Research Article

Operating window perspective integrated TOPSIS approach for hybrid electrical automobile selection

Yusuf Tansel İç[1] · Esra Şimşek[1]

Abstract

To reduce vehicle-related environmental pollution, environmental regulations should be taken into account in different levels of sustainable product development process. As a result of the increasingly emitted CO_2 and serious energy shortage electrical or hybrid automobiles are one of the possible alternatives for customers. In this study, an operating window perspective based Taguchi-TOPSIS model is developed for the hybrid electrical automobile selection problem. Operating window is a range of attributes' values that the operating parameters meet the specified functional parameters yielding the best results in economic and technological terms. The operating window's upper and lower boundaries are defined as limits. More than two limit modes usually cannot be characterized by a one-dimensional operating window. After obtaining attribute values for the hybrid electrical automobile alternatives, the TOPSIS method is used for the ranking of the alternatives. The developed selection model is tested on a case study and satisfactory results are obtained.

Keywords Hybrid electrical automobile · Taguchi method · Automobile selection · Multi-Attribute Decision Making · Operating window · TOPSIS

1 Introduction

The hybrid electrical automobiles are gaining acceptance with customers. On the other hand, their selection is becoming a more complex task with the increased number of mark and models [11]. In the literature, there are some methodologies developed to select hybrid electrical automobiles. For example, Vahdani et al. [21] considered the fuel buses selection problem using fuzzy multi-criteria decision making (MCDM) model. In their study, fuel cell (hydrogen), electricity, and methanol were considered as fuel types. For the purpose of selecting suitable buses, many attributes including qualitative and quantitative ones such as price, efficiency, and capability have been taken into account. Tzeng et al. [20] used an integrated AHP[1]-TOPSIS[2]-VIKOR[3] model for alternative-fuel buses selection for public transportation in Taiwan. Safaei Mohamadabadi et al. [19] proposed a PROMETHEE[4] model to select renewable fuel-based transport vehicles. Yavuz et al. [24] presented a fuzzy decision making model that used hesitant linguistic evaluations of multiple decision makers for the vehicle selection problem. Yedla and Shrestha [25] examined the selection of transportation options in Delhi/India. "CNG buses", "CNG cars", and "4-stroke 2-wheelers cars" were evaluated based on 6 attribute— emission reduction potential, energy saving potential, availability of technology, cost of operation, barriers to implementation, and adaptability of the option. Yavaş et al. [23] examined customers' attention in

[1] Analytic Hierarchy Process.

[2] Technique for Order Preference by Similarity to Ideal Solution.

[3] Vlsekriterijumska Optimizacija I Kompromisno Resenje- in Serbian (Multi-criteria Optimization and Compromise Solution).

[4] Preference Ranking Organization Method for Enrichment and Evaluations.

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buying a car by using the AHP and ANP[5] methods. Kabak and Uyar [12] presented an integrated ANP-PROMETHEE model for the selection of a new vehicle. Lee et al. [13] proposed a 3-level Fuzzy AHP model for the selection of electric vehicle battery technology. Wu et al. [22] presented an integrated model for obtaining the engineering characteristics of electrical vehicle by Quality Function Deployment (QFD), DEMATEL[6] technique and VIKOR method together under fuzzy environment. Biswas and Das [3] proposed a customers' perspective based hybrid electrical car selection model using MABAC[7] method. They used vehicle cost, mileage, tail pipe emission, comfortableness and high tank size volume for long drive attributes of their MCDM model. Fenwick and Daim [5] described and analysed a decision making model for selection of a hybrid car. They used a hierarchical decision model. They used 3 attributes namely seating capacity, horse power, fuel economy and base price. Roy et al. [15] proposed a combined model for selection of automobile. The integrated model includes Fuzzy AHP and PROMETHEE II methodologies. They used cost, safety, and look criteria for their Fuzzy AHP-PROMETHEE II combined model. Hamurcu and Eren [7] proposed an integrated model using technical car specifications from producers' catalogues for electrical car selection problem that combined AHP, TOPSIS and goal programming methods.

The proposed methodologies in the literature generally use catalogue values of hybrid electrical automobile. The values used in the approaches are taken from hybrid electrical automobiles manufacturers. However, some values (attributes/specification) such as cost, torque, and fuel consumption have upper and lower limits.

The optimum factor condition of the attributes, which makes the selection more 'robust' for the different driving conditions (noises), is then obtained by performing the factor design. Factor design is also commonly referred to as 'robust design' [6]. The robust design proposed by Taguchi includes three formulations, each of which is suitable for different objectives and minimizes the effects of uncontrollable (noise) factors by maximizing the signal to noise (S/N) ratios. These are; minimum is best (*MinBest*), nominal is best (*NormBest*), and maximum is best (*MaxBest*) [8].

In addition to those, there is one more metric called Operating Window (*OpWin*) which is identified by Clausing [4]. The operating window upper and lower boundaries (or limits) are defined as operational conditions. In principle three or even more dimensional operating windows can be used [1, 2, 4].

In the case of *MinBest*:

$$\text{maximize } S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{1}$$

In the case of *NormBest*:

$$\text{maximize } S/N = -10\ \log\left(\frac{\bar{y}^2}{S^2}\right) \tag{2}$$

$$\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i \tag{3}$$

$$S^2 = \frac{1}{n-1}\sum_{i=1}^{n}\left(y_i - \bar{y}\right)^2 \tag{4}$$

In the case of *MaxBest*:

$$\text{maximize } S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \tag{5}$$

In the case of *OpWin*:

$$\text{maximize } S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2 \frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \tag{6}$$

In the above formulations, y_i is the experimental result of the ith response, n is the total number of replications, $\bar{y}$ is the average of observed data, and S^2 is the variance of y_i values. The steps used in applying the operating window perspective based Taguchi-TOPSIS method are given in Fig. 1. The application steps of the TOPSIS method are presented in Appendix 1 [10, 14].

Noise (i.e. the variation in driver) has a major role in the OW methodology to robustness and it is basis for the OW. The aim is to extend the OW as much as possible during the driving condition that will make the OW as expansive as possible for the hybrid automobile. Any of the types of noise factors/attribute can be used as the basis for the OW. In the hybrid automobile selection problem, the OW is based on a driver oriented (customer-use profile) noise, the fuel consumption, second hand price, and torque in considering the noise factor to use as the basis for the OW. An example for the fuel consumption is shown in Fig. 2.

To the best knowledge of the authors, an approach that checks the bound levels of catalogue specifications via OW presented by the hybrid electrical automobile manufacturers is not available in the literature. So, this is main the contribution of the paper to the literature.

[5] Analytic Network Process.

[6] Decision-Making Trial and Evaluation Laboratory.

[7] Multi-attributive border approximation area comparison.

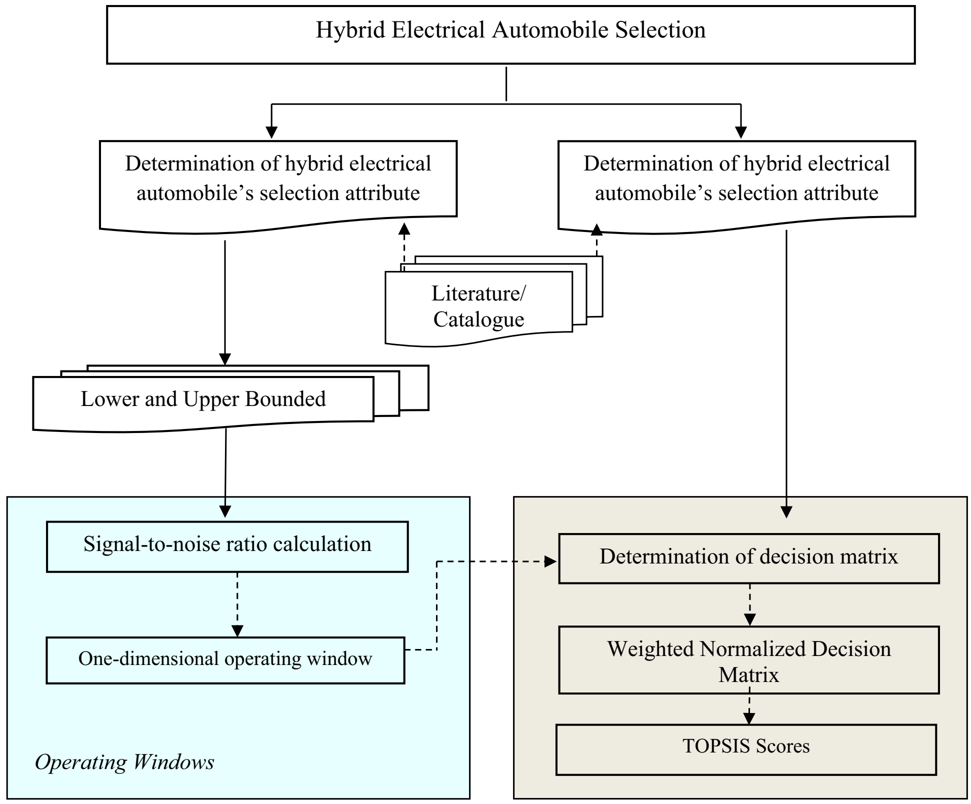


Fig. 1 The OW-TOPSIS-Taguchi application steps

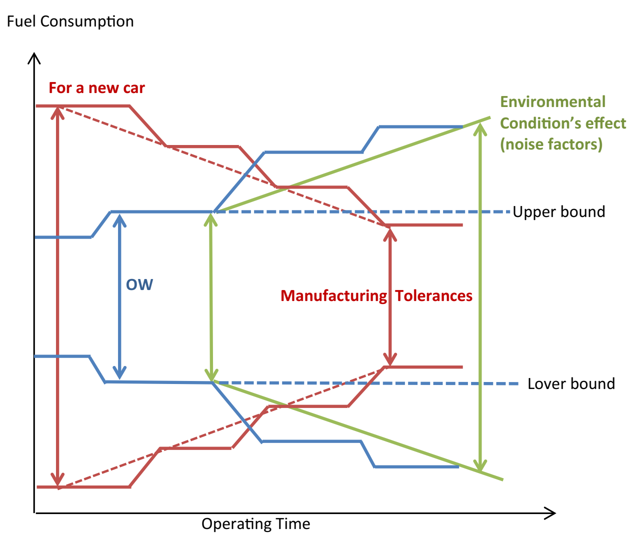


Fig. 2 An illustration of OW-manufacturing tolerance relationship [4]

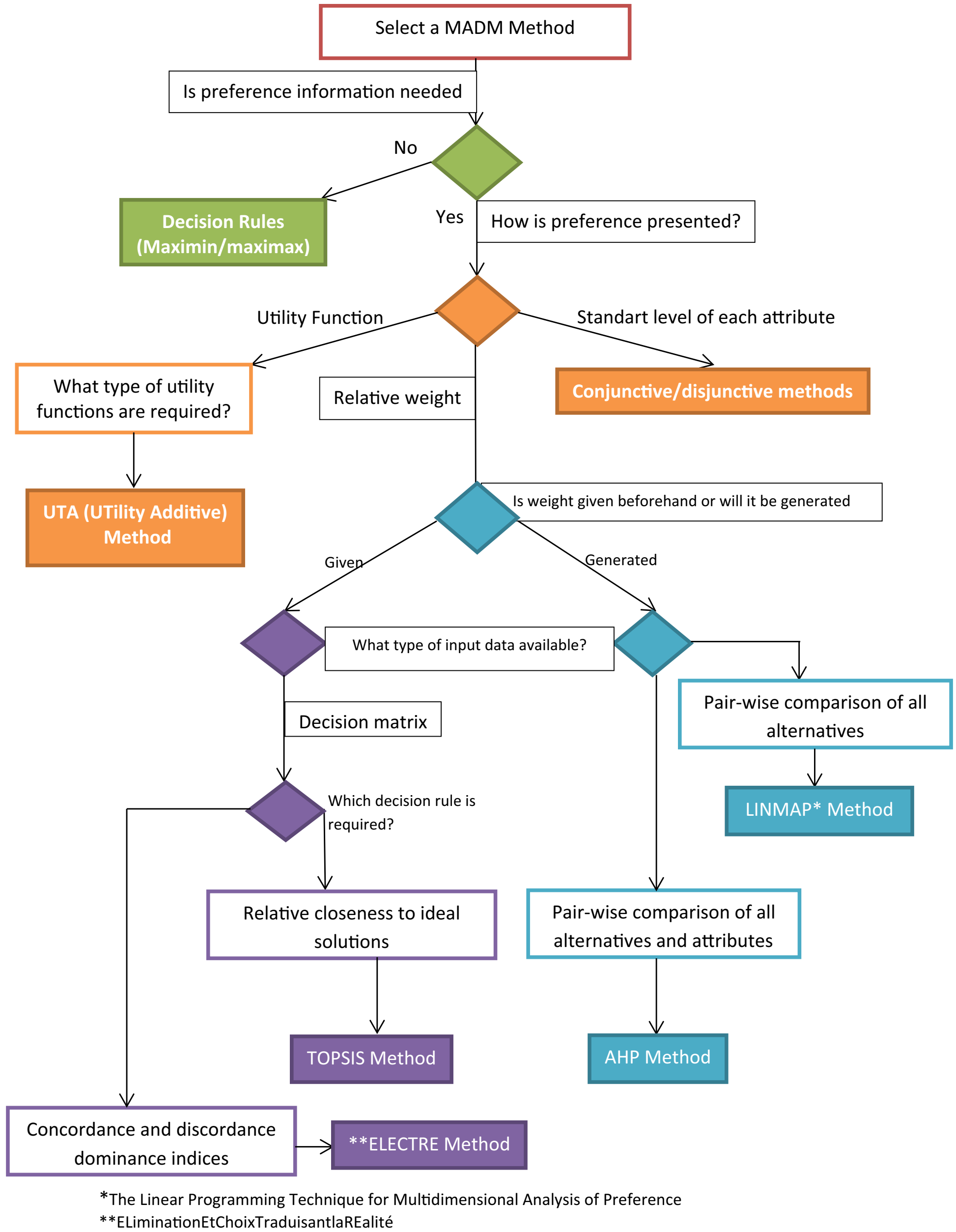
Instead of using average values, operating window, which is the sources of the upper and lower values in the catalogue specifications, can be incorporated in a multi attribute model. With such an approach the hybrid electrical automobile alternatives are ranked according to the technical and economical attributes. Our study aims to develop such an approach using TOPSIS, which is the most preferred MADM approach in equipment/machine selection literature since it is simple and easy to use [9, 16, 18].

Sen and Yang [17] states that "…The selection of an appropriate MADM methods mainly based on what input evaluation data is required and how designer's preferences are acquired and represented. The rules for selecting an appropriate MADM method can therefore be divided into two subsets. One subset of rules can be used to differentiate the ways in which preference information is elicited and represented in a MADM method. The other can be used to distinguish the types of input evaluation data which can be processed in a MADM method. Figure (see Fig. 3) illustrates some of the rules of choice for selecting an appropriate MADM method…"

According to the Fig. 3, a choice rule for selecting the TOPSIS method for hybrid automobile selection problem may be listed as follows:

If preferences can be elicited in terms of the relative weights, and
If relative weights are given beforehand or will it be generated, and
If the input data is available for decision matrix format, and
If the relative closeness to ideal and negative ideal solutions are important for the alternative rankings
Then the TOPSIS method is suggested for our study.

Fig. 3 MADM model selection procedure (adapted from [17])



For most MADM model like hybrid automobile selection this assumption is acceptable. In the following sections, the OW based Taguchi-TOPSIS model is developed.

2 Operating window perspective based Taguchi-TOPSIS model for hybrid electrical automobile selection

Motor capacity, CO_2 emission, Torque, Style, Price, Second Hand Price, and Fuel/Electric Consumption are the main attributes that are critical in determining a suitable hybrid electrical automobile. Generally it is an effective way to determine the most critical noise, or compound factor of noise in OW applications. This is determined by considering the environmental interactions, customer-use orientation and/or interactions with other subsystems of hybrid automobile. In the hybrid automobile example, some consideration of the hybrid automobile system will give us some important hints about the noise factors. Therefore, fuel consumption, torque and second hand price are selected to determine the operating window. The selection attribute are linked together in the developed OW-Taguchi-TOPSIS model to obtain ranking of hybrid automobiles (Fig. 1). However, it is necessary to obtain the operating window provided by different levels of each attribute before calculation of the ranking scores

Table 1 Hybrid electrical automobiles and their performance values

Mark	Model	Cubic Motor capacity (l)	Body Type	CO_2 Emission (g/km)	Number of Service Point in Turkey	Warranty (years)	Price (TL)	Fuel Consumption (l/100 km)				Torque			Second Hand Price			
								Combined	Urban	Extra-Urban	OW	Min (rpm)	Max (rpm)	OW	Option 1 (TL)	Option 2 (TL)	Option 3 (TL)	OW
TOYOTA	Yaris	1.5	5	82	58	5	107,850	3.6	3.3	3.6	−0.033	3600	4400	−0.17372	66,500	72,500	76,500	−2.04967
	Auris	1.8	5	91	58	5	167,350	4.1	3.9	4.1	−0.011	142	4000	−22.9858	115,000	N/A	N/A	9.64E−16
	Auris Hybrid Touring Sports	1.8	5	96	58	5	186,350	4.1	4.6	3.6	−0.258	1400	2800	−1.9382	130,445	149,080	167,715	−1.973
	RAV 4	2.5	5	118	58	5	274,600	5.1	5.1	4.9	−0.007	210	270	−0.27146	192,220	219,680	247,140	−1.973
	Prius	1.8	5	84	58	5	309,820	3.6	3.6	3.6	3E−05	142	3600	−22.0732	79,000	78,000		−0.0007
	C-HR	1.8	5	86	58	5	196,800	3.8	3.4	4.1	−0.151	142	3600	−22.0732	137,760	157,440	177,120	−1.973
KIA	CT 200 h	1.8	5	94	58	3	1,414,468	4.1	4.1	4	−0.003	142	207	−0.60283	990,127	1,131,574	1E+06	−1.973
	Niro	1.6	5	88	56	5	163,500	3.8	3.8	3.8	5E−06	1000	2400	−2.97411	152,500	N/A	N/A	0
HYUNDAI	IQNIQ	1.6	5	92	76	5	168,000	3.9	3.9	3.9	1E−05	147	4000	−22.686	129,900	N/A	N/A	0
VOLVO	X C 90 T8 2.0 Twin Engine	2	5	120	33	3	633,988	2.1	2.1	2.1	0	2200	5400	−3.11265	605,000	N/A	N/A	4.82E−16
BMW	X 5 Drive 40 e	2	5	77	39	2	885,000	3.3	3.3	3.3	0	350	600	−1.20496	605,000	631,300	N/A	−0.00786
	i8	1.5	2	49	39	2	1,250,800	2.1	2.1	2.1	0	320	3700	−15.3052	675,000	N/A	N/A	4.82E−16
	740 Le X Drive	2	5	45	39	2	1,038,100	2	2.4	2.5	−0.007	1550	4400	−4.05789	726,670	830,480	934,290	−1.973

Table 2 Decision matrix

Mark	Model	Cubic motor capacity (lt)	Fuel Consumption (l/100 km)	Body type	CO_2 Emission (g/km)	Number of service point in Turkey	Warranty (years)	Second hand price	Price	Torque
TOYOTA	Yaris	1.5	−0.03284	5	82	58	5	−2.04967	107850	−0.17372
	Auris	1.8	−0.01086	5	91	58	5	9.64E−16	167,350	−22.9858
	Auris Hybrid Touring Sports	1.8	−0.25837	5	96	58	5	−1.973	186,350	−1.9382
	RAV 4	2.5	−0.00695	5	118	58	5	−1.973	274,600	−0.27146
	Prius	1.8	0.000028	5	84	58	5	−0.0007	309,820	−22.0732
	C-HR	1.8	−0.15133	5	86	58	5	−1.973	196,800	−22.0732
	CT 200 h	1.8	−0.00265	5	94	58	3	−1.973	1,414,468	−0.60283
KIA	Niro	1.6	0.0000048	5	88	56	5	0	163,500	−2.97411
HYUNDAI	IQNIQ	1.6	0.000014	5	92	76	5	0	168,000	−22.686
VOLVO	X C 90 T8 2.0 Twin Engine	2	0	5	120	33	3	4.82E−16	633,988	−3.11265
BMW	X 5 Drive 40 e	2	0	5	77	39	2	−0.00786	885,000	−1.20496
	i 8	1.5	0	2	49	39	2	4.82E−16	1,250,800	−15.3052
	740 Le X Drive	2	−0.00724	5	45	39	2	−1.973	1,038,100	−4.05789
Weight		5	10	4	10	4	4	7	9	8
Normalized Weight		0.082	0.164	0.066	0.164	0.066	0.066	0.115	0.148	0.131

Table 3 Hwang and Yoon's 1–10 scale [17]

Attribute evaluation	Value
Extremely unimportant	0
Very unimportant	1
Unimportant	3
Average	5
Important	7
Very important	9
Extremely important	10

of automobiles. Types of the three attributes and their calculated operating windows are summarized in Table 1.

As a first step in obtaining ranking scores of hybrid electrical automobiles using the TOPSIS model, the decision matrix are provided in Table 2. Then, the importance weights of each attribute are determined using the 1–10 scale according to the possible consumer profiles. The relative weights of these attributes can be directly assigned by the customer/user on the basis of the Hwang and Yoon's 1–10 scale defined in Table 3. Once the weights are obtained, the ranking score of each hybrid electrical automobile can be calculated as illustrated in Table 4.

3 Comparison of OW-based TOPSIS model

The ranking results of the OW-based TOPSIS model are then compared with the classical TOPSIS model and presented in Table 4. The differences in hybrid electric automobiles' rankings are increased. For example, "X 5 Drive 40 e" is ranked second in OW-based TOPSIS model whereas it is ranked tenth in classical TOPSIS model out of the thirteen automobiles. The results show that completely different rankings are provided by the two models for "X 5 Drive 40 e". The OW-based TOPSIS model captures the special operating values of "X 5 Drive 40 e". The real performance of the "X 5 Drive 40 e" can be determined by not technical specification values but by its OW. This example illustrates the advantages of using OWs instead of single or average catalogue specifications in ranking hybrid automobiles especially when they will be used in special driving conditions.

It is evident from decision matrix that "X 5 Drive 40 e" outperforms in respect of combined fuel consumption (one of the most important criterion for selection model) in comparison to other alternatives. The performance of "Yaris" and "C-HR" is not significant in this criterion. But they are third and fourth automobiles by using the classical TOPSIS method (they are eightieth and twelfth automobiles by using the OW- TOPSIS method). Another important criterion (weight scale is 10) is CO_2 emission which ultimately increases global warming. In this respect, "X 5 Drive 40 e" possesses a 77 g/km emission whereas "Yaris" has an 82 g/km emission, and "C-HR" has an 86 g/km emission. Therefore, in two important attribute "X 5 Drive 40 e" is performing better than "Yaris" and "C-HR". However, it is also observed in Fig. 4. For anyone looking at a low CO_2 emission and also low fuel consumption hybrid automobile, the "X 5 Drive 40 e" should be better for a given attribute. Although "X 5 Drive 40 e" performs better than others in CO_2 emission and fuel consumption, it ranks lower in the conventional TOPSIS method due to its high price and relatively low torque values. However, in the OW-TOPSIS method, especially in second hand price, torque and fuel consumption, has been able to provide a more appropriate ranking by optimizing the dominant values of price and torque.

Table 4 TOPSIS results

Mark	Model	OW-based TOPSIS model				Classical TOPSIS model			
		S_i^*	S_i^-	C_i	Rank	Si*	Si-	C_i	Rank
TOYOTA	Yaris	0.031	0.160	0.837	8	0.034	0.095	0.735	3
	Auris	0.030	0.163	0.846	7	0.040	0.089	0.688	9
	Auris Hybrid Touring Sports	0.145	0.096	0.397	13	0.042	0.082	0.660	11
	RAV 4	0.040	0.166	0.807	10	0.060	0.072	0.545	13
	Prius	0.026	0.165	0.866	5	0.034	0.082	0.706	5
	C-HR	0.091	0.096	0.514	12	0.036	0.087	0.707	4
KIA	CT 200 h	0.035	0.153	0.815	9	0.047	0.067	0.591	12
	Niro	0.025	0.177	0.877	3	0.038	0.084	0.689	7
HYUNDAI	IQNIQ	0.030	0.168	0.847	6	0.039	0.090	0.695	6
VOLVO	X C 90 T8 2.0 Twin Engine	0.040	0.165	0.804	11	0.041	0.090	0.688	8
BMW	X 5 Drive 40 e	0.020	0.165	0.892	2	0.030	0.059	0.667	10
	İ 8	0.024	0.155	0.868	4	0.023	0.077	0.773	2
	740 Le X Drive	0.013	0.153	0.922	1	0.010	0.088	0.898	1

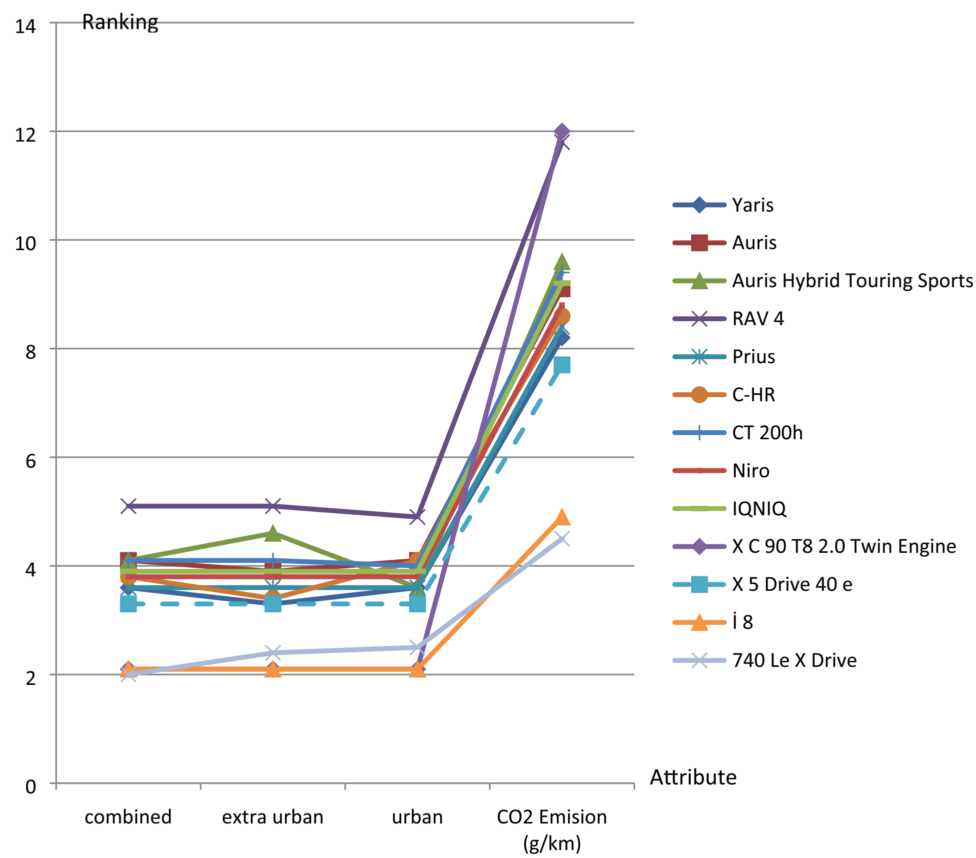


Fig. 4 Performance comparison for alternative hybrid automobiles

Table 5 Weight scenarios

Scenarios	Cubic motor capacity	Fuel consumption	Body type	CO_2 emission	Number of service point in Turkey	Warranty	Second hand price	Price	Torque
Original	5	10	4	10	4	4	7	9	8
I: For the short term user type[a]	8	4	10	5	7	8	6	4	4
II: For the classical user (long-term consumer) type[b]	7	7	6	7	10	10	3	6	6
III: For the sportive user type[c]	3	8	10	3	3	6	10	10	10

[a]She is a university student. She wishes to select a hybrid car with low total cost with basic requirements. She wishes to have a new hybrid car for driving from her home to the university campus

[b]He is an engineer in his late 50 s just retired. He is environmentally conscientious and wants a low CO_2 emitted hybrid automobile. He often goes from Ankara to İstanbul to see his son 5–6 times per year, a distance of 900 km each time. So, performance (i.e. torque) is less of an issue than fuel consumption and warranty

[c]She is a woman in her late-30 s and needs a sportive hybrid car to go trekking areas with lots of sports equipment for relaxing depending on her busy job

As a further study, the authors wanted to analyze the impact of the weight selection on the TOPSIS score for the different type automobile user (customer) as illustrated in Table 5. Three different weight sets (denoted as Scenarios I-III in Table 5) are generated and TOPSIS rankings of the automobiles are calculated and provided in Table 6.

The ranking results of the OW-based Taguchi-TOPSIS model for three weight scenarios are then compared with the classical TOPSIS model using Spearman's rank correlation test and presented in Table 6 for three specific scenarios. The Spearman's rank correlation test calculates the test statistics (Z) of the differences in the rankings which are presented in the last row of Table 6. If the Z value derived by Eq. (5) and

Table 6 Ranking differences with respect to three different weight sets

Model	Original		A–B	Scenario I		C–D	Scenario II		F–G	Scenario III		H–I
	A	B		C	D		F	G		H	I	
	TOPSIS	OW-TOPSIS		TOPSIS	OW-TOPSIS		TOPSIS	OW-TOPSIS		TOPSIS	OW-TOPSIS	
Yaris	3	8	−5	9	10	−1	2	7	−5	3	9	−6
Auris	9	7	2	7	5	2	6	5	1	7	8	−1
Auris Hybrit Touring Sports	11	13	−2	10	13	−3	8	13	−5	10	13	−3
RAV 4	13	10	3	12	4	8	12	8	4	13	7	6
Prius	5	5	0	5	3	2	3	4	−1	6	4	2
C-HR	4	12	−8	4	12	−8	4	12	−8	4	12	−8
CT 200 h	12	9	3	3	9	−6	13	9	4	11	10	1
Niro	7	3	4	11	6	5	7	3	4	8	1	7
IQNIQ	6	6	0	8	8	0	5	6	−1	5	5	0
X C 90 T8 2.0 Twin Engine	8	11	−3	6	7	−1	9	10	−1	2	3	−1
X 5 Drive 40 e	10	2	8	2	1	1	11	2	9	9	2	7
İ 8	2	4	−2	13	11	2	10	11	−1	12	11	1
740 Le X Drive	1	1	0	1	2	−1	1	1	0	1	6	−5
Spearman rank correlation test's result	r_s:		0.429			0.412			0.319			0.242
	Z:		1.485			1.428			1.104			0.837

(6) exceeded 1.645 (α = 0.05), the null hypothesis (H_0) was rejected. It was predicted that there is evidence of a positive correlation between the two sets of rankings.

$$r_s = 1 - \left[\frac{6 \cdot \sum_{j=1}^{K} (d_j)^2}{K \cdot (K^2 - 1)} \right] \tag{5}$$

$$Z = r_s \sqrt{(K - 1)} \tag{6}$$

where d_j indicates the ranking difference of automobile *j*, *K* is the number of automobile and r_s indicates the Spearman's rank-correlation coefficient.

It can be seen that all three results (1.485,1.428,1.104, and 0.837) are lower than 1.645. The lower values tell us that there is no statistical significance between the ranking results of the two approaches. These scenarios can be extended for similar exercises in commercial users, multi-users segments. As the proposed OW-TOPSIS model is generic in nature, it can be used for different automobile selection problems especially electrical vehicles.

4 Conclusion

The hybrid electrical automobile selection model provides an alternative approach to the selection models that use catalogue specifications and it is especially recommended, when the multi-level technical specifications will be used under different driving conditions for long time durations. It should be noted when using an OW-Taguchi-TOPSIS model; the success of the ranking results is sensitive to the correct selection of attributes and the assigning of their weight numbers. The attribute weight scores are assigned depending on customer/user; and hence their correctness depends on the customers' preferences and country differences of hybrid electrical automobile usage.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Appendix 1: TOPSIS application steps

Step 1: Developing the decision matrix

In the decision matrix, n and *m* represent the number of automobiles and the number of attribute. a_{ij} represents the performance value for automobile *i* at attribute *j*.

$$D = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1m} \\ a_{21} & a_{22} & \dots & a_{2m} \\ \dots & \dots & \dots & \dots \\ a_{n1} & a_{n2} & \dots & a_{nm} \end{bmatrix} \tag{7}$$

Step 2: Determining the weighted normalized decision matrix

The weighted normalized decision matrix is obtained by using Eq'n (8), (9), (10) respectively:

$$r_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^{n} a_{ij}^2}} \tag{8}$$

and,

$$R = \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1m} \\ r_{21} & r_{22} & \dots & r_{2m} \\ \dots & \dots & \dots & \dots \\ r_{n1} & r_{n2} & \dots & r_{nm} \end{bmatrix} \tag{9}$$

$$V = \begin{bmatrix} w_1 r_{11} & w_2 r_{12} & \dots & w_m r_{1m} \\ w_1 r_{21} & w_2 r_{22} & \dots & w_m r_{2m} \\ \dots & \dots & \dots & \dots \\ w_1 r_{n1} & w_2 r_{n2} & \dots & w_m r_{nm} \end{bmatrix} \tag{10}$$

where, w_j; $j = 1,\ldots,m$, and $\sum_{j=1}^{m} w_j = 1$. In this stage we can use Hwang and Yoon's 1–10 scale (Table 6). This type of scaling assumes that a scale value of 9 is three times as favorable as a scale value of 3 (Sen and Yang, 1994).

Step 3: Calculation of A^* and A^- ideal solutions

Ideal solutions:

$$A^* = \left\{ (\max_i v_{ij} \middle| j \in J), (\min_i v_{ij} \middle| j \in J' \right\} \rightarrow A^* = \left\{ v_1^*, v_2^*, \dots, v_m^* \right\} \tag{11}$$

$$A^- = \left\{ (\min_i v_{ij} \middle| j \in J), (\max_i v_{ij} \middle| j \in J' \right\} \rightarrow A^- = \left\{ v_1^-, v_2^-, \dots, v_m^- \right\} \tag{12}$$

where A^* is the best result for each attribute. A^- is the worst result for each attribute.

Step 4: Calculation of (S_i^*), (S_i^-) and (C_i^*) for each automobile

Ranking scores are calculated according to Eq. (13), Eq. (14), and Eq. (15) respectively.

$$S_i^* = \sqrt{\sum_{j=1}^{m} \left(v_{ij} - v_j^*\right)^2} \quad (13)$$

$$S_i^- = \sqrt{\sum_{j=1}^{m} \left(v_{ij} - v_j^-\right)^2} \quad (14)$$

$$C_i^* = \frac{S_i^-}{S_i^- + S_i^*} \quad 0 \le C_i^* \le 1 \quad (15)$$

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