sustainability

MDPI

Article

Evaluation of the Environmental Effect of Automated Vehicles Based on IVIULWG Operator Development

Shuang Kan, Wei Lyu * and Shiyu Zhao

School of Business Administration, Northeastern University, Shenyang 110169, China
* Correspondence: lvweineu@stumail.neu.edu.cn; Tel.: +86-139-4020-4363

Abstract: The automated vehicle (AV) industry is a new growing industry of great interest. The environmental friendliness of AVs represents a core characteristic of their leap-forward development. The environmental effect of AVs, including its evaluation framework and algorithm, is a leading research area for continued technological innovation and market development in this field. This study focuses on three environmental aspects: the energy effect of AVs, the traffic effect of AVs on ground space, and the air effect of AVs on three-dimensional atmospheric space. First, an environmental effect evaluation indicator system that includes nine indices for AVs is constructed to be the basis for management decision making. Second, the interval-valued intuitionistic uncertain fuzzy (IVIUF) evaluation variable is used to solve the problem of data features that incorporate "crisp numbers" and "fuzzy numbers". Moreover, geometric weights are added based on the generalized correlation aggregation operator. Then, the IVIUL-weighted geometric (IVIULWG) operator is developed, which includes the objective and subjective information of "crisp numbers" and "fuzzy numbers" and makes the mathematical characteristics more scientific and accurate. Finally, an evaluation example is used to validate the effectiveness and practicability of the algorithm.

Keywords: automated vehicles; environmental effect; interval-valued intuitionistic uncertain linguistic-weighted geometric (IVIULWG); multi-criteria evaluation

check for updates

Citation: Kan, S.; Lyu, W.; Zhao, S. Evaluation of the Environmental Effect of Automated Vehicles Based on IVIULWG Operator Development. *Sustainability* **2022**, *14*, 9669. https://doi.org/10.3390/su14159669

Academic Editor: Peng Jing

Received: 15 June 2022
Accepted: 4 August 2022
Published: 5 August 2022

1. Introduction

With the acceleration of intelligence in human society in the context of new energy in recent years, the development and deployment of automated vehicles (AVs) have become a new focus of investment, both by governments and enterprises. Currently, major vehicle manufacturers and technology giants are developing and testing AVs [1]. Traditional vehicle enterprises, such as Audi, BMW, Ford, Volkswagen, General Motors, and Toyota, have gradually experienced an evolutionary development path, from Level 0 (No Driving Automation) to Level 2 (Partial Driving Automation) and then to Levels 4 and 5 (High-Level Automation and Full Automation, respectively) [2]. However, some technology giants, such as Apple, Google, and Baidu, have adopted a revolutionary approach, in which they make full use of their technological advantages to directly develop Level 4 and 5 AVs. Some scholars have predicted that Level 4 and 5 AVs will see commercial use on a large scale in the next 10 to 30 years [3] and will contribute to 50% of total vehicle sales in 2040 [4]. Simultaneously, with the rapid development of artificial intelligence and navigation and communication technologies, the AV industry has become a new growing industry of great interest around the world, and the number of related studies has grown exponentially [5]. In terms of research content and methods, there is a trend of pluri-disciplinary cross-sectional studies, for example, on traffic safety, energy structure, environmental protection, and economic growth [6].

The latest research report issued by Securing America's Future Energy (SAFE) revealed the effect of autonomous driving on the future economy and labor market. The academic community has also engaged in an increasing number of in-depth discussions on the environmental friendliness of AVs from the perspectives of technology and management. The environmental friendliness of AVs is claimed and expected to be a core characteristic of their leap-forward development over conventional vehicles (CVs). From the perspective of management decision research, the evaluation framework of the environmental effect of AVs and its evaluation algorithm are a pilot study to regulate technological innovation and market development in this field. Scholars have studied the environmental effect of AVs based on different disciplines, research purposes, and dimensions. A great deal of research has emerged from independent and discrete perspectives and differs in its conclusions. With respect to the effect of AVs on traffic conditions, many scholars agree that the widespread deployment of AVs can reduce the incidence of traffic accidents and jams. For example, Bagloee et al. (2016) indicated that without inducing additional demand, AVs can reduce traffic congestion and improve traffic efficiency by reducing traffic accidents and through intelligent planning and high-speed cruising [7]. However, some researchers have drawn opposite conclusions; for example, AVs can improve the mobility of the elderly, unlicensed, and disabled people in addition to adolescents who are not able to drive CVs [8]. This may lead to an increase in the demand for AVs or in vehicle miles traveled (VMT) [9] and a further increase in the number of vehicles running on the road system, with no significant improvements in easing traffic congestion.

Regarding the other dimensions of the environmental effect of AVs, such as fuel saving and air pollution, scholars have highlighted air quality improvement indicators on which AVs directly act. Some scholars have indicated that AVs act on greenhouse gases (GHGs), which can be cut by 40 to 60% [10]. Other scholars have indicated that AVs act on CO_2 emissions and have obtained predicted results of CO_2 emissions being cut by 7 to 20% in one study [11] or by 87 to 94% in another study [12]. It seems that the conclusions drawn by different researchers vary a great deal and are somewhat arbitrary. Overall, the status of these studies indicates that an evaluation system to determine the environmental effect of AVs has not yet been formed. Thus, the basis of this study is to establish a scientific evaluation system that incorporates the results of multiple disciplines and that reflects the structural scientificity of environmental effect evaluation.

There is a small number of studies in which evaluation algorithms have been used to assess the effect of AVs. For example, Dogan et al. (2020) adopted a fuzzy decision-making model that combines AHP and TOPSIS with intuitionistic fuzzy sets (IFS) to solve the corridor selection problem that occurs when AVs are used as a means of transport [13]. Bakioglu and Atahan (2021) proposed a new hybrid multi-criteria decision-making (MCDM) method based on a combination of AHP and TOPSIS in a Pythagorean fuzzy environment to address the AV-related risk priority problem [14]. Regarding the difficulty of the current research, the road testing of AVs has not been extensively conducted, and there is a lack of simulation data on AVs. There has been a lack of academic attention and algorithms to evaluate the environmental effect of AVs comprehensively. Moreover, in addition to some quantifiable "crisp numbers" (e.g., CO_2 emissions), there is a large number of "fuzzy numbers" with irregular semantics (e.g., traffic congestion alleviation). The development of algorithms and technologies that can simultaneously retain and maximize the retention of the two original types of information is urgently required. Simultaneously, AVs are still undergoing simulation experiments, and the information on industrial technologies and development platforms is ever changing. Their elastic and scalable application should be taken into account in algorithm research.

In this study, to address the above-mentioned issues, an evaluation indicator system to determine the environmental effects of autonomous vehicles is constructed. Based on this, interval-valued intuitionistic uncertain linguistic fuzzy (IVIUF) numbers are used to study the evaluation. The main contributions of this study are as follows: methods are developed to combine crisp numbers and fuzzy numbers as well as two-level status data and intermediate state data in the evaluation. Ordered weighted averaging aggregation operators are introduced to multi-criteria decision making, and the interval-valued intuitionistic uncertain linguistic-weighted geometric (IVIULWG) operator is developed to ensure the fuzzy attribute of crisp numbers in IVIUF research; otherwise, the weighted arithmetic average would become a simple arithmetic average of the S values. Hence, the expected values of the calculation results have more comprehensive attributes.

This study is structured as follows: First, research on the environmental effect of AVs is introduced. In Section 2, the environmental effect and evaluation criteria of AVs are provided, and an evaluation indicator system is built to improve the basis for management decision making and industrial development. Section 3 relates to evaluation algorithm development. In this paper, the interval-valued intuitionistic uncertain linguistic (IVIUL) information (IVIUL semantics) form is used to solve the problem of data features that describe the coexistence of "crisp numbers" and "fuzzy numbers" based on correlation transformation. Geometric weights are added to maximize the retention of the objective and subjective evaluation interval information of "crisp numbers" and "fuzzy numbers. Additionally, the IVIUL-weighted geometric (IVIULWG) operator is developed. Based on an example of the IVIULWG operator, in Section 4, the effectiveness and practicability of the algorithm are validated. Finally, the conclusions and future work are presented in the last section. The research in this paper on the comprehensive evaluation of the environmental effects of AVs provides a practical reference that will enable the government (policy makers) to predict and pre-evaluate the environmental effects of AVs through the formulation of a related indicator system and the establishment of an algorithm in the context of the rapid development and upcoming arrangement of AVs to help the implementation of market access and emission regulation. Additionally, this research can be extended to include uncertainties about the environmental effects of future AVs [15].

2. Construction of the Environmental Effect Evaluation Indicator System for AVs

Environmental effects refer to changes in the structures and functions of environmental systems caused by human activity or natural processes. According to the nature of environmental changes, environmental effects can be divided into environmental biological effects, environmental chemical effects, and environmental physical effects. This study focuses on the environmental physical effects of AVs. A review of relevant literature is conducted. Additionally, the sources of interaction for AVs and their environmental physical effects as well as the spatial stratification of the environment are taken into account to construct an environmental effect evaluation indicator system for AVs from the perspectives of the environmental effects (or energy effects) of AVs, the environmental effects of AVs on ground space (or traffic effects), and the environmental effects of AVs on three-dimensional atmospheric space (or air effects). Meanwhile, when indicators are selected, there is full consideration of the development direction of science and technology for AVs based on the industrial technology service platform as well as on policy regulation tendencies.

2.1. Traffic Environment

(1) Safety and crashes

Currently, there are approximately 1.35 million deaths caused by road traffic accidents around the world each year. Traffic accidents are mainly considered to be caused by the human error of drivers. In the United States alone, if road traffic accidents were cut by 1%, USD 800 million could be saved each year [16]. Research by the Federal Highway Administration showed that 25% of traffic congestion arises from traffic accidents, and the share of collision accidents is close to 50% [17]. Researchers have reported that by eliminating the human error of drivers, AVs can lower the incidence of traffic accidents by over 33% or even 90%. For AVs, although opinions differ on the potential improvement for traffic accidents under existing regulations, securing on-board passengers and other road users who interact with AVs is a precondition for improving the environmental friendliness of AVs.

(2) Traffic efficiency

The research roadmap for the improvement of traffic efficiency by AVs is mainly sourced from two perspectives: first, reducing traffic accident-related congestion and stop-and-go behavior. When AVs are widely used, communication tools such as vehicle-to-vehicle technology (V2V) can be used to improve the perception of road conditions and the stability of traffic flow at higher cruising speeds and shorter time headway. Second, the mobility of AVs will contribute to increased accessibility. After people who cannot drive CVs choose autonomous driving, VMTs will increase by 14% [18]. The synergy and hedging between the two perspectives above can influence traffic efficiency simultaneously.

(3) Road capacity

Simulation studies on synchronous acceleration/deceleration have shown that AVs can form a platoon through inter-vehicle communication. AVs can continuously scan and monitor the surrounding traffic and can perform refined braking or acceleration operations. For this reason, vehicles that are ahead and behind in a platoon can maintain a shorter distance, thus increasing the number of vehicles on the road. On the existing road system, low-level Avs that are capable of adaptive cruising have demonstrated the potential and feasibility of this application [19]. Connected AVs can increase the throughput and capacity of roads by a factor of four [20].

(4) Parking space

The breakthrough of AVs being able to park in a wider variety of parking spaces is an important indicator that reflects their environmental effect. According to statistics, traditional vehicles are idle 96% of the time during their design life cycle. In particular, shared AVs (SAVs) can reduce traffic density and increase the utilization rate of vehicles by 75% [6]. Through simulation research, Martinez and Viegas (2017) indicated that the use of SAVs can reduce 90% of the traffic flow on the road [21]. Second, AVs can reduce the need for parking in urban spaces due to their limitless fluidity, as they can park themselves in remote areas. Based on this, simulation research conducted by Zhang and Guhathakurta (2017) demonstrated that an AV can increase the number of parking spaces by 20% and reduce vehicle ownership by 5% [22]. Thus, AVs, if taken as moving platforms rather than cars only, can trigger novel urban design, that is, the contemporary car is not only a driving machine, but a parking machine as well.

2.2. Energy Consumption

Generally, traditional vehicles use fossil fuels as their power source, resulting in increasingly serious problems, such as increased carbon emissions, air pollution, and global warming. Because of the differences in the design of AVs in terms of, for example, electrification and the use of hybrid power sources, energy consumption should be taken into full account in the evaluation of energy consumption reduction in the context of AV penetration into the market.

(1) Fuel saving

Energy consumption reductions are derived from several considerations, including lightweight design, path optimization for intelligent hazard and obstacle avoidance, and eco-driving. First, in traditional vehicle design, safety-related facilities occupy more than 20% of the body weight, and a 10% reduction in body weight means energy saves of 6 to 7% [23]. Extra facilities can be removed from AVs because of their effective guarantee of safety, thus contributing to lightweight design. Second, with the aid of V2V and V2I technologies, AVs can perceive the surrounding traffic environment and the operating status of other AVs in a real-time, dynamic manner; intelligently avoid hazards and obstacles; and optimize the path, thus reducing energy consumption. Third, the refined control of eco-driving can improve the smoothness and stability of road traffic by eliminating stop-and-go driving behavior and is expected to reduce energy consumption by 15 to 30% [24,25]. The platooning of AVs is also believed to have the capacity to reduce air assistance and to thus reduce fuel consumption by 3 to 25% [26]. Additionally, cooperative adaptive cruise control (CACC) technology has been reported to achieve 98%, 93%, and 33% reductions in time headway deviation, unsafe conditions, and instantaneous fuel consumption, respectively [27].

(2) Alternative fuel

Currently, electrification mainly contributes to increasing the fuel efficiency of vehicles [28]. The low efficiency of electric vehicles (EVs) is mainly caused by the frequent use of EVs for short-distance transportation because of the limitation of battery capacity and the mismatch between the distribution of charging stations and the intended parking location [29]. A fleet of SAVs can make up for these shortcomings of EVs. AVs consume energy during both production and charging, and most of the energy comes from traditional fossil fuels. However, because the enhanced sensor and computing power requirements of AVs increase the electric power consumption of AVs by 8% [30], the total energy consumption of AVs during their entire life cycle still needs to be considered during evaluation.

(3) Fuel efficiency

The fuel efficiency of traditional vehicles is determined by their engine parameters, air resistance, weight, and the characteristics of their fuels. Researchers have found that the average energy conversion rate of EVs is three times that of traditional vehicles with internal combustion engines [13]. An important reference indicator for optimizing the environment of AVs is the improvement of fuel efficiency. The main indicators under consideration include the lightweight body design of AVs and the reduction of air resistance with the help of intelligent platooning. Additionally, Lee and Choi (2018) indicated that the fuel status of EVs clearly has different effects on the ground environment when they run at low speeds and under different road conditions [31]. For vehicles with SAE automation Levels 1 to 3, which have features such as cruise control and smooth braking, fuel efficiency can be increased by as much as 39% [10].

2.3. Air Environment

Important evaluation indicators for environmental monitoring under the current industrial system include urban air conditions. The environmental issues and urban air pollution caused by the greenhouse effect have increasingly become the focus of public concern. The GHG emissions and nitrogen oxide (NOx) content in the air are indicators for measuring air quality that have been universally adopted by the current research community.

(1) Greenhouse gases

The NASA Environmental Institute has proposed four major GHGs: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases. The capacity of AVs to reduce GHGs is mainly determined by several factors: First, the updated energy power system. It has been reported that the GHGs generated by battery-powered EVs during the entire life cycle of the car are approximately half of those generated by traditional vehicles. Second, the continued intelligent improvement of autonomous decision-making and automatic control functions has objectively promoted low-carbon mobility (LCM). For example, green light-optimized speed advisory (GLOSA) technology has been reported to be capable of CO_2 emission reductions in addition to traffic flow improvements through V2X communication [27].

Third, AVs have also updated the mobility concept to include on-demand mobility, car-sharing, and other LCM methods. Greenblatt and Shaheen (2015) indicated that the use of shared vehicles in forms such as car-sharing, ride-sharing/carpooling, transportation networks, and e-hail services based on actual need has objectively reduced VMT [32].

(2) NOx levels

The effect of traditional road traffic on air pollution is reflected in the continued rise in vehicle exhaust emissions and in NOx levels in particular. Avs mainly affect air pollution as a result of the following factors: the eco-driving technology of AVs, whether the use of AVs can increase VMT, the dependence of AVs on fossil fuels (vehicles with internal combustion engines are more likely to cause pollution than EVs), and the degree of integration of AVs with public transport [33]. Stern (2019) demonstrated that V2V communication between AVs and eco-driving can reduce traffic flow fluctuations and can shorten acceleration and deceleration cycles and are expected to reduce CO_2 emissions by 15% and NOx emissions by 73% [34]. Through a numerical simulation, Rafael et al. (2020) compared the differences in urban air quality under three conditions: no AVs, 30% AV penetration, and 30% AVs powered by electric power. The results indicated that 30% AV penetration results in a slight increase (<1%) in NOx emissions, whereas AVs powered by electric power can reduce NOx emissions by 4% [35].

Based on the above analysis, an environmental effect evaluation indicator system for AVs is constructed in this study, as shown in Table 1.

Table 1. Environmental effect evaluation indicator system for AVs.

First-Level Indicator	Second-Level Indicator
Energy environmental effect	A_1: Fuel saving
	A_2: Alternative fuel
	A_3: Fuel efficiency
Traffic environmental effect	A_4: Safety and crashes
	A_5: Traffic efficiency
	A_6: Road capacity
	A_7: Parking space
Atmosphere environmental effect	A_8: Greenhouse gases
	A_9: NOx levels

3. IVIULWG Operator: Evaluation Methodology for the Environmental Effect of AVs

There are two types of data sources that can be used to create environmental evaluation indicators for AVs. The first type generally consists of standard monitoring data, statistical data, and experimental data, such as data on fuel consumption, the fuel utilization rate, exhaust emissions, and NOx levels, which are "crisp data." Regarding the common characteristics of such data, although the data are divided into, for example, absolute numbers, relative numbers, and proportional numbers, they have clear numerical values and quantitative representations, which can be used to determine the level of their effect. The other data source is a combination of subjective and objective evaluation indicators, such as traffic safety and traffic efficiency. Because AVs are undergoing industrial growth, the industry access and measurement standards for such indicators are fuzzy, but possible interval values of their data are still clear.

3.1. IVIUF Evaluation Number

After the full consideration of the data features, IVIUF semantics were selected as the environmental effect evaluation algorithm for Avs in this study. The reason for this is that, through conversion, IVIUF semantics can improve the description of the complex coexistence of crisp and fuzzy numbers in evaluation indicators. Regarding the IVIULWG operator formed when considering geometric weights, it not only accurately conveys the subjective hesitancy of the evaluator in the initial evaluation information but also objectively forms all initial information into comprehensive and applicable evaluation results. The intuitionistic confirmation and non-confirmation of IVIUF semantics are excellent for adaptability and can be automatically adjusted with the classification of industrial norms, the extensive improvement of AV road tests, and the gradual improvement of quantitative criteria; that is, the algorithm is highly sustainable.

3.1.1. Definition of IVIUF

IVIUF semantic information and its operator belong to the fuzzy MCDM method, which corresponds to a decision-making method with uncertain and fuzzy information. This study belongs to Intuitionistic Fuzzy Sets (IFS) research, which was formed by Zadeh, Atanassov, and Gargov (1996) [36]. In this paper, the IVIUF semantic expression method is selected, the judgment results are formed, and the affirmation and hesitation of the judgment results [36] are presented. The reasons for adopting IVIUF semantics in this study are as follows: First, this algorithm can describe the coexistence of "crisp numbers" and "fuzzy numbers" in the evaluation of the environmental effects of AVs. Second, IVIUF not only maximizes the retention of the objective evaluation interval information of "crisp" and "fuzzy" numbers, but also highlights the intuition of a subjective evaluation in environmental effect evaluation, thereby forming sufficient state information and stronger mathematical characteristics. In this study, relevant research results were collected to form the following definition of IVIUF:

Definition 1. *Uncertain linguistic evaluation interval variable* $\widetilde{S} = \left[S_{\theta(\widetilde{a}_j)}, S_{\tau(\widetilde{a}_j)}\right]$.

Let $S = \{s_1, s_2 \ldots s_n\}$ be a linguistic term set with odd cardinality. In any label, S_i represents a possible value of a linguistic variable. For instance, S = {S_1, S_2, S_3, S_4, S_5}, where S_1 = extremely poor, S_2 = poor, S_3 = medium, S_4 = good, S_5 = extremely good. S has an arbitrary subset interval of S, $\widetilde{S} = \left[S_{\theta(\widetilde{a}_j)}, S_{\tau(\widetilde{a}_j)}\right]$, where $S_{\theta(\widetilde{a}_j)}$ and $S_{\tau(\widetilde{a}_j)} \in S$ are in an ascending state; $S_{\theta(\widetilde{a}_j)}$ represents a low-level evaluation in the ascending state; and $S_{\tau(\widetilde{a}_j)}$ represents a high-level evaluation.

Definition 2. *Membership degree interval value* $\widetilde{u} = \left[u^L(\widetilde{a}_j), u^U(\widetilde{a}_j)\right]$.

The state of intuitionistic perception and confirmation for the establishment of an uncertain linguistic variable $\widetilde{S}$ is called the membership degree interval value. The fuzzy evaluation values of the membership degree interval or certainty, $\widetilde{u} = \left[u^L(\widetilde{a}_j), u^U(\widetilde{a}_j)\right]$, are arranged in ascending order (j denotes the evaluation dimension).

Definition 3. *Non-membership degree interval*$\widetilde{v} = \left[v^L(\widetilde{a}_j), v^U(\widetilde{a}_j)\right]$.

The non-membership degree interval, $\widetilde{v} = \left[v^L(\widetilde{a}_j), v^U(\widetilde{a}_j)\right]$, is an unconfirmed state of intuitionistic perception established for an uncertain linguistic variable $\widetilde{S}$ and is also sorted in ascending order, with uncertainty $v^L(\widetilde{a}_j) < v^U(\widetilde{a}_j)$. Because the hesitancy factor is allowed, $0 \le u^L(\widetilde{a}_j) + v^L(\widetilde{a}_j) \le 1$ and $0 \le u^U(\widetilde{a}_j) + v^U(\widetilde{a}_j) \le 1$.

Definition 4. *IVIUF evaluation indicator* $\widetilde{a}_j = \left\{\left[S_{\theta(\widetilde{a}_j)}, S_{\tau(\widetilde{a}_j)}\right], \left[u^L(\widetilde{a}_j), u^U(\widetilde{a}_j)\right], \left[v^L(\widetilde{a}_j), v^U(\widetilde{a}_j)\right]\right\}$.

In this paper, the IVIUF number is an evaluation indicator that describes the evaluated object. The IVIUF evaluation indicator is described in the following form: $\widetilde{a}_j = \left\{\left[S_{\theta(\widetilde{a}_j)}, S_{\tau(\widetilde{a}_j)}\right], \left[u^L(\widetilde{a}_j), u^U(\widetilde{a}_j)\right], \left[v^L(\widetilde{a}_j), v^U(\widetilde{a}_j)\right]\right\}$. The variable matrix that considers multiple objects and attributes can be simply described as $\widetilde{A}_j = \left(\left[S_{\alpha_j}, S_{\beta_j}\right], \left([a_j, b_j], [c_j, d_j]\right)\right)$, where j denotes the number of evaluation objects.

3.1.2. IVIUF Semantics for Environmental Effect Evaluation Indicators

(1) "Crisp" data in the evaluation indicator system

Established national grading standards exist in the AV industry. Alternatively, industry experts can develop authoritative grading standards. This type of "crisp" data can be divided into an odd number of intervals according to their grades, from poor to excellent.

The smaller the interval label, the lower the rating. “Crisp” data are only within one evaluation interval. For the interval value that corresponds to “crisp” data, the membership degree interval and non-membership degree are highly objective because the interval value is formed based on accurate data.

For example, for A_9 NOx levels in the indicator system, “its nitrogen oxides emissions are lower than 0.05 g” according to the standards of the AV industry that correspond to the interval value in IVIUF semantics, thus forming a value interval of [0, 0.05]. Consider the classification of nitrogen oxide emissions into five intervals as an example: [0.05–0.04) corresponds to Level 1, the interval value [0.04–0.03) corresponds to Level 2, and the interval value [0.03–0.02) corresponds to Level 3. Similarly, different NOx emission intervals corresponding to Levels 1 to 5 can be obtained, which represent the intervals “S_1-S_2-S_3-S_4-S_5” and the five interval characteristics of “very poor-poor-qualified-good-excellent.” If the NOx value of a certain AV brand is 0.033–0.025, its interval value can be determined as $[s_2, s_3]$. If the objective accuracy of the data is evaluated, its membership degree and non-membership degree can be expressed as (1, 1) and (0, 0) in the case of extreme accuracy. If there is high doubt about the detection environment, it can be expressed as (0.2, 0.4) and (0.5, 0.6), for example.

(2) “Fuzzy” data in the evaluation indicator system

At present, there are increasing doubts about the contributions of AVs to the improvement of traffic efficiency. Thus, there have been a large number of evaluations based on “fuzzy” information. Because empirical testing and road testing of AVs have not been conducted on a large scale, it is impossible to make judgments and to divide intervals based on data. Therefore, it is still necessary to rely on the subjective experience of experts for judgment. It is believed that even if experts have diverse evaluation ideas, by combining the evaluations of multiple experts and taking the average of their evaluation results, the industry’s overall judgments on the type of AVs can be obtained.

For instance, for A_5, the traffic efficiency indicator in the indicator system, the upper and lower limits of the evaluation values can be divided into an odd number of evaluation intervals, from poor to excellent, based on experts’ comprehensive evaluations. If the evaluation value is obtained based on the data acquired by stratification, sampling, or comparative inference, it is necessary to assess whether the interval is evenly distributed. Experts can be invited to subjectively judge the membership and non-membership degrees of intuitionistic intervals based on their professional experience and judgments.

3.2. IVIULWG Operator Development

The evaluation matrix $\widetilde{A}_j$ can be obtained according to IVIUF Definitions 1 to 3 in Section 3.1 and to the environmental effect evaluation indicator system for AVs formed in this paper. Considering the coexistence of “crisp” data and “fuzzy” data in the evaluation matrix, the volume of “crisp” data information in the initial evaluation is retained as practically as possible.

In the case of an ample sample size, because of the uncertainty regarding intuition about the evaluation objects, the evaluation data are relatively concentrated, but a small number of data are distributed at the top and bottom of the evaluation set. Clearly, the two types of data should not be treated equally. The data at both extremes of the evaluation set should be assigned higher weights.

In the algorithm development process, geometric weights are added to the evaluation matrix, and the IVIULWG operator is developed.

Step 1: Prepare the IVIUF evaluation data:

Relying on the evaluation indicator system and related information, the experts can form an IVIUF evaluation matrix of the evaluation objects. If $\widetilde{A}_j = \left\{ \left[s_{\alpha_j}, s_{\beta_j} \right], \left[a_j, b_j \right], \left[c_j, d_j \right] \right\}$ (j = 1, 2, ..., n) is a group of IVIUF variables and $\widetilde{A}_1 = \left\{ \left[s_{\alpha_1}, s_{\beta_1} \right], \left[a_1, b_1 \right], \left[c_1, d_1 \right] \right\}$, $\widetilde{A}_2 = \left\{ \left[s_{\alpha_2}, s_{\beta_2} \right], \left[a_2, b_2 \right], \left[c_2, d_2 \right] \right\}$, then the basic algorithm is as shown in Equations (1) and (2). Equations (1) and (2) are the results derived from the achievements made in mathematics. They are the calculation rules for any two IVIUF numbers and correspond to the addition and multiplication rules, respectively

$$\widetilde{A}_1 + \widetilde{A}_2 = \left\{ \left[s_{\alpha_1+\alpha_2}, s_{\beta_1+\beta_2} \right], \left[1-(1-a_1)(1-a_2), 1-(1-b_1)(1-b_2) \right], \left[c_1c_2, d_1d_2 \right] \right\} \quad (1)$$

$$\widetilde{A}_1 \otimes \widetilde{A}_2 = \left\{ \left[s_{\alpha_1\alpha_2}, s_{\beta_1\beta_2} \right], \left[a_1a_2, b_1b_2 \right], \left[1-(1-c_1)(1-c_2), 1-(1-d_1)(1-d_2) \right] \right\} \quad (2)$$

Step 2: Introduce the position weight:

First, the IVIULWG operator needs to determine the interval distribution of the evaluation numbers by sorting the IVF numbers in the evaluation interval, sorting the membership and non-membership degree intervals from low to high, and assigning different weights to the evaluation numbers in different locations of the distribution.

Assuming $\omega = (\omega_1,\ \omega_2, \ldots, \omega_n)$ is a weighted vector of $\widetilde{A}_j$ (j = 1, 2, ..., n) and $\omega_j \in [0,1]$, $\sum_{j=1}^{n} \omega_j = 1$, the following factors that consider the use of geometric weights are added based on the generalized correlation aggregation operator of the IVIUF information. With reference to the research results of Wang and Yager [37,38], the method of assigning location weights is shown in Equation (3). Equations (4) and (5) are the calculation rules of the IVIUF numbers after the position weight ω_j is introduced:

$$\omega_j = \frac{C_{n-1}^{j}}{2^{n-1}}, where\ j = 0, 1, \ldots,\ n-1\ and\ \sum_{j=1}^{n} \omega_j = 1 \quad (3)$$

$$\widetilde{A}_1^{\lambda} = \left\{ \left[s_{\alpha_1{}^{\lambda}}, s_{\alpha_2{}^{\lambda}} \right], \left[(a_1)^{\lambda}, (b_1)^{\lambda} \right], \left[1-(1-c_1)^{\lambda}, 1-(1-d_1)^{\lambda} \right] \right\} \quad (4)$$

$$\widetilde{A}_1^{\lambda_1} \otimes \widetilde{A}_1^{\lambda 2} = \left(\widetilde{A}_1 \right)^{\lambda_1+\lambda_2} \quad (5)$$

Step 3: Introduce the indicator importance weight:

The MCDM algorithm is designed to evaluate the comprehensive attributes of multi-attribute objects. It requires the determination of the importance of different indicators (or an indicator layer that is composed of several sub-indicators) in the comprehensive evaluation, that is, the subjective weight. If the subjective weight of the evaluation number $\widetilde{A}_1$ is λ, then the calculation rule is

$$\lambda \widetilde{A}_1 = \left\{ \left[s_{\lambda\alpha_1}, s_{\lambda\alpha_2} \right] \left[1-(1-a_1)^{\lambda}, 1-(1-b_1)^{\lambda} \right], \left[(c_1)^{\lambda}, (d_1)^{\lambda} \right] \right\} \quad (6)$$

$\widetilde{A}_j$ mix of two weights is used for the IVIULWG operator in this study. One of the weights is the location weight of the indicator (or indicator layer) data, that is, an objective weight, which can be assigned because of its different relative position in the evaluation interval. The other weight is the importance weight of different indicators (or indicator layers), that is, a subjective weight, which can be assigned according to the importance of the evaluation indicators of the environmental effects of AVs. The IVIULWG operator, which is formed through a mix of the above weights, makes the data-use process more scientific.

Step 4: Develop the IVIULWG aggregation operator: A generalized correlation aggregation factor is adopted based on related results obtained in IFS research. Equations (7) and (8) provide the aggregation rule of the IVIULWG operator, and Equation (9) calculates the comprehensive evaluation attribute value of the IVIULWG operator, or the expected value:

$$\text{IVIULWG}\left(\widetilde{A}_1, \widetilde{A}_2 \ldots\ldots \widetilde{A}_n \right) = \begin{bmatrix} j=1 & j=1 \\ \otimes_{s_{(\alpha_j)}}{}^{\omega}, & \otimes_{s_{(\beta_j)}}{}^{\omega_j} \end{bmatrix}, \left[\prod_{j=1}^{n} (a_j)^{\omega_j}, \prod_{j=1}^{n} (b_j)^{\omega_j} \right], \left[1 \otimes \prod_{j=1}^{n} (1 \otimes c_j)^{\omega_j}, 1 \otimes \prod_{j=1}^{n} (1 \otimes d_j)^{\omega_j} \right] \quad (7)$$

$$\Lambda\left(\widetilde{A}_1, \widetilde{A}_2 \ldots\ldots \widetilde{A}_n \right) = \sum_{j=1}^{n} \omega_j \widetilde{A}_j = \left\{ \left[s_{x_n}, s_{y_n} \right], \left[1 - \prod_{j=1}^{n} \left(1-a_j\right)^{\omega_j}, 1 - \prod_{j=1}^{n} \left(1-b_j\right)^{\omega_j} \right], \left[\prod_{j=1}^{n} \left(c_j\right)^{\omega_j}, \prod_{j=1}^{n} \left(d_j\right)^{\omega_j} \right] \right\}, \quad (8)$$
$$\text{where } x_n = \sum_{j=1}^{n} \omega_j a_j, y_n = \sum_{j=1}^{n} \omega_j b_j$$

$$E(\widetilde{a}) = [1 + (a+b)/2 - (c+d)/2]/2 \times S_{(\alpha+\beta)/2} = S_{[(\alpha+\beta)\times(a+b+2-c-d)]/8} \quad (9)$$

Based on the IVIULWG operator, the expected value can be formed after the operation of the multi-dimensional and multi-objective IVIUF evaluation matrix [39], which is an MCDM operator. The expected value exhibits the characteristics of "crisp numbers." The operator's value can be directly used for comparison, although it does not have the connotation of evaluation. Considering the ascending order of the definition domain of the IVIUL evaluation information of the indicator, the larger the expected value, the better the evaluation result.

3.3. Application of the IVIULWG Operator

Based on the correlation transformation, selecting the IVIUL semantics form can solve the problem of data features that describe the coexistence of "crisp numbers" and "fuzzy numbers" in the environmental effect evaluation of AVs. Additionally, geometric weights are added based on the generalized correlation aggregation operator of IVIUL information. The developed IVIULWG operator improves the retention of the respective objective and subjective information of "crisp" numbers and "fuzzy" numbers. The methods for combining crisp numbers and fuzzy numbers as well as two-level status data and intermediate state data in the evaluation are determined. The credibility of the fuzzy attributes of IVF research is improved; otherwise, the weighted arithmetic average would become a simple arithmetic average on the S values. Furthermore, the expected values of the calculation results are more comprehensive in terms of their attributes. The IVIULWG operator can be directly applied to, for example, the numerical comparison, ranking, and classification of multiple subjects and serves different management decision-making purposes.

4. Numerical Example: Optimization Problem Based on the IVIULWG Operator

The optimal selection of environmental effects for s is a typical MCDM problem. In the following section, an illustrative example of based on the IVIULWG operator is presented. Assume that there is a panel with four possible AVs, that is, T*i* (*i* = 1, 2, 3, 4). The best AV is chosen as the "Star of the Year".

According to the requirements of the evaluation indicator system in Table 1, relevant data or information about the four AV brands was provided to the knowledgeable experts. All of the data came from an industry platform, the official websites of the brands, simulations, and actual measurements. Relevant information (e.g., industry regulations and existing industrial standards) was also submitted to three experts as supporting materials for the evaluation.

Step 1: Prepare the IVIUF evaluation data

The three experts were invited to provide their evaluations based on the IVIUF numbers. The uncertain linguistic evaluation set adopted comprised a five-level interval in ascending order and had the following corresponding meanings: {S_1 = extremely poor, S_2 = poor, S_3 = medium, S_4 = good, S_5 = extremely good}.

During the expert evaluation, the indicators with "crisp" characteristics in the indicator system were classified into five interval values based on the normative standards of industry data. The three experts determined the interval value based on the actual data of each AV brand, with the corresponding membership and non-membership intervals showing great objectivity. For indicators with "fuzzy" characteristics, the experts were asked to evaluate the interval value of the indicators directly based on their professional experience and accomplishments and to assign membership and non-membership information using their intuition. The comprehensive evaluation results of the three experts are the comprehensive evaluation values of the four brands. In this example, the evaluation weights randomly assigned by the three experts were 0.35, 0.29, and 0.36, respectively.

Through sorting, a 3 × 9 evaluation matrix of the environmental effect evaluation indicator system assigned by the three experts (K_1, K_2, K_3) to the four brands could be obtained, as shown in Table 2.

Table 2. Initial IVIUF evaluation values assigned by three experts to four vehicle brands.

Knowledge Expert	Indicator	T_1	T_2	T_3	T_4
K_1	A_1	$<[S_3,S_3], [0.8,0.9], [0.1,0.1]>$	$<[S_2,S_2], [0.8,0.9], [0.1,0.1]>$	$<[S_4,S_4], [0.7,0.8], [0.1,0.2]>$	$<[S_3,S_3], [0.8,0.9], [0.1,0.1]>$
	A_2	$<[S_2,S_3], [0.7,0.8], [0.2,0.3]>$	$<[S_1,S_2], [0.6,0.7], [0.2,0.3]>$	$<[S_4,S_5], [0.6,0.8], [0.1,0.2]>$	$<[S_3,S_4], [0.7,0.8], [0.1,0.2]>$
	A_3	$<[S_4,S_5], [0.8,0.8], [0.1,0.2]>$	$<[S_2,S_3], [0.6,0.7], [0.2,0.3]>$	$<[S_3,S_4], [0.7,0.8], [0.1,0.2]>$	$<[S_3,S_4], [0.6,0.7], [0.1,0.2]>$
	A_4	$<[S_3,S_4], [0.7,0.7], [0.2,0.3]>$	$<[S_1,S_2], [0.7,0.8], [0.1,0.1]>$	$<[S_2,S_3], [0.6,0.7], [0.2,0.2]>$	$<[S_4,S_5], [0.7,0.8], [0.1,0.1]>$
	A_5	$<[S_2,S_4], [0.5,0.6], [0.2,0.3]>$	$<[S_2,S_4], [0.4,0.5], [0.3,0.4]>$	$<[S_3,S_5], [0.5,0.6], [0.3,0.4]>$	$<[S_1,S_3], [0.5,0.6], [0.2,0.3]>$
	A_6	$<[S_3,S_5], [0.6,0.6], [0.2,0.3]>$	$<[S_1,S_3], [0.5,0.6], [0.2,0.3]>$	$<[S_2,S_4], [0.5,0.7], [0.1,0.2]>$	$<[S_3,S_5], [0.5,0.6], [0.2,0.3]>$
	A_7	$<[S_1,S_3], [0.5,0.7], [0.3,0.4]>$	$<[S_2,S_4], [0.5,0.6], [0.3,0.3]>$	$<[S_3,S_5], [0.5,0.6], [0.2,0.3]>$	$<[S_2,S_4], [0.4,0.5], [0.2,0.3]>$
	A_8	$<[S_3,S_4], [0.6,0.6], [0.1,0.2]>$	$<[S_1,S_2], [0.6,0.8], [0.2,0.3]>$	$<[S_3,S_4], [0.7,0.8], [0.1,0.2]>$	$<[S_2,S_3], [0.7,0.8], [0.1,0.1]>$
	A_9	$<[S_2,S_3], [0.7,0.8], [0.1,0.1]>$	$<[S_1,S_2], [0.6,0.7], [0.2,0.3]>$	$<[S_3,S_4], [0.7,0.8], [0.1,0.1]>$	$<[S_3,S_4], [0.7,0.7], [0.2,0.2]>$
K_2	A_1	$<[S_2,S_2], [0.8,0.8], [0.1,0.2]>$	$<[S_3,S_3], [0.8,0.9], [0.1,0.1]>$	$<[S_3,S_3], [0.8,0.9], [0.1,0.1]>$	$<[S_4,S_4], [0.8,0.8], [0.1,0.2]>$
	A_2	$<[S_1,S_2], [0.7,0.8], [0.1,0.1]>$	$<[S_3,S_4], [0.6,0.7], [0.2,0.3]>$	$<[S_2,S_3], [0.6,0.8], [0.2,0.2]>$	$<[S_4,S_5], [0.6,0.7], [0.3,0.3]>$
	A_3	$<[S_4,S_5], [0.6,0.7], [0.3,0.3]>$	$<[S_3,S_4], [0.7,0.8], [0.1,0.1]>$	$<[S_3,S_4], [0.7,0.8], [0.1,0.1]>$	$<[S_3,S_4], [0.6,0.7], [0.2,0.2]>$
	A_4	$<[S_2,S_3], [0.6,0.7], [0.2,0.3]>$	$<[S_1,S_2], [0.7,0.8], [0.2,0.2]>$	$<[S_2,S_3], [0.6,0.7], [0.2,0.3]>$	$<[S_3,S_4], [0.7,0.8], [0.2,0.2]>$
	A_5	$<[S_3,S_5], [0.4,0.5], [0.3,0.4]>$	$<[S_2,S_4], [0.5,0.6], [0.2,0.3]>$	$<[S_2,S_4], [0.5,0.7], [0.2,0.3]>$	$<[S_2,S_4], [0.4,0.6], [0.2,0.3]>$
	A_6	$<[S_2,S_4], [0.5,0.6], [0.2,0.3]>$	$<[S_2,S_4], [0.4,0.5], [0.2,0.2]>$	$<[S_3,S_5], [0.5,0.6], [0.2,0.3]>$	$<[S_3,S_5], [0.6,0.7], [0.2,0.3]>$
	A_7	$<[S_1,S_3], [0.4,0.6], [0.1,0.2]>$	$<[S_1,S_3], [0.5,0.6], [0.2,0.3]>$	$<[S_3,S_5], [0.4,0.5], [0.3,0.4]>$	$<[S_2,S_4], [0.4,0.5], [0.2,0.3]>$
	A_8	$<[S_3,S_4], [0.7,0.8], [0.1,0.2]>$	$<[S_1,S_2], [0.6,0.7], [0.1,0.2]>$	$<[S_3,S_4], [0.7,0.7], [0.2,0.2]>$	$<[S_2,S_3], [0.6,0.7], [0.2,0.3]>$
	A_9	$<[S_1,S_2], [0.6,0.7], [0.2,0.3]>$	$<[S_3,S_4], [0.7,0.8], [0.1,0.1]>$	$<[S_2,S_3], [0.7,0.8], [0.1,0.1]>$	$<[S_4,S_5], [0.7,0.7], [0.2,0.2]>$
K_3	A_1	$<[S_3,S_3], [0.8,0.9], [0.1,0.1]>$	$<[S_2,S_2], [0.7,0.8], [0.1,0.2]>$	$<[S_4,S_4], [0.8,0.9], [0.1,0.1]>$	$<[S_4,S_4], [0.8,0.8], [0.1,0.1]>$
	A_2	$<[S_2,S_3], [0.6,0.7], [0.2,0.2]>$	$<[S_3,S_4], [0.7,0.7], [0.2,0.2]>$	$<[S_2,S_3], [0.6,0.7], [0.2,0.2]>$	$<[S_3,S_4], [0.7,0.8], [0.1,0.1]>$
	A_3	$<[S_3,S_4], [0.7,0.8], [0.1,0.1]>$	$<[S_2,S_3], [0.6,0.7], [0.2,0.2]>$	$<[S_4,S_5], [0.7,0.8], [0.1,0.2]>$	$<[S_2,S_3], [0.7,0.8], [0.1,0.1]>$
	A_4	$<[S_3,S_4], [0.6,0.7], [0.2,0.2]>$	$<[S_2,S_3], [0.6,0.7], [0.2,0.2]>$	$<[S_2,S_3], [0.5,0.7], [0.2,0.3]>$	$<[S_3,S_4], [0.7,0.8], [0.1,0.1]>$
	A_5	$<[S_2,S_4], [0.5,0.6], [0.2,0.3]>$	$<[S_3,S_5], [0.4,0.5], [0.2,0.2]>$	$<[S_2,S_4], [0.5,0.6], [0.1,0.2]>$	$<[S_1,S_3], [0.4,0.6], [0.1,0.2]>$
	A_6	$<[S_3,S_5], [0.4,0.5], [0.2,0.3]>$	$<[S_1,S_3], [0.5,0.6], [0.2,0.3]>$	$<[S_3,S_5], [0.5,0.7], [0.2,0.3]>$	$<[S_2,S_4], [0.5,0.6], [0.3,0.4]>$
	A_7	$<[S_2,S_4], [0.5,0.6], [0.1,0.2]>$	$<[S_2,S_3], [0.6,0.7], [0.2,0.3]>$	$<[S_3,S_4], [0.7,0.8], [0.1,0.1]>$	$<[S_3,S_5], [0.5,0.6], [0.2,0.3]>$
	A_8	$<[S_2,S_3], [0.7,0.8], [0.2,0.2]>$	$<[S_3,S_4], [0.7,0.7], [0.2,0.3]>$	$<[S_2,S_3], [0.6,0.7], [0.2,0.3]>$	$<[S_3,S_4], [0.7,0.8], [0.1,0.1]>$
	A_9	$<[S_2,S_3], [0.6,0.7], [0.2,0.2]>$	$<[S_3,S_4], [0.7,0.8], [0.1,0.2]>$	$<[S_2,S_3], [0.6,0.7], [0.2,0.2]>$	$<[S_3,S_4], [0.7,0.7], [0.1,0.1]>$

Step 2: Introduce the position weight and importance weight

Considering that three experts were involved in this case, from Equation (4), the position weight could be derived as $\omega = (1/4, 1/2, 1/4)$. Subjective weights (λ = 0.06, 0.12, 0.12, 0.12, 0.08, 0.04, 0.16, 0.09, 0.21) were assigned to the primary indicators A_j (j = 1, 2, 3, ... , 9). According to the IVIULWG operator algorithm, the comprehensive attribute values of the expert evaluations of each vehicle brand, $\widetilde{E}_{Ti}^{k}$, or the results of the IVIUF evaluations for each vehicle brand by different experts (as shown in Table 3) can be calculated, where E denotes the expected value, k denotes each expert's serial number (K_1, K_2, K_3), and T_i denotes the serial numbers of the different vehicle brands (T_1, T_2, T_3, T_4).

Table 3. IVIULWG evaluation of four vehicle brands by three experts.

	Knowledge Expert 1 (K_1)	Knowledge Expert 2 (K_2)	Knowledge Expert 3 (K_3)_
$\widetilde{E}_{T1}^{k}$	$<[S_{2.39},S_{3.61}], [0.66,0.74], [0.15,0.21]>$	$<[S_{1.92},S_{3.14}], [0.58,0.69], [0.16,0.24]>$	$<[S_{2.34},S_{3.56}], [0.60,0.71], [0.20,0.24]>$
$\widetilde{E}_{T2}^{k}$	$<[S_{1.42},S_{2.64}], [0.60,0.71], [0.19,0.25]>$	$<[S_{2.14},S_{3.36}], [0.63,0.74], [0.14,0.18]>$	$<[S_{2.46},S_{3.52}], [0.63,0.71], [0.17,0.22]>$
$\widetilde{E}_{T3}^{k}$	$<[S_{3.02},S_{4.24}], [0.62,0.73], [0.13,0.20]>$	$<[S_{2.47},S_{3.69}], [0.61,0.72], [0.18,0.21]>$	$<[S_{2.56},S_{3.62}], [0.62,0.74], [0.15,0.19]>$
$\widetilde{E}_{T4}^{k}$	$<[S_{2.71},S_{3.93}], [0.63,0.71], [0.17,0.22]>$	$<[S_{3.06},S_{4.28}], [0.61,0.69], [0.23,0.28]>$	$<[S_{2.74},S_{3.96}], [0.64,0.73], [0.12,0.13]>$

Step 3: Obtain the comprehensive performance of an AV based on the operator

The group's comprehensive attribute value $\widetilde{E}_{Ti}$ for different vehicle brands can be obtained by integrating the above comprehensive attribute value, $\widetilde{E}_{Ti}^{k}$, based on the IVIULWG operator. The results of the comprehensive IVIUF evaluation conducted by the experts for each brand, $\widetilde{A}_{\mathrm{Ti}}$, are as follows:

$\widetilde{A}_{\mathrm{T1}} = <[S_{2.25},S_{3.61}], [0.78,0.65], [0.48,0.59]>$

$\widetilde{A}_{\mathrm{T2}} = <[S_{2.32},S_{3.56}], [0.77,0.66], [0.48,0.58]>$

$\widetilde{A}_{\mathrm{T3}} = <[S_{2.43},S_{3.57}], [0.79,0.66], [0.49,0.62]>$

$\widetilde{A}_{\mathrm{T4}} = <[S_{2.03},S_{3.39}], [0.79,0.68], [0.43,0.58]>$

The total expected value of the environmental effects of T_1, T_2, T_3, and T_4 are calculated according to Equation (9):

$E(\widetilde{A}_{\mathrm{T1}}) = S_{2.181}$, $E(\widetilde{A}_{\mathrm{T2}}) = S_{1.875}$, $E(\widetilde{A}_{\mathrm{T3}}) = S_{2.499}$, $E(\widetilde{A}_{\mathrm{T4}}) = S_{2.578}$.

Step 4: Select the "Star of the Year"

Based on the expected value of the environmental effect evaluation obtained based on the IVIULWG operator, according to the ranking of the judgment intervals from low to high, the authors were aware that, after the evaluation, the larger the expected value of a brand, the better the environmental benefits of that brand's AVs. The brand expectation values were sorted in descending order as needed, $E(\widetilde{A}_{T4}) > E(\widetilde{A}_{T3}) > E(\widetilde{A}_{T1}) > E(\widetilde{A}_{T2})$, which means that the comprehensive performance of the environmental effect of brand T_4 was the highest and can be evaluated as the "Star of the Year".

5. Conclusions

From the perspective of government management decision making, in this paper, an environmental effect evaluation indicator system for AVs was constructed, and the data features that describe the coexistence of "crisp numbers" and "fuzzy numbers" in the indicator system were considered. The IVIULWG operator was developed in combination with the fuzzy interval value feature of IVIUF semantic information. Additionally, AV selection by three experts from three evaluation dimensions and based on nine evaluation indicators was demonstrated using an example, which proved the practicability and effectiveness of the evaluation method.

The IVIULWG operator was used for the environmental effect evaluation of AVs and the evaluation method formed in this study. The scope of application and algorithms have great room for expansion. It is possible to the sort AVs of different brands and models directly and to then determine the evaluation level for market access selection according to the requirements of management decision making. For example, policy-makers can apply the evaluation results as the market access conditions for AVs, that is, in combination with the actual minimum expected value of brands obtained on the market, the highest and lowest expected values of environmental effect evaluation can be divided into several levels. If a vehicle reaches a certain level or above, then the government can issue a marketing license to that vehicle. Meanwhile, the realization of an environmental effect evaluation for AVs can encourage different AV manufacturers to track the reasons for their low evaluation results retrospectively and can, conversely, urge manufacturers to enhance technical follow-up, thus achieving the optimal environmental effect of AV industry resources.

Currently, although certain experimental data for some AVs have been obtained in a simulated environment or closed road environment, the rationality of data use is still limited because of the difficulty of accessing AV-related data and because there is little existing data, with existing data not being included in national regulations. Empirical research can be taken into account in a follow-up study to further verify and optimize the evaluation indicator system and data aggregation algorithm proposed in this paper.

Author Contributions: Conceptualization, S.K. and W.L.; methodology, S.K. and W.L.; software, S.Z.; validation, S.Z.; resources, S.K.; data curation, S.Z.; writing—original draft preparation, S.K. and W.L.; writing—review and editing, W.L.; supervision, S.K.; project administration, S.K.; funding acquisition, S.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Humanities and Social Science Fund of the Ministry of Education of China, grant number 21YJA630041.

Data Availability Statement: Simulation data are available from the corresponding author (W.L.) on request.

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

References

1. Raj, A.; Kumar, J.A.; Bansal, P. A multicriteria decision making approach to study barriers to the adoption of autonomous vehicles. *Transp. Res. Part A Policy Pract.* **2020**, *133*, 122–137. [CrossRef]
2. *J3016_202104*; Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles; SAE International: Pittsburgh, PA, USA, 2021.
3. Litman, T. *Autonomous Vehicle Implementation Predictions: Implications for Transport Planning*; TRID: Victoria, BC, Canada, 2021.
4. Duarte, F.; Ratti, C. The impact of autonomous vehicles on cities: A review. *J. Urban Technol.* **2018**, *25*, 3–18. [CrossRef]

5. Gandia, R.M.; Antonialli, F.; Cavazza, B.H.; Neto, A.M.; Lima, D.A.D.; Sugano, J.Y.; Nicolai, I.; Zambalde, A.L. Autonomous vehicles: Scientometric and bibliometric review. *Transp. Rev.* **2019**, *39*, 9–28. [CrossRef]
6. Fagnant, D.J.; Kockelman, K. Preparing a nation for autonomous vehicles: Opportunities, barriers and policy recommendations. *Transp. Res. Part A Policy Pract.* **2015**, *77*, 167–181. [CrossRef]
7. Bagloee, S.A.; Tavana, M.; Asadi, M.; Oliver, T. Autonomous vehicles: Challenges, opportunities, and future implications for transportation policies. *J. Mod. Transp.* **2016**, *24*, 284–303. [CrossRef]
8. Li, S.; Sui, P.C.; Xiao, J.; Chahine, R. Policy formulation for highly automated vehicles: Emerging importance, research frontiers and insights. *Transp. Res. Part A Policy Pract.* **2019**, *124*, 573–586. [CrossRef]
9. Sivak, M.; Schoettle, B. *Influence of Current Nondrivers on the Amount of Travel and Trip Patterns with Self-Driving Vehilces*; University of Michigan Transportation Research Institute: Ann Arbor, MI, USA, 2015.
10. Igliński, H.; Babiak, M. Analysis of the potential of autonomous vehicles in reducing the emissions of greenhouse gases in road transport. *Procedia Eng.* **2017**, *192*, 353–358. [CrossRef]
11. Anderson, J. Inside out or outside in? Translating margins, marginalizing translations. The case of francophone pacific writing. *TranscUlturAl A J. Transl. Cult. Stud.* **2013**, *5*, 1689–1699. [CrossRef]
12. Barth, M.; Boriboonsomsin, K. Energy and emissions impacts of a freeway-based dynamic eco-driving system. *Transp. Res. Part D Transp. Environ.* **2009**, *14*, 400–410. [CrossRef]
13. Dogan, O.; Deveci, M.; Canıtez, F.; Kahraman, C. A corridor selection for locating autonomous vehicles using an interval-valued intuitionistic fuzzy AHP and TOPSIS method. *Soft Comput.* **2020**, *24*, 8937–8953. [CrossRef]
14. Bakioglu, G.; Atahan, A.O. AHP integrated TOPSIS and VIKOR methods with Pythagorean fuzzy sets to prioritize risks in self-driving vehicles. *Appl. Soft Comput.* **2021**, *99*, 106948. [CrossRef]
15. Wang, W.; Wu, Y. Is uncertainty always bad for the performance of transportation systems? *Commun. Transp. Res.* **2021**, *1*, 100021. [CrossRef]
16. Klaver, F. The economic and social impacts of fully autonomous vehicles. Compact 2020; pp. 57–63. Available online: https://www.compact.nl/en/articles/the-economic-and-social-impacts-of-fully-autonomous-vehicles/ (accessed on 17 May 2022).
17. Federal Highway Administration. *Traffic Congestion and Reliability: Linking Solutions to Problems*; Federal Highway Administration: Washington, DC, USA, 2004.
18. United Nations, The Population Division of the Department of Economic and Social Affairs. *World Population Ageing 2019*; United Nations: New York, NY, USA, 2019; ISBN 9789211483260.
19. Ploeg, J.; Serrarens, A.F.A.; Heijenk, G.J. Connect & Drive: Design and evaluation of cooperative adaptive cruise control for congestion reduction. *J. Mod. Transp.* **2011**, *19*, 207–213. [CrossRef]
20. Fernandes, P.; Nunes, U. Platooning with IVC-enabled autonomous vehicles: Strategies to mitigate communication delays, improve safety and traffic flow. *IEEE Trans. Intell. Transp. Syst.* **2012**, *13*, 91–106. [CrossRef]
21. Martinez, L.M.; Viegas, J.M. Assessing the impacts of deploying a shared self-driving urban mobility system: An agent-based model applied to the city of Lisbon, Portugal. *Int. J. Transp. Sci. Technol.* **2017**, *6*, 13–27. [CrossRef]
22. Zhang, W.; Guhathakurta, S. Parking spaces in the age of shared autonomous vehicles: How much parking will we need and where? *Transp. Res. Rec.* **2017**, *2651*, 80–91. [CrossRef]
23. Brooker, A.D.; Ward, J.; Wang, L. Lightweighting Impacts on Fuel Economy, Cost, and Component Losses; SAE Technical Paper. 2013. Available online: https://doi.org/10.4271/2013-01-0381 (accessed on 22 May 2022).
24. Kang, L.; Sarker, A.; Shen, H. Velocity optimization of pure electric vehicles with traffic dynamics and driving safety considerations. *ACM Trans. Internet Things* **2021**, *2*, 1–24. [CrossRef]
25. Brown, A.; Repac, B.; Gonder, J. *Autonomous Vehicles Have a Wide Range of Possible Energy Impacts*; NREL, University of Maryland: Golden, CO, USA, 2013.
26. Wadud, Z.; MacKenzie, D.; Leiby, P. Help or hindrance? The travel, energy and carbon impacts of highly automated vehicles. *Transp. Res. Part A Policy Pract.* **2016**, *86*, 1–18. [CrossRef]
27. Zhong, Z.; Lee, J.; Zhao, L. Multiobjective optimization framework for cooperative adaptive cruise control vehicles in the automated vehicle platooning environment. *Transp. Res. Rec.* **2017**, *2625*, 32–42. [CrossRef]
28. Mazur, C.; Offer, G.J.; Contestabile, M.; Brandon, N.B. Comparing the effects of vehicle automation, policy-making and changed user preferences on the uptake of electric cars and emissions from transport. *Sustainability* **2018**, *10*, 676. [CrossRef]
29. Melis, W.J. The future of electrical vehicles. Autonomous Vehicles: Intelligent Transport Systems and Smart Technologies 2014. pp. 509–530. Available online: https://www.researchgate.net/publication/290364043_The_future_of_electrical_vehicles (accessed on 22 May 2022).
30. Raposo, A.; Grosso, M.; Macías, F.; Galassi, E.; Krasenbrink, C.; Krause, A.; Levati, J.; Saveyn, A.; Thiel, B.; Ciuffo, C. *An Analysis of Possible Socio-Economic Effects of a Cooperative, Connected and Automated Mobility (CCAM) in Europe*; Publications Office of the European Union: Luxembourg, 2018; ISBN 978-92-79-85856-7.
31. Lee, H.; Choi, H. Comparison of fuel efficiency and economical speed for internal combustion engine vehicle and battery electric vehicle using backward-looking simulation. *J. Mech. Sci. Technol.* **2017**, *31*, 4499–4509. [CrossRef]
32. Greenblatt, J.B.; Shaheen, S. Automated vehicles, on-demand mobility, and environmental impacts. *Curr. Sustain. Energy Rep.* **2015**, *2*, 74–81. [CrossRef]

33. Rojas-Rueda, D.; Nieuwenhuijsen, M.J.; Khreis, H.; Frumkin, H. Autonomous vehicles and public health. *Annu. Rev. Public Health* **2019**, *41*, 329–345. [CrossRef]
34. Stern, R.E.; Chen, Y.; Churchill, M.; Wu, F.; Delle Monache, M.L.; Piccoli, B.; Seibold, B.; Sprinkle, J.; Work, D.B. Quantifying air quality benefits resulting from few autonomous vehicles stabilizing traffic. *Transp. Res. Part D Transp. Environ.* **2019**, *67*, 351–365. [CrossRef]
35. Rafael, S.; Correia, L.P.; Lopes, D.; Bandeira, J.; Coelho, M.C.; Andrade, M.; Borrego, C.; Miranda, A.I. Autonomous vehicles opportunities for cities air quality. *Sci. Total Environ.* **2020**, *712*, 136546. [CrossRef]
36. Zadeh, L.A. Fuzzy sets. In *Fuzzy Sets, Fuzzy Logic, and Fuzzy Systems: Selected Papers by Lotfi A Zadeh*; World Scientific: Singapore, 1996; pp. 394–432.
37. Wang, Y.; Xu, Z.S. A new method of giving OWA weights. *Math. Pract. Theory* **2008**, *38*, 51–61.
38. Yager, R.R. On ordered weighted averaging aggregation operators in multicriteria decisionmaking. *IEEE Trans. Syst. Man Cybern.* **1988**, *18*, 183–190. [CrossRef]
39. Kan, S.; Guo, F.; Li, S. An approach to evaluating the knowledge management performance with interval-valued intuitionistic uncertain linguistic information. *J. Intell. Fuzzy Syst.* **2016**, *30*, 1557–1565. [CrossRef]