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Development of Driving Fatigue Strain Index Using Fuzzy Logic to Analyze Risk Levels of Driving Activity

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The objective of this study is to develop a Driving Fatigue Strain Index using fuzzy logic to analyze the risk levels of driving activity among road users. Driving fatigue is always related to the driving activity and has been identified as one of the vital contributors to the road accidents and fatalities in Malaysia. Therefore, the present paper introduces the use of fuzzy logic for the development of strain index to provide the systematic analysis and propose an appropriate solution in minimizing the number of road accidents and fatalities. The development of strain index is based on the six risk factors associated with driving fatigue; muscle activity, heart rate, hand grip pressure force, seat pressure distribution, whole-body vibration, and driving duration. The data is collected for all the risk factors and consequently, the three conditions or risk levels are defined as “safe”, “slightly unsafe”, and “unsafe”. A membership function is defined for each fuzzy conditions. IF-THEN rules were used to define the input and output variables which correspond to physical measures. This index is a reliable advisory tool for providing analysis and solutions to driving fatigue problem, which constitutes the first effort toward the minimization of road accidents and fatalities.

Keywords : fatigue, strain index, fuzzy logic, risk levels, membership function.

1. Introduction

The ninth and tenth Malaysia Plan^{(1), (2)} indicated that Malaysia aspires to be a developed country by 2020 and as the developed country, Malaysia had improvised the transportation, road, and highway systems. This improvisation had encouraged the infrastructures, facilities, and comfort-ability among the road users. Indirectly, the driving activity becomes important as this medium is being practical, cheaper, and faster in connecting human from one to another place. Driving is the controlled operation and movement of motorized vehicles with wheels such as a car by a human⁽³⁾.

Driving is the complex activity, where the interaction between the driver, the vehicle, and the environment are continuous and numerous.

However, in some occurrences driving activity can give the negative effect to human. Driving activity can cause accidents and fatalities to a human in daily life as they get fatigued while driving. Driving fatigue is a feeling of drowsiness due to longer driving period, monotonous road condition, adverse climatologically environment or individual characteristics is direct or contributing factor in road accidents⁽⁴⁾. Previous study by⁽⁴⁾, stated that the subjective feeling of fatigue, which combined with negative effects on performance due to time spent on cognitively demanding tasks can somehow affect the driving performance due to sleepiness, monotonous driving environmental condition and the length of driving period as proved by the previous study⁽⁵⁾⁻⁽⁷⁾.

Many countries around the world including Malaysia are facing a major problem with road accidents and fatalities. In fact, World Health Organization (WHO) has reported that road accidents are the ninth most common cause of death and the prediction number of fatalities to be approximately 1.24 million⁽⁸⁾. The data revealed by WHO shows that the fatality rate in Malaysia is the highest among the Association of Southeast Asian Nations (ASEAN) countries and developed countries in the world^{(8), (9)}. The WHO's data in Fig. 1

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and Fig. 2 prove that Malaysia has a significant traffic and driving problem based on the high fatality rate.

Based on provisional data by the Royal Malaysian Police (RMP), Department of Statistic Malaysia, Malaysia Institute of Road Safety Research (MIROS), and Ministry of Transport, there were 7,152 road fatalities and 521,466 road accidents have been reported in 2016⁽¹⁰⁾⁻⁽¹³⁾. Besides, the research by⁽¹⁴⁾ has made a prediction on fatalities in Malaysia and reported that there will be 10,716 fatalities during 2020. The in-depth crash investigation on some cases carried out by MIROS has found that driving fatigue is one of the top contributors to the road accidents in Malaysia from 2007 until 2013⁽¹⁵⁾.

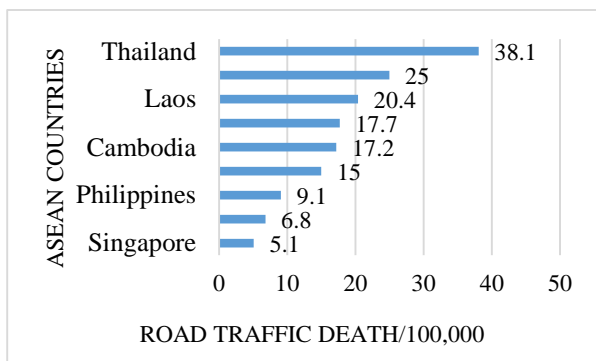


Fig.1. Road fatality rate of Malaysia versus ASEAN⁽⁸⁾

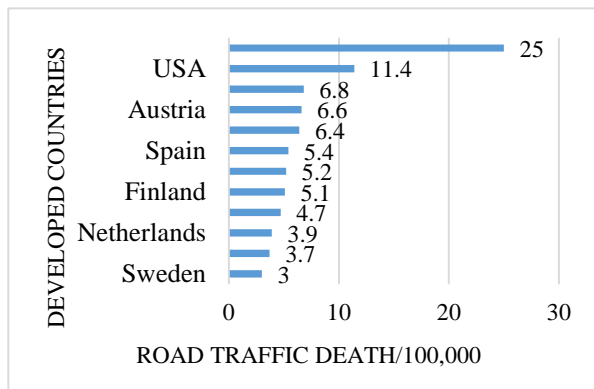


Fig.2. Road fatality rate of Malaysia versus developed countries⁽⁸⁾

Hence, this study is to counter these problems and issues by developing the Driving Fatigue Strain Index (DFSI) to quantify the risk level, analyze, and propose a solution to reduce the number of road accidents associated with driving fatigue. This index will give a warning or reminder, and alert to the road users about the risk level and condition of the driving whether is safe or unsafe conditions level. The strain index is a semi-quantitative analysis that results on the numerical score (SI score) that is believed to correlate with the risk levels of driving fatigue. This study is the extension and improvement from the author's previous study entitled "Development of Driving Fatigue Strain Index to Analyze Risk Levels of Driving Activity"⁽¹⁶⁾. In the previous study by the authors, the strain index was developed using the multiplicative

interaction among the risk factors by representing the product of all multipliers that correspond to all risk factors⁽¹⁶⁾. However, the proposed relationship between the risk rating criteria and the multipliers are the subject to criticism as the ratings and multipliers are based on the author's professional judgment. In previous study, the positive criteria such as non-fatigue, little fatigue, very fit, comfort, moderate, and fairly has been assigned with the multipliers from the value of 1 to 3, while the negative criteria such as fatigue, very fatigue, discomfort, and unfit has been assigned with the value of 81. These values are based on the simple calculation and professional judgement. The multiplier's value is used to get the DFSI values and the level of driving conditions. However, the main problem is the value of multipliers are not flexible as the values give the big different between the criteria. For example, the rating criteria of muscle activity is moderate fatigue with risk level between 130.00 μ V to 300.00 μ V, is assigned with multiplier of 3. Meanwhile, if the rating criteria is fatigue with risk level between 301.00 μ V to 600.00 μ V is assigned with multiplier of 81. Hence, this study improves the DFSI by developing the strain index using fuzzy logic. Fuzzy logic is based on the concept of partial membership function in a set described by the membership function (μ_A), which is a curve that defines how each point in the input space is mapped to a membership value described by real values $0 \leq [\mu_A(x)] \leq 1$.

Fuzzy logic is highly demanded in an industrial application in order to model non-linear input-output relations as fuzzy provides a constructive way of turning qualities into mathematics⁽¹⁷⁾⁻⁽¹⁸⁾. Besides, the fuzzy logic for pattern recognition and approximate information processing and artificial neural networks (ANN) have been used in a variety of areas, including process control, engineering management, business, medical diagnosis, biomechanics, human factors and cognitive simulations⁽¹⁹⁾⁻⁽²⁵⁾. However, based on reviewing the previous study, fuzzy logic has limited applications on the ergonomics aspect and approach such as analyzing the risk level of driving activity. The previous study and reported references should be consulted for additional information, guidelines and examples on fuzzy logic⁽¹⁷⁾⁻⁽³⁸⁾. This paper has presented the development of the driving fatigue strain index (DFSI) using fuzzy logic to quantify the risk levels of fatigue associated with driving activity and propose a solution to minimize the risk of driving fatigue in order to reduce the number of road accidents and fatalities in Malaysia.

2. Methodology

This paper focused on the development of driving fatigue strain index (DFSI), which consist several steps that need to be passed through as the foundation for this development. Some of the steps are similar to the previous study by the authors⁽¹⁶⁾. This section will give a brief explanation of the development of DFSI.

2.1 Acquisition of Knowledge The first step in developing the DFSI was the acquisition of knowledge. The knowledge, which acts as the brain to process the input data and information received by the system, can be acquired by extracting, structuring, and organizing knowledge from one or more sources^{(16), (39), (40)}. In this study, the knowledge is acquired and achieved by conducting the pre-survey, performing the real road test, reviewing the previous journals and articles, referring the guidelines and international

standards from authorized organizations and bodies, and getting an expert opinion from ergonomist and engineer. The data and information about the risk factors; muscle activity (MA), heart rate (HR), hand grip pressure force (HGF), whole-body vibration (WBV), seat pressure distribution (SPD), and driving duration (DD) that significantly contributed to the driving fatigue are examined and obtained by conducting and performing the pre-survey and the real road test experiment. This survey and real road test experiment are participated by Malaysia’s road users, using the national car and Malaysia’s road system, and driving through Malaysia’s road environment.

Besides, the authors gathered the knowledge by reviewing the previous research, articles or journals, and online database. There are seven main journals⁽⁴¹⁾⁻⁽⁴⁷⁾ have been reviewed and referred as the guidelines for the development of DFSI. Instead of that, the authors has referred the authorized organization, and society or bodies such as International Standard Organization (ISO), Royal Malaysia Police (RMP), *Perusahaan Otomobil Nasional*(PROTON), and Malaysian Institute of Road Safety Research (MIROS) to obtained information and data regarding the standard, laws and regulations, and the statistics data on the number of road accidents and fatalities in Malaysia. In addition, the expert opinion such as ergonomics practitioners, road safety practitioners, and academician gives a huge contribution to this study.

2.2 Integration of KnowledgeIn this stage, the risk factors and ergonomics evaluation tools are processed to integrate them. The risk factors of driving fatigue and the evaluation tools are matched together to quantify the risk levels and directly developed the DFSI. The six risk factors are identified as the vital factor contributing to the driving fatigue and has been assigned to the human-machine-environment domain as shown in Fig. 3.

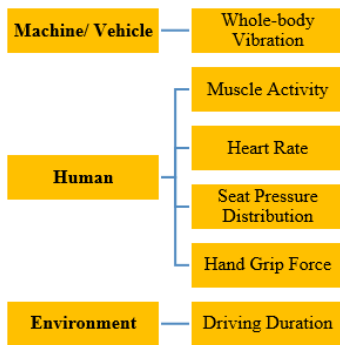


Fig.3. Human-machine-environment domain

The risk factors are selected based on the real road test experiment and a previous study that has proven all these factors give a significant effect on fatigue while driving⁽⁴¹⁾⁻⁽⁴⁷⁾. Besides, some of the previous studies has been used as the guideline to quantify the risk levels of each risk factors as reflected in Table 1.

Table 1. List of the previous study used as guidelines.

Risk Factors	Previous Studies
Muscle Activity (MA)	(48), (49)
Heart Rate (HR)	(50), (51)
Hand Grip Force (HGF)	(52), (53)
Seat Pressure Distribution (SPD)	(54)
Whole-Body Vibration (WBV)	(55)
Driving Duration (DD)	(56)

2.3 Build a Fuzzy Inference SystemThe DFSI was developed based on the fuzzy logic, which based on the concept of partial membership in a set described by the membership function (MF). MF is a curve that defines how each point in the input space is mapped to a membership value between 0 and 1. In this stage, the fuzzy inference system (FIS) was built. FIS is the process of formulating the mapping from a given input to an output using fuzzy logic. In order to build the FIS, the fuzzy logic toolbox graphical user interface (GUI) by the MATLAB software was used. There are five primary GUI tools for building, editing, and observing the FIS in the toolbox; FIS editor, MF editor, rule editor, rule editor, and surface viewer.

FIS editor displays information about a FIS such as input and output, and FIS type as shown in Fig. 4. The inputs or also known as the linguistic variable of this study consists of the six risk factors; MA, HR, WBV, HGF, SPD, and DD. While the linguistic variable DFSI is the output variable of this study. This study using the Mamdani-type as the inference method, which is based on a simple structure of max and min operations. For data defuzzification, this study uses centroid average (CA) method. This is because the approaches provide a better solution than other methods⁽³⁶⁾. Defuzzification is the process of producing a quantifiable result in fuzzy logic.

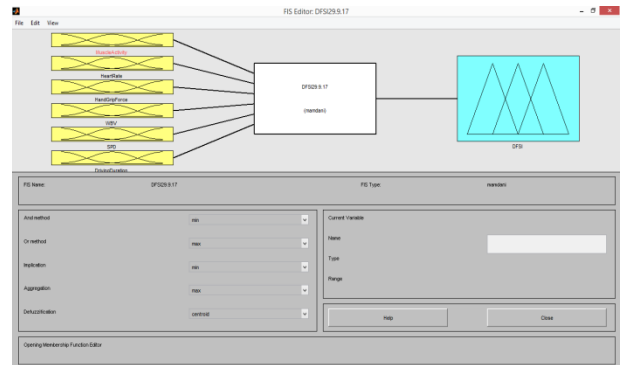


Fig. 4. FIS editor.

The linguistic variables and its universe of discourse (i.e. range) are divided into fuzzy sets defined by the MF, which indicates the

degree of membership in that set as shown in Fig. 5 and Fig. 6. The fuzzy sets represent the linguistic value of the linguistic variables for a specific input value x . For example, the variable ‘WBV’ is divided into five fuzzy sets; ‘low acceleration’, ‘slightly acceleration’, ‘moderate acceleration’, ‘high acceleration’, and ‘very high acceleration’.

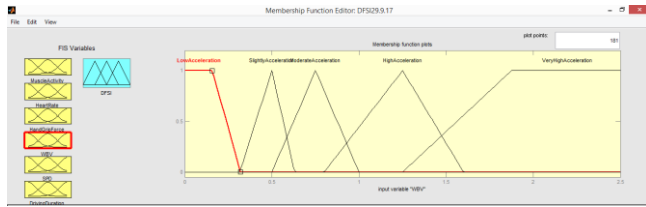


Fig. 5. MF editor displaying the example of linguistic variable ‘WBV’ in term of fuzzy sets.

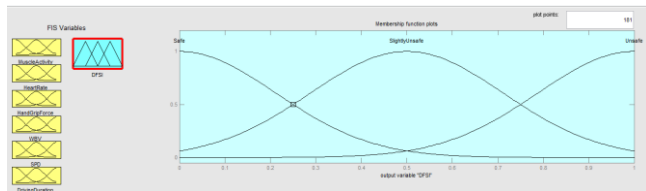


Fig. 6. MF editor displaying the example of linguistic variable ‘DFSI’ as the output variable.

The input value of each fuzzy sets is based on the risk criteria and risk levels of the risk factor as discussed in the previous study by the authors⁽¹⁶⁾. For example, the input WBV of $x = <0.315 \text{ m/s}^2$ belongs to partially to the fuzzy set ‘low acceleration’ as shown in Table 2.

Table 2. Rating criteria and risk levels ⁽¹⁶⁾.

Risk Factor					
MA (μV)	HR (bpm)	HGF (N)	WBV (m/s^2)	SPD (kPa)	DD (min)
Little fatigue: $52 \geq 129$	Very fit: <84	Non-fatigue: ≥ 189.60	Comfort: < 0.315	Comfort: ≤ 5.80	Non-fatigue: < 40
Moderate fatigue: $130 \geq 300$	Fit: 84 – 105	Mild Fatigue: $57.80 > 189.60$	Little comfort: $0.315 > 0.63$	Discomfort: > 5.80	Fatigue: ≥ 40
Fatigue: $301 \geq 600$	Average: 106 – 122	Fatigue: < 57.80	Fairly comfort: $0.50 > 1.0$		
Very fatigue: $601 \geq 1100$	Unfit: >122		Discomfort: $0.8 > 1.6$		
			Very discomfort: 1.25- 2.5		

The input value of fuzzy sets is real numbers. The authors use the typical and simplest membership function that is triangular, trapezoidal and Gaussian membership function. Simple membership function allow the author to graphically represent a fuzzy set. Besides, using the more complex functions does not add more precision. The triangular function was defined by a lower limit a , an upper limit b , and value m , where $a < m < b$ as shown in Fig. 7. While, the trapezoidal function was defined by a lower limit a , an upper limit d , a lower support limit b , and an upper support limit c , where $a < b < c < d$ as shown in Fig. 8

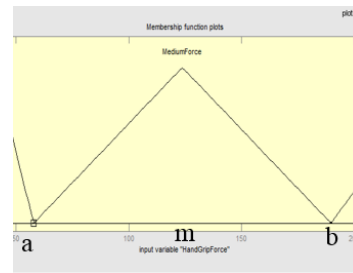


Fig. 7. Triangular function.

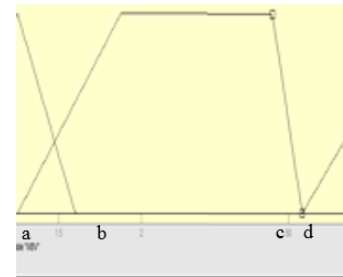


Fig. 8. Trapezoidal function.

Another function used in this study is Gaussian function, which defined as central value m and standard deviation $k > 0$. The smaller the k is, the narrower the “bell” is as shown in Fig. 9.

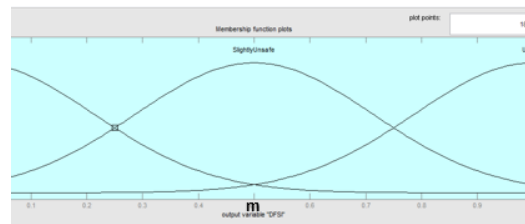


Fig. 9. Gaussian function.

In the FIS, the inferences rules are required for fuzzy reasoning. The IF-RULE statement format is used to express the inference rule. As mentioned earlier, the Mamdani-type, which is based on a simple structure of max and min operation was used as the inference method. The rule editor GUI was used to edit the list of inference rules that define the behavior of the system as shown in Fig. 10.

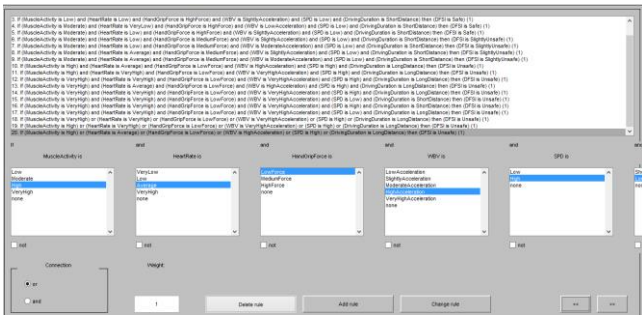


Fig. 10. The rule editor for constructing and editing the rule statement.

The rule editor allows the authors to construct the rule statement automatically. The example of the Mamdani-type model uses IF-THEN rules:

Rule 1 IF MA is Low AND HR is Very Low AND HGF is High Force AND WBV is Low Acceleration AND SPD is Low AND DD is Short THEN DFSI is Safe

Rule 2 IF MA is High AND HR is Average AND HGF is Low Force AND WBV is High Acceleration AND SPD is High AND DD is Long THEN DFSI is Unsafe

Where ‘Very Low’, ‘Low’, ‘Average’, ‘High’, ‘Very High’, ‘Safe’, and ‘Unsafe’ are fuzzy sets; MA, HR, HGF, WBV, SPD, DD, and DFSI are linguistic variables. The linguistic variables MA, HR, HGF, WBV, SPD, and DD are the input variables, while the linguistic variable DFSI is the output. In the rules, the connector AND can be replaced by OR and they are evaluated respectively by the operation of intersection and union. There is 20 rules statement in this study was constructed by the authors as shown in Fig. 10.

After constructing the rule statement, a road map of the whole fuzzy inference system for a system formed by six linguistic variables, ‘MA’, ‘HR’, ‘HGF’, ‘WBV’, ‘SPD’, and ‘DD’, each described by respective fuzzy was displayed on the rule viewer as shown in Fig. 11. The output is represented by the linguistic variable ‘DFSI’ described by three fuzzy sets; ‘safe’, ‘slightly unsafe’, and ‘unsafe’. The rule viewer interpreted the entire fuzzy inference process and show how the shape of certain membership function influences the overall result.

The knowledge available on the DFSI produced by the interaction of six variables is described by 20 fuzzy rules. The color regions represent the fuzzy set obtained by the evaluation of each rule for the six inputs. The final aggregated output is obtained by combining the color regions, and the defuzzificated value represents a measure of the degree of DFSI derived from the combination of the input values.

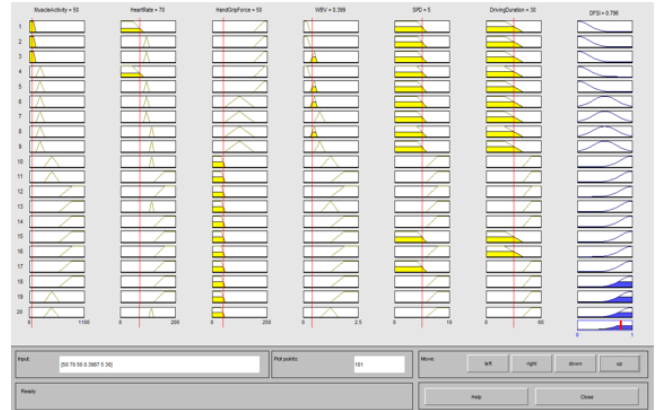


Fig. 11. The example of the road map for the whole fuzzy inference display on rule viewer.

3. Results and Discussion

The DFSI methodology is tested and demonstrated by the authors using a data set available from the previously performed⁽⁴¹⁾⁻⁽⁴⁷⁾. Table 3 presents the example data set available from the previous studies. The author presented three examples, which represented three driving conditions; safe, slightly unsafe, and unsafe.

Table 3. The example of data sets⁽⁴¹⁾⁻⁽⁴⁷⁾.

Risk Factors	Set 1	Set 2	Set 3
MA	50.0000 μ V	150.0000 μ V	50.0000 μ V
HR	100.0000 bpm	100.0000 bpm	70.0000 bpm
HGF	200.0000 N	125.0000 N	50.0000 N
WBV	0.2000 m/s ²	0.2000 m/s ²	0.3987 m/s ²
SPD	5.0000 kPa	5.0000 kPa	5.0000 kPa
DD	10.0000 min	10.0000 min	30.0000 min

By using the FIS, the values of each linguistic variables are entered into the rule viewer to get the defuzzification value represents a measure of the degree of DFSI. Fig. 12(a), Fig. 12(b), and Fig. 12(c) shows the rule viewer, which reflected the results of the analysis.

A zoomed version of the rule viewer for the fuzzy inference process based on the Mamdani-type is shown in Fig. 13(a), Fig. 13(b), and Fig. 13(c). As the input value in entered into the system, the rule viewer will show the value of DFSI that are 0.242, 0.5, and 0.796.

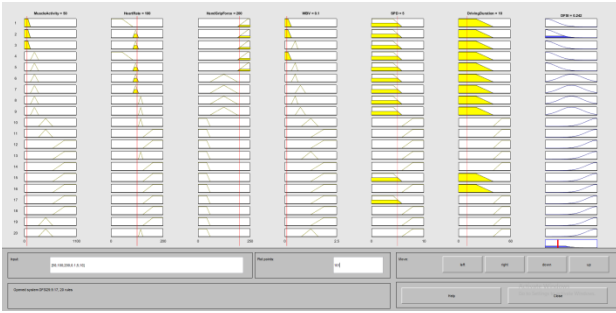


Fig. 12(a). The value of linguistic variables (Set 1) are entered into the rule viewer

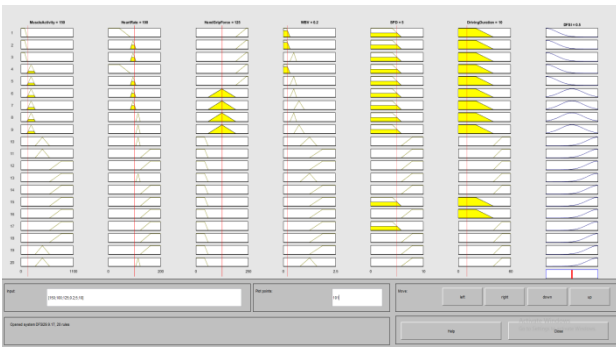


Fig. 12(b). The value of linguistic variables (Set 2) are entered into the rule viewer

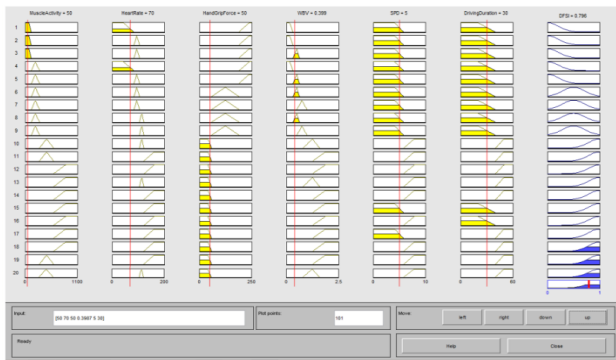


Fig. 12(c). The value of linguistic variables (Set 3) are entered into the rule viewer

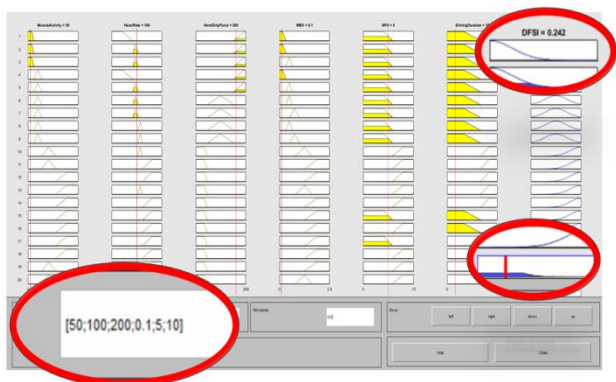


Fig. 13(a). The zoomed version of the rule viewer of FIS for set 1

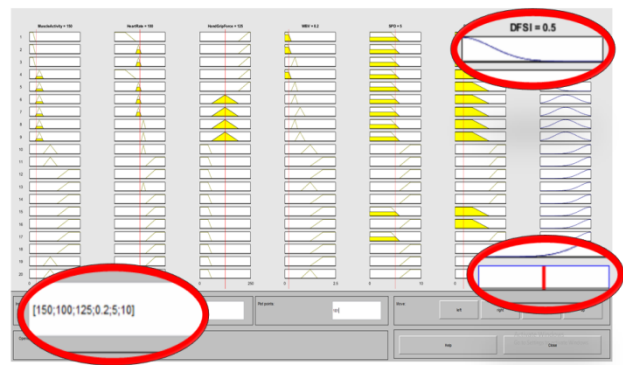


Fig. 13(b). The zoomed version of the rule viewer of FIS for set 2

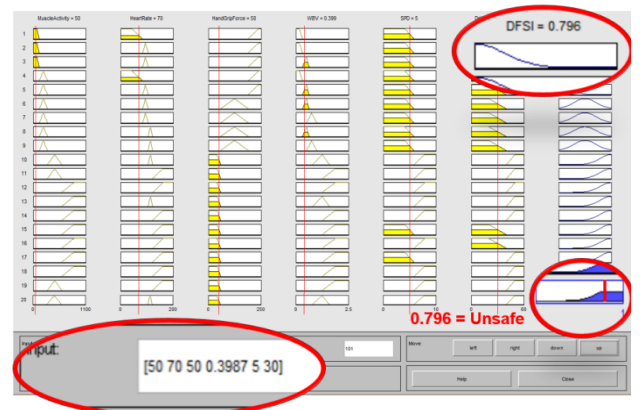


Fig. 13(c). The zoomed version of the rule viewer of FIS for set 3

The final DFSI's output is obtained by combining the color regions fuzzy sets, and the defuzzificated value that are 0.242, 0.5, and 0.796, represents a measure of the degree of DFSI derived from the combination of the input values of linguistic variables. Fig. 14(a), Fig. 14(b), and Fig. 14(c) show the membership function plot for the linguistic variable 'DFSII', which gives a clear picture of getting the safe, slightly unsafe, and unsafe condition. As explained earlier, the DFSI has three fuzzy sets; safe, slightly unsafe, and unsafe. Table 4 summarizes the results from the demonstration.

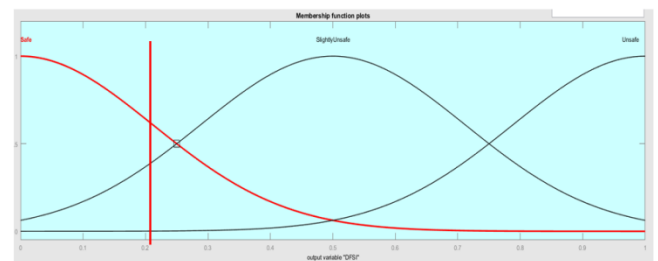


Fig. 14(a). Membership function plots for the DFSI of set 1.

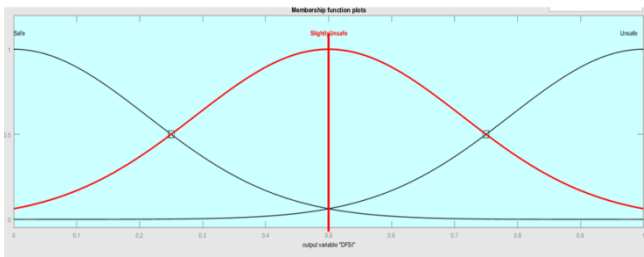


Fig. 14(b). Membership function plots for the DFSI of set 2.

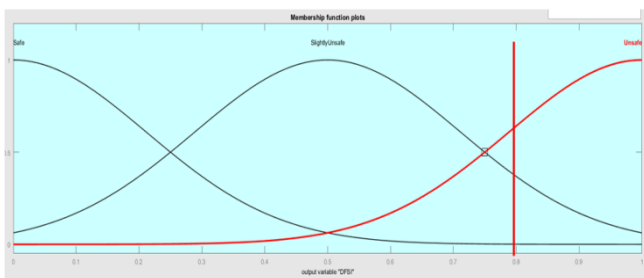


Fig. 14(c). Membership function plots for the DFSI of set 3.

Table 4. Result summarization

Set	DFSI	Driving Condition
1	0.242	The driving conditions are considered safe and the these conditions are the best and need to be maintained to ensure a driver is comfortable and safe
2	0.5	The driving conditions are considered slightly unsafe and that condition can harm the driver and possibility to involve in accidents.
3	0.796	The driving conditions are considered unsafe and the driver is not allowed to drive the car as the condition can lead to road accidents

4. Conclusion

The present paper introduces a novel approach based on fuzzy logic for the development of DFSI. The use of fuzzy set theory and fuzzy set inference system presents advantages over a traditional mathematical approach due to its ability to model uncertainty derived from fuzziness and subjectivity. Besides, fuzzy logic is capable to combine quantitative data with qualitative information in a systematic way by using fuzzy IF-THEN rules.

In the development of DFSI for the driving condition evaluation, the most significant variables that affect the driving fatigue are identified, their relation is analyzed, and the linguistic variables,

fuzzy sets, and fuzzy IF-THEN rules are determined to describe the behavior of the factors. The DFSI is expected to be useful for the risk assessment methodology to quantify the driving condition level associated with the driving activity. The DFSI based on fuzzy logic introduced here is just the first step, and additional work is required.

Conflict of Interest

There is no conflict of interest.

Acknowledgement

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