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Enhancing Road Traffic Flows Across Multiple Roundabouts Using Adaptive Neuro-Fuzzy Inference System

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Abstract

One of the classical problems of modern cities is traffic congestions. Their negative effects on health, education, and economy cannot be overemphasized. The Kaduna metropolis, which has eight roundabouts and one underpass between Kakuri and Hayin Banki often experience traffic congestions and efforts, which include un-signalized and static-timed signalization at the roundabouts have proven to ineffective. However, no application of computational intelligence tools, which are dynamic, adaptive and have proven to better at effective scheduling of traffic flows. Therefore, this research proposes and developed traffic controllers based on adaptive neuro-fuzzy inference systems' clustering methods. The grid partitioned, subtractive clustering and fuzzy C-means clustering controllers were used in a simulation of urban mobility traffic simulation and the results showed that all the ANFIS-based dynamic controllers essentially outperformed the usual 30s and 25s static controller in terms of minimization of vehicular average waiting time. The grid partition controller performed best as it minimized the average waiting time by over 24% over the 30s controller.

Keywords: ANFIS, Roundabout, traffic congestions, Kaduna

1. Introduction

Traffic congestion is one of the classical problems associated with modern cities. This is due to the exponential growth in the number of vehicles being owned by individuals and corporations without a commensurate growth in the number and capacities of roads in the cities. The challenges associated with traffic congestions have extant implications on the economic, health and social wellbeing of the populace of those cities. Therefore, a lot of research efforts have been directed towards solving this classical problem (Inţă, 2017; Zachariah, Odion, & Saidu, 2020). Increasing the numbers and capacities of roads seeks to minimize traffic congestion problems within cities. However, the cost associated with the construction of roads is usually too expensive; besides, it increases the complexity of road networks leading to the introduction of intersections of various kinds. Roundabouts are considered effective intersections over their cross-intersections counterpart due the safety, flows and level of service enhancement they provide. The introduction of various scheduling techniques such as static and dynamic phase duration signalization is what has influenced these parameters (Chimdessa, Kassa, & Lemecha, 2013; Corriere & Guerrieri, 2012; Osei, Adams, Ackaah, & Yolanda, 2019). However, effective traffic flow scheduling at roundabouts are yet attained. There is always room for innovative approaches to enhance traffic flows taking into consideration various parameters. The application of computational intelligence tools to traffic scheduling has proven most effective since such tools are able to take into consideration the various parameters associated with traffic flows. Computational intelligence tools such as genetic algorithms, artificial bee colony, particle swamp optimization, fuzzy logic, neural networks, adaptive neuro-fuzzy inference systems, etc. have been used in different problems and road traffic flows scheduling. the adaptive neuro-fuzzy inference systems (ANFIS) have demonstrated significant abilities in various control problems since they have both the capabilities of fuzzy logic and neural networks (Al-madi & Hnaif, 2022; Oluwafemi, Oumar, Omar, & Onyia, 2019; Zachariah, Odion, Saidu, & Yabuwat, 2021).

Road traffic flows within the Kaduna metropolis is usually greeted with high congestions. These congestions are undesirable as they have consequences on the health, economic, and educational sectors of the state. In order to enhance traffic flows within the metropolis, the Government have embarked on road capacity expansion and conversion of Leventis roundabouts to an underpass. However, it is well known that this solution is only temporary and cannot eliminate the road traffic congestion experienced within the metropolis (Ayuba, Zachariah, & Damuut, 2018; Zachariah, Ayuba, & Damuut, 2017). The application of computational intelligence in such classical problem as this have proven promising, no known such application in the Kaduna metropolis. Manual traffic schedule or static phase traffic light systems used to minimize the effect of traffic congestions within the city have also proven ineffective. Thus, this research proposes the application of adaptive neuro-fuzzy inference system for traffic schedule within the metropolis. The ANFIS controllers are modelled based on the different clustering methods to determine which clustering method yields the best results when used as controller across multiple roundabouts.

2. Literature Review

In Osei et al. (2019), microsimulation was employed to model various roundabouts configurations in order to evaluate performance in terms of maximizing capacities and minimized traffic delays at the roundabouts. The authors reported 50% improvement in capacity and minimized traffic queues and delays when using signalized roundabout configuration. The limitation of this study is that it focused on the geometric design parameters, which essentially requires costly constructions. In Soroyewun et al. (2018), a traffic control system developed based on internet of things was proposed with the aim of minimizing the waiting time for both the motorist and pedestrian. This followed the observation that most traffic control systems have no consideration for pedestrian delays, weather condition and time period of the day. The developed internet of things framework integrated neuro-fuzzy inference system with five input variables having four membership functions each. This resulted in seven hundred and sixty-eight (768) fuzzy rules. Although the authors reported the suitability of developed framework for intersections, the high number of fuzzy rules implies computational burden, and other overheads interfacing with other internet of things devices. In Oluborode et al. (2020), an adaptive neuro-fuzzy inference system was modelled using five cross-intersection parameters as input and Gaussian membership function for the fuzzification of the crisp inputs. The simulation developed showed that the application of ANFIS model as controller resulted in minimized vehicular delays compared to the traditional controller. However, the limitation of the study is in the simulation. It was reported that a total of eighty (80) vehicles were simulated in over 323-time duration with and average waiting time of over 17-time duration. In real world traffic scenario, more traffic volumes are experienced than what was simulated. Also, it assumes that no turnaround traffic flows at the cross-intersection, which is not a realistic representation of what is obtainable in real-life. In Mittal and Chawla (2020), a three inputs having five fuzzy sets ANFIS model was implemented and used as controller at an intersection. Round-robin approach was used for the assignment of green phase to the different flows of the intersection and the ANFIS model determines the green phase durations. The results of the simulation were reported to have minimized the average waiting time and improved level of service at the intersection. Also, in (Ghassan, Younes, & Ghassan, 2018), effective traffic schedule was seen as a precursor for minimizing the concentration of harmful substance emitted by vehicles. ANFIS model was developed to accept two input variables and using three generalized bell-shaped membership function, it was able to achieve the goal of enhancing air quality when used as controller at the roundabout.

3. Materials and Methods

For the purpose of this research, openstreetmap (.OSM) was used to acquire the road network as it is in reality. Simulation of Urban Mobility (SUMO) was used to model traffic scenarios and TraCI4Matlab was used to control SUMO objects such as traffic lights at the various roundabouts.

3.1 Data collection

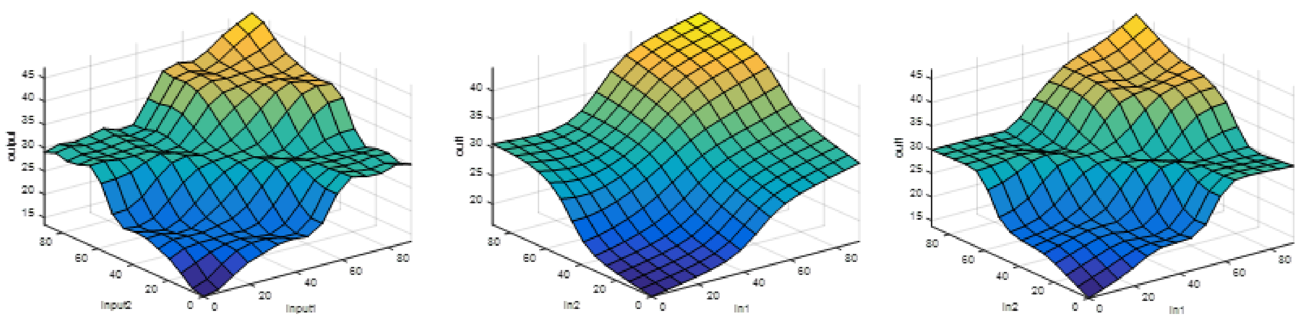
Data collection was performed to estimate the approximate number of vehicles arriving the roundabouts. Vehicular count was performed and recorded by volunteers, who were trained and given the templates that allowed the classification of vehicles into light, moderate and heavy vehicles as well as recording the number of vehicles that have arrive the roundabouts in fifteen minutes (15min.) time. This classification was based on the guide from Federal Highway Administration of United States of America. The summary of vehicular arrival rates is as shown in Table 1.

Table 1: Week's Hourly Average of Vehicular Arrival Rates

	Peak Period			**Sum**	**Off-Peak Period**			**Sum**
	Heavy	**Moderate**	**Light**		**Heavy**	**Moderate**	**Light**	
Average	46	168	136	**350**	26	45	32	**103**

3.2 Modelling of Controllers

Three ANFIS models, which were based on the clustering methods were modelled in this research. The grid partitioned clustering (GPC), subtractive clustering (SC) and fuzzy C-means (FCM) clustering methods were modelled to have two input variables, the queue length and waiting time of vehicles at the roundabouts. The grid partitioned ANFIS model was a 5 fuzzy sets of Gaussian membership function. The subtractive clustering ANFIS model used a radius of 10 and the fuzzy C-means clustering ANFIS model used 10 clusters. The data used for training the model was acquired from repeated trainings that started with a basic fuzzy inference system until the final dataset was obtained. The ANFIS controller were trained using the default training algorithms. That is, gradient descent and least-squares estimation algorithms. The surface plots of the models are shown in Figure 1A-C.



A: Grid Partition Model **B: Subtractive Clustering Model** **C: Fuzzy C-Means Model**

Figure 1: Surface Plots of ANFIS Models

3.3 Simulation Modeling

This research considered a section of Kaduna metropolis road network for traffic flow enhancements. The considered road network consisted of eight roundabouts and one underpass. The arterial inflows have varying number of lanes ranging from one to three lanes. OSM was able to capture this network adequate and only little modification was necessary to implement the newly constructed underpass, replaced the Leventis roundabout. The considered road network is as shown in Figure 2.

In order to assessed the implemented controllers, simulation scenarios with vehicular arrival rates derived from the estimated hourly averages of Table 1 is shown in Table 2. The vehicles were implemented to have speeds based on their classification as given by the Federal Road Safety Corps of Nigeria. Heavy vehicles had a speed of 45KMPH while the light and moderate vehicles had a speed of 50KMPH.

Figure 2: Considered Road Network

Table 2: Vehicular Hourly Arrival Rates

Scenario	Heavy	Moderate	Light	Total Vehicle Per Hour
Scanty Saturation	2	4	4	10
Extreme Under-Saturation	5	30	25	60
Under-Saturation	4	56	40	100
Saturation	10	200	140	350
Over-Saturation	20	400	280	700
Extreme Over-Saturation	20	600	380	1000

4. Results and Discussions

The modelled controllers implemented in this research were assessed in terms of parameters training and testing using mean square error (MSE) and root mean square error (RMSE); as well as in terms simulation results performances using average waiting time (AWT). The training and testing was performed using 70:30 ratios.

From Table 3, the results of training the ANFIS models is presented. It clear that the grid partition controller (DefaultGridPartFIS) performed better than both the subtractive clustering and fuzzy C-means models. The GPC model achieved MSE of approximately 0.32 and RMSE of 0.56 in the training phase and approximately the same in the testing phase. The fuzzy C-means model (DefaultFCMFIS) achieved an MSE of approximately 0.62 and RMSE of approximately 0.79 in the training phase; while achieving an MSE of 0.64 and RMSE of 0.80 in the testing phase. The subtractive clustering (DefaultSubCluFIS) model achieved an MSE of 2.53 and RMSE of 1.60 in the training phase; while achieving an MSE of 2.46 and RMSE of 1.57 in the testing phase.

Table 3: Training Performance of ANFIS Clustering Methods

Controller	**Training**		**Testing**	
	MSE	**RMSE**	**MSE**	**RMSE**
DefaultFCMFIS	0.62241	0.78893	0.63949	0.79968
DefaultSubCluFIS	2.5284	1.5901	2.4621	1.5691
DefaultGridPartFIS	0.31706	0.56308	0.3169	0.56294

The simulation results of the performances of the modelled controllers are as shown in Table 4 – 6. The performance of the modelled controllers was compared to the usual static (fixed-timed) controllers. That is, 30s and 25s controllers often used in Kaduna metropolis and other locations in Nigeria. The simulation was made to run for seven thousand seconds (7000s). This was to ensure that the simulation reaches a stability rate of vehicular flows, which will show the reliability of the performances of the controllers in all considered scenarios.

From Table 4, the performance of fuzzy C-means controller was assessed against the 30s and 25s static controllers. The results showed that in terms of AWT, the FCM controller outperformed both the 30s and 25s controllers in some scenarios and underperformed in some. The overall average performance of the FCM controller in terms of AWT compared to the 30s controller showed that the FCM controller essentially outperformed the 30s controller by an average of approximately 16%. Also, comparing the performance of the FCM controller to that of 25s controller, the results showed that the 25s controller outperformed the FCM controller in terms of both the AWT by less than 1%. This implies that on the assumption that traffic flows constantly follow the said pattern, the 25s static controller would be a better choice for road traffic flows. However, it is known that traffic flows patterns usually experience abrupt changes. Thus, the FCM controller, which is dynamic and able to change phase duration allocation to the different flows based on the considered traffic parameters may still be a better choice for long term and continuous performance reliability.

Table 4: Fuzzy C-Means Clustering Model Simulation Results

Scenarios	**30s**	**25s**	**FCM**	**Performance of FCM over 30s**	**Performance of FCM Over 25s**
	AWT (s)	**AWT (s)**	**AWT (s)**	**% AWT**	**% AWT**
Scanty Saturation	27.75	88.83	25.62	7.68	71.16
Extreme Under-Saturation	495.15	638.77	507.57	-2.51	20.54
Under-Saturation	672.02	533.23	601.41	10.51	-12.79
Saturation	936.54	526.35	614.82	34.35	-16.81
Over-Saturation	659.11	550.51	507.00	23.08	7.90
Extreme Over-Saturation	554.36	683.89	530.55	4.29	22.42
Average				**16.36**	**-0.29**

Table 5: Subtractive Clustering Model Simulation Results

Scenarios	**30s**	**25s**	**SC**	**Performance of SC over 30s**	**Performance of SC Over 25s**
	AWT (s)	**AWT (s)**	**AWT (s)**	**% AWT**	**% AWT**
Scanty Saturation	27.75	88.83	33.70	-21.42	62.07
Extreme Under-Saturation	495.15	638.77	504.56	-1.90	21.01
Under-Saturation	672.02	533.23	484.64	27.88	9.11
Saturation	936.54	526.35	549.40	41.34	-4.38
Over-Saturation	659.11	550.51	629.61	4.48	-14.37
Extreme Over-Saturation	554.36	683.89	836.35	-50.87	-22.29
Average				**17.95**	**2.84**

From Table 5, the performance of SC controller was compared to the static 30s and 25s controllers. It is clear from the results that SC controller outperformed the 30s static controller by an average of approximately 18% in terms AWT. Also, comparing the results of SC dynamic controller to that of 25s static controller, the result showed that SC controller slight outperformed the 25s in terms of AWT by approximately 3%. This implies that under the considered scenarios, the 25s static controller outperformed the 30s static controller and may be a better choice compared to the 30s static controller. However, the SC dynamic controller presents itself a better controller compared to the two static controllers.

From Table 6, the performances of GPC dynamic controller were compared to those of 30s and 25s static. The results showed that the GPC dynamic controller outperformed the 30s static controller by an average of approximately 24% in terms of AWT. In terms AWT, the GPC dynamic controller slightly outperformed the 25s static controller by approximately 2%. The GPC dynamic controller achieved higher better performance compared to the other dynamic controllers implies that for the considered road traffic scenarios, the controller was better at training the tunable parameters of the controller than the SC and FCM controllers. The higher better performance achieved with GPC dynamic controller agrees with most research in this area that have employed GPC-based controllers for traffic scheduling purposes.

Table 6: Grid Partitioned Model Simulation Results

Scenarios	**30s**	**25s**	**GPC**	**Performance of GPC over 30s**	**Performance of GPC Over 25s**
	AWT (s)	**AWT (s)**	**AWT (s)**	**%AWT**	**% AWT**
Scanty Saturation	27.75	88.83	26.26	5.36	70.43
Extreme Under-Saturation	495.15	638.77	278.01	43.85	56.48
Under-Saturation	672.02	533.23	482.32	28.23	9.55
Saturation	936.54	526.35	760.42	18.81	-44.47
Over-Saturation	659.11	550.51	624.16	5.30	-13.38
Extreme Over-Saturation	554.36	683.89	747.49	-34.84	-9.30
Average				**24.05**	**2.04**

5. Conclusion

This research aimed at enhancing road traffic flows through the minimization of vehicular average waiting time and determining the ANFIS clustering method that would yield better results in terms of model tuning and traffic simulation. The ANFIS models showed superior performances in comparison to the benchmark static controllers by generally minimizing the average waiting time. This was because of the fact that the ANFIS models are capable of handling the uncertainties inherent in traffic flows and adaptively scheduling their flows to achieve minimal waiting times by vehicles. The implication of the results obtained in this research include the minimization of travel times, concentration of harmful substances around the considered road network. It also implies that health of those around the considered road networks would face minimized risks.

ANFIS models trained using the default training algorithms, the gradient descent and least-squares estimations have the inherent challenges of performance bottlenecks at training due to the redundant computations of the gradient descent and thus, may not generate controllers that are adequately trained. Thus, other optimization algorithms may be used in training the ANFIS controllers to determine if better performance may be achieved.

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