International Journal of Industrial Engineering and Technology.
ISSN 0974-3146 Volume 5, Number 1 (2013), pp. 47-60

http://www.irphouse.com

A Group Decision Support Methodology to Weight Diesel Engine's Operating Parameters by Using Analytical Hierarchy Process and Delphi

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ABSTRACT

An inexorable growth of energy demand, in particular the transportation sector, rapidly depletes fossil fuels. A number of conflicts of interest usually take place in terms of performance, emission and economic aspect. Each parameter has a different importance. Hence, researchers should have a methodology to weight each parameter to make appropriate decisive conclusions. In this research, an integrated AHP-Delphi method is developed for weighting nine diesel engine parameters. The result shows that AHP can convert a specialist's perceptions into numerical values efficiently. The Delphi method can manage a diverse set of a specialist's opinions and obtain the group consensus within a certain iteration. The final result reveals that fuel price, efficiency, particulate matter (PM), engine torque and oxides of nitrogen (NO_x) receive a relatively high importance in a diesel engine's parameters, while carbon dioxide (CO_2), hydrocarbon (HC), engine power and carbon monoxide (CO) show less significance. The discussion, conclusion, and recommendation are also presented.

1. INTRODUCTION

Developments of world society and economic aspects speed up the world's energy demand together with deteriorating environmental consequences, mainly resulting from an over-dependence on fossil fuels. Nevertheless, it is shown that the increase of reserved fuel is higher than the consumption rate [1-2]. However, energy demand has an inexorable growth. It is predicted that the fossil fuel production is approaching a peak and will rapidly decline and become a global crisis. Fossil fuels have high potential in terms of energy density compared to other energy sources. That is why the importance of fossil fuels is irrefutable. However, there are several negative aspects such as environmental impact, economic dependence and running out of fossil fuels [1, 3-4]. It is reported that two thirds of the fossil oil is used in the transportation sector, also including diesel and gasoline. Alternative energies can contribute to reducing need for fossil fuel and increase the global energy security. Unfortunately, alternative energies are not free and are limited by their inherent intermittent nature. In vehicle engine applications, not only engine performance is considered. It is suggested that operation cost (fuel cost) and the external cost (pollution damage) must be taken into account [5].

Previous researches in alternative energy field have performed to complete all the practical aspects since they investigated the characteristics in various engine sizes, operating loads and speeds. There are, for example, Jinlin [6] and Niraj [7] who survey more than 300 research papers and conclude that diesel engine can operate with biodiesel in many different mixing ratios, including neat biodiesel. The advantages of using biodiesel are the cheaper price, lower particulate matter (PM), carbon monoxide (CO) and hydrocarbon (HC) emissions, while the engine performance slightly reduced with increments in specific fuel consumption (SFC), carbon dioxide (CO) and oxides of nitrogen (NO_x) emissions. A perceptible conflict of interest among fuel price, engine performance and engine exhaust emissions occur here. However, the discussions cannot finally confirm which mixing ratio is the most appropriate, since the decision making must be done under multiple criteria, which is one of significant research gaps in this field.

According to this research gap, the paper intends to determine the weights of each important diesel engine parameters, which can help researchers make an appropriate judgment under multi-criteria situations. To achieve this objective, engine outputs are considered as decision parameters. Significant weight of parameters is determined by using integrated analytical hierarchy process (AHP) and the Delphi method.

2. AHP AND DELPHI METHOD

The objective of the research is to weight engine output parameters, which are classified into three categories 1) engine performance 2) engine emissions and 3) economic aspect. Specialists are needed for the evaluating process. In general, evaluation is usually dealing with a human’s opinions. Thus, the process needs a structural method that helps the specialists dealing with decisions. Firstly, the method must be able to convert specialists’ subjective into numerical data, which is possible for mathematical calculation. Secondly, since human evaluation is imprecise and unsatisfactory for a reliable result, the research process has to verify their uniformities or consistencies. Finally, specialists always have different opinions because of their work experiences and backgrounds. The decision methodology must be capable of managing the extreme values and contribute to an agreement in group decision.

Two methods are applied to improve the quality of a specialist’s evaluations, which are AHP and the Delphi method. AHP is one of the decision tools which convert human sensitivity to the quantitative data via making pairwise comparisons between elements [8-9]. The main steps are as follows. Specialists have to establish the judgment matrix. Let A represent a pairwise comparison matrix, while a_{ij} signifies a preference weight of a_i obtained by comparison with a_j. The relative significant between two elements is rated using an AHP comparison scale with the values in table 1 [10]. This gives a matrix as follows.

$$A = \left[a_{ij}\right] = \begin{bmatrix} 1 & a_{12} & . & . & a_{1n} \\ 1/a_{12} & 1 & . & . & a_{2n} \\ . & . & . & . & . \\ . & . & . & . & . \\ 1/a_{1n} & 1/a_{2n} & . & . & 1 \end{bmatrix} \quad (1)$$

The maximal eigenvalue ($\lambda_{\max}$) is calculated by equation (2) and equation (3) [11].

$$A = \begin{bmatrix} 1 & a_{12} & . & . & a_{1n} \\ 1/a_{12} & 1 & . & . & a_{2n} \\ . & . & . & . & . \\ . & . & . & . & . \\ 1/a_{1n} & 1/a_{2n} & . & . & 1 \end{bmatrix} * \begin{bmatrix} W_1 \\ W_2 \\ . \\ . \\ W_n \end{bmatrix} = \begin{bmatrix} W_1' \\ W_2' \\ . \\ . \\ W_n' \end{bmatrix} \quad (2)$$

$$\lambda_{\max} = \left(1/n\right) \times \left(W_1'/W_1 + W_2'/W_2 + W_3'/W_3 + \ldots + W_n'/W_n \right) \quad (3)$$

Finally, the consistency of the pairwise comparisons must be checked. The indicators in AHP are the consistency index (CI) and consistency ratio (CR) which are shown in equation (4) and equation (5). The judgment matrix is inconsistent if consistency ratio is more than 0.1. Then, specialists must reevaluate to achieve a consistent matrix [12]. Finally, Taleai [13], and Escobar [14] found that if each decision has an acceptable inconsistency, the group result will be also acceptable.

$$CI = \frac{\lambda_{\max} - n}{n-1} \quad (4)$$

$$CR = \frac{CI}{RI} \quad (5)$$

Specialists generally have diverse opinions. There should be one more process to manage these extreme values, which means group consensus among a number of specialists should be achieved. Delphi technique represents a method for aggregating group judgments, which can increase decision efficiency [13, 15]. Delphi collects data with multiple iterations to attain consensus. The feedback information allows the specialists to reassess their decisions in previous iterations. Thus, the results can be adjusted by each specialist obtained from the feedback provided by other specialists. The Delphi technique is an anonymous procedure. Practically, three or four iterations are sufficient to reach consensus in most cases [16-18]. It is concluded that the number of Delphi experts is changeable. They should not be considered as the representative pooling of the decisions if the decision size is too small. But if the size is too large, the problems of low response rate and time use can occur [16].

Single used or combination of AHP and the Delphi technique can be found in literatures [19-21]. Firstly, Delphi is used to identify important factors or criteria from specialists. Then, AHP is used to identify the weight [13, 17-18, 22]. The second application can be explained as "AHP is integrated into a Delphi framework" [15, 23]. In this process, AHP is repeated after specialists receive anonymous feedback, which is articulated by the other specialists. This research is performed as the second case, which certainly acquires more iterations but it efficiently increases the group's consistency and reduces consistency ratio as well.

3. METHODOLOGY

The methodology of this research is shown in figure 1. Torque, power, thermal efficiency, HC, CO, CO_2, NO_x, PM and fuel price are the nine important parameters [24-26]. AHP method can be used to pairwise comparisons among 9 parameters, which means 36 pairs must be evaluated by each specialist. This is not an appropriate process since some specialists cannot evaluate every parameter. It is certainly a time consuming process and generates unacceptable consistency. The solution is recommended by Ramanathan [27]. They divide the parameter into categories. Therefore, each category reduces the number of judgments and, finally, the consistency increases. According to this recommendation, nine parameters have been categorized into three groups, which are (1) engine performance, (2) exhaust emission and (3) economic (price). These groups are in the main criteria level as shown in figure 2. Each criterion also consists of sub criteria as follows. Engine performance topic consists of engine torque, power and thermal efficiency. Emission topic consists of HC, CO, CO_2, NO_x and PM, while economic topic considers only fuel price.

This research decides to survey from eight specialists for each questionnaire according to the suggestion of Hallowell [19] and Monica [28]. Questionnaires are sent to specialists, who are chosen on the basis of their professional reputation, work experience and research activities. All specialists have science and engineering backgrounds. According to figure 2, the AHP model requires aggregating the evaluation of each category. Specialists corresponding to this step are four researchers and professors in energy, automotive, chemical, environmental engineering. Moreover, two officials from the Thailand Ministry of Energy and two researchers from the Thailand institute of scientific and technological research also attended this process. Thus, eight specialists, who have vision in terms of economics, attend this research.

Each evaluation is checked for the consistency. If the consistency ratio is unacceptable, that specialist must re-evaluate until the result reaches an acceptable value. All results are aggregated by geometric mean [10, 29] and calculate the weight of each parameter. At this moment, the Delphi process starts to perform. The entire raw and analyzed data are sent to each specialist. They have the chance to see other evaluations namelessly and reconsider their results. Every iteration still needs the consistency check. The iteration can be repeated until specialists do not change their decisions, which means the group decision reaches consensus. Finally, weight of each parameter can be accomplished.

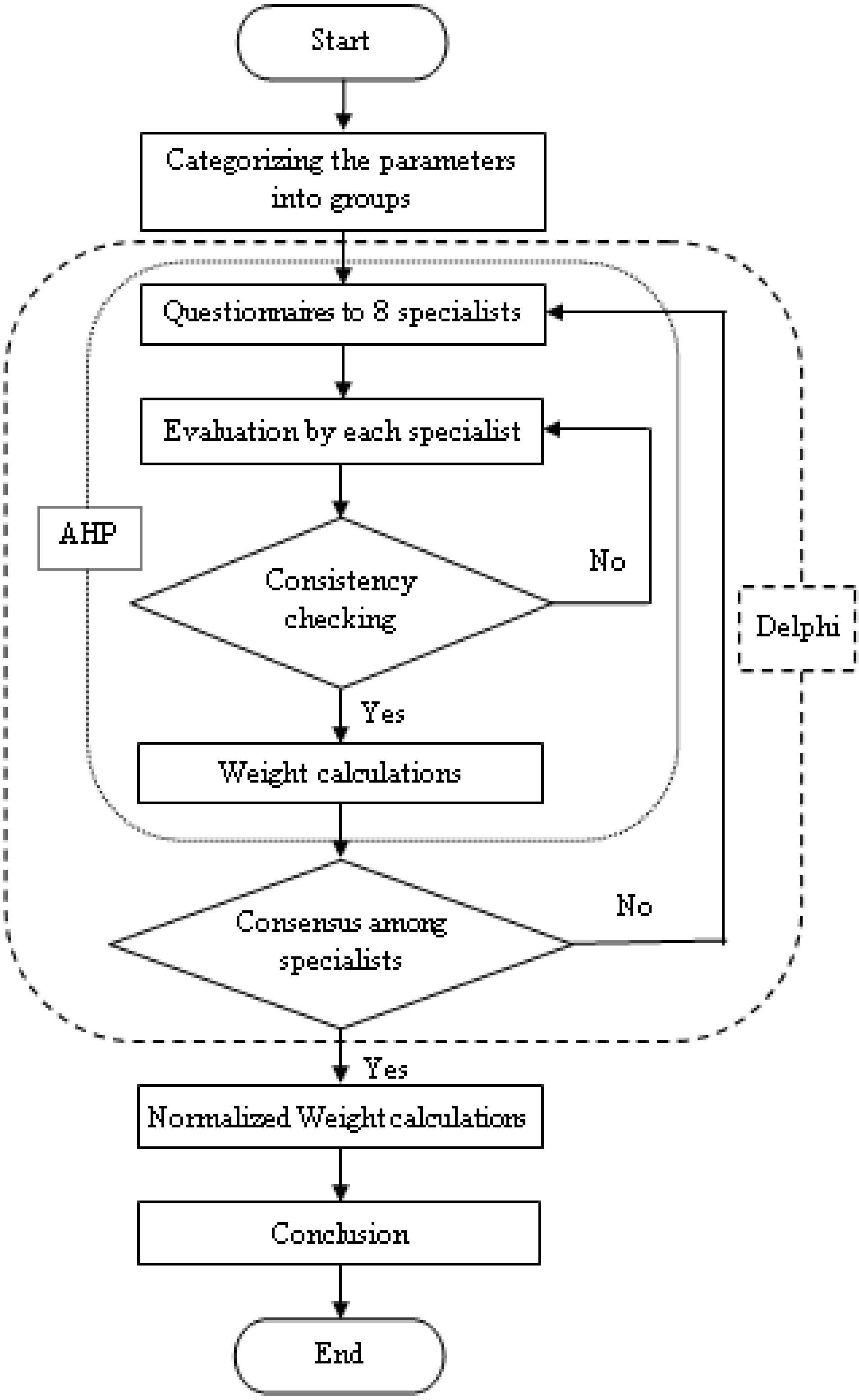

Figure 1 Research Methodology

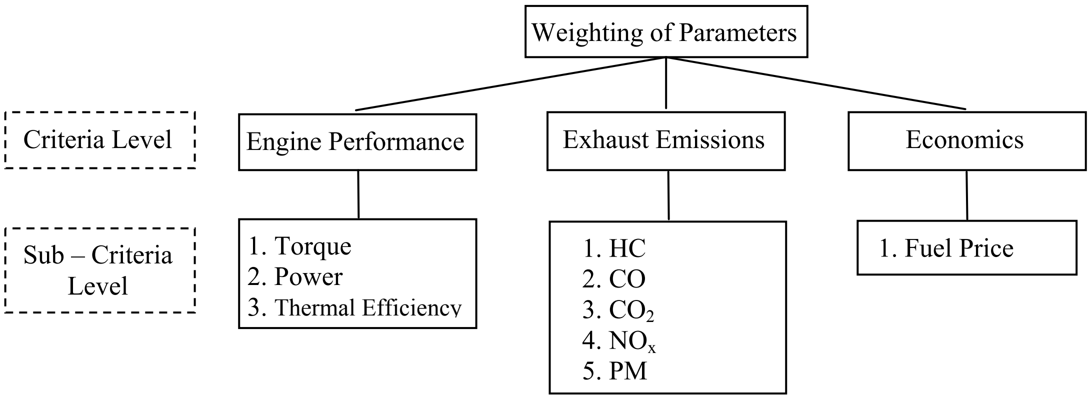

Figure 2 AHP model for deriving the weights of parameters

4. RESULTS AND DISCUSSIONS

The integrated AHP-Delphi methodology is applied to weight engine parameters. Pairwise AHP comparison scale is already shown in table 1, while an example of the questionnaire is shown in appendix A. In the study, the AHP-Delphi process can achieve the group consensus, which is presented in detail as follows in appendix A.

Table 1 Pairwise comparison scale for AHP preference [10]

Scale	Definition	Explanations
1	Equal importance (or weight)	Two criteria contribute equally to objectives.
3	Weak/moderate importance of one over another	Experience and judgment slightly favoured one criterion over another.
5	Essential or strong importance	Experience and judgment strongly favour one criterion over another.
7	Very strong or demonstrated importance	A criterion is favoured very strongly over another; its dominance demonstrated in practice.
9	Absolute importance	The evidence favouring one criterion over another is of the highest possible order of affirmation.
2, 4, 6 and 8	Intermediate values between the two adjacent scale values	Used to represent compromise between the priorities listed above

4.1 Weighting of main criteria parameters

Main criteria parameters, according to figure 2, consist of performance, emissions and economics. The initial result from AHP shows large diversities of opinions among specialists. Hence, more iteration in Delphi has to be implemented. Iteration begins when each specialist anonymously receives the initial result. The result consists of raw data of each specialist and a graphical presentation of the weights which resulted from the pairwise comparisons. An example of the initial result is presented in figure 3. The most outstanding benefit of this step is to provide the interaction necessary for the specialists to reconsider their decisions.

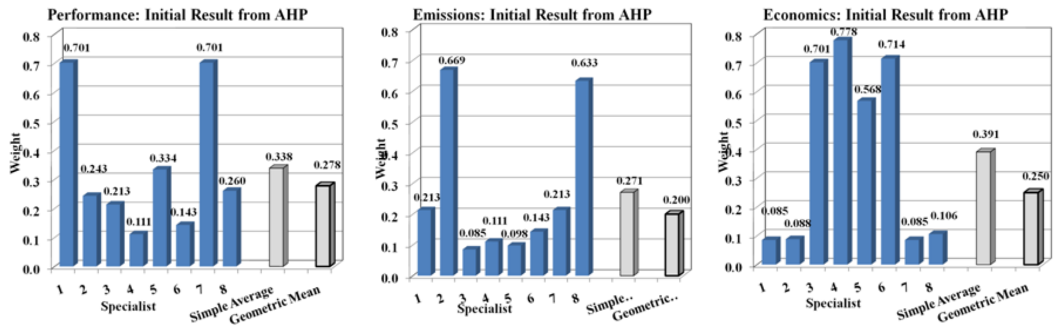

Figure 3 Weights of main criteria parameters from the initial result from AHP

After reviewing the initial results, specialists are asked for repeating the AHP process. It shows that iteration can rapidly reduce extreme values. In other words, the iteration decreases diversities of viewpoints among eight specialists. Observation is given to the smaller gaps between "simple average" and "geometric mean" values. These data are shown in table 2. However, more iteration is needed in order to ensure that the group decision achieves the consensus. After a certain iteration, most specialists insist on their previous results, which finally means that the group decision is terminated here. Figure 4 presents the differences between "simple average" and "geometric mean" of main criteria in graphical presentation. The gaps between two values are getting smaller and become constant. This certifies that diversities of viewpoints among eight specialists decrease and reach the group consensus. Finally, the weight of main criteria parameters equal to geometric means [10, 29] and are concluded in table 3.

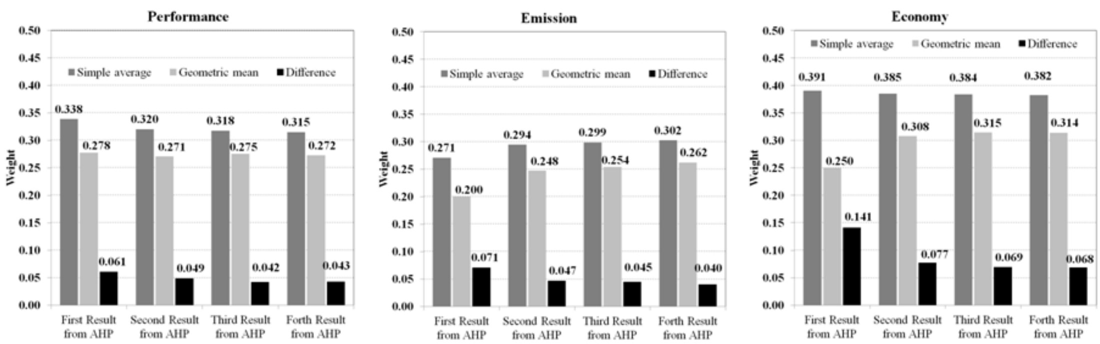

Figure 4 Simple average and geometric mean comparisons

Table 2 Result from AHP for main criteria evaluations

Main Criteria	Result from AHP	Simple Average	Geometric Mean	Difference
Performance	Initial (First) Result	0.338	0.278	0.061
	Second Result	0.032	0.271	0.049
	Third Result	0.318	0.275	0.042
	Fourth Result	0.315	0.272	0.043
Emission	Initial (First) Result	0.271	0.200	0.071
	Second Result	0.294	0.248	0.047
	Third Result	0.299	0.254	0.045
	Fourth Result	0.302	0.262	0.040
Economy	Initial (First) Result	0.391	0.250	0.141
	Second Result	0.385	0.308	0.077
	Third Result	0.384	0.315	0.069
	Fourth Result	0.382	0.314	0.068

Table 3 Weights of main parameters

Main Parameters (Group)	Weight	Normalized Weight
1. Engine Performance	0.272	0.321
2. Exhaust Emission	0.262	0.309
3. Economic (price)	0.314	0.370
Group summation	0.849	1.000

4.2 Weighting of sub criteria parameters

According to figure 2, engine performance consists of torque, power and efficiency. Exhaust emission consists of CO, CO_2, HC, NO_x and PM, while the economic aspect considers only the fuel price. Thus, an integrated AHP-Delphi group decision technique is applied again for weighting sub criteria parameters in engine performance and exhaust emission categories. In this step, it is very crucial to inform and emphasize to all specialists that this research is focusing only on diesel engine parameters. Since diesel and gasoline engines have totally different ignition phenomena, this leads to different uses and amount of exhaust emissions.

Questionnaires are sent to specialists for their decisions. The data collecting and analysis processes are similar to the detail in section 4.1. Figure 5 shows an example of the result in engine performance category. It is found that only three iterations are enough for the group consensus. Exhaust emission category also has the similar procedure with three iterations. Table 4 concludes the final results and shows the weights in each category.

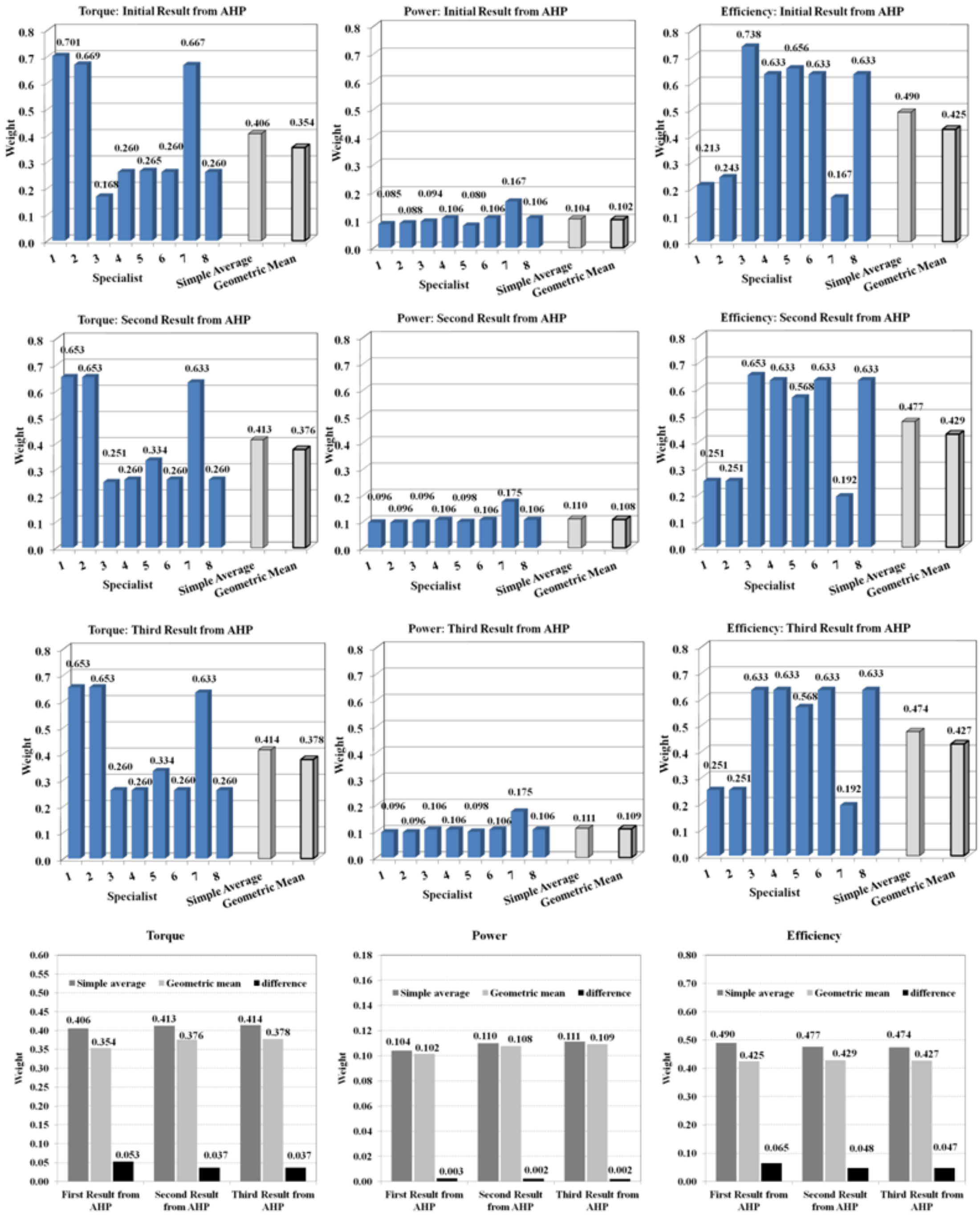

Figure 5 Weights of parameters in engine performance category

Table 4 Weights in each category

Category 1: Engine Performance			Category 2: Exhaust Emissions			Category 3: Economic		
Parameter	**Weight**	**Normalized Weight**	**Parameter**	**Weight**	**Normalized Weight**	**Parameter**	**Weight**	**Normalized Weight**
Torque	0.378	0.413	CO	0.073	0.081	Fuel price	1.000	1.000
Power	0.109	0.119	CO_2	0.126	0.140			
Efficiency	0.427	0.467	THC	0.116	0.128			
			NO_x	0.190	0.210			
			PM	0.397	0.440			
Summation	0.914	1.000	Summation	0.901	1.000	Summation	1.000	1.000

4.3 Final weights of the engine parameters

One method to find the summative weights is to multiply the weights of parameters (Table 4) with the weight of that group (Table 3). However, this method shows one weak point that the weights decrease as the number of parameters in the group increases. Nevertheless, Ramanathan [27] suggests a solution by using equation (6) in this case.

$$W_i = \left(\frac{p_i}{p*}\right) \times A \qquad (6)$$

The details of calculation and the weights of each engine parameter are finally shown in table 5. Table 5 reveals that diesel engine parameters have different weights. "Fuel price" is ranked in the first priority with the weight of 21.04%. This conforms to several researches since they have discussed the impacts of this parameter in term of economics [30], policy [31] and alternative fuel technology issues [32-33]. Among specialists' consensus, the uniqueness of diesel engine is outstanding thermal efficiency and high engine torque at low engine speed. The result shows that engine power is not an important diesel engine parameter since it is ranked in the eighth priority with the weight of 4.66%. This is because power is calculated from the product of torque and engine speed, while diesel engine usually functions in low speed applications.

Table 5 Final weights of the engine parameters

Rank	Parameter	Calculation $W_i = \left(\frac{p_i}{p*}\right) \times A$	Weight	Normalized Weight	Percentage
1	Fuel price	$W_i = \left(\frac{1.000}{1.000}\right) \times 0.370$	0.370	0.210	21.04%
2	Efficiency	$W_i = \left(\frac{0.467}{0.467}\right) \times 0.321$	0.321	0.183	18.26%
3	PM	$W_i = \left(\frac{0.440}{0.440}\right) \times 0.309$	0.309	0.176	17.56%
4	Torque	$W_i = \left(\frac{0.413}{0.467}\right) \times 0.321$	0.284	0.161	16.15%

5	NO_x	$W_i = \left(\frac{0.210}{0.440}\right) \times 0.309$	0.148	0.084	8.39%
6	CO_2	$W_i = \left(\frac{0.140}{0.440}\right) \times 0.309$	0.098	0.056	5.57%
7	HC	$W_i = \left(\frac{0.128}{0.440}\right) \times 0.309$	0.090	0.051	5.12%
8	Power	$W_i = \left(\frac{0.119}{0.467}\right) \times 0.321$	0.082	0.047	4.66%
9	CO	$W_i = \left(\frac{0.081}{0.440}\right) \times 0.309$	0.057	0.033	3.25%
Summation			1.759	1.000	100.00 %

Diesel engine generally generates a visible and harmful PM emission. Thus, "efficiency", "PM" and "engine torque" are in the second to the fourth rank with very slightly different values. Excluding PM emission, NO_x is always discussed in diesel engine researches. The weight of NO_x is 8.39%, while specialists seem to pay less attention to other emissions (CO_2, HC and CO). This can be explained by saying that a diesel engine is always operating at lean burn condition. The amounts of CO_2, HC and CO emissions from a diesel engine are very low compared to that of a gasoline engine. These results can be obviously seen in many researches [34-35]. Moreover, some researches exclude these three emissions from their scope of research [36]. According to table 4, weights of these emissions are only 5.57%, 5.12% and 3.25% respectively.

5. CONCLUSIONS AND RECOMMENDATIONS

Previous diesel engine researches have shown difficulties in multi-criteria decision making because researchers do not have the weight of each diesel engine parameter. This research aims to develop a method to evaluate and weight nine parameters in three main categories, including performance, emission and economics. The selected method must fulfill three requirements as follows. Firstly, it must convert specialists' subjective into numerical data. Secondly, specialists' evaluations must be verified by the process. Lastly, specialists' opinions must be managed and achieve the group consensus. Hence, an integrated AHP process into the Delphi technique is investigated in this research. Nine parameters are classified into three groups and are weighted by eight specialists, recruited from their educational and professional backgrounds. During the process, AHP can convert a specialist's perceptions into numerical values very efficiently, while the Delphi method is a very powerful tool to manage a diverse set of specialist's opinions and obtain the group consensus. This can be noticed from the difference between "simple average" and "geometric mean".

The weakness of integrated AHP-Delphi method found that specialists must evaluate by AHP several times, which is definitely time-consuming. Furthermore, this is a risk to get low response rates from the specialists. However, the absence of face-to-face meeting gives each specialist a chance to perceive one another's result and reconsider their decision, which is a very outstanding point of the process. This process also allows researchers to notice a clear trend of the results and can successfully finish the evaluation process within three iterations. The result shows that fuel price, efficiency, PM emission, torque and NO_x emission receive a high significance with the weights of 21.04%, 18.26%, 17.56%, 16.15% and 8.39% respectively, while, CO_2, HC, power and CO show less importance. This research can be applied to many diesel engine researches, such as alternative diesel fuels, combustion systems, fuel supply systems etc. since the result encourages researchers to make decision more reasonably and more logically than using their personal opinions. However, it is important to note that this research recruits eight Thai specialists. Their decisions are generally based on Thailand technological, economical and social background. The weight of each parameter can be slightly changed, if is investigated in the other parts of the world due to different contexts or situations.

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APPENDIX A: The questionnaire to specialists for pairwise comparison

Questionnaire to Specialists

Main Criteria

Performance	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Emissions
Performance	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Economics
Emissions	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Economics

Sub Criteria: Engine Performance

Torque	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Power
Torque	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Efficiency
Power	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Efficiency

Sub Criteria: Emissions

CO	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CO_2
CO	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	THC
CO	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	NO_x
CO	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PM
CO_2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	THC
CO_2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	NO_x
CO_2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PM
THC	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	NO_x
THC	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PM
NO_x	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PM