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Alternative-Fuel based Vehicles for Sustainable Transportation: A Fuzzy Group Decision Supporting Framework for Sustainability Prioritization

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Abstract: The development of alternative-fuel vehicles has been recognized as a promising way for emissions reduction from transportation. This study aims to develop a fuzzy group decision supporting framework for sustainability prioritization of alternative-fuel based vehicles. A criteria system which consists of thirteen evaluation criteria in environmental, economic, technological and social aspects was developed for sustainability assessment of alternative-fuel vehicles. The linear goal programming priority based Fuzzy Analytic Hierarchy Process was employed to determine the weights of the evaluation criteria for sustainability assessment of alternative-fuel vehicles, and Fuzzy Group Multi-Attribute Decision Analysis which allows multiple groups of stakeholders to participate in the decision-making process for rating the alternative-fuel vehicles with respect to the evaluation criteria was developed for sustainability prioritization of alternative-fuel vehicles. Three alternative-fuel based vehicles including compressed natural gas based, liquid petroleum gas based, and biodiesel based vehicles were studied by the developed method, and the sustainability sequence of these three scenarios from the most sustainable to the least is biodiesel based vehicle, compressed natural gas based vehicle and liquid petroleum gas based vehicle, thus, China's administration should give the first priority to biodiesel based vehicle under the current context of China. The results were validated by the fuzzy TOPSIS method, and sensitivity analysis was also carried out to test the effects of the weights of the evaluation criteria on the sustainability order of the three alternative-fuel based vehicles.

Keywords: Alternative-fuel vehicles; transportation; fuzzy set; group decision making; multi-criteria decision analysis

1. Introduction

Transportation contributed to about 15% of the global greenhouse gas (GHG) emissions, the ratio of GHG emission contributed by transportation will increase as the transportation of goods in a global level is expect to contentiously increase (Pålsson and Johansson, 2016;OECD,2010). Climate change has caused many large impacts on economy, natural and managed ecosystems, and human health, etc. In order to mitigate the climate change potential, the reduction of GHG emissions from transportation is of vital importance. However, Gajjar and Mondol (2016) pointed out that emissions reduction from road transport sector became more complex and complicated due to the vast array of competing alternative technologies and measures which are available to both the consumers and the administrators. For instance, there are various alternative-fuel vehicles for emissions reduction and promoting the concept of sustainable and low-carbon transportation, i.e. electric vehicles, hydrogen fuel cell vehicles, liquid natural gas based vehicles, and biodiesel based vehicles, etc. The prioritization of these alternative-fuel vehicles is beneficial for the stakeholders/policy-makers to draft appropriate strategies for suitable promoting the development of alternative-fuel vehicles. However, it is usually difficult for the stakeholders/policy-makers to know the priority order to different alternative-fuel vehicle due to the difference in their relative performances on economic, environmental and technological aspects. Accordingly, developing the method for comparative evaluation of different alternative-fuel vehicles and determine their priority order is of vital importance.

There are many studies focusing on using the multi-criteria decision making (MCDM) or multi-attribute decision analysis methods for ranking the alternative-fuel vehicles. For instance, Mohamadabadi *et al*. (2009) employed Preference Ranking Organization Method for Enrichment and Evaluations (PROMETHEE) to rank different road transportation fuel-based vehicles including both renewable and non-renewable energy based on vehicles, and both the hard and the soft criteria were used to rank the renewable and non-renewable transportation fuel vehicles. Lanjewar *et al*. (2015) developed a hybrid multi-criteria decision making method by combining graph theory and analytic hierarchy process to rank the alternative fuels for transportation. Streimikiene *et al*. (2013) employed the interval TOPSIS method which can address uncertainties for comparative assessment of energy technologies for road transport, because the life cycle emissions (i.e. particulates, greenhouse gases, CO and NO_x, etc.) and private costs of different scenarios vary in an interval. T*zeng* et al. (2005) used the Analytic Hierarchy Process (AHP) method to determine the relative importance of the evaluation criteria for assessing the alternative-fuel buses, and TOPSIS and VIKOR were applied simultaneously to determine the best compromise alternative fuel mode with comparisons. However, sometime it is difficult or even impossible to obtain the exact data of the alternative-fuel vehicles with respect to the evaluation. For example, Sehatpour *et al.* (2017) employed the PROMETHEE method to evaluate the alternative fuels for light-duty vehicles in Iran, but the data of these alternatives scenarios with respect to the evaluation criteria were based on the subjective judgments of the experts, as some data cannot be obtained. Yavuz *et al*. (2015) used a hierarchical hesitant fuzzy linguistic model to evaluate the alternative-fuel vehicles, and linguistic terms were employed to determine the relative importance of the criteria and rate the alternative-fuel vehicles with respect to the evaluation criteria. Meanwhile, the accurate determination of the weights of the evaluation criteria is of vital importance for accurately ranking of the alternative-fuel vehicles. However, the most popular weighting method-AHP cannot accurately and exactly incorporate the opinions and preferences of the decision-makers when establishing the comparison matrix for determining the weights of the evaluation criteria due to the subjectivity and vagueness existing in human judgments. Fuzzy set theory can effectively address. For example, Onat *et al*. (2016) employed life cycle sustainability assessment method to collect the data with respect to the criteria in the three pillars of sustainability (economic, social and environmental aspects), and the

Intuitionistic Fuzzy Multi-Criteria Decision Making and Technique for Order Preference by Similarity to Ideal Solution methods were used to rank the alternative passenger vehicles. Moreover, the evaluation of the alternative-fuel vehicles usually involves multiple groups of stakeholders, and different stakeholders have different preferences, thus, determining the priority order of the alternative-fuel vehicles should incorporate the opinions of different stakeholders. In other words, group decision-making on ranking the alternative-fuel vehicles is prerequisite. Based on the above-mentioned literature reviews, it could be concluded that there are three research gaps for ranking the alternative-fuel vehicles:

(1) The difficulty of accurately incorporating the opinions and preferences of the decision-makers when calculating the weights of the evaluation criteria;
(2) The difficulty of obtaining the data of the alternative-fuel vehicles with respect to the evaluation criteria;
(3) The lack of the method for incorporating the opinions and willingness of different stakeholders.

This study aims to develop a fuzzy group decision supporting framework which can address the above-mentioned three gaps for sustainability ranking of the alternative-fuel vehicles. Besides the introduction, the remaindering parts of this study have been structured as follows: the criteria system for sustainability assessment of alternative-fuel vehicles was developed in section 2; section 3 presented the fuzzy group decision supporting method for ranking the alternative-fuel vehicles according to their sustainability performances; an illustrative case was studied in section 4; sensitivity analysis and validation was carried in section 5; and finally this study has been discussed and concluded in section 6.

2. Criteria for sustainability assessment

There are various studies about comparative assessment of alternative fuels for transportation. For instance, Streimikiene *et al*. (2013) employed six criteria in environmental and economic dimensions for road transport technologies, and they are GHG, PM10, NO_x, CO, and HC emissions in environmental aspect and cost in economic aspect. Five criteria including vehicle cost, fuel cost, distance between refueling stations, number of vehicle options available to the consumer, and GHG emissions were used to rank the renewable and non-renewable transportation fuel vehicles (Mohamadabadi *et al*., 2009). Twelve criteria were used for evaluating the alternative-fuel vehicles, e.g., purchase cost, operation cost, safety, perceived quality, filling station availability, GHG emission, social welfare impact, market penetration and secondary market development, etc. (Yavuz *et al*., 2015). Fourteen criteria, including imports (foreign purchases) , gross operating surplus (business profits), gross domestic product (GDP), employment, and government tax in economic dimension, injuries, carbon footprint, water withdrawal, energy consumption, and hazardous waste generation in social dimension, and fishery, grazing, forestry, cropland, and CO_2 uptake land in environmental dimension, were used to measure the life cycle sustainability performance of different alternative vehicle technologies (Onat *et al*., 2016). A criteria system which includes energy supply, energy efficiency, air pollution, noise pollution, industrial relationship, cost of implementation, costs of maintenance, vehicle capacity, was established to have a multi-attribute evaluation of alternative-fuel buses (Tzeng *et al*., 2005). It is apparent that different decision-makers/stakeholders established different evaluation criteria systems for evaluating the alternative-fuel vehicles, because different decision-makers/stakeholders have different preferences and willingness.

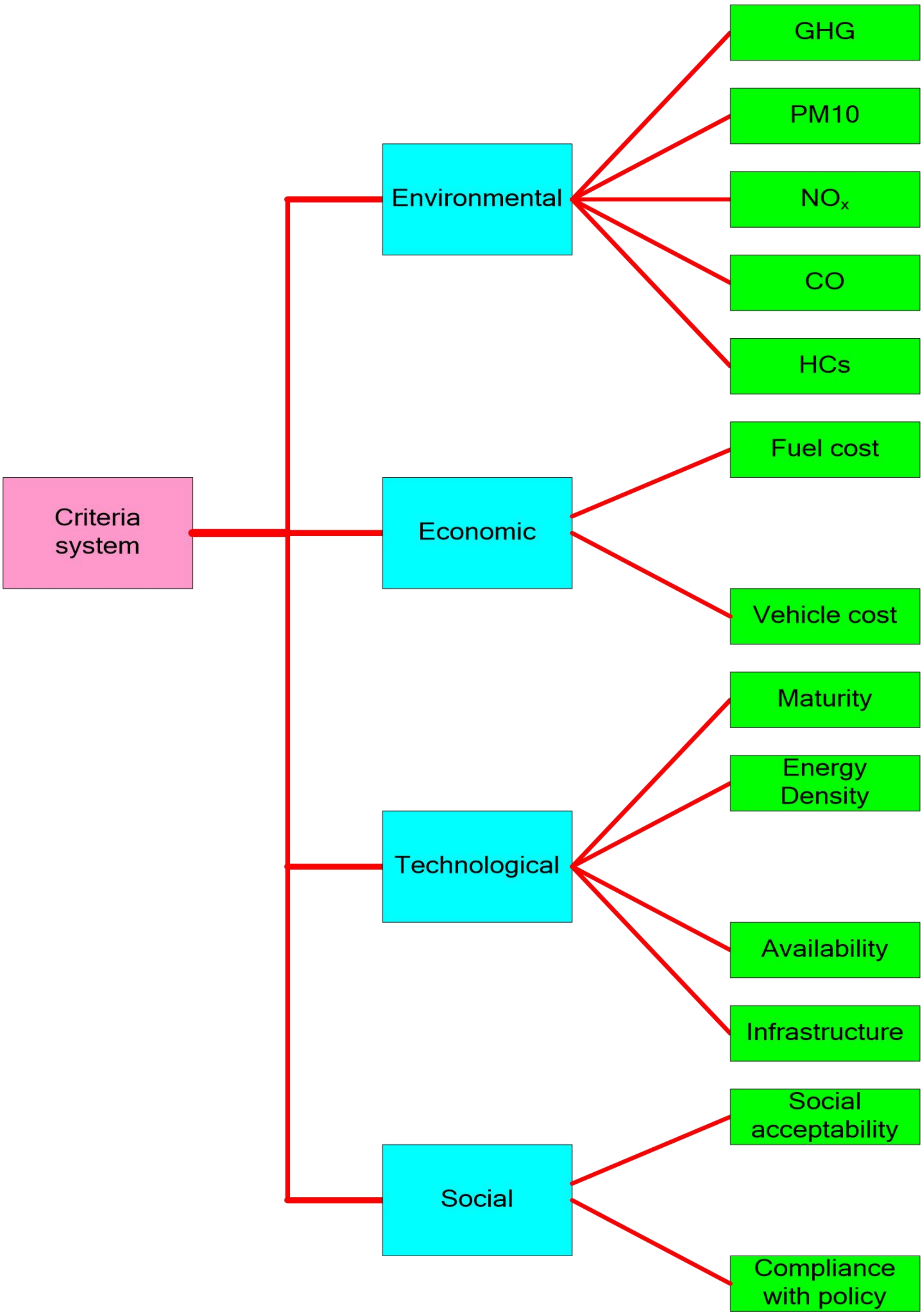

Figure 1: The criteria systems for sustainability assessment of alternative-fuel vehicles

Based on the above-mentioned literature reviews, a criteria system (see Figure 1) which consists of thirteen criteria in four aspects, and they are the emissions of GHG, PM10, NO_x, CO and HCs in environmental aspect, fuel cost and vehicle cost in economic aspect, maturity, energy density, availability, and infrastructure in technological aspect, and social acceptability and compliance with policy. The definitions of these criteria have been specified as follows:

(1) Environmental aspect: GHG, PM10, NO_x, CO and HCs in environmental aspect refer to the emissions of greenhouse gases, particulate matter less than 10 mm in size, nitrogen oxides, carbon monoxide, and hydrocarbons per vehicle per km (Streimikiene *et al*., 2013; Luo *et al*., 2017a; Luo *et al*., 2017b);

(2) Economic aspect: fuel cost and vehicle cost refer to the cost of fuels per km and the average vehicle cost, respectively (Streimikiene *et al*., 2013);

(3) Technological aspect: maturity refers to technological maturity of alternative-fuel vehicles; energy density refers to the embodied energy per unit volume; availability refers to the current production and retail availability for vehicles; and infrastructure refers to the perfection degree of the distribution infrastructure for supporting the corresponding alternative-fuel vehicles (Sehatpour *et al.*, 2017); and

(4) Social aspect: social acceptability is used to measure the acceptance of the stakeholders when adopting the alternative-fuel vehicles; and compliance with policy refers to the supporting degree of governmental policies and regulations on some certain alternative-fuel vehicles.

3. Fuzzy group decision supporting framework

A group decision supporting framework was developed in this study based on fuzzy set theory for ranking the alternative fuels for transportation according to their comprehensive sustainability performances. The preliminary knowledge was firstly introduced in section 3.1: then, the linear goal programming priority based Fuzzy Analytic Hierarchy Process was presented in section 3.2; finally, a novel Fuzzy Group Multi-Attribute Decision Analysis for ranking the alternative fuels was developed in section 3.3.

3.1 Preliminary knowledge

Definition 1. Positive triangular fuzzy numbers (Dimuro, 2011; Molinari, 2016)

The positive triangular fuzzy number $\tilde{x}$ is a triple-tuple $\tilde{x} = \left(x^1, x^2, x^3\right)$ which satisfies $0 < x^1 \le x^2 \le x^3$. The membership function of x with respect to fuzzy set $\tilde{x}$ can be determined by Eq.1.

$$\mu_{\tilde{A}}(x) = \begin{cases} 0 & x \le a^1 \\ L(x) & a^1 < x \le a^2 \\ R(x) & a^2 < x \le a^3 \\ 0 & x > a^3 \end{cases} \tag{1}$$

where $L(x) = \dfrac{x - a^1}{a^2 - a^1}$ is a continuous strictly increasing linear function

with $L\left(a^1\right) = 0, L\left(a^2\right) = 1$ and $R(x) = \dfrac{a^3 - x}{a^3 - a^2}$ is a continuous strictly decreasing linear

function with $R\left(a^2\right) = 1, R\left(a^3\right) = 0$.

Definition 2. Arithmetic operations (Tadić et al., 2014; Opricovic, 2011; Mayyas *et al.*, 2016)

Assuming that $\tilde{x} = \left(x^1, x^2, x^3\right)$ and $\tilde{y} = \left(y^1, y^2, y^3\right)$ are two positive triangular fuzzy numbers, and the arithmetic operations between them were illustrated in Eq.2-8.

Addition

$$\tilde{x}+\tilde{y}=\left(x^1,x^2,x^3\right)+\left(y^1,y^2,y^3\right)=\left(x^1+y^1,x^2+y^2,x^3+y^3\right) \tag{2}$$

Subtraction

$$\tilde{x}+\tilde{y}=\left(x^1,x^2,x^3\right)+\left(y^1,y^2,y^3\right)=\left(x^1+y^1,x^2+y^2,x^3+y^3\right) \tag{3}$$

Multiplication

$$\tilde{x}\times\tilde{y}=\left(x^1,x^2,x^3\right)\times\left(y^1,y^2,y^3\right)=\left(x^1y^1,x^2y^2,x^3y^3\right) \tag{4}$$

Division

$$\tilde{x}\div\tilde{y}=\left(x^1,x^2,x^3\right)\div\left(y^1,y^2,y^3\right)=\left(x^1/y^3,x^2/y^2,x^3/y^1\right) \tag{5}$$

Reciprocal

$$1/\tilde{x}=1/\left(x^1,x^2,x^3\right)=\left(\frac{1}{x^3},\frac{1}{x^2},\frac{1}{x^1}\right) \tag{6}$$

Multiplication with scalar

$$\alpha\tilde{x}=\left(\alpha x^1,\alpha x^2,\alpha x^3\right) \tag{7}$$

Division with scalar

$$\tilde{x}/\alpha=\left(x^1/\alpha,x^2/\alpha,x^3/\alpha\right) \tag{8}$$

where $\alpha>0$ is a real number.

Definition 3. Euclidean distance

$$d(\tilde{x},\tilde{y}) = \sqrt{\left(x^1 - y^1\right)^2 + \left(x^2 - y^2\right)^2 + \left(x^3 - y^3\right)^2} \tag{9}$$

where $d(\tilde{x},\tilde{y})$ represents the Euclidean distance between $\tilde{x}$ and $\tilde{y}$.

3.2 The linear goal programming priority based Fuzzy Analytic Hierarchy Process

The linear goal programming priority based Fuzzy Analytic Hierarchy Process (LGPPFAHP) method was specified in the following four steps based on the work of Wang and Chin (2008):

Step 1: Determining the fuzzy pair-wise comparison matrix by using the positive triangular fuzzy numbers.

Assume that there are a total of n factors (i=1,2,…, n) to be studied, and the i-th criterion was denoted by C_i. In order to overcome the weaknesses existing in human's judgments, i.e. vagueness, ambiguity and subjectivity, the LGPPFAHP uses the positive triangular fuzzy numbers, which can describe the preferences/opinions of the decision-makers more accurately than the nine-scale system (the numbers from 1 to 9 and their reciprocals which are commonly used in the traditional AHP) to compare the relative importance/priority between each pair of factors, to establish the fuzzy comparison matrix. The fuzzy pair-wise comparison matrix can be established by the decision-makers using the triangular fuzzy numbers presented in Table 1. The fuzzy comparison matrix and the elements in this matrix were illustrated in Eq.1 and Eq.2, respectively.

$$\tilde{M} = \begin{vmatrix} (1,1,1) & \tilde{m}_{12} & \cdots & \tilde{m}_{1n} \\ 1/\tilde{m}_{12} & (1,1,1) & \cdots & \tilde{m}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/\tilde{m}_{1n} & 1/\tilde{m}_{2n} & \cdots & (1,1,1) \end{vmatrix} \tag{10}$$

$$\tilde{m}_{ji} = \frac{1}{\tilde{m}_{ij}} = \left(\frac{1}{m_{ij}^3}, \frac{1}{m_{ij}^2}, \frac{1}{m_{ij}^1}\right) \tag{11}$$

where $\tilde{M}$ is the fuzzy comparison matrix, $\tilde{m}_{ij} = \left(m_{ij}^1, m_{ij}^2, m_{ij}^3\right)$ is a triangular fuzzy number which represents the relative importance of the C_i compared with C_j, and m_{ij}^1, m_{ij}^2 and m_{ij}^3 are the three elements of the triangular fuzzy number $\tilde{m}_{ij}$.

Table 1: The linguistic variables and their corresponding fuzzy numbers for establishing the fuzzy pairwise comparison

Linguistic scales	Abbreviations	Fuzzy scales
Equal importance	E	(1,1,1)
Weak importance	W	(2/3,1,3/2)
Moderate importance	M	(1,3/2,2)
Fairly strong importance	FS	(3/2,2,5/2)
Very strong importance	VS	(2,5/2,3)
Absolute importance	A	(5/2,3,7/2)
Reciprocals of these	RW, RM, RFS, RVS, RA	The reciprocals of these fuzzy number

Sources: modified from Tseng *et al*. (2009)

Step 2: Decomposing the fuzzy comparison matrix into three crisp nonnegative matrices.

The fuzzy comparison matrix presented in Eq.1 can be divided into three crisp nonnegative matrices including (see Eqs. 12-14). The elements of cell (i, j) in these three matrices are the three elements of $\tilde{a}_{ij}$ that is the element of cell (i,j) in the fuzzy comparison matrix $\tilde{A}$, respectively.

$$M_1 = \begin{vmatrix} 1 & m_{12}^1 & \cdots & m_{1n}^1 \\ 1/m_{12}^3 & 1 & \cdots & m_{2n}^1 \\ \vdots & \vdots & \ddots & \vdots \\ 1/m_{n1}^3 & 1/m_{2n}^3 & \cdots & 1 \end{vmatrix} \qquad (12)$$

$$M_2 = \begin{vmatrix} 1 & m_{12}^2 & \cdots & m_{1n}^2 \\ 1/m_{12}^2 & 1 & \cdots & m_{2n}^2 \\ \vdots & \vdots & \ddots & \vdots \\ 1/m_{n1}^2 & 1/m_{2n}^2 & \cdots & 1 \end{vmatrix} \tag{13}$$

$$M_3 = \begin{vmatrix} 1 & m_{12}^3 & \cdots & m_{1n}^3 \\ 1/m_{12}^1 & 1 & \cdots & m_{2n}^3 \\ \vdots & \vdots & \ddots & \vdots \\ 1/m_{n1}^1 & 1/m_{2n}^1 & \cdots & 1 \end{vmatrix} \tag{14}$$

Step 3: Establishing the linear programming to determine the fuzzy weights of the factors.

The objective of this programming is to minimize the overall degree of inconsistency of the fuzzy comparison matrix determined in step 1, and the constraints of this programming were presented in Eqs.15-24.

$$Minimize \quad D = e^T(E^+ + E^- + \Gamma^+ + \Gamma^- + \Delta) \tag{15}$$

$$(A_L - I)W_U - (n-1)W_L - E^+ + E^- = 0 \tag{16}$$

$$(A_U - I)W_L - (n-1)W_U - \Gamma^+ + \Gamma = 0 \tag{17}$$

$$(A_M - nI)W_M - \Delta = 0 \tag{18}$$

$$\omega_i^L + \sum_{j=1, j\neq i}^{n} \omega_j^U \geq 1, i = 1, 2, \cdots, n \tag{19}$$

$$\omega_i^U + \sum_{j=1, j\neq i}^{n} \omega_j^L \leq 1, i = 1, 2, \cdots, n \tag{20}$$

$$\sum_{i=1,}^{n} \omega_i^M = 1 \tag{21}$$

$$W_U - W_M \geq 0 \tag{22}$$

$$W_M - W_L \geq 0 \tag{23}$$

$$W_L, E^+, E^-, \Gamma^+, \Gamma^-, \Delta \geq 0 \tag{24}$$

where D represents the total deviations to reflect the degree of inconsistency of the fuzzy comparison matrix $\tilde{A}, W_L = \left(\omega_1^L, \omega_2^L, \cdots, \omega_n^L\right)^T$, $W_M = \left(\omega_1^M, \omega_2^M, \cdots, \omega_n^M\right)^T$, and $W_U = \left(\omega_1^U, \omega_2^U, \cdots, \omega_n^U\right)^T$ are the matrices in which the element of cell (i,1) are the three elements of $\tilde{\omega}^i$, respectively. $\tilde{\omega}^i = \left(\omega_i^L, \omega_i^M, \omega_i^U\right)$ represents the fuzzy weight of the *i*-th criterion, and ω_i^L, ω_i^M, and ω_i^U are the three elements of $\tilde{\omega}^i$ respectively.

$e^T = (1,1,\cdots,1), E^+ = \left(\varepsilon_1^+, \varepsilon_2^+, \cdots, \varepsilon_n^+\right)^T, E^- = \left(\varepsilon_1^-, \varepsilon_2^-, \cdots, \varepsilon_n^-\right)^T, \Gamma^+ = \left(\gamma_1^+, \gamma_2^+, \cdots, \gamma_n^+\right)^T$,

$\Gamma^- = \left(\gamma_1^-, \gamma_2^-, \cdots, \gamma_n^-\right)^T$, and $\Delta = \left(\delta_1, \delta_2, \cdots, \delta_n\right)^T$ are all nonnegative deviation vectors.

Step 4: Defuzzification and normalization.

The fuzzy weight of the i-th criterion by $\tilde{\omega}^i = \left(\omega_i^L, \omega_i^M, \omega_i^U\right)$ can be defuzzified into crisp weights by the Mean Area (MA) method (Ren *et al.*, 2015), as presented in Eq.25. Finally, the crisp weights can be normalized according to Eq.26.

$$\omega_i^{'} = \frac{\omega_i^L + 2\omega_i^M + \omega_i^U}{4} \tag{25}$$

$$\omega_i = \omega_i^{'} \Big/ \sum_{i=1}^{n} \omega_i^{'} \tag{26}$$

where $\omega_i^{'}$ is the defuzzified weight of the i-th criterion, and ω_i is the normalized weight of the i-th criterion.

3.3 Fuzzy Group Multi-Attribute Decision Analysis

A novel Fuzzy Group Multi-Attribute Decision Analysis (FGMADA) was developed in this study for prioritizing the alternatives, and it consists of five steps:

Step 1: Scoring the alternatives with respect to the evaluation criteria. A set of linguistic variables (see Eq.27) including "Very Poor", "Poor", "Moderately Poor", "Moderate", "Moderately Good", "Good", and "Very Good" can be used to rate the alternatives with respect to each evaluation criterion (You *et al.*, 2010).

$$S = \{s_0, s_1, s_2, s_3, s_4, s_5, s_6\}$$
$$= \{VP(Very\ Poor), P(Poor), MP(Moderately\ Poor), M(Moderate), MG(Moderately\ Good), G(Good), VG(Very\ Good)\}$$
(27)

It is worth pointing out that the users can set the set of the linguistic variables according to their requirements and the actual conditions. As for a set of linguistic variables consisting of T elements $S = \{s_0, s_1, \cdots, s_T\}$, the linguistic terms s_i can be transformed into triangular fuzzy numbers according to Eq.28.

$$r_i = \left(r_i^1, r_i^2, r_i^3\right) = \left(\max\{(i-1)/T, 0\}, i/T, \min\{(i+1)/T, 1\}\right) \tag{28}$$

Taking the set of the linguistic variables presented in Eq.27 as an example, these linguistic variables can be transformed into:

$$s_0 = VP(Very\ Poor): r_0 = \left(\max\{(0-1)/6, 0\}, 0/6, \min\{(0+1)/6, 1\}\right) = \left(0, 0, 1/6\right) \tag{29}$$

$$s_1 = P(Poor): r_1 = \left(\max\{(1-1)/6, 0\}, 1/6, \min\{(1+1)/6, 1\}\right) = \left(0, 1/6, 1/3\right) \tag{30}$$

$$s_2 = MP(Moderately\ Poor): r_2 = \left(\max\{(2-1)/6, 0\}, 2/6, \min\{(2+1)/6, 1\}\right) = \left(1/6, 1/3, 1/2\right) \tag{31}$$

$$s_3 = M(Moderate): r_3 = \left(\max\{(3-1)/6, 0\}, 3/6, \min\{(3+1)/6, 1\}\right) = \left(1/3, 1/2, 2/3\right) \tag{32}$$

$$s_4 = MP(Moderately\ Good): r_4 = \left(\max\{(4-1)/6, 0\}, 4/6, \min\{(4+1)/6, 1\}\right) = \left(1/2, 2/3, 5/6\right) \tag{33}$$

$$s_5 = G(Good): r_5 = \left(\max\{(5-1)/6, 0\}, 5/6, \min\{(5+1)/6, 1\}\right) = \left(2/3, 5/6, 1\right) \quad (34)$$

$$s_6 = VG(Very\ Good): r_6 = \left(\max\{(6-1)/6, 0\}, 6/6, \min\{(6+1)/6, 1\}\right) = \left(5/6, 1, 1\right) \quad (35)$$

As for problem with a total of m alternatives ($A_1, A_2, \ldots, A_m$.) with the considerations of n evaluation criteria ($C_1, C_2, \ldots, C_n$) which were evaluated by a total of K decision-makers/stakeholders (k=1,2,…,K) participating in the process of rating the alternatives with respect each of the evaluation criteria, denotes the evaluation of the *k*-th decision-maker on the *i*-th alternative with respect to the *j*-th criterion by r_{ij}^k, the decision-making matrix can be represented by Eq.36 after the rating process.

$$\begin{array}{cccccc} & A_1 & A_2 & \cdots & A_m \\ C_1 & \tilde{r}_{11} & \tilde{r}_{21} & \cdots & \tilde{r}_{m1} \\ C_2 & \tilde{r}_{12} & \tilde{r}_{22} & \cdots & \tilde{r}_{m2} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ C_n & \tilde{r}_{1n} & \tilde{r}_{2n} & \cdots & \tilde{r}_{mn} \end{array} \quad (36)$$

where $\tilde{r}_{ij} = \sum_{k=1}^{K} r_{ij}^k / K$ in cell (j,i) of the decision-making matrix represents the relative priority of the *i*-th alternative with respect to the *j*-th evaluation criterion.

Step 2: Determining the ranking matrix of the alternatives according to their performances with respect to each evaluation criterion. The comparison of the performances of the alternatives with respect to each evaluation criterion can be determined by Eq.37 according to You *et al*. (2010).

$$\begin{aligned} P\left(\tilde{r}_{ij} \geq \tilde{r}_{tj}\right) = p_{it}^j = \lambda \max\left\{1 - \max\left\{(b^m - a^l)/(a^m - a^l + b^m - b^l), 0\right\}\right\} \\ + \left(1-\lambda\right)\max\left\{1 - \max\left\{(b^u - a^m)/(a^u - a^m + b^u - b^m), 0\right\}\right\} \end{aligned} \quad (37)$$

where $P\left(\tilde{r}_{ij} \geq \tilde{r}_{tj}\right) = p_{it}^{j}$ represents the possibility of the *i*-th alternative be greater than the *t*-th alternative with respect to the *j*-th criterion.

The possibility matrix with respect to the *j*-th criterion can be determined, as presented in Eq.38.

$$P^{j} = \begin{matrix} 0.5 & p_{12}^{j} & \cdots & p_{1m}^{j} \\ p_{21}^{j} & 0.5 & \cdots & p_{2m}^{j} \\ \vdots & \vdots & \ddots & \vdots \\ p_{m1}^{j} & p_{m2}^{j} & \cdots & 0.5 \end{matrix} \tag{38}$$

The priority performance (PP) of the *i*-th alternative with respect to the *j*-th criterion can be determined by Eq.39 according to Xu (2002).

$$PP_{i} = \frac{1}{m}\left(\sum_{j=1}^{m} p_{ij}^{j} + 1 - \frac{m}{2}\right) \quad i = 1, 2, \cdots, m \tag{39}$$

According to the PPs of the alternatives, and the ranking matrix with respect to each evaluation criterion can be determined, as presented in Eq.40.

$$R^{j} = \begin{matrix} C_{j} & 1 & 2 & \cdots & m \\ A_{1} & r_{11}^{j} & r_{12}^{j} & \cdots & r_{1m}^{j} \\ A_{2} & r_{21}^{j} & r_{22}^{j} & \cdots & r_{2m}^{j} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_{m} & r_{m1}^{j} & r_{m2}^{j} & \cdots & r_{mm}^{j} \end{matrix} \tag{40}$$

where R^{j} is the ranking matrix with respect to the *j*-th criterion, and $r_{it}^{j}\left(i = 1, 2, \cdots, m; t = 1, 2, \cdots, m\right)$ is a binary variable 0-1, when it equals 1, it means that the *i*-th alternative has been ranked in the *t*-th position according to its performance with respect to the j-th criterion; while when it equals 0, it means that the *i*-th alternative has not been ranked in the *t*-th position according to its performance with respect to the j-th criterion.

Step 3: Determining the weighted ranking matrix with respect to each evaluation criterion. The weighting ranking matrix with respect to the *j*-th criterion can be determined by Eq.41. $r_{it}'^{j}$ can be recognized as the supporting degree of ranking the *i*-th alternative in the *t*-th position with respect to the *j*-th criterion.

$$WR^j = \begin{matrix} C_j & 1 & 2 & \cdots & m \\ A_1 & \omega_j r_{11}^j & \omega_j r_{12}^j & \cdots & \omega_j r_{1m}^j \\ A_2 & \omega_j r_{21}^j & \omega_j r_{22}^j & \cdots & \omega_j r_{2m}^j \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_m & \omega_j r_{m1}^j & \omega_j r_{m2}^j & \cdots & \omega_j r_{mm}^j \end{matrix} = \begin{matrix} C_j & 1 & 2 & \cdots & m \\ A_1 & r_{11}'^j & r_{12}'^j & \cdots & r_{1m}'^j \\ A_2 & r_{21}'^j & r_{22}'^j & \cdots & r_{2m}'^j \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_m & r_{m1}'^j & r_{m2}'^j & \cdots & r_{mm}'^j \end{matrix} \tag{41}$$

where WR^j represents the weighted ranking matrix with respect to the *j*-th criterion, and $r_{it}'^{j}$ is the element of cell (i,t) in the weighted ranking matrix.

Step 4: Determining the sum weighted ranking matrix. The weighted sum ranking matrix can be obtained by Eq.42.

$$WR = \sum_{j=1}^{m} WR^j = \begin{matrix} C_j & 1 & 2 & \cdots & m \\ A_1 & d_{11} & d_{12} & \cdots & d_{1m} \\ A_2 & d_{21} & d_{22} & \cdots & d_{2m} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_m & d_{m1} & d_{m2} & \cdots & d_{mm} \end{matrix} \tag{42}$$

where d_{it} represents the supporting degree of ranking the *i*-th alternative in the *t*-th position.

Step 5: Determining the programming for determine the priority order of the alternatives. A programming model which aims at optimizing the total supporting degree of the ranking was developed for ranking the alternatives (Li, 2003; Ren *et al.*, 2013).

$$Max\, S = \sum_{i=1}^{m} \sum_{t=1}^{m} d_{it} x_{it} \tag{43}$$

Meanwhile, it should satisfy that each alternative can only be ranked in one position, and one position can also only accommodate one alternative. Accordingly, this programming should satisfy:

$$\sum_{t=1}^{m} x_{it} = 1 \qquad i = 1, 2, \cdots, m \tag{44}$$

$$\sum_{i=1}^{m} x_{it} = 1 \qquad t = 1, 2, \cdots, m \tag{45}$$

x_{it} is a binary variable 0-1, when it equals 1, it means that the *i*-th alternative has been ranked in the *t*-th position; when it equals 0, it means that the *i*-th alternative has not been ranked in the *t*-th position, so it could be obtained that

$$x_{it} = \{0,1\} \tag{46}$$

where S is the total supporting degree of the ranking

After solving the programming, the priority of the m alternatives can be determined.

4 Case study

In order to illustrate the developed model for sustainability prioritization of alternative-fuel based vehicles for transportation, three representative alternative-fuel vehicles in China have been studied in this section, and they are:

Compressed natural gas based vehicle (CNG): CNG is the compressed form of natural gas, and CNG is steadily becoming a viable alternative recently because of its advantages of lower fuel cost, great potential for greenhouse gases mitigation, lower noise level, and lower particulate emissions (Goulding *et al.*, 2016).

Liquid petroleum gas based vehicle (LPG): LPG, is the generic name of commercial propane and butane, so-called "autogas", is the byproduct of natural gas processing and petroleum refining which mainly consists of propane, some propylene, butane and other light hydrocarbons (Raslavičius *et al*., 2014). LPG has a special property that it becomes liquid at atmospheric temperature if appropriately compressed, and reverts to gas when the pressure has been lowered, and this special property makes LGP suitable for transportation and storage in the form of liquid as an alternative fuel (Adland *et al*., 2008).

Biodiesel based vehicle (B): Biodiesel which has been recognized as a promising candidate fuel used in diesel engines refers to the monoalkyl esters of animal fats or vegetable oils, the most significant advantage of biodiesel is its environmental friendliness compared with gasoline and petroleum diesel, because it can produced by a variety of non-staple crops, i.e. soybean, rapeseed and palm oils (Demirbas, 2007).

The thirteen criteria on four dimensions have been used for sustainability prioritization of the three alternative fuels for transportation, the LGPPFAHP method was firstly employed to determine the weights of the four dimensions as well as that of the criteria in each dimension. Taking the determination of the weights of the four dimensions as an example:

Step 1: Determining the fuzzy pair-wise comparison matrix for determining the weights of the four dimensions by using the triangular fuzzy numbers. For instance, the decision-makers held the view that relative importance of the "environmental dimension" over the "economic dimension" is "moderate importance (M)" which corresponds to (1,3/2,2), and (1,3/2,2) was put in cell (1,2) of the comparison matrix. In a similar way, all the elements in the comparison matrix can be determined, and the result was presented in Table 2.

Table 2: Fuzzy comparison matrix with respect to the four categories

	Environmental	Economic	Technological	Social
Environmental	(1,1,1)	(1,3/2,2)	(2/3,1,3/2)	(3/2,2,5/2)
Economic	(1/2,2/3,1)	(1,1,1)	(1/2,2/3,1)	(1,3/2,2)
Technological	(2/3,1,3/2)	(1,3/2,2)	(1,1,1)	(2,5/2,3)
Social	(2/5,1/2,2/3)	(1/2,2/3,1)	(1/3,2/5,1/2)	(1,1,1)

Step 2: The fuzzy comparison matrix presented in Table 2 can be decomposed into three crisp nonnegative matrices (see Eqs.47-49).

$$A_L = \begin{vmatrix} 1 & 1 & 2/3 & 3/2 \\ 1/2 & 1 & 1/2 & 1 \\ 2/3 & 1 & 1 & 2 \\ 2/5 & 1/2 & 1/3 & 1 \end{vmatrix} \tag{47}$$

$$A_M = \begin{vmatrix} 1 & 3/2 & 1 & 2 \\ 2/3 & 1 & 2/3 & 3/2 \\ 1 & 3/2 & 1 & 5/2 \\ 1/2 & 2/3 & 2/5 & 1 \end{vmatrix} \tag{48}$$

$$A_U = \begin{vmatrix} 1 & 2 & 3/2 & 5/2 \\ 1 & 1 & 1 & 2 \\ 3/2 & 2 & 1 & 3 \\ 2/3 & 1 & 1/2 & 1 \end{vmatrix} \tag{49}$$

Step 3: Establishing the linear programming to determine the fuzzy weights of the four dimensions. According to Eqs.15-24, the following programming can be established, and Eqs.50-59 correspond to each of the equations in Eqs.15-24, respectively.

$$Minimize \quad D = \varepsilon_1^+ + \varepsilon_2^+ + \varepsilon_3^+ + \varepsilon_4^+ + \varepsilon_1^- + \varepsilon_2^- + \varepsilon_3^- + \varepsilon_4^- + \gamma_1^+ + \gamma_2^+ + \gamma_3^+ + \gamma_4^+ + \gamma_1^- + \gamma_2^- + \gamma_3^- + \gamma_4^- + \delta_1 + \delta_2 + \delta_3 + \delta_4 \quad (50)$$

$$\begin{aligned}
&\omega_2^U + 2/3\,\omega_3^U + 3/2\,\omega_4^U - 3\omega_1^L - \varepsilon_1^+ + \varepsilon_1^- = 0\\
&1/2\,\omega_1^U + 1/2\,\omega_3^U + \omega_4^U - 3\omega_2^L - \varepsilon_2^+ + \varepsilon_2^- = 0\\
&2/3\,\omega_1^U + \omega_2^U + 2\omega_4^U - 3\omega_3^L - \varepsilon_3^+ + \varepsilon_3^- = 0\\
&2/5\,\omega_1^U + 1/2\,\omega_2^U + 1/3\,\omega_3^U - 3\omega_4^L - \varepsilon_4^+ + \varepsilon_4^- = 0
\end{aligned} \quad (51)$$

$$\begin{aligned}
&2\omega_2^L + 3/2\,\omega_3^L + 5/2\,\omega_4^L - 3\omega_1^U - \gamma_1^+ + \gamma_1^- = 0\\
&\omega_1^L + \omega_3^L + 2\omega_4^L - 3\omega_2^U - \gamma_2^+ + \gamma_2^- = 0\\
&3/2\,\omega_1^L + 2\omega_2^L + 3\omega_4^L - 3\omega_3^U - \gamma_3^+ + \gamma_3^- = 0\\
&2/3\,\omega_1^L + \omega_2^L + 1/2\,\omega_3^L - 3\omega_4^U - \gamma_4^+ + \gamma_4^- = 0
\end{aligned} \quad (52)$$

$$\begin{aligned}
&-3\omega_1^M + 3/2\,\omega_2^M + \omega_3^M + 2\omega_4^M - \delta_1 = 0\\
&2/3\,\omega_1^M - 3\omega_2^M + 2/3\,\omega_3^M + 3/2\,\omega_4^M - \delta_2 = 0\\
&\omega_1^M + 3/2\,\omega_2^M - 3\omega_3^M + 5/2\,\omega_4^M - \delta_3 = 0\\
&1/2\,\omega_1^M + 2/3\,\omega_2^M + 2/5\,\omega_3^M - 3\omega_4^M - \delta_4 = 0
\end{aligned} \quad (53)$$

$$\begin{aligned}
&\omega_1^L + \omega_2^U + \omega_3^U + \omega_4^U \geq 1\\
&\omega_2^L + \omega_1^U + \omega_3^U + \omega_4^U \geq 1\\
&\omega_3^L + \omega_1^U + \omega_2^U + \omega_4^U \geq 1\\
&\omega_4^L + \omega_1^U + \omega_2^U + \omega_3^U \geq 1
\end{aligned} \quad (54)$$

$$\begin{aligned}
&\omega_1^U + \omega_2^L + \omega_3^L + \omega_4^L \leq 1\\
&\omega_2^U + \omega_1^L + \omega_3^L + \omega_4^L \leq 1\\
&\omega_3^U + \omega_1^L + \omega_2^L + \omega_4^L \leq 1\\
&\omega_4^U + \omega_1^L + \omega_2^L + \omega_3^L \leq 1
\end{aligned} \quad (55)$$

$$\omega_1^M + \omega_2^M + \omega_3^M + \omega_4^M = 1 \quad (56)$$

$$\begin{aligned}
&\omega_1^U - \omega_1^M \ge 0 \\
&\omega_2^U - \omega_2^M \ge 0 \\
&\omega_3^U - \omega_3^M \ge 0 \\
&\omega_4^U - \omega_4^M \ge 0
\end{aligned} \tag{57}$$

$$\begin{aligned}
&\omega_1^M - \omega_1^L \ge 0 \\
&\omega_2^M - \omega_2^L \ge 0 \\
&\omega_3^M - \omega_3^L \ge 0 \\
&\omega_4^M - \omega_4^L \ge 0
\end{aligned} \tag{58}$$

$$\begin{aligned}
&\left(\omega_1^L, \omega_2^L, \omega_3^L, \omega_4^L\right)^T \ge 0 \\
&\left(\varepsilon_1^+, \varepsilon_2^+, \varepsilon_3^+, \varepsilon_4^+\right)^T \ge 0 \\
&\left(\varepsilon_1^-, \varepsilon_2^-, \varepsilon_3^-, \varepsilon_4^-\right)^T \ge 0 \\
&\left(\gamma_1^+, \gamma_2^+, \gamma_3^+, \gamma_4^+\right)^T \ge 0 \\
&\left(\gamma_1^-, \gamma_2^-, \gamma_3^-, \gamma_4^-\right)^T \ge 0 \\
&\left(\delta_1, \delta_2, \delta_3, \delta_4\right)^T \ge 0
\end{aligned} \tag{59}$$

After solving the programing, it could be obtained the minimum value of the total deviations $D = 0.0118$, it reflects the degree of inconsistency of the fuzzy comparison matrix is low, because the value of the total deviations is near 0. In other words, the established comparison matrix has high consistency, and the results were summarized in Table 3.

Table 3: The results of the programming presented in Eqs.50-59

ω_1^L	ω_1^M	ω_1^U	ω_2^L	ω_2^M	ω_2^U	ω_3^L	ω_3^M
0.2394	0.3125	0.3477	0.1686	0.2143	0.2506	0.2629	0.3304
ε_1^-	ε_2^-	ε_3^-	ε_4^-	γ_1^+	γ_2^+	γ_3^+	γ_4^+
0	0	0	0	0	0	0	0
ω_3^U	ω_4^L	ω_4^M	ω_4^U	ε_1^+	ε_2^+	ε_3^+	ε_4^+
0.3568	0.1247	0.1429	0.1532	0	0	0	0.0091
γ_1^-	γ_2^-	γ_3^-	γ_4^-	δ_1	δ_2	δ_3	δ_4
0	0	0	0	0	0	0	0.0027

Step 4: The fuzzy weights of the four dimensions can be defuzzified and normalized. According to Eq.25, the crisp weights of the four dimensions can be obtained. Taking the crisp weight of the "environmental dimension" as an example:

$$\omega_{Environemntal} = \frac{\omega_{Environmental}^L + 2\omega_{Environmental}^M + \omega_{Environmental}^U}{4} = \frac{0.2394 + 2\times 0.3125 + 0.3477}{4} = 0.3030$$

(60)

In a similar way, the weights of the other three dimensions can also be determined, and the results were presented in Table 4.

Table 4: The crisp weights and the normalized weights of the four dimensions

	Environmental	Economic	Technological	Social
Crisp weights	0.3030	0.2120	0.3201	0.1409
Normalized weights	0.3105	0.2172	0.3280	0.1444

Similarly, the local weights of the criteria in each dimension can be determined, and the results were presented in Tables 5-7. It is worth pointing out that the two criteria in social aspects, namely, social acceptability and compliance with policy, were recognized as equally important, this, their local weights in social aspect are 0.5000 and 0.5000, respectively.

Table 5: The fuzzy comparison matrix for determining the weights of the five criteria in environmental aspect

	GHG	PM10	NO_x	CO	HCs
GHG	(1,1,1)	(1/2,2/3,1)	(3/2,2,5/2)	(3/2,2,5/2)	(2/3,1,3/2)
PM10	(1, 3/2,2)	(1,1,1)	(2,5/2,3)	(2,5/2,3)	(1,3/2,2)
NO_x	(2/5,1/2,2/3)	(1/3,2/5,1/2)	(1,1,1)	(2/3,1,3/2)	(2/5,1/2,2/3)
CO	(2/5,1/2,2/3)	(1/3,2/5,1/2)	(2/3,1,3/2)	(1,1,1)	(1/2,2/3,1)
HCs	(2/3,1,3/2)	(1/2,2/3,1)	(3/2,2,5/2)	(1,3/2,2)	(1,1,1)
Fuzzy weights	(0.1803,0.2272,0.2489)	(0.2560, 0.3166,0.3203)	(0.0942,0.1165,0.1281)	(0.1032,0.1250,0.1384)	(0.1642,0.2147,0.2421)
Crisp weights	0.2209	0.3024	0.1138	0.1229	0.2089
Normalized weights	0.2280	0.3121	0.1175	0.1268	0.2156
D=0.0253, it indicates the established comparison matrix has high consistency					

Table 6: The fuzzy comparison matrix for determining the weights of the two criteria in economic aspect

	Fuel cost	Vehicle cost
Fuel cost	(1,1,1)	(1/2,2/3,1)
Vehicle cost	(1,3/2,2)	(1,1,1)
Fuzzy weights	(0.3333,0.4000,0.5000)	(0.5000,0.6000,0.6667)
Crisp weights	0.4083	0.5917
Normalized weights	0.4083	0.5917

D=0, it indicates the established comparison matrix has high consistency

Table 7: The fuzzy comparison matrix for determining the weights of the four criteria in technological aspect

	Maturity	Energy density	Availability	Infrastructure
Maturity	(1,1,1)	(3/2,2,5/2)	(1,3/2,2)	(2/3,1,3/2)
Energy density	(2/5,1/2,2/3)	(1,1,1)	(1/2,2/3,1)	(1/2,2/3,1)
Availability	(1/2,2/3,1)	(1,3/2,2)	(1,1,1)	(2/3,1,3/2)
Infrastructure	(2/3,1,3/2)	(1,3/2,2)	(2/3,1,3/2)	(1,1,1)
Fuzzy weights	(0.2544,0.3215,0.3397)	(0.1380,0.1642,0.1854)	(0.1880,0.2437,0.2762)	(0.1987,0.2705,0.3132)
Crisp weights	0.3093	0.1630	0.2379	0.2632
Normalized weights	0.3178	0.1675	0.2444	0.2704
D=0.0274, , it indicates the established comparison matrix has high consistency				

After determining the weights of the four dimensions and that of the criteria in each dimension, the global weights of the criteria can be determined by calculating the product of the local weight of the criterion with the weight of the dimension to which the criterion belongs to, and the results were summarized in Table 8.

Table 8: The global weights of the criteria

	Weights	Criteria	Local weights	Global weights
Environmental	0.3105	GHG	0.2280	0.0708
		PM10	0.3121	0.0969
		NO_x	0.1175	0.0365
		CO	0.1268	0.0394
		HCs	0.2156	0.0669
Economic	0.2172	Fuel cost	0.4083	0.0887
		Vehicle cost	0.5917	0.1285
Technological	0.3280	Maturity	0.3178	0.1042
		Energy density	0.1675	0.0549
		Availability	0.2444	0.0802
		Infrastructure	0.2704	0.0887
Social	0.1444	Social acceptability	0.5000	0.0722
		Compliance with policy	0.5000	0.0722

There are three groups of decision-makers from China in the decision-making process, including academic group (DM#1), administrator group (DM#2), and user group (DM#3). The first group (DM#1) consists of seven experts of alternative fuels for transportation including three professors of transportation engineering, two senior researchers of renewable energy, and two PhD candidates of low-carbon transportation. The second group (DM#2) consists of five administrators including two senior managers from the corporate of renewable energy vehicles and three administrators from the Planning Bureau of the local government. The third group (DM#3) consists of five drivers and three passengers who cannot drive. A director was select for coordinating meeting of each group for rating the three alternative fuels for transportation to achieve consensus. The results of rating the three alternative fuels using linguistic variables (see Eq.27) by three groups of decision-makers were presented in Table 9.

Table 9: The relative performances of the three alternatives with respect to the evaluation criteria using linguistic variables

	CNG	LPG	B
GHG	s_2, s_3, s_2	s_1, s_1, s_2	s_4, s_5, s_6
PM10	s_5, s_6, s_3	s_2, s_5, s_4	s_1, s_3, s_2
NO_x	s_6, s_5, s_4	s_3, s_4, s_3	s_0, s_2, s_1
CO	s_1, s_2, s_2	s_2, s_3, s_4	s_3, s_5, s_3
HCs	s_2, s_1, s_1	s_3, s_4, s_5	s_2, s_3, s_3
Fuel cost	s_0, s_2, s_1	s_0, s_1, s_0	s_4, s_2, s_5
Vehicle cost	s_3, s_5, s_3	s_2, s_4, s_3	s_3, s_5, s_5
Maturity	s_6, s_4, s_3	s_3, s_4, s_4	s_3, s_2, s_1
Energy density	s_2, s_2, s_3	s_3, s_1, s_2	s_4, s_5, s_6
Availability	s_3, s_3, s_2	s_1, s_2, s_3	s_0, s_2, s_0
Infrastructure	s_2, s_4, s_3	s_1, s_3, s_2	s_2, s_0, s_1
Social acceptability	s_3, s_6, s_6	s_3, s_2, s_4	s_4, s_6, s_5
Compliance with policy	s_5, s_3, s_4	s_2, s_3, s_2	s_5, s_6, s_6

It is worth pointing out that the rating of the three alternative fuels with respect to the evaluation criteria were based on their relative performances. As for the cost-type criteria (i.e. GHG, PM10, and CO, etc.), the less the values of the fuels with respect to these criteria, and the better the alternative fuels will be. Accordingly, a higher score will be assigned to the alternative fuels whose values with respect to the cost-type criteria are lower. While for the benefit-type criteria (i.e. maturity, energy density, and social acceptability, etc.), the greater the values of the fuels with respect to these criteria, the better the alternative will be. Accordingly, a higher score will be assigned to the alternative fuels whose values with respect to the type-type criteria are higher.

After rating the alternative fuels, the linguistic variables presented in Table 9 can be transformed into triangular fuzzy numbers according to Eqs.29-35. After determining all the elements in the decision-making matrix, the ranking matrix with respect to each of the evaluation criteria can be determined. Taking the ranking matrix with respect to social acceptability as an example:

The performances of CNG with respect to social acceptability determined by the three groups of decision-makers/stakeholders are s_3, s_6, s_6, respectively, and they can be transformed into $(1/3,1/2,2/3)$, $(5/6,1,1)$, and $(5/6,1,1)$, respectively. According to Eq.36, the performance of CNG with respect to social acceptability is $(2/3,5/6,8/9)$. In a similar way, the performance of LPG and B with respect to social acceptability can also be determined, and they are $(1/3,1/2,2/3)$ and $(2/3,5/6,1)$.

According to Eq.37, the comparisons between each pair of the three alternative fuels with respect to social acceptability can be determined. For instance, the probability of CNG be greater than B with respect to social acceptability can be determined by Eq.61.

$$p_{CNG,B}^{social\ acceptability} = 0.5\max\left\{1-\max\left\{(5/6-2/3)/(5/6-2/3+5/6-2/3),0\right\}\right\}$$
$$+\left(1-0.5\right)\max\left\{1-\max\left\{(1-5/6)/(8/9-5/6+1-5/6),0\right\}\right\} \quad (61)$$
$$=0.3750$$

Therefore, all the elements in the possibility matrix with respect to social acceptability can be determined, as presented in Eq.62.

$$\begin{array}{cccc} & CNG & LPG & B \\ CNG & 0.5000 & 1 & 0.3750 \\ LPG & 0 & 0.5000 & 0 \\ B & 0.6250 & 1 & 0.5000 \end{array} \quad (62)$$

The priority performance of the three alternative fuels with respect to social acceptability can be determined by Eq.39, and the results were presented in Eq.63-65.

$$PP_{CNG} = \frac{1}{3}\left(0.5000+1+0.3750+1-\frac{3}{2}\right) = 0.4583 \quad (63)$$

$$PP_{LPG} = \frac{1}{3}\left(0+0.5000+0+1-\frac{3}{2}\right) = 0 \quad (64)$$

$$PP_{B} = \frac{1}{3}\left(0.6250+1+0.5000+1-\frac{3}{2}\right) = 0.5437 \quad (65)$$

It could be obtained that $PP_B > PP_{CNG} > PP_{LPG}$, thus, the priority order of the three alternative fuels with respect to social acceptability from the best to least is biodiesel, compressed natural gas, and liquid petroleum gas. According to Eq.40, the ranking matrix with respect to social acceptability can be determined, and the result was presented in Eq.66.

$$\begin{array}{cccc} & 1 & 2 & 3 \\ CNG & 0 & 1 & 0 \\ LPG & 0 & 0 & 1 \\ B & 1 & 0 & 0 \end{array} \tag{66}$$

Similarly, the ranking matrices with respect to some other criteria can also be determined, and the results were summarized in Table 10.

Table 10: The ranking matrices with some other evaluation criteria

GHG	1	2	3	PM10	1	2	3	NO_x	1	2	3	CO	1	2	3
CNG	0	1	0	CNG	1	0	0	CNG	1	0	0	CNG	0	0	1
LPG	0	0	1	LPG	0	1	0	LPG	0	1	0	LPG	0	1	0
B	1	0	0	B	0	0	1	B	0	0	1	B	1	0	0
HCs	1	2	3	Fuel cost	1	2	3	Vehicle cost	1	2	3	Maturity	1	2	3
CNG	0	0	1	CNG	0	1	0	CNG	0	1	0	CNG	1	0	0
LPG	1	0	0	LPG	0	0	1	LPG	0	0	1	LPG	0	1	0
B	0	1	0	B	1	0	0	B	1	0	0	B	0	0	1
ergy density	1	2	3	Availability	1	2	3	Infrastructure	1	2	3	Compliance with policy	1	2	3
CNG	0	1	0	CNG	1	0	0	CNG	1	0	0	CNG	0	1	0
LPG	0	0	1	LPG	0	1	0	LPG	0	1	0	LPG	0	0	1
B	1	0	0	B	0	0	1	B	0	0	1	B	1	0	0

According to Eqs.41-42, the sum weighted ranking matrix can be determined, as presented in Eq.67.

$$\begin{matrix} & 1 & 2 & 3 \\ CNG & 0.4065 & 0.4873 & 0.1063 \\ LPG & 0.0669 & 0.4459 & 0.4873 \\ B & 0.5267 & 0.1338 & 0.4065 \end{matrix} \tag{67}$$

After determining the sum weighted ranking matrix, the programming for determining the priority order of these three alternative fuels for transportation can be determined according to Eqs.43-46, and the established programming were presented in Eqs.68-71.

$$\begin{aligned} Max\, S = & 0.4065x_{11} + 0.4873x_{12} + 0.1063x_{13} + 0.0669x_{21} \\ & +0.4459x_{22} + 0.4873x_{23} + 0.5267x_{31} + 0.1338x_{32} + 0.4065x_{33} \end{aligned} \tag{68}$$

$$\sum_{t=1}^{3} x_{it} = 1 \qquad i = 1,2,3 \tag{69}$$

$$\sum_{i=1}^{m} x_{it} = 1 \qquad t = 1,2,3 \tag{70}$$

$$x_{it} = \{0,1\} \tag{71}$$

After solving this programming, the maximum value of the total supporting degree of the ranking is 1.5013, and the results of the variables were presented in Table 11.

Table 11: The results of the programming (Eqs.68-71)

Variables	x_{11}	x_{12}	x_{13}	x_{21}	x_{22}	x_{23}	x_{31}	x_{32}	x_{33}
	0	1	0	0	0	1	1	0	0

Accordingly, it could be obtained that biodiesel based vehicle was recognized as the most sustainable options among these three scenarios, followed by compressed natural gas based and liquid petroleum gas based vehicles. The results are reasonable, because biodiesel based vehicle has the best economic performances (the lowest fuser and vehicle cost), meanwhile it also has the least GHG and CO emissions. Moreover, the energy density, the social acceptability and compliance with policy of biodiesel is the highest. However, it is worth pointing out that the sustainability ranking was based on the current conditions of China as well as the opinions/preferences of the selected representative groups of decision-makers/stakeholders. The sustainability order of the three alternative-fuel vehicles may change with the technological development of these alternative-fuel vehicles and the progress in infrastructure construction. In addition, the preferences and willingness of the decision-makers/stakeholders also have significant impacts on the sustainability order of the three alternative-fuel based vehicles (see the results in sensitivity analysis). Accordingly, the sustainability order of the three alternative-fuel vehicles may also change when the decision-makers/stakeholders have been changed.

5 Sensitivity analysis and validation

In order to validate the results determined by the developed FGMADA method, the fuzzy TOPSIS method (Sun ,2010) was also employed to determine the sustainability order of the three alternative-fuel vehicles for transportation, and the comparisons of the results determined by these two methods were presented in Table 12.

Table 12: The comparisons of the sustainability ranking determined by the FGMADA method and the fuzzy TOPSIS method

	CNG	LPG	B
Ranking by the developed method	2	3	1
Ranking by fuzzy TOPSIS	2	3	1

The sustainability order of the three alternative-fuel vehicles determined by the fuzzy TOPSIS method is consistent with that determined by the developed FGMADA method. However, it is worth pointing out that this does not mean that the priority orders determined by these two methods are always the same though the results determined by these two methods are the same in this case, because there is a significant difference between these two methods- the FGMADA method cannot comprehensively use the gaps between the alternatives with respect to the evaluation criteria.

Sensitivity analysis was also carried by altering the weights of the thirteen criteria, and the following fourteen cases have been studied:

Case 0: Equal weights-all the thirteen criteria were assigned an equal weight (0.0769);

Case (2-14): A dominant weight (0.52) was assigned to one criterion and the other criteria were assigned an equal weight (0.04).

The results of sensitivity analysis were presented in Table 13. It is obvious that the sustainability order of the three alternative-fuel vehicles varies with the change of the weights of the evaluation criteria. In other words, the weights of the thirteen criteria have highly impacts on the sustainability order of the three alternative-fuel vehicles for transportation.

Table 13: The results of sensitivity analysis

	CNG	LPG	B
Case 0	2	3	1
Case 1	2	3	1
Case 2	1	2	3
Case 3	1	2	3
Case 4	3	2	1
Case 5	3	1	2
Case 6	2	3	1
Case 7	2	3	1
Case 8	1	2	3
Case 9	2	3	1
Case 10	1	2	3
Case 11	1	2	3
Case 12	2	3	1
Case 13	2	3	1

6 Discussion and conclusion

This study aims at developing a group multi-attribute decision analysis method for sustainability ranking of the alternative-fuel vehicles for promoting the development of sustainable transportation or green transportation. A generic criteria system which consists of thirteen criteria in environmental, economic, technological and social aspects for sustainability ranking of alternative-fuel vehicles for transportation was developed. The linear goal programming priority based Fuzzy Analytic Hierarchy Process which allows the users to use the fuzzy numbers to establish the comparison matrix were employed to determine the weights of the evaluation criteria. A novel Fuzzy Group Multi-Attribute Decision Analysis method which allows multiple groups of stakeholders using linguistic to rate the alternative-fuel vehicles was developed to determine the sustainability order of the alternative-fuel vehicles.

In order to illustrate the developed model, three representative alternative-fuel vehicles including compressed natural gas based, liquid petroleum gas based, and biodiesel based vehicles were studied, and biodiesel based vehicles was recognized as the most sustainable in the current conditions of China. The fuzzy TOPSIS method was also used to determine the sustainability order to the three alternative-fuel vehicles, and the results determined by the fuzzy TOPSIS were consistent to that determined by the FGMADA method developed in this study. To some extent, it indicates the proposed method is feasible for determining the sustainability order of the alternative-fuel vehicles. Sensitivity analysis was also carried out by changing the weights of the evaluation criteria, and it could be concluded that the sustainability order of the three alternative-fuel vehicles was sensitive to the weights of the evaluation criteria. According to the results of the case study, it could be summarized that the developed method has the following advantages:

(1) Linguistic variables which can describe the opinions and preferences of the decision-

makers/stakeholders were used to establish the comparison matrix for weights determination and rate the alternative-fuel vehicles with respect to the evaluation criteria;

(2) Multiple groups of decision-makers /stakeholders were allowed to participate in the decision-making process.

However, the developed fuzzy group multi-attribute decision analysis also has a drawback-the ranking of the alternatives cannot effectively utilize the different between the alternatives with respect to each evaluation criterion. The future work of the authors will focus on developing a method which can incorporate the utilization of the alternatives with respect to each evaluation criterion for ranking the alternative-fuel vehicles for transportation.

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