

SELECTION OF COMMERCIALY AVAILABLE ALTERNATIVE PASSENGER VEHICLE IN AUTOMOTIVE ENVIRONMENT

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Abstract. *There has been a paradigm shift in the automobile industry due to e-mobility which reduces green-house gas emission and air pollution. In this context, selection of the most feasible automotive passenger vehicle is a complex decision-making problem due to the use of different power source, technology, specification and price. In this paper, five alternative vehicles based on fuel cell, hybrid electric, battery electric, plug in hybrid electric and compressed natural gas bi-fuel are evaluated using an integrated criteria importance through inter-criteria correlation (CRITIC) - Combined Compromise Solution (CoCoSo) method. CRITIC method is used to obtain the weights of the vehicle selection criteria, whereas, CoCoSo method is employed to rank the vehicles considering different technical and operational criteria such as greenhouse gas emission, fuel economy, vehicle range, accelerating time, annual fuel cost and vehicle base model cost. It is found that battery electric vehicle out performs all other considered alternatives. The validity of the results is verified by comparing with other well popular MCDM methods. Further, a sensitivity analysis is conducted by changing the criteria weights to establish the stability of the model.*

Key words: *Alternate passenger vehicle selection, CoCoSo, CRITIC, sensitivity analysis*

1. Introduction

Alternate fuel vehicles are those which can be fueled in part or full by electricity, hydrogen, biodiesel, compressed natural gas (CNG), liquefied petroleum gas (LPG)

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and ethanol as compared to the conventional petrol and diesel-based vehicles. The most commonly used alternate vehicles are battery-electric, hybrids, plug-in hybrids and fuel cell vehicles in addition to vehicles based on ethanol, biodiesel, biogas and hydrogen. The total environmental impact of the vehicle fleet is likely to decrease if conventional vehicles are replaced by alternate fuel vehicles. The alternate electric vehicle (EV) technology reduces emission, increases energy efficiency, does not have any energy consumption at static condition and also boosts with low ambient noise. Fuel cells, similar to EVs, also have no tailpipe emission, no corrosion to the engine and it is also quiet in operation. Hybrid EVs (HEVs) and plug-in HEVs (PHEVs) use a combination of internal combustion engines (ICE) along with an electric motor and reduce fuel consumption and green-house gases (GHGs). Bi-fuel vehicle is another type of alternate vehicle which reduces the tailpipe emission than petrol and diesel engines. According to a report (IEA 2019) that in 2018, more than 5.1 million the electric car was sold globally, out of these more than 66% of electric cars were battery EVs (BEVs). Market share of electric car has been steadily increasing from 50% (2012) to 68% (2018). China, Europe and United States are the world's largest electric car market. The report also indicated that by the end of 2018, global stock of electric busses was 4,60,000 while the same for two wheelers was 260 million. In 2018, sales of light-commercial vehicles were around 2,50,000 units and medium electric truck reached in the range of 1000-2000 units. In the same year, global EV stock aided publicly accessible 5.2 million light-duty vehicle chargers and 1,57,000 fast chargers for buses. It is also observed that, in 2018, EVs used about 58 terawatt-hours of electricity and produced 41 million tonnes of carbon-dioxide equivalent (CO_{2e}) on the road, that mean EVs saved 36 million tonnes of CO_{2e} as compared to an equivalent internal combustion engine vehicle.

In EV 2030 scenario, global EV sales are expected to be around 23 million (excluding two/three-wheelers) and would cut demand for fuel-based vehicles. BEVs and PHEVs are presently using electricity for battery charging. The current global average carbon intensity of electricity generation (518 gms of CO_{2e} /kWh) emits huge amount of GHG if the power generation mix is controlled by a high carbon source. CO₂ emissions at EVs are significantly reduced as the power generation is controlled by a low carbon power source. But in some countries, like India where the electric power is mainly produced by coal, therefore, hybrid vehicles emit lower GHG than the EVs. Further, the emission reduction potential of EVs over their entire life cycle can further be raised if electricity generation can be made decarbonized. Future concept in automobile sector now has been drastically changed. Therefore, the future demand for automobile sectors are renewable or alternate energy-based vehicles which can reduce emission from tailpipe and equivalent CO₂ emission from different sources. Therefore, appropriate selection of the alternate fuel car is now one of the most challenging areas and considered as a multi-attribute decision-making (MADM) process for stake holders like customers and governmental agencies due to the presence of several mutually conflicting attributes/criteria.

It has been observed that very less research works have yet been carried out in MADM domain focusing on the selection of the most feasible alternate fuel cars. Biswas & Das (2018a) applied entropy and multi-attributive border approximation area comparison (MABAC) methods for hybrid vehicle selection problems. Car model

cost, fuel economy, tank size, tail pipe emission and passenger volume were considered as the predominant selection criteria. Further, Biswas & Das (2018b) adopted fuzzy-analytic hierarchy process (AHP) and MABAC method for commercially available electric vehicle selection for a case study of United States. Various technical and operational attributes like fuel economy, base model pricing, quick accelerating time, battery range and top speed were considered. Biswas & Saha (2019) proposed a novel MADM approach for evaluating commercially available scooters and considered kerb weight, mileage, top speed, fuel tank capacity and price as the influential criteria.

In this paper, an endeavor is attempted to integrate two vastly used MADM methods, namely criteria importance through inter-criteria correlation (CRITIC) and Combined Compromise Solution (CoCoSo) for the evaluation and ranking of five alternative environment friendly vehicles. The CRITIC method is used to determine the weight coefficients associated with each vehicle selection criterion. Ranking of the vehicles is achieved using the CoCoSo method. Five different types of passenger vehicles such as Toyota Mirai (fuel cell vehicle), Tesla Model 3 (BEV), Toyota Prius eco (HEV), Honda clarity plug in (PHEV) and Chevrolet Impala Bi-Fuel (CNG vehicle) are considered as the alternatives. Fuel economy, range in mile, annual fuel cost (in \$), accelerating time from 0 to 60 mile per hour, vehicle cost (in \$) and tail pipe emission in gram/mile are considered as the attributes based on the data available in manufacturers' websites and catalogues. Finally, a sensitivity analysis is also performed to check the effect of changing criteria weights on the ranking performance of the integrated model.

The paper is organized as follows: after the introduction and literature review, section 2 presents the mathematical formulation of CRITIC and CoCoSo methods. Section 3 presents an application of the hybrid method for ranking of cars. A sensitivity analysis for the novel method is presented in Section 4. Section 5 presents the discussion and concluding remarks and directions for future research is presented in section 6.

2. Methodology

This section presents the mathematical formulations of CRITIC and CoCoSo methods which are subsequently applied for the evaluation of the alternate passenger cars.

2.1. CRITIC Method

CRITIC method was originally developed by Diakoulaki et al. (1995) for estimating criteria weights in MADM environment. Here correlation analysis is used to distinguish between different criteria (Yilmaz & Harmancioglu, 2010). This method is basically based on analytical testing of the decision matrix in order to determine the information contained by the criteria. There are many successful applications of CRITIC method for a wider range of applications such as pharmaceutical industries (Diakoulaki et al., 1995), water resource management model (Yilmaz & Harmancioglu, 2010), index system of city's soft power (Guo et al., 2013), financial statement of stock exchange (Kazan & Ozdemir, 2014) and non-traditional machining process (Madic & Radovanovic, 2015). CRITIC method has the following simple steps, as detailed below:

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Step-1. Formation of the decision matrix:

$$x_{ij} = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ \dots & \dots & \dots & \dots \\ x_{m1} & x_{m2} & \dots & x_{mn} \end{bmatrix}; i = 1, 2, \dots, m; j = 1, 2, \dots, n. \quad (1)$$

Step-2. Normalization of the decision matrix using the following equations:

$$r_{ij} = \frac{x_{ij} - \max x_{ij}}{\max x_{ij} - \min x_{ij}}; \text{ for benefit criteria} \quad (2)$$

$$r_{ij} = \frac{\max x_{ij} - x_{ij}}{\max x_{ij} - \min x_{ij}}; \text{ for cost criteria} \quad (3)$$

Step- 3: Calculation of symmetric linear correlation matrix (m_{ij}):

A linear correlation coefficient between the each pair of criteria is estimated using the following equation to quantify the conflict resulted among different criteria. It can be seen that the more discordant the scores of the alternatives in two criteria i and j , the lower the value m_{ij} .

$$m_{ij} = \frac{\sum_{i=1}^m (r_{ij} - \bar{r}_j)(r_{ik} - \bar{r}_k)}{\sqrt{\sum_{i=1}^m (r_{ij} - \bar{r}_j)^2 \sum_{i=1}^m (r_{ik} - \bar{r}_k)^2}} \quad (4)$$

Step- 4: Determination of the objective weight of a criterion also requires the estimation of both standard deviation of the criterion and its correlation with other criteria. In this regard, the weight of the j^{th} criterion (w_j) is obtained using the following expression.

$$w_j = \frac{C_j}{\sum_{j=1}^n C_j} \quad (5)$$

where, C_j is the amount of information contained in the criterion j and is determined as follows:

$$C_j = \sigma \sum_{j'=1}^n 1 - m_{jj'} \quad (6)$$

where σ is the standard deviation of j^{th} criterion and is the correlation coefficient between the two criteria. A higher value of C_j signifies greater amount of information contained in a particular criterion, hence it is provided with higher weight value.

2.2. Combined Compromise Solution (CoCoSo) Method

Yazdani, Zarate, Zavadskas, & Turskis, (2018) established the CoCoSo method. It is based on the integration of two most popular MCDM methods namely Simple

Additive Weighting (SAW) and Exponentially Weighted Product (MEP). Previous researchers applied CoCoSo methods in different area such as evaluation of electric vehicles under sustainable automotive environment (Biswas et al. 2019), manufacturing process (Acharya & Murmu, 2019), sustainable supplier selection (Zolfani et al. 2019). CoCoSo method consists of the following easy steps:

Step1. Formation of the original decision matrix $X=[x_{ij}]_{m \times n}$.

Step2. Then normalize the decision matrix as $N=[n_{ij}]_{m \times n}$ using Eqs (2) and (3).

Step3. Estimation of sum of weighted comparability (S_i) sequence and power weighted comparability sequences (P_i) for each alternative respectively.

$$S_i = \sum_{j=1}^n (w_j r_{ij}) \tag{7}$$

$$P_i = \sum_{j=1}^n (r_{ij})^{w_j} \tag{8}$$

Step 4. Computation of relative weights of the alternatives:

In this step, three aggregated appraisal scores are used to generate relative performance scores of the alternatives, using the following equations:

$$k_{ia} = \frac{P_i + S_i}{\sum_{i=1}^m (P_i + S_i)} \tag{9}$$

$$k_{ib} = \frac{S_i}{\min S_i} + \frac{P_i}{\min P_i} \tag{10}$$

$$k_{ic} = \frac{\lambda(S_i) + (1 - \lambda)(P_i)}{(\lambda \max S_i + (1 - \lambda) \max P_i)} \tag{11}$$

Step 5: The final ranking of the alternatives is determined based on k_i values: Higher k_i values indicate better position of the alternatives in the ranking pre-order.

$$k_i = (k_{ia} k_{ib} k_{ic})^{1/3} + 1/3(k_{ia} + k_{ib} + k_{ic}) \tag{12}$$

3. Case study

Now to explore the application potentiality of the integrated CRITIC-COCoSo model, a case study comprising five alternative vehicles is now considered under passenger car category with six criteria. The details are given in Table 1. The data set is retrieved from different manufacturers' websites and catalogue. Description of the considered evaluation criteria is provided in Table 2. Out of the six criteria, fuel economy (C1) and range (C2) are considered as beneficiary criterion or higher the better and rest four criteria are considered as non-beneficiary criterion or lower the better. Fuel cell EVs (FCEVs) are fueled with pure hydrogen gas and this is converted to electricity by the fuel cell. It is produce no harmful tailpipe emissions. FCEVs are attached with other advanced technologies like regenerative braking systems, which capture the energy lost during braking and store it in a battery. Driving range of this

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vehicle is very high. FCEVs are beginning to enter the consumer market in around the world. Toyota Mirai is the popular car under category of FCEV.

All BEVs get electricity from rechargeable battery packs. Benefits of the s as compare to conventional fuel are energy efficiency (EV convert above 60% of the electrical energy to power at the wheels), environmental friendliness, reduced energy dependency, smooth operation, less noise and less maintenance. Only the drawbacks are shorter driving range and high recharging time. An example of BEV is Tesla Model 3.

HEVs run by an ICE in combination with electric motors. In case of full hybrid vehicles, battery charging is done through a regenerative braking mechanism and ICE. This type of vehicle does not require plug in to charge. The benefits of HEVs are high fuel economy and low tailpipe emissions over ICE-based vehicles. Example of HEV is Toyota Prius eco.

PHEVs have an ICE and an electric motor where batteries provide the power to the motor and liquid fuel (mainly petrol or diesel) is used for the ICE. This type of vehicle has lower operating costs and low amount of fuel consumption in comparison to the conventional vehicles. PHEVs produce lower levels of GHGs, depending on the electricity source. The example of PHEV is Honda clarity.

In ICE vehicles, CNG is stored in a tank as compressed gaseous state. This fuel is used in light, medium, and heavy duty applications. Driving range is generally less in these vehicles than that of a diesel or petrol powered vehicle due to the the lower energy density. The advantages of CNG are high mileage and reduced GHG emissions over conventional petrol and diesel fuels. Light commercial vehicles are typically equipped with dedicated or bi-fuel systems. Chevrolet Impala bi-fuel car is a popular example of CNG vehicle.

Table 1. Decision matrix for selection of alternate car

Alternate fuel car	Fuel economy (Mi/ gallon) (C1)	Range (miles) (C2)	Annual fuel cost(\$) (C3)	Acceleration (0-60mph) (C4)	Cost (\$) (C5)	Tail pipe emission (gms/mile) (C6)
Toyota Mirai (A1)	67	312	1250	9.4	58365	0
Tesla model 3 (A2)	133	240	500	3.7	39500	0
Toyota Prius eco (A3)	56	633	700	10.2	28000	158
Honda-clarity plug in (A4)	110	340	700	9.5	34320	57
Chevrolet Impala Bi-Fuel (CNG) (A5)	20	360	1850	7.9	37,570	405

Sources: Manufacturing website and www.fueleconomy.gov

Table 2. Descriptions of different criteria for selecting best alternate car

Criteria	Description
C1	It indicates that how much mile the vehicle can go by using a quantity of fuel. It is expressed in mile per gallon. Improve fuel economy saves money, reduces climate change, and reduces oil dependence cost.
C2	Range means that the maximum distance the car can travel between two subsequent charging for electric vehicle but in case of petroleum fuel it indicates that how much distance covered a car by from full tank to empty tank. Its unit is mile. Range on a tank assumes 100% of fuel in tank will be used before refueling.
C3	Its calculates, based on 45% highway, 55% city driving, 15,000 annual miles and current fuel prices. (Diesel per gallon price \$2.97, petrol regular fuel price \$2.55 and electricity \$0.13/kWh)
C4	It signifies that how much time is required to accelerate the car from 0 to 60 Mile per hour. It is identifies by time(in seconds)
C5	It is the selling price of vehicle in dollar.
C6	Tail pipe emission is the exhaust gas of the vehicle which produced after the combustion of fossil fuels. It is expressed as gram per mile. These are the responsible for greenhouse effect, causing climate change, photochemical smog, acid rain, reducing visibility, aggravating heart and lung diseases.

At first, the criteria weights for the alternate fuel car selection case study are computed using CRITIC method. As the initial step, the decision matrix of Table 1 is first normalized using Eqs. (2) and (3) respectively for beneficial and cost criteria, as shown in Table 3. This table also presents the σ values. Subsequently, inter criteria correlation values are presented in Table 4. Finally, the criteria weights are estimated using Eqn. (5), as shown in Table 5. According to the weight values of Table 5, C2 is the most important criterion, whereas C3 is the least important criterion.

Table 3. Normalized decision matrix

Alternate fuel car	C1	C2	C3	C4	C5	C6
A1	0.42	0.18	0.44	0.12	0.00	1.00
A2	1.00	0.00	1.00	1.00	0.62	1.00
A3	0.32	1.00	0.85	0.00	1.00	0.61
A4	0.80	0.25	0.85	0.11	0.79	0.86
A5	0.00	0.31	0.00	0.35	0.68	0.00
Standard deviation (σ)	0.396	0.382	0.408	0.403	0.375	0.419

Table 4. Correlation coefficient values of paired criteria

Criteria	C1	C2	C3	C4	C5	C6
C1	1	-0.4753	0.8368	0.5254	0.0038	0.8128
C2	-0.4753	1	0.0784	-0.636	0.5809	-0.3156
C3	0.8368	0.0784	1	0.2341	0.3286	0.7452
C4	0.5254	-0.636	0.2341	1	-0.0522	0.1747
C5	0.0038	0.5809	0.3286	-0.0522	1	-0.3741
C6	0.8128	-0.3156	0.7452	0.1747	-0.3741	1

Table 5. Weights of the BEV selection criteria

Criteria	C1	C2	C3	C4	C5	C6
C _j	1.306	2.204	1.134	1.916	1.692	1.659
W _j	0.132	0.222	0.114	0.193	0.171	0.167

After finding out of criteria weights using the CRITIC method, the considered alternate fuel car selection problem is now solved by CoCoSo method. After the formation of the decision matrix of Table 1, normalized decision matrix, sum of weighted comparability sequence, power weight of comparability sequences and the overall score of the alternatives are determined using the respective equations provided in Section 2. The final ranking of the considered vehicle alternatives is obtained according to the descending order of the *k* values (Table 6). This table indicates that Tesla model 3 (A1) is the most favorite vehicle while Chevrolet Impala Bi-Fuel (A5) emerges out as the least preferred alternative.

In Table 6, ranking of the alternative cars is also verified by comparing the performance of the integrated CRITIC-CoCoSo method with some of the well popular MADM methods like technique for order preference by similarity to an ideal solution (TOPSIS) (Chiang & Cheng, 2009) and MABAC (Pamucar & Cirovic, 2015) methods. As can be seen from Table 6 that A2 (Tesla model 3) remains the best alternative for all the considered MADM methods.

Table 6. Calculated score values in CoCoSo method and rank comparison

Alternate fuel car	Si	Pi	Kia	Kib	Kic	Ki	CoCoSo	MABAC	TOPSIS
A1	0.34	4.15	0.19	2.98	0.75	2.05	4	4	4
A2	0.71	4.92	0.23	4.77	0.94	3.00	1	1	1
A3	0.63	4.76	0.22	4.39	0.90	2.80	3	2	3
A4	0.56	5.28	0.24	4.30	0.97	2.84	2	3	2
A5	0.25	2.52	0.12	2.00	0.46	1.33	5	5	5

4. Sensitivity Analysis

The aim of the sensitivity analysis (SA) is to assess the impact of different parameters on the ranking performance of the integrated model.

4.1 Influence of criteria weights

Results of any MADM method depend on criteria weights to a great extent. Sometimes, the final selection may change when there is a change in the weight coefficients of the criteria. In this section, a sensitivity analysis is performed to assess how changes in the criteria weights affect the ranking of the alternative fuel cars by interchanging the criteria weight values in order of 6C_2 i.e. for the six considered criteria (C1–C6), the total number of possible interchanges becomes fifteen (6C_2). Here, 6 represents the number of criteria and 2 represents the number of criteria chosen at a time. Thus, in the sensitivity plot (Fig. 1), all sets of priority rankings of alternate fuel vehicle are presented. It may be observed from the sensitivity plot that the rank of the alternatives have no changes with the interchanging of criteria weights. From Fig. 1, it is clear that Tesla model 3 remains the best alternative and Chevrolet impala bi-fuel (CNG) remains the least preferred choice for the considered case study.

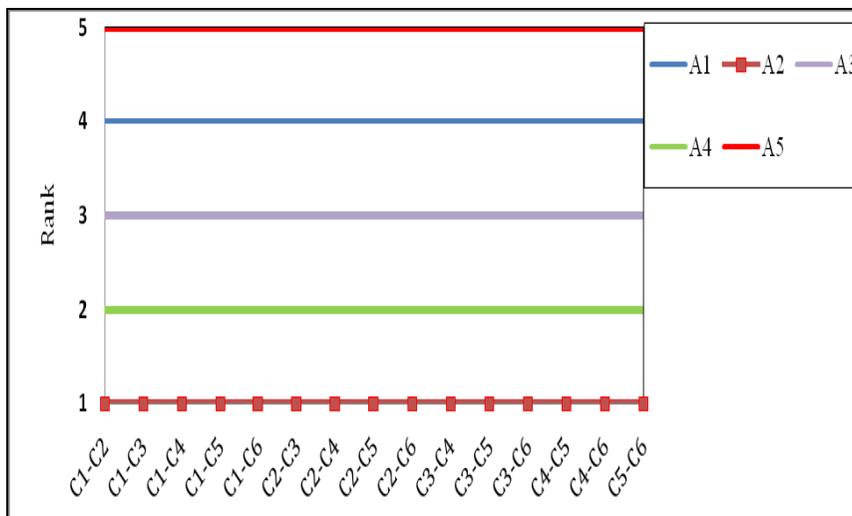


Figure 1. Sensitivity analysis by varying criteria weights

4.2 Influence of λ value in CoCoSo ranking

While applying the CoCoSo method, the associated λ value is generally assumed to be 0.5. However, in actual practice, it ranges from 0 to 1. Fig. 2 shows the effects of varying λ values in the range of 0 to 1. It is observed that there is no change in the ranking orders of the considered alternatives, thus establishing the stability of the ranking order, given by the integrated model.

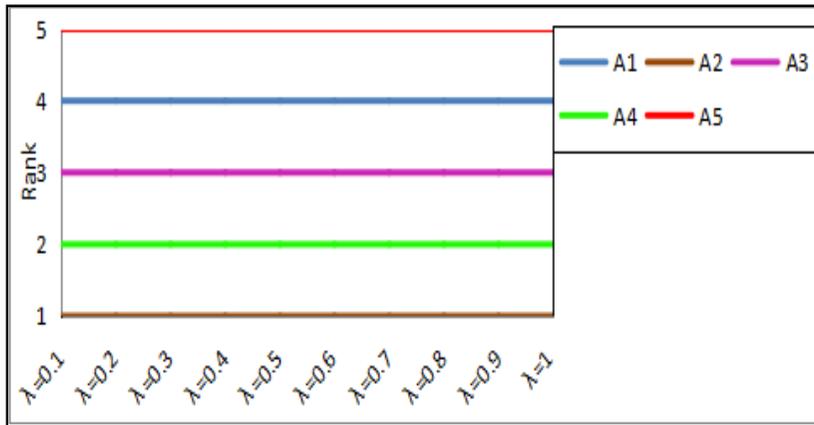


Figure 2. Sensitivity analysis for alternate fuel car by changing the λ value

5. Results and Discussion

In the context of global sustainability scenario, alternate fuel cars with higher mileage, longer range, lower annual fuel cost, quick acceleration, low price possible vehicle and reduced tail pipe emission can further reduced the tendency of global warming. In this paper, six important vehicle selection criteria has been considered and explained. The first two criteria (C1 and C2) are considered as beneficiary criterion (higher the better) and rest four criteria are considered as non-beneficiary criterion (lower the better). In order to avoid subjective judgments, CRITIC method is used for computing the criteria weights. Finally, a sensitivity analysis is shown to confirm the robustness of the ranking and further support the decision when selecting the final result. Tesla model 3 emerges out as the best alternative, which has been supported by other MADM methods like MABAC and MOORA that has been shown in Fig. 1. It is well understood from Fig. 2 that there are no changes of ranking of the alternative even their change in criteria weights. Fig. 3 establishes the robustness of the method as altering the values of λ in the range of 0.1 to 1, could not affect the ranking order at all. It is also observed that in comparison to other MADM methods in the literature, the adopted integrated model is very simple to understand and easy to execute and involves very less amount of mathematical calculations.

6. Conclusions

The proposed CRITIC-CoCoSo model is proven to be an effective decision-making tool to evaluate alternate fuel cars under requirement perspective of societal demand. It is also evident from the SA that the ranking of the alternate fuel cars does not change while interchanging the criteria weights. This indicates the strength of the integrated CRITIC-CoCoSo model. BEVs have no tail pipe emission and present EVs have longest range as similar to the conventional fuel cars along with lower operating costs. It is expected that the future BEVs will be backed with

faster acceleration technology and high range capabilities. CNG cars have high amount of tail pipe emission, high annual fuel cost and very low fuel economy. The suggested methodology can be used for any type of vehicle selection problems having any number of criteria and alternatives.

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