

Article

# Towards a Fair and More Transparent Rule-Based Valuation of Travel Time Savings

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Received: 15 January 2019; Accepted: 6 February 2019; Published: 13 February 2019



**Abstract:** The value of travel time savings (VOTTS) is one of the most important variables for calculating the benefits of transportation projects. However, the way it is currently calculated (usually via discrete choice models) is complex, tedious and subject to a reasonable level of uncertainty. Furthermore, the method is not easily understood by government officials who use the VOTTS for appraisal and the citizens are not fully aware how such values are calculated. This lack of understanding and transparency in methodology may lead to misuse of the VOTTS during transport project appraisals which in turn can result in unfair transport decisions for citizens, government and the environment. To solve these problems, a fuzzy logic rule-based approach is proposed. With this approach, the rules can be made based on economic and behavioral theories by experts, government officials and citizens (via surveys). This approach makes it understandable to everyone how values are calculated. To test the applicability of the approach, a simple numerical example is presented by estimating the VOTTS of various countries using their gross domestic product-purchasing power parity (GDP-PPP) and the traffic congestion level. Results are then compared to values obtained from a recent metanalysis on VOTTS in Europe and some official VOTTS.

**Keywords:** value of travel time savings; fuzzy logic; rule-based systems; transport project evaluation; cost benefit analysis; traffic congestion; transport planning

## 1. Introduction

The value of travel time savings (VOTTS) is a very important component of most cost-benefit analyses (CBA) of transportation projects. It is estimated that travel time gains make up about 60 to 80% of the benefits of transportation infrastructure projects [1]. It is well-known that transportation infrastructure projects have both socio-economic and environmental effects which means that any mistakes in the project evaluation could result to socio-economic and environmental problems in the long run. Such an important evaluation variable like VOTTS could have serious consequences for the goals of sustainability of transportation projects if not calculated properly. Given the importance of this variable, it is no surprise that most developed countries like the Netherlands, UK, Denmark and Sweden have established recommended values which are used for project evaluation [2–4]. These recommended values are usually calculated via stated preference surveys where respondents are given choices to make a trade-off between cost and time. Discrete choice models are then applied to the responses to calculate the average VOTTS. The methods used in the survey design and model estimations are well-established (standardised) and are mathematically rigorous, thus making the results generally acceptable. Although this process sounds straightforward, the actual effort needed to carry out the surveys, estimate the values and arrive at the recommended VOTTS is very enormous and time consuming. For this and other reasons, most national value of time studies are carried out every 5 to 10 years.

Despite the effort, time, money and expert knowledge required for such studies the results are still very much subject to uncertainties. The main sources of uncertainty in such studies are from the design of the survey and the model estimation. Sometimes there is ambiguity in the attribute levels to use for time and cost as these also affect the estimated VOTTS [5,6]. It is also possible that respondents do not answer as expected (non-trading habits) or get tired because of the many trade-offs they make (usually between 6 and 12 trade-offs) [6]. Furthermore, the chosen model may not fully capture how respondents make their choices. For instance, there is uncertainty in the type of theory respondents use to select their response as most models currently use utility maximisation whereas regret minimisation could also be used [7,8]. In most studies, the uncertainties in the design and model estimation are normally just discussed and some solutions offered to mitigate them. There are usually not many discussions on alternative approaches for calculating the VOTTS. The main reason is that the models used are based on economics and behavioural theories which have long been established and there is available expertise and commercial software for both survey design and model estimations.

The complexity of the survey design, and model estimation techniques make most studies understandable only to experts. Additionally, the sample of respondents used in the survey may not be a good representative of the whole population. To solve this issue, estimated values must be converted to recommended VOTTS after a weighting by distance, income and trip purpose [2–4]. These recommended VOTTS are then presented to the government. To give further credibility to the method of calculating values, the whole process is normally subjected to external audit by various experts in the field [3]. Obviously, it is difficult to explain such designs and models to government officials who use these values for project evaluation. Therefore, such recommended VOTTS are usually taken at face value, albeit with a bit of scepticism. There is, however, not much that can be done about it since government officials are usually not experts in the topic.

Very few studies have proposed a different, transparent and practical approach for the estimation of VOTTS. Most studies are usually focused on developing more complex methods to capture better human behaviour [5]. Other studies focus on improving the survey design techniques to make it easier for people to respond and improve the plausibility of results [9,10]. One important reason for the lack of different approaches for estimating VOTTS is that it is not observable but rather derived from a trade-off involving cost and time. These models are generally grouped under the name of discrete choice modelling [11,12]. In this modelling framework, travellers are faced with a series of trade-offs between a longer journey at cheaper cost and a shorter journey with a higher cost. The VOTTS is then calculated and interpreted as a traveller's willingness to pay to save an hour of travel time [11,12]. Other studies have also used such trade-off techniques to estimate the distribution of VOTTS in a non-parametric way [13,14].

Generally, the VOTTS of an individual cannot be directly calculated using a classical regression technique. Some studies have used meta-analysis to create regression models to estimate VOTTS, but they must assume a model [15,16]. What is normally done is to use the income to infer the VOTTS for example by saying VOTTS is about some percentage of the hourly income, the so-called cost saving approach (CSA) [16]. Apart from income, studies have shown that variables like comfort of the travel, trip length etc. also affect VOTTS [16]. However, even though all these variables are known to affect VOTTS, it still not certain to what extent they do so.

To tackle the problem of the uncertainty and understandability of VOTTS results, a new estimation approach is proposed based on fuzzy logic and expert knowledge. Fuzzy logic is a well-known technique for handling uncertainty [17]. The main advantage is that it is close to the way humans think and express uncertainty. So, a variable maybe considered high, low, very high etc. Also, humans often make simple rules to help them in decision making. Fuzzy logic has been applied successfully to solve many transportation problems ranging from traffic control to transportation planning. A review of the applications of fuzzy logic in transport can be found in [18]. In contrast to previous studies, this paper does not focus on using fuzzy logic for choice modelling (route choice, mode choice) [19–22] but rather

it proposes to use a fuzzy inference system (FIS) to directly estimate VOTTS of an individual, country (or at least of a group of people).

The proposed approach is chosen for two reasons. First, the rules can be implemented based on economic and behavioural theories, by experts, government officials, citizens (via surveys) etc. The rules can be updated or modified periodically according to current trends. This makes it understandable to everyone how VOTTS are calculated.

The second reason is that the model outputs and the uncertainties of the current methods can be incorporated in the model input and output of the fuzzy model. For example, findings from various VOTTS studies using choice models and other related techniques can be used to define membership functions for inputs, rules and the final output.

Given the nature of the proposed method, equating the VOTTS calculated by the fuzzy method with that estimated from standard discrete choice and related economic models is not justified because the values are calculated from rules rather than by economic theory. The main purpose of this paper is to put forward a research agenda for a fair, more transparent rules-based approach for the future calculation of VOTTS which will be used for evaluating transportation projects. The proposed method is easy to implement and can be used as an alternative means of calculating VOTTS or as a supporting tool for VOTTS estimations from discrete choice or other related econometric models.

The rest of the paper is organised as follows. In the next section a brief description of the current method for estimating VOTTS using discrete choice is presented. This is followed by a description of fuzzy logic and the fuzzy inference system in general. Thereafter, a conceptual model of the proposed approach is presented and discussed. Then a simple numerical example is presented using the proposed approach to illustrate the method and check validity of outputs. Finally, a discussion of how the proposed fuzzy method can be improved and incorporated into current VOTTS estimation methods is presented.

## 2. Theoretical Background

### 2.1. Value of Travel Time Savings (VOTTS) from Discrete Choice Model

The VOTTS is derived from choices made by individuals in a stated choice experiment. The simplest experiment consists of a series of choices between time and cost attributes. The choice experiments are carefully designed using efficient designs such that the VOTTS can be estimated [9]. Discrete choice models use the theory of utility maximization which postulates that when faced with choices rational individuals choose the one that maximises their utility [23]. In the context of VOTTS, the systematic utility function ( $U$ ) can be expressed as a linear function of both cost and time defined as follows [3,23]:

$$U = \beta_c C + \beta_t T \quad (1)$$

where  $\beta_c$  and  $\beta_t$  are the marginal utilities of the cost of travel ( $C$ ) and travel time ( $T$ ), respectively. The VOTTS savings is derived as the ratio  $\frac{\beta_t}{\beta_c}$ . This is the marginal rate of substitution between time and money [3]. Note that the complete utility function contains an unobserved error term which is assumed to follow a certain distribution usually distributed independently, identically extreme value [23]. This assumption leads to classical logit models. Using the choices made by respondents, the parameters  $\beta_c$  and  $\beta_t$  can be estimated using standard techniques like maximum likelihood estimation.

### 2.2. Fuzzy Logic and Fuzzy Inference System (FIS)

In this section, a brief description of fuzzy sets and fuzzy inference systems is given. The goal is not to go into the details of this method as it is well established; rather, the focus is on the elements relevant for this paper. A more concise introduction to fuzzy logic and fuzzy inference systems can be found in [24].

### 2.2.1. Fuzzy Sets

Fuzzy sets introduced by Lofti Zadeh [17] is an alternative way of representing uncertainty. In classic set theory, an object either belongs to a set or it does not. Fuzzy sets help to represent the uncertainty (or lack of complete information) whether an object belongs to the set or not [25]. This is achieved by assuming that the object belongs to the set with a certain degree in the closed interval [0 1]. Formally, a fuzzy set is defined as: Let  $X$  be a universe of discourse. The fuzzy set  $A$  is characterised by its membership function [25,26]:

$$\mu_A(x) : X \rightarrow [0, 1] \text{ for } x \in X \quad (2)$$

The membership functions usually represent “linguistic” variables such that they are easily understandable. For example, the cost of travel may be described by the linguistic variables, high, medium and low each with their corresponding membership function. Using these membership functions, membership values can then be assigned for each cost of travel in a specified range of values. This membership value indicates how low, medium or high a given travel cost is. The most common membership function is the triangular membership function defined as [25,26]:

$$A(x) = \begin{cases} \frac{x-a}{b-a} & \text{for } a \leq x \leq b \\ \frac{c-x}{c-b} & \text{for } b \leq x \leq c \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

The fuzzy number is usually represented by  $A = (a, b, c)$  its centre value  $b$ , the left and right values  $a$  and  $c$ .

### 2.2.2. Fuzzy Rules

These are rules made using the linguistic variables like low, medium, high. They enable decision making in a simple and human-like manner. Fuzzy rules are usually of the form IF  $A$  then  $B$  [27]. Where  $A$  and  $B$  are linguistic variables representing input and output respectively. For example, a simple transportation rule could be IF travel time of a mode is HIGH, THEN mode share is expected to be LOW. It is then left for experts to decide which range of travel time is considered HIGH and which range of mode share is considered LOW. Once this is known, these rules can then be used to make decisions concerning expected mode shares given the travel time of the mode. One advantage of using fuzzy rules for decision making is that we do not have to know the exact value of the variables (input or output) but just a range. This is very close to the how humans think since it is more likely that they use simple rules to make decisions with approximate values rather than complex mathematical equations and exact values [27].

### 2.2.3. FIS

This is a decision-making system which uses a set of fuzzy rules. The FIS uses a set of input and a knowledge base (rules and data) to make inference about a set of outputs [24,25]. The rules and data are usually supplied by experts with experience in that subject. A fuzzy inference system is made up of 5 components [24] (Figure 1):

- A **fuzzification** unit: this transforms the crisp value into the interval [0 1] using a specified membership function.
- A **rule-base**: this contains IF-THEN rules used to represent a link between the input and output variables.
- A **database**: this contains the membership functions of the linguistic variables used in the fuzzy rules.
- **Decision unit**: this is where an inference is made by using the specified rules to get a fuzzy output.

- Defuzzification unit:** In this unit, the fuzzy output from the decision unit is converted to a final crisp output.

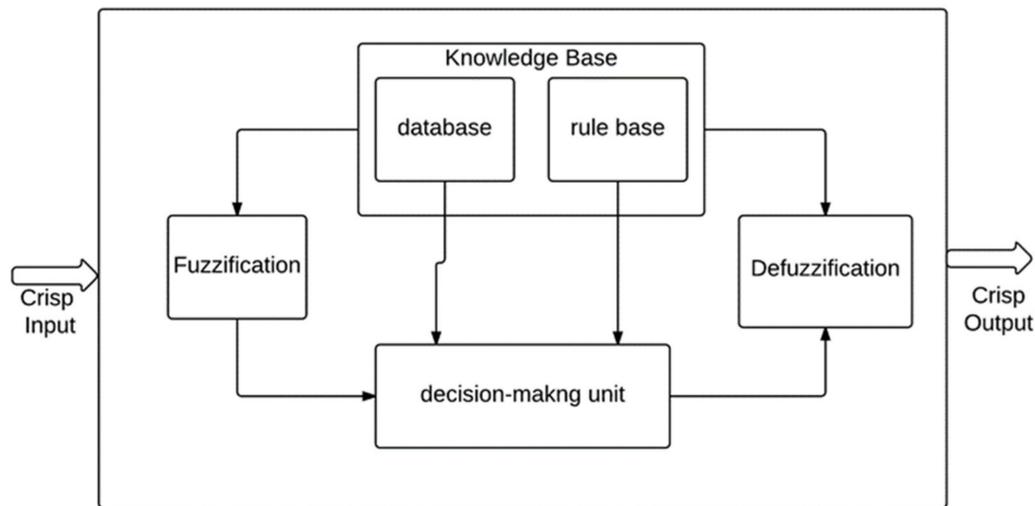


Figure 1. Fuzzy inference system (FIS). Adapted from [24].

In contrast to most artificial intelligence (AI)-based techniques which are black-box models, all inputs, rules and outputs of a fuzzy inference system can be easily scrutinised and modified accordingly. This makes it very suitable for evaluating variables like VOTTS which are subject to debate and uncertainty.

In the next section, we present a conceptual model using FIS which can be used to support the estimation of VOTTS. The conceptual model is general and can be used in any a VOTTS studies.

### 3. Methodology

#### 3.1. Proposed Conceptual Model

A generalised rule-based model for estimating the VOTTS is proposed. The model is basically a FIS comprising of rules defined by a consensus of experts, citizens and government officials (Figure 2). This is to increase the transparency and understandability of the process used to calculate the VOTTS. The output of the model is the VOTTS. The input for the model can be various variables which have significant effects on the VOTTS. The proposed model may be constructed based on values from previous VOTTS or independently. The structure of the model is explained below.

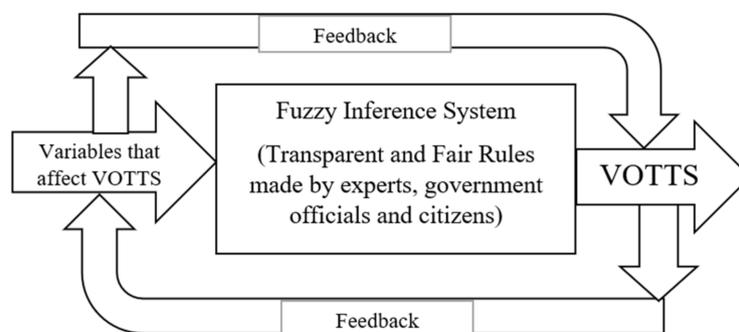


Figure 2. Conceptual model.

### 3.1.1. Input Variables

The chosen input variables should be those that are known to directly affect the VOTTS. Generally, many variables affect the VOTTS like the transport mode [28], the region [29], temporal differences [30], individual differences [31]. However, for appraisal purposes, the VOTSS is usually not differentiated by all these variables except by the transport mode [32]. Various studies have shown that income has a significant effect on the VOTTS [4,15]. However, care should be taken when using this variable since it automatically gives higher VOTTS to those with high income and lower VOTTS to low income earners. For the purpose of the model, an average income can be used, or income can be excluded entirely. This is to ensure that everyone is considered equal during the calculation of the VOTTS.

Another important variable is the comfort of travel. It has been shown in various studies that travellers' VOTTS are higher when a trip is made in a crowded or congested condition [33,34]. This comfort variable can be easily incorporated in the proposed model through surveys on the travel conditions or other directly thorough calculated delays. Other variables like trip distance can also be used but it is debatable how much effects they have and whether it is appropriate to differentiate VOTTS based on trip distance [4,29,32].

The choice of input variables to use should be made via consensus between, experts and government officials considering evidence from previous studies.

### 3.1.2. Membership Functions

The membership functions and linguistic variables can be easily defined by experts and government officials or by citizens (via surveys). For example, government can classify income levels as low, medium high, experts can classify trip distance as short, medium and long distance and citizens can classify transport comfort levels as low, medium and high comfort through a survey.

The shape of the membership functions (triangular, trapezoidal, Gaussian etc) can be chosen based on expert advise). This also applies to the defuzzification techniques to use. Note that optimizing membership functions can also be performed automatically without expert intervention. Most techniques rely on genetic algorithms [35–38]. These methods can also be applied in this context. However, if such methods are used, they should be subject to evaluation before the final results are accepted.

### 3.1.3. Rule Base

The rule base should be defined by experts, government officials and through surveys from citizens. The rules should be understandable, plausible and fair. An example of a rule could be:

IF Comfort Level is low THEN VOTTS is HIGH. This rule is easy to understand for experts, government officials and citizens. The rule is also plausible because, when people travel under uncomfortable conditions they would want to arrive at their destination as quickly as possible (i.e., higher VOTTS). Finally, this rule is fair because it does not distinguish between the rich and poor, or type of travel mode etc. This is true for all modes and for all groups of travel and travel purposes.

### 3.1.4. Output Variable

The output is the VOTTS. Since the true value is not known, experts together with government officials can agree on values. The advantage of this model is that the exact values do not need to be known but just a range of values. These range of values can be supplied by experts or from previous studies like those in [15,16]. Also, linguistic variables like Low, Medium, High, Very High can be used to describe VOTTS. This can depend on different factors such as previous studies, GDP of the country, availability of transport funds. For example, VOTTS of 15 \$/h may be considered high in one country and medium in another country.

### 3.1.5. Feedback Loop

To improve the model accuracy, a feedback loop between input and output should be maintained. This can be done by periodically updating rules, membership functions to reflect current trends. These periodic updates can be done based on recent surveys or value of time studies or based on economic, social or environmental trends. This will make the proposed method compatible with existing discrete choice models. The feedback loop can also be used as a means of validating output from the model and comparing it with those of discrete choice models. For example, if recent studies show that a new variable is now important in calculating the VOTTS, this variable can be included when building the rule-base. This can also be done if a variable becomes less important for instance due to technological advances. A typical example is the use of automated vehicles instead of a normal car. The idea of wasting time in traffic becomes questionable because an automated vehicle could provide comfort like an office and allow productive use of the time spent in congestion.

### 3.2. Numerical Example

To illustrate the proposed approach, a simple numerical example is presented using two input variables, economic prosperity of the country and travel comfort level. These two variables are chosen because the way in which they affect VOTTS is easily understandable, plausible and fair to all (within the country). The economic prosperity of a country determines the wage-rate which in turn determines how much money travellers can trade-off for shorter travel time. According to previous studies, VOTTS increases with increase in GDP with an elasticity close to 1.0 [16].

The variable comfort of travel is normally determined by the level of crowding in case of public transport or by the traffic congestion level for car travel. Studies have shown that the lower the comfort level, the higher the VOTTS. The way this is represented is through crowding and congestion multipliers which have been estimated depending on the level of comfort [33,34].

In this example, the gross domestic product-purchasing power parity (GDP-PPP) is used as input variable instead of the nominal GDP. This is because it reflects both the economic prosperity and standard of living of the country [16].

For the comfort level of travel, the average number of hours spent in traffic congestion is used. Of course, this applies to car travel but it is possible to illustrate the method with it. Other variables like public transport crowding can also be used if available. The GDP-PPP data is from the World Bank 2017 ranking [39]. The congestion data is from the INRIX traffic scorecard report 2017 [40]. The values for the VOTTS are based on ranges from previous studies [16].

### Linguistic Variables

Five Linguistic variables are used for the GDP and 4 variables for the traffic congestion level. The output variable (VOTTS) has 4 linguistic variables (Table 1).

**Table 1.** Linguistic variables.

	Linguistic Variables				
Gross domestic product (GDP) (\$k)	Low [0 20]	Lower Middle [10 40]	Middle [30 60]	Upper Middle [50 80]	High [60 130]
Traffic (h)	Low [0 20]	Moderate [10 40]	Congested [30 60]	Highly Congested [50 120]	
Value of travel time savings (VOTTS) (\$/h)	Below Average [0 10]	Average [5 20]	Above average [15 30]	Very High [25 40]	

The values chosen for the membership functions of the linguistic variables are those that reflect the names of the variable (Figure 3). The approach is to first determine how many linguistic variables are needed for each input and output, then the most representative value is assigned as the middle value of each linguistic variable. The value for the middle linguistic variable is chosen close to the overall average value for each variable. For example, the average GDP for all countries in the list is \$42.64k so the linguistic variable “Middle” is in the range [30 60] with GDP values between \$40k and \$50k surely “Middle”. After that, the next criteria is that there should be a reasonable overlap between the variables [24]. Starting from the middle linguistic variable the other linguistic variables are created such that the overlap gives a reasonable membership function value [24]. Similar approach is applied to both the traffic congestion and VOTTS variables (Figures A1 and A2 Appendix A). There are various methods of constructing membership functions for linguistic variables [41,42] but this approach is adopted for simplicity. In practical applications, it is expected that membership functions and linguistic variables will be selected based on expert opinion with contribution from both the government and citizens or by optimization [35–38].

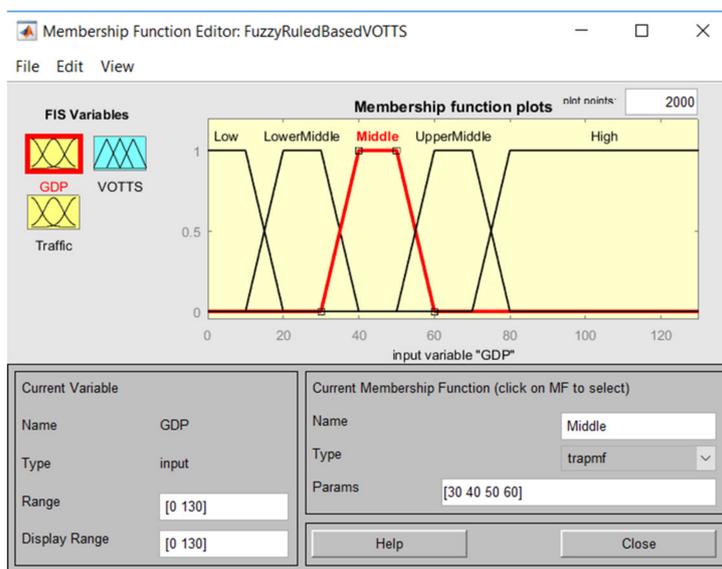


Figure 3. Membership function and linguistic variable for gross domestic product (GDP).

### 3.3. Rules

A total of 26 rules are generated. The rules are made based on how the two variables (GDP and Traffic) are expected to affect the VOTTS (see Section 3.2). Some selected subsets of the rules are shown in Table 2 below (see Appendix A, Figure A3, for all rules).

Table 2. Example Rules.

No	Rule
3	IF GDP is Low AND Traffic is Congested THEN VOTTS is Average
10	IF Traffic is Highly Congested then VOTTS is Above Average
11	IF GDP is Lower Middle AND Traffic is Low THEN VOTTS is Below Average
17	IF GDP is Middle AND Traffic is Congested THEN VOTTS is Average
18	IF GDP is Middle AND Traffic is Highly Congested THEN VOTTS is Above Average
20	IF GDP is Upper Middle AND Traffic is Moderate THEN VOTTS is Average
26	IF GDP is High AND Traffic is Highly Congested THEN VOTTS is Very High

For most rules, it is assumed that the GDP plays a more important role than congestion. Income is the most important variable that affects VOTTS [15,16]. The income level of a country is determined by its GDP. Countries with higher GDP generally tend to have higher average income and thus the VOTTS is expected to be high. The more money individuals earn, the more they are willing to pay to save travel time. For example, if GDP is High, VOTTS should be above average regardless of the congestion level since there is enough money to pay to save time. On the other hand if GDP is Low, then VOTTS should be Average. This is expected because even if traffic is congested and you do not have enough disposable income, you may not have enough to pay to save travel time. Nevertheless, some rules are also inserted to consider fairness, for example if Traffic is highly congested then the VOTTS should be above average. This is regardless of the GDP. The idea is that people should not be allowed to suffer in highly congested conditions just because the country or region has a low GDP. This type of rule could be used by organisation such as the World Bank for evaluating projects especially in low-income countries who suffer from severe traffic congestion.

**Membership functions:** the trapezoidal membership functions are used for all three variables. The main reason is that the range of values for the linguistic variables are more realistic. Trapezoidal membership functions are chosen for simplicity because they help represent more values in the core. This is more flexible than using a single value [43]. This is particularly suited for this application since it is difficult to assign just one value as being High, Medium or Low for the variables used like traffic congestion, GDP and VOTTS.

The triangular membership functions or any other membership function can also be used. The purpose of the paper is not to show which choice of membership shape is better but rather to show that a transparent and rule-based approach is better in estimating VOTTS because every decision made like rules, type of variable, membership functions can be easily scrutinized and modified in a fair and transparent way. Obviously for the model to be used for appraisal, the choices made will be based on consensus between experts, government officials and citizens.

The complete model was built using MATLAB (2017a) Fuzzy Logic Designer using the default settings. The structure of the model is shown below (Figure 4).

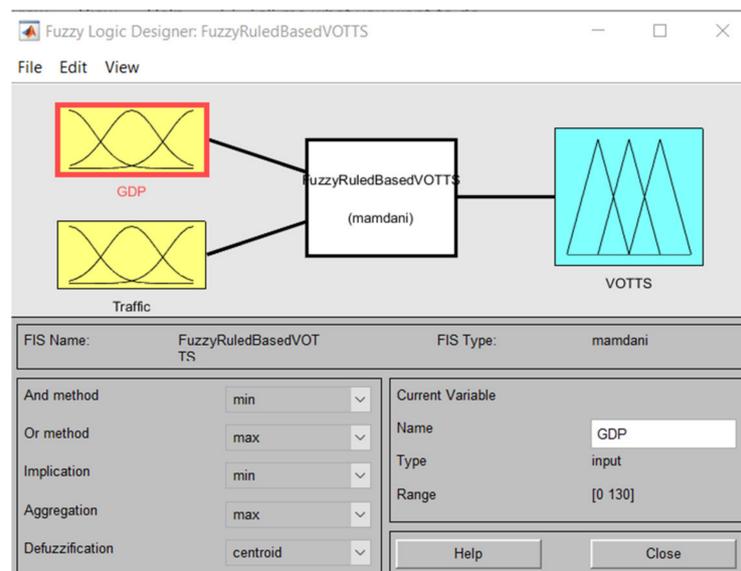
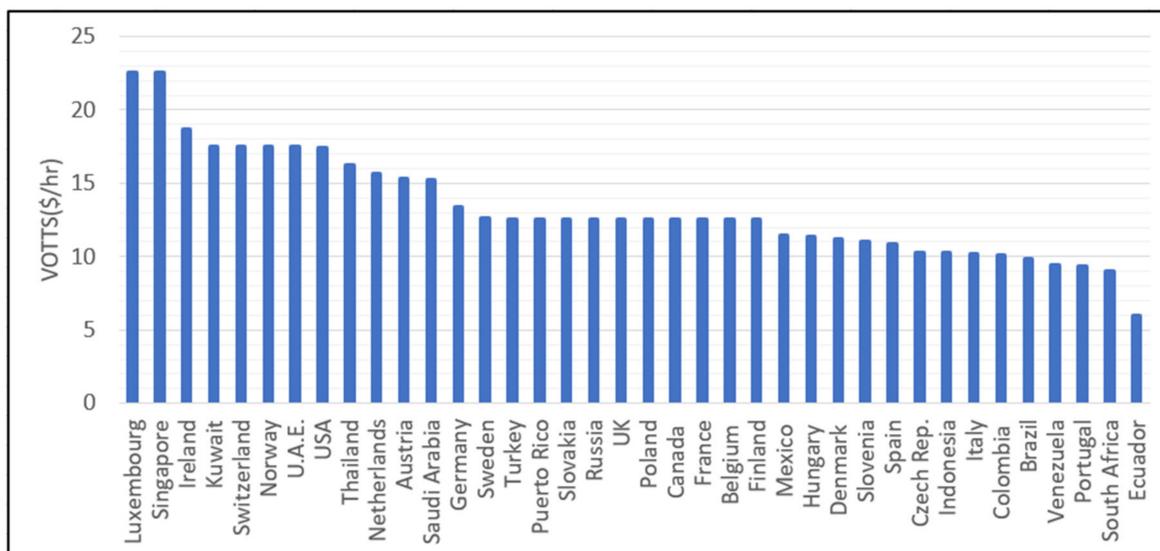


Figure 4. MATLAB model.

#### 4. Results and Discussion

The proposed FIS is used to calculate VOTTS for various countries in the INRIX traffic report card and is shown in Figure 5 below (See Appendix A, Table A1, for exact estimates for all countries).

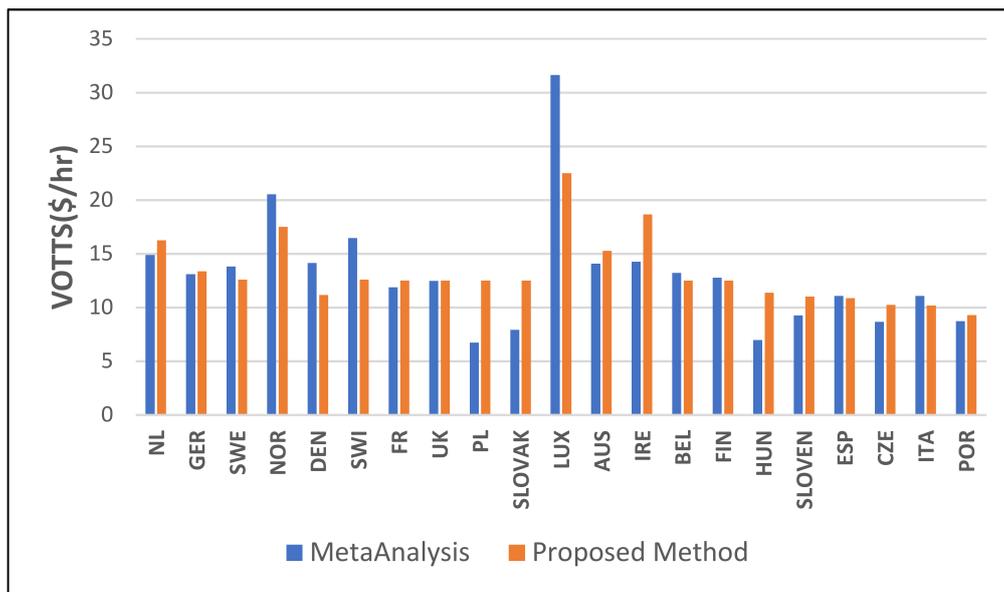


**Figure 5.** Estimated VOTTS for all countries in the INRIX traffic score card.

As expected, countries with lower GDP have low VOTTS while those with high GDP have high VOTTS with the exception of Thailand which has relatively high VOTTS despite its low GDP. This is due to its highly congested traffic situation which should justify a high VOTTS. In normal appraisals the VOTTS is expected to be lower than the one estimated here but this will be unfair to its citizens given the stress they have to go through daily. If the project is handled by an external body such as the World Bank, then the higher estimated value should be used. If the project is sponsored by the country alone, then government can decide whether a VOTTS is considered high or not and they may use lower values. For fairness, it is better that the government's willingness to pay to save a citizen one hour of travel should be higher than what the citizen is willing to pay especially for lower-income countries. The ability to include fairness rules in the proposed model is an extra advantage over discrete choice models. Discrete choice models will normally produce higher VOTTS for countries with high GDP regardless of the level of congestion in the country. This does not favour poor countries.

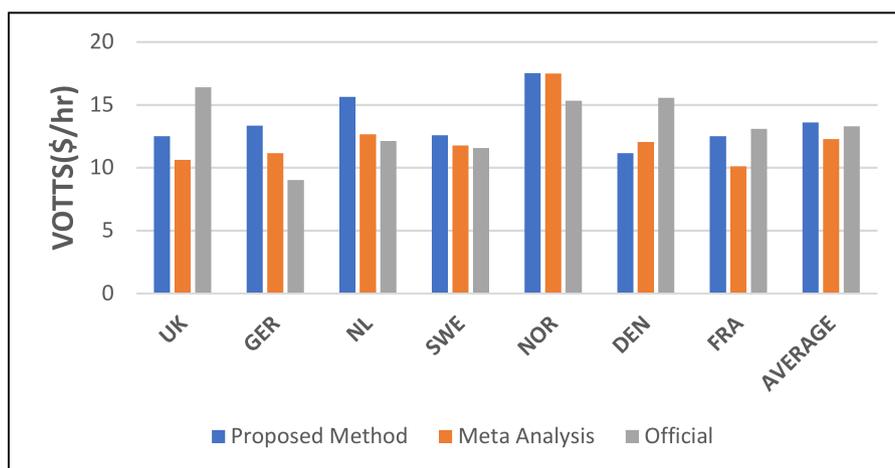
To check the validity of estimated results, a comparison is made with a recent metanalysis of VOTTS in European countries [16]. The comparison is made for the average value for car traffic with congestion for both commuting and leisure [16]. The metanalysis values were in 2010 equivalent euros. For a fair comparison, the values are all converted to 2017-dollar equivalent by taking into account average euro inflation (consumer price index (CPI) ratio of approximately 1.09) from 2010 to 2017 [44]. The average euro to dollar exchange rate is taken as 1 euro to 1.2 dollars [45]. The original values can be found in [16]. Note that the estimated VOTTS are not directly comparable to the ones estimated from discrete choice and econometric models since we use rules to infer VOTTS. However, the estimated VOTTS are compared to those estimated from discrete choice and econometric models as a benchmark.

Figure 6 shows the difference between the metanalysis estimate and the estimated values. As expected, the proposed model calculates lower values compared to metanalysis values for high GDP countries such as Luxembourg and Switzerland. On the other hand, the model estimates higher values for lower GDP countries such as Poland, Hungary and Slovakia. This is because of the fairness rules introduced in the model. For projects sponsored by the European Union, it will be wise to use such augmented values for lower GDP regions with moderate traffic congestion and use reduced values for high GDP regions with slightly better traffic conditions. For most countries, the metanalysis and the estimated values do not differ by more than 10%. The average VOTTS from the estimated model is almost the same as the model from metanalysis (see Appendix A, Table A2). This shows that the proposed model gives plausible results.



**Figure 6.** Comparison of estimated VOTTS for some European countries in the INRIX traffic score card with metaanalysis values in [14].

Figure 7 below shows the estimated values compared to official recommended VOTTS for a number of countries (see Appendix A Table A3 for exact estimates). The official values are those for car travel except for UK which is for all modes. All values have been converted to 2017 dollars as stated before. Again, the average estimated VOTTS from the model is close to the average official values for the VOTTS further supporting the view that the proposed model can be used to estimate or recommend official VOTTS for countries and regions. However, there are noticeable differences. For instance, the official values for UK and Denmark are much higher than the estimated values. The model values are much closer to the metaanalysis estimates for both countries. The average congestion in UK is much higher than in Denmark so the high official values for UK is justifiable but that’s not true for Denmark. The Danish government could consider lowering their official VOTTS for car travel because the congestion level is not very high.



**Figure 7.** Estimated VOTTS for some European countries compared to official values in [14].

On the other hand, the official values for Germany and the Netherlands are lower than the estimated values. The average congestion in the Netherlands is lower than in Germany, so the lower official values for Netherlands is justifiable but that’s not true for Germany. The German government could consider increasing their official VOTTS for car travel to compensate for the congestion level.

#### 4.1. Sensitivity Analysis (Membership Function type)

As with most fuzzy inference systems, the membership function type used can affect the results. Although this is not the focus of the paper, we test the scenario where all trapezoidal membership functions (except the extreme values, see Appendix A Figure A4 are replaced by triangular membership functions [46]. The same set of rules were used for the FIS. The Figure 8 below shows the estimated VOTTS for all countries using the triangular membership functions compared to trapezoidal membership functions. The changes in VOTTS were below 2 \$/h for most countries. However, some countries like Germany, Sweden and Denmark have noticeable changes.

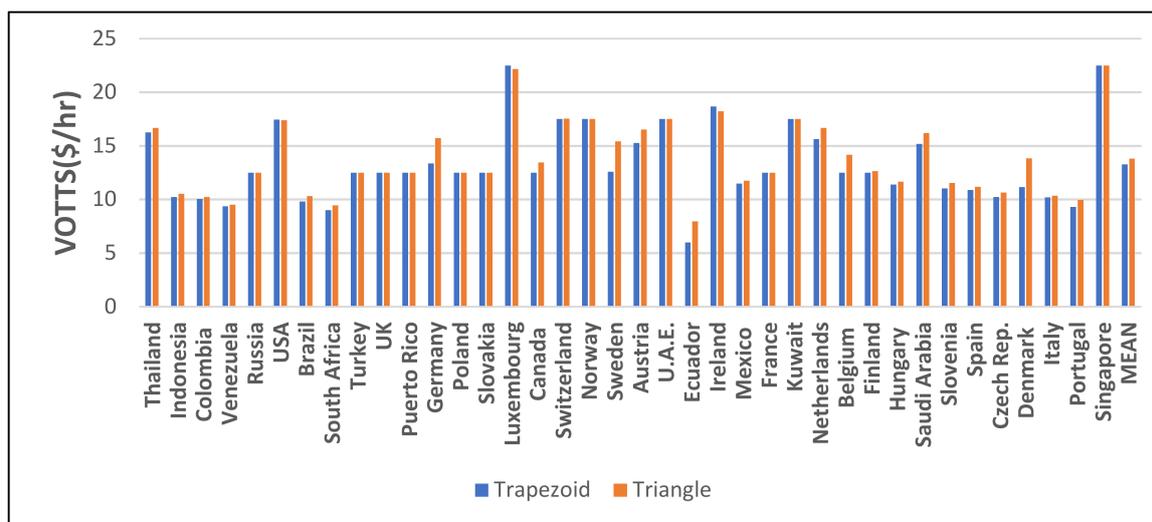


Figure 8. Estimated VOTTS using trapezoidal and triangular membership functions.

This shows that indeed choices like membership types and values can affect the model result. However, as stated before, the purpose of the paper is not to show which choice of membership shape is better but rather to show that a transparent and rule-based approach is better for estimating VOTTS because every decision made like rules, types of variables, membership functions can be easily scrutinized and modified in a fair and transparent way. The final model (rules, membership function types and values) to be used will depend on consensus between expert, government and citizens. This is an advantage of the proposed method when compared to the current approach of using discrete choice.

#### 4.2. Sensitivity Analysis of Fairness Rules

It is expected that the fairness rules used in the model when reduced or modified can affect model results. The case of rule reduction is tested. The original model uses 26 rules to make inferences. Twenty rules make use of the two variables GDP and traffic while six of those rules were introduced for fairness which make use of either traffic or GDP. A simple sensitivity analysis is performed by reducing the number of rules from 26 to 20. The six rules which use only one variable were removed. Figure 9 shows the difference between the VOTTS predicted for all countries under both scenarios.

The FIS with 20 rules gave generally lower values than the one with 26 rules. This is because the rules concerning GDP and traffic congestion gives higher values when the GDP of the country is high or when the traffic is congested. Countries like Switzerland, Norway, Kuwait and Saudi Arabia with high GDP but with a relatively good traffic condition now have reduced VOTTS. In contrast, countries like Indonesia, Colombia, Venezuela with lower GDP but heavy traffic conditions now have a higher VOTTS. This clearly shows the fairness issue discussed before. The results show that the proposed method can use rules to reduce the effect of estimating high VOTTS for high GDP countries and low

VOTTS for low GDP countries. This makes it suitable for use by bodies such as the World Bank in determining the VOTTS to be used for the appraisal of projects in a fair and transparent manner.

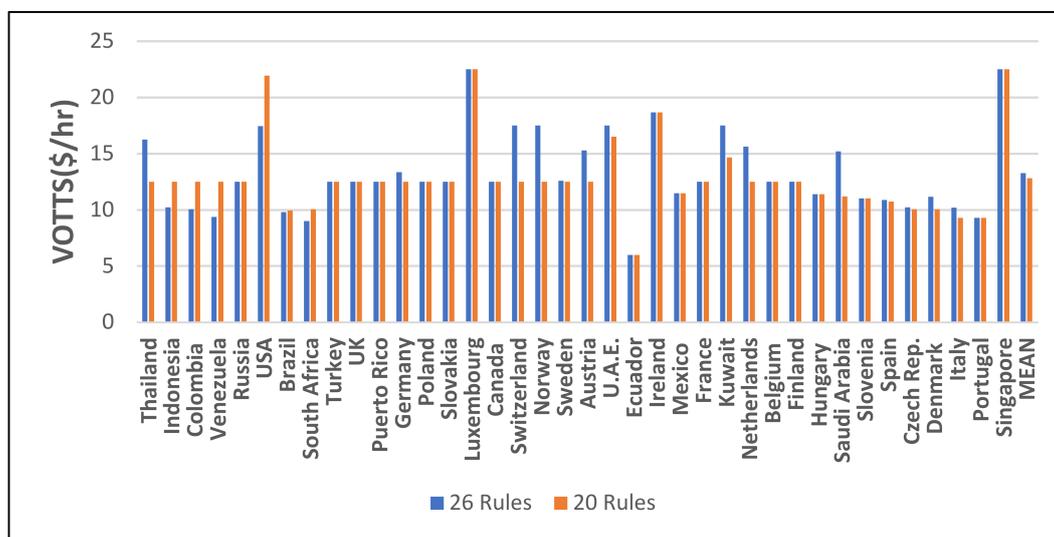


Figure 9. Estimated VOTTS for all countries using 20 and 26 rules.

## 5. Conclusions

A rule-based approach for estimating VOTTS has been proposed. The results show that the proposed model can give plausible values despite the simple rules used. The advantage of the model is the simplicity, understandability and transparency. All the processes and rules used to derive results can be easily scrutinised. The rules can be subject to a vote by governments, experts and citizens. This high level of flexibility and transparency is not available in current discrete choice models. The model can be applied for estimating VOTTS for urban regions, countries or even for the estimation of individual VOTTS. Another advantage is that fairness can be introduced in the rules, through input and output membership functions. For example, the government can decide which VOTTS is considered High, Medium or Low. The citizens can decide which comfort level is considered High, Medium or Low. This can be achieved through a survey. In this way, values that are considered fair can be used for the linguistic variables. The linguistic variables and their values can be appropriately chosen in a transparent way such that the model is completely understandable to the government, experts and the public.

Obviously, this model is not a replacement for econometric and discrete choice models but rather can serve as complementary estimation tool for such models. VOTTS estimated from discrete choice models are based on sound mathematical and economic theory whereas the proposed model is based on human experience and fairness principles. However, the model outputs and the uncertainties of the current discrete choice methods can be incorporated in the model input and output of the rule-based model. For example, findings from various VOTTS studies using choice models and other related techniques can be used to create membership functions for inputs, rules and the final output. Further research is needed to verify whether rules are enough to fully and correctly estimate VOTTS.

A limitation of the model is that the flexibility of the method makes it also vulnerable to misuse. For example, who decides what is a high VOTTS during projects: government, citizens or experts? Some variables can be more important than others: should weights apply to rules? This could pose a problem during implementation.

Another limitation of the method is that the variables used should be continuous. Categorical variables like gender or transport modes are difficult to fuzzify. If the proposed method is to be used for categorical variables, then they must be converted to continuous variables. Discrete choice models can handle both categorical and continuous variables. In future research, the proposed model will

be applied for country wide estimation of VOTTS of individuals and various trip purposes and then compare values to those obtained from discrete choice models.

**Author Contributions:** The two authors contributed equally to most aspects of the paper.

**Funding:** This research received no external funding.

**Conflicts of Interest:** The authors declare no conflict of interest.

### Appendix A

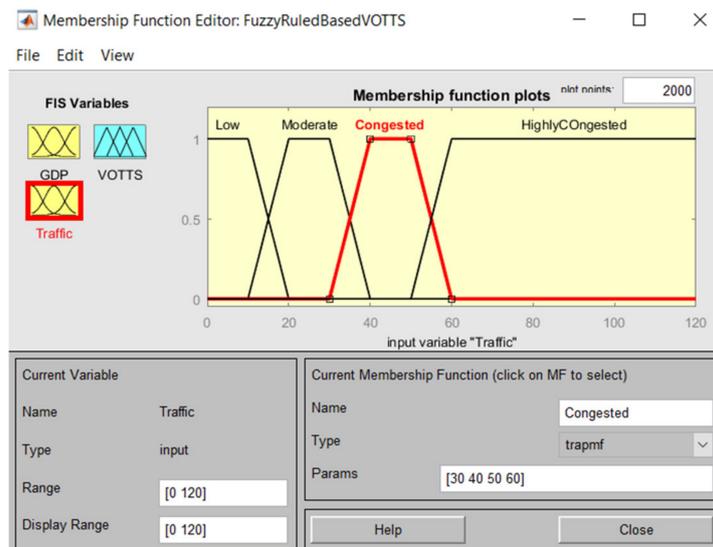


Figure A1. Membership function and linguistic variable for traffic congestion.

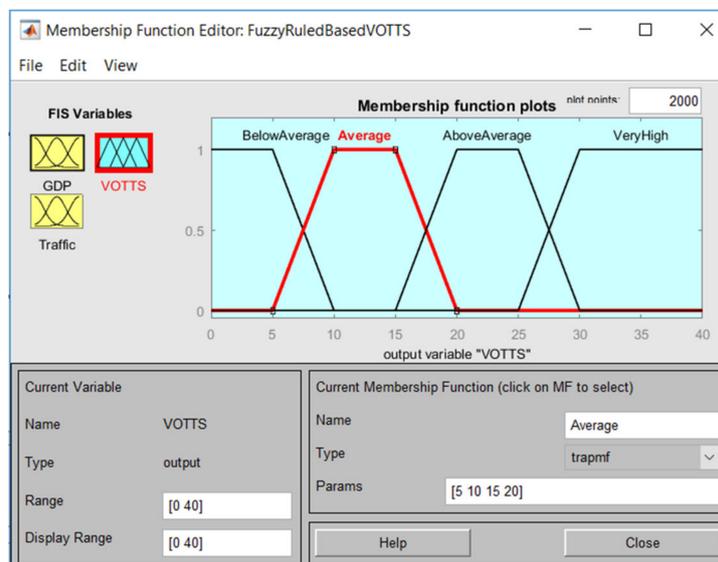
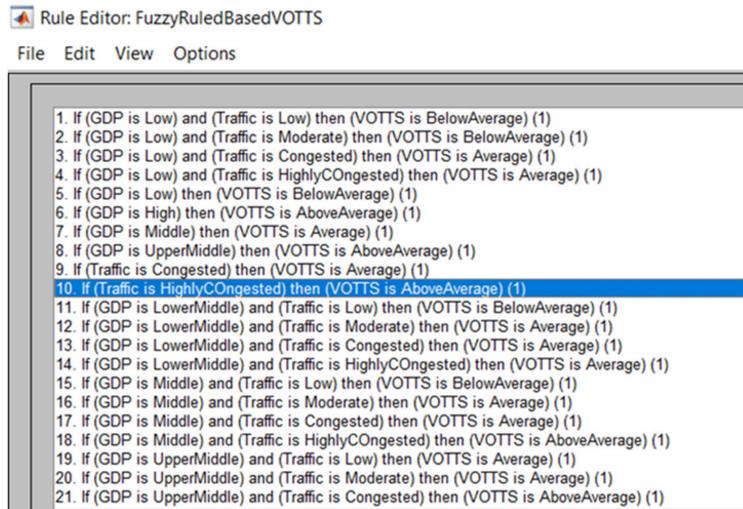
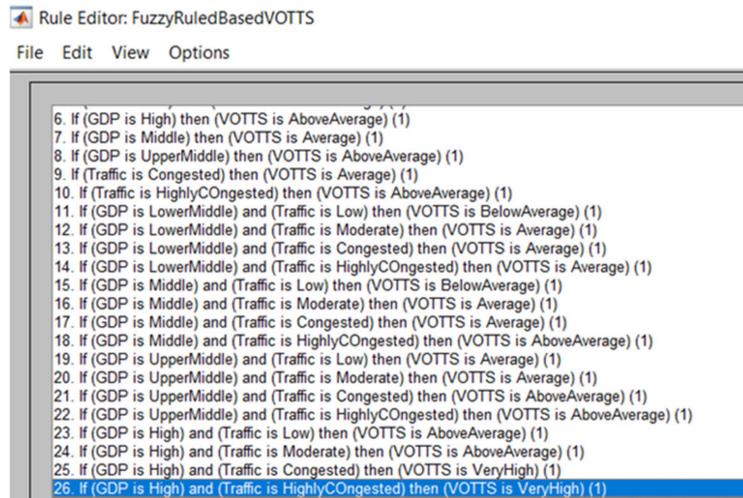


Figure A2. Membership function and linguistic variable for VOTTS.



(a)



(b)

Figure A3. All rules.

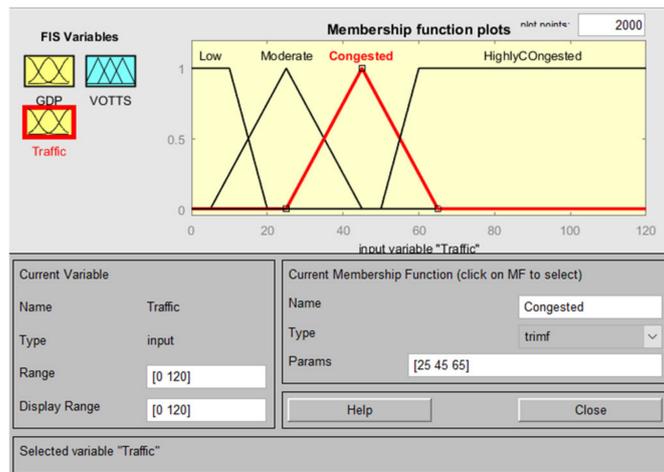


Figure A4. Triangular membership function and linguistic variable for traffic congestion.

**Table A1.** Estimated values of the proposed model compared value, from metanalysis values in [14].

Country	Estimated (\$/h)	Meta-Analysis (\$/h)	Difference ( $\times 100\%$ )	Abs ( $\times 100\%$ )
LUX	22.50	31.62	-0.41	0.41
SWI	12.58	16.45	-0.31	0.31
DEN	11.16	14.12	-0.27	0.27
NOR	17.50	20.54	-0.17	0.17
SWE	12.58	13.81	-0.10	0.10
ITA	10.18	11.07	-0.09	0.09
BEL	12.50	13.20	-0.06	0.06
FIN	12.50	12.76	-0.02	0.02
ESP	10.87	11.07	-0.02	0.02
UK	12.50	12.47	0.00	0.00
GER	13.35	13.10	0.02	0.02
FR	12.50	11.88	0.05	0.05
POR	9.29	8.72	0.06	0.06
AUS	15.27	14.07	0.08	0.08
NL	16.24	14.87	0.08	0.08
CZE	10.23	8.65	0.15	0.15
SLOVEN	11.02	9.26	0.16	0.16
IRE	18.66	14.25	0.24	0.24
SLOVAK	12.50	7.93	0.37	0.37
HUN	11.37	6.96	0.39	0.39
PL	12.50	6.73	0.46	0.46
MEAN	<b>13.23</b>	<b>13.03</b>	0.03	0.17

**Table A2.** Estimated and official values.

Country	Estimated (\$/h)	Meta-Analysis (\$/h)	Official (\$/h)
UK	12.50	10.62	16.38
Germany	13.35	11.16	9.02
Netherlands	15.63	12.66	12.11
Sweden	12.58	11.76	11.56
Norway	17.50	17.49	15.32
Denmark	11.16	12.03	15.54
France	12.50	10.12	13.09
AVG	13.60	12.26	13.29

**Table A3.** Estimated VOTTS for various countries.

Country	GDP (\$×1000)	Hours Lost in Traffic (h)	Estimated VOTTS (\$/h)
Thailand	17.871	56	16.24
Indonesia	12.284	51	10.21
Colombia	14.552	49	10.03
Venezuela	12.400	42	9.36
Russia	25.533	41	12.50
USA	59.532	41	17.43
Brazil	15.484	36	9.80
South Africa	13.498	36	8.99
Turkey	27.916	32	12.50
UK	43.877	31	12.50
Puerto Rico	37.895	31	12.50
Germany	50.715	30	13.35
Poland	29.291	29	12.50
Slovakia	32.111	29	12.50
Luxembourg	103.662	28	22.50
Canada	46.378	27	12.50
Switzerland	65.006	27	17.50
Norway	60.978	26	17.50
Sweden	50.07	26	12.58
Austria	52.558	25	15.27
U.A.E.	73.879	24	17.50
Ecuador	11.617	23	5.99
Ireland	76.305	23	18.66
Mexico	18.149	23	11.46
France	42.779	22	12.50
Kuwait	71.943	22	17.50
Netherlands	52.941	22	15.63
Belgium	47.561	21	12.50
Finland	45.192	21	12.50
Hungary	28.375	18	11.37
Saudi Arabia	53.845	18	15.19
Slovenia	34.802	18	11.02
Spain	38.091	17	10.87
Czech Republic	36.916	16	10.23
Denmark	50.541	16	11.16
Italy	39.817	15	10.18
Portugal	32.199	15	9.29
Singapore	93.905	10	22.50

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