A Method of Driver Distraction Evaluation Using Fuzzy Logic

Phone usage as a driver's secondary activity: Case study

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Abstract—**A novel method for evaluating driver distraction and situation awareness while performing a secondary task using a fuzzy set theory is proposed in this paper. A fuzzy inference engine realization process based on simple matrix operations is described in detail. The drivers' performance is evaluated referring to the vehicle behavior, in particular, the abilities to keep the vehicle in the center of the lane and to observe the speed limit. The evaluation technique was tested on a vehicle mock-up driving simulator. Text messaging on a cell phone is studied as a secondary distractive activity. Driver-in-the-loop experimental results as well as the conclusions regarding different age, gender, and driving experience groups are discussed.**

Keywords—fuzzy logic; performance evaluation; vehicle safety; real-time systems

I. INTRODUCTION

Nowadays, people spend more time than ever behind a steering wheel. However, not all drivers can remain constantly focused on their primary tasks – performing maneuvers, reading traffic signs, monitoring traffic, overcoming weather – while driving. Frequently, they perform different kinds of secondary tasks that are not related to safe driving and, on the contrary, may be extremely dangerous due to drivers' increasing workload [1, 2, 3].

The tasks that may potentially affect driving are divided into two main groups: interaction with in-vehicle features, such as vehicle information and entertainment systems, and items brought into the vehicle, such as portable devices [1]. Nevertheless, there are no certain measures which could evaluate the influence of the secondary tasks on drivers' situation awareness and level of vigilance and therefore conclude what secondary activity leads to a potential traffic accident, to what degree it can be dangerous, and how to eliminate its effect.

In the current decade, portable electronic devices, such as cell phones or smartphones, became an essential part of everyday life. However, phones are often used in cases when they may lead to a dramatic aftermath and even cause serious accidents with fatal consequences [4].

Only in the USA, fatalities of drivers involved in vehicle crashes increased by 7.2% in 2015 over 2014 [5]. Among different causes of traffic accidents, driver distraction is considered one of the most common, especially among young drivers (58% in the period 2007–2013) [6]. Notably dangerous is the usage of portable electronic devices, such as e-readers, cell phones, tablets, or MP3 players while driving [7]. Although the AAA Foundation for Traffic Safety reports that 81.1% of surveyed drivers are aware that "text messaging or emailing while driving are a very serious threat to their personal safety", still 11.2% of drivers regularly read text messages while driving. What is more, 8.2% of them admit to typing or sending texts [7].

The development of a robust method for driver distraction evaluation while performing a secondary task is of interest for both road safety foundations and vehicle manufacturers. It could help the first group in establishing traffic safety policies, and the second one in improving human-machine interface systems that would be intuitive and logical, thus producing minimum drivers disturbance. A driver distraction and human-machine interface evaluation technique also offer the possibility to test and evaluate such advanced driver assistance systems as collision avoidance, lane departure warning, and others.

Various approaches were offered for an evaluation of driver distraction and situation awareness. Drivers' eye tracking or head movement are among the oldest techniques [8]. The effect of hands-free cell phone conversations was examined in [9] using eye-tracking data. Different age groups of drivers (novice drivers, young adults, and older adults) were studied on their ability to recognize risks [10]. Separate groups of novice drivers were tested on risk awareness in [11]. Eye movement was involved in evaluation in the above studies. Eye tracking was also used in driver distraction evaluation while having a conversation with a passenger [12].

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Another widely used group of evaluation methods is based on vehicle dynamic performance. Using driving simulators, drivers' steering ability, speed limit maintenance, brake and gas pedal actuation as well as reaction time can be accepted as a measure for the driver distraction estimation. In [4, 13], the level of driver distraction was evaluated via steering wheel performance and lane-keeping ability. In the first work, the effects of handheld and hands-free phone conversations while driving were studied. In the second one, the steerability was tested using clear, large, and high luminance visual scenes.

Driving behavior characterization was developed by combining fuzzy and probabilistic models [14]. The driving performance was tested in real time. A gap between vehicles and vehicle velocity were used as evaluation measures.

Another methodology uses the ability of experimentation subjected for maintenance the spatial location knowledge while performing dynamic real-time tasks, such as driving, air traffic control, flying, and others. For example, a recall of vehicle location and focus on the location of potentially hazardous cars were used in [3] as a measures for the level of situation awareness.

Finally, some researchers went further and combined several measures to evaluate driver distraction while interacting with in-vehicle secondary tasks. Researchers in [2] used the mean speed and deviation from the posted speed limit to measure driver distraction. Thereafter, a multidimensional subjective workload index, the NASA Task Load Index, of the perceived workload was recorded. In [15], the authors combined eye and head movement data with lane keeping.

Fuzzy theory [16] is not a novel idea in driver behavior and distraction detection. Fuzzy logic (FL) was applied as an online driving style recognition system [17]. The system has a high accuracy in driving style classification. However, the application was tested only via simulation. In [18], a driver activity index was designed using FL.

In [19, 20], driver face monitoring systems were introduced. The fuzzy algorithms were applied to detect driver fatigue and distraction. The first work uses the driver's position in a vehicle. The system in the second paper collects the driver's eye and face symptoms as the fuzzy expert system inputs. Finally, four levels of driver distraction FL classification using EEG signals were offered [21]. Unfortunately, the researchers did not study yet the secondary task influence on the driving quality.

An old evaluation method used in ŠKODA AUTO a.s. Technology Centre (Mladá Boleslav, Czech Republic) has some drawbacks. First, driver distraction is only recorded when the participant drives outside the road boundaries. Even driving close to a road marking can be significantly dangerous for both the driver and for other traffic participants, which is not yet considered. Second, vehicle speed maintenance is not considered in the old method. However, it has been observed that many drivers significantly decelerate (even down to a full stop) while performing a secondary task. To study the level of driver distraction while performing a secondary activity more accurately, the development of a new advanced driver situation awareness and distraction evaluation technique is required. Following the driver's expectations, the most suitable in view of driving safety human-machine interface is to be suggested for installation in a real passenger vehicle.

In the first step of the research, it is proposed to extend the driver performance evaluation by two measures: lane keeping and optimal vehicle velocity maintenance ability. The authors believe that these two measures are among the most important ones for safe vehicle operation, which, in turn, is a driver's primary task. Considering that it is quite difficult to use two independent variables for a comparative evaluation, FL is applied in this study to transform the vehicle dynamic behavior into a single output, namely, the level of driver distraction. FL is known to be a perfect approach for empirical modeling of human behavior reasoning because it allows considering several vague inputs simultaneously [16, 22].

Furthermore, the Sugeno-type fuzzy inference system is realized here with simple matrix operations. This approach makes a fuzzy algorithm easy to program using such languages as C, C++, MATLAB® script, and many others.

The next section describes the fuzzy inference system as well as the evaluation method in detail. The driver distraction test is conducted on a driving simulator test rig. As cell phone usage while driving is one of the most dangerous tasks [7], it is studied as a secondary activity. The participants of the driver-in-the-loop experiment were divided into three groups based on their gender, age, and driving experience. Section III is dedicated to the experimental facilities and procedure. The experiment results are introduced and discussed in Section IV. Finally, the research outcomes are concluded in Section V.

II. FUZZY LOGIC DRIVER DISTRACTION EVALUATOR

A general FL inference system diagram is introduced in Fig. 1. It may have a multiple number of inputs and outputs. The input numerical signals are called "crisp". They are translated into the fuzzy sets through a fuzzification process. A fuzzy set, in turn, is a pair consisting of an element in the universe of discourse (UOD) and a degree of certainty of a membership function (MF). The rule-base block stores a linguistic knowledge, which is used to convert the fuzzy input sets into the fuzzy output sets by the inference engine. The fuzzy set outputs are then turned back to the real numbers using a defuzzification procedure.

A. Inference mechanism

In the fuzzy inference engine presented here, the fuzzification process turns the crisp input into a column vector every element of which equals to a degree of certainty a relevant MF μ^{MF}, which can be any quantity between 0 and 1.

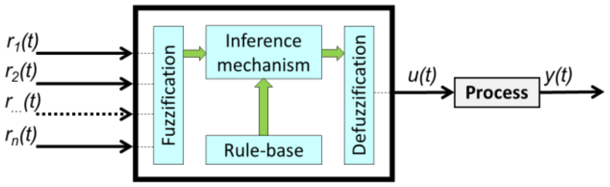

Fig. 1. Fuzzy logic inference diagram: $r_1(t)$ – first input; $r_2(t)$ – second input; $r_n(t)$ – n^{th} input; $u(t)$ – fuzzy logic output/process input; $y(t)$ – process output.

For a “2 inputs – 1 output” system, for instance, the first input turns into an $n\times 1$ column vector a, where n is a number of MFs for the first input. The second input turns into an $m\times 1$ column vector b, where m is a number of MFs for the second input. Next, a dyadic product of two vectors, a and b, generates an $m\times n$ matrix C:

$$C = b\otimes a = ba^T = \begin{bmatrix} b_1\\ b_2\\ \vdots\\ b_m \end{bmatrix}\begin{bmatrix} a_1 & a_2 & \cdots & a_n \end{bmatrix} = \tag{1}$$

$$= \begin{bmatrix} b_1\cdot a_1 & b_1\cdot a_2 & \cdots & b_1\cdot a_n\\ b_2\cdot a_1 & b_2\cdot a_2 & \cdots & b_2\cdot a_n\\ \vdots & \vdots & \ddots & \vdots\\ b_m\cdot a_1 & b_m\cdot a_2 & \cdots & b_m\cdot a_n \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1n}\\ c_{21} & c_{22} & \cdots & c_{2n}\\ \vdots & \vdots & \ddots & \vdots\\ c_{m1} & c_{m2} & \cdots & c_{mn} \end{bmatrix}.$$

The fuzzification procedure example for a “2 inputs – 1 output” system with the linear MFs is introduced in Fig. 2. The first input is turned into a 3×1 while the second input is turned into a 5×1 column vector. The size of each vector depends on the number of MFs chosen for each input variable. After applying (1), the 5×3 matrix C is obtained (Fig. 2) every element of which is a real number between 0 and 1.

A fuzzy logic rule-base consists of the modus-ponens-form linguistic rule “If-Then", and is often introduced as a table. In our approach, a rule-base table is represented as an $m\times n$ matrix R. This transformation from the modus-ponens rules table to a matrix is shown in Fig. 3. It is important to note that the matrix elements are the constant values. Thus, this fuzzy inference method makes the system similar to the zero-order Sugeno inference system.

Next, matrix D is obtained as a Hadamard product for the same dimension matrices C and R:

$$D = C\circ R = \begin{bmatrix} b_1\cdot a_1\cdot r_{11} & b_1\cdot a_2\cdot r_{12} & \cdots & b_1\cdot a_n\cdot r_{1n}\\ b_2\cdot a_1\cdot r_{21} & b_2\cdot a_2\cdot r_{22} & \cdots & b_2\cdot a_n\cdot r_{2n}\\ \vdots & \vdots & \ddots & \vdots\\ b_m\cdot a_1\cdot r_{m1} & b_m\cdot a_2\cdot r_{m2} & \cdots & b_m\cdot a_n\cdot r_{mn} \end{bmatrix} = \tag{2}$$

$$= \begin{bmatrix} d_{11} & d_{12} & \cdots & d_{1n}\\ d_{21} & d_{22} & \cdots & d_{2n}\\ \vdots & \vdots & \ddots & \vdots\\ d_{m1} & d_{m2} & \cdots & d_{mn} \end{bmatrix}$$

The defuzzification process is the last step in every fuzzy inference system. During the defuzzification procedure, the fuzzy sets are converted back to the crisp output. In our case, the constructed matrices are transformed to a single numerical value by finding a weighted average of the matrix elements. The FL inference technique output u is obtained by dividing the sum of the elements in matrix D by the sum of the elements in matrix C:

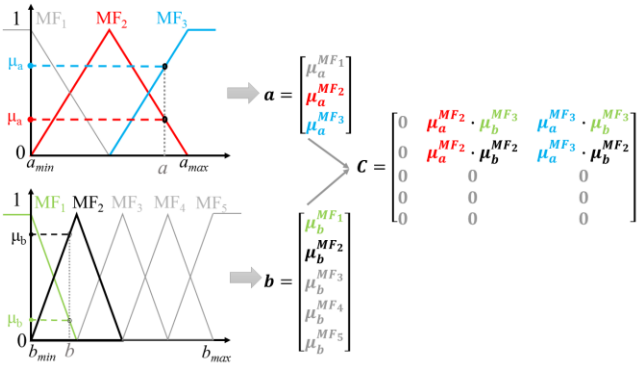

Fig. 2. Fuzzification process visual explanation.

$$u = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m} d_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{m} c_{ij}}; \qquad i = 1,2,\ldots,n; \qquad j = 1,2,\ldots,m, \tag{3}$$

where d_{ij} is an element of the i^{th} row and j^{th} column of D and c_{ij} is an element of the i^{th} row and j^{th} column of C.

B. Fuzzy logic driver distraction evaluator

The FL driver distraction evaluator has a “2 inputs – 1 output” structure. The offset dx between the road centerline and the position of the car on the road serves as a first input. Second input is the difference dv between the speed limit on a road segment and the real vehicle speed. Thus, the vehicle dynamic performance is tracked for driver distraction evaluation.

Symmetrically dispersed MFs of the triangular (linear) shape are designed for both inputs. The linear narrow shape of MFs ensures fast response and they are simple for programming. The MFs overlap with each other over the whole UOD. Symmetrical dispersion guarantees equal sensitivity of the inputs.

The FL input and output variables must have a closed frontier [*min*, *max*] of the UOD. For dx, a UOD restriction was narrowed to [0, 1.5]. A UOD of the speed difference input dv lies in the range [0, 12]. Both inputs have three MFs.

The output variable represents the driving distraction in percentages. Thus, the output UOD is bounded within [0 100].

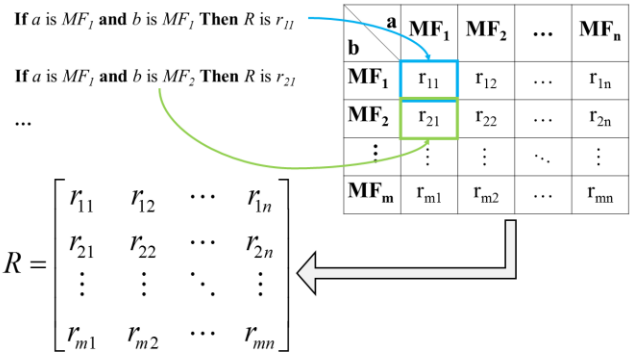

Fig. 3. Transformation of a fuzzy logic rule-base into an $m\times n$ matrix.

TABLE II. FUZZY LOGIC EVALUATION RULE-BASE

Driver Distraction		***dx***		
		close	***far***	***out***
dv	***good***	*no*	*negligible*	*low*
	bad	*no*	*medium*	*high*
	awful	*very_low*	*very_high*	*inacceptable*

Singletons represent the consequent MFs as the set of values with an equal step between each set: {*no* = 0, *negligible* = 14.3, *very_low* = 28.6, *low* = 42.9, *medium* = 57.2, *high* = 71.5, *very_high* = 85.8, *inacceptable* = 100}.

The FL evaluation was realized via the modus-ponens-form rule "If-Then". The inference system has two inputs and one output. The linguistic knowledge is stored in a 3×3 matrix, the elements of which are the values of the output sets. Table I shows the linguistic relation between the variables. The MFs are named suitably for human understanding. An example of the linguistic input-output mapping is as follows:

IF the vehicle middle point is "*far*" off the road centerline **AND** driver's speed limit observation is "*bad*", **THEN** Driver Distraction is "*medium*".

The three-dimensional surface of the designed FL inference mechanism is displayed in Fig. 4. The FL driver distraction evaluator design summary is introduced in Table II.

III. METHODOLOGY

A. Subjects

The participants of the driver distraction experiment were employees of IPG Automotive GmbH (Karlsruhe, Germany). All participants (13 male and 5 female) took part in the experiment voluntarily. Their age ranged between 24 and 39 (mean 30.11). The participants' driving experience ranged between 1 and 21 years (mean 11.33).

Before the experiment, the drivers were questioned regarding their use of electronic devices, such as tablets, smartphones, laptops, or e-readers while driving. Two participants stated that they never use them while driving; two drivers admitted to the occasional use of a device. The rest of the participants reported that they rarely use electronic devices. All the participants pointed out that they are aware of the danger of using devices while driving.

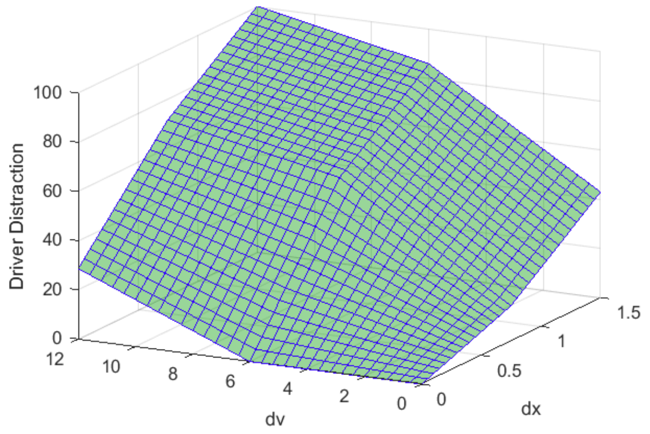

Fig. 4. Driver distraction fuzzy evaluator three-dimensional surface.

TABLE I. FUZZY LOGIC EVALUATOR OUTLOOK

Parameter	**Fuzzy logic evaluator**
Structure	Multi-input, single-output
Crisp input	*dx* = [0, 1.5] (3 MFs) *dv* = [0, 12] (3 MFs)
Crisp output	Driver Distraction = [0 100] (8 Singletons)
Input membership functions	Linear symmetric
Inference mechanism	Matrix (Sugeno's)
Rule-base	9 modus ponens
Defuzzification	Geometric center

B. Apparatus

The vehicle mock-up driving simulator equipment System Experience Platform (SEP) is shown in Fig. 5. The test rig has a steering wheel and two pedals: acceleration and brake. The SEP has two liquid-crystal displays and it can be extended to up to three displays. The virtual world is shown on a display which is placed in front of the driver. The SEP has an adjustable driver's seat.

The virtual vehicle model has a manual transmission. The driver can monitor the vehicle's speed on the head-up display. The performance data are collected with 50Hz frequency (0.02 s sample period). The SEP supports real-time integration with MATLAB®/Simulink® (Natick, MA, USA) and CarMaker by IPG Automotive (Karlsruhe, Germany).

C. Procedure

The participants drove a two-way, two-lane highway road of a total length of 10,626 m. The lane width was 3.5 m. The road had three segments with different speed limits (30, 50 and 90 km/h) and curvatures. The road shape was displayed on one of the SEP screens. The drivers could also track their position on the road. There were neither other vehicles nor

Fig. 5. The static System Experience Platform driving simulator.

pedestrians nor animals modeled in the virtual world.

Before the experiment, the drivers received unlimited time to familiarize themselves with the test rig. Each driver passed at least one full road lap. Thus, the participants were familiar with the road in advance.

During the experiment, the drivers were asked to drive in the right lane, keeping the car in the middle of the lane, and to observe all traffic signs. While the participants were driving in the virtual world, one of the experiment organizers sent text messages to the cell phone prepared for the participants. The drivers were requested to answer the text messages and to continue driving following all traffic rules.

The drivers were instructed to have a natural chat conversation. The experimenter asked the participants simple questions. For instance, "How are you?", "What are your plans for the weekend?" and similar. The secondary task period was captured starting when the drivers took the phone in their hands and ending when they put the phone aside. The experimenter allowed a reasonable time between the distractive messages. Therefore, each participant drove roughly the equal amount of time both when distracted and when free of the secondary task.

IV. RESULTS AND DISCUSSIONS

In this section, the outcomes of the driver-in-the-loop experiment are discussed. The results of driver distraction evaluation based on the FL for a random driver are shown in Fig. 6. The periods with a green background represent the time of interaction between the driver and the cell phone. The blue curves indicate the driver distraction level in percent. For all the participants, the evaluation results are quite similar: a high percentage during texting and a low evaluation during free driving.

Although all the participants were familiar with the road curvature, they were performing significantly better (low percentage of distraction) during normal driving compared to the times when they were texting. For instance, one random driver whose drive is presented in Fig. 6, in a period from 350 to 410 seconds, was performing badly for a quite lengthy period, around one minute. In real life, this could potentially lead to severe injury or even fatal accidents. In short, the proposed evaluation technique recognizes when and how strongly (in percent) the driver is distracted.

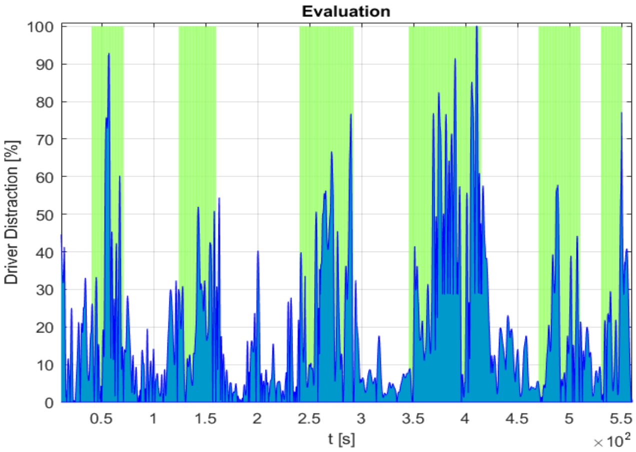

Fig. 6. Driver distraction versus time plot: green background symbolizes the secondary task accomplishment period. Evaluation example for one of the experiment participants.

To calculate the driver distraction performance, first, the area of the driver distraction curve was found (Fig. 6, blue) using a trapezoidal rule. Second, the area value was divided by the total time the driver was distracted with the cell phone texting chat (Fig. 6, green background).

Therefore, all the driver's evaluations were summarized and distributed between three main groups that were formed according to the participants' gender, age, and driving experience. The average performance for different group members was calculated. Fig. 7 introduces the results of driver distraction in each group.

Two subgroups according to the participants' responses were formed for a gender group: female and male. Referring to the experiment results, the male drivers performed a secondary activity better than their female colleagues did.

Two groups were distributed into subgroups regarding the mean age and driving experience of the participants. In the age group, the drivers were divided into younger than 30 years old and the ones of 30 years or older. The last group formed the drivers with less than 11 years of driving experience and the drivers who had at least 11 years of experience.

Among young experiment participants and those older than 30 years, the performance difference was not significant. Younger drivers showed slightly better performance. In contrast, in the experienced group, participants that were more skilled performed noticeably better than the beginners did.

CONCLUSION

This paper presents an evaluation method based on a fuzzy set theory focusing on a driver distraction while performing a secondary task. An inference mechanism easily realizable in programming languages and based on matrix operations is described. A driver-in-the-loop experiment on driving while performing a secondary task is conducted. Text messaging on the cell phone was examined as a secondary task.

The designed FL inference system evaluates driver distraction considering several aspects concurrently: lane keeping and the ability to observe the speed limit. The

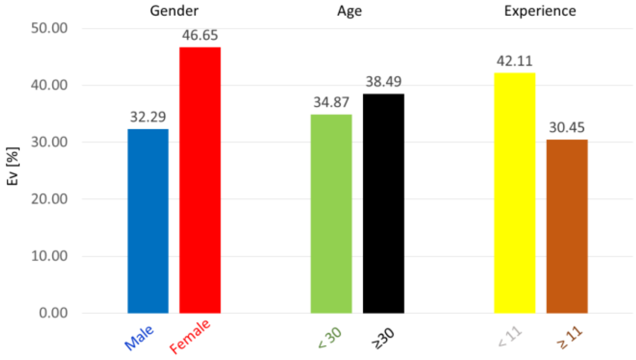

Fig. 7. Driver distraction comparison results for the three groups: gender, age and driving experience.

experiment's results show that the proposed method allows to recognize and to calculate the level of driver distraction in percentage based on safe vehicle dynamic performance. The presented method allows for driver distraction experiments to be conducted more accurately compared to the old one used in the laboratory as it involves more input measures.

Further research might be directed towards the advancement of the evaluation methodology. In particular, other parameters of vehicle dynamics are expected as new algorithm inputs. In addition, the mechanism improvement via the combination of different evaluation approaches is planned.

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