was a reduction in buses' travel times, with a negative effect on other vehicles. (Davol, 2001) also recommended after this study to allow bus priority whenever feasible instead of prohibiting it even if it had a great impact on other vehicles.

(Dion and Rakha, 2003) integrated transit signal priority in their study within the adaptive traffic signal control system using SCOOT (real-time signal control system). Their research concluded that the implementation of TSP system regardless of the traffic control system is beneficial. Greater benefits were obtained to the scenario by offering the only opportunity to approach buses under adaptive controls. Finally, an obvious negative impact was caused by the general traffic. However, it could be minimized by the adjustments of the adaptive control systems to the real observed traffic conditions. The below table (1) shows some examples of TSP implementation experiencing the impact of deployment of transit signal priority in U.S. corridors.

Table (1): Examples of TSP implementation experience in the USA

Author/Location	TSP Strategy	Measure of Effectiveness	Impact of using TSP
(Kishore,) / Arlington, Virginia, USA	Green Extension (5 seconds)	Travel Time	Average travel time was reduced by 10.13%
		Stops	Average bus speed increased by 11.27%
	Red Truncation (5seconds)	Average Delays	Average vehicles speed decreased by 22.68% in cross streets
		Average Speed	Average vehicles travel time increased by 29.82%
(Ova, and Smadi, 2001)/ City of Fargo, North Dakota, USA	Early Green (30-minute transit headway)	Side-street approach person-delay	Early green TSP strategy better than green extension strategy
	Green Extension (30-minute transit headway)	Network person-delay	15-minute headway gave similar results for both TSP strategies
	Early Green (15-minute transit headway)	Bus travel time	Side-street approach person delay for early green lower than green extension strategy
	Green Extension (15-minute transit headway)	Bus delay time	
(Hedden, C. and Kopp, C., 2009)/ JFK South, Hudson County, New Jersey, USA	Green Extension	Intersection Performance	50 intersections were more appropriate to use TSP
	Red Truncation		Only two intersections were less appropriate to use TSP
(Vlachou, and Collura, 2010)/ Burlington, city of Vermont, USA	Ten seconds green extension	Average travel time	Improvement in the overall bus travel time in both routes
		Average delay	No significant delay occurred for the buses in the opposed directions
	Ten seconds green extension but with 15-minute bus headway	Side-street queue	
		Waiting time for outbound buses	No significant delay occurred for the non-transit traffic as well

2. Data Collection

Data were needed to test the base condition along the study corridor; to optimize signal plans for the four studied intersections, to compare different signal plans scenarios simulation results with the base case scenario, and to compare between using exclusive bus lanes or mixed traffic lanes configurations. The following Figure (3) shows the data needed for the analysis.

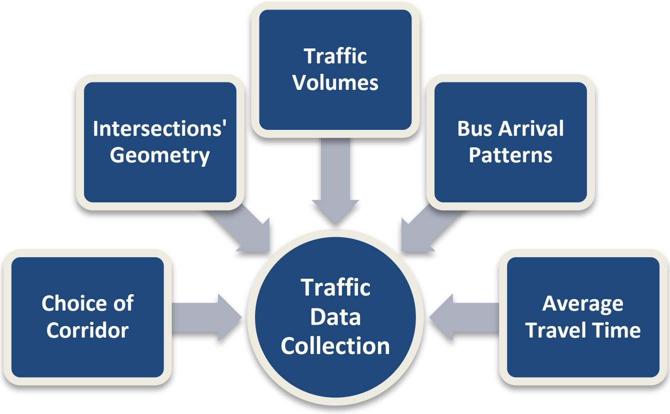

Figure (3): The data needed for the analysis

The data collection process for the above-mentioned data will be carried out before the analysis. The collected data will be used in the following software: Synchro®, PTV Vissim, and VisVAP 2.16 ©. Therefore, it will be collected manually using a team of twenty civil students from the faculty of engineering, Ain Shams University, who worked simultaneously at all the intersections' approaches during AM peak between 8:00 to 9:00 AM. All data collection was carried out on Tuesday 20th October 2015, a normal working day in October.

2.1 Choice of Corridor

Mostafa El Nahas corridor, which is located in Nasr City, Cairo, Egypt, was chosen for the study. This corridor has the exclusive bus lanes that introduced to Cairo traffic network in 2014, (Al Ahram Journal, 2014). The chosen study segment consists of four intersections in a row in this corridor, from the intersection with Makram Ebeid St., passing through intersections with Abbas El Akkad St., and Al Tayaran St., till the intersection with Youssef Abbas St. Also, the corridor's users (pedestrian) suffer from lack of safety while crossing the corridor due to their random crossings and the behavior of the drivers. Figure (4) shows the study segment of the corridor.

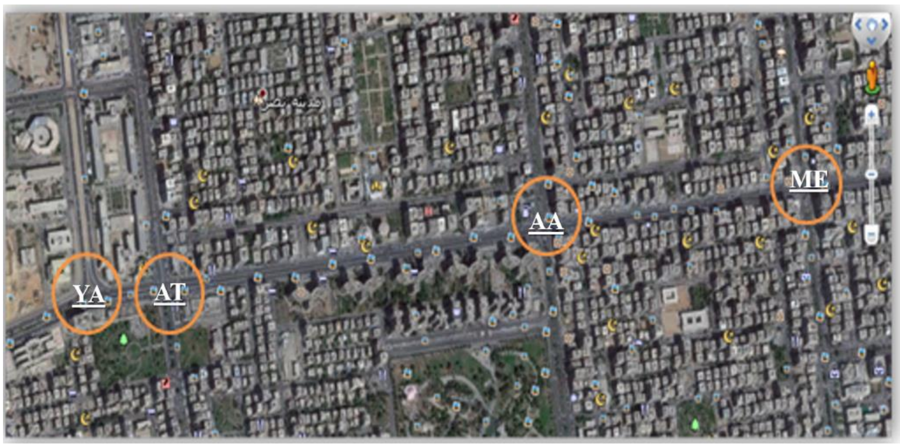

Figure (4): Study segment of Mostafa El Nahas Corridor

2.2 Intersection Geometry

The studied area contains four intersections. Each intersection consists of four approaches. A field visit was carried out in order to get the number of lanes in each approach for each intersection, the existence of channelization, and the existence of medians. Lanes, medians, and pavements widths were measured using Google Earth Pro.

2.3 Traffic Volumes

The traffic volumes' counts were carried out every fifteen minutes. Vehicles were classified as passenger cars and buses. The following Figure (5) shows the total numbers of vehicles expressed in terms of maximum traffic flow rate (Q) in each period in the studied four intersections in the chosen segment of Mostafa El Nahas Corridor.

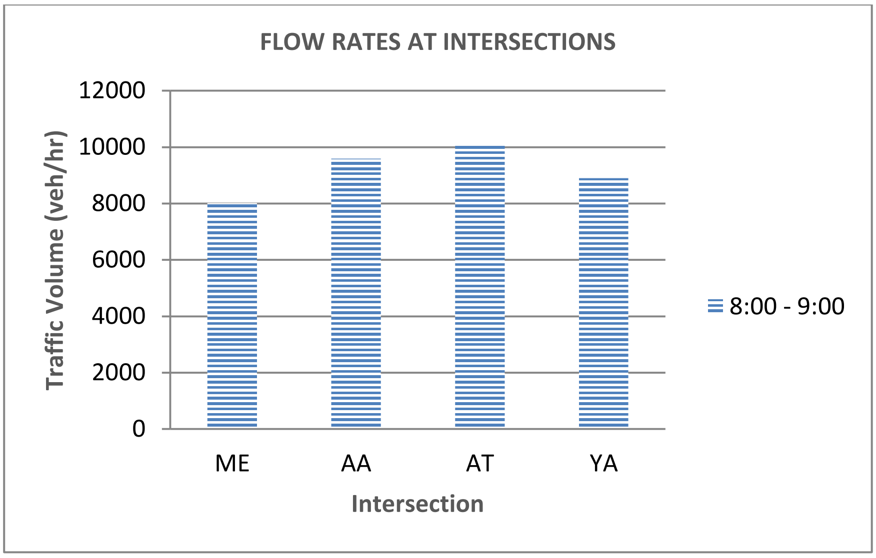

Figure (5): Maximum flow rates at intersections

2.4 Bus Arrival Patterns

The bus arrival times during AM peak were recorded in both directions; Makram Ebeid to Youssef Abbas direction (East to West) and vice versa. They were used to calculate the average bus volume per hour. The following table (2) shows the number of buses in each direction for the study period. It shows that around 2% only of the traffic volumes are buses.

Table (2): Average number of buses in both directions per hour

Buses	Direction	8:00 - 9:00
	ME to YA	49
	YA to ME	45

The bus frequency was measured in order to use it for calculating the average time headway between buses using the following equation, (Roess, et al., 2004).

$$h = \frac{3600}{q}$$

Where:

h: The time headway
q: Buses frequency

2.5 Average Travel Time

By applying the moving observer on the same day and simultaneously with the traffic volumes counts, the travel time between each two intersections in a row was measured several times, and the average travel time between two consecutive intersections was calculated. From these average travel times, the speed of the moving car could be calculated.

3. Optimization of Intersections

After the data collection, the analysis was carried out in three steps; first, optimizing the current and pre-timed scenarios, second, micro-simulating the optimized scenarios, and third, introducing new TSP scenarios in the micro-simulation software and comparing them with the pre-timed scenario. The used software for optimization was Synchro® 8.0, for micro-simulation was PTV Vissim 7.0-16, and for coding the TSP algorithm was VisVAP 2.16 ©.
Synchro® 8.0 was used for the four intersections optimization of the study segment of the corridor, Synchro® 8.0 is macroscopic traffic software that uses the capacity analysis in optimization, using High Capacity Manual 2000 (HCM 2000 – chapter 16). It was chosen to perform the optimization of the study segment of the corridor containing the four intersections for the AM peak for two corridor geometries: exclusive bus lanes configuration and mixed traffic lanes configuration.

3.1 Exclusive Bus Lanes Configuration Optimization

The exclusive bus lanes network in the study corridor was optimized using Synchro® 8.0 for the AM peak period. Split phasing plans were used in the four intersections using maximum possible cycle lengths of 250 seconds. Those split phasing plans were assumed to be the base current case for those four intersections in the study segment of Mostafa El Nahas corridor.

After running the software for all of the four intersections. Both cycle lengths and phases were optimized for split phasing scenarios. The optimized phases timings and cycle lengths are shown in the following table (3).

Table (3): Split phases timings and cycle lengths – AM peak

AM peak					
Phase time	North approach	South approach	East approach	West approach	Cycle length
ME	54	38	82	66	240
AA	49	57	75	59	240
AT	45	60	63	72	240
YA	53	-	85	102	240

Average delay and levels of service for each intersection were extracted as preliminary results of the optimized intersection to compare the signal types effect and traffic volumes variation. The results showed enormous delays, above 80 seconds by hundreds, in all the intersections in the AM peak period; and it gave LOS of 'F' in all the intersections.

3.2 Mixed Traffic Lanes Configuration Optimization

After using the pre-build mixed traffic lanes network consisting of the four intersections in the study corridor and after adding a lane for each direction instead of the exclusive bus lanes, the network was optimized using Synchro® 8.0 as done before for the exclusive bus lanes configuration.

The same phasing scenarios were used and optimized for AM peak period with maximum possible cycle lengths of 250 seconds. Both cycle lengths and phases were optimized for the split phasing scenario. The optimized phases timings and cycle lengths are shown in the following table (4).

Table (4): Split phases timings and cycle lengths – AM peak

AM peak – Split					
	North approach	South approach	East approach	West approach	Cycle length
ME	58	41	74	72	245
AA	54	63	73	55	245
AT	54	63	55	73	245
YA	56	-	79	105	240

Average delay and levels of service for each intersection were also extracted from Synchro® 8.0. The results showed also enormous delays, even after changing the network to mixed traffic lanes configuration and increasing the capacity of Mostafa El Nahas Corridor by adding a lane in each direction. All the intersections gave LOS of 'F' for split phasing.

4. Micro-Simulation Analysis

After the pre-timed signal optimization that was carried out for different scenarios, PTV Vissim 7.0 was used for micro-simulation analysis. PTV Vissim is the world's leading microscopic simulation software that is time step-oriented and a behavior-based tool. PTV Vissim is used for modeling urban networks, rural networks, and pedestrian as well, (Mathew and Rao, 2007).

To start the simulation on PTV Vissim 7.0, the study segment network for both exclusive bus lanes configuration and mixed traffic lanes configuration should be built on PTV Vissim. As done before on Synchro®, the intersections geometry was used from the previously collected data. The simulation was conducted for the AM peak period, using the optimized signal plans for the fixed signals. The following figure (6) shows the simulated scenarios.

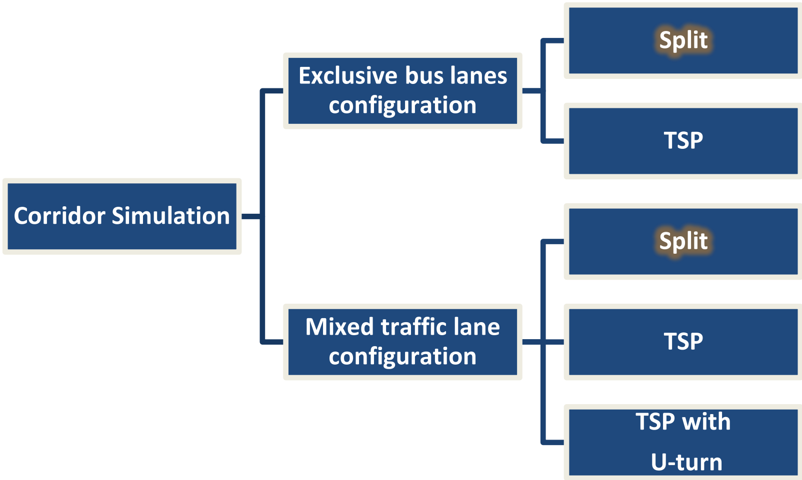

Figure (6): The simulated scenarios using PTV Vissim 7.0

PTV Vissim was run five times for each of the above-mentioned scenarios. The MOEs were extracted from PTV Vissim for each scenario, taking the trimmed weighted average in each measure of effectiveness.

4.1 Exclusive Bus Lanes Configuration with Split Signal Phasing

Using the optimized signal timings which resulted from Synchro®, a lot of iterations were carried out to decide the best sequence of the signal phases in the signal plan; that gives the least delay values using the split signal phasing strategy. The MOEs of average vehicles delay, average bus delay, and average vehicles network performance were extracted from the PTV Vissim output measurements, and the trimmed averages were calculated; in order to use it to evaluate each scenario. Table (5) shows the summarized resulted MOEs for this scenario.

Table (5): Resulted MOEs for exclusive bus lanes configuration with split signal phasing

Measure of Effectiveness (MOE)	Value
Network performance	330 seconds/vehicle.
Least weighted average delay/Direction	289 seconds/vehicle/ Al Tayaran St., South-North direction.
Highest weighted average delay/Direction	959 seconds/vehicle/ Mostafa El Nahas corridor's West-East direction.
Average bus delay along Mostafa El Nahas corridor	East-West direction towards Ring Road: 347 seconds/bus, West-East direction towards 6th of October Bridge: 465 seconds/bus.

The previous table shows high network performance represented by vehicles delay, high travel time, high average vehicle delays for all measurements' directions, and also high bus delays along Mostafa El Nahas corridor, for both directions.

4.2 Mixed Traffic Lanes Configuration with Split Signal Phasing

After micro-simulating the exclusive bus lanes configurations, the mixed traffic lanes configurations took place in simulation. The pre-prepared network for mixed traffic lanes configuration was used. And exactly the same procedures that were done before in the previous configuration were taken place in this configuration as well. The MOEs were extracted and summarized in the following table (6).

The measurements gave high values of average delays; above 240 seconds/vehicle for all the measurements. The weighted average bus delay for the two directions of the corridor increased more than the previous exclusive bus lanes configuration.

Those results were logical because the exclusive bus lanes were removed and the buses have to mingle with other types of vehicles. In contrast with the exclusive bus lanes configuration, buses drive in constant speed without any lane changing or conflicting with other vehicles along the links; which cause massive delays when exist.

Table (6): Resulted MOEs for mixed traffic lanes configuration with split signal phasing

Measure of Effectiveness (MOE)	Value
Network performance	310 seconds/vehicle.
Least weighted average delay/Direction	232 seconds/vehicle/ Makram Ebeid St., South-North direction.
Highest weighted average delay/Direction	1116 seconds/vehicle/ Mostafa El Nahas corridor's East-West direction
Average bus delay along Mostafa El Nahas corridor	East-West direction towards Ring Road: 1263 seconds/bus, West-East direction towards 6th of October Bridge: 879 seconds/bus

4.3 Exclusive Bus Lanes Configuration with TSP

4.3.1 Sensitivity Analysis

On the basis of the following methodology shown in Figure (7), the MOEs of network performance and nodes' delays were extracted. The trimmed averages were calculated and represented in the following Figures (8) and (9), showing the average nodes' delays and the average network performance consecutively.

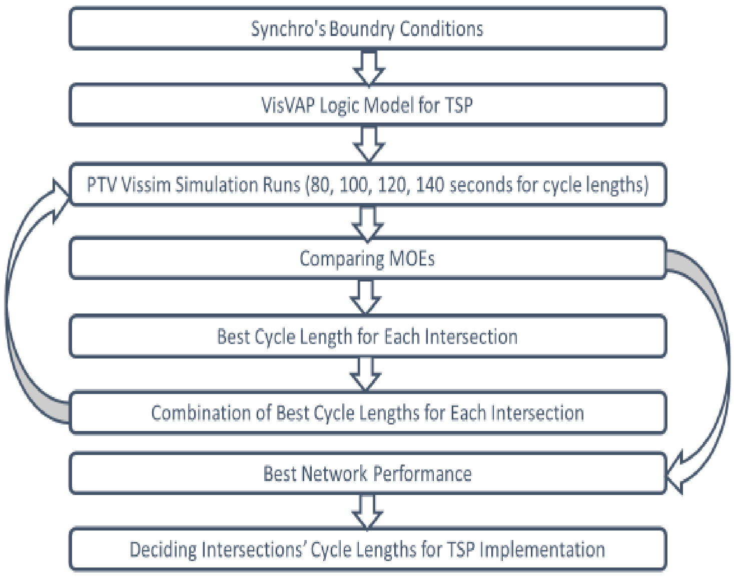

Figure (7): Methodology used for cycle lengths sensitivity analysis

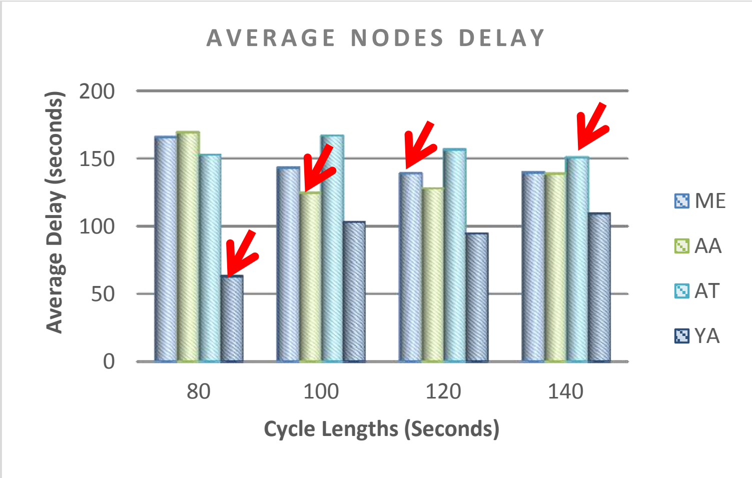

Figure (8): Average nodes delay comparison in (seconds/vehicle) for different cycle lengths – Exclusive bus lanes configuration with TSP

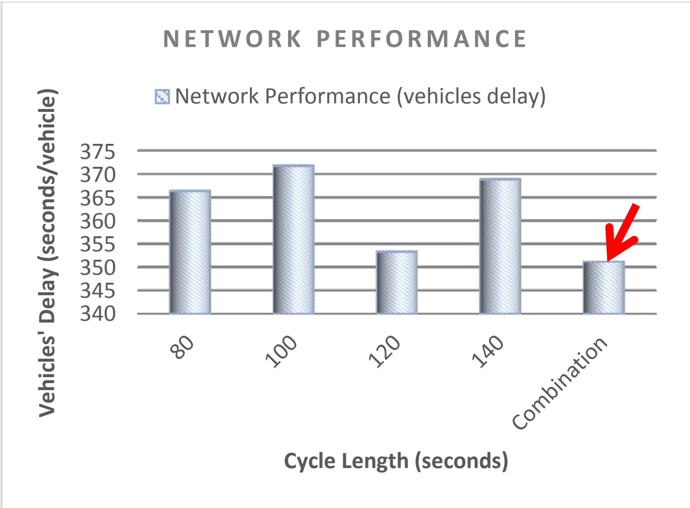

Figure (9): Average network performance comparison in (seconds/vehicle) for different cycle lengths – Exclusive bus lanes configuration with TSP

As a result, it was concluded that the best MOEs for the exclusive bus lanes configuration was based on the following cycle lengths: 120 seconds for Makram Ebeid intersection, 100 seconds for Abbas El Akkad intersection, 140 seconds for Al Tayaran intersection, and 80 seconds for Youssef Abbas intersection. This combination of cycle lengths was chosen to be used in the TSP analysis for the exclusive bus lanes configuration; as it gave the best MOEs.

4.3.2 TSP Analysis

TSP analysis was carried out by using the optimized signal timings' percentages (boundary conditions) on VisVAP 2.16 © logic, and by inputting both the (*.PUA) and (*.VAP) files on PTV Vissim 7.0 signal controllers. The following table (7) shows the resulted MOEs from the simulation. The network performance was higher than in the same exclusive bus lanes configuration without TSP.

Table (7): Resulted MOEs for exclusive bus lanes configuration with TSP

Measure of Effectiveness (MOE)	Value
Network performance	363 seconds/vehicle.
Least weighted average delay/Direction	77 seconds/vehicle/ Mostafa El Nahas' East-West bus lane. And 79 seconds/vehicle/ Mostafa El Nahas' West-East bus lane.
Highest weighted average delay/Direction	959 seconds/vehicle/ Abbas El Akkad's South-North direction.
Average bus delay along Mostafa El Nahas corridor	East-West direction towards Ring Road: 77 seconds/bus, West-East direction towards 6th of October Bridge: 79 seconds/bus.

In this scenario, it was noticed that the average delay for exclusive bus lanes configuration and both parallel directions of Mostafa El Nahas corridor decreased. The increase in delay occurred in the opposed directions (North and South directions) that don’t have priority. Focusing on the bus delay only, it was found that the weighted average bus delays were very low compared to the previous average bus delays for non-TSP scenarios. However, it was logical for those values to have such a deduction because in this case, bus dedicated lanes existed with an implementation of signal priority that was given to buses as well.

4.4 Mixed Traffic Lanes Configuration with TSP

4.4.1 Sensitivity Analysis

The second scenario was the mixed traffic lanes configuration, and the same procedures of sensitivity analysis were carried out as previously done in the bus lanes configuration, based on the methodology shown previously in Figure (7).

The charts represent the MOEs of average nodes delay and the average network performance as shown in the following Figures (10) and (11). The least average nodes delay results were higher than those in the exclusive bus lanes configuration. Also, it was noticed that the cycle lengths’ timings were higher as well.

According to the results, two combinations were added to the analysis. The first combination consists of the following cycle lengths (100 seconds for Makram Ebeid and 140 seconds for Abbas El Akkad, Al Tayran, and Youssef Abbas). The second combination consists of the following cycle lengths (100 seconds for Makram Ebeid and Youssef Abbas, and 140 seconds for Abbas El Akkad and Al Tayran).

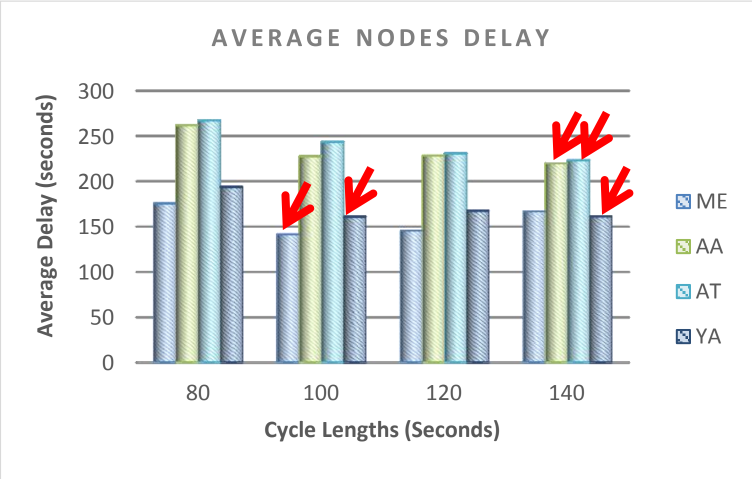

Figure (10): Average nodes delay comparison in (seconds/vehicle) for different cycle lengths – Mixed traffic lanes configuration with TSP

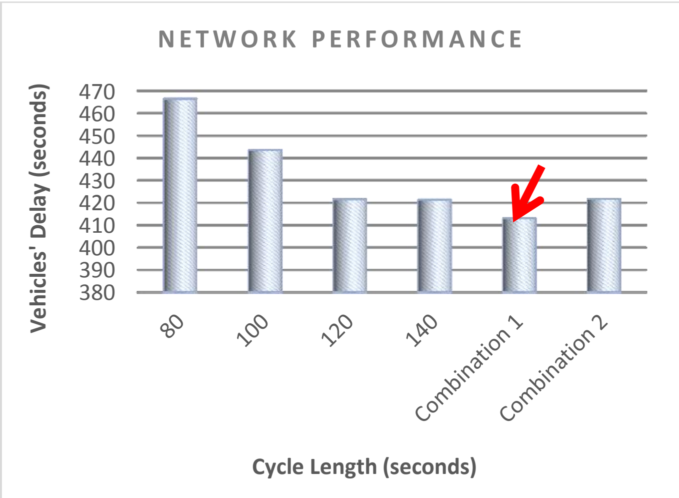

Figure (11): Average network performance comparison in (seconds/vehicle) for different cycle lengths – Mixed traffic lanes configuration with TSP

The results showed that the best MOEs for the mixed traffic lanes configuration was based on the following cycle lengths: 100 seconds for Makram Ebeid and 140 seconds for Abbas El Akkad, Al Tayran, and Youssef Abbas, (first combination's cycle lengths).

The delay was noticed to be more than the first configuration of exclusive bus lanes. This combination of cycle lengths was chosen to be used in the TSP analysis for the mixed traffic lanes configuration; as it gave the best MOEs.

4.4.2 TSP Analysis

The same procedures of TSP analysis were carried out as previously done in exclusive bus lanes configuration. The resulted MOEs were summarized in the following table (8). In this scenario, the MOEs' values were higher than non-TSP scenario's values for the same configuration. Also, weighted average travel time for this configuration gave higher results than the previous exclusive bus lanes configuration.

As for the average delay for buses, it was noticed that removing the dedicated exclusive bus lanes in this configuration resulted in increase in average bus delays.

Table (8): Resulted MOEs for mixed lanes configuration with TSP

Measure of Effectiveness (MOE)	Value
Network performance	435 seconds/vehicle.
Least weighted average delay/Direction	403 seconds/vehicle/ Al Tayran's South-North direction.
Highest weighted average delay/Direction	1358 seconds/vehicle/ Mostafa El Nahas corridor's East-West direction.
Average bus delay along Mostafa El Nahas corridor	East-West direction towards Ring Road: 1328 seconds/bus, West-East direction towards 6th of October Bridge: 352 seconds/bus.

4.5 <u>Mixed Traffic Lanes Configuration with TSP and U-turns</u>

4.5.1 <u>Sensitivity Analysis</u>

The mixed traffic lanes model was updated and the U-turns were added at the following locations showed in Figure (12), and left turn movements at the intersections of Mostafa El Nahas corridor were prohibted. This model was optimized first using Synchro® 8.0 to use the optimized signal timings while running the model on PTV Vissim 7.0.

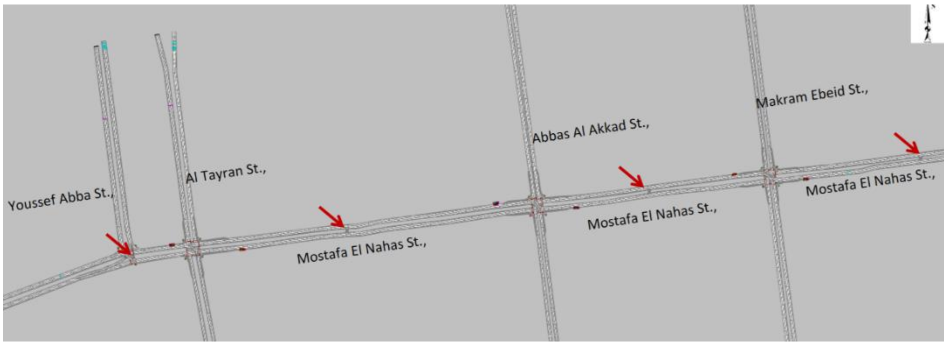

Figure (12): Mixed traffic lanes configuration network with U-turns on PTV Vissim

The sensitivity analysis was carried out based on the previously mentioned methodology, Figure (7). Afterward, trimmed averages were calculated and used to represent the MOEs in the following Figures (13) and (14). These Figures show the average nodes delay and the average network performance consecutively.

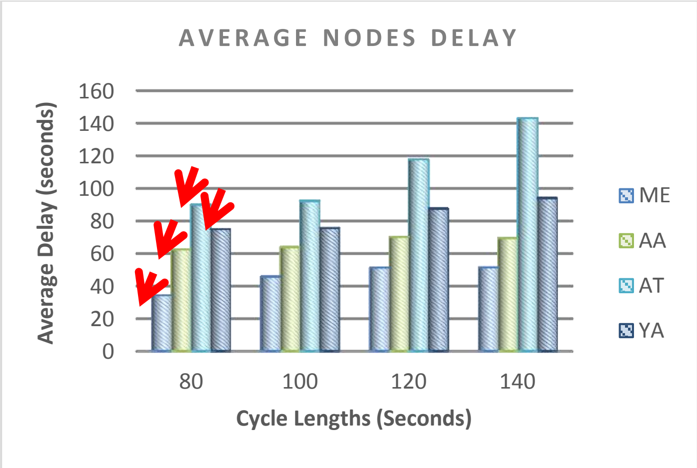

Figure (13): Average nodes delay comparison in (seconds/vehicle) for different cycle lengths – Mixed traffic lanes configuration with U-turns and TSP

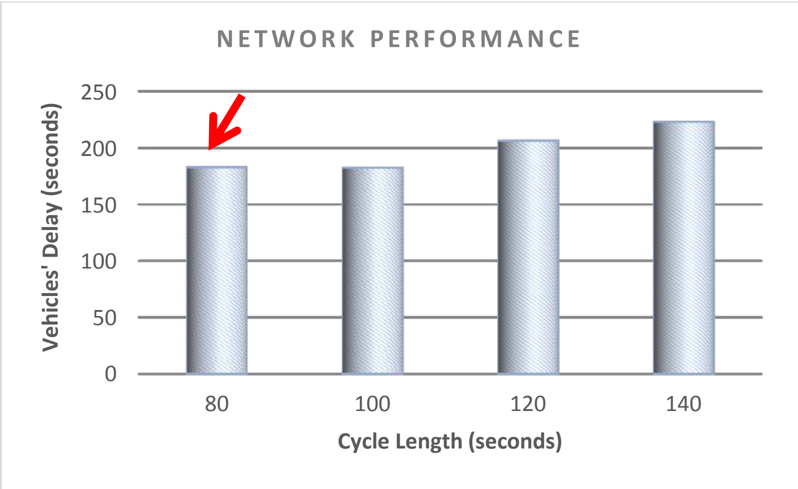

Figure (14): Average network performance comparison in (seconds/vehicle) for different cycle lengths – Exclusive bus lanes configuration with TSP

The least average nodes delay results were lower than the two previous exclusive bus lanes and mixed traffic lanes TSP configurations. Also, it was noticed that the cycle lengths' timings were much lower than the previous scenarios as well, except for Youssef Abbas intersection, as it had the same cycle length in the exclusive bus lanes configuration.

Concluded from the previous charts, the best MOEs for the mixed traffic lanes configuration, with U-turns and prohibiting left turn movements at intersections for East and West direction, was based on 80 seconds cycle lengths for the four intersections.

4.5.2 TSP Analysis

After conducting the same analysis on this scenario, the resulted MOEs showed that the network performance was the lowest among all TSP scenarios. Table (9) shows the MOEs resulted from the simulation of this scenario.

The results showed that the average vehicles delay decreased a lot after using the mixed traffic lanes configuration with U-turns and TSP algorithm. Moreover, it was noticed that the average delay for the bus in both directions of Mostafa El Nahas corridor decreased than the previous mixed traffic lanes configuration without U-turns.

Table (9): Resulted MOEs for mixed lanes configuration with U-turns and TSP

Measure of Effectiveness (MOE)	Value
Network performance	154 seconds/vehicle.
Least weighted average delay/Direction	39 seconds/vehicle/ Abbas El Akkad's North-South direction.
Highest weighted average delay/Direction	622 seconds/vehicle/ Abbas El Akkad's South-North direction.
Average bus delay along Mostafa El Nahas corridor	East-West direction towards Ring Road: 183 seconds/bus, West-East direction towards 6th of October Bridge: 151 seconds/bus.

5. Results

The results from all the previously simulated scenarios were compared to decide the best fit scenario for such a case of a very congested urban corridor located in Cairo (Mostafa El Nahas corridor).

5.1 Average Vehicle Delay Comparison

The following Figure (15) shows the average delay comparison for all previously simulated scenarios. The least average vehicles' delay values were for mixed traffic lanes configuration with U-turns and prohibiting the left turn movements at the intersections of the main corridor, and with the application of TSP in signal controllers.

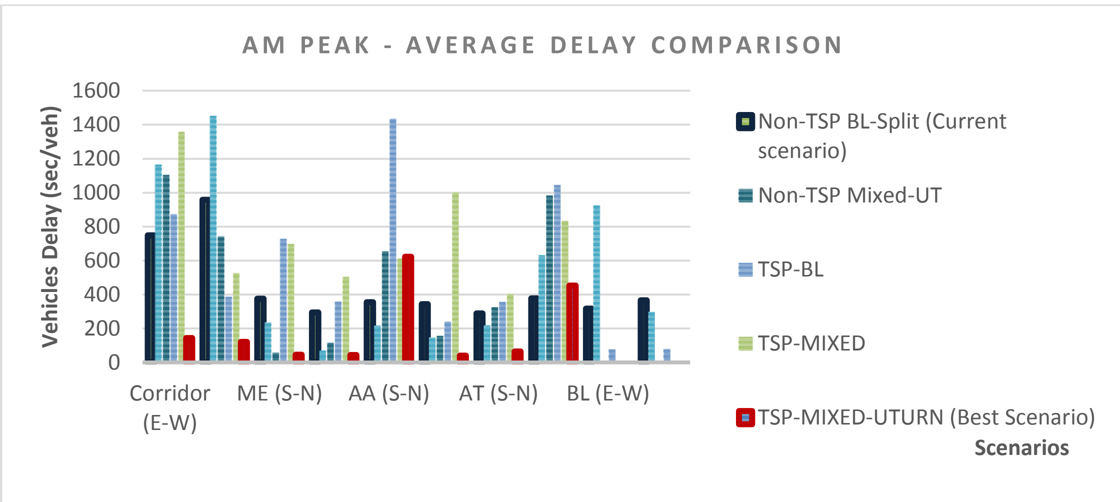

Figure (15): Average vehicles delay comparison for all TSP and non-TSP scenarios

5.2 Average Bus Delay Comparison

Because this research concentrates on the effect of using transit signal priority on an urban corridor in Cairo (Mostafa El Nahas corridor), and especially its effect on buses delays and whole network performance, the average bus delays along Mostafa El Nahas corridor's both directions were a very important MOE to decide the best scenario for this corridor. As a result, extracting only buses delays from the whole types of vehicles delays results were carried out on PTV Vissim 7.0 for each scenario (TSP and non-TSP scenarios). The following chart in Figure (16) was drawn.

The best scenario that gave the least average bus delay in both directions of Mostafa El Nahas corridor was for the exclusive bus lanes configuration with transit signal priority. This scenario gave an average bus delay of 79 seconds/bus for both directions; because of using dedicated exclusive bus lanes with transit signal priority in parallel. This gives the best average bus delay although it is not the best scenario for the average vehicles delay and average travel time.

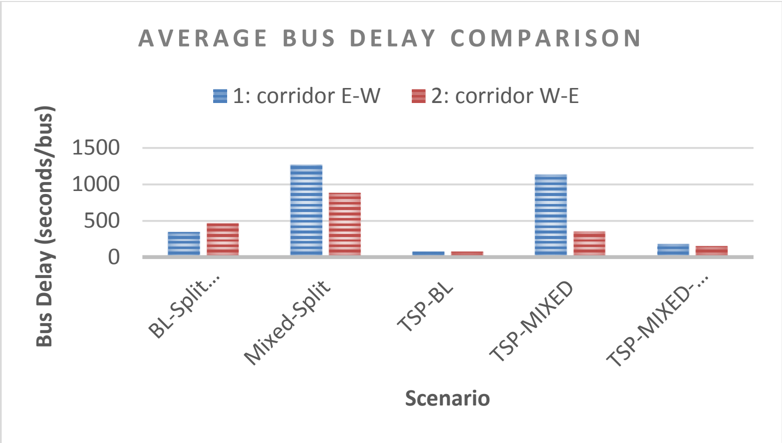

Figure (16): Average bus delay comparison for all TSP and non-TSP scenarios

5.3 Average Network Performance Comparison

Comparing the overall performance of the network is a must to decide the best scenario that gave the least average delay in the whole network. The following Figure (17) shows the comparison between the average network performances delays. As in the previously discussed MOEs comparison, the best scenario was the mixed traffic lanes configuration with U-turns that prohibits left turn movements at intersections in Mostafa El Nahas corridor, with the implementation of TSP.

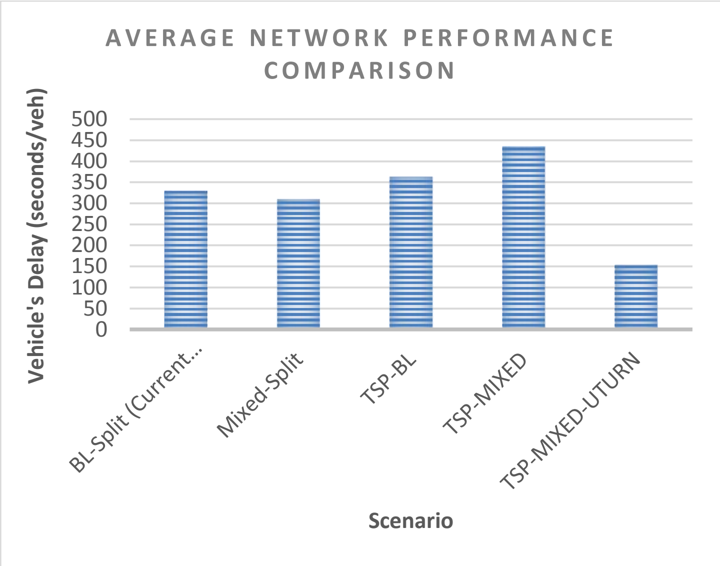

Figure (17): Average network performance comparison for all TSP and non-TSP scenarios

From all the previous compared MOEs, they indicated that the best scenario that gave least average delay along links, nodes, and whole network was the mixed traffic lanes configuration with U-turns and with the implementation of TSP in the model.

6. Summary and Conclusions

In this research, a segment of Mostafa El Nahas Corridor was chosen in order to compare the TSP and non-TSP scenarios. The chosen study corridor consisted of four consecutive intersections that suffer from severe congestion during peak hours. This corridor also has exclusive bus lanes. The research summary and conclusion is as follow:

- An optimization was carried out for the four intersections. Two different scenarios of corridor geometry were optimized using Synchro® 8.0. The first one was the existing scenario for the corridor including the exclusive bus lanes in the middle. The other scenario was the mixed traffic lanes configuration after removing the exclusive bus lanes and increasing the number of lanes by one lane in each direction.
- The optimization was carried out for split signal phasing plans for the AM peak. This optimization resulted in the optimized cycle lengths for each intersection. It also resulted in the optimized signal plans as well.
- The optimized signal plans and cycle lengths were used in PTV Vissim in order to micro-simulate the fixed signal plans for the two scenarios. The simulation analysis was divided into two main categories: Non-TSP scenarios and TSP scenarios.
- In order to micro-simulate the TSP scenarios, the bus developed priority algorithm was created using VisVAP 2.16 ©. The algorithm was to give the bus the green light when the detector was occupied by it, but only after checking that the red time of all the other approaches didn't exceed the decided maximum red for the intersection.
- The decided cycle lengths for each intersection in TSP scenarios resulted from the sensitivity analysis.

- The developed TSP algorithm uses mainly red truncation, green extension, phase insertion, and/or phase rotation according to the bus pattern.
- The second stage was to micro-simulate the TSP and non-TSP scenarios and compare between them. The best scenario was the mixed traffic lanes configuration with U-turns that prohibit left turn movements at intersections at the main corridor. It gave least average delay along links, nodes, and whole network among all the studied scenarios was the mixed traffic lanes configuration with U-turns and with the implementation of TSP in the model.

6.1 Recommendations

From the previous summary and conclusions of the study, the following is recommended:

- Before implementing TSP, an integrated study should be carried out for the congested corridor. Congestion problems should be decided and traffic congestion reduction measures should be introduced and studied for implementation.
- In order to develop a good traffic management for an urban corridor, the whole reasons of traffic congestion should be determined first such as (on street parking, users' behavior, impacts of activities and new projects... etc.), and solutions for each reason should be introduced.
- Using consolidated traffic management approach that includes bus priority as one of the measures in the consolidated plan, will solve not only bus problems but also other traffic measures that cause congestion.
- The entry and exit points of the whole corridor should be studied so that the traffic flows could be managed.
- The circulation of traffic flows in the local streets around the corridor should be studied; as a part of the traffic management of the corridor.
- Public awareness to people should be done before introducing the TSP system; to ensure that the behavior of the user will be proper towards the new system.
- The implementation of bus priority should be intelligent and introduced to users gradually. In parallel, monitoring the performance should be carried out, and fine-tuning the performance using trial field operation.
- After full implementation of TSP system, monitoring should be carried out periodically and fine-tuning should be carried out along with it, especially seasonal fine-tuning.
- Severe traffic regulations should be applied; in order to prevent the congestion that caused by the drivers' behaviors in Cairo.
- Coordination between intersections with the implementation of TSP is recommended to be included in the future researches.
- The study of the corridor in case of prohibiting through and left turn movements along the intersections, and depending only on U-turns is also recommended to be included in the future researches.

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