Istraživanjaiprojektovanjazaprivredu
Journal of Applied Engineering Science

Original Scientific Paper

DOI:10.5937/jaes0-28642
Paper number: 20(2022)3, 988, 821-830
*www.engineeringscience.rs * ISSN 1451-4117 * Vol.20, No 3, 2022*

THE VALIDITY OF A DECENTRALISED SIMULATION-BASED SYSTEM FOR THE RESOLUTION OF ROAD TRAFFIC CONGESTION

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Intelligent transport systems are cheaper and easier to implement than other forms of solutions to road traffic congestion. Intelligent Transport Systems (ITS) allow information about road traffic to be collected and transmitted to the Traffic Controllers to respond to traffic congestion appropriately. This research study aims to design and test a simulation-based intelligent transport system for predicting traffic flow patterns. The simulation-based system proposed has a decentralised configuration. Road sections are isolated digitally in a decentralised structure and fed relevant information to predict future traffic states and transmit predicted information to other road sections. Two models of control configuration are created based on the same road network, the first is a decentralised model, and the second is a centralised model (no isolated road sections) to be used as a data source for the decentralised model. The simulated system used decentralised model configurations to predict traffic patterns at road intersections. Due to the lack of actual traffic data, a centralised model serves as the digital twin for the designed decentralised model. The two models were simulated using Anylogic Personal Learning Edition 8.5.2. simulation software, and after testing and result extraction, it was discovered that the decentralised model configuration was not valid for representing the non-uniformity of actual-world traffic patterns. The decentralised model had too few similar inflow and outflow rates to the centralised model in both the complex and straightforward road network cases. However, the decentralised model scored 89% in vehicle population density compared to the centralised model in the simple road network case but could not replicate the good result when the road network becomes complex.

Keywords: Road traffic prediction, flow rate, decentralised, centralised, intelligent transport system

1 INTRODUCTION

Transportation is an integral part of society. Transportation represents the means, methods and systems through which people, goods and services are moved from one place to another. In the modern age, it is one of the more critical parts of living. It affects the individual and all communities of the world. Transportation also dictates the standard of living of members of the community. In an area with no good roads or other convenient means of transit, the people living in such areas will not easily access goods and services. Many developing nations have inadequate transport systems, including poorly planned and built (presently damaged) roads, insufficient mass transit systems, and ineffective traffic regulations [1]. For example, the Nigerian transport sector is responsible for 3% of the country's Gross Domestic Product (GDP), of which the road subsector contributes 90%. The huge dependence on road transportation for moving persons, goods and services can cause traffic congestion. A survey carried out in major Nigerian cities led to the discovery that 87.2% of respondents experienced traffic congestion in their cities of residence and that Lagos state is the city that experienced the most traffic congestion [2].

Defining road traffic congestion is a bit difficult due to differences associated with operational and user perspectives. Some of the definitions of road traffic congestion in the literature include:

- The Joint Transport Research Centre (2007) of the Organization for Economic Cooperation and Development (OECD) defines road traffic congestion as follows: "Traffic Congestion is a situation in which demand for road space exceeds supply."
- The European Conference of Ministers of Transport (ECMT) provides the following definition of road traffic congestion: "Congestion is the impedance vehicles impose on each other, due to the speed-flow relationship, in conditions where the use of a transport system approaches capacity".

Traffic congestion is also the relative impedance to vehicle motion as the road approaches maximum capacity, the point where vehicle inflow exceeds vehicle outflow. Some significant causes of traffic congestion include poor parking habits, poor road network, inadequate road capacity, lack of parking facilities, poor traffic control/management, poor drainage, heavy vehicles, poorly designed junctions/roundabouts and lack of efficient mass transport system. Remedies to this problem include building good roads and other transport networks, developing mass transit systems in the country, proper traffic planning, management/maintenance schemes and regular education of road users. All these solutions are alright, but a decentralised simulation-based system for resolving road traffic congestion is considered to check its validity in this research study.

Traffic simulation uses mathematical models to imitate traffic flow, usually with software applications' help. Simulation of traffic systems is important because transportation is a crucial aspect of today's society. Traffic simulation is necessary to know how traffic systems work and how people interact with the traffic systems. The understanding gained from simulation results is used to design and operate traffic systems efficiently. The existing literature concentrates on road traffic congestion patterns, prediction, and modelling to the best of the authors' knowledge. A few studies deal directly with road traffic congestion resolution but from the standpoint of a centralised model. Due to the heterogeneity of road traffic, especially in dense urban cities. Even simulation-based solutions require more computational power to handle the complex dynamics of road traffic from a centralised perspective if road traffic heterogeneity is considered. Hence, the need to explore the possibility of developing decentralised models for resolving road traffic congestion. The decentralised road traffic model promises to require less complex algorithms and lower computational power to resolve road traffic congestions. To the authors' knowledge, the existing literature does not address the validity of a decentralised simulation-based system for road traffic congestion resolution.

This research study aims to design, create and test the validity of a scalable decentralised simulation-based model that can predict traffic flow patterns and provide necessary information to resolve traffic congestion. AnyLogic Personal Learning Edition 8.5.2. simulation software was used for the simulation study. A road network was modelled using two different configurations: a centralised and a decentralised configuration. The two models were simulated to determine if the decentralised model can adequately represent and predict the traffic flow states of a road network.

The approach taken by this research study builds on established knowledge and applications of existing technology. It will provide a fully detailed experimental look into the capabilities of a decentralised simulation-based system to resolve road traffic congestion.

The following section reviews relevant past works related to the proposed research study. The methodology section charts the proposed system's design: it contains the methods, sources and software used to design the proposed decentralised simulation-based system for resolving road traffic congestion. The section on results discusses the simulation results. A conclusion and a list of references are provided at the end of the article.

2 REVIEW OF RELATED WORKS

Traffic congestion patterns were classified to ease the problem of resolving traffic congestion using recent artificial intelligence tools. The existing literature has used point-based and area-based clustering techniques to classify traffic congestion patterns [3]. The clustering techniques are based on segmentation and domain knowledge. A system that can effectively classify congestion stages was developed in [4]. Data was collected and pre-processed to simplify the complex system. Then the optimal features were selected using the whale optimisation algorithm, which was done by resolving convex optimisation issues and the features were used to classify the various congestion stages. The entire system showed a 9.3% improvement in traffic jam stage classification. The potential drivers or causes of road traffic congestion were extracted using clustering techniques applied to spatiotemporal patterns of road traffic congestions acquired from an online map [5]. Traffic congestions are further studied using spatiotemporal data from real-time traffic patterns observed over time [6]. Image classification was used to predict road traffic congestion in [7] using a convolutional neural network (CNN). The road traffic images used were acquired from closed-circuit televisions (CCTVs).

A new method of solving traffic congestion was proposed in [8]. Traffic flow was optimised by controlling the speed limits of different areas to reduce and control the inflow of vehicles. The study showed that traffic flow optimisation could be modelled as a Markov decision process. The study successfully used Q learning to train a neural network about the traffic policies used to regulate speed limits. The neural network model could make traffic predictions and react proactively to predicted congestion. The study also showed that the suggested method was only suitable for datasets with some specific characteristics. Else, the proposed neural network model became too inconsistent for live application. Q-learning was used to control multi-agent traffic lights and efficiently reduce traffic congestion in non-stationary environments by slightly increasing hold times or release times in different areas to divert or speed up traffic flow [9]. The proposed system worked without prior data or a model and was suitable for work in non-stationary environments. The problem with this approach was that large-scale traffic avoided in one area might appear in another. The dynamic nature of pre-road-crash traffic was studied in [10]. The relationship between road traffic conditions and accident risk gives precursors to improve the safety of road users. Although traffic congestion was not explicitly studied, the reference to the probability of traffic congestion should an incident occur on the road is notable. The study applied machine learning techniques to predict road crashes using the evolving nature of road traffic just before a crash.

The heterogeneous nature of road traffic has been modelled using various statistical tools [12]. The underlying factor for accuracy in modelling road traffic patterns is the validity of the model's road traffic heterogeneity. A variable-length cell transmission using state variables that can describe road traffic congestion fonts was proposed by [11] to mathematically model traffic states. Road traffic heterogeneity also affects the ability to study road traffic congestions at the microscopic and macroscopic levels. Validation and verification of traffic models are briefly pointed out in [11], and the procedures for validation and verification of traffic models are created and explained in detail. A well-planned road traffic solution considers many factors in its formulation, especially at the microscopic level. A study of road traffic heterogeneity simulated developing nations' irregular and non-lane-based road traffic patterns [12]. The study considered the diverse and unpredictable nature of roads in developing countries using a microscopic traffic simulator that can visualise traffic flow and provide road traffic statistics for the unstructured nature of road traffic in developing nations. The model used timed automata to model the macroscopic level of road traffic conditions and enable the varying traffic parameters like driver behaviour. The study in [13] used an extended particle hopping model to mimic vehicular traffic patterns. Large-scale heterogeneous urban road networks are optimised to prevent traffic congestion [14]. The signals generated from road traffic monitoring are used to ease congestion on urban road networks.

The causes of road traffic congestion are wide and varied. Still, road traffic shows some repetition in the pattern observed, studied, and documented for advanced road traffic studies and traffic congestion prediction. The study of road traffic congestion covers variables that are not predictable due to its erratic causative events. In one such study involving unpredictable road traffic, a visualisation tool was proposed and used to evaluate traffic congestion [15] and make decisions to ease traffic congestion caused by planned special events. According to the study, prior incidents cause non-recurring road traffic congestion. The primary traffic incidents may generate secondary traffic incidents. A study focused on preventing non-recurring road traffic congestion caused by previous and secondary incidents [18]. The role of the traffic monitoring control (TMC) facility in ensuring the timely resolution of traffic congestion was elaborated in a study carried out in [16] to resolve traffic congestion using cognitive radio, deep learning techniques, and long-range (LoRa) modules. The experiment used a centralised model to help the TMC inform road users to avoid areas of the road that are already congested. The study dwelled more on using the information fed to the multi-level TMC to notify drivers of congested routes.

SATURN road traffic modelling tool was used to study the effect of the car-free day and odd-even plate number policy on traffic flows on regularly congested roads in Bandung, Indonesia. The study submitted that the policy could be circumvented and its intended benefits jeopardised, except special measures are taken to ensure that road users intentionally align with the proposed approach [17]. MATsim was used to simulate the effect of dedicated bus lanes on urban traffic congestion [18]. The study showed improved road traffic flow after implementing a dedicated bus lane on a congested urban road.

Extensive data generated from road traffic helps with traffic control and mobility. The traditional way of collecting road traffic data through fixed-location sensors and GPS devices was improved using aerial systems [19]. Aerial systems were proposed to gather accurate road traffic data, especially in urban areas that consistently experience road traffic congestion. The critical technology employed was a hierarchical intelligent control system. The hierarchical system consists of an Agent-Based Control system (ABC), an Artificial Transport system (ATS) and an Intelligent Transport System (ITS). The strategy used each car as individual agents sending information to the system to create a pool of data to predict and control traffic. The problem with the plan was its large information pool. Processing such a large amount of data takes time and slows down the system's response to traffic pattern changes.

Centralised road traffic modelling is abundant in the existing literature. This study seeks to validate a decentralised simulation-based system for resolving road traffic congestion.

3 METHODOLOGY

The proposed system is a simulation model where each road section predicts its future state by itself (i.e. decentralised simulation) using real-world data. The designed system indicates traffic states and assists human traffic controllers. The proposed method validates road network designs.

Two models were designed using Any-Logic simulation software. The first was a centralised model, and the second was a decentralised model. The centralised system was a 'stand-in' for real-world traffic data. The centralised model was simulated, and traffic data was extracted. The data at the start of the centralised model simulation was extracted and used as the start point for the decentralised model to see how well the decentralised model can predict traffic flow rates. The traffic data for the decentralised model was subsequently extracted and discussed.

Any-Logic simulation software allows the creation of digital twin versions of road networks. Each road is simulated individually with real-world-like data. After simulation, information is transmitted to road users and traffic controllers through the data transmission equipment (including application services or digital road signs). In some cases, the traffic controller can be situated at the traffic management centre, like when artificial intelligence (AI) is used to control traffic lights. Due to the lack of traffic data from the real world, another similar simulated model was used as the 'stand-in' for actual-world data. The first designed model shows how data is transmitted between road sections and how the various areas operate independently. The second model is more complex. It has sensors to detect traffic states and lights to illustrate how traffic controllers control the traffic from remote locations. (i.e. traffic management centre). In Figure 1, the decentralised model gets its data from the centralised (close to real-world model) and uses the information acquired to predict traffic patterns and assist traffic controllers in preventing traffic jams.

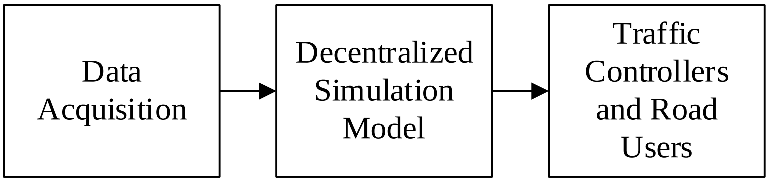

Fig. 17. Functional Block Diagram of Proposed Decentralized Traffic Prediction and Control System.

Traffic data was first acquired and sent to the transport management centre for data extraction and model creation. As illustrated in Figure 2, the transport management centre is the Any-Logic simulation software in this research study. The software was used to create the road network models from which data may be extracted, analysed, documented and forwarded to road users and traffic controllers. The controllers and variables for the centralised model and the road network under consideration were connected fully, and its traffic data was extracted for use in the decentralised model. Figure 3 shows the decentralised model where the road network is independent. The road network was divided, and each division was considered a separate part. The two model configurations are modelled and simulated in "Any-logic Version 8.5.2 "due to its extensive road library and other features. Any-Logic 8 is a simulation software suite used to design, simulate and test road traffic models. It has a comprehensive list of road components that can be used to create complex road traffic systems. Each road component in the library has parameters that can be easily modified to simulate vehicle flow rate accurately. The centralised and decentralised road traffic model configurations are applied to the same road network. The centralised traffic model's simulation data acts as input starting data for the decentralised model.

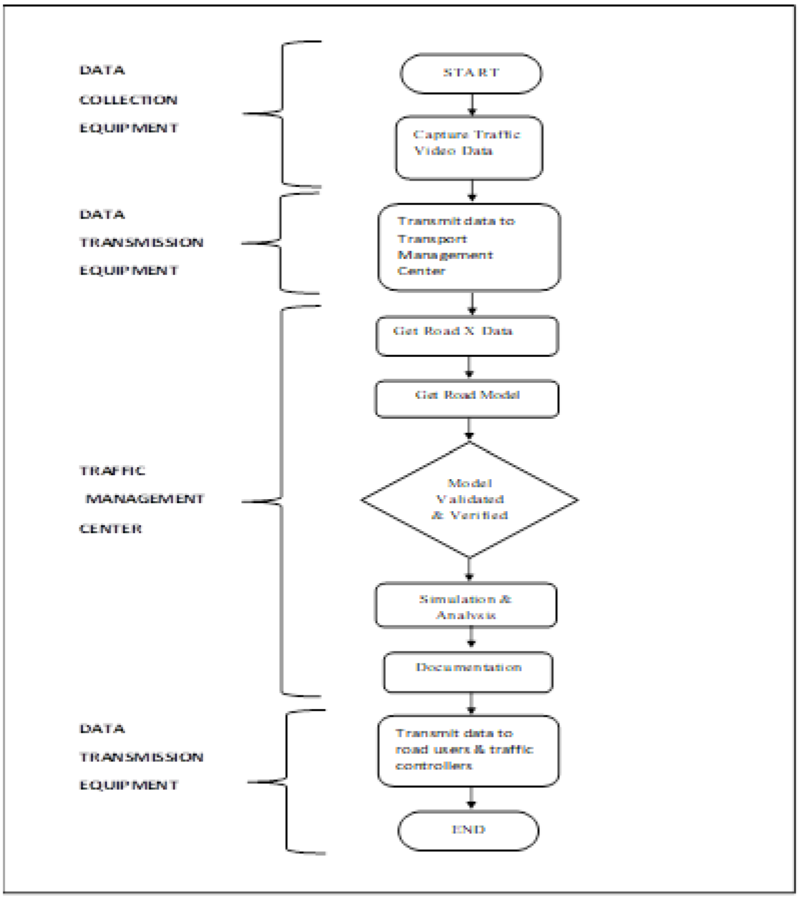

Fig. 18. Flow Chart of Proposed Traffic Prediction and Control System.

This arrangement also helps with the measurement of flow rate accuracy. The configurations used to simulate the centralised and decentralised model traffic pattern are shown in Table 1 along with all parameters and values used to imitate real-world traffic scenarios.

The simulation was done to understand how the decentralised system works in a road configuration to resolve traffic congestion. As illustrated in Figure 3, each system consists of acentralised and decentralised model, its controller and some datasets for result analysis. The controller controls the vehicle speed and flow rate. The vehicles are transferred from one road section to the next, perfectly illustrating how the decentralised system proposed would work by transferring vehicle data between abstracted road sections. The road sections would then use received traffic data to simulate possible future states. This simulation's centralised model was created as a stand-in for actual traffic data. Hence the vehicle flow rate used in the centralised model was used as the flow rate for the decentralised model. The results of the simulations were collected, compared and analysed for the validation of the decentralised model.

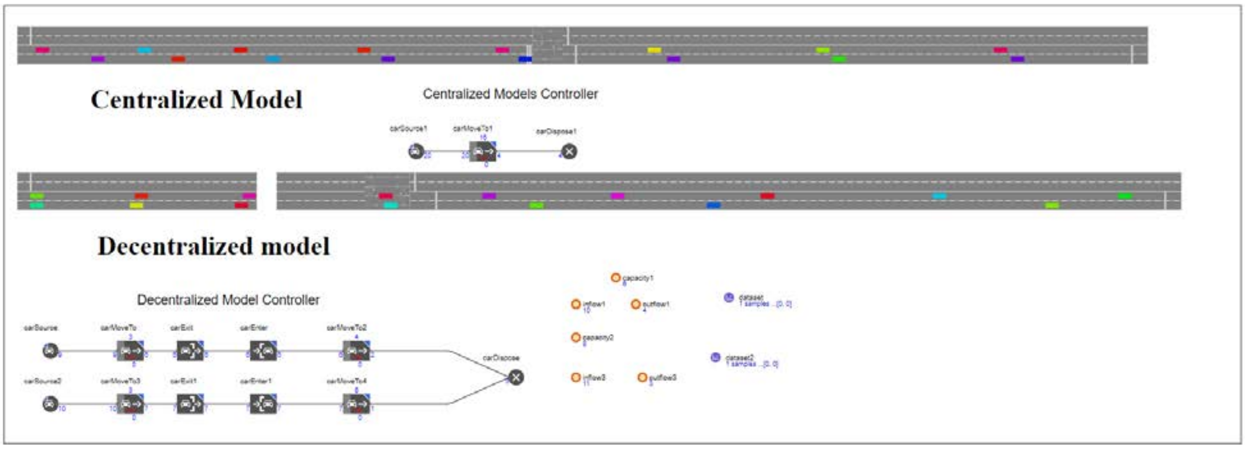

Fig. 19. The Centralised and Decentralised Road Simulation with Traffic.

Table 13. The Centralised Model's Component Configuration

Component	Value
Vehicle Speed	60 km/hr.
Car inflow rate (for areas above marked with red circles) A, B, E Car inflow rate (for areas above marked with yellow circles) C, D	5000 cars/hour 1000 cars/hour
Destination probability Probability of vehicle going to other roads Probability of car returning to its source road	 0.222 0.111

Table 14. The Decentralised Model's Component Configuration

Component	Value
Vehicle Speed	60 km/hr
Car inflow rate (for areas above marked with red circles) Road A, B, I Car inflow rate (for areas above marked with yellow circles) Road E, H	5000 cars/hour 1000 cars/hour
Road C Road D Road F Road G	Vehicle data from Road D Vehicle data from Road C Vehicle data from Road G Vehicle data from Road F
Destination probability	Value

Road Section A, B, C For vehicles generated at source Road A, B, C a. Probability of going to Road C. b. Probability of returning to the source. c. Probability of going to a destination other than source or Road C. d. Probability of vehicles from road c going to Road A or B. e. Probability of vehicles from road c to road c. **Road Section D, E, F** For vehicle generated at source Road E a. Probability of going to road D. b. Probability of going to road F. c. Probability of going to road E. For Vehicles from road D a. Probability of going to road E b. Probability of going to road F c. Probability of returning to road D For Vehicles from road F a. Probability of going to road E b. Probability of going to road D c. Probability of returning to road F **Road Section G, H, I** For vehicles generated at source Road H, I a. Probability of going to Road G. b. Probability of returning to the source. c. Probability of going to a destination other than the source or Road G. d. Probability of vehicles from road G going to Road I or H. e. Probability of vehicles from road G to road G.	0.667 0.111 0.222 0.5 0 0.4445 0.4445 0.111 0.222 0.667 0 0.222 0.667 0 0.667 0.111 0.222 0.5 0

4 RESULTS AND DISCUSSION

In simulating the centralised model, the network was first designed to be a simplified presentation of traffic flow rates. The vehicles have a limited top speed, and only one type of vehicle was used in the simulation. In the centralised road network, there are multiple points where data was extracted. The coloured circles represent road ends, the sources and destinations of simulated vehicles. The Green braces represent areas where flow rates and vehicle population density are collected for result validation. The road ends with green letters are data transfer points where vehicle data gets transferred between abstracted sections.

Figures 4 and 5 show the data collection points for the centralised and decentralised models, respectively. Some of the information collected from the centralised model includes:

Fig. 20. Centralised Model Data Extraction Points.

- The probability of target destinations. The likelihood is calculated at the intersections. The output flows of each junction are compared to the total input flow to the hub. The probability of target destinations at the 5th minute is shown in Table 3 as data extracted from the highlighted exit and entry points. The extracted possibilities formed a part of the input data for the decentralised model.
- The output flow rates (yellow circles) measured for the centralised model is shown in Table 4. The EX1 – EX4 represent the first to fourth simulation.
- Starting Point Data: This is the data at the (red circles) and intersections. It consists of the input and exit flow rates data at the crossroads. It is the data used in the decentralised model for prediction.

The starting point data was fed into the decentralised model, and the simulation was run. The decentralised model is a proper representation of the system if it can replicate the flow rate of the centralised system shown in Figure 6 to a certain degree. Throughout the simulation of the decentralised model, its data was extracted and recorded. The extracted data were compared to the data of the centralised model for validation. The simulation of the decentralised model with traffic flow at the fifth (5th) minute is shown in Figure 7. Table 5 shows the decentralised model's output flow rates (yellow circles). The EX1 – EX4 represent the first to fourth simulation.

Fig. 21. Decentralised Model Data Extraction Points.

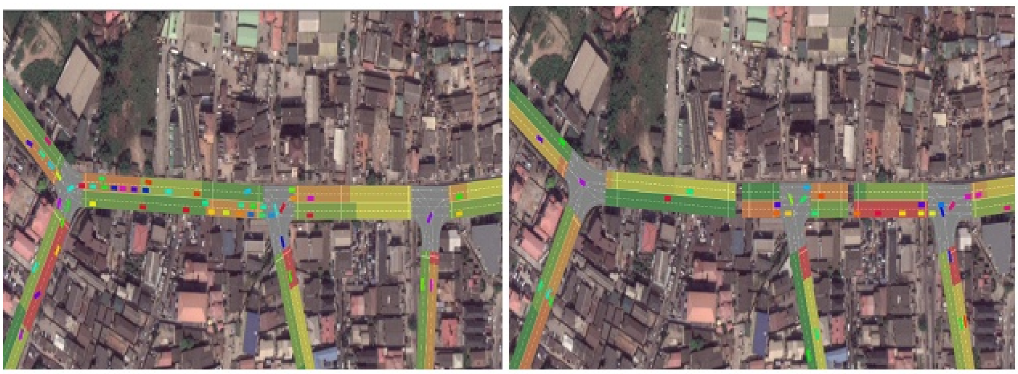

Fig. 22. Early Stage of Simulation (5 Minutes) for Centralised Model.

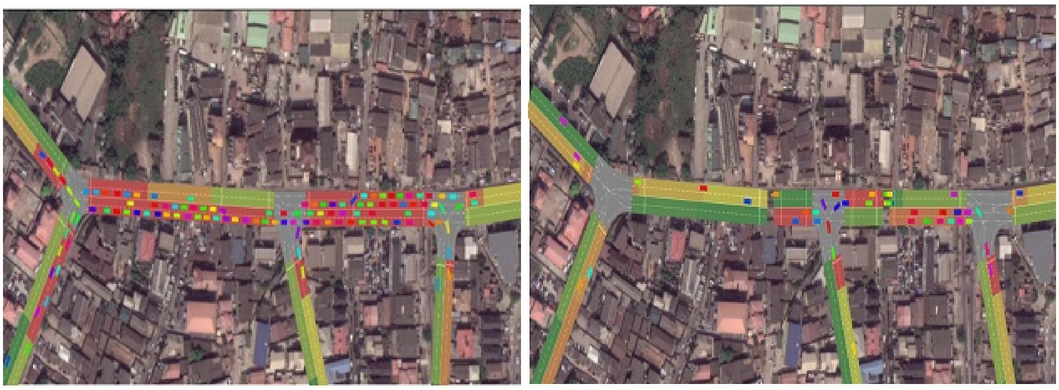

Fig. 23. Early Stage of Simulation (5 Minutes) for Decentralized Model

Table 15. Probability of Target Destinations from the Centralized Model.

Probability	PA	PB	PC	PD	PE	PF	PG
5th	0.33	0.44	0.28	0.5	0.14	0.37	0.40

After the simulations, the flow rates and vehicle population density as a function of time were obtained and plotted, as shown in Figure 8 and Figure 9. Figure 8 shows that the decentralised model could not simulate flow rates correctly. The decentralised model's validity deduction was based on its flow rates.

Table 16. Result of Simulation Output Flow Rates for Centralized Model (Yellow Circles) for first five minutes.

Minutes	Centralized Model EX1 (Cars/Sec)	Centralized Model EX2 (Cars/Sec)	Centralized Model EX3 (Cars/Sec)	Centralized Model EX4 (Cars/Sec)
1	3348.333	979.5343	2360.905	1538.042
2	254.3844	853.4732	576.7263	1694.889
3	2481.863	1245.507	910.8111	705.1592
4	388.5	710.9075	863.9158	228.2194
5	1690.721	5094.93	1651.117	462.2519

The similarity in flow rate between the decentralised and the centralised model was very close to zero, indicating that the flow rate of the decentralised model was not similar to that of the centralised model.

Table 17. Result of Simulation Output Flow Rates for Decentralized Model (Yellow Circles) for first five minutes

Minutes	Decentralized Model EX1 (Cars/Sec)	Decentralized Model EX2 (Cars/Sec)	Decentralized Model EX3 (Cars/Sec)	Decentralized Model EX4 (Cars/Sec)
1	461.5298	754.2829	1665.566	860.824
2	631.48	444.4444	753.8	169.8447
3	1164.026	597.6841	12398.02	169.8447
4	1559.404	593.9849	613.1718	757.835
5	631.5789	738.3454	593.108	1127.881

However, from Figure 9, the vehicle population density of the centralisedand decentralised models was very similar, with a score of 89%. Despite the decentralised model being unable to model the flow rates of a simple centralised system properly, it could adequately model the "vehicle population density per time". The dissimilarity between the centralised model's flow rates and the decentralised model may result from the time lag between the various road sections of the decentralised model. It could also be caused by the speed of the vehicles and the decentralised model behaviour.

Simulations were carried out using complex road networks. The first simulation gave a glimpse into the validity of decentralised models of simple road systems, as rendered in Figure 3. A decentralised model of a complex road system was also simulated and tested. The complicated road system is shown as three (3) connected intersections with flowing traffic. The simulation process was similar to the simple road network case. The road was modelled as a centralised whole in Figure 6 and then abstracted and broken apart for the decentralised model in Figure 7. As in the simple road network, the centralised model served as an initial traffic data source for the decentralised model. Information such as the paths cars seem to traverse and vehicle inflow rates were collected from the centralised model and used in the decentralised model. The two models were simulated, and comparisons were made between the results obtained for the two models.

The simulation results were acquired after a simulation running time of 60-minutes. The results were extracted from the flow rate log as it changes over a 60-minute duration for the two simulations, and part of the results are presented for the first five minutes in Table 4 (Centralized) and Table 5 (Decentralised). The 60-minute flow rate graphs of the two models were plotted. The plots showed how the traffic was formed in each simulation model. The flow rate for both models in the complex road network case is shown in Figure 8. The plot shows that the decentralised model did not accurately model the flow rate of the centralised model. The vehicle population density of the two models in Figure 9 also differs.

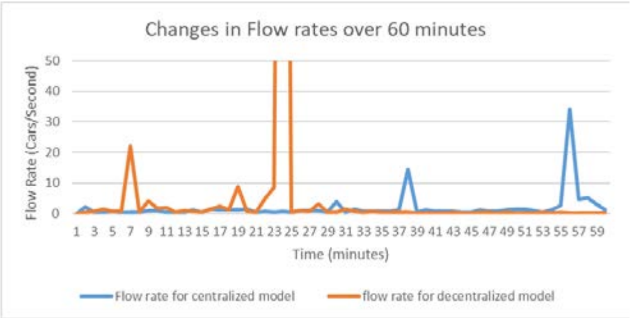

Fig. 24. Validation of Decentralised Model by Comparison with Centralised Model Using Flow Rate.

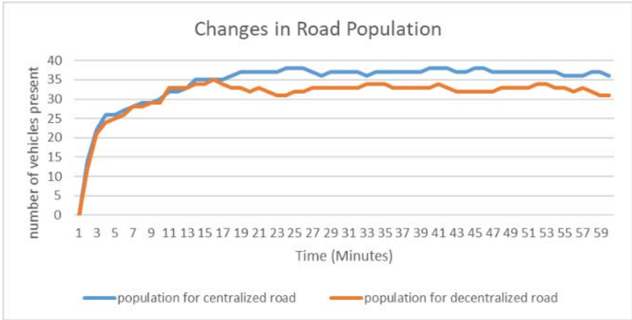

Fig. 25. Validation of Decentralised Model by Comparison with Centralized Model Using Population.

However, both configurations are attempts to model the same traffic network. The flow rates in the centralised model are much noisier, i.e. not uniform, compared to the flow rates of the decentralised model.

This disparity between the two models is due to the design of the decentralised network as it is an attempt to simulate the road networks while reducing the unpredictable aspects of driver behaviour, accidents and unexpected blockages. The decentralised model also does not have the non-uniformity experienced in actual traffic flow patterns. The simulation results for the complex road network case showed that the decentralised model could not accurately model the traffic flow rate of the centralised one. The decentralised model performed poorly when the resulting flow rates and vehicle population density were compared to the centralised one for the complex road network scenario, even for specific forward and backward lanes. The decentralised model failed to act as a good model for complex road systems due to time lag during the transfer of harvested data from the centralised model to the abstracted road sections of the decentralised model. The accuracy of the decentralised model may be improved if there exists a way to compensate for time lags, driver behaviour, and unexpected blockages.

5 CONCLUSION

This study was carried out to validate the performance of a decentralised model for resolving traffic congestion. The simulations proved that the decentralised model could not accurately model the flow rate of either the simple road network or the complex road network. The discrepancy may be due to the time lag when traffic data moves between abstracted road sections. The decentralised model's vehicle population density in the simple road network case closely matched that of the centralised model. Still, the excellent result was not replicated in the complex road network case. The design of the decentralised system may be improved to match that of the centralised model. Still, for practical applications, the decentralised model should be limited to simple road networks, where the time lag would not drastically reduce accuracy. It is not advisable to use the decentralised model for complex road networks.

6 ACKNOWLEDGEMENT

The authors acknowledge the sponsorship of the Covenant University Centre for Research, Innovation and Discovery (CUCRID), Ota, Ogun State, Nigeria.

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Paper submitted: 30.09.2020.

Paper accepted: 03.05.2021.