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Estimating Driver Behavior Measures Related to Traffic Safety by Investigating 2-Dimensional Uncertain Linguistic Data—A Pythagorean Fuzzy Analytic Hierarchy Process Approach

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Abstract: Human behavior has been estimated as a factor too uncertain and complex to investigate road safety issues. By utilizing recent expansions of ordinary fuzzy sets, experts in the field have intended to handle the vagueness of human behavior in sustainable transport systems by using linguistic terms for assessment. Pythagorean Fuzzy sets (PFSs) are considered a superior method that has been developed for multi-criteria decision-making (MCDM), which enables assigning of both membership and non-membership functions in a large domain area. A novel Pythagorean Fuzzy Analytic Hierarchy Process (PF-AHP) is performed to assess and prioritize critical driver behavior criteria designed into a hierarchical model based on data gathered from observed driver groups in Budapest city. Accordingly, based on the aggregated weights, the criterion 'lapses' is prioritized as the most critical factor connected to road safety. The criterion 'disobey speed limits' is found to be the least critical factor, followed by 'disobey overtaking rules' as the second least. For a comparative analysis, the case of dependent criteria has been considered. Pythagorean Fuzzy DEMATEL method has been applied to determine dependencies between the criteria. Through the dependencies, a network of criteria has been constructed and the Pythagorean Fuzzy Analytic Network Process (ANP) conducted to interpret the results. Moreover, sensitivity analyses have been carried out to examine its robustness by applying different case scenarios.

Keywords: human behavior; road safety; multi-criteria decision making; Pythagorean Fuzzy Analytic Hierarchy Process; prioritize

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1. Introduction

The global road safety report estimates that the annual number of deaths in traffic accidents has reached 1.35 million [1]. Globally, European roads have been declared the safest, with a 19% decrease in road fatalities over the past six years. Although the strategic goal for sustainable development of halving the number of deaths in traffic accidents between 2010 and 2020 has been achieved, it is worth intending to protect every single life [2]. The performance of Hungary in road safety is below the European Union (EU) average. On Hungarian roads, 64 people per million inhabitants died in 2018, indicating a 1% rise compared to the previous year [3]. When the situation analysis of the Road Safety Action Program is examined, it seems that most of the traffic accidents were caused by human-related issues; so minimizing human-related issues becomes an extremely dynamic goal to make the roads safe [4].

Human behavior plays a very significant role in the sustainable transport system, with previous research findings showing human factors to be a primary cause in almost 90% of the traffic crashes on the roads [5–7]. Also, a study observed that driving behavior is one of the basic driver-related components that directly affect road safety [8]. Several driver behavior factors have been detected as dynamic, intentional rule violations and errors due to less driving experience, while others were due to inattention, momentary faults or failure to perform a function—the latter generally connected to age [9,10]. Driving behavior evaluation has been considered a crucial constraint for traffic studies. The studies provide valuable data on generally three main topics that can be classified as road safety analysis, microscopic traffic simulation, and intelligent transportation systems [11]. A resolution by the Council of Ministers approved on 24 September 2019 on the "Strategy for the Sustainable Transport Development by 2030" emphasized on the need to increase transport accessibility in the country, and enhance the safety of traffic users and competence of the transport sector by creating a sustainable, innovative, coherent, and user-friendly transport network at the national, European, and global levels [12]. A sustainable transportation system can provide access to people, opportunities, and goods and services in an efficient, safe, and equitable way without affecting the environment. Sustainable transportation can serve all groups of people in the city in a way that is within its environmental carrying capability and is rational to both users and providers of the system [13].

MCDM is an innovative area of operational study in quantitative hazard assessment classification. MCDM presents a wide assortment of approaches to decision makers (DMs) and experts who are well complemented with the intricacy of decision-making issues. MCDM approaches primarily contain human intervention and decisions [14]. MCDM approaches involve estimating and deciding alternatives under conflicting criteria while considering the choices provided by DMs [15]. The major elements of an MCDM approach involve alternatives, criteria against assessed alternatives, alternatives scores on criteria, and criteria weights signifying the relative significance of each criterion in comparison with others [15].

In risk-assessment literature, researchers utilize valuable MCDM methodologies such as AHP to rank deterrents or development actions of risky systems [16,17]. AHP, developed by Saaty (1990) [18], is based on the hierarchic MCDM issue involving an objective, criteria, and alternatives. The AHP has the benefits of hierarchical arrangement definition, presentation of the issue in a structural way, and incorporation of all the decisions with structured links. After the design of the hierarchy, linguistic expressions are utilized by evaluators to do pairwise comparisons (PCs). These linguistic expressions are transformed into numerical values by implementing fuzzy sets that are capable of focusing on the vagueness and uncertainty of the assessment processes [18]. At present, numerous studies combine AHP approaches with the system of fuzzy logic, which provides risk prioritization according to threat level and yields a consistent model for risk assessment. The use of such risk assessment models can be found in several fields, such as the risk assessment of floor water incursion in coal mines [19], driver behavior criteria [20], and information technology developments [21]. Previous studies utilized fuzzy AHP to estimate and give priority to the most important driver behavior criteria related to road safety for Budapest drivers [22] and those from different cultures [23]. Furthermore, the triangular fuzzy method was integrated with the best–worst method (F-BWM) to better estimate the nominated driver behavior criteria for the development of a consistent decision process related to road safety issues [24]. However, there is a demand for a better and more flexible description of membership tasks in fuzzy MCDM approaches. In this study, the adopted model targets to examine and rank the most crucial driver behavior factors and sub-factors affecting road safety based on evaluators' responses in order to alleviate the uncertainty of non-expert assessments.

The PFS, an expansion of intuitionistic fuzzy sets, was created with the objective of generating a larger domain area for evaluators in stating their decisions regarding the impreciseness and vagueness of the studied complex problem. It attains this objective because the evaluators do not have to designate membership and non-membership grades whose total is at ultimate 1. Though the total squares of such degrees should be at ultimate 1, the weight scores achieved through the PF-AHP method will be utilized as inputs for prospectively factor in risk assessment methods [25]. The extensions aim to cope with the uncertainty and decide the indeterminacy more consistently. PFSs enable the statement on a larger frame of membership and non-standard membership grades that allow experts to consider uncertainty more efficiently than others of fuzzy extensions [26].

The main aim of the work is to estimate and rank the ultimate essential factors affecting road safety by utilizing the PF-AHP method and its application. The questionnaire created on the fuzzy scale is utilized to assess the responses of different drivers' groups using PCs. The work prioritizes specified factors developed in three levels of hierarchical structure by giving weight to each factor. Finally, high-rank driver behavior factors that can drastically affect road safety are highlighted.

2. Materials and Methods

In this section, the fundamentals of PFS and applied methodology are presented in detail.

2.1. Pythagorean Fuzzy Sets

Pythagorean Fuzzy sets (PFSs) were introduced by Yager (2013) [27] based on intuitionistic type-2 fuzzy (IFS2) sets initially created by Atanassov (1999) [28]. In PFSs, instead of ordinary fuzzy sets, there are two functions called membership and non-membership that represent the degree of belonging and non-belonging. Through this representation, presenting decision makers/experts hesitancy on their evaluations can be available in the mathematical representations. The mathematical procurement of a PFS is described in Definition 1 as follows:

Definition 1. *(Yager, 2013) [27]. Let X be a fixed set. A PFS* $\widetilde{L}$ *is an object in X having the following form:*

$$\widetilde{L} \cong \left\{x, \mu_{\widetilde{L}}(x), \vartheta_{\widetilde{P}}(x); x \in X\right\} \tag{1}$$

where the functions $\mu_{\widetilde{L}}(x) : X \to [0,1]$ and $\vartheta_{\widetilde{P}}(x) : X \to [0,1]$ define the degree of membership and non-membership of the elements $x \epsilon X$ to L, respectively. For each $x \epsilon X$, it holds that:

$$0 \leq \mu_{\widetilde{L}}(x)^2 + \vartheta_{\widetilde{L}}(x)^2 \leq 1 \tag{2}$$

Also, $\pi_L(x) = \sqrt{1 - \mu_{\widetilde{L}}(x)^2 - \vartheta_{\widetilde{L}}(x)^2}$ is the hesitation degree of the element $\widetilde{L}$ in set X. In a similar way, we obtain $0 \leq \pi_{\widetilde{L}}(x)^2 \leq 1$ by using Equation (2).

Definition 2. *(Zhang & Xu, 2014) [29] [. Let* $\widetilde{A} \cong \mu_{\widetilde{A}}, \vartheta_{\widetilde{A}}$ *and* $\widetilde{B} \cong \mu_{\widetilde{B}}, \vartheta_{\widetilde{B}}$ *be Pythagorean Fuzzy Numbers (PFNs), and* $\lambda > 0$. *Some arithmetical operations of PFNs can be epitomized as follows:*

$$\widetilde{A} \oplus \widetilde{B} \cong \sqrt{\mu_{\widetilde{A}}^2 + \mu_{\widetilde{B}}^2 - \mu_{\widetilde{A}}^2 \mu_{\widetilde{B}}^2},\ \vartheta_{\widetilde{A}} \vartheta_{\widetilde{B}} \tag{3}$$

$$\widetilde{A} \otimes \widetilde{B} \cong \mu_{\widetilde{A}} \mu_{\widetilde{B}},\ \sqrt{\vartheta_{\widetilde{A}}^2 + \vartheta_{\widetilde{B}}^2 - \vartheta_{\widetilde{A}}^2 \vartheta_{\widetilde{B}}^2} \tag{4}$$

$$\lambda \widetilde{A} = \left(\sqrt{1 - (1 - \mu^2)^{\lambda}}, \vartheta^{\lambda}\right) \tag{5}$$

$$\widetilde{A}^{\lambda} = \left(\mu^{\lambda}, \sqrt{1 - (1 - \vartheta^2)^{\lambda}}\right) \tag{6}$$

2.2. Interval Valued Pythagorean Fuzzy Sets

Zhang (2016) [30] introduces interval-valued PFSs (IV PFSs). The mathematical assimilation of an IV-PFS is depicted as follows:

Definition 3. *(Garg, 2016) [31]. An IV-PFS in $\widetilde{L}$ is denoted over X can be represented as follows:*

$$\widetilde{L} \cong \{x, \mu_{\widetilde{L}}(x), \vartheta_{\widetilde{P}}(x); x \in X\} \tag{7}$$

where $\mu_{\widetilde{L}}(x) \subseteq [0,1]$ and $\vartheta_{\widetilde{L}}(x) \subseteq [0,1]$ are interval numbers such that $0 \leq \sup\mu_{\widetilde{L}}(x) + \sup\vartheta_{\widetilde{L}}(x) \leq 1$ for all $x\epsilon X$.

For convenience, let $\mu_{\widetilde{L}}(x) = [a,b]$ and $\vartheta_{\widetilde{L}}(x) = [c,d]$, then this pair is often denoted by $\widetilde{L} = [a,b],[c,d]$ and named an IV PFN where,

$$[a,b] \subseteq [0,1],\ [c,d] \subseteq [0,1],\ \text{and } 0 \leq b^2 + d^2 \leq 1 \tag{8}$$

Similar to PFSs, the hesitancy degree of this IV PFN is given as

$$\widetilde{\pi}_L = \left[\sqrt{1-b^2-d^2}, \sqrt{1-a^2-c^2}\right] \tag{9}$$

Definition 4. *Let* $\widetilde{A} \cong [\mu_{\widetilde{A}L}, \mu_{\widetilde{A}U}], \left[\vartheta_{\widetilde{A}_L}, \vartheta_{\widetilde{A}_U}\right]$ and $\widetilde{B} \cong [\mu_{\widetilde{B}L}, \mu_{\widetilde{B}U}], \left[\vartheta_{\widetilde{B}_L}, \vartheta_{\widetilde{B}_U}\right]$ *be IV-PFNS, and $\lambda > 0$. The arithmetical operations of these IV PFNs are declared as follows:*

$$\widetilde{A} \oplus \widetilde{B} \cong \left[\sqrt{\mu^2_{\widetilde{A}_L} + \mu^2_{\widetilde{B}_L} - \mu^2_{\widetilde{A}_L}\mu^2_{\widetilde{B}_L}}, \sqrt{\mu^2_{\widetilde{A}_U} + \mu^2_{\widetilde{B}_U} - \mu^2_{\widetilde{A}_U}\mu^2_{\widetilde{B}_U}}\right], \left[\vartheta_{\widetilde{A}_L}\vartheta_{\widetilde{B}_L}, \vartheta_{\widetilde{A}_U}\vartheta_{\widetilde{B}_U}\right] \tag{10}$$

$$\widetilde{A} \otimes \widetilde{B} \cong \left[\mu_{\widetilde{A}_L}\mu_{\widetilde{B}_L}, \mu_{\widetilde{A}_U}\mu_{\widetilde{B}_U}\right], \left[\sqrt{\vartheta^2_{\widetilde{A}_L} + \vartheta^2_{\widetilde{B}_L} - \vartheta^2_{\widetilde{A}_L}\vartheta^2_{\widetilde{B}_L}}, \sqrt{\vartheta^2_{\widetilde{A}_U} + \vartheta^2_{\widetilde{B}_U} - \vartheta^2_{\widetilde{A}_U}\vartheta^2_{\widetilde{B}_U}}\right] \tag{11}$$

$$\lambda\widetilde{A} = \left[\sqrt{1-\left(1-\mu_{\widetilde{A}_L}\right)^{\lambda}}, \sqrt{1-\left(1-\mu_{\widetilde{A}_U}\right)^{\lambda}}\right], \left[\vartheta^{\lambda}_{L}, \vartheta^{\lambda}_{U}\right] \tag{12}$$

$$\widetilde{A}^{\lambda} = \left[\mu^{\lambda}_{\widetilde{A}_L}, \mu^{\lambda}_{\widetilde{A}_U}\right], \left[\sqrt{1-\left(1-\vartheta_{\widetilde{A}_L}\right)^{\lambda}}, \sqrt{1-\left(1-\vartheta_{\widetilde{A}_U}\right)^{\lambda}}\right] \tag{13}$$

2.3. Pythagorean Fuzzy AHP Method

The pseudo code of Pythagorean Fuzzy AHP (PF-AHP) method is given in Algorithm 1 as follows:

Algorithm 1. Pseudo representation of PF-AHP [25].

Input : n: number of groups, $(n = 1, \ldots, k)$
m : number of evaluation criteria, $(m = 1, \ldots, i)$
m^k_{ij} : linguistic comparison of i^{th} criterion over j^{th} criterion based on group k
Output: w^k_i : local weights of the criterion i based on group k
for $n \leftarrow 1$ **to** k **do**
Step 1:
Construct the linguistic pairwise comparison matrix (PCM) $\left(\widetilde{L} = \left(\widetilde{l}_{ij}\right)_{m\times m}\right) \Rightarrow$ Based on Table 1 *
Step 2: Check consistency ratio (CR) based on Saaty's algotithm [32].
$CR = \frac{CI}{RI}$
where CI is the consistency index and RI randomness index.
if $CR > 0.1$ **then**
return Step 1;
else
go Step 3;
end
Step 3:
Convert linguistic terms into corresponded IV PFNs $\left(\widetilde{R} = \left(\widetilde{r}_{ij}\right)_{m\times m}\right) \Rightarrow$ Based on Table 1 *

Step 4: Obtain the difference matrix $\left(D = \left(d_{ij}\right)_{m\times m}\right)$ by using the following equations :

$$d_{ij_L} = \mu^2_{ij_L} - \vartheta^2_{ijU}$$
$$d_{ij_U} = \mu^2_{ij_U} - \vartheta^2_{ij_L}$$

where $d_{ij} = \left(d_{ij_L}, d_{ij_U}\right)$.

Step 5: Calculate IMM $\left(S = \left(s_{ij}\right)_{m\times m}\right)$ by using the following equations :

$$s_{ij_L} = \sqrt{1000^{d_{ij_L}}}$$
$$s_{ij_U} = \sqrt{1000^{d_{ij_U}}}$$

Step 6: Obtain the indeterminacy value $\left(h_{ij}\right)$ by using the following equation :

$$h_{ij} = 1 - \left(\mu^2_{ij_U} - \mu^2_{ij_L}\right) - \left(\vartheta^2_{ij_U} - \vartheta^2_{ij_L}\right)$$

Step 7:

Multiply the indeterminacy degrees with $\left(S = \left(s_{ij}\right)_{m\times m}\right)$ matrix for finding the matrix of weights $\left(T = \left(t_{ij}\right)_{m\times m}\right)$ by using the following equation :

$$t_{ij} = \left(\frac{s_{ij_L} + s_{ij_U}}{2}\right)h_{ij}$$

Step 8: Find the priority weights (w^k_i) by using the following equation :

$$w^k_i = \frac{\sum_{j=1}^{m} w_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{m} w_{ij}}$$

end

*: To illustrate Saaty's consistency procedure, we converted linguistic terms to values in the traditional AHP scale [32].

The implemented scale for the linguistic terms is depicted in Table 1 as follows.

Table 1. Linguistic Scale for the IVPF-AHP method [32].

Linguistic Terms	IV PFNs
Certainly Low Important—CLI	<[0, 0, [0.9, 1]>
Very Low Important—VLI	<[0.1, 0.2], [0.8, 0.9]>
Low Important—LI	<[0.2, 0.35], [0.65, 0.8]>
Below Average Important—BAI	<[0.35, 0.45],[0.55, 0.65]>
Average Important—AI	<[0.45, 0.55],[0.45, 0.55]>
Above Average Important—AAI	<[0.55, 0.65],[0.35, 0.45]>
High Important—HI	<[0.65, 0.80], [0.2, 0.35]>
Very High Important—VHI	<[0.8, 0.9], [0.1, 0.2]>
Certainly High Important—CHI	<[0.9, 1], [0, 0]>

3. Application

In this section, based on available data, we adopted the PF-AHP method for the evaluation of drivers' behavior factors that directly affect road safety. In the following sub-sections, we present the data-gathering process, problem structure, and steps of the applied method.

3.1. Questionnaire Survey

There has been vital work performed to identify and resolve comportments that reduce driving safety. The Driver Behavior Questionnaire (DBQ) pushes for its endurance and leading employ among various implements [33,34]. To measure problematic driving behavior, DBQ was primarily created as an implement in connected studies in the 1990s [35]. Accordingly, DBQ pushes for their longevity and leading use to detect problematic driver behaviors.

The current research utilized the questionnaire survey designed on a fuzzy scale [20] to prioritize critical driver comportments connected to road safety using the PF-AHP method. A questionnaire survey was conducted as a data source that considered three automobile driver groups in the city of Budapest, Hungary. The first driver group (Group 1) included foreigners living in Hungary with a Hungarian driver license and adequate driving experience. Foreign citizens can get a driver's license if they have lived for six months in Hungary. A recent study stated that considerable regional differences exist in driving attitudes towards road safety issues [23]. Also, a previous study indicated that these differences should play an essential part in planning road safety policies and campaigns [36]. Previous studies have found that self-reported driving behaviors are related to both active and passive road accidents among drivers in different countries [37]. While the second group (Group 2) included experienced drivers with much more driving experience, the third group (Group 3) had young drivers with little driving experience. The study was conducted on 35 randomly nominated members of every driver group. The pattern size could be reflected as illustrative due to the phenomenon of "the wisdom of crowds", where assessors answer calculations representing their knowledge in an effective way. Solomon argued that when it comes to preference evaluations, even a relatively small group of people (over 20 members as a rule of thumb) can be representative because of the filtration of extreme opinions [38]. These members were asked to provide linguistic judgment data based on the specified questionnaire.

The questionnaire survey consisted of two parts: the first was implemented to obtain demographic data about the drivers who participated, and outcomes were presented in Table 2. The second part intended to estimate critical driver behavior criteria affecting road safety as presented in the conducted outcomes and discussion part.

Table 2. Sample features of evaluators [32].

Variables	Group G1	Group G2	Group G3
N	35	35	35
Age			
Mean	32.246	38.274	21.635
SD	5.641	3.672	2.737
Sex (1 = male, 0 = female)			
Mean	1.0	0.883	0.785
SD	0.0	0.353	0.317
Driving Experience			
Mean	3.523	17.326	1.852
SD	2.721	2.714	1.041
Driver Occupation (1 = job, 0 = student)			
Mean	0.912	1.0	0.361
SD	0.542	0.0	0.648

3.2. Driver Behavior Model

Driver attitude or behavior has been studied as one of the ultimate considerable factors for safe movement on the road. The main observed factors that forthrightly affected road safety were driving attitude, driving experience, and driver perception of road traffic hazards [8]. Reason et al. (1990) [39] proposed three types of driving behavior, i.e., lapses, errors, and violations, and investigated the connection between driving behavior and its involvement in accidents. Slips and lapses are inevitable when utmost caution is not exercised. Human error is an unintentional judgment or action. Violations are intentional failures—intentionally performing the wrong action. DBQ with elongated violations was recently used to evaluate aberrant driver behaviors [40–42]. The extended version of the DBQ incorporates aggressive and ordinary violations along with lapses and errors [43].

The current research considered that a well-proved driver behavior model [20] consists of 21 driver behavior items designed in a three-level hierarchical arrangement as presented in Figure 1. The first hierarchical level incorporates three main driver attitude criteria such as 'violations', 'lapses', and 'errors'. These main driver attitude criteria are broken down into related sub-criteria in the second hierarchical level. Level 2 further breaks down the two specified sub-criteria, 'ordinary' and 'aggressive' violations, into more sub-criteria. A summary of 20 studied driver behavior factors influencing road safety is stated in Table 3, which is assembled in three levels based on their characteristics. Table 3 also provides explanations for each factor, abbreviation, and associated reference.

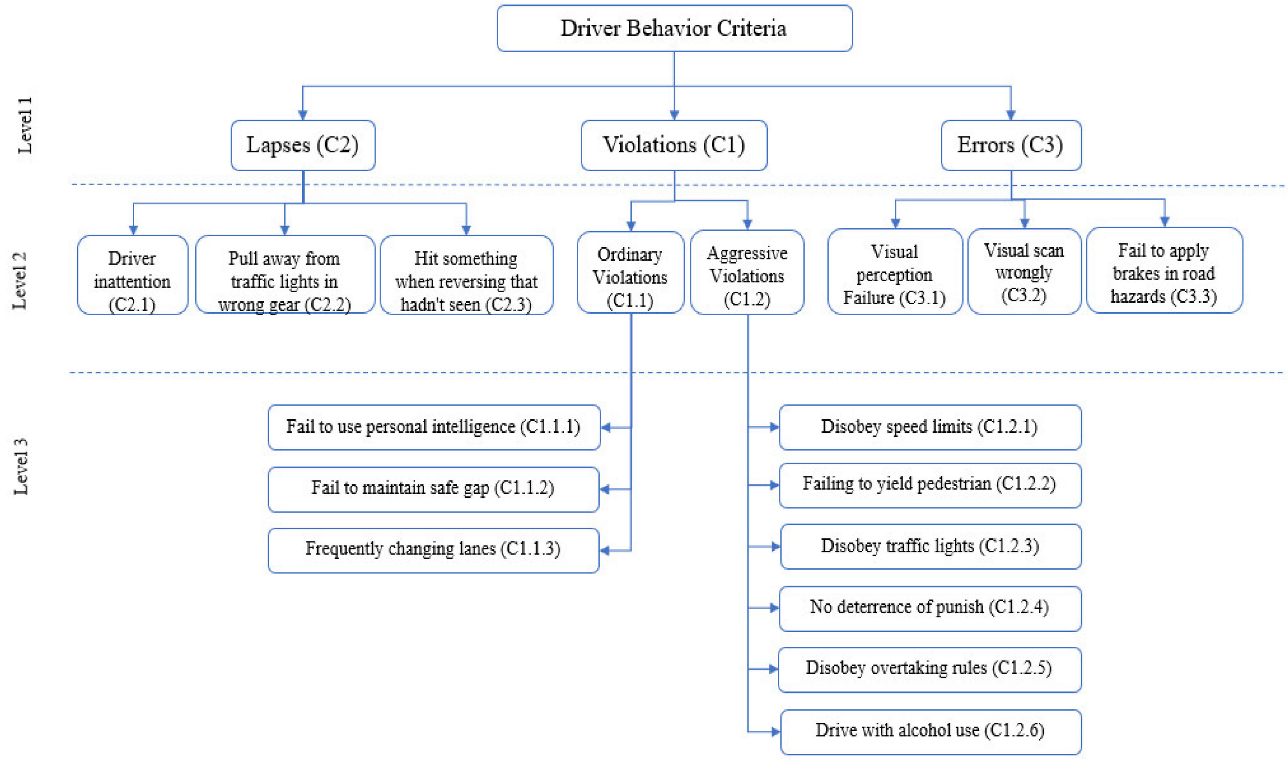

Figure 1. Driver behavior model [20].

Table 3. Presentation of driver behavior factors and abbreviations [20].

	Driver Behavior Factors	Importance for Road Safety
Level 1	Violations (C1)	Road Traffic Violations (RTVs) are the most serious, posing definite risk to other road users [44]
	Lapses (C2)	Lapses were observed as a predictor in crash involvement among other predictors in Qatar-based research [45]
	Errors (C3)	It has been noticed that both driving error and driving style are correlates of crash involvement [34]
Level 2	Ordinary violations (C11)	Previous study results observed the significance of ordinary violations as a correlation to accident involvement [34]
	Aggressive violations (C12)	Aggressive violations were found in critical correlation with crash involvement but alongside strong connection with ordinary violations [46]
	Driver inattention (C21)	Klauer et al. (2006) estimated that approximately 25–30% of traffic conflicts are associated with driver inattention, but argued that the true involvement of inattention may be as high 70% [47]
	Pull away from traffic lights in wrong gear (C22)	A UK-based study flagged "pull away from traffic lights in wrong gear" as aberrant driver behavior [48]
	Hit something that hadn't been seen when reversing (C23)	"Hit something that hadn't been seen when reversing" was measured highest with one other factor in factor analysis [49]
	Visual perception failure (C31)	Perception failure (both on the part of the rider and other road users) was inspected as the most typical factor in road crashes [50]
	Visual scan wrongly (C32)	Wide visual scanning is a significant component of safe driving [51]
	Fail to apply brakes in road hazards (C33)	"Hazard-based duration model" was introduced to examine the effects related to vehicle dynamic variables on driver's braking behavior [52]

Table 3. *Cont.*

	Driver Behavior Factors	Importance for Road Safety
Level 3	Fail to use personal intelligence (C111)	Intelligent transport system is facilitating a change in safety concentration to decrease the incidence of crashes [53]
	Fail to maintain safe gap (C112)	Gap acceptance was noticed as one of the most significant factors related to traffic safety at intersections [54]
	Frequently changing lanes (C113)	Risk exposure level specifies how long a subject vehicle is exposed to risky conditions that could probably lead to a crash while changing lanes [55]
	Disobey speed limits (C121)	Speeding is one of the most common and critical aberrant driving behaviors that negatively influence the safety of the violators themselves and the rest of the motorized public [56]
	Fail to yield to pedestrians (C122)	In terms of involving factors, 14.2% fatalities were attributed to failure to yield right of way at crossings [5]
	Disobey traffic lights (C123)	One of the most likely reasons for the high number of road crashes and injuries is due to beating traffic lights [57]
	No deterrence punishment (C124)	A 2016 meta-analysis specified that fine increases between 50% and 100% are related to a 15% decrease in traffic violations [58]
	Disobey overtaking rules (C125)	It was found that dangerous overtaking accounted for 41% of all drivers who died in traffic in 2006 [59]
	Drive with alcohol use (C126)	Even with a small amount of alcohol consumption, drivers are twice as likely to be involved in a traffic collision than when sober [60]

3.3. Steps of the Application

The application starts with the construction of PCMs based on hierarchy, which is given in Figure 1. As in Step 1, constructed PCMs by employing the scale presented in Table 1 for Group 1 are presented in Appendix A.

For the illustration of the methodology, main criteria evaluation with respect to objectives based on Group 1 judgments is given with all its steps.

For Step 2, consistency procedure based on Saaty's algorithm is applied to check the consistency ratio (CR) of the PCM. The matrix obtained after the transformation for the algorithm is depicted in Table 4:

Table 4. Converted PCM for consistency procedure.

wrt Goal	C1	C2	C3
C1	1	3	0.33
C2	0.33	1	0.2
C3	3	5	1

Since CR is calculated as 0.0334, we continue with the next step.

For Step 3, linguistic terms are converted and $\widetilde{R} = (\widetilde{r}_{ij})_{3\times3}$ is depicted in Table 5.

Table 5. $\widetilde{R} = \left(\widetilde{r}_{ij}\right)_{3\times3}$ matrix of the comparison.

wrt Goal	C1	C2	C3
C1	<[0.4, 0.55], [0.4, 0.55]>	<[0.5, 0.65], [0.3, 0.45]>	<[0.45, 0.3], [0.45, 0.5]>
C2	<[0.3, 0.45], [0.5, 0.65]>	<[0.4, 0.55], [0.4, 0.55]>	<[0.2, 0.35], [0.6, 0.75]>
C3	<[0.5, 0.65], [0.3, 0.45]>	<[0.6, 0.75], [0.2, 0.35]>	<[0.4, 0.55], [0.4, 0.55]>

For Step 4, the difference matrix $\left(D = (d_{ij})_{3\times3}\right)$ is computed as in Table 6.

Table 6. Difference matrix of the comparison.

wrt Goal	C1	C2	C3
C1	(−0.143, 0.143)	(0.048, 0.333)	(−0.333, −0.048)
C2	(−0.333, −0.048)	(−0.143, 0.143)	(−0.523, −0.238)
C3	(0.048, 0.333)	(0.238, 0.523)	(−0.143, 0.143)

For Step 5, interval multiplicative matrix (IMM) $\left(S = (s_{ij})_{3\times3}\right)$ is obtained after calculations as in Table 7.

Table 7. IMM of the difference matrix.

wrt Goal	C1	C2	C3
C1	(0.611, 1.636)	(1.178, 3.153)	(0.317, 0.849)
C2	(0.317, 0.849)	(0.611, 1.636)	(0.165, 0.44)
C3	(1.178, 3.153)	(2.271, 6.078)	(0.611, 1.636)

After finding the indeterminacy degrees in Step 6, the matrix of weights $\left(T = (t_{ij})_{3\times3}\right)$ is constructed which is given in Table 8.

Table 8. Matrix of weights.

Criterion	Weight
C1	2.77
C2	1.44
C3	5.34
Sum	9.54

For the last step of the PF AHP, the weights obtained in Step 7 are normalized and the local weights are calculated. The outcomes are presented in Table 9.

Table 9. Weights of the main criteria based on Group 1 judgments.

C1	0.29
C2	0.15
C3	0.56

4. Results and Discussion

The PF-AHP method can be recommended for all decision support systems in which layman evaluators measure the fundamentals of the decision system, mostly in methods where pairwise comparisons are adopted. In addition, the proposed model allows experts to better understand the whole assessment procedure. This consequence has been proved by our survey data. The proposed integrated process could help decision-makers focus on high-ranked critical factors affecting road safety to fulfill the criteria for sustainable transport system. Through the applied algorithm for each comparison matrix, the outcomes of the application are calculated (Table 10).

For a broader analysis, for driver Group 1 the application outcomes indicated the criterion 'errors' (C3) as the ultimate critical factor connected to road safety for the first level of structure. In the same way, the criterion 'lapses' (C2) was determined as the least effective factor based on the outcomes. Instead of Group 1, the criterion 'lapses' (C2) obtained the first rank as the ultimate effective criterion. Through the evaluation of all groups, the criterion 'lapses' (C2) was determined as the ultimate effective Level-1 criterion. For Level 2, application outcomes depicted 'failure to apply brakes in road hazards' (C33) as the ultimate crucial factor, followed by 'ordinary violations' (C11), while 'pull away from traffic lights in the wrong gear' (C22) was noticed as the least critical factor in comparison with others. For Level 3, application outcomes showed 'fail to maintain a safe gap' (C112) as the ultimate critical factor followed by 'fail to use personal intelligence' (C111) while application outcomes found 'disobey overtaking rules' (C121) as the least critical criteria based on measured weight scores.

Table 10. Outcomes of the application.

G1			G2			G3			Aggregated Weight	
Criterion	**Local Weight**	**Global Weight**	**Criterion**	**Local Weight**	**Global Weight**	**Criterion**	**Local Weight**	**Global Weight**	**Criterion**	**Final Weight**
C1	0.290	0.290	C1	0.206	0.206	C1	0.175	0.175	C1	0.224
C2	0.151	0.151	C2	0.397	0.397	C2	0.650	0.650	***C2***	***0.399***
C3	0.559	0.559	C3	0.397	0.397	C3	0.175	0.175	C3	0.377
C11	0.788	0.229	C11	0.123	0.025	C11	0.212	0.037	C11	0.097
C12	0.212	0.062	C12	0.877	0.181	C12	0.788	0.138	C12	0.127
C111	0.290	0.066	C111	0.151	0.004	C111	0.397	0.015	C111	0.028
C112	0.559	0.128	C112	0.559	0.014	C112	0.206	0.008	C112	0.050
C113	0.151	0.034	C113	0.290	0.007	C113	0.397	0.015	C113	0.019
C121	0.039	0.002	C121	0.031	0.006	C121	0.034	0.005	C121	0.004
C122	0.145	0.009	C122	0.117	0.021	C122	0.058	0.008	C122	0.013
C123	0.145	0.009	C123	0.225	0.041	C123	0.241	0.033	C123	0.028
C124	0.095	0.006	C124	0.033	0.006	C124	0.125	0.017	C124	0.010
C125	0.039	0.002	C125	0.059	0.011	C125	0.078	0.011	C125	0.008
C126	0.537	0.033	C126	0.535	0.097	C126	0.464	0.064	C126	0.065
C21	0.559	0.084	C21	0.313	0.124	C21	0.559	0.364	C21	0.191
C22	0.151	0.023	C22	0.084	0.033	C22	0.151	0.098	C22	0.051
C23	0.290	0.044	C23	0.603	0.239	C23	0.290	0.189	C23	0.157
C31	0.109	0.061	C31	0.191	0.076	C31	0.109	0.019	C31	0.052
C32	0.227	0.127	C32	0.099	0.039	C32	0.227	0.040	C32	0.069
C33	0.664	0.371	C33	0.710	0.282	C33	0.664	0.116	C33	0.256

For driver Group 2, application outcomes depicted 'lapses' (C2) and 'errors' (C3) as the ultimate critical factor connected to road safety for the first level of hierarchical structure while 'violations' (C1) was observed as the least critical factor based on measured weight scores. For Level 2, application outcomes showed 'fail to apply brakes in road hazards' (C33) as the ultimate critical factor, followed by 'hit something that had not been seen when reversing' (C23), while 'ordinary violations' (C11) were observed as the least critical factor as compared to others. For Level 3, application outcomes showed 'drive with alcohol use' (C126) as the ultimate critical factor, followed by 'disobey traffic lights' (C123), and 'fail to use personal intelligence' (C111) as the least critical criteria based on measured weight scores.

For driver Group 3, outcomes depicted 'lapses' (C2) as the ultimate critical factor connected to road safety for the first level of hierarchical structure while 'violations' (C1) and 'errors' (C3) were observed as the least critical factors based on measured weight scores. For Level 2, 'driver inattention' (C21) was found to be the ultimate critical factor, followed by 'hit something that had not been seen when reversing' (C23), while 'visual perception failure' (C31) was observed as the least essential fact as compared to other specified factors. For Level 3, application outcomes showed 'drive with alcohol use' (C126) as the ultimate critical factor, followed by 'disobey traffic lights' (C123), while application outcomes found 'disobey overtaking rules' (C121) as the least critical criteria based on measured weight scores.

Based on aggregated weights, the criterion 'lapses' (C2) was found to be the ultimate critical factor connected to road safety. Previous outcomes of the factor analysis depicted that mostly lapses elements loaded on errors, which was a combination of lapses and errors and some violation elements [61]. The criteria 'fail to apply brakes in road hazards' (C33), 'violations' (C1), 'driver inattention' (C21), and 'aggressive violations' (C12) were also found to be major risks due to high weight scores. However, the criterion 'disobey speed limits' (C121) was found to be the least critical factor as compared to other observed factors while 'disobey overtaking rules' (C125) was observed as the second-least critical factor connected to road safety. A previous questionnaire-based study found that Budapest drivers were less compliant with speed limits [62], while a recent study observed the complex relationships of significant driver behavior factors related to road safety in decision-making, which aids in consequently improving the consistency of decisions for sustainable traffic safety. Linkage of research data with transport authorities and traffic management agencies could aid in implementing effective road safety plans and increasing the sustainable level of traffic safety [20]. Some of the improvements that a city can make for establishing a sustainable transport system and decreasing traffic accidents are setting high standards of training for public transit drivers, ensuring compliance to safe operation measures, establishment of safe crosswalks and other pedestrian infrastructure, conducting a safety audit of the road network, and setting up dedicated lanes for public transit buses [13].

4.1. Comparative Analysis

Optimism and pessimism are basic personal–psychological attributes that both define and indicate how a person reacts to his or her professed environment. Optimists interpret their lives and future conditions of the world positively, while pessimists interpret their lives and future conditions of the world depressingly. Similarly, optimists think in terms of high overall efficacy and promising results, but pessimists think in terms of less overall efficacy and undesirable results [63]. Psychology indicates that in a core network, dispositional optimism mechanism allows for evolving coping behavior or habits that are more expected to lead to anticipated results [64,65].

In the interpretation of multi-criteria decision-making issues, optimism and pessimism can imitate individual variances of different decision makers. Besides, they manage to be both dependable and durable. It shows that optimism and pessimism reliably impact how the decision maker responds to a decision environment. Hence, an understanding of their impact on the decision-making procedure is very useful and valuable in multiple criteria decision study [63]. In our application, driver behavior factors and sub-factors are evaluated based on the no-dependency-among-themselves situation. Through that, the PF-AHP method is performed. For a comparison of the outcomes, we develop pessimistic estimations based on the DEMATEL technique, where pessimism is measured using pessimistic point operators. With a pessimistic attitude, driver behavior factors and sub-factors affect each other and cause high-risk driver behavior, affecting road safety. Through the outcomes of DEMATEL, dependencies are determined and a network of criteria is constructed. Then, based on the dependencies, pairwise comparison matrices are re-constructed. Based on the results of re-constructed pairwise comparison matrices, a supermatrix is constructed and then converged to obtain the new weights of driver behavior criteria connected to road safety. Two academicians who are experts in human behavioral effects on traffic safety evaluate the criteria for the Pythagorean DEMATEL method. Based on the evaluations, dependencies are determined (Appendix B).

Based on the dependencies, the network of criteria and pairwise comparison matrices are constructed. Since there is no dependency between C11 and C12 with any other criteria, they are evaluated out of the network separately. Based on the calculations, the weights of the criteria are calculated as in Table 11.

Table 11. Weights of the Level-2 criteria based on the constructed network.

Criteria	Weight
C21	0.54
C22	0.42
C23	0.04
C31	0.09
C32	0.21
C33	0.7

For Level-3 criteria, weights are calculated as in Table 12.

Table 12. Weights of the Level-2 criteria based on the constructed network.

Criteria	Weight
C111	0.24
C112	0.5
C113	0.26
C121	0.02
C122	0.06
C123	0.09
C124	0.08
C125	0.03
C126	0.72

Through the results, the most important criteria remain the same at each level. Moreover, C11 and C12 are not evaluated with respect to Level-2 criteria network since they have no dependency on any Level-2 criteria.

4.2. Sensitivity Analysis

The reliability of the model is supported by sensitivity analyses that observe a range for the weights' values and are consistent with alternative outcomes. One-at-a-time sensitivity analyses are also applied to observe the shifts in all levels. The analyses are based on group dominance. For each group, weights are assigned, and then the shifts are observed. The pattern for the analyses is given in Table 13:

Table 13. Sensitivity analysis pattern.

Weight of the Dominance Group	In Case of G1 is Dominant and Other Groups Are Equal Weighted	In Case of G2 is Dominant and Other Groups Are Equal Weighted	In Case of G3 is Dominant and Other Groups Are Equal Weighted
	Obtained Weights of the Criteria		
0.4	New weights of the criteria	…	…
0.5	⋮	⋱	…
0.6	⋮	⋱	…
0.7	⋮	⋱	…
0.8	…	…	…

We first check Level 1, which is for the main criteria. Figure 2 presents the shifts with respect to weight changes of the groups.

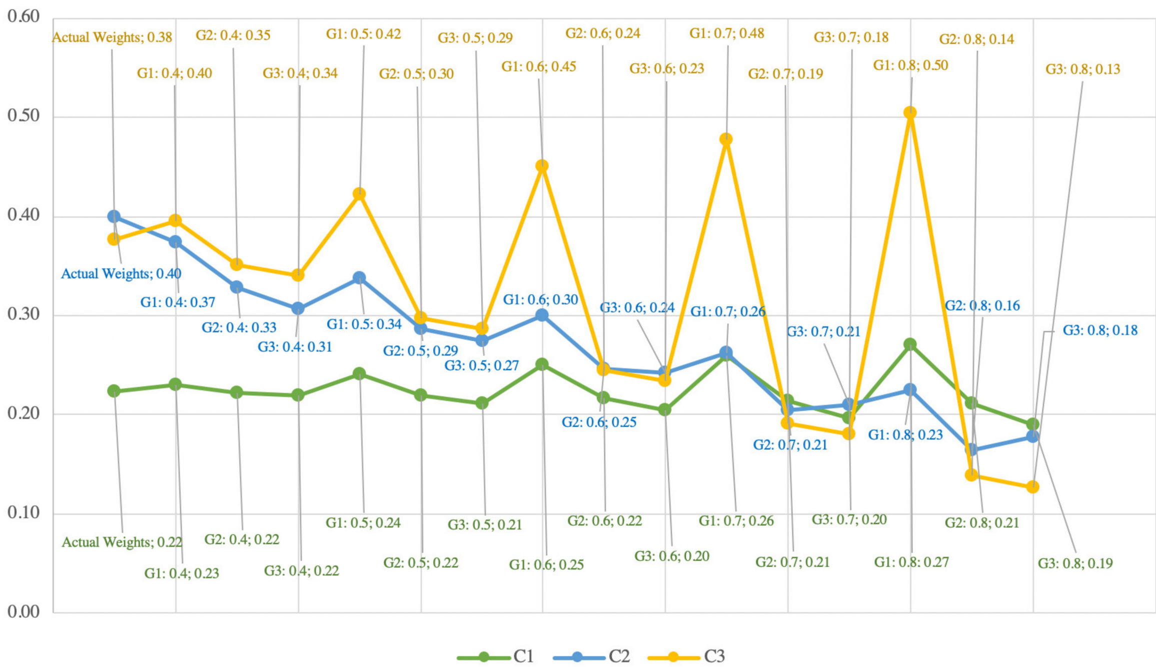

Figure 2. Weights of Level-1 criteria with respect to changes.

To visualize more clearly, the weights of the groups are multiplied by 10. As it can be seen from Figure 2, criterion C1 has small changes for each group. It is also deduced that its weight is the ultimate consistent when compared with other criteria over each group's dominance. For criterion C2, it staidly decreases against other criteria while the weights of the groups increase. Criterion C3 fluctuates most based on the changes. Moreover, when the dominance group is Group 1, criterion C3 has the highest weight when compared with other criteria. Also, in all levels of weights for the groups, Group 1 affects criteria at most. As a result of this analysis, one infers that C1 has the maximum consensus level. The groups are assigned approximate values when they evaluate it. In the same way, C3 criterion has the ultimate fluctuated values during evaluation. For further research, we believe that more focus groups are needed to evaluate the C3 criterion.

Secondly, the pattern is applied to Level-2 criteria. Figure 3 presents the shifts with respect to weight changes of the groups.

At first, as a result of the application, criterion C33 has the highest weight and criterion while C22 has the lowest. During the sensitivity analysis, the ranks are mostly preserved except for some shifts. Criterion C33 is affected most when it is compared with other criteria. Its peak points are obtained when the weights of Group 2 are equal to 0.5 and 0.7, respectively. Criterion C33 and criterion C21 are almost converged while the weights of Group 1 equal 0.7. Moreover, they have approximate values in the below situations:

Group 1 weight is equal to 0.6, therefore Group 2 and Group 3 are equal to 0.20.

Group 1 weight is equal to 0.7, and the others are 0.15.

Group 2 weight is equal to 0.6, and the others are 0.20.

Group 3 weight is equal to 0.5, and the others are 0.25.

Group 3 weight is equal to 0.6, and the others are 0.20.

In addition, C11 has the second rank when the weight of Group 2 is equal to 0.5. However, after that level, it tends to fall. The ultimate constant criteria among Level-2 criteria are criterion C31 and criterion C22. During the pattern, their values are the least affected criteria. Their evaluation for the group is mostly converged.

Lastly, we also check the effects of the groups for Level 3. Figure 4 presents the shifts with respect to weight changes of the groups.

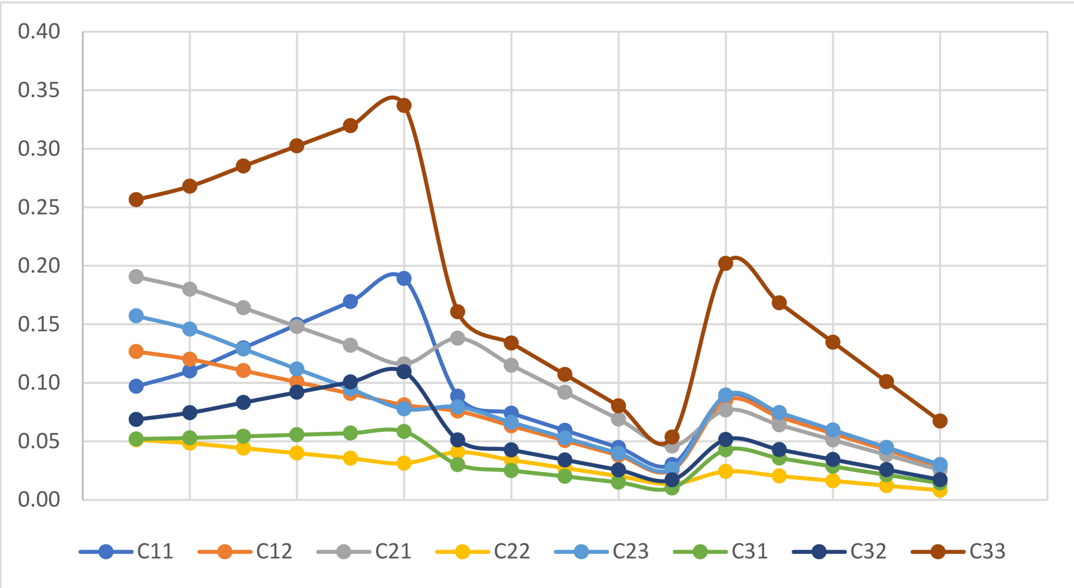

Figure 3. Weights of Level-2 criteria with respect to changes.

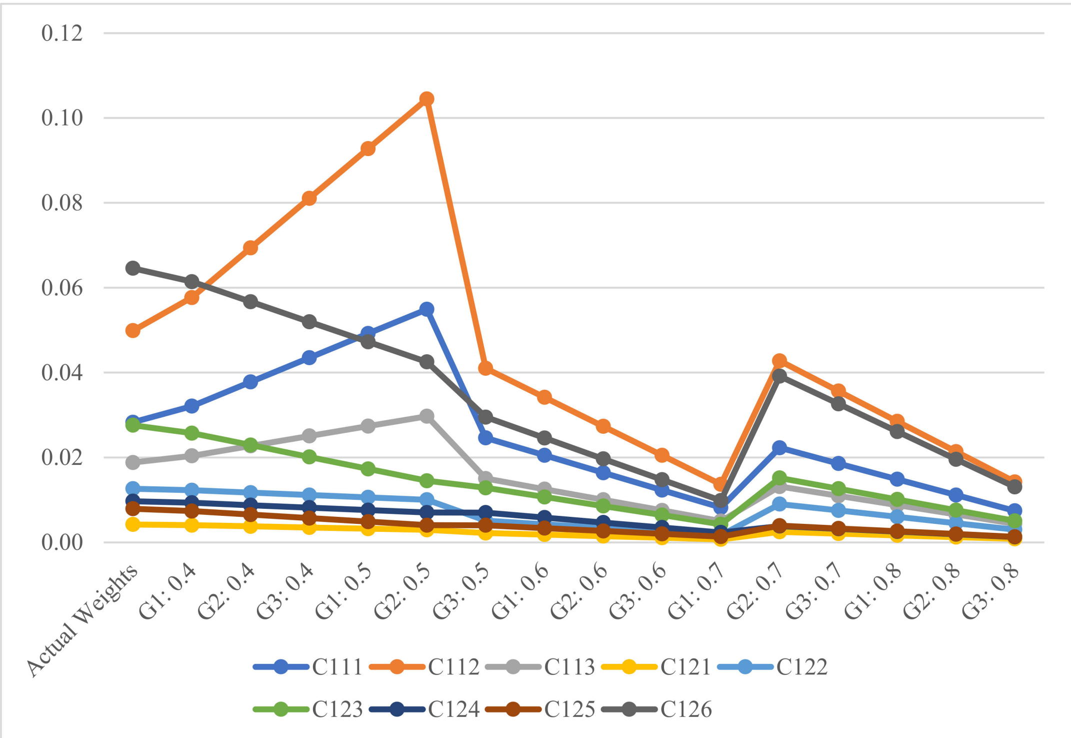

Figure 4. Weights of Level-3 criteria with respect to changes.

In third-level analysis, since the weights are mostly less than 0.1, shifts are fewer than other levels. When the weights of the groups are increased, criterion C112 moves into first place and has the maximum weight among Level-3 criteria. The two peak points are reached when the weights of Group 2 are equal to 0.5 and 0.7. Moreover, when Group 1 and Group 2 weights are equal to 0.5, C111 moves to second rank. Since the weights of C121, C122, C124, and C125 are small values, the dominance of the groups over them is affected slightly.

Through the analyses, it is observed that all PCMs are sensitive to changes in group weights. Since the ultimate effective criteria have remained in most cases, it can be said that the result of the application is reliable against variations in main criteria weights.

5. Conclusions

The consistency and, conversely, conflicts in driver behavior factors inducing crash risk may alternate due to different driving characteristics. The PF-AHP method is a useful evaluation to overcome uncertainty of driver behavior in managing complex road safety issues. For driver group G1, application outcomes depicted 'errors' (C3) as the ultimate critical factor connected to road safety for Level 1 of the hierarchical model. For Level 2, the application outcomes showed 'fail to apply brakes in road hazards' (C33) as the ultimate critical factor, followed by 'ordinary violations' (C11). For Level 3, application outcomes showed 'fail to maintain a safe gap' (C112) as the ultimate critical factor followed by 'fail to use personal intelligence' (C111). For driver group G2, application outcomes showed 'lapses' (C2) and 'errors' (C3) as the ultimate critical factor connected to road safety for Level 1 of the hierarchical structure. For Level 2, application outcomes showed 'fail to apply brakes in road hazards' (C33) as the ultimate critical factor followed by 'hit something that had not been seen when reversing' (C23). For Level 3, application outcomes showed 'drive with alcohol use' (C126) as the utmost critical factor followed by 'disobey traffic lights' (C123).

For driver group G3, application outcomes showed 'lapses' (C2) as the most critical factor connected to road safety for Level 1 of the hierarchical model. For Level 2, application outcomes showed 'driver inattention' (C21) as the utmost critical factor followed by 'hit something that had not been seen when reversing' (C23). For Level 3, application outcomes showed 'drive with alcohol use' (C126) as the uttermost critical factor followed by 'disobey traffic lights' (C123). Based on aggregated weights, the criteria 'lapses' (C2) is the most critical factor connected to road safety as compared to all other specified factors. The criterion 'disobey speed limits' (C121) is found to be the least critical factor as compared to other observed factors. This evaluation could be valuable in making drivers aware of individual traffic risks for each country. Linkage of estimated data with traffic authorities may also assist in the implementation of effective local road safety policies.

Since our system has presented meaningful outcomes based on calculations we made, it can be a useful decision-making support technique to deal with uncertain data. Researchers and policymakers can implement our model to obtain robust outcomes that are backed by sensitivity analyses.

For further studies, data can be extended by adding new surveys from cities that have a similar social background [66]. Comparison of different data sets can enable us to extend this work to construct proactive behavioral systems. Moreover, a new section of questionnaires can be added to measure indeterminacy. As a new uncertainty characteristic needs to be overcome through the calculations, neutrosophic or hesitant sets can be applied to handle it [67–69] while other significant elements of the transport system, such as vehicles, road infrastructure, and the environment, should be studied dynamically for achieving sustainable development goals.

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Institutional Review Board Statement: This survey by the Department of Transport Technology and Economics at Budapest University of Technology and Economics conducts a study on 'Estimating Driver Behavior Measures Related to Traffic Safety by Investigating 2-Dimensional Uncertain Linguistic Data—A Pythagorean Fuzzy Analytic Hierarchy Process Approach'. The principal intention of this work is to identify and rank the nominated significant factors and sub-factors influencing road safety based on participants' answers on a specified questionnaire survey. This survey is for academic research only, does not participate in any business activity, and does not reveal any personal information. The questionnaire survey data were collected from professionals of the above-specified department through online Google forms. The motives/aims of the survey were told to respondents. They were also assured about their anonymity and the confidentiality of their responses. Their participation was absolutely voluntary, and they were not compensated in any way.

Informed Consent Statement: Not applicable.

Data Availability Statement: Please contact the corresponding author.

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

Appendix A

Table A1. Constructed PCMs based on Group 1 judgments.

			Group 1			
wrt Goal	C1	C2	C3			
C1	AI	AAI	BAI			
C2	BAI	AI	LI			
C3	AAI	HI	AI			
wrt C1	C11	C12				
C11	AI	HI				
C12	LI	AI				
wrt C2	C21	C22	C23			
C21	AI	HI	AAI			
C22	LI	AI	BAI			
C23	BAI	AAI	AI			
wrt C3	C31	C32	C33			
C31	AI	BAI	VLI			
C32	AAI	AI	BAI			
C33	VHI	AAI	AI			
wrt C11	C111	C112	C113			
C111	AI	BAI	AAI			
C112	AAI	AI	HI			
C113	BAI	LI	AI			
wrt C12	C121	C122	C123	C124	C125	C126
C121	AI	LI	LI	BAI	AI	CLI
C122	HI	AI	AI	AAI	HI	LI
C123	HI	AI	AI	BAI	HI	LI
C124	AAI	BAI	AAI	AI	AAI	VLI
C125	AI	LI	LI	BAI	AI	CLI
C126	CHI	HI	HI	VHI	CHI	AI

Table A2. Constructed PCMs based on Group 2 judgments.

			Group 2			
wrt Goal	C1	C2	C3			
C1	AI	BAI	BAI			
C2	AAI	AI	AI			
C3	AAI	AI	AI			
wrt C1	C11	C12				
C11	AI	VLI				
C12	VHI	AI				
wrt C2	C21	C22	C23			
C21	AI	HI	BAI			
C22	LI	AI	VLI			
C23	AAI	VHI	AI			
wrt C3	C31	C32	C33			
C31	AI	AAI	LI			
C32	BAI	AI	VLI			
C33	HI	VHI	AI			
wrt C11	C111	C112	C113			
C111	AI	LI	BAI			
C112	HI	AI	AAI			
C113	AAI	BAI	AI			
wrt C12	C121	C122	C123	C124	C125	C126
C121	AI	LI	VLI	AI	BAI	CLI
C122	HI	AI	BAI	HI	AAI	LI
C123	VHI	AAI	AI	HI	HI	BAI
C124	AI	LI	LI	AI	BAI	CLI
C125	AAI	BAI	LI	AAI	AI	CLI
C126	CHI	HI	AAI	CHI	CHI	AI

Table A3. Constructed PCMs based on Group 3 judgments.

			Group 3
wrt Goal	C1	C2	C3
C1	AI	LI	AI
C2	HI	AI	HI
C3	AI	LI	AI
wrt C1	C11	C12	
C11	AI	LI	
C12	HI	AI	
wrt C2	C21	C22	C23
C21	AI	HI	AAI
C22	LI	AI	BAI
C23	BAI	AAI	AI

Table A3. *Cont.*

Group 3						
wrt C3	C31	C32	C33			
C31	AI	BAI	VLI			
C32	AAI	AI	BAI			
C33	VHI	AAI	AI			
wrt C11	C111	C112	C113			
C111	AI	AAI	AI			
C112	BAI	AI	BAI			
C113	AI	AAI	AI			
wrt C12	C121	C122	C123	C124	C125	C126
C121	AI	BAI	VLI	LI	BAI	CLI
C122	AAI	AI	LI	BAI	BAI	VLI
C123	VHI	HI	AI	AAI	HI	BAI
C124	HI	AAI	BAI	AI	AAI	LI
C125	AAI	AAI	LI	BAI	AI	VLI
C126	CHI	VHI	AAI	HI	VHI	AI

Appendix B

Table A4. Dependencies of the criteria.

Level-2 Criteria									
	C21	C22	C23	C11	C12	C31	C32	C33	
C21	0	1	0	0	0	0	1	1	
C22	1	0	0	0	1	1	1	1	
C23	0	0	0	0	s0	0	1	0	
C11	0	0	0	0	0	0	0	0	
C12	0	1	0	0	0	0	1	1	
C31	0	1	0	0	0	0	1	1	
C32	1	1	1	0	1	1	1	1	
C33	1	1	0	0	1	1	1	1	
Level-3 Criteria									
	C111	C112	C113	C121	C122	C123	C124	C125	C126
C111	0	0	0	0	0	0	0	0	1
C112	0	0	0	0	0	0	0	0	1
C113	0	1	0	1	0	0	1	1	1
C121	0	0	1	0	1	1	1	0	1
C122	0	0	0	1	0	1	1	1	1
C123	0	0	0	0	1	0	1	0	1
C124	1	1	1	1	1	1	1	1	1
C125	0	0	0	0	0	1	1	0	1
C126	1	1	1	1	1	1	1	1	1

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