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# Optimization Using Simulation of Traffic Light Signal Timings

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**Abstract**

Traffic congestion has become a great challenge and a large burden on both the governments and the citizens in vastly populated cities. The main problem, originally initiated by several factors, continues to threaten the stability of modern cities and the livelihood of its habitants. Hence, improving the control strategies that govern the traffic operations is a powerful solution that can solve the congestion problem. These improvements can be achieved by enhancing the traffic control performance through adjusting the traffic signal timings. This paper focuses on finding various solutions for the addressed problem through the optimization using simulation of traffic signal timings under oversaturated conditions. The system under study is an actual road network in Alexandria, Egypt; where, numerous data have been collected in different time intervals. A series of computer simulation models to represent the actual system as well as proposed solutions have been developed using the ExtendSim simulation environment. Furthermore, an evolutionary optimizer is utilized to attain a set of optimum/near-optimum signal timings to minimize the total time in system of the vehicles, resulting in an improved performance of the road network. Analysis of experimentation results shows that the adopted methodology optimizes the vehicular flow in a multiple-junction urban traffic network.

## Keywords

Modeling and simulation, optimization using simulation, traffic control management, analysis of stochastic systems

## 1 Introduction

Traffic Congestion is a crucial problem in large urban areas characterized by high population densities. The utilization of the cities' road network exceeds its planned capacity, leading to a crushing inflation in the numbers of vehicles waiting to be served in line. Massive queues build up, waiting times increase drastically, and the overall productivity is affected, as the working force may never reach its destination at the right time. The environmental effect also represents another aspect of the problem due to the high rates of fuel consumption, energy losses, toxic exhausts and gas emissions.

There exist three major types of traffic control modes; Chaotic, Pre-timed and adaptive traffic systems. In the chaotic system, the signal timings are fixed through all periods of the day. Chaotic system, currently applied in Alexandria's road network, is the most primitive type of control systems, because it does not consider the balance in the demand-supply allocation problem. Pre-timed systems are more advanced, where adequate time-plan is developed, in order to assign different signal light timings to different periods of the day based on the demand pattern. Each period of the day characterized by an average demand, is given different signalization settings. Finally, the adaptive traffic control system is state-dependent. It can instantly adjust the timing intervals rendered to a specified control point according to the fluctuating demand crossing that point. Data about the demand is collected using modern sensing devices, sent to a controller, which translates these data to a set of correspondent signal timing settings. Selecting the appropriate control strategy that best optimizes the vehicular flow in the network (whether pre-timed or adaptive) is a major issue in traffic engineering (Roess et al., 2010).

This paper's main aim is to minimize the traffic congestion through the optimization using simulation of traffic light signal timings in a road network exhibiting severe traffic density. A case study of a specific road network in Alexandria, Egypt is chosen to test the adopted methodology. The results show a drastic improvement in the network's performance. The paper is organized as follows; Section 2 is a brief review of previous related work and how it has affected our simulation models. Section 3 presents a clear description of the problem statement, the system under study, the data collection and analysis process. A thorough description of the different simulation models implemented; SM1, SM2, and SM3, is given in Section 4. Section 5 shows the experimentation results generated from the different simulation models. The results are further compared to each other in Section 6. The verifications and the validations are demonstrated in Section 7 and are followed by the conclusions in Section 8.

## 2 Related Work

A traffic system is a complex stochastic system that is characterized by a large number of dynamic random variables. Demand patterns change dramatically through all periods of the day and are usually hard to estimate using naive approaches. This certainly adds to the complexity of the problem. Therefore, untraditional methods should be adopted in order to address the problem. Simulation and optimization using simulation is a powerful computational approach that can overcome the complexity of real-life systems. Nowadays, Simulation is nearly indispensable in every traffic control research contribution. It is applied as either a powerful solution methodology through testing the performance of the systems and suggesting better scenarios, or as an evaluation tool for other solution methodologies. In addition, optimization using simulation strives to reach the optimal signalization conditions using specified decision criteria such as the minimization of queue lengths, waiting times, delays, number of stops, maximization of the vehicles throughput or the synchronization of the traffic lights, etc ...

Literature addressing simulation of stochastic systems based on real-time collected data include the work of (Krajzewicz et al., 2005; Kazama et al., 2007; Salimifard and Ansari, 2013; Amborski et al., 2010). However, despite notable improvements, a large broad of the research conducted in the area of traffic signalization control is based on estimated data or does not explicitly mention the use of actual field data (Chin et al., 2011; Stevanovic et al., 2011; Hewage and Ruwanpura, 2004).

Many researchers prefer to carry out simulation and optimization using simulation experiments by means of non-commercial software packages; whether individually developed or open-source software packages (Krajzewicz et al., 2005; Kazama et al., 2007; Ebrahim Fouladvand et al., 2004; Amborski et al., 2010). On the other hand, Commercial-On-The-Shelf (COTS) software packages are also frequently used among researchers (Taale, 2000; Stevanovic et al., 2011; Salimifard and Ansari, 2013; Pengdi et al., 2012). Despite the fact that COTS are costly, the use of commercial software in simulating traffic environment guarantees faster runs, shorter processing times, more reliable results and infinite number of experimentations. The most important advantage of the use of COTS is that they are easily accessible and familiar for every researcher for further contributions.

Ebrahim Fouladvand et al. (2004); Salimifard and Ansari (2013); Hewage and Ruwanpura (2004) were concerned about the problem of signalization control in isolated intersections. They managed to solve the problem effectively offering promising contributions in optimizing the vehicular flow. However, fewer researchers managed successfully to model an urban traffic control network consisting of several multiple intersections, taking into consideration the interdependency between them (Kalganova et al., 1999; Stevanovic et al., 2011; Yun and Park, 2012).

This paper optimizes the overall traffic performance on two major interdependent intersections in a highly populated urban area. Simulation modeling is carried out using a well-known software package ExtendSim, widely used in research activities. In addition, the simulation models developed in this paper are practical rather than theoretical; they are based on an accurate field data collection plan, followed by a statistical analysis of the obtained data in order to reach an effective solution for the congestion problem in a totally stochastic traffic environment found in the city of Alexandria.

## 3 System under Study

The system under study is a road network consisting of two major signalized intersections in Alexandria, Egypt. One of the intersections has a tramway crossing it and therefore we have named it Tramway intersection (T) and the other intersection is on the coastline and therefore has been named Coastline intersection (C). These two intersections have been chosen since they exhibit oversaturation and extreme traffic conditions.

The map of the T and C intersections is given in Figure 1. Intersection T has four control points numbered from 1 to 4 with the T subscript. The first control point ($1_T$) has two branches; $1A_T$ and $1B_T$. These two branches have been given different symbols since they receive a different amount of traffic during simulation. A control point is a point in the network having characteristic demand pattern and whose flow is opposing to one of the existing streams, therefore, signalization is needed to regulate the vehicular flow.

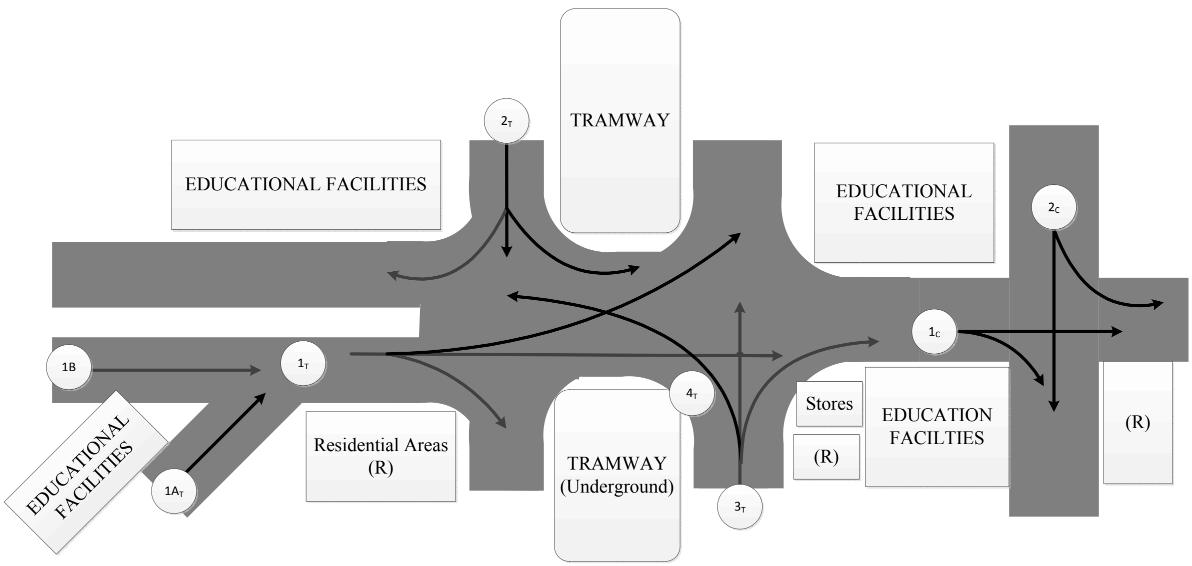


Figure 1: Major road network in Alexandria, Egypt (system under study)

### 3.1 Defining Phase Sequence

This is the process of enumerating all the feasible states or phases and determining the sequence of traffic states in a road network.

Table 1: General form for phase transition sequence.

| State | Control Point | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | ... | M | State Timing |
| A | {G,R} | {G,R} | {G,R} | | {G,R} | $T_A$ |
| B | {G,R} | {G,R} | {G,R} | | {G,R} | $T_B$ |
| B | {G,R} | {G,R} | {G,R} | | {G,R} | $T_C$ |
| ... | | | | | | ... |
| N | {G,R} | {G,R} | {G,R} | | {G,R} | $T_N$ |

Table 1 shows the pre-set state sequence for the given control points. There are two possible states for a single control point; either green (G) or red (R). The amber light timing interval is assumed to be a constant and therefore it is not considered a decision variable in the optimization problem. Each control point inside each intersection in the road network is studied to determine the feasible states and the required phase sequence. Each state is held for a certain amount of time T. Since T varies from each state to another, each T has been subscripted with the state symbol.

### 3.2 Planning for Data Collection

There is extreme variability in the incoming traffic volumes. Therefore, an accurate data collection methodology should be planned carefully to provide a reliable estimate of traffic volumes and dissipation rates.

The day is classified into time periods or intervals having characteristic demand patterns as shown in Table 2. This classification is left to the experience and field observation of the traffic engineer in charge and depends basically on the location of the network under study, which defines the peak and non-peak intervals. Reaching the most accurate classification was an iterative process based on the continuous review of data collectors. Each period of the day has a different demand pattern and as a result, it will be assigned a different value of signal timing. The time periods classified as peak times, indicate the times when vehicular demand is at its maximum, resulting in the largest queue lengths and waiting times, as a result of those times being rush hours.

Table 2: Classification of the day into periods of characteristic demand

| Period | Time Interval | Peak/ non-peak |
|---|---|---|
| 1 | 7-9 AM | PEAK |
| 2 | 9-1 PM | NON-PEAK |
| 3 | 1-5 PM | PEAK |
| 4 | 5-11 PM | NON-PEAK |
| 5 | 11-7 AM | NON-PEAK |

### 3.3 Collected Data

It is essential that data be first filtered using statistical analysis procedures, to eliminate any outliers or exceptional values and to find their correspondent probability distributions. Integration of Statfit (data analysis software, developed by Geer Mountain Corporation) and Microsoft Excel 2010 was used for that purpose as shown. Figure 2 shows a snapshot from the Statfit software while it is being used to fit the collected data into a certain probability distribution.

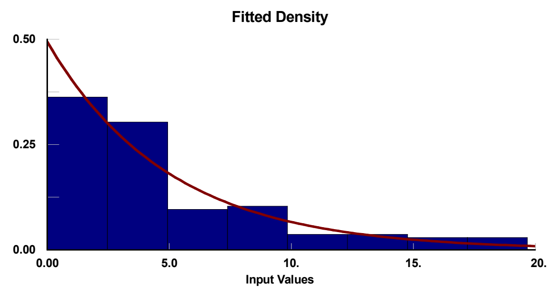


Figure 2: Probability distribution fitting using Statfit.

Actual data were collected and analyzed for the following parameters:

**Arrival rates (vehicles/sec)** $\lambda$: Arrival rates are characteristic system parameters representing the demand pattern at control points.

**Departure rates (vehicles/sec)** $\mu$: Departure rates are characteristic system parameters representing the throughput and the volume capacity at control points

**Left/Right turn volumes and proportions** $V_{secondary}$: Left/Right Turn volumes must be measured, and expressed as a proportion from the total demand pattern of the approach at control points.

**Actual signal timings** $TG_{actual}$ **and** $TR_{actual}$: The actual green timing interval $(TG)$ and actual red timing interval $(TR)$ at control points are very important in order to compare them with the reached solutions and calculate the percentage improvement in system performance (if any).

**Average signal time lost** $TL_{actual}$: This parameter represents the amount of time lost in a state timing due to spill-back and blockages from previous states. The parameter is an indicator of actual system performance and helps making an adequate estimation of the amber signal timing required for state transition and traffic conflict minimization.

**Estimated road capacities** $L$: The geometrical capacity of the road (control point) represents the maximum queue length that can accumulate in this control point without blocking other junctions.

## 4 Development of Simulation Models

This section discusses the development of a series of simulation models using the ExtendSim simulation environment. Three simulation models are developed: SM1, SM2 and SM3. SM1 is a simulation model that accurately represents the actual system under study. It evaluates the current performance in order to identify the problem and illustrate the weak performance of the current situation. Hence, SM2 is developed in order to enhance the performance of the system through carrying out major adjustments to the phase sequence, the signalization process, as well as finding a better set of signal timings based on a heuristic trial-and-error approach. SM3 is a simulation model developed in order to reach the optimum set of signalization settings based on a specified overall performance measure using the evolutionary optimizer of ExtendSim.

## 4.1 Simulation Modeling of the Actual System (SM1)

The simulation model SM1, which accurately represents the actual system, consists of two major signalized intersections in Alexandria, Egypt adopting the chaotic traffic policy.

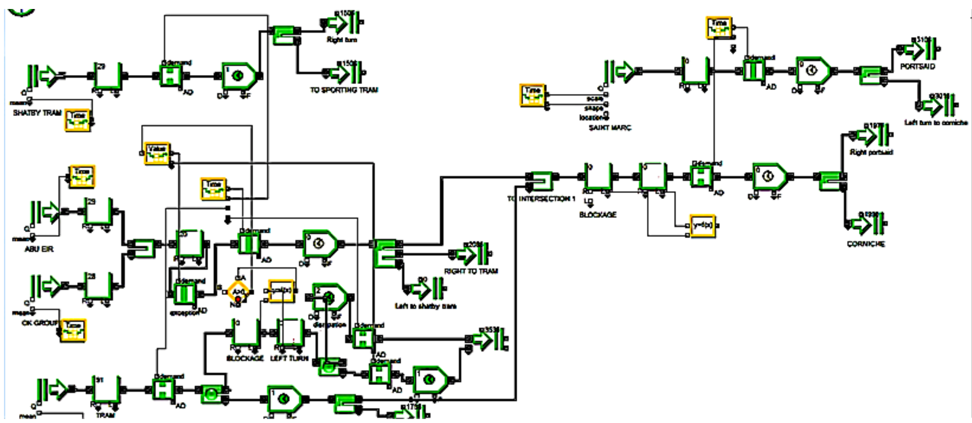

Figure 3: ExtendSim model of the actual system SM1

Figure 3 shows a snapshot of the simulation model developed using ExtendSim to represent the road network under study. Analysis of the average values of queue lengths and waiting times shows that the actual system exhibits weak performance, low dissipation rates, and large queuing lines. Therefore, in the following subsections, different scenarios are proposed in order to improve the actual performance and reduce the traffic congestion at that intersection.

## 4.2 Simulation Modeling for (SM2)

This simulation model SM2 will be based on an accurate pre-timed traffic strategy, where the cycle length, the phase sequence and the signal interval timings are assigned to the correspondent junction over a single period interval. Each period, characterized by a unique demand pattern, will be assigned different signalization settings. Another modification to the system is the development of an adequate phase plan, through defining an additional control point that needs to be involved in the signalization process.

## 4.3 Optimization Using Simulation (SM3)

The optimization of the traffic light signals for the simulated models is performed using the ExtendSim built-in evolutionary optimizer. The decision variables in the optimization process are the traffic state timings $(T_{ik})$ for each control point $i$ inside the intersection $k$, and the cycle times $(CT_k)$ of each intersection $k$ in the network. Equation (1) shows the relation between the red and green traffic signal timings ($TR$ and $TG$) and the state timings $CT$ in any traffic intersection:

$$CT_k = \sum_{i=A}^{N} T_{ik} = (TG+TR)_{j_k}, \forall j = \{1,2,...,M\} \tag{1}$$

Where:

- $k$ : the intersection ID number in a road network.
- $i$ : the state index, as each traffic intersection consists of a number of alternating states.
- $j$ : the control point that needs to be signalized.
- $N$ : maximum number of feasible states in an intersection.
- $M$ : maximum number of control points.

The response variables in the optimization process will be the maximum queue lengths signified by $MQ \in \{MQ_1, MQ_2, MQ_3, MQ_4, MQ_5, MQ_6\}$ at each control point, and the average time spent by a vehicle in the system at each control point signified by $avgCT \in \{avgCT_1, avgCT_2, avgCT_3, avgCT_4, avgCT_5, avgCT_6\}$.
The proposed objective function given in equation (2) tends to maximize the average efficiency of the time spent in system by a vehicle. $\overline{TS_j}$ in equation (2) signifies $avgCT_j$ in our model and on ExtendSim. The time in system is defined as the difference between the time when a vehicle enters the system at any given control point, and the time when it exits it. Based on this definition, the vehicle's time in system is to be measured at each control point for all the intersections in the road network.

$$Max.\ of\ Z = \left( \sum_{j=1}^{M} \frac{\overline{TS_j^*}}{\overline{TS_j}} \right) \times \frac{1}{M} \tag{2}$$

Where:

- $M$ : maximum number of control points
- $\overline{TS_j^*}$ : the best average time in system
- $\overline{TS_j}$ : the actual average time in system

In equation (2), $\overline{TS_j^*}$ at each control point is calculated based on a heuristic approach. For each control point, the most favorable conditions are set (longer green timings and shorter red timings), in order to achieve the shortest time that the vehicle can spend in the system.

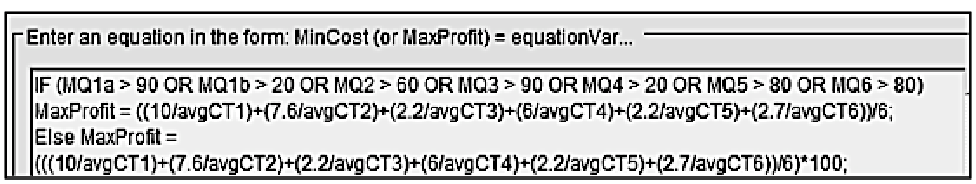


Figure 4: Coding the objective function in ExtendSim Optimizer

Figure 4 shows the definition of the objective function inside ExtendSim Optimizer environment; where, the objective function is written in the form of an IF ELSE equation to set the soft constraints stating that maximum number of vehicles in queue must be within road capacities.
The objection function states that if any of the maximum queue lengths sets are exceeded, then the maximum profit will equal the average of the sum of the best average times in system divided by their respective actual average time in system, for every given control point. Otherwise, if the soft constraints are satisfied, then the maximum profit is equal to the former multiplied by 100 in order to endorse this solution and give it more weight than the solution violating the soft constraints.
The hard constraints are also defined in this model to include the logical limits of the traffic state timings. Extreme small and large values of traffic state timings are rejected, and hence the feasible range of state timings has to be clearly specified as shown in Figure 5. In addition, the difference between two state timings has to be within a certain range. Another hard constraint is that all traffic timings are multiples of ten (Equation 3), which is imposed on all decision variables presented earlier.

$$T_{ik} = 10 \times \text{round}\left(\frac{t_{ik}}{10}\right) \tag{3}$$

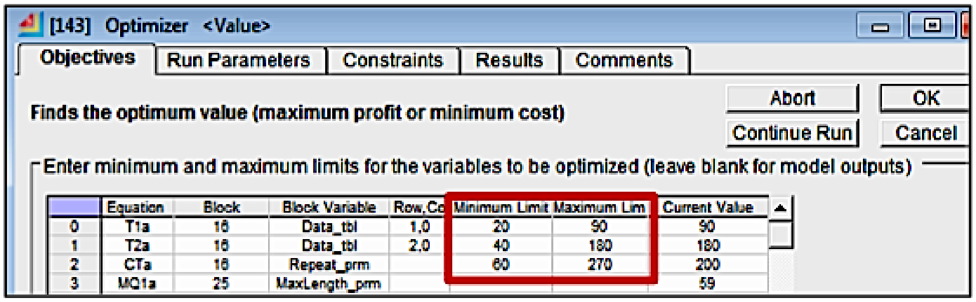


Figure 5: Hard constraints defined

# 5 Experimentation Results

Experimentation is carried out on the developed models. Results are assessed based on the obtained values of the following critical performance metrics:

| | | |
|---|---|---|
| $LQ_{av}$ | : | The average queue length achieved in a single control point for a specified period. |
| $WQ_{av}$ | : | The average vehicular waiting time achieved in a single control point for a specified period. |
| $LQ_{gen}$ | : | The general average queue length for the network under study. |
| $WQ_{gen}$ | : | The general average waiting time for the network under study. |
| $LQ_{gen} \times WQ_{gen}$ | : | An overall performance measure of the network under study. |

## 5.1 Experimentation and Results (SM2)

In SM2, the objective of the experimentation is to obtain a combination of signal timings of each control point that achieves the minimum of queue lengths, waiting times and cycle time in the network from a set of feasible scenarios based on a heuristic trial and error experimental approach.

## 5.2 Experimentation and Results (SM3)

The optimization model SM3 is run at a convergence level of 0.995. The signal timings obtained through optimization using simulation are shown in Table 3. The performance metrics resulting from the optimization experiment are presented in Table 4.

Table 3: Optimized Signal Timings

| | | | Period | | | | |
|---|---|---|---|---|---|---|---|
| Intersection | Control Point | Timing | 7-9am | 9-1pm | 1-5pm | 5-11pm | 11-7am |
| T | 1 | $TG_{1T}, TR_{1T}$ | 40, 40 | 20, 40 | 40, 50 | 20, 70 | 20, 80 |
| | 2 | $TG_{2T}, TR_{2T}$ | 20, 60 | 20, 40 | 30, 60 | 50, 40 | 60, 40 |
| | 3 | $TG_{3T}, TR_{3T}$ | 40, 20 | 40, 20 | 50, 40 | 70, 20 | 80, 20 |
| | 4 | $TG_{4T}, TR_{4T}$ | 20, 60 | 20, 40 | 20, 70 | 20, 70 | 20, 80 |
| | | Cycle time | 80 | 60 | 90 | 90 | 100 |
| C | 1 | $TG_{1C}, TR_{1C}$ | 80, 20 | 80, 20 | 20, 80 | 70, 20 | 80, 20 |
| | 2 | $TG_{2C}, TR_{2C}$ | 20, 80 | 20, 80 | 80, 20 | 20, 70 | 20, 80 |
| | | Cycle time | 100 | 100 | 100 | 90 | 100 |

Table 4: Performance Metrics of the optimized signal timings

| | | Period | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 7-9am | | 9-1pm | | 1-5pm | | 5-11pm | | 11-7am | |
| Intersection | Control Point | $LQ_{av}$ | $WQ_{av}$ | $LQ_{av}$ | $WQ_{av}$ | $LQ_{av}$ | $WQ_{av}$ | $LQ_{av}$ | $WQ_{av}$ | $LQ_{av}$ | $WQ_{av}$ |
| T | $1_{AT}$ | 1.04 | 3.1 | 1.6 | 3.9 | 0.9 | 2.7 | 0.03 | 0.2 | 0.009 | 0.09 |
| | $1_{BT}$ | 0.6 | 3.86 | 0.7 | 3.2 | 0.7 | 2.7 | 0.02 | 0.2 | 0.005 | 0.07 |
| | $1_T$ | 10.2 | 20.8 | 12.9 | 21.1 | 10.3 | 17.3 | 7.6 | 30 | 6.4 | 35.2 |
| | $2_T$ | 9.8 | 22.9 | 6.7 | 16.8 | 10.6 | 25.6 | 4.34 | 11.1 | 7.1 | 35.6 |
| | $3_T$ | 9,7 | 9.6 | 2.3 | 3.5 | 10.8 | 10.8 | 1 | 2.1 | 0.4 | 1.5 |
| | $4_T$ | 6.8 | 17.2 | 2.5 | 9.5 | 5.4 | 13.5 | 5 | 24.8 | 0.6 | 5.9 |
| C | $1_C$ | 27 | 2.4 | 18.4 | 36.3 | 1.3 | 2.4 | 12.9 | 55.4 | 10.6 | 67 |
| | $2_C$ | 2.06 | 58.6 | 1.8 | 2.3 | 30.5 | 38 | 2.5 | 2.7 | 1.6 | 2.3 |

# 6 Analysis of Results

In this section, average queue length and waiting time over the different periods are calculated for each simulation model (SM1, SM2 and SM3) in order to assess the performance of each scenario and compare the obtained results. Table 5 shows the general average queue length and waiting time for each simulation model; SM1, SM2, and SM3.

Table 5: Performance Metrics of the optimized signal timings

| Measure | Simulation Model | | |
|---|---|---|---|
| | SM1 | SM2 | SM3 |
| $LQ_{gen}$ | 12.58 | 8.03 | 6.12 |
| $WQ_{gen}$ | 25.09 | 17.11 | 16.76 |
| $LQ_{gen} \times WQ_{gen}$ | 316 | 138.5 | 102 |

These values can be represented in a comparison bar chat as shown in Figure 6.

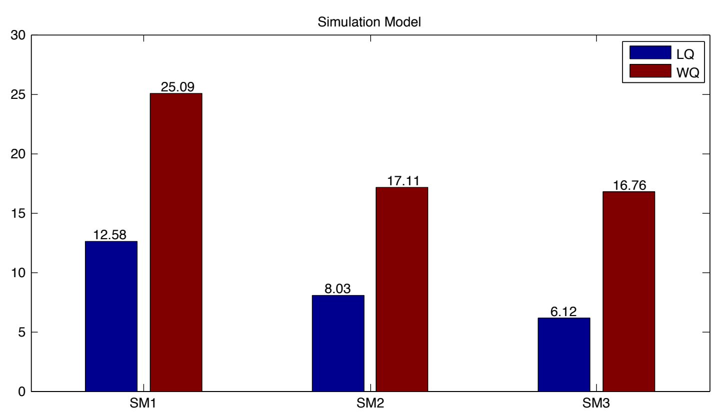


Figure 6: General performance metrics for each scenario.

Hence, the percentage improvements of SM2 and SM3 can easily be computed as shown in Table 6.
Figure 7 illustrates the comparison between the SM2, which is based on simulation heuristic experimentation, and the SM3, which is based on the optimizer, in terms of the percentage improvements they achieved. Both simulation models show improved results, however, the SM3 that uses the evolutionary method for optimization excels according to all performance metrics.

Table 6: Percentage Improvements from the actual system

| Measure | Simulation Model | |
|---|---|---|
| | SM2 | SM3 |
| $LQ_{gen}$ | 36% | 51% |
| $WQ_{gen}$ | 32% | 33% |
| $LQ_{gen} \times WQ_{gen}$ | 69% | 72% |

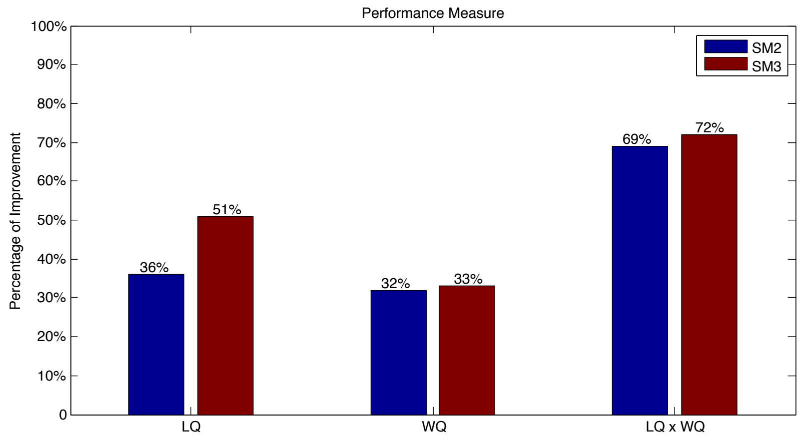


Figure 7: Percentage improvements of SM2 and SM3.

# 7 Verification and Validation of the Developed Models

Throughout the modeling process, various verification and validation steps have been carried out to ensure that the model is an accurate representation of the system under study. The verification of the simulation models has been performed using visual tools such as the 2D and 3D animation tool of the ExtendSim8, and moreover all the results have been tested against all the conditions embedded in the decision blocks.

The validation, on the other hand, has been carried out by comparing the system outputs, such as the queuing lengths and the waiting times generated by the model to the data observed on the field showing insignificant deviations. The values of the queuing lengths and waiting times have been further validated by performing a correlation analysis between them and the arrival rates at each control point. Queuing values have proven to be increasing with the increase in arrival rates and vice-versa, which corresponds to the logical behavior of the queuing theory.

# 8 Conclusions

This paper has shed light on one of the vital problems that threaten the splendor of the beautiful city of Alexandria, and the livelihood of its citizens. The absence of a reliable control strategy that regulates the traffic control operation is one of the main motives of this problem. Computer simulation has been suggested as a reliable solution to handle the problem. The actual performance of the current situation, under the current circumstances, has been simulated (SM1). It has been demonstrated that the current state of the system clearly exhibits weak performance, due to the extreme values of queue lengths and vehicular waiting times that have been detected. Moreover, simulation has been utilized to develop better scenarios for the system. SM2, a proposed simulation model for the system, through making a major change in the road network's phase plan and operational logic, has been suggested and proven to exhibit remarkable improvement in terms of performance metrics. General average queue length has decreased by 36%, while the average vehicular waiting time has been reduced by 32%. In addition, optimization using simulation has arisen as one of the main solution techniques in this paper. Using an evolutionary optimizer, the set of signal timings controlling the road network under study has been optimized and simulated. Favorable results have been attained, signifying the success of the optimization experiments. The general average queue length has decreased by 51%, while the general vehicular waiting time has reduced by 33%. The improvements are considerably large because of the ineffectiveness of the actual traffic management policy currently adopted in Alexandria's road network, which is not based on adequate demand-capacity studies. This paper emphasizes on enhancing the traffic performance through adequate management of signalization settings in order to solve the congestion problem that threatens the splendor of this beautiful city.

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## Biography

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