Application of Fuzzy Mamdani Model in Traffic Flow of Vehicles at Signalized Road Intersections

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Abstract— Over ***the last decade, increase in urban population as a result of continuous migration from rural to urban part of the country has led to availability of more vehicles on the road causing serious traffic bottlenecks, which is a big challenge in our society today. This study aims to develop an algorithm based on signalized traffic control system to address the constant repetitive traffic congestion problem in South Africa. The Fuzzy Mamdani model (FMM) was implemented using MATLAB R2020. Within the period of investigation, the number of connecting vehicles, the time taken for vehicles to navigate at road intersections and the distance covered by the vehicles before intersection were noted as input and output variables. Membership functions for input, output variables were defined, rules were developed based on available parameters and dataset obtained. The result obtained from the FMM showed a great improvement in the system, the model is capable of reducing the problem of traffic congestion significantly at signalized road intersections. However, further research can be conducted at different traffic conditions to further prove the trustworthiness of the FMM Model.***

Keywords—Fuzzy Mamdani Model; Traffic congestion; Signalized Road intersection;

I. INTRODUCTION

Traffic congestion is among the primary problems which has negative impacts on the development of urban areas in the world[1][2]. It is important to note that traffic congestion is unavoidable in developing and developed countries, it occurs on a daily basis. Nevertheless, people are frequently experiencing the adverse effects of traffic congestion, e.g., disturbances in-vehicle mobility, high level of fuel consumption, longer travel times and others. Although traffic congestion is inevitable, transportation engineers and researchers have come up with ways to either tackle it or eliminate it from road transportation systems [1]. To monitor traffic congestion on roads, transportation researchers have come up with sophisticated real-time monitoring equipment such as inductive loop detectors and video image processors [3], these monitoring equipment have created a unique opportunity to predict traffic flow conditions [4][5][6]. Several methods and techniques can be used to reduce or eliminate traffic congestion, these methods has to do with construction of high occupancy vehicle lanes, quick reaction to traffic impending accidents, and construction of a new transportation framework. However, these methods seem not to be enough to solve the monumental problem of traffic congestion. The main issue is focused on actualization of traffic control guidance by applying pre-existing and available transportation resources more efficiently [1].

The notion of intelligent transportation systems (ITS) occurred in the early 1990s [2] to improve the effectiveness of what are called "surface transportation systems" by effective planning and implementing of workable solutions to help eliminate or reduce transportation problems by using innovative information and advanced communication technologies. ITS is applied because of the upward surge of traffic demand in developed countries and ensuring that transportation infrastructure is used adequately. The major drawback of applying artificial intelligence systems in road transportation networks is the mind-set of people towards the methodology, majority of individuals, especially road users are of the opinion that the incorporation of artificial intelligence (AI) system, to support road transportation would totally or partially replace humans at workplace, they are also of the opinion that cyber-attacks is possible via introduction of AI systems [7]

At present, road transportation systems primary objective is to improve the application of alternative transportation systems and improve the efficiency of the road traffic flow by using various transportation methods such as the route guidance systems (like a GPS or google maps), improving traffic light signals, proper management of vehicle accidents and prediction of traffic flow. All these transportation methods have two (2) similarities, they are: (a) To have a comprehensive understanding of the concept of traffic flow based on specific locations and (b) manage its growth. To achieve these two similarities, each of these similarities is over-reliance on conventional mathematical techniques (e.g., statistical regression) and is sometimes inadequate to thoroughly tackle and solve the complexities of road traffic control features and interrelationships [1].

However, traffic congestion is solely based on the behavioural aspects of human drivers (non-autonomous vehicles). Because traffic-related decision-making is dependent on uncertainty, imprecision, and partial lies from the human driver's aspect. It is imperative and compulsory not to exclude the human factor while developing equations focused on transportation modelling. Also, it causes a severe upward surge in complexities and intricacies in transportation computation and the Time it takes to execute it. Therefore, it is imperative to adopt a global strategy to help solve traffic congestion issues which has to do with uncertainties such as as decision making process that involve the navigational pattern of the driver, differences in traffic data, and transportation analysis under uncertainty. Approaching real-life traffic congestion is based on subjective knowledge (i.e., linguistic data) than using conventional analytical methods. This is usually achieved where the aim and objectives are to evaluate or adopt a knowledge-based technique in traffic control of non-autonomous vehicles at a signalized road intersections [1].

The proposed model to be used in this paper is dependent on the theory of the fuzzy Mamdani model, a model capable of handling ambiguities or stochastic information or uncertainties at signalized road intersections due to its analytical, predictive strength, qualitative and linguistic characteristics . It comprises two input variables, which gives comprehensive insights into the concept of traffic congestion at a signalized road intersections, and one output variable, which is used to determine the severity of traffic congestions at road intersections. This proposed approach of implementing the fuzzy Mamdani model is an exposition of the strength of computational intelligence techniques in problem solving which will help to properly understand the concept behind having comprehensive knowledge about traffic congestion. Conventional analytical methods are usually ineffective when handling issues associated with traffic congestion, the dependent variables while considering traffic datasets are too complicated or not clearly defined. Nonetheless, in real-life traffic occurrences, it has been noted that traffic cases are usually difficult to investigate or evaluate using "traditional" mathematical methods. This is because of the presence of subjective decision-making in many traffic occurrences. The traffic situations can select the best route, driver's decision making, entrenched level of service (LOS), defining criteria for optional routing, etc. However, pre-existing computational traffic models for solving problematic traffic congestion and road transportation problems cannot effectively tackle road transportation uncertainties and traffic congestion vagueness, various fuzzy set theory methods have been proposed to solve this problem.

A fuzzy logic system is a modern optimization technique that can efficiently approximate any type of real-life continuous non-linear functions to a higher degree of efficiency [8]. Expressions such as ambiguity, uncertainty, and vagueness are common when explaining traffic-related issues and traffic congestion. [9] Stated that unclear logical statements lead to the formation of algorithms that can be applied in ambiguous data to formulate complicated inferences. [10] are among the first transportation researchers to come up with the notion that fuzzy logic can solve real-life traffic situations and road transportation problems. [11], [12], [13][14][15] showcased the importance of fuzzy set theory by using these methods to find a comprehensive solution to traffic flow problems.

The fuzzy logic theory relies heavily on the notion that human thinking's primary elements are not figures but fuzzy set labels. However, the pervasiveness of fuzzy logic in human thinking ability proposes that almost all the logic supporting human reasoning is not because of the conventional pair of multivalued logic reasoning but because of what we called fuzzy truths, fuzzy connectives, and fuzzy laws of inference [9]. In other words, fuzzy logic, fuzzy sets, and fuzzy inference techniques offer assistance in obfuscating unclear and inefficient concepts. This can be formulated by representing 'X' as a non-empty set. A fuzzy set A in 'X' is represented by its membership function

$$\mu A: X \rightarrow [0, 1]$$

μA(X) = degree of membership of element X contained in fuzzy set A for every x∈X. The degree to which x is A is not false is simply acknowledged as the degree of membership of x in A [16]. A fuzzy set is an extension of the traditional set, also known as a crisp set. The crisp set can be defined as when an element either belong or do not belong, while the fuzzy set comprises elements with a level of membership, which can be either completely belonging to the set or not belonging to the set. Hence, fuzzy logic has the capability of solving the fundamental concept of what is called partial truth. Partial truth means the truth with parameters between fully true and fully false. There are two primary terms used in fuzzy logic for modelling; they are: Membership functions (MFs) and Fuzzy inference systems (FIS). Membership function curves are typically used to explain the relationship of elements of input space. This question always arises "do they belong/do they not belong" to a fuzzy set by attracting every element with corresponding membership value in a closed unit interval [0-1]. There are five well-known shapes of membership function in the fuzzy inference system. They are:

Triangular Membership function; Trapezoidal Membership Function; Gaussian Membership function; generalized bell and sigmoidal Membership function.

Congestion and analysis of traffic flow at a road intersection.

Notwithstanding, if the shape of the membership function is either triangular or trapezoidal, it can only be used for one fuzzy set. Usually, more than one membership function is frequently used to explain a single input variable. *The main question is how we can apply a fuzzy inference system to predict traffic flow performance, especially at a signalized road intersection.* A fuzzy inference system can be defined as combining the mapping from specific input variables to a specific output by applying fuzzy logic [16]. The fuzzy inference process comprises several phases, phases such as; redefining and fuzzyfying input variables, using fuzzy rules and fuzzy operators, using implication technique, using aggregation technique defuzzification (optional).

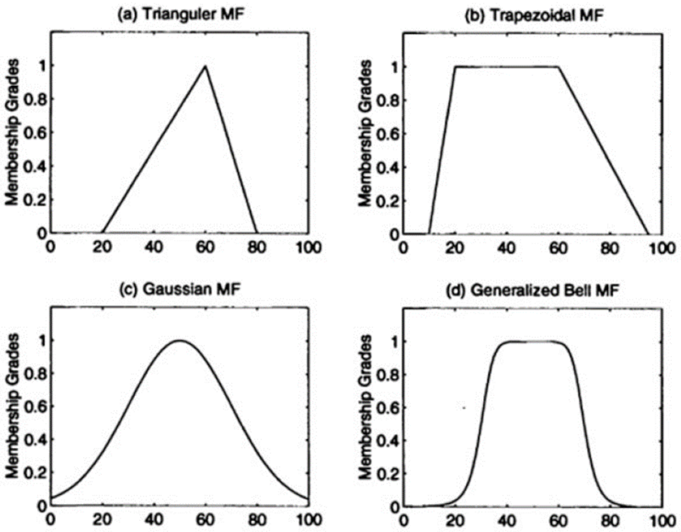

Fig 1: The four most commonly used membership functions in fuzzy logic[17] .

There two primary types of fuzzy inference systems (FIS), they are Mamdani and Sugeno; these type of FIS was first proposed by [18] and [19] respectively. The important difference between these two is that they have different ways to determine output parameters. Mamdani fuzzy inference system was one of the first control systems created by applying fuzzy set theory. The Mamdani method was created during the year 1975 to synthesize a group of linguistic control rules, which are gotten from non-automatic human operators (experienced), e.g., An experiment is carried out in controlling a steam engine and combination of boilers.

Mamdani's experiment is dependent on the research paper wrote by [9] this paper was based on fuzzy algorithms for complicated inference systems and decision methodologies. Sugeno fuzzy inference system is preferred over the Mamdani inference system when an inference system's output membership functions are linear or constant. This inference system improves the effectiveness of the defuzzification approaches because of the simplified computational requirements. In the Sugeno fuzzy inference system, the system applied weighted average data points to determine the centroid, unlike the mamdani inference system, which integrates across the two-dimensional function. Mamdani fuzzy model is presently the most used fuzzy methodology in the road transportation system.

One of the challenging problems during a fuzzy inference system is defining input features of a traffic dataset; it involves both dexterity and experience in the specific area of application of the fuzzy inference system. The first step after knowing what your input variables are is converting the crisp numerical values of choosing input parameters via membership functions into degrees of membership of the fuzzy set. The only rule a membership function has to adhere to is fulfilling the [0-1] interval rule. The most straightforward and most widely used membership function is the triangular membership function or, in some exceptional circumstances, Gaussian, sigmoidal or polynomial function. Sometimes, it is usually the case that the fuzzy inference system comprises more than one or two input variables. In a fuzzy inference system, it is imperative to create a mechanism that illustrates how to initiate input parameters to output space. This is carried out by enumerating if-then fuzzy rules. A single fuzzy if-then rule adheres to the concept:

If x is A, Then y is B

The first part is called the antecedent, x is the input parameter. The rest is the consequent, and y is the output parameter. The pair of A and B are known as the linguistic parameters, which allows this type of conditional statement to perform as identical to human being judgment. The antecedent is commonly explained with more than one fuzzy sets. The combination of these membership parameters to achieve a resulting efficient value is achieved by applying fuzzy operators. The most widely used fuzzy operators are AND and OR, these operators use min and max function as connectors of formerly linguistic parameters. Over the years, different types of transportation researchers have come up with ways to use the combination of artificial neural network and fuzzy inference system (Takagi-Sugeno or Mamdani) to tackle the problem of traffic congestion, especially from the perspective of but not limited to traffic control, traffic flow, traffic lights, vehicular sped and traffic density.

II. MATERIALS AND METHODS

Location and traffic datasets

Traffic datasets used in this research study were collected from Mikros traffic monitoring (MTM), the company is a subsidiary of a syntell group of companies in conjunction with the South Africa Ministry of transportation. The traffic dataset was collected from the N1 route in South Africa Road network. The N1 route passes through all the major cities in South Africa, such as Polokwane, Pretoria, Johannesburg, Bloemfontein, Middleburg, and Capetown. It is noteworthy to point out that the reason why this study focuses on the N1 route is because of its comprehensive coverage of the South Africa road transportation network and the high volume of vehicles travelling on the road through this route per day. The high traffic congestion and road accidents been experienced at signalized intersections along this road makes this pathway the focus of this research.

Fig 2: An aerial view of a signalized road intersection along the NI road.

The equipment used to obtain traffic datasets on this road network are:

Inductive loop detectors: These are detectors that comprise an embedded wire, an oscillator, and a cable wire, which gives easy access to traffic signals to pass through the loop detector to a traffic counting equipment usually installed beside the road. This traffic counting equipment is activated by a change in the equipment's magnetic field when a non-autonomous or autonomous vehicle travelled over the loop [20] .

Weight-in-motion sensor: This type of traffic data collection device is used to count vehicles and determine vehicles' weight and classification on the road. They can also be called Weigh In Motion (WIM). Apart from these weight in motion sensors, there are also bending plates, capacitive strip, and Mat and Piezo-electric cable.

Video Camera: This device is not only used for counting vehicles on the road; it is also used to monitor traffic offenders. It captures vehicles' details, details such as the plate numbers, vehicular speed, and Time it takes the vehicles to move from one location to another. The only disadvantage of this device is that it is easily affected by the weather, especially during the rainy season.

Sample of the 100 traffic datasets used for the FMM analysis is shown in Table 1.0.

Table 1: Sample of the traffic datasets used for the FMM

Vehicular speed	Distance	Time
48	30	105
41	32	97
47	44	76
40	39	98
41	47	87
40	35	80
46	39	92
31	21	80
55	35	91
42	26	75

Fuzzy Mamdani Model (FMM)

The Fuzzy Mamadani Model as a computational intelligence technique has the capability to produce a good solution on rule viewer possess using linguistic terminologies by creating standard membership functions and developing standard rules for accurate solution during alpha cuts. There is no doubt that the model will perform at a high degree of accuracy as it is appropriate for estimating any real continuous function in a complex stochastic set. The primary reason why Fuzzy and ANFIS are suitable for the generation of mapping relationships among inputs and output datasets is because of its capability to seek interpretable IF_THEN rules, this modern soft computing method is considered a preferable choice than other computational intelligence techniques due to easy mapping and sensitivity rules [21][22][23].

FMM formulation process can be categorized into the: fuzzification process, rule process, normalization process, defuzzification and summation. The architecture of the FMM model is presented in Figure 3., with speed and distance as the input variables for traffic control at road intersections.

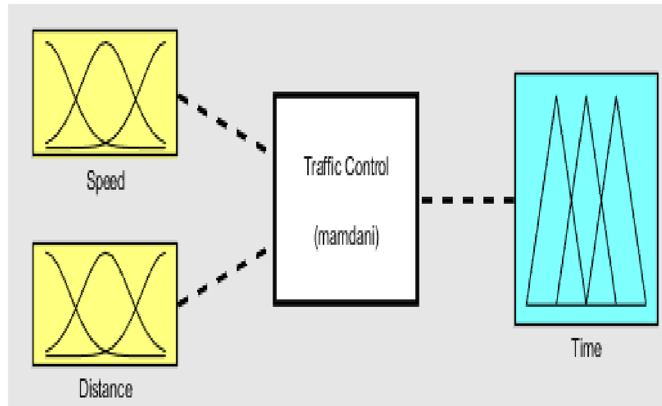

Fig 3: Architecture of the fuzzy Mamdani Model for traffic flow of the vehicles at the road intersection.

III. RESULTS AND DISCUSSIONS

Fuzzy Mamdani Model was used to find the shortest time required to navigate along road intersections. Triangular membership functions was used for output mapping considering available information obtained for traffic dataset. The Gaussian membership function was used to map the input dataset (vehicular speed and distance) as shown in Figure 3. Some assumptions were made based on Fuzzy Mamdani rules developed for the traffic dataset. These assumptions are based on observations made at the intersections within the period of investigation, as well as periodic observation noticed from the available dataset collected from the aforementioned company. Table 2. Shows part of the rules developed out of one hundered and twenty rules. For the first road intersection, when speed is high and distance is low then the estimated time observed is very low. For the second road intersection, when speed is high and distance is low, then estimated time is equally very low. For third intersection, when speed is high and distance is very low, estimated time is very low.

Table 2: The Mamdani fuzzy rules for the traffic datasets

Road Intersections	Speed (Unit)	Distance	Estimated Time (Unit)
1	H	Lo	VLo
2	H	Lo	VLo
3	H	VLo	VLo
4	H	Lo	VLo
4	H	VLo	VLo

5	H	Lo	Lo

Note: H = High, Lo = low, VLo = very low

Fig 3 shows that at signalized road intersections, it is important to observe the speed, distance and time as important variables. The fuzzy inference system was used to obtain an optimum performance of a traffic flow performance using the vehicles' speed, distance been covered by the vehicles before they arrive at intersections, and the Time it takes the vehicles to reach the intersection. Dataset representing input variables (speed and distance) were fed into the fuzzy toolbox using the Mamdani class function. The MF plot for distance and speed is presented in Figure 4 and 5.

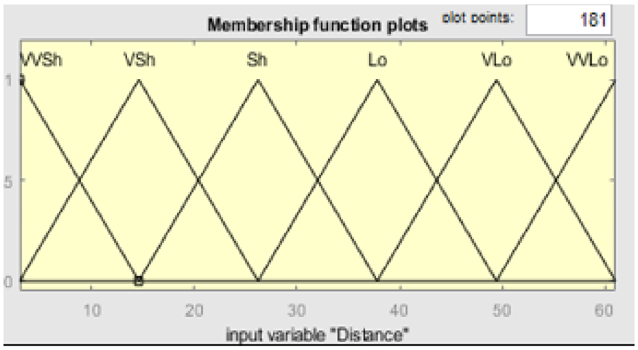

Fig 4: FMM membership function for Distance

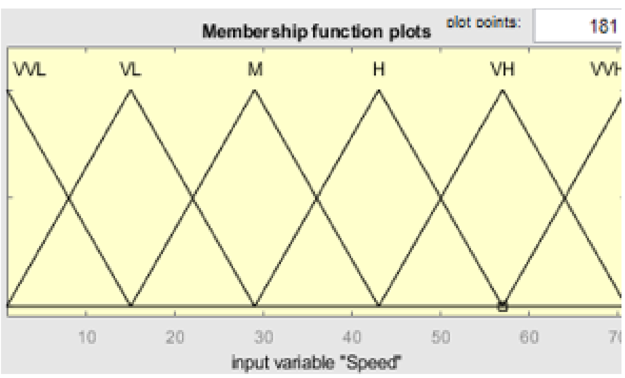

Fig 5: FMM membership function for Speed

Triangular MFs are used to represent the input variables (speed and distance). Mapping of the values was accurately done considering lowest value of vehular speed and distance covered to highest values. Rules have been accurately developed too. This led to the establishment of the rule viewer for alphacuts based on the mapping that was done. The sensitivity rule viewer from alphacut gave the three-dimensional surface plots of the fuzzy mamdani model as presented in Figures 6 and 7.

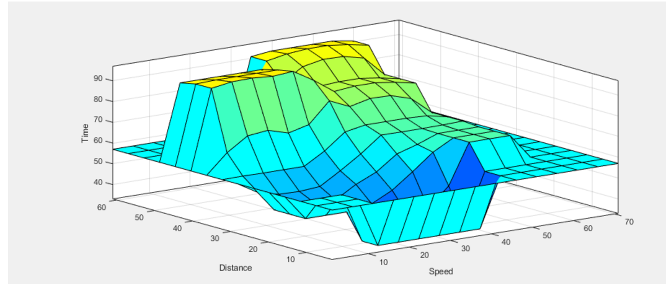

Fig 6. 3D plot showing time interval based on vehicles' speed and distance covered at first intersection.

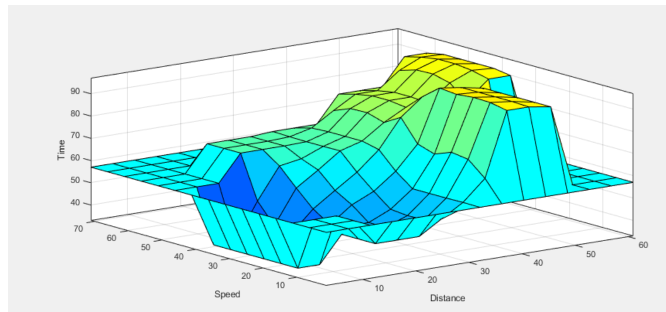

Fig 7. 3D plot showing time internal of the vehicles' speed and distance covered at second intersection.

Considering Table 2.0, based on linguistic terminologies and observations, about one hundred and twenty rules have been developed:

1. IF the speed of the vehicle approaching the intersection is high AND the distance of the vehicle navigating towards road intersection is short, THEN the travel time is observed to be short.

2. ELSE if the speed of the vehicles at a road intersection is low, AND the distance of the vehicle navigating towards road intersection is long, THEN the travel time is observed to be longer.

The primary objective is to reduce the traffic congestion of vehicles at the intersections. It is also important to note the number of queuing vehicles at road intersections, that is, vehicles waiting for the traffic lights to turn green (W(A)). The fuzzy mamdani model as a computational technique helped to allocate priority base on rules and MFs, to vehicles with the highest demand for green time. The Fuzzy Mamdani model gave a good performance during analysis on the rule viewer platform. The Fuzzy Mamdani model's effectiveness and efficiency are much better than the Takagi Sugeno model, actuated, and feed controller in different conditions [24]. The fuzzy mamdani results clearly shows high level of performance. Research conducted by shows a better prediction of Fuzzy model compared with other conventional methods.

IV. CONCLUSIONS AND FUTURE WORK

This research study has addressed traffic congestion from the perspective of traffic flow at signalized road intersections considering parameters like vehicular speed, distance, and Time. The Fuzzy Mamdani model was effectively used to solve this problem at signalized road intersections. However, it is noteworthy to point out that this research focused on traffic control at signalized intersections, specific research still needs to be carried out at un-signalized road intersections. This paper has clearly shown the superiority of the FMM model for resolving traffic congestion issues compared to other conventional methods such as the Markov chain model and other statistical and soft computing techniques simulation model.

V. ACKNOWLEDGEMENT

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