Road Traffic Optimization for Mid-sized African Cities – Application of Fuzzy Algorithms and Computer Vision

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***Abstract*—Traffic congestion in urban areas is a global challenge - leading to stifled economic growth, increased road accidents and atmospheric pollution, among other negative trends. Existing traffic management solutions have proven to be largely ineffective in medium-size African cities. Wireless sensor networks have emerged as possible cost-effective solutions, especially in under-developed countries. In this paper, we present a solution for detection and quantification of traffic congestion at signaled isolated four-way junctions in order to optimize traffic flow. The research utilizes optical sensors to collect road parameters and fuzzy logic to quantify and then prioritize entry. Simulations are used to compare strategies employed by traffic signals; the interest being to observe which of the two traffic light management schemes is more effective. The two schemes compared in this paper implement fairly weighted round-robin and fuzzy algorithms.**

Keywords—fuzzy algorithms, wireless sensor networks, computer vision, road traffic congestion, Maseru, Lesotho

I. Introduction

Congestion is defined as a situation in which transport participants cannot move in a desired or favorable manner. Congestion is not limited to vehicles; pedestrians can also cause and be involved in congestion. It refers to the phenomenon when capacity of infrastructure is exceeded [1]. As far back as 2007, effects of congestion were identified as a global phenomenon at a conference held by the Organization for Economic Co-operation and Development. The conference presented evidence of a steady increase in congestion in many urban areas of member countries [2].Apart from additional time spent in transit, there is a financial cost attached to occurrence of these traffic jams. [3] in their paper stated that “in South Africa, the cost of traffic congestion to businesses is estimated at 15 million Rands per hour, this is exclusive of cost of fuel and maintenance of vehicles”.

There is also an environmental impact as a result of exhaust fumes released by vehicles. The overall cost of traffic is calculated in various ways, including but not limited to, assessing outlay needed to reduce traffic volumes to optimal road capacity. One other method is to compute the marginal cost each vehicle entering into the jam imposes on other motorists involved [4]. Traffic lights at multi-way junctions in most medium-sized cities function by allowing entry into the junction using predetermined timing, giving each entry the same duration of time allowed based on historic data but not taking account of the prevailing situation.

Consider that in the morning, heavier traffic is flowing towards the city with less flowing in the opposing direction. Traffic lights, however, allocate the same amount of time for traffic to flow in both directions. This is ineffective as wait time of vehicles going into town is prolonged.

The increased amount of traffic congestion is attributed to increasing numbers of cars [5]. The most widely practiced solution to congestion is implementation of traffic lights. The problem with this is that the volume of traffic differs at different times of the day leading to problems when the volume is larger on one side and less on others, resulting in a waste of resources. This wasting of resources is one of the problems this research has aimed to eliminate by employing the use of Internet of Things (IoT). Fig 1 is used to illustrate the problem.

Traffic lights cycle through the entry points North, South, East and West (N, S, E and W) respectively, giving each point equivalent time to let traffic through. The problem arises when, for example, there is one car on the S entry and four on the E entry. The S entry will be given the same duration as E entry even though there are fewer cars on it, on E. The same argument goes for all adjacent points.

One solution for this problem would be to increase road infrastructure as number of cars increases. The challenge with this solution is that in most medium sized cities the land close to the road is already occupied by buildings which cannot be relocated. The second impediment to this approach is the unavailability of financial means to construct new roads.

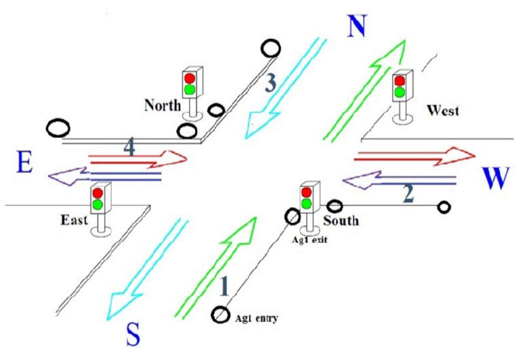


Fig 1:Current setup of traffic lights

The aim of this research was therefore to solve problems encountered by motorists using IoT enabled devices; specifically, to reduce occurrences and intensiveness of congestion. The objectives were then set out as to: (1) create methodologies that collect and aggregate road parameters thus making it possible to quantify road congestion; (2) use Wireless Sensor Networks (WSNs) to control traffic lights such that rate of traffic flow increases.

II. Literature Review

There are various definitions of traffic congestion, each depending on the observer's point of view. The first definition relates to demand capacity, the second to travel time, and the last to cost [6]. "When vehicular volume on a transportation facility exceeds the capacity of that facility, the result is a state of congestion" [7]. There has been an increase in the number of road users that has not been met by a corresponding increase in the availability of road networks [8].

A. *Traffic Congestion Types*

Congestion is divided into three types, these being recurring, non-recurring [9] and pre-congestion [10]. Recurring congestion occurs at known and expected locations and times; it is known where the congestion is going to take place and in most cases motorists are aware of how to avoid it. This can for example, occur when people travel to and from work. There are also sections in a road network that are known to have bottlenecks not owing to the road infrastructure but to traffic volume.

Non-recurring congestion is defined as unusual or unexpected congestion that happens due to unforeseen circumstances [11] . This type of congestion is not known or anticipated and is usually worse than recurring congestion as more motorists end up being caught up in it.

The last type, that is less obvious comes as result of other road networks being congested. This congestion is called pre-congestion, when it has become apparent to road users that there is congestion on a given section of road; motorists who traditionally use that portion of road then transfer to another road [12]. This results in the formation of 'new' congestion; this can easily be misconstrued as non-recurring.

Given the various definitions of congestion and types, it follows that its causes are determined by the definition adopted. The general causes of congestion include: too many cars on a road network, changes in capacity of road infrastructure, driver behavior, employment patterns, and economic status [13]. There are three clusters that group causes of congestion depending on their proximity to the actual road network. These clusters are macro-level dynamics: causes of traffic that are directly related to the status of the road; micro-level dynamics: these relate to causes that are associated with demand of road facilities; and the last is indirect dynamics, with random variables that contribute to commencement of congestion such as weather and events. Fig 2 reflects some of the causes of congestion [9].

Costs of congestion involves amongst others, reduced speeds and increased travel times. These impose some kind of cost on commuters. In business; these costs are funneled down to consumers of commodities. Some of the costs are environmental [14], such as noise and air pollution. The costs of congestion are subdivided into two categories.

Direct costs refer to consequences of congestion that are readily observable; when road networks are congested, there are going to be delays. Running and maintenance costs will accrue as a result of the car idling longer than necessary. Indirect costs address less obvious costs of congestion such as loss of life due to accidents and increased commodity prices. Fig 3 shows how congestion can be detrimental to a society [15]. The rise in social income leads to the purchase of more vehicles which will in turn lead to less development owing to increased traffic congestion.

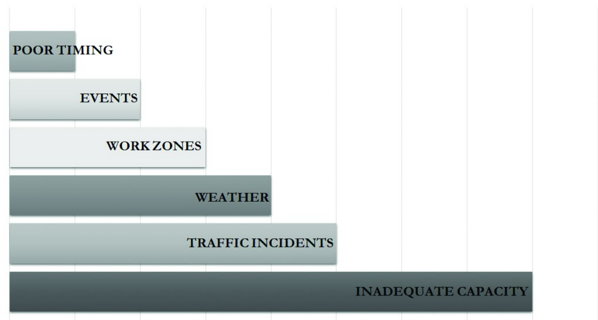


Fig 2: Causes of congestion

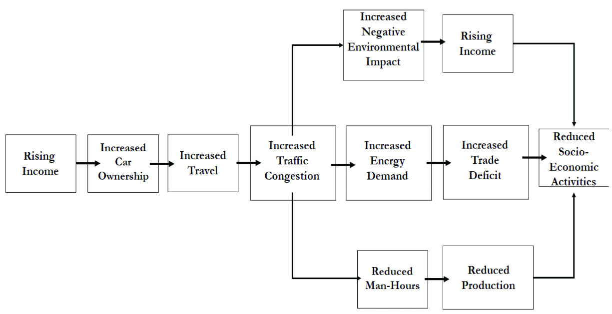


Fig 3: Impacts of congestion

B. Traffic Congestion Measuring

In order to monitor and manage traffic, it has to be quantifiable [16], requiring qualitative or quantitative statistics. Values that are used to measure congestion can be grouped into three; being basic measures, ratio measures, and Level of Service (LOS); which has proved to be the most comprehensive measure of congestion due to usage of multiple parameters [17]. The parameters that are used to measure LOS include vehicle density, volume to capacity ratio, average vehicle speed and delays at particular intersections. Fig 4 depicts the use of LOS in a multilane highway: the first column is the LOS with 'A' being good and 'F' being bad [18].

C. Traffic Management Strategies

Management and monitoring of congestion have become important in many countries and has spawned the need for management schemes such as traffic lights and efficient land use [19]. With regards to traffic lights, there are mainly two strategies used: fixed and real time. The former works with preset timing, duration of the signal displayed on the light is pre-set from past experience giving no consideration to current status. The latter relies on real time conditions of the road; decisions on how to manage traffic lights are based on the prevailing traffic parameters such as count of cars, speeds and direction [20]. The use of fuzzy logic to control traffic was first proposed by Pappis and Mamdani [21]. The common parameters used are number of queued cars, rate at which cars are entering and leaving the queue (hence speed) and average wait time.

The implementation of fuzzy logic in traffic management is as a result of unstructured parameters with no empirical method of comparison [22]. Consider that when controlling traffic at a four-way junction, an official might think in this manner: "If traffic is heavier on the north or south lanes than traffic on the east and west, then allow more traffic to flow from the north or south". 'If–then' rules can be used in fuzzy algorithms with the added advantage of quantifying parameters with terms such as 'longer' and 'shorter'. Using intelligent traffic lights should optimize the flow of traffic and reduce congestion [23].

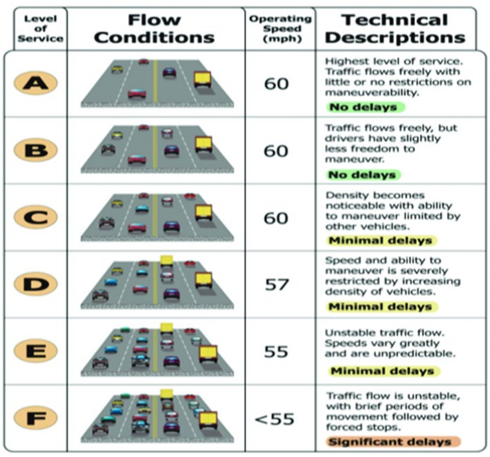


Fig 4: Level of service

D. Intelligent Traffic Management Systems (ITMS)

The idea of objects with embedded electronics that can communicate has been around for over a decade. What is new is the idea that everyday objects such as refrigerators, cars to wallets could connect to the Internet, enabling autonomous communication with each other and the environment [24]. IoT is being applied in domains such as smart homes and cities, wearables, healthcare, industry and agriculture [25].

E. Image Processing and Analysis

Image processing and analysis have resulted in what is termed 'computer vision'. The accelerated interest is born out of the fact that computational expenses have been diminished [26]. This has made it possible to collect and manipulate multi-dimensional signals such as video and pictures. The goals of this manipulation can be split into three categories: (1) image processing, (2) image analysis, and (3) image understanding. The remainder of this section will focus on image processing and analysis, concentrating on traffic monitoring and management.

The earliest approaches to vehicle identification and tracking included the combined or separate application of spatial and temporal analysis on video sequences [27]. In general, vehicle detection and tracking has been performed using one of the following methodologies: (1) point detection and tracking; this methodology is fast and provides consistent results independent of illumination [28]; (2) edge detection, which employs morphological algorithms and which in comparison to point detection, is negatively affected by diminishing illumination [27]; (3) Frame differencing techniques are relatively easier to implement and yield better consistency and accuracy in comparison to the above- mentioned while also being computationally cheap, although it requires usage of a reference image [29].

Many researchers have attempted to use visual input to count and ascertain speed of vehicles. Rahman proposed the application of stereoscopic vision, using two cameras placed at a known distance apart; this approach, however, requires the calibration of two cameras [30]. To mitigate this, a camera that can acquire two images at different viewpoints can be used, but this still presents a problem of reduced resolution limiting the accuracy of detection [31].

III. Methodology

The solution developed takes the form of a software framework. This was then implemented as a system prototype similar to an Early Warning System (EWS). Elements of low-cost, applicability (in developing countries) and usability were incorporated. The EWS comprises of data- gathering, analysis, information-dissemination and user response [32]. Putting together the various components of an EWS resulted in an architecture that was employed in the development of an ITS with three main components: (1) data collection, (2) integration and analysis, and (3) control and dissemination. The architecture is shown in fig 5.

A. Data Collection

The data collection layer is responsible for collection of actual traffic data. The collected data needs to be real time so that ITS can provide reliable and usable information. The traffic parameters that are collected are number of cars counted and speed of individual cars; this counting of cars then makes it possible to calculate the 'needed' parameter – road segment density.

There are several technologies that can be implemented to collect these parameters; including inductive loops, acoustic sensors and visuals. Inductive loops have an installation drawback as the road infrastructure will need to be excavated. The drawback with using acoustics is that a city is inherently noisy, so the noise from the surroundings would have an adverse impact on the quality of gathered data. Consequently, use of video cameras presents a 'better' solution. Below follows a discussion on how parameters of interest will be extracted from video streams.

Counting cars involves segmenting the video stream into frames, then observing the changes from one frame to another. The calculations of speed involve the use of intrinsic and extrinsic components of the camera. The video analysis is performed using Open Source Computer Vision (OpenCV) which is a set of libraries that are aimed at computer vision.

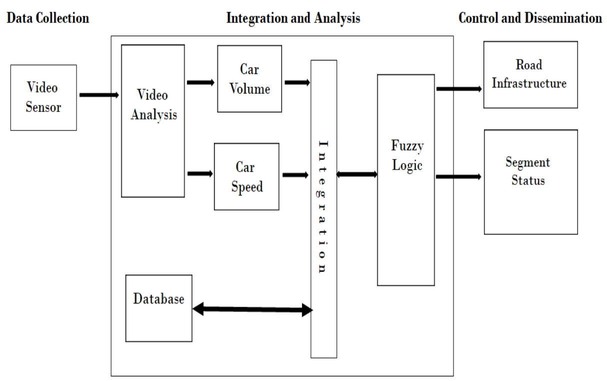


Fig 5: Intelligent traffic systems framework

B. Video Processing

a) Converting RGB to grayscale: Grayscale images contain 8-bit data per pixels information, resulting in a smaller data set in comparison to RGB image. To convert an image from RGB to grayscale, we implemented the conversion method recommended by Radiocommunication sector of International Telecommunications. The method is reflected in (1). The resultant image is smoothed using the Gaussian Blur; (2), where x and y represent the row and column locations of each pixel on the image and δ the standard deviation.

$$y = 0.299R + 0.58G + 0.114B \quad (1)$$

$$G(x, y) = \frac{1}{2\pi^2} e^{\frac{-(x^2+y^2)}{2\delta^2}} \quad (2)$$

b) Foreground Estimation: There are various techniques used for foreground estimation within a video stream. The method implemented in this study is frame differencing. This method is relatively easy to apply and computationally inexpensive. It relies on comparing two consecutive frames. The video stream was recorded with one camera; therefore, the sizes of the images and frames are the same. The result of comparing two consecutive frames is a new image that shows the differences between them. The difference is then translated to the presence of motion from the first frame to the second.

Let f_k be the k^{th} frame and f_{k+1} be the neighboring $(k+1)^{th}$ frame with $P_t(x, y)$ being the pixel at location (x, y) on the t^{th} frame and δ set the threshold value, function $FE_{f_k, f_{k+1}}(x, y)$ is used to estimate the foreground between frames and is defined by (3).

$$FE_{f_k, f_{k+1}}(x, y) = \left(\left|P_{f_{k+1}}(x, y) - P_{f_k}(x, y)\right| > \delta\right) \quad (3)$$

$$FE_{f_k, f_{k+1}}(x, y) = \begin{cases} 1, \left|P_{f_{k+1}}(x, y) - P_{f_k}(x, y)\right| > \delta \\ 0, \quad otherwise \end{cases}$$

The result is a binary image in which every pixel whose result of $FE_{f_k, f_{k+1}}(x, y)$ is set to 1 and will be white if the difference is larger than δ and set to 0, hence black otherwise. The threshold to which the pixel difference is compared is used to reduce the noise within the video stream. The value of the threshold is reliant on the intrinsic and extrinsic parameters of the camera being used.

c) Vehicle Detection and Countring: In order to establish whether the detected motion is a vehicle or not, Binary Large Object (blob) detection was implemented. The frame differencing methodology is very sensitive and would be able to detect moving branches of a tree. Given that the camera is within a city, it was also desired for the motion of people not to be considered. The blob detection function in OpenCV is a function that groups pixels that are in "motion" together, bounded by those that are not moving. This would consequently group those pixels within the same area of the frame together if the pixels are white and surrounded by black pixels.

The function then allows for the storage of each blob, also availing parameters about the blob such as size, circularity and convexity. In a city, vehicles in general would be the largest moving objects, hence the size parameter was used to classify a blob of a given size as a vehicle. The exact size of a blob that would then be classed as a vehicle was reliant on the location (distance) of the camera in relation to the road.

As each blob enters the Region of Interest (ROI), it is assigned an identification number, a frame number, a time stamp and (x, y) coordinates are extracted and these values are stored. A bounding box is created on the blob with the center of the blob being used as the center of the box. As each box is created, a counter keeps count of all the blobs in the RIO and this parameter serves as the count of cars that are in the scene. The red box around the vehicle in is the bounding box that has been drawn, see fig 6.

d) Vehicle Speed: The speeds at which individual vehicles are travelling is calculated using the parameters stored for each blob as well as the parameters of the video stream. Using the blob data that has been maintained from the initial detection of a blob to the time at which the blob is destroyed, the average speed of the vehicle is calculated using the linear motion $v = \frac{d}{t}$ where v is the velocity of the vehicle, d is the travelled distance and t is the travel time in the video stream.

The time t in seconds during which the blob was in the scene is calculated using the frame at which the frame started being tracked (blobcreated – blobdestroyed) which is the frame as which the blob was destroyed and the framerate in seconds. Let D also denote the distance in meters of the ROI - this is the distance that the cars in the ROI would travel while being observed. The speed v at which vehicles are travelling in m/s is calculated using (4).

$$v = \frac{D}{\left(\frac{blobcreated - blobdestroyed}{framerate}\right)} \quad (4)$$

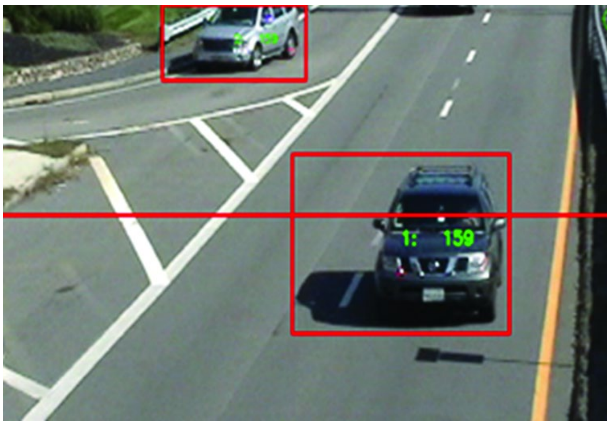


Fig 6:Object detection

C. Fuzzy Logic

Conventional traffic control management at a signaled intersection is implemented with circulation through all entry points into a junction; this methodology fails to deal efficiently with varying degrees of LOS [33]. The layer is also responsible for assigning each entry point a level of priority; that is, each point is allocated a weight that determines when the lane is to be allowed to enter the intersection. The layer makes use of the collected traffic parameters which are stored in a database. The parameters are extracted from the database and fed to the fuzzy algorithm.

a) Lane Priority: To decide on lane priority, we make use of two input parameters, these being the length of the queue on an entry point that is in the red phase (this is the lane that is currently not entering the intersection) and the wait times of each of the entry points; the output parameter is the priority the lanes will each be allocated. Some of the fuzzy rules that are used to determine the wait are illustrated in table 1. The lane that has the highest priority is given right of way on the 'next' circulation but will not be allowed entry into the intersection again before each lane has been given the opportunity at least once.

b) Green Time Extension: The duration of time each lane is allowed entry into the junction (green phase) is also determined using fuzzy logic. This module is responsible for determining how long (in seconds) the green phase is extended; the extension time is capped at 60 seconds with a minimum of 10 seconds. Some of the rules that are used to determine the extension tome are illustrated in table 2.

Table 1: Lane priority rules

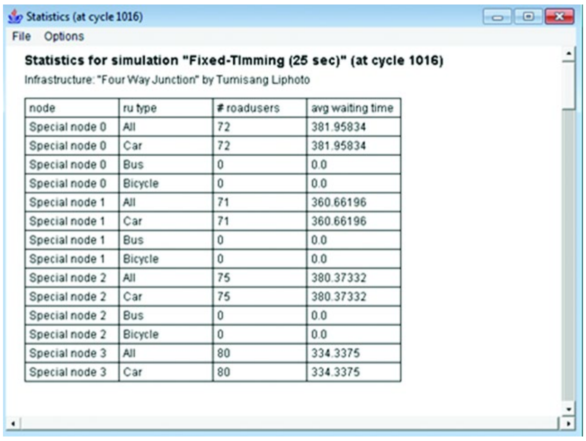
Queue Length	**rule**	**Wait Time**	**rule**	**Priority**
short	AND	short	THEN	low
short	AND	medium	THEN	low
medium	AND	medium	THEN	medium
medium	AND	long	THEN	medium
high	AND	long	THEN	high
high	AND	short	THEN	medium

Table 2: Extension time rules

Queue Length	**rule**	**Wait Time**	**rule**	**Priority**
short	AND	short	THEN	low
short	AND	medium	THEN	low
medium	AND	medium	THEN	medium
medium	AND	long	THEN	medium
high	AND	long	THEN	high
high	AND	short	THEN	medium

D. Testing and Evaluation

Two simulations were run with the statistic of interest being the average junction wait time. Fixed-timing simulation was run in such a way that every entry point into the junctions was given 25 seconds per phase. The results of the simulation are shown in fig 7. The total number of cars that crossed the junction was 302 and the average wait time was 56 seconds. The simulation that used fuzzy logic was ran and the results are shown in fig 8. The total number of vehicles that crossed the junction are 629 with an average wait time of 48 seconds representing a 14% decrease in wait time. The number of cars recorded were manually counted and compared to the number identified by the system. Table 3 shows the result of this analysis, an 82% accuracy was noted.



Statistics (at cycle 1016)

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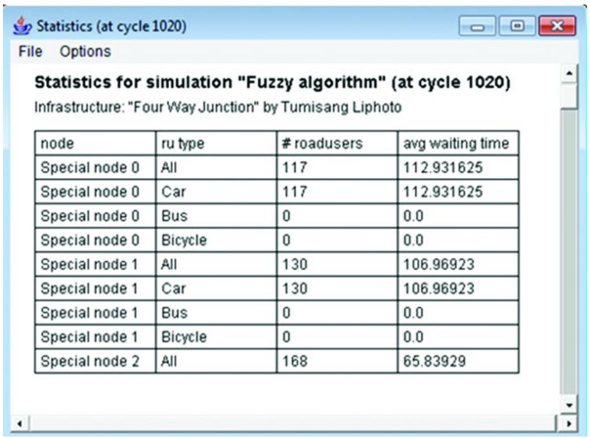
Statistics for simulation "Fixed-Timming (25 sec)" (at cycle 1016)

Infrastructure: "Four Way Junction" by Tumisang Lipholo

node	ru type	# roadusers	avg waiting time
Special node 0	All	72	381.95834
Special node 0	Car	72	381.95834
Special node 0	Bus	0	0.0
Special node 0	Bicycle	0	0.0
Special node 1	All	71	360.66196
Special node 1	Car	71	360.66196
Special node 1	Bus	0	0.0
Special node 1	Bicycle	0	0.0
Special node 2	All	75	380.37332
Special node 2	Car	75	380.37332
Special node 2	Bus	0	0.0
Special node 2	Bicycle	0	0.0
Special node 3	All	80	334.3375
Special node 3	Car	80	334.3375

Fig 7: Fixed-timing results



Statistics (at cycle 1020)

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Statistics for simulation "Fuzzy algorithm" (at cycle 1020)

Infrastructure: "Four Way Junction" by Tumisang Lipholo

node	ru type	# roadusers	avg waiting time
Special node 0	All	117	112.931625
Special node 0	Car	117	112.931625
Special node 0	Bus	0	0.0
Special node 0	Bicycle	0	0.0
Special node 1	All	130	106.96923
Special node 1	Car	130	106.96923
Special node 1	Bus	0	0.0
Special node 1	Bicycle	0	0.0
Special node 2	All	168	65.83929

Fig 8: Fuzzy logic results

Table 3: Results of vehicle counting

Manually counted	89	Identified from video stream	94
		counted once	67
		counted more than once	12
		not counted	15

The speeds of the vehicles were also recorded and compared to speeds that were set on the cruise control; table 4 shows the results. The observed standard deviation was recorded at 3.24 $km/_h$. The error in the calculations of speeds increases as the true speed of the vehicle increases. This error will, however, not be of significance as cars in a city travel at lower speeds than they would on the highway.

Table 4: Vehicle speed measurement

Trial	Program speed (km/h)	Cruise control speed (km/h)	Difference (km/h)
1	50	46	4
2	55	53	2
3	60	64	-4
4	70	72	-2
5	80	82	-2
6	90	89	1
7	100	105	-5
8	120	124	-4

The above results indicate that reduced wait times and increased rate of flow at traffic lights can be reduced using IoT. This will lead to a reduction in the concentration of pollutants that result from exhaust fumes as the number of vehicles stationary will be reduced. The benefits of reduced CO_2 concentration in cities is beneficial as it would reduce the carbon footprint of the city and make for a cleaner environment.

IV. Conclusion and Future Works

In this paper an Internet of Things-based traffic management system is presented. The major aim of the system is to mitigate the impacts of congestion, whether environmental or societal. In this work, video-based sensors are used to collect traffic parameters from the road infrastructure. The parameters of interest are the number of cars and the speeds at which the cars are travelling. The other parameter that was of interest was the observations made by motorists on a road. Various techniques of video analysis were presented, as well as discussions on why the methods used were preferred over the others.

The parameters obtained were analyzed and subjected to fuzzy algorithms. The resulting values are the extension time of the green phase on traffic lights as well as the determination of the congestion level of a road network. The research question has been answered in that the research showed via simulation that rate of traffic flow is increased in reactive traffic lights compared to static traffic lights. The last research question was responded to by reflecting that the respondents to the survey showed a belief that constant provision of road status would reduce the frequency and intensity of congestion. Overall, the work presented here is a step in the right direction to limit the impact of congestion in African cities. However, more work still needs to be done in order to expand the current system in to a fully-fledged traffic management system. Here some of the improvements are presented that are intended to be incorporated in future works.

At present the current system works only for an isolated road, it is therefore envisaged that a more comprehensive solution be provided that is able to manage and disperse traffic information about an entire road network. Above that, it is also envisaged that a solution that is able to predict traffic flow be implemented. With privacy taken into account, more research is planned into having mobile devices to automatically provide their locations and travel speeds, resulting in a truly ubiquitous system.

It is also envisaged that a more robust detection algorithm that may be able to separate vehicles and shadows be used. This will be beneficial as it will reduce the error rate of the detection. In addition, the detection algorithm should also be able to continue tracking vehicles that at some point were hidden in the scene, maybe as a result of being 'behind' another larger vehicle.

This research was essential as it demonstrated the possibility of enhancing transport management systems for medium- sized African cities. The improvement of transport management in such cities should lead to reduction in wasted resources (time and money). Traffic departments in medium- sized African cities will benefit from this research as the results will aid in the planning of traffic management as well as provide a means for cheaply implementing an Intelligent Transport Management System (ITMS).

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