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Abstract—Traffic congestion is one of the prevailing challenges of modern cities. The negative impacts on educational, economical, health, and social activities are too numerous and great to mention or quantify with absolute accuracy. Efforts to deal with traffic congestions through construction and expansion of new and existing road networks have not yielded the desired result due to the associated cost. The introduction of static (or fixed-timed) and some basic dynamic controllers at isolated point of interest are ineffective and costly. Therefore, this research employed Adaptive Neuro-Fuzzy Inference System, ANFIS-based controller to perform optimized traffic control at nine (9) roundabouts of Kaduna metropolis in a coordinated manner. The results obtained from the simulated scenarios showed that ANFIS-based controller outperformed the 30s and 25s static traffic controllers by 65.97% and 62.32% respectively. An investigation into the choice of ANFIS membership type and number is recommended to determine if better results may be obtained for the considered road infrastructure.

Keywords—Optimization, Multi-connected, Traffic Congestions, Adaptive Neuro-Fuzzy Inference System, Traffic Control Systems, Roundabouts

I. INTRODUCTION

Social, health and economic impact of traffic congestions remains a major concern for both developed and developing nations. Efforts are directed towards the development and implementation of inexpensive, but effective methods of managing and minimizing traffic congestions. Automated Traffic Control Systems (ATCS) is most economical methods for traffic congestions management against the manual traffic management approach as well as the expansion of road infrastructures in terms of number and capacity [1]–[4]. Automated traffic control systems may be static (fixed-timed), actuated or dynamic. The Static Traffic Control Systems (STCS) and Actuated Traffic Control Systems have several disadvantages that makes them unsuitable for implementation in the continuously dynamic traffic densities experienced at different locations and times on the road networks with conflicting right-of-ways. Dynamic Traffic Control Systems (DTCS) are effective real-time traffic control approaches, which consider the dynamism of traffic densities and other parameters. Therefore, DTCS are often implemented on road infrastructures with conflicting right-of-ways such as ordinary intersections or roundabouts [5]–[8].

Roundabouts are special intersections that are circular and have the advantages of higher motorists’ safety and minimize traffic delays compared to their counterpart, the ordinary intersections, where two or more roads crossover themselves. Roundabouts (as well as ordinary intersections) may be signalized or un-signalized. Signalized roundabouts have ATCS installed to manage the traffic flows at the roundabouts, whereas the un-signalized roundabouts allow the motorist to negotiate right-of-ways using ordinary driving (or traffic) rules. The un-signalized roundabouts expose motorists and pedestrians to a higher risk of accidents as patience-less, inexperienced or unknowledgeable drivers have the tendencies of causing confusions that could lead to accidents. Therefore, the implementation of DTCS at Signalized roundabouts further enhances the performance of the roundabouts in terms of safety and minimized delays [9]–[11].

Signalized intersections (both roundabouts and ordinary intersections) are often controlled independently of others; in which case they are referred to as isolated intersections. This isolated control usually suffices as the most cost-effective option when the intersection is isolated in real life. That is, it is too far away from another intersection. However, in the case of multiple connected intersections
that are close to each other, a coordinated control is usually not only cost-effective but often yields better performance [5], [8], [12]–[14].

Isolated ordinary intersections or roundabouts have had STCS and DTCS controllers implemented, which have yielded positive results compared to those that served as benchmarks. However, there is always a need for improvements as the solutions are soon overstretched by the increasing number of vehicles on the roads [15]. Tools such as particle swarm optimization, fluid dynamics models, artificial neural networks, fuzzy logic, adaptive neuro-fuzzy inference systems, etc. have been used in optimizing the efficiency and effectiveness of various controllers used in different fields such as power systems, road safety management tools, isolated and coordinated traffic control systems, etc. [4], [7], [11], [16].

Therefore, this paper considers a case of multi-connected roundabouts having STCS controllers, and attempt to propose an optimized coordinated DTCS controller, which will allow the exploration of coordinated traffic controls for the general good and benefits of road users. The dynamism, as well as optimized phase duration determination, is achieved using ANFIS model.

II. PROBLEM STATEMENT

Kaduna North and Kaduna South Local Government Areas of Kaduna State are two major local governments that make up the Kaduna metropolis. They may be referred to as the economic and social hub of the state following that most Government Ministries, Departments and Agencies as well as major markets, private businesses and schools (both Secondary and Tertiary institutions). The other two Local Government Areas that adjoin to make the metropolis are Chikun and Igabi Local Governments. The implication is that most populace of Kaduna State often have to need to access the Town (as it is often called) for various educational, social and economic activities. For this study, it is from here referred to the Central Area.

In ideal traffic conditions, access to the Central Area is without unnecessary delays. However, this not the case as long traffic queues are often observed on the roads that lead to the Central Area. This is especially true considering the road network from around Queen of Apostles Catholic Church, Kakuri through to Kaduna-Zaria road. The high traffic congestions experienced on this road infrastructure is a result of the fact that ever-increasing population of the Kaduna metropolis live outside of the Central Area but are mostly engaged in educational, social or economic activities taking place in the Central Area. The usual unpleasant effects of traffic congestions are the experience of the motorist, pedestrians and inhabitants along with the said road infrastructure [7], [10].

The continuous efforts to contend the cumulative sum of vehicles in the State has led to the construction and expansion of the said road infrastructure as well as others. These efforts have led to the introduction of Nine (9) roundabouts along with the said road infrastructure due to the advantages of roundabouts over the ordinary intersection. These roundabouts are either signalized or un-signalized. The signalized roundabouts have STCS and DTCS controllers implemented for traffic flow management. All of these efforts are yet to yield the desired expectations of ideal traffic conditions. Traffic congestion persists in the Central Area of the metropolis and requires better solutions to minimize the negative effects that come with it. Therefore, this research proposes coordinated traffic control systems for the Nine (9) roundabouts and develops an ANFIS model to implement a dynamic traffic control system at the roundabouts. This is an attempt to advance the level of effective traffic management along with the considered road infrastructure, which if not done may further increase the level of negative effects already experienced in the region [15].

III. LITERATURE REVIEW

In [17], the theoretical concepts of coordinated control of traffic control systems was presented leading to the design of coordinated traffic control of multiple intersections considering cities of China. In an attempt to design the coordinated traffic control, vehicular average speed, fleet, and traffic turns were considered as the influencing factors. The model of the coordinated traffic control system was simulated in Verkehr in Städten SIMulation model (VISSIM) and the results showed that the delays, average parking time and several vehicles passing the intersections for the coordinated traffic control system showed significant improvement over the existing system.

In [18], a mathematical model for a coordinated traffic control system for multiple intersections. Two-way arterial roads were considered for coordination based on bandwidth approach. Network decomposition techniques were used to minimize the computational complexity of the system. The developed model was simulated in VISSIM and the results were assessed for effectiveness and efficiency in terms of vehicular travel times, delays, stops and queues. The results obtained were considered effective and efficient.

In [19], coordinated traffic control for multiple intersections was developed based on bandwidth progression techniques and different models of pedestrian delays. The coordinated traffic control model considered different traffic conditions of vehicles and pedestrians using bilevel programming problems. The developed algorithm was tested on the VISSIM simulation platform. The analysis of the results revealed that a trade-off between efficiencies of large intersections and progression band; and that delays associated with pedestrians can be minimized.

In [20], the limitation of non-coordinated traffic controllers is acknowledged and a network of local controllers managing the traffic flows of various intersections are built and integrated such that coordination can be achieved by another controller. The local controllers are built as pre-timed signals controls whose signals plans are assessed and coordinated with those of other controllers in the network. The analysis of the system showed promising results leading to a positive conclusion that such hierarchical approach for traffic control coordination may be built and deployed.
In [21], an adaptive traffic control system is developed based on machine learning techniques. Machine learning techniques such as a k-nearest neighbour, decision tree, Bayesian classification, support vector machine and extreme learning algorithms were considered. The proposed system was based on a decision tree algorithm was numerically analyzed for nine ordinary intersections and the results proved the efficiency of the approach.

In [22], the deep reinforcement learning approach is adopted to manage large vehicular traffic networks in cities. The continuous identification of critical nodes of the network using data-driven approaches, while the traffic signal is controlled using deep reinforcement learning leads to the optimality of the traffic management of the network. The developed technique was simulated and the results were outperformed those of the baseline methods.

These researches have considered simple and complex networks of ordinary intersections but none considered the case of roundabouts. Following the advantages of roundabouts over ordinary intersections, a case of coordinated traffic control of multiple roundabouts may yield better results. Therefore, this research sought to use an adaptive neuro-fuzzy inference system approach to manage traffic flows of nine roundabouts that are unique to themselves in terms of designs and number of inbound and outbound traffic flows.

IV. MATERIALS AND METHODS

For this research, the simulation approach is adopted. The road network, vehicular traffic flows, traffic control systems and sensors for detection, counting and tracking of waiting times are all simulated. Therefore, this section presents the materials and methods used in carrying out this research.

A. OpenStreetMap

OpenStreetMap (OSM) is a community project that provides editable map data of the world [23]. It was used in this research to capture the map of the road infrastructure. This is to ensure that the geometric designs of the road network are accurate. The map shown in Figure 1 is a simplified view of the nine roundabouts considered in this research. The roundabouts are labelled with red colour.

B. Simulation of Urban Mobility

Simulation of Urban Mobility (SUMO) is an open project that allows the development of realistic traffic scenarios. SUMO is a suitable tool that is gaining popularity since it allows for the manipulation and control of its objects from suitable Application Programming Interfaces such as Traffic Control Interface for MATLAB (TraCI4MATLAB), Traffic Control Interface for Java (TraCI4J), and others [24], [25]. For this research, the acquired OSM object, traffic light control systems, vehicular traffic flows and the sensors for detection of traffic volumes were implemented in SUMO.

C. MATLAB and TraCI4MATLAB

Matrix Laboratory (MATLAB) was used in the design of ANFIS models and execution of TraCI4MATLAB API to interface ANFIS to SUMO and control the traffic lights control systems of the roundabouts.

The Five Gaus2 Membership Function type ANFIS model had two inputs and a single output as shown in Figure 2. It was trained with Six Hundred and Thirty-Six (636) data elements randomly generated and tuned by expert advice. The training and retraining of the model conceded to an error of 0.0050423. That is, it had an accuracy of 95.5%. The generated twenty-five (25) fuzzy rules produced the surface plot shown in Figure 3.

The inputs were traffic queue lengths and waiting times. The queue lengths and waiting times of vehicles waiting to utilize the roundabouts are fundamentals parameters that influence driving behaviours of a motorist, which has implications on the traffic conditions. Thus, queue lengths and waiting times, which the sensors supply at the end of every cycle and fed as input to the ANFIS model, which

Figure 1: Map Showing Considered Roundabouts

![Image of considered roundabouts map](image-url)
determines the suitable phase duration for the next cycle. Phase duration, as determined by and the output of the ANFIS model is used to set the length of the green wave of the traffic light for a given flow at the roundabouts. The tuning of ANFIS parameters was done using the Hybrid Learning Method, which employs Least-Squares and Gradient Descent Learning algorithms.

Most STCS in Nigeria often use either 25s or 30s green phase duration. Some of the traffic lights control systems on the roundabouts considered in this research use 25s green wave duration while some use the 30s green wave duration. Therefore, both the 25s and 30s systems were developed and tested in this research.

V. SIMULATIONS AND RESULTS DISCUSSIONS

This research developed simulation models of STCS and DTCS. The DTCS was the ANFIS model described in section 3. The models were subjected to the same traffic volumes and their performances in terms of average waiting time (or delays) at the nine roundabouts was assessed. The traffic volumes were set at seventy (70), three hundred and fifty (350) and one thousand, four hundred 1400 vehicles per hour for all major roads of the considered road infrastructure. This represented Under-Saturated Traffic Condition (USTC), Saturated Traffic Condition (STC) and Over-Saturated Traffic Condition (OSTC) respectively. This section presents the simulation models results.

Two STCS simulation models having 25s and 30s green wave phase allocation for the different traffic flows at the roundabouts were modeled and the results of each of those models were compared to that of the ANFIS-based DTCS as shown in TABLE I.

From TABLE I, the results of twenty-five seconds (25s) STCS was compared with those of thirty seconds (the 30s) STCS. The 25s STCS outperformed the 30s STCS when traffic volumes were considered to be USTC and OSTC both in terms of the average waiting time and number of collisions. However, when traffic volumes were set to be saturated, the 30s STCS outperformed the 25s STCS in both cases too.

In terms of maximum queue lengths of waiting for vehicles at the considered roundabouts, it is clear from Figure 4.1A and Figure 4.1B that the maximum queue length for a 30s STCS controller was fourteen (14) vehicles on the North-Southern flows and seven (7) vehicles on West-Eastern flows when traffic volumes were set to undersaturated flows. For the STC shown in Figure 4.2A and Figure 4.2B, comparing the 25s STCS controller to 30s STCS controller showed that the 25s STCS controller had shorter queue (maximum number of the vehicle that waited) at the roundabouts in the West-Eastern flows. However, for the OSTC shown in Figure 4.3A and Figure 4.3B, the 30s STCS controller had the shorter queues in the West-Eastern flows compared to the 25s STCS.

From TABLE I, comparing the results of ANFIS-based DTCS controller to the 30s and 25s STCS controllers showed that the ANFIS-based DTCS outperformed both the 30s and 25s STCS controllers in terms of average waiting times in the USTC, STC and OSTC. ANFIS-based DTCS outperformed 30s and 25s STCS by 84.90% and 82.88% in the USTC; 55.36% and 56.64% in the STC; 66.57% and 61.24% in the OSTC respectively. However, the STCSs no vehicular crash in the case of USTC while the ANFIS-based DTCS had one (1). However, the STCSs had crash cases in the case of STC and OSTC while the ANFIS-based controller had none.

In terms of a maximum number of vehicles that waited at the roundabouts in when ANFIS-based DTCS controller was used, the maximum number of vehicles was only nine (9) against the twelve (12) and fourteen (14) when the 30s and 25s STCS controllers were used in the USTC as shown in Figure 4.1A-Figure 4.1C. In the case of STC, the maximum number of vehicles that waited at the roundabouts was fifty (50) vehicles against the ninety (90) vehicles in the North-Southern flows and twenty-five (25) against thirty-five (35) vehicles in the West-Eastern flows as shown in Figure 4.2A-Figure 4.2C. Finally, in the case of OSTC, the maximum number of vehicles that waited at the roundabouts in the West-Eastern flows was thirty (30) vehicles against fifty (50) and forty-three (43) vehicles in the case of 25s and 30s STCS controllers as shown in Figure 4.3A-Figure 4.3C. Therefore, the general performances of the controllers as shown in TABLE I shows the overall average waiting times for 30s STCS controller was 13.64s, 25s STCS controller was 12.32s and DTCS controller was 4.64s. This implies that the 25s STCS outperformed the 30s STCS by 9.68% while the ANFIS-based DTCS controller outperformed 30s STCS controller by 65.97% and 25s STCS controller by 62.32%. This shows the capability and the potential of the DTCS over the STCS.
TABLE I. COMPARATIVE RESULTS OF SIMULATED MODELS

<table>
<thead>
<tr>
<th>Simulated Models</th>
<th>30s STCS</th>
<th>25s STCS</th>
<th>% Perfor. (25s Against 30s STCS)</th>
<th>DTCS</th>
<th>% Perfor. (DTCS Against 30s STCS)</th>
<th>% Perfor. (DTCS Against 25s STCS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AWT</td>
<td>4.45</td>
<td>3.92</td>
<td>11.79</td>
<td>0.67</td>
<td>84.90</td>
<td>82.88</td>
</tr>
<tr>
<td>NC</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>AWT</td>
<td>9.47</td>
<td>9.75</td>
<td>-2.96</td>
<td>4.23</td>
<td>55.36</td>
<td>56.64</td>
</tr>
<tr>
<td>NC</td>
<td>0</td>
<td>1</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>100.00</td>
</tr>
<tr>
<td>AWT</td>
<td>27.00</td>
<td>23.29</td>
<td>13.77</td>
<td>9.03</td>
<td>66.57</td>
<td>61.24</td>
</tr>
<tr>
<td>NC</td>
<td>4</td>
<td>1</td>
<td>75.00</td>
<td>4.64</td>
<td>65.97</td>
<td>62.32</td>
</tr>
<tr>
<td>Average Performances</td>
<td>13.64</td>
<td>12.32</td>
<td>9.68</td>
<td>4.64</td>
<td>65.97</td>
<td>62.32</td>
</tr>
</tbody>
</table>

a. AWT: Average Waiting Time
b. NC: Number of Collisions

Figure 4.1A: Maximum Queue Lengths for USTC with 30s STCS Controller

Figure 4.1B: Maximum Queue Lengths for USTC with 25s STCS Controller
Figure 4.1C: Maximum Queue Lengths for USTC with DTCS Controller

Figure 4.2A: Maximum Queue Lengths for STC with 30s STCS Controller

Figure 4.2B: Maximum Queue Lengths for STC with 25s STCS Controller
Figure 4.2C: Maximum Queue Lengths for STC with DTCS Controller

Figure 4.3A: Maximum Queue Lengths for OSTC with 30s STCS Controller

Figure 4.3B: Maximum Queue Lengths for OSTC with 25s STCS Controller
VI. CONCLUSION

Since traffic congestions, serious negative implications on the educational, health, social and economic status of every economy, the need to find workable solutions to minimize these effects remains a necessity. This research employed Adaptive Neuro-Fuzzy Inference System in a coordinated manner to solve the traffic problems around nine roundabouts in Kaduna metropolis of Kaduna State, Nigeria. From obtained results, ANFIS-based DTCS outperformed the STCS irrespective of the green phase duration used. However, a closer consideration of the individual results shows that the performance, whether statics or dynamic largely depends on the traffic conditions such as traffic volumes, vehicular allowable speeds, geometric parameters of the road infrastructure under consideration. This research cannot claim to have solved the problem of traffic congestion in its entirety. Therefore, a lot needs to be done to advance the effectiveness of the results of traffic controllers with extensive consideration of the various necessary parameters. Besides, the choice of number and type of membership functions has significant impact on the controller. This presents another opportunity to develop another ANFIS model for traffic control on the considered road infrastructure.

REFERENCES


