Modelling Traffic Flow on Cloverleaf Interchange

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Abstract

The rapid urbanization alters the life style in high scale and metropolitan cities adapt traffic diverting structures like interchanges and bridges to handle the ever increasing traffic growth. It is high time to effectively utilize these traffic systems, hence a traffic model explaining the effective travel pattern is obligatory. Fuzzy logic is an effective concept in interpreting and reciprocating performance similar to human reasoning and can describe complex systems in linguistic terms instead of numerical values. In this study, a system was established based on Fuzzy Inference System (FIS) with output data as Vehicular Speed (*S*) and input data as various highway geometric elements. The study was conducted on two steps as for up-ramp condition and down-ramp condition. Two Traffic models ($TF_{up}$and TF_{dn}) were developed with radius of curvature, super elevation, frictional coefficient and slope as governing factors. The inferences show that these models can be used to predict and understand the traffic flow along the interchanges with the effect of gravity and friction on the travelling vehicle. A correlation was established between the geometric elements and speed of the vehicle. A simulation study and real life data analysis were performed to demonstrate model fitting the performances of the proposed model.

*Keywords:*Traffic flow, interchange, fuzzy inference system, fuzzy membership function, fuzzy clustering.

1. Introduction

Traffic is the stream of vehicles moving on highway and congestion happens when this stream comprises of slow moving vehicles. The rapid urbanisation alters the life style in high scale and metropolitan cities adapt traffic diverting structure like interchange to handle such congestion. For efficient design and utilization of any such structure it is essential to know about the traffic flow, hence a model explaining the same is essential. Earlier studies on traffic flow define it evidently that the traffic flow is dependent on the structural property of the traffic facility and also on the driver behaviour. Various studies relate the driver's response to specific conditions to predict the behavioural pattern and to develop different numerical models. Though such elaborate studies were done, no particular model could depict the realistic scenario, as the governing factors for each situation vary. In this study, an effort is made to develop

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a model for an interchange, as it plays an integral part in managing traffic without interruption.

For an intricate study, the case of a cloverleaf interchange is chosen. This work is aimed at:

I. To study the effect of gravitational force existing on the vehicle moving along the loop of the interchange
II. To study the relation between speed and the slope involving gravity and friction
III. To develop model for the interchange studying the driver behaviour.

Conventional macroscopic models on traffic flow, like Pipe's, Forbes's and General Motors models are conserved in this case as there will be more number of variables, consequently microscopic simulation model is to be adopted which is an effective tool for analysing wide variety of dynamical problems.

This paper is divided into five sections of which this is the first to introduce the matter. The second section presents a review of the past work done on modelling traffic flow. In the third section the proposed models are defined. The fourth section validates the models by summarizing results obtained from comparison of observed and simulated values. The last section concludes the paper.

2. Literature review

Before describing the work done in this study some crucial earlier studies in this area are presented in the foregoing paragraphs.

Chakroborty et al. (2004) studied the driver behaviour in uninterrupted traffic flow to develop a microscopic model which aims to predict the driver behaviour in diverse driving circumstances and the response of driver including both steering and speed control were analysed.

Hassan and Easa (2003) studied the effect of vertical alignment on driver perception of horizontal curves and found that perception of the driver of the road features ahead is an important human factor and should be addressed in road design. They voiced that, an erroneous perception of the road can lead to actions that may compromise traffic safety and the poor coordination of horizontal and vertical alignments is believed to cause such wrong perceptions. Through statistical analysis they suggested that the horizontal curvature looked consistently sharper when it overlapped with a crest curve and consistently flatter when it overlaps with a sag curve.

Sarutipand et al. (2003) redefined the conventional car-following model as the response depends both on the stimulus and sensitivity; as stimulus is a function of relative speed and sensitivity is a function of speed and headway.

Olstam and Tapani (2004) compared and described the car-following models used in the four traffic micro-simulation software packages AIMSUN, MITSIM, VISSIM, and the Fritzsche car-following model. It resulted in similarity between the behaviour of the models even though the modelling approaches were different in the four different cases.
Rothery(1992)studied the analysis of local and asymptotic stability in a platoon of vehicles and provided a mathematical driving model with scientific foundation. It provided a steady state description of single lane traffic flow with regard to safety and traffic characteristics which can help to develop advance automatic vehicle control systems.

Brockfeld et al. (2004) studied that whenever a microscopic model is developed an error of 15.1% to 16.2% is observed. The error is due to the negligence of prime factors which governs the vehicle characteristics. It is obligatory to understand the impact of each of these factors and their importance in deciding the vehicle characteristics when a model tries to depict the realistic situation.

Wang et al. (2005) studied driver behaviour and its effects on traffic flow at three-lane roundabouts and developed Multi-stream Minimum Acceptable Space (MMAS) Cellular Automata (CA) models to simulate heterogeneity and inconsistency of driver behaviour and subsequent interactions were analysed.

Wang and Coifman (2008) studied the vehicular traffic for multi-lane and developed two models. The models when compared by fundamental traffic parameters resulted in variation because the model considered lane changes but in reality such change-over will cause platoons reducing the traffic flow.

Ruskin and Wang (2002) studied traffic flow at urban un-signalised intersection using cellular automata by simulating the heterogeneity and inconsistency of driver behaviour. The study exposed the driver distribution having a noticeable impact on capacity of major and minor traffic streams.

Chacon (2012) studied the effect of driver behaviour on freeway traffic flow. A model was developed by simulating the driver behaviour in recreated segment of freeway by incorporating real data. The result obtained evidently proves that there is an optimal following distance which improves traffic flow.

Lindgren and Tantiyanugulchai(2003) studied traffic flow at a suburban interchange by simulating two traffic models (Paramics and VISSIM) for a diamond interchange and results showed irregular arrival patterns along the ramp terminals hence modelling traffic along the adjacent intersections became necessary. The results also prompted to determine the required number of model runs as results differed with every random data due to its stochastic nature.

3. Proposed Model

In the former studies, commonly the traffic flow models were developed as statistical prediction model with limited parameters. From the analysis it is preferred to use fuzzy logic, as decision making is a human quality and no precise inference could be attained by other logical means.

This section explains the proposed fuzzy logic model, where an attempt has been made to predict the Speed (*S*) with respect to the various highway geometricelements.

Fuzzy logic is a mathematical tool for modelling that explains any natural phenomenon for decision making in the absence of complete and precise information. Their role is significant as it can express any natural phenomenon especially related to human decision making using linguistic variables, which is not possible using any mathematical expression.

The proposed model is quantifying the speed of the vehicle travelling along the ramp of the interchange considering various geometric elements of alignment of the highway as premise variables. The components of proposed model using fuzzy inference system (FIS) are the fuzzification, rules, aggregation and defuzzification as illustrated in Figure 1.

The proposed model developed is similar as Mamdani type fuzzy inference system and quantifies the vehicular speed with the help of fuzzy logic toolbox in MATLAB release R2009a.

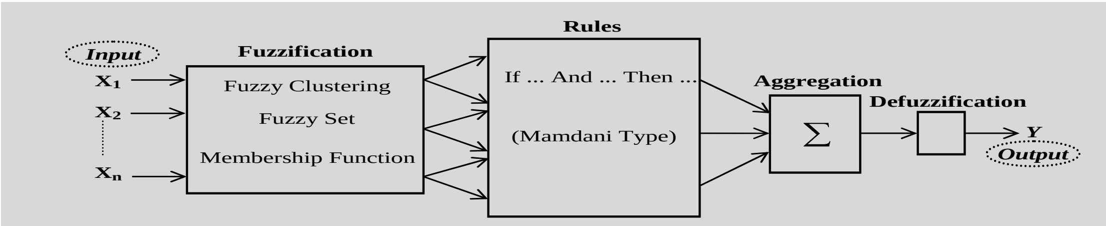

Figure 1: Schematic Diagram of Proposed Model Structure

Fuzzy *c*-mean clustering method is applied in this model for defining the parameters of the membership function of input variables and grouped according to their membership values with the help of fuzzy logic toolbox in MATLAB. The output result of fuzzy *c*-mean clustering aids to develop the membership function on modelling.

Summary of fuzzy clustering for the up-ramp is shown in table 1.

Table1: Fuzzy Clustering of Up-Ramp (TF_{up})

Input variables	*Fuzzy clustering*		
	Group	*Group Centre*	*Group Range*
Radius of Curvature	1	38	25-45
	2	50	40-65
Super-Elevation	1	4.8	4-5.5
	2	6	5-7
Slope	1	0.04	0.025-0.05
	2	0.055	0.045-0.07

Similarly, fuzzy clustering of the down ramp which consists of three input variables: radius of curvature, frictional coefficient and slope, is completed.

Now, derivation of the membership functions for both input and output variables and their linguistic representation is induced to accomplish fuzzification of the variables. The deterministic values of the input variables are converted to membership degree of fuzzy sets. These fuzzy sets are labelled with commonly used linguistic values. Triangular, trapezoidal types of membership function have been used for this model. The fuzzyfication operation of Super-Elevation (*SE*) and Frictional Coefficient (*FC*) has been presented in this paper in figure 2 and figure 3.

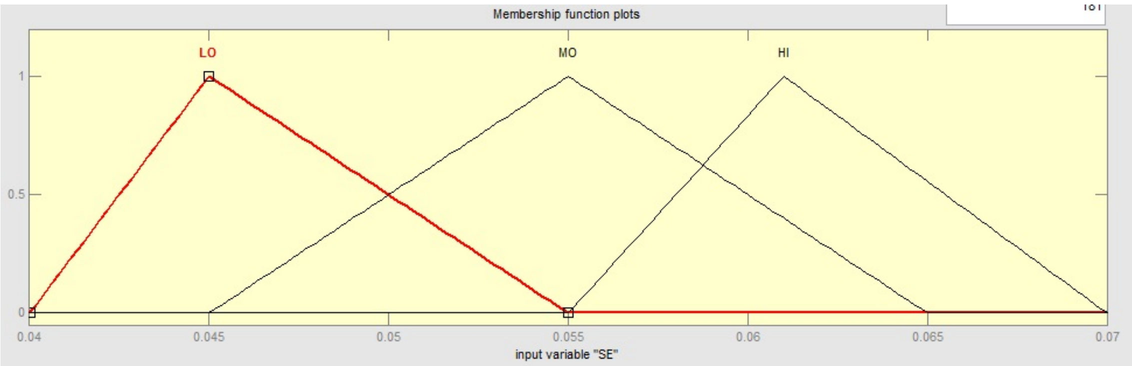

Figure 2: Fuzzification of the Input Variable Super-Elevation (*SE*)

Mathematical expressions of the membership functions of the fuzzy subsets are also depicted in this paper. Of all the nine fuzzy subsets of the output variable speed, membership functions of some of it are depicted in mathematical form. The membership function of the fuzzy subset ‘low’ of the variable ‘super-elevation’ is represented by equation 1.

$$\mu(lo)=\begin{cases}0; x<0.04\\ \frac{x-0.045}{0.045-0.040};\frac{0.045-x}{0.055-0.045}; 0.04<x<0.05; 0.045<x<0.055\\ 0; x>0.055\end{cases} \quad (1)$$

Similarly, membership function of the fuzzy sub-set ‘moderate’ for the same input variable ‘super-elevation’ is cited mathematically in equation 2 where the boundary conditions for *x* are predictable.

$$\mu(mo)=\begin{cases}0\\ \frac{x-0.045}{0.055-0.045};\frac{0.065-x}{0.065-0.055}\\ 0\end{cases} \quad (2)$$

Similarly, membership function of the fuzzy sub-set ‘high’ for the input variable ‘super-elevation’ is shown mathematically in equation 3 where the boundary conditions for *x* are predictable.

$$\mu(hi)=\begin{cases}0\\ \frac{x-0.055}{0.06-0.055};\frac{0.07-x}{0.07-0.06}\\ 0\end{cases} \quad (3)$$

The input variable frictional coefficient is composed of three triangular fuzzy subsets in the model viz. Smooth, satisfactory and rough.

Membership function for the fuzzy subset ‘smooth’ of the input variable frictional coefficient is mathematically expressed in equation 4 where the boundary conditions for *x* are predictable. Fuzzy clustering of the frictional coefficient which is a factor considered in the modelling of the down ramp (TF_{dn}) is tabled concisely for the convenience of comprehension.

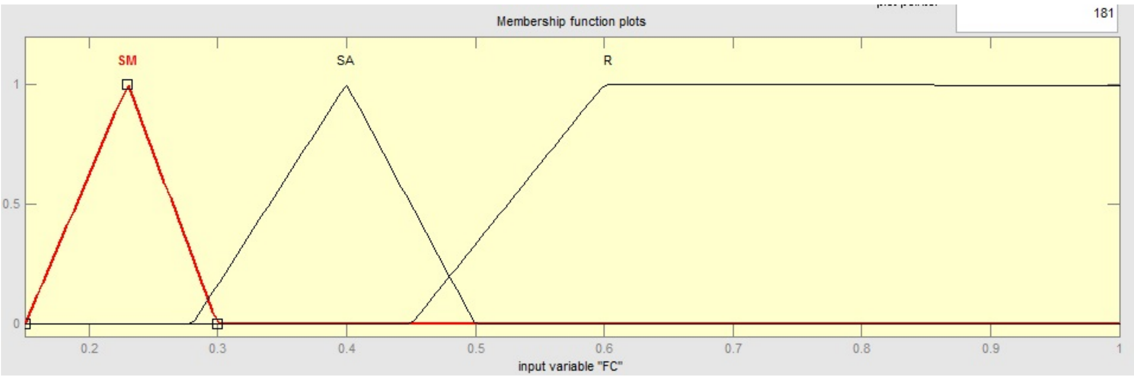

Figure 3: Fuzzification of the Input Variable Frictional Coefficient (*FC*)

$$\mu(sm) = \begin{cases} 0 \\ \dfrac{x - 0.15}{0.23 - 0.15}; \dfrac{0.3 - x}{0.3 - 0.23} \\ 0 \end{cases} \quad (4)$$

Similarly, membership functions of the fuzzy sub-sets ‘satisfactory’ and ‘rough’ for the input variable ‘frictional coefficient’ is shown mathematically in equation 5 and equation 6, where the boundary conditions for x are predictable.

$$\mu(sa) = \begin{cases} 0 \\ \dfrac{x - 0.28}{0.4 - 0.28}; \dfrac{0.5 - x}{0.5 - 0.4} \\ 0 \end{cases} \quad (5)$$

$$\mu(r) = \begin{cases} 0 \\ \dfrac{x - 0.45}{0.6 - 0.45}; \dfrac{1.0 - x}{1.0 - 0.6} \\ 0 \end{cases} \quad (6)$$

The output variable is categorised into nine triangular fuzzy subsets due to distribution of data for both the models. Fuzzyfication procedure of the output variable speed is presented by figure 4. Membership functions of some of the nine fuzzy subsets are shown here, which are mentioned as ‘low’ and ‘desirable’.

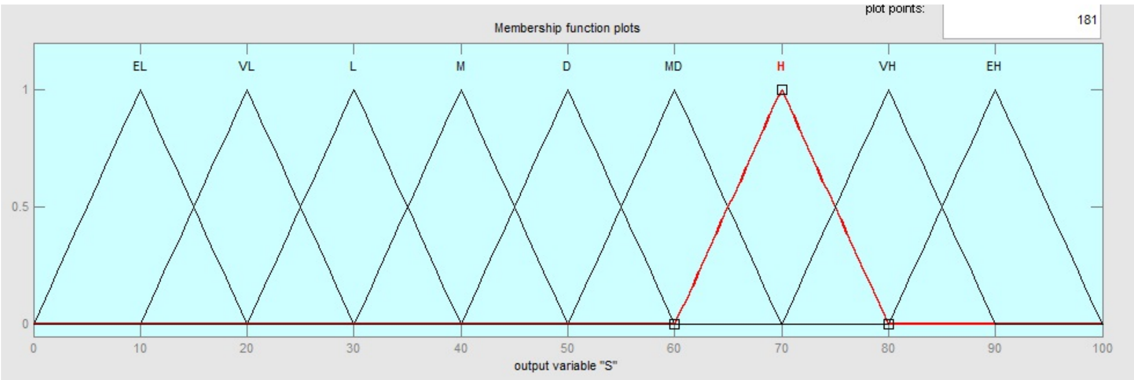

Figure 4: Fuzzification of Output Variable Speed(*S*)

Membership functions of the fuzzy subsets 'low' and 'desirable' of the output variable speed is explained in equation 7 and 8 where the boundary conditions for x are predictable.

$$\mu(L) = \begin{cases} 0 \\ \frac{x-20}{30-20}; \frac{40-x}{40-30} \\ 0 \end{cases} \quad (7)$$

$$\mu(D) = \begin{cases} 0 \\ \frac{x-40}{50-40}; \frac{60-x}{60-50} \\ 0 \end{cases} \quad (8)$$

In this model, fuzzy rule sets are formulated relating input variables to the output variable and 24 rule sets have been proposed pertaining to mamdani type rule system. Each fuzzy rule gives a single number that represents the truth value of that rule. The input for the implication process is a single number given by the antecedent, and the output is a fuzzy set. The summation operation method has been used for aggregation process. Some of the rules are presented here. Before that all the subsets of the input sets and output set should be stated.Here,*R* is Ramp {Up (*UP*) or Down (*DN*)}, *SL* is Slope {Gradual (*G*) or Steep (*ST*)},*RC* is Radius of Curvature {Critical (*C*) or Gradual (*G*)},*SE* is Super-Elevation {Low (*L*) or Moderate (*MO*) or High (*H*)}, *FF*is Friction Factor{Smooth (*SM*) or Satisfactory (*SA*) or Rough (*R*)} and *S* is Speed {having nine subsets,Extremely low (*EL*), Very low (*VL*), Low (*L*), Moderate (*M*), Desirable (*D*), Most Desirable (*MD*), High (*H*), Very High (*VH*), and Extremely High (*EH*)}.It must be mentioned here that by sensitivity analysis it was found that for Up-Ramp, Friction Factor (*FC*) and for Down-Ramp, Super-Elevation (*SE*) becomes insignificant, so they do not contribute to the respective rules accordingly.

Rule 1: If (*R* is *UP*) and (*SL* is *G*) and (*RC* is *C*) and (*SE* is *L*) then (*S* is *L*)

Rule 2: If (*R* is *UP*) and (*SL* is *G*) and (*RC* is *C*) and (*SE* is *H*) then (*S* is *M*)

Rule 3: If (*R* is *UP*) and (*SL* is *G*) and (*RC* is *G*) and (*SE* is *L*) then (*S* is *MD*)

……………….

Rule 22: If (*R* is *DN*) and (*SL* is *G*) and (*FF* is *S*) and (*RC* is *C*) then (*S* is *M*)

Rule 23: If (*R* is *DN*) and (*SL* is *G*) and (*FF* is S) and (*RC* is *C*) then (*S* is *MD*)

Rule 24: If (*R* is *DN*) and (*SL* is *G*) and (*FF* is *S*) and (*RC* is *G*) then (*S* is *H*).

De-fuzzification process is an operation in which each aggregated fuzzy output converts into a single crisp value through the developed fuzzy rules. Centre of gravity (CoG) de-fuzzification method has been applied for the fuzzy model. Equation 9 is the mathematical expression of the CoG de-fuzzification method for the discrete fuzzy systems.

$$y^* = \frac{\sum_{i=1}^{n} y_i \mu_U(y_i)}{\mu_U(y_i)} \quad (9)$$

Where y^* is the output variable of one set of input variables. Variables in the right hand side of the equation are input variables.

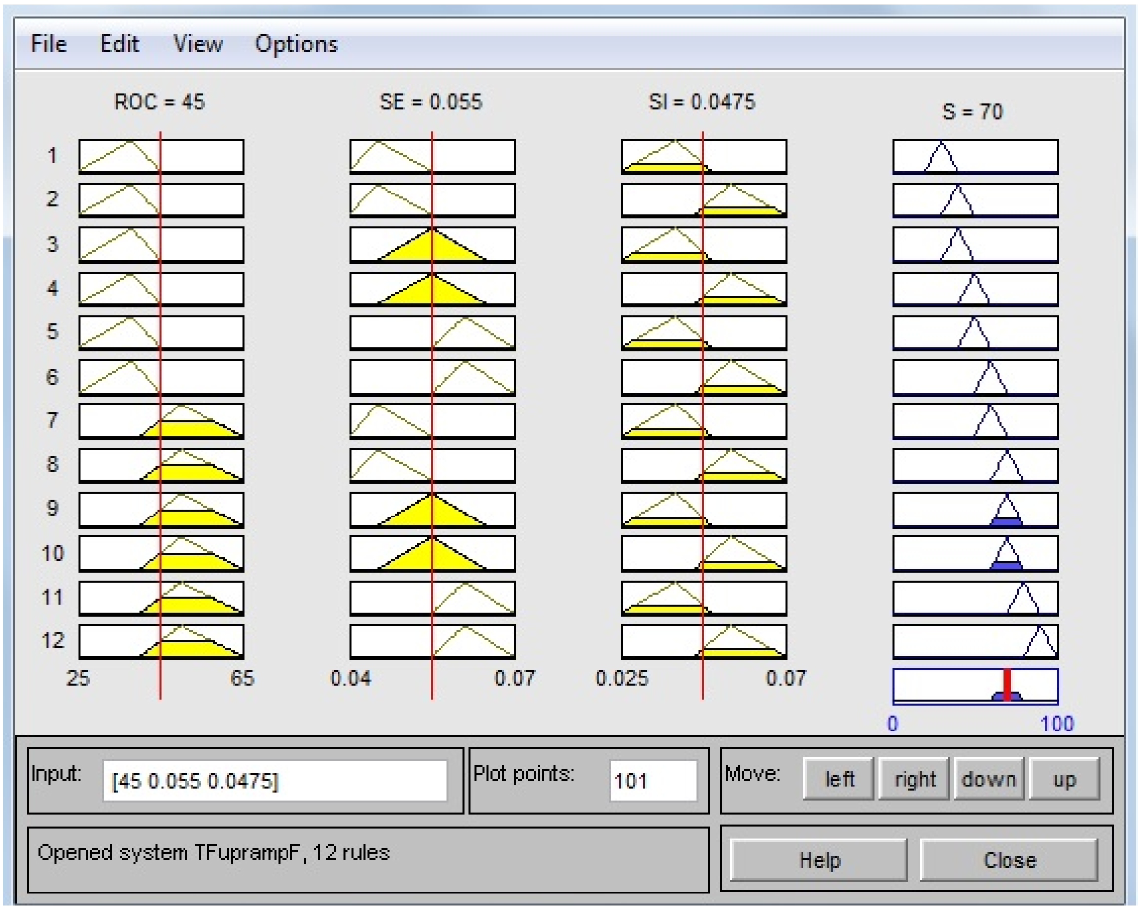

Figure 5: Rules for Up-Ramp Condition

4. Validation of the Model

Some empirical observation are made on speed based on the inputs such as Radius of Curvature, Super-Elevation as primary factors for Up-Ramp and taking Radius of Curvature and Frictional Coefficients as primary factors for Down-Ramp. Two regression models are made. These are given in equations 10 and 11. Speed is calculated for every 5 meters interval of the Radius of Curvature, for 0.5% interval of Super-Elevation, for every 0.05 units of Frictional Coefficients.

The values of the Speed data of the combined linear regression analysis are compared with the simulated results produced corresponding with each set of input data of validation set group. The simulated and observed data are plotted graphically in figure 6 and figure 7 as scatter plots.

$$speed\ (Up - Ramp) = 1.210\,(RC) + 155.216126\,(SE) - 1.504 \quad (10)$$

$$speed\ (Down - Ramp) = 0.510\,(RC) + 82.29\,(FC) - 3.193 \quad (11)$$

When the model results are examined in details it was observed that as far as the simulation results are concerned, the Speed value (*S*) obtained from empirical observation and obtained from model are almost same with the model error as 8.75% in $TF_{up}$and 6.85% in TF_{dn}. Hence, the models can be used to predict the speed of the vehicle travelling on the loops of the interchange.

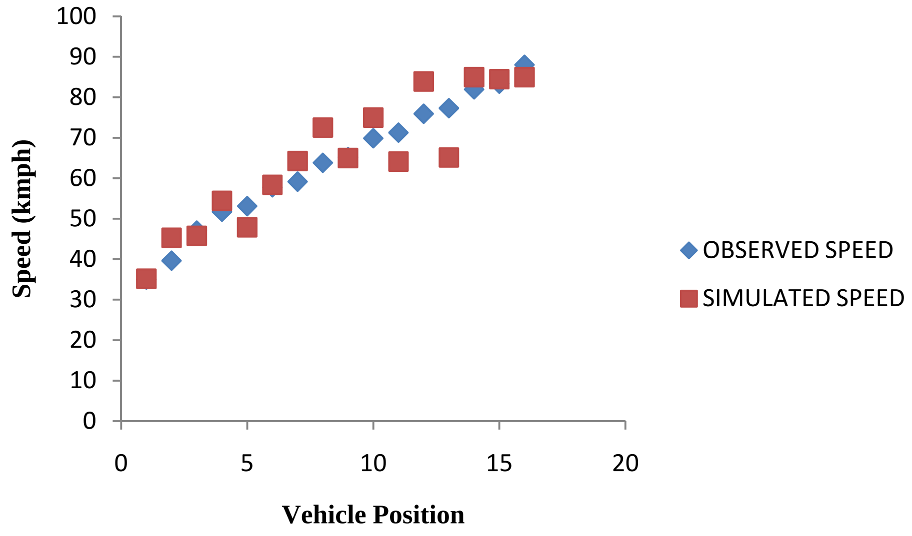

Figure 6: Simulated Speed Versus Observed Speed forUp-Ramp

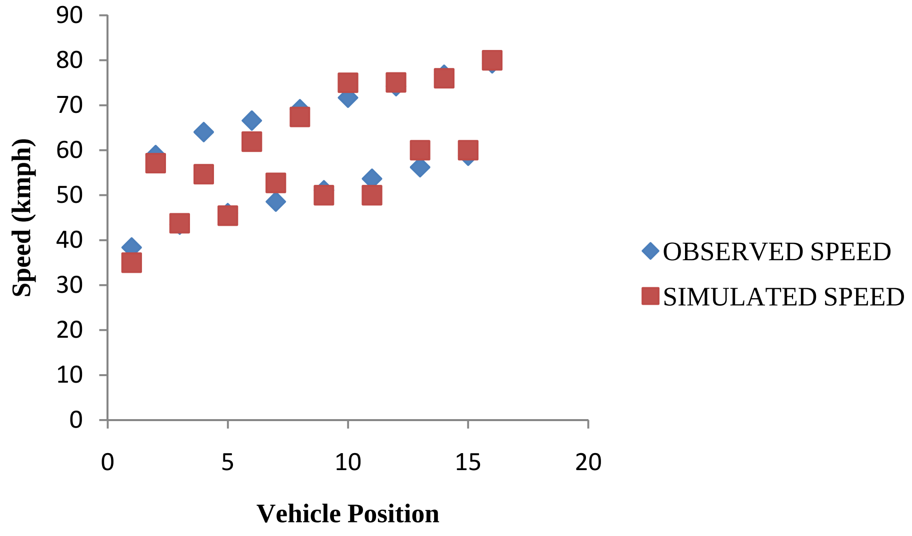

Figure 7: Simulated Speed Versus Observed Speed forDown-Ramp

5. Conclusion

The objective of the study was to develop a model that can be used to estimate the vehicular speed on the ramps of the interchange. Eventually, this study produced traffic flow model considering driver and vehicular behaviour. In this model, a system was established between the output data, Speed (*S*) and input data such as various highway geometric elements, i.e., Radius of Curvature (*RC*), Super-Elevation (*SE*), Frictional Coefficient (*FC*) and Slope (*SL*) of the ramp.

In interpretation of complication between the highway geometric elements, Fuzzy Inference System (FIS) based speed analysis was proposed. The conventional algorithms are conservative in comparison to fuzzy logic as it provides an extensive use of linguistic data set variables and to implement expertise decisions. Two traffic flow models were proposed which provide the speed of the vehicle on the ramp such as $\mathbf{TF_{up}}$ (Traffic flow model for Up-Ramp) and $\mathbf{TF_{dn}}$ (Traffic flow model for Down-Ramp).

Simulation results and Statistical analysis indicated that, several highway geometrics parameter are very significant to determine vehicle speed. The governing factors, Radius of Curvature andSuper-Elevation have great impact on vehicle speed moving on the Up–Ramp of interchange. Also the Radius of Curvature andFrictional Coefficient has greater influence on vehicle speed moving on the Down–Ramp of interchange.

Further studies are encouraged in defining more geometric factors that governs the speed of the vehicle moving against gravity. It is significant to develop more precise traffic model that can predict the impact of each geometric alignment elements on the travelling vehicle and effectively represent the realistic travelling scenario.

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