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APPLICATION OF MULTI-CRITERIA ASSESSMENT IN EVALUATION OF MOTOR VEHICLES' ENVIRONMENTAL PERFORMANCES

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Original scientific paper

Concern for environment is an important element and obligation in contemporary automobile manufacturing. This paper presents an approach to assess environmental performances of motor vehicles by the application of multi-criteria assessment tools. Within the first part of the paper the multi-criteria problem is presented, with special emphasis on selection of criteria for assessment of passenger vehicles' environmental performances. The second part of the paper describes the application of a multi-criteria assessment according to two approaches – VK Software and Compromise Programming (CP) method. The obtained results are compared and discussed.

Keywords: *environmental performance, motor vehicles, multi-criteria analysis, multi-criteria evaluation*

Primjena višekriterijske analize za vrednovanje ekoloških performansi kod motornih vozila

Izvorni znanstveni članak

Briga o zaštiti okoliša je bitan element i obveza u suvremenoj automobilskoj industriji. U ovom je radu predstavljen prikaz vrednovanja ekoloških performansi motornih vozila primjenom alata višekriterijskog ocjenjivanja. Prvi dio rada opisuje višekriterijski problem i izbor kriterija za vrednovanje ekoloških performansi motornih vozila. U drugom dijelu rada je opisana primjena višekriterijskog ocjenjivanja primjenom dva pristupa – VK Softvera i metode kompromisnog programiranja (CP), a dobiveni rezultati su uspoređeni i raspravljeni.

Ključne riječi: *ekološke performanse, motorna vozila, višekriterijska analiza, višekriterijsko vrednovanje*

1 Introduction

Special attention in implementation of advanced technologies in design of new generations of passenger motor vehicles is focussed on reducing the impacts on environment. Automotive manufacturers are struggling to improve their products and to fulfil environmental protection regulations and standards by developing new solutions to decrease the fuel consumption, noise and toxic emissions, to increase the recyclability, etc. [20]. To meet each successive emissions regime, automotive companies have invested considerable research and development resources to create new combustion control technologies. These include items such as direct injection fuel systems, engine mapping software, and variable air intake systems. Consequently, vehicle manufacturers have to reconcile toxic emissions criteria including carbon monoxide (CO), hydrocarbons (HC) and nitrous oxide (NOx). Recently, concerns have included the issue of (non-toxic) carbon dioxide (CO_2) emissions [3].

Assessment of automobiles' environmental performances is a multidisciplinary challenge that requires participation of experts from different fields (technical, economic and social) in order of assessment criteria grading as well as of evaluating different alternatives due to criteria. This is why the multi-criteria assessment (MCA) can be of help in achievement of the appointed goal [10]. The following section provides a short review of specific approaches in assessment of passenger vehicles' environmental performances by MCA.

Yousefi and Hadi-Vencheh [20] applied two MCA methods to evaluate improvement fields of Iran automobile manufacturing industry. Customers' criteria based on the research literature, experts, mechanics, sellers and customers' ideas were selected. Features which characterized main criteria were: technical features (engine specification, safety, speed, comfortableness and relaxation), aesthetic (internal design, external design, colour and variety), manufacturer (manufacturer country, manufacturer company, brand), tools availability (availability of spare parts, availability of consumption tools), economical aspects (automobile price, fuel consumption, payment flexibility), social aspects (advertisement, society atmosphere, owners' satisfaction). The obtained results were compared and combined.

Bouwman and Moll [5] compared various Dutch passenger transportation systems by studying their complete life-cycle energy use. They used MCA to compare transportation systems according to their use of space, costs and travel time.

Each alternative scheme for treating a vehicle at its end of life has its own consequences from a social, environmental, economic and technical point of view. Disassembly, reuse, and recycling are a common way of treatment for waste electronic equipment [12], devices, and machines such as passenger vehicle at end of life. A specific MCA approach based on Preference Ranking Organization Method for Enrichment and Evaluations (PROMETHEE) method was proposed in [8] for selection of best compromise alternative scheme for treating vehicle at its end of life. PROMETHEE based preference ranking was also used in non-country specific study [3] where small set of motor vehicles was ranked based on constituents of their exhaust emissions. The alternative ranking analyses also considered different levels of importance associated with the four criteria (emissions) considered, namely, CO_2, CO, HC and Nox.

In [11], a multi-criteria assessment model was developed to rank different road transportation fuel-based vehicles (both renewable and non-renewable) using a PROMETHEE method. Vehicles based on gasoline, gasoline–electric (hybrid), E85 ethanol, diesel, B100 biodiesel, and compressed natural gas (CNG) were considered as alternatives. These alternatives were ranked based on five criteria: vehicle cost, fuel cost, distance between refuelling stations, number of vehicle options available to the consumer, and greenhouse gas (GHG) emissions per unit distance travelled.

Boureima et al. [4] included an overview of environmental vehicle assessment tools in report task. Report overviewed the following eco-rating systems for vehicles: Life cycle assessment (LCA), Eco-Efficiency, Ecoscore, ACEEE's green Book, EPA Green vehicle guide, The Cleaner Drive, The CAIR Environmental Rating system, ETA Car Buyer's Guide, The VCD's list of environmentally friendly vehicles, Ecotest, and others. The purpose of research in CLEVER project [2] was to perform an evaluation of the different scenarios: the baseline, realistic and progressive scenario by means of a MCA. For this purpose, a combination of the PROMETHEE GAIA methodology and the Analytic Hierarchy Process (AHP) is used. Overall, the scenarios were evaluated based on the following criteria and their own subcriteria: environmental effectiveness (fleet emissions (CO_2 eq./NOx/particulate matter), average ecoscore, impact on mobility (amount of km-s driven, modal choice) and feasibility (budgetary impact, technical feasibility, socio-political acceptance). Environmental effectiveness was found to be the criteria with highest preference according to two groups of experts for group decision making.

The previous analysis confirms the convenience and usefulness of the MCA approaches in various environmental evaluations related to motor vehicles and automotive industry. This paper presents an attempt of MCA application in evaluation of passenger motor vehicles' environmental performances. Approach was described through application on five Toyota Auris car models.

2 An approach to multi-criteria assessment of motor vehicles' environmental performances

Within this part of the paper an approach for multi-criteria evaluation of the motor vehicles' environmental performances, is presented. Considering the long-standing commitment of Toyota Company to environmental protection, which is also reflected through the availability of data in relation to the environmental performances, the approach is presented through a case study that included assessment of five types of Auris car model [18].

The goal of the study, selected criteria and sub-criteria as well as alternatives, are presented through the decision tree in Fig. 1. On the bases of available data for five Auris types, with respect to the study goal - the assessment of vehicles' environmental performances, the following eight criteria are selected:

1) fuel consumption,
2) CO_2 emissions,
3) CO emissions,
4) HC emissions,
5) NOx emissions,
6) emission of particulates,
7) noise level, and
8) engine power.

As the data related to fuel consumption and CO_2 emissions is available for three driving regimes - combined, urban and extra urban driving, this was utilised to define the sub-criteria level for these two parameters. The values of selected parameters i.e. criteria, are given in Tab. 1.

2.1 The applied methodology of multi-criteria assessment

Multi-criteria assessment was carried out by the application of VK Software. The main concept, modular structure and interface of the VK Software are presented in Fig. 2 and Fig. 3, while a more detailed presentation is given in [1].

The very first and the most sophisticated step is the criteria weighting. It is important to note that VK software comprises three weighting methods based on: Fullers triangle (FT), Analytic hierarchy process (AHP) and Reduction coefficients (RC).

Final score of the alternatives is obtained through multiplication of the normalized criteria values and the

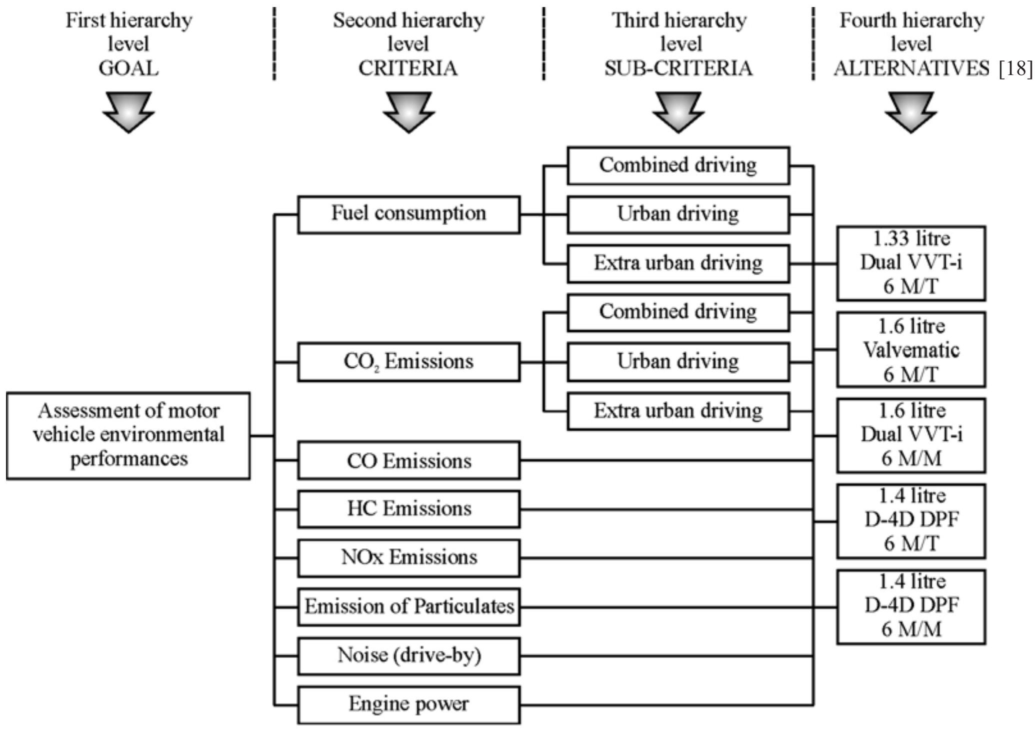

Figure 1 Decision tree for assessment of motor vehicle environmental performances

Table 1 Performance data [18]

Criteria		Criteria type	1.33 litre Dual VVT-i 6 M/T	1.6 litre Valvematic 6 M/T	1.6 litre Dual VVT-i 6 M/M	1.4 litre D-4D DPF 6 M/T	1.4 litre D-4D DPF 6 M/M
Fuel consumption / mpg	Combined driving	Max	47,9	42,8	44,8	58,9	57,6
	Urban driving	Max	39,2	32,8	35,3	49,6	48,7
	Extra urban driving	Max	55,4	51,4	52,3	65,7	64,2
CO_2 / g/km	Combined driving	Min	136	153	146	128	130
	Urban driving	Min	165	198	184	152	154
	Extra urban driving	Min	119	127	125	114	116
CO / g/km		Min	0,25	0,372	0,387	0,11	0,10
HC / g/km		Min	0,06	0,026	0,037	0,00	0,00
NOx / g/km		Min	0,02	0,011	0,019	0,12	0,13
Particulates / g/km		Min	0,00	0,00	0,00	0,0005	0,0004
Noise / dB(A)		Min	69	69	70	67	68
Power / DIN hp		Max	101	132	132	90	90

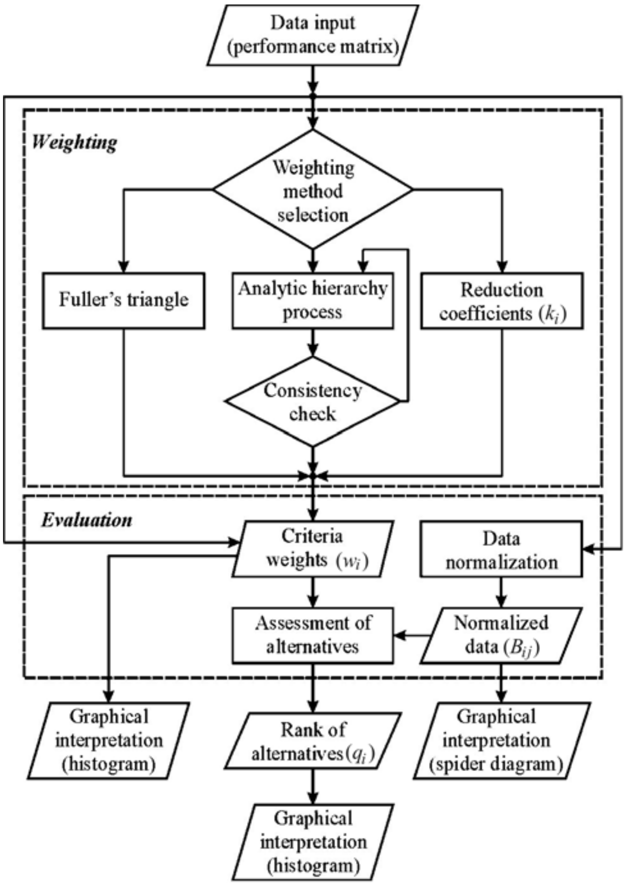

Figure 2 Flow chart of VK Software [1]

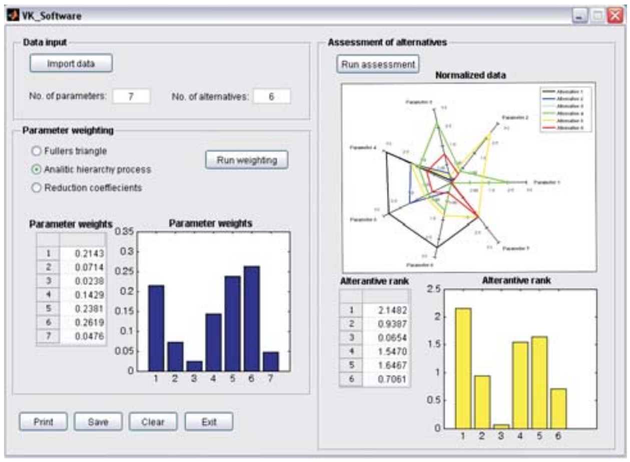

Figure 3 VK Software main panel [1]

assigned weights:

$$q_i = \sum_{j=1}^{m} w_j b_{ij}, \quad i = 1, 2, ..., n, \tag{1}$$

where:
b_{ij} – normalized criteria,
w_j – criteria weight,
m – total number of criteria, and
n – total number of alternatives.

Criteria weights are assigned using one of the three previously mentioned methods (FT, AHP, RC), while the normalization is done according to:

$$b_{ij} = \frac{a_{ij} - u_j}{s_j}, \quad i = 1, 2, ..., n; \ j = 1, 2, ..., m, \tag{2}$$

where:
a_{ij} – ordered value of j-criteria (assigned +/– for y_{ij} values depending on the j-criteria type),
u_j – artificial vector (minimal values from a_j),
s_j – standard deviation of ordered j-criteria:

$$s_j = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(a_{ij} - \bar{a}_j)^2}, \quad j = 1, 2, ..., m, \tag{3}$$

where:
$\bar{a}_j$ – j-mean value of criteria.

Difference between the criteria that have to be minimized/maximized is done by multiplying the j columns of performance matrix $Y=[y_{ij}]$, whose environmental impact is obviously negative, by –1. The result is a matrix $A=[a_{ij}]$, with ordered values of j-criteria, having the same dimensions as Y. Higher dimensionless values q_i of the i-th alternative indicate better environmental performances and vice versa.

2.2 The approach implementation

In this study, special attention was given to criteria weighting, considering the influence of weight assignment on the final multi-criteria assessment result [14, 19]. Taking into account the ability of AHP to precisely assign weight to criteria [13, 15], this method was selected for calculation of weight coefficients.

In the process of weight assignment the following studies were considered. Michiels et al. [9], predicted for 2020 the external environmental cost for transport as: 111,9 Euro/kg for particulate matter smaller than 2,5 μm; 2,5 Euro/kg for NOx and 0,042 Euro/kg for CO_2 eq. Castro et al. [6] gave the overview of the environmental impact of the average vehicle on a regional, national or community level. They used SimaPro software version 4 and the Idemat 2000 database and the results of the study showed that the largest environmental impact occurred in the use phase – over 90 %. Moreover, the use of the fossil fuels was identified as the dominant impact even for the production phase, NOx emissions were among the smallest emissions to air in quantity but responsible for 36 % of the life cycle impact. Finally, CO_2 was identified as the largest emission to air, but accountable for only 6 % of the environmental impact.

Timmermans et al. [16] developed the Ecoscore methodology as an environmental vehicle rating tool built on a LCA framework through a sequence of five steps: inventory, classification, characterization, normalization and weighting. For passenger vehicles they defined the following values for the weighting factors: global warming 50 %, human health 20 %, ecosystems 20 %, and noise level 10 %.

Considering the previous, weighting of criteria in this study (Tab. 2) was performed in the following way:

- particulates, fuel consumption and NOx are considered as the most important criteria,
- CO_2, HC and CO as criteria of middle importance, and
- noise level and engine power as the least important criteria.

On sub-criteria level (Tab. 3) it was assumed that combined, urban and extra urban driving have the same influence on fuel consumption and CO_2 emissions. Therefore, the assigned weights for these sub-criteria are the same for fuel consumption and CO_2 emissions, as presented in Tab. 4.

Table 2 AHP comparison matrix for criteria

Second hierarchy level*: Criteria	Fuel consumption	CO_2	CO	HC	NOx	Particulates	Noise	Engine power	Weights
Fuel consumption	1	3	7	7	3	3	9	9	0,341
CO_2	1/3	1	3	3	1/3	1/5	3	5	0,089
CO	1/7	1/3	1	1/3	1/7	1/5	3	3	0,041
HC	1/7	1/3	3	1	1/5	1/5	3	3	0,055
NOx	1/3	3	7	5	1	1/3	7	5	0,170
Particulates	1/3	5	5	5	3	1	9	9	0,255
Noise	1/9	1/3	1/3	1/3	1/7	1/9	1	3	0,028
Engine power	1/9	1/5	1/3	1/3	1/5	1/9	1/3	1	0,021

* Calculated inconsistency for pair-wise comparisons was 0,08 at second hierarchy level

Table 3 AHP comparison matrix for sub-criteria

Third hierarchy level*: sub-criteria (driving)	Combined	Urban	Extra urban	Weights
Combined	1	1/3	5	0,279
Urban	3	1	7	0,649
Extra urban	1/5	1/7	1	0,072

* Calculated inconsistency for pair-wise comparisons was 0,06 at third hierarchy level

Table 4 Calculation of criteria weights

Criteria on the second hierarchy level	Criteria weights	Criteria on the third hierarchy level	Criteria weights	Final criteria weights
Fuel consumption	0,341	Combined driving	0,279	0,095
		Urban driving	0,649	0,221
		Extra urban driving	0,072	0,025
CO_2	0,089	Combined driving	0,279	0,025
		Urban driving	0,649	0,058
		Extra urban driving	0,072	0,006
CO	0,041	-	-	0,041
HC	0,055	-	-	0,055
NOx	0,170	-	-	0,170
Particulates	0,255	-	-	0,255
Noise	0,028	-	-	0,028
Engine power	0,021	-	-	0,021
Sum of criteria weights	1,000	Sum of criteria weights		1,000

3
Results and discussion

Obtained results of multi-criteria assessment from VK Software are presented in Fig. 4 as normalized data and in Fig. 5 as alternative rank.

In order to verify the VK Software results the same problem was solved using a different multi-criteria method named Compromise Programming (CP) [21] and the results are shown in Figs. 6 and 7. The final result of CP method is calculated as:

$$L_{p,i} = \left[\sum_{j=1}^{m} w_j^p \left\{ 1 - \left(\frac{a_j^* - a_{ij}}{a_j^* - a_j^-} \right) \right\}^p \right]^{\frac{1}{p}} \qquad (4)$$

$$1 \leq p \leq \infty,\ i = 1, 2, ..., n;\ j = 1, 2, ..., m,$$

where:
p – indicates the distance measure,
m – number of criteria,
n – number of alternatives,
a_j^* – ideal solution of j-criteria (a_j maximum value),
a_j^- – anti-ideal solution of j-criteria (a_j minimum value),
a_{ij} – ordered value of j-criteria (described in section 2.2),
w_j – weight of j-criteria.

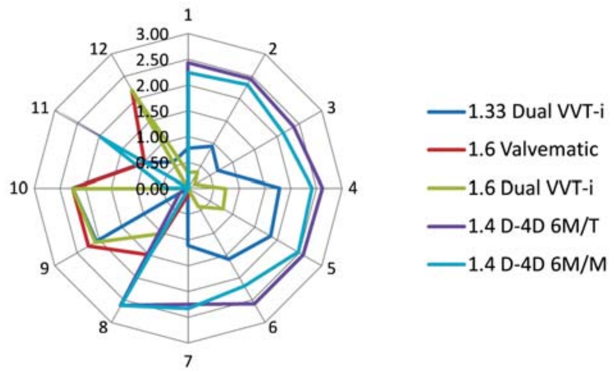

Figure 4 Normalized data (VK Software)

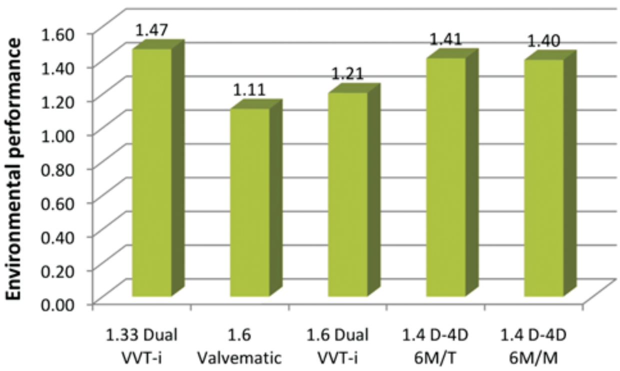

Figure 5 Alternative rank (VK Software)

Higher dimensionless values $L_{p,i}$ of the i-th alternative indicate better environmental performances and vice versa. In this case the p parameter for CP assessment, representing the importance attached to the deviation of each alternative from its ideal value, was set as $p = 1$. The final multi-criteria result, alternative rank, obtained by VK Software and CP method is identical for both approaches (Figs. 5 and 7).

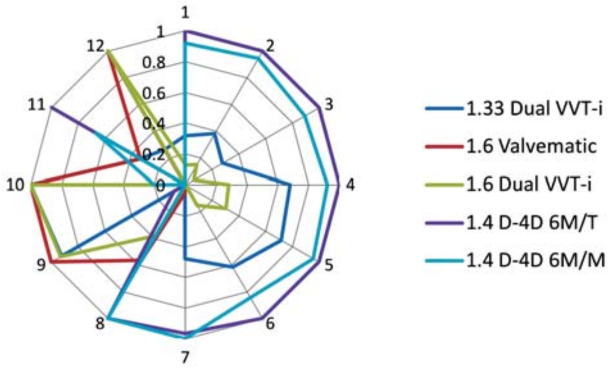

Figure 6 Normalized data (CP)

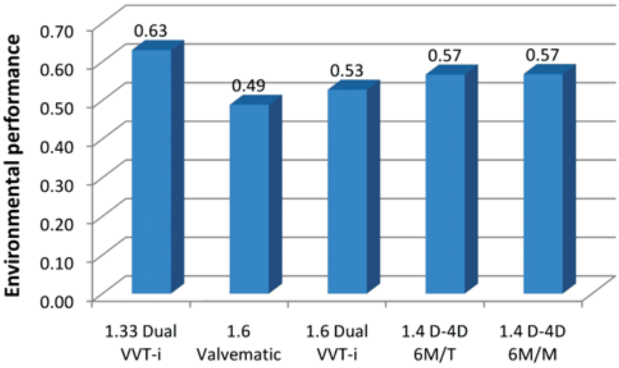

Figure 7 Alternative rank (CP)

Although the environmental performances data for motor vehicles are similar in values (Tab. 1), multi-criteria assessment showed the differences in final alternative ranks. Multi-criteria assessment of motor vehicles environmental performances revealed the following results:

- The models of 1.33 litre engine and 1.4 litre diesel engines (alternatives 1.33 litre Dual VVT-i 6 M/T, 1.4 litre D-4D DPF 6 M/T and 1.4 litre D-4D DPF 6 M/M) were assessed as of highest environmental performances, where 1.33 litre engine has the best alternative rank while both 1.4 litre diesel engines have almost the same environmental performance;
- The models with 1.6 litre engines (alternatives 1.6 litre Valvematic 6 M/T and 1.6 litre Dual VVT-i 6 M/M) were assessed as poor compared to other engines, where the 1.6 litre Dual VVT-i 6 M/M model has a slight advantage in environmental performance over 1.6 litre Valvematic 6 M/T model.

Normalized data are shown in Figs. 4 and 6 by polar (also known as spider) diagrams, where criteria are presented as axes and numbered from 1 to 12. This type of diagram is a convenient one for presenting of matrix data especially for complex environmental impacts [17]. Polar diagrams in Figure 4 and Figure 6 show that alternatives representing diesel engines (1.4 D-4D 6M/T and 1.4 D-4D 6M/M) are of very similar environmental performances regarding criteria 1 to 8 (forming a bow shape). As in case of alternative ranks, spider diagrams for both methods look very similar, verifying the VK Software wide applicability and satisfying functionality. Final results could be analyzed with sensitivity analysis, such as [7], to obtain more information about the multi-criteria problem and future research should include application of these methods.

4 Conclusion

Presented in the paper is an approach to multi-criteria assessment of motor vehicles' environmental performances, accomplished by VK Software and verified by CP method. Obtained results from the both MCA approaches showed high correspondence with identical final ranks, confirming the VK Software applicability. Special focus within the assessment was on the weighting of selected criteria - fuel consumption, exhaust emissions, noise, and engine power. The final MCA result showed that there is a difference in environmental performances of five types of Toyota Auris model.

Future research should be focused on data uncertainty and sensitivity analysis in order of assessment of MCA final results. Moreover, in adding of additional criteria such as vehicle safety, price, and service, those can add to the value of this study. Ideal alternative can also be added to support limit values for European emission standard (Euro 5) for passenger motor vehicles, thus final results could be comparable with other type of passenger vehicles.

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