Mathematics and ICT Bring New Intelligent Traffic Light Control System

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Abstract— As road networks in urban areas become increasingly complex and complicated when accommodating for the fast-growing numbers and diversity of vehicles and infrastructure, researchers have a tremendous interest in designing intelligent and robust traffic light control systems to manage traffic. Traditional traffic light control (TLC) systems operate on a fixed time basis, whereby each stream of traffic is allocated a fixed amount of time for vehicles to move through the intersection. This system's main drawback is that it does not account for actual traffic densities, leading to longer waiting times and higher fuel consumption. With the emergence and proliferation of digital technologies in the 21st century, humans have begun to use technology in every facet of their daily lives, including getting help in performing dull, dirty, and dangerous tasks that can be automated and repetitive. This paper combines ICT and mathematics to design a new robust system for traffic light control. A novel Intelligent Traffic Light Control System (ITLCS) model is proposed to accommodate the immediate number of vehicles and pedestrians' presence at the intersections. The system has been implemented in selected software for testing and validation, and the analytics are highlighted. The arterial aim is to show the importance of mathematics, which can produce a robust and intelligent system that can achieve a better traffic flow at varying traffic densities when combined with ICT.

Keywords— traffic light controller, mathematics, ICT, waiting time, fuel consumption

1. Introduction

Traffic congestion on roads, highways, and motorways is a major concern and problem in many cities worldwide. This congestion occurs when traffic volume generates a demand for space more than the available street capacity. While construction of additional roads, highways, and motorways is always visible together with the consistent addition of extra lanes, the demand for more road space remains with the increasing population, improving spending power, the industrial revolution, and changing lifestyle of the populace [1]. These invariably lead to traffic congestion, visible in developed and developing countries alike. The Fiji Islands is no exception.

Traffic congestion can be classified under recurring and non-recurring types [2]. Recurring traffic congestion could be classified as infrastructure-related, and non-recurring could be classified into three categories; environmental, mechanical, and human-related [3].

Infrastructure development is the hidden troll contributing to traffic congestion in many urban and suburban areas and is arguably human-caused. The world revolves and is rapidly changing about infrastructure as it is so vast. Nevertheless, this may not be anyone's fault initially as no one foresees the escalating demands on roads in the future. However, improper planning can be the root cause. The environment also plays a role in contributing to traffic congestion [3]. Multiple studies, news articles, and reports have shown that traffic congestion increases during rainy and unfavorable weather conditions. Rainy and foggy weather slows down traffic flow and has an uncontrollable effect on road conditions and contributes to accidents, which subsequently leads to further congestions. For instance, due to a landslide in Dilkusha Nausori Princes Road, one of the two main roads connecting Suva and Nausori, was closed for two days in January 2019 [4]. Mechanical failure is another factor that can cause traffic congestion. While it can be argued that mechanical failure could be categorized into human-caused, such as if a driver failed to maintain the vehicle's tires properly, this is not always the case. External factors can also contribute to mechanical failures, such as a sharp object on the road that can cause a breakdown while driving, even if it is well maintained. It is challenging for a driver to get his/her vehicle off the road in case of a breakdown. It is the case because other drivers rush to get around the stopped vehicle. Moreover, humans contribute most to traffic congestion due to distracted, drunk, drowsy, emotional, and dangerous driving.

The negative impacts of congestion are a waste of energy, air pollution, delays, loss of opportunities, economic loss, wear and tear, and road rage due to stressed and frustrated drivers [5]. The positive impact of road congestion on drivers is that they are organized in the sense that timings of their trips have changed to avoid the negative consequences. Slow traffic flow minimizes fatal road accidents. Many countermeasures impact improving road congestion, such as improving road infrastructure usage by modern and logical thinking, such as carpooling, online shopping, and improved road policies. Rural and urban planning can have a considerable impact on future traffic congestion [6]. Increasing the road capacity since the demand is high, and school opening hours can also reduce traffic congestion. The most important out of all is the traffic management system, which has the most impact. The better the system, the less is the traffic congestion [7].

The intelligent traffic management system continues to garner tremendous support due to the introduction and integration of Information and Communications Technology (ICT) tools and technologies in traffic control for safety on roads and to combat traffic congestion [8]. ICT tools and technologies, including mobile apps [21] and as recent as blockchain architecture [29], are a set of heterogeneous technologies (hardware and software) that enable electronic communication, data collection, and data processing in distributed networks. ICT use in the transport system is different according to complexity, beginning from simple electronic communication (signals) to intelligent and autonomous transportation with various mechanical systems [23–28], and finally to the interactive and highly intelligent applications for management and traffic control [9].

An intelligent traffic management system is a combination of services and tools, connected to various transportation modes and traffic management software. The most common uses of such systems are providing citizens with detailed transportation information, shortening the commute duration, preventing downtime, and reducing traffic jams. There are different ITS designs, and they vary in technology and application, from basic management systems such as car navigation; traffic signal control systems; blockchain-based systems; container management systems; variable message signs; automatic number plate recognition or speed cameras to monitor applications, such as security CCTV (close circuit television) systems; and to more advanced applications that integrate live data and feedback from a number of other sources, such as parking guidance and information systems; weather information; and bridge devising systems.

Traffic lights are signaling devices positioned at road intersections, pedestrian crossings, and other locations to control competing flows of traffic. There is growing research on how traffic light systems are managed and coordinated to ease the congestion and maximize the traffic flow. To this effect, the literature is inundated with copious algorithms, techniques, and strategies [10–21].

Intelligent Traffic Light Control System can ease traffic congestion to some level. Therefore, there is a need to have traffic light control systems that can cater to different densities of traffic. Traditional traffic light control systems manage traffic on a fixed time manner. Each traffic light state is assigned a fixed duration of time before the next state is executed. The order in which the states occur is a repeated pattern and is not altered regardless of traffic density. This approach works fine for lower traffic densities but does not cope well as traffic densities increase.

It started to become evident that the fixed time approach had much room for improvement. Thus more inventive traffic control systems employ sensors, inductive loops, and even image processing technology as vehicle detection techniques to better control traffic. Vehicle detection is critical in traffic control as it allows the system to 'sense' the presence of cars and, more importantly, the length of queues at an intersection. Therefore, the system can prioritize lanes or states and respond accordingly.

In this paper, the proposed Intelligent Traffic Light Control System seeks to promote free-flow of traffic and lessen waiting time at intersections. This is achieved by taking into account the immediate traffic situation and reacting accordingly. The proposed system's main objective is to demonstrate system efficiency compared to the efficiency of the fixed time system. The efficiency is indicated through the average flow of vehicles through the intersection against the traffic density. The simulations were conducted using the MATLAB environment. The results indicated that the proposed system is indeed more efficient than the existing system for varying densities.

The rest of the paper is organized as follows: Section 2 presents the literature review on ITLC systems. In Section 3, the methodology of the proposed ITLCS is presented. The mathematical modeling of the proposed ITLCS is given in Section 4. Section 5 shows the simulations results proposed ITLCS and the results are compared with the results of the existing fixed time system. Finally, in Section 6 the future work, which could be carried out, has been discussed.

2. Background

As research for this project, a background of intelligent traffic light control (TLC) systems is explored via the study of various journals related to the topic. This review of related literature compares unique existing intelligent TLC systems or ones that are still being developed. Comparisons are drawn with regards to the procedure to which the method entails, its performance, and any drawbacks it may have. In doing so, this review will generate a greater understanding of the topic of this project.

In recent decades, the number of vehicles on national roads has seen a dramatic increase. This can be accounted for increased vehicle ownership brought about by the decrease in the cost of purchase for vehicles. This may be due to the cheaper cost of production materials or manufacturing methods. It may also be due to changes in lifestyles for citizens, especially in urban areas where readily available transportation is necessary due to the fast-paced nature of urban living. Furthermore, citizens not owning vehicles are still numerous and therefore require public transportation, and with the increase in population, the number of public transpiration vehicles must increase proportionally. This increase in vehicular presence, therefore, demands an efficient means of traffic control.

In Fiji, traffic light systems are the primary means of controlling traffic, and these tend to be riddled with inefficiencies. Faults are frequent in occurrence and result in confusion and frustration, and dangerous situations for road users. Increased traffic congestion during peak hours has even seen the conventional traffic light systems be abandoned in favor of having police personnel conduct traffic until congestion decreases. Therefore, an intelligent TLC system would be beneficial for Fiji.

Advancements towards intelligent TLC systems have been made because it promises improved traffic flow control. Numerous iterations of these have been developed, one such being the use of radio frequency identification (RFID) tags on vehicles along with a Centralized Computer System (CCS) [10]. This particular system involves the individual tagging vehicles with RFID tags that communicate information regarding the vehicle's direction of movement, speed, and traffic volume, to the CCS. The CCS logs the data received from individual vehicles and processes it via a Central Data Processing System (CDPS) and determines the appropriate control decision to be made. This determination is done according to the congestion of vehicles on the different traffic streams at the intersection. This entails a 'Green' signal for the most congested traffic stream, with the 'Red' signal for the remaining ones. This action continues until the congestion is reduced in the 'Green' traffic stream, allowing for the less congested streams to continue. The proposed system [10] is subject to the road type and traffic laws of the country. This intelligent TLC system's advantage is that data is supplied and processed in real-time, thus allowing for accurate control decisions. However, as all vehicles on the road will require RFID tagging for the system to be appropriately implemented, this consequently implies that every vehicle will be monitored electronically. Naturally, this brings about the question of an individual's right to privacy and also security.

In another study [17], a similar method is employed, but the Digital Signal Processor (DSP) chips are used as the central controller, and there is no use of RFID tags. As in [10], a CCS is used, and the system is based on the various states of different traffic lights at an intersection, with the states being either 'Red', 'Yellow', or 'Green'.

In publication [15], an improved traffic control system model based on discrete event simulation is discussed. The model developed in Simulink/SimEvent toolbox includes a controller with two input and output switches and a traffic signal logic block, which contains the fixed time controller algorithm. An intersection is modelled with four lanes or 'approaches' wherein each lane has a straight traffic stream and a right-turning stream. Each stream is also a queue, and the First in-First out (FIFO) rule governs all vehicles queued within that stream. The model's performance in [15] is investigated by using two test conditions, the first being when vehicles arrive within the 15 seconds of one another and the second being when vehicles arrive 5 seconds apart. The latter and former states are models for low traffic and high traffic volumes, respectively, and the arrival times between vehicles are exponentially distributed. It is seen that vehicles in the queue and the average waiting times are less in lower-traffic volume, which is desirable. However, this improved model can be made more efficient.

A predictive interval microscopic TLC model is proposed in [12] for urban traffic systems. The model utilizes agents that control traffic light signals at intersections and are self-organizing. The control system depends on predicted delay intervals, which signifies predicted results. The agents can identify these results and ignore control decisions that have adverse effects on the model. The model's results obtained via computer simulations prove the model to be of improved performance compared to conventional TLC methods. This was particularly true for non-organized traffic streams.

Helbing et al. put forward a self-organizing traffic light (SOTL) system that is section-based and uses an autonomous adaptive control strategy [19]. Real-time availability of vehicle-flow information of the system allows for large-scale synchronization of traffic lights. This means that instances of 'green-wave' synchronization patterns are achieved, which are dependent on the traffic condition before and after an intersection. The traffic condition mentioned here is determined using the queue's length at a road section and the delay time for each vehicle in the queue. The results of this particular SOTL system suggest that it can manage traffic efficiently for non-uniform road networks and at roads with varying traffic flow. Furthermore, cycle times for the system is not fixed because of its self-organizing nature.

Another SOTL system is suggested by Gershenson [21] in 2005, whereby stigmergic-coordination of traffic lights using vehicles is employed. This is in contrast to having traffic lights communicating with one another. The three self-organising control methods' performance was contrasted against that of two non-adaptive methods with fixed cycles in this paper. The former methods were found to be superior in efficiency and adaptability. These conclusions were drawn from the fact that the self-organizing methods accurately detected varying conditions in traffic patterns, such as traffic density, and adapting to these conditions efficiently. Also, the system proposed in [21] generated platoon-groupings for large groups of traffic and gave preference to these groupings and queuing vehicles at intersections.

Nevertheless, another SOTL system is suggested in [14], which employs elementary cellular automaton (ECA) on a more complex, hexagonal intersection network. Cellular automata models are ideal for modeling simple highway networks, and this model uses Rule 184 to emulate vehicle behavior. At the same time, the traffic lights and intersections were simulated using various coupled, non-homogeneous ECA. The model used situations where two to three intersections were considered at any one time to examine the performance of two traffic light controllers. The first controller used the 'Green Wave' method, while the second used self-organizing control. The green wave method involves creating fixed cycles and phases of 'Green', 'Red' and 'Yellow' traffic light states to allow maximum traffic to flow through an intersection. The self-organizing method, on the other hand, will adapt to real-time traffic flow continually. The comparison between the two control methods was made against a baseline defined by the calculation of a theoretical optimum dependent on the traffic light controller type. Results generated from simulations showed that the second control method performed almost optimally as it was able to adapt well to the test scenarios and varying traffic densities.

Also, a variation of the SOTL control method is developed by de Gier et al. which is based on the Nagel-Schreckenberg (NaSch) cellular automaton. To examine the network-independent features and its robustness, the control scheme was first implemented on an existing network of roads in a Melbourne suburb in Australia and then simulated on a square grid network. Empirical data was used for the first implementation, whereas the second used hypothetical data. This SOTL scheme was then evaluated against a non-adaptive control scheme, and this revealed that the SOTL method was superior in terms of traffic speed, flow, density, and queue length. Also, the study shows considerably fewer fluctuations in these characteristics.

Furthermore, the TLC scheme involving a decentralized control strategy centered on the anticipation of short-term traffic flow was brought forward by Lämmer and Helbing. The study highlighted the inability of decentralized control strategies to handle real traffic patterns. Also, two strategies, of which the proposed control scheme comprises, account for its superiority over conventional control methods. The first strategy is an optimisation strategy continually applied by default, as long as explicit conditions of traffic demand and desired service interval are met. However, if these conditions become saturated, a stabilization strategy comes into effect to clear queues, after which control is reverted to the former strategy. The combination of these two strategies accounted for the proposed control method's superior performance.

The proposed intelligent TLC system is based on an Interval Microscopic model that uses Interval Based Representation and Cellular Automaton techniques.

3. Methodology

In this paper, we propose an optimized solution for an intelligent traffic light system.

Existing traffic control system

Modern traffic light design in terms of appearance has been standardized, but this is the only factor that has remained the same. Much like during the industrialization era, traffic has again reached a point where traffic control systems' advancements need to be undertaken. However, now these advancements are more on the technological aspect.

Existing traffic control systems delve into and emphasize vehicle detection techniques and prediction algorithms to handle the traffic better. Vehicle detection techniques revolve around sensors, inductive loops, and various image processing methods. With the emergence of machine learning and other such prediction algorithms, forecasting congestion has been a field of interest in intelligent traffic light control systems.

As shown in figure 1, the traffic control system that is representing a T-junction operated based on fixed time delay periods. The existing road network has six lanes feeding into the intersection and three lanes leaving the intersection. Six traffic lights are corresponding to each lane and one pedestrian light.

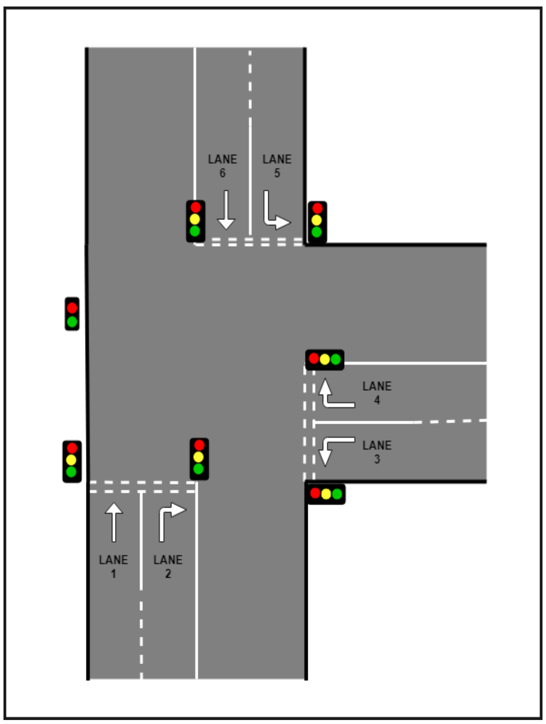

Fig. 1. Existing road network.

The existing system operates on a fixed time basis wherein each lane is assigned a fixed amount of time for a green light. Another way of looking at this is that each traffic 'state' is assigned a certain period before the next state is executed. A state is a set of traffic light configurations. The existing system also follows the same order of states regardless of vehicle occupancy. This means that the system will always execute states in the same order and only change once the assigned time expires.

Table 1 shown below indicates the configurations of the traffic lights at each state. The system has four central states (State 1-4) with four transition states. Transition states allow the central states to changeover in a seamless manner, and as aforementioned, the order of states does not vary with one exception. In-State 4, all the lights are configured to Red so that all traffic is stopped and pedestrians are allowed to cross the intersection. However, State 4 is only executed if the pedestrian button is pressed, i.e., pedestrians let the system know that they are waiting to cross. If the pedestrian button is not pressed, the system assumes that no pedestrians are waiting and thus opts to move from State 3 to State 1 using transition State' 3 to 1'. The timing for each state is discussed in a later section of this report.

Table 1. State of the existing system

State	Traffic Light 1	Traffic Light 2	Traffic Light 3	Traffic Light 4	Traffic Light 5	Traffic Light 6
1	Green	Green	Green	Red	Red	Red
2	Green	Red	Red	Red	Green	Green
3	Red	Red	Green	Green	Red	Red
4	Red	Red	Red	Red	Red	Red
1 to 2	Green	Yellow	Yellow	Red	Red	Red
2 to 3	Yellow	Red	Red	Red	Yellow	Yellow
3 to 4	Red	Red	Yellow	Yellow	Red	Red
3 to 1	Red	Red	Green	Yellow	Red	Red

Proposed intelligent traffic control system

The proposed ITLCS is based on Cellular Automata (CA) theory. Cellular Automata are discrete mathematical models that are made up of infinite regular cells placed to form a grid. CA models are widely used to study the behavior of systems of varying complexities such as neural networks, the interaction between groups of individuals, cryptography, fluid flow, distributed computing, nature of life, and for our interest; traffic flow.

Each cell is defined by one of any finite number of states governed by a set of transition rules. At every time step, each cell's state is updated according to the states of its neighbors, with respect to the transition rules. For simple CA models, there are usually only two states. A set of cells is a generation, and as the transition rules are applied to one generation, the next generation is formed.

For the proposed ITLCS, CA is used to simulate the progression of traffic flow – the car's movement through the grid. The movement of the vehicles in the simulated environment is governed by certain rules discussed further in the next section.

4. System Mathematical Modeling

The proposed smart traffic light system mathematical modeling is presented in this section. The system is majorly defined by three factors: vehicle velocity, vehicle position, and the cost function, each of which is expressed as an ordered pair. The velocity of vehicles approaching the intersection is defined as

$V_i(t) = [v_i^-(t), v_i^+(t)]$

where

$v_i^-(t)$ is the lower-end point and
$v_i^+(t)$ is the upper-end point.

The lower and upper end points are updated according to:

$$v_i^-(t) = \min\{v_i^-(t-1)+1, g_i^-(t), v_{max}^-\}$$
$$v_i^+(t) = \max\{v_i^+(t-1)+1, g_i^-(t), v_{max}^+\}$$

where

$v_i^{-/+}(t-1)$ is the lower-end/upper-end position of vehicle i at time step t-1

$g_i^-(t)$ is the number of empty cells in front of vehicle i at time step t

$v_{max}^{-/+}$ is the lower-end/upper-end maximum velocity

The position of the vehicles,

$X_i(t) = [x_i^-(t), x_i^+(t)]$ are updated with respect to the vehicle velocity:

$$x_i^-(t+1) = x_i^-(t) + v_i^-(t)$$
$$x_i^+(t+1) = x_i^+(t) + v_i^+(t)$$

where

$x_i^{-/+}(t+1)$ is the predicted lower-end/upper-end position of vehicle i at time step t+1
$x_i^{-/+}(t)$ is the current lower-end/upper-end position of vehicle i at time step t

A cost function is used to determine the cost of possible control actions, and from this, the control action with the lowest cost is selected and executed. The cost is defined in terms of time delay intervals

$C(\alpha) = [c^-(\alpha), c^+(\alpha)]$ and it is obtained by:

$$c^-(\alpha) = \min\{\sum_i \sum_i w_i^-(t), \sum_i \sum_i w_i^+(t)\},$$
$$c^+(\alpha) = \max\{\sum_i \sum_i w_i^-(t), \sum_i \sum_i w_i^+(t)\},$$

where

$$w_i^-(t) = \begin{cases} 1, v_i^-(t) = 0, \\ 0, else. \end{cases}$$

$$w_i^+(t) = \begin{cases} 1, v_i^+(t) = 0, \\ 0, else. \end{cases}$$

5. System Implementation

The proposed smart traffic light system is implemented in software using MATLAB programming language.

System efficiency is measured and compared against that of the existing system. System efficiency was measured in terms of the average flow of cars with respect to the level of traffic density.

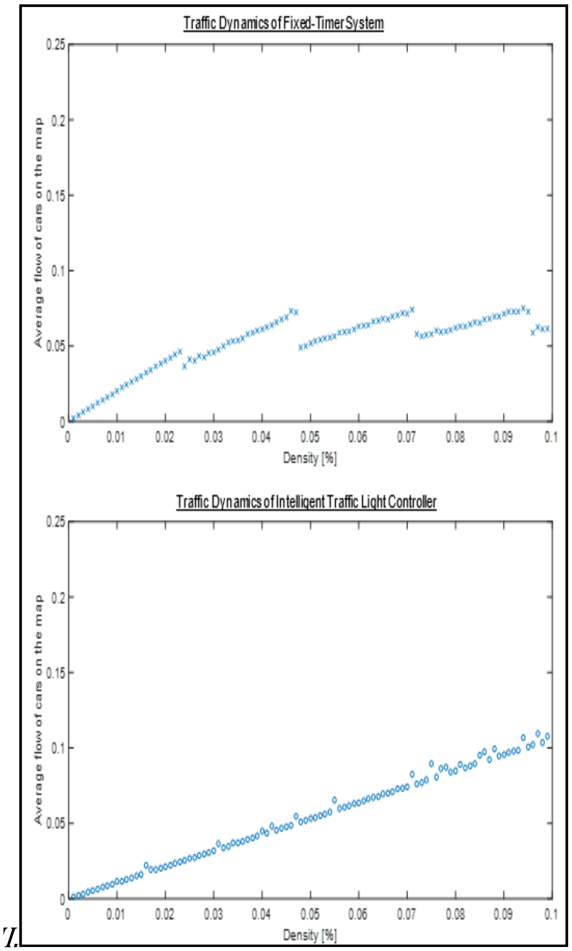

Fig. 2. Computer simulation results in low traffic density.

The traffic grid is a cross intersection with a torus geometry. Both systems were simulated on the same grid, and two sets of results were taken – low density and high density.
The density range is from 0% to 10%, with intervals of 0.01%.

As shown below in Figure 2 above, the fixed-timer system showed peaking average flow at three different densities of about 4.5%, 7%, and 9.5%. The proposed ITLCS showed much better results with a robust linear progression, with a steady increase of average flow as densities increased. Simulation results for densities ranging from 0% to 100% at intervals of 0.1%.

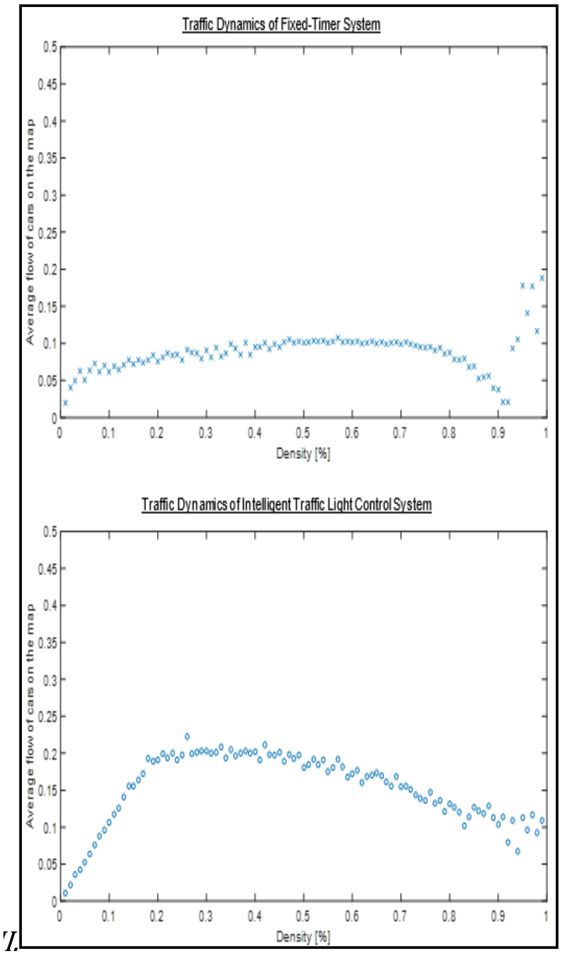

Fig. 3. Computer simulation results in high traffic density.

As shown in figure 3 shown above, the fixed-time system results indicated a constant average flow for densities of approximately 45% to 70% with high outlying values towards a density of 100%. However, after the density reaches roughly 75%, the efficiency drastically declines until 90%.

The proposed ITLCS demonstrated a short constant average flow for densities of about 20% to 50%. While the efficiency seems to drop toward a 100% density, it still performs much better than the existing system.

Computer simulation results show a clear indication of the efficiency of the proposed ITLCS over the existing fixed-time system. For low densities (0-10%), the fixed-time system demonstrated acceptable efficiencies for most low densities. However, there are unexpected and sudden 'drops' at specific densities. As seen in Figure 2, as the average flow steadily increases, it reaches a sudden drop, which is immediately beginning to steadily increase again. It can be assumed that the sudden drops are due to the probable lull in traffic. As the traffic density is low and the system is expected to manage traffic efficiently. As expected, the proposed ITLCS performs much more efficiently than the existing system.

For higher densities of traffic, the proposed ITLCS still demonstrates a more than acceptable efficiency. However, the existing system unexpectedly can cope with densities of up to 80%. However, the proposed ITLCS has again proven to manage traffic at high densities without losing too much efficiency.

6. Conclusion

This paper discusses the design, implementation of an intelligent traffic light system based on input data gathered from sensors. Computer simulation and actual prototype were used to validate the proposed system design and to show its effectiveness.

The introduction of new algorithms has enhanced the decision-making strategies of the control agents of the intelligent traffic light control system. The data related to vehicle detection such as position and velocity parameter which is also a major system variables were obtained. These variables/parameters then were utilized to derive the cost function with predicted delays and evaluation, which then executes the optimal control decisions for the state of each traffic lights at a particular junction.

In proportion to the proposed approach, an existing road network i.e. T-junction network consisting of six lanes approaching the intersection was modelled while also considering the pedestrian crossing. The simulation result exhibits that the intelligent traffic light control system has many capabilities to clear the traffic flow during high traffic densities and low traffic densities. Since the ITLC system's simulation deals efficiently with distributed densities, note that density is not only the parameter that the intelligence only considers. The system's intelligence was the mathematical technique known as cellular automata, which was employed to work with data on interval microscopic level to procure an optimal control decision. Also, note that more transition sates ITLCS enables the system not to follow the sequence like the fixed timer system, which allows the system to work well with non-uniform traffics.

Obtained results show that the proposed system is promising and effective in controlling road traffic flow and easing traffic congestion. We plan to further extend this work by applying other techniques and adding intelligence to the system controller to optimize performance better.

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