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# An integrated AHP – Delphi group decision approach to weight engine's performance and emission parameters

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## ABSTRACT

The energy demand is increasing with damaging environmental consequences. Alternative fuels for combustion engines draw many attentions and have been investigated world widely. Researchers have been working on various engine sizes and operating conditions. But the research gap is found that researchers can only explain the relation between parameter without final decision in real application as it deals with several criteria. The objective of this research is to weight the frequently used engine parameters, which helps researchers to make a better decision under multi-criteria situation. The engine parameters are classified into three groups and weight by the integrated AHP-Delphi method, which converts opinions into numerical values. Moreover, it can deal with a group decision making to obtain the consensus of specialists. The result shows the three most important decision parameters are engine torque, fuel price and PM emission with the weights of 0.2920, 0.2715 and 0.1729, respectively. While the result shows that $CO_2$ is the least significant decision parameter with the weight of 0.0132.

## 1. INTRODUCTION

The accessibility and environmental impact of energy resource involve the development of the world economic and society. The energy demand has been increasing together with damaging environmental consequences. The most important

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point is the energy demand has an unavoidable growth. It is believed that the fossil fuel production is very close to the peak and will soon rapidly decline and unavoidably become a global crisis. Alternative energies can contribute to reducing need on fossil fuel and increase the global energy security.

Alternative fuels for internal combustion engines draw many people attention and have been investigated world widely. Gasoline engines have already been investigated with many types of fuels such as hydrogen, liquefied petroleum gas, natural gas, ethanol, and gasohol, while diesel engine experimentations have been conducted with biodiesel, diesohol, pyrolysis oil and also gaseous fuels. Previous researches revealed both advantages and disadvantages of each kind of fuels in term of engine performance, exhaust emission and also economical aspect. Literatures seemed to complete all the technical aspects since they investigated the characteristics in various engine sizes, operating loads and speeds. However, it was very obvious that researcher could only explain the relations between their dependent factors and independent factors without any final decision for the real application. For example, Jinlin (2011) and Niraj (2013) reviewed more than 300 research papers and conclude that diesel engine can operate with biodiesel in different mixing ratios, including neat biodiesel (B100). It was found that the advantages of using biodiesel were the reduction in price, particulate matter (PM), carbon monoxide (CO) and hydrocarbon (HC) emissions, while that engine performance slightly decreased with increments in specific fuel consumption (SFC), carbon dioxide (CO) and oxides of nitrogen ($NO_x$) emissions. The results showed a very apparent conflict of interest among fuel price, engine performance and exhaust emissions. Nevertheless, the discussions cannot absolutely suggest which mixing ratio is optimal, since the decision making must be done under several criteria, which is the most significant research gap in this field.

According to this research gap, the research aims to identify the weights of engine parameters, which can help researchers to make an appropriate decision under multi-criteria situation. To achieve the objective of the research, engine outputs are considered as decision parameters. Then specialists evaluate the significant of parameters by applying analytical hierarchy process (AHP). Delphi method is also applied to increase the quality of group decision making.

## 2. THEORY AND LITERATURE REVIEW

Since the goal of this research is to weight many engine output parameters, including engine torque, power, efficiency, HC, CO, $CO_2$, $NO_x$, PM and fuel price. Experts or specialists are required for evaluating the significant of these parameters. This research needs a structured tool that helps the specialists dealing with decisions under some further requirements. Firstly, the tool must be able to convert specialist 'sensitivities into numerical data, which leads to the weight calculation. Secondly, since it is obvious that human evaluation is sometimes unclear and insufficient for a reliable result, the chosen tool must have a potential to check their reliabilities or consistencies. Lastly, as the specialists are recruited from different work experiences and backgrounds, they possibly have totally different opinions. The tool must be able to manage the extreme values and contribute to a consensus in group decision making.

This research applies two methods to improve the reliability of their evaluations, which are AHP and Delphi method. AHP is one of decision tools that can integrate human perceptions with the quantitative calculation of weight. This evidently can improve efficiency in decision making. The basic processes in AHP are specifying criteria and making pair-wise comparisons between elements. The process consists of main steps as follow. After the decision parameters are identified, researchers have to establishing the judgment matrix. Let $A$ represent a pair-wise comparison matrix, while $a_{ij}$ denotes 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. This gives a matrix as follows.

$$A = [a_{ij}] = \begin{bmatrix} 1 & a_{12} & . & . & a_{1n} \\ 1/a_{12} & 1 & . & . & a_{2n} \\ . & . & . & . & . \\ . & . & . & . & . \\ 1/a_{1n} & 1/a_{2n} & . & . & 1 \end{bmatrix} \tag{1}$$

**Table 1** Pair-wise comparison scale for AHP preference

| Scale | Definition | Explanations |
|---|---|---|
| **1** | Equal importance | Two criteria contribute equally to objectives |
| **3** | Weak/moderate importance of on over another | Experience and judgment slightly favored one criteria over another |
| **5** | Essential or strong importance | Experience and judgment strongly favor one criteria over another |
| **7** | Very strong or demonstrated importance | A criteria is favored very strongly over another; its dominance demonstrated in practice |
| **9** | Absolute importance | The evidence favoring one criteria 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 |

The maximal eigenvalue or principal eigenvalue ($\lambda_{\max}$) is calculated by equation (2) and equation (3).

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

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

Finally, the consistency of the pair-wise comparisons needs to be checked. The consistency measures used in AHP is the consistency index ($CI$) and consistency ratio ($CR$) which can be calculated by equation (4) and equation (5). If consistency ratio is more than 0.1, the judgment matrix is inconsistent. Judgments matrix should be reevaluated to obtain a consistent matrix (Xingyu 2007). After testing consistency, all judgments are aggregated by geometric mean, which is an appropriate rule for combining individual judgments to obtain the group judgment for each pare-wise comparison (Byun 2001). If the individual decision makers have an acceptable inconsistency, the results in group decision will be acceptable as well (Taleai 2008, Escobar 2004).

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{4}$$

$$CR = \frac{CI}{RI} \tag{5}$$

Together with AHP, Delphi technique represents one of the methods for aggregating group judgments, which can improve efficiency in decision making (Taleai M2008, Byun 2001). Delphi technique is widely used in various fields of study. It collects data with multiple iterations to reach consensus among a number of specialists. The feedback process allows the specialists to reassess their initial judgments about the data provided in the previous iterations. Thus, the results in previous iterations can be changed by each specialist based on their ability to review and evaluate the feedback provided by other specialists. Delphi technique is characterized by anonymous responses.

Noise is communication that happens in a group process or face-to-face meeting, which distorts the data and deals with group interests rather than focusing on problem solving (Hsu 2007). Theoretically, Delphi technique can be iterated continuously until consensus is achieved. However, not more than three or four iterations are normally sufficient to reach consensus in most cases (Hsu 2007, Sharma 2003, Zhu 2011).

Merging AHP method and Delphi technique seems to be very productive. Literatures find that there are two applications of integrated AHP-Delphi method. Firstly, Delphi technique is used to identify criteria or important factors from specialist opinions. AHP is then used to define their weight or significant (Taleai 2008, Liao 2010, Zhu 2011, Pirdashti 2011). The other type of AHP-Delphi integrated procedure can be explained as "AHP is integrated **into** a Delphi framework". In this procedure, AHP is repeated after the specialists receive anonymous feedback, which are articulated by the other specialists. Each specialist both reconsiders criteria and repeats rating (Byun 2001, Tavana 2003). This research is conducted by the second method, which absolutely takes more iterations but it can efficiently increase the group's consistency and reduce consistency ratio.

## 3. METHODOLOGY

Research methodology consists of three main parts. First part is to find proper decision parameters and classify into groups. The second part is dealing with specialists for the group decision making. The third part is the AHP which is integrated inside the Delphi loop process. Finally, the result of the group decision making is accomplished as shown in figure 1.

After nine important engine parameters have been set, the AHP method needs to make pair-wise comparisons among 9 parameters, which means 36 pair-wise comparisons must be evaluated by each specialist. This is definitely not an appropriate procedure since some specialists cannot evaluate all of them and it certainly leads to unacceptable consistency. The technique to solve this problem is suggested by Ramanathan (1995). They divide the parameter into categories or groups. Each category also reduces the number of judgments to be made by any single specialist and increase the consistency.

Nine parameters have been categorized into three groups, which are (1) engine performance issue, (2) exhaust emission issue and (3) economic (price) issue. Performance issue consists of engine torque, power and thermal efficiency. Emission issue consists of HC, CO, $CO_2$, $NO_x$ and PM, while economic issue considers only the fuel price, as shown in figure 2.

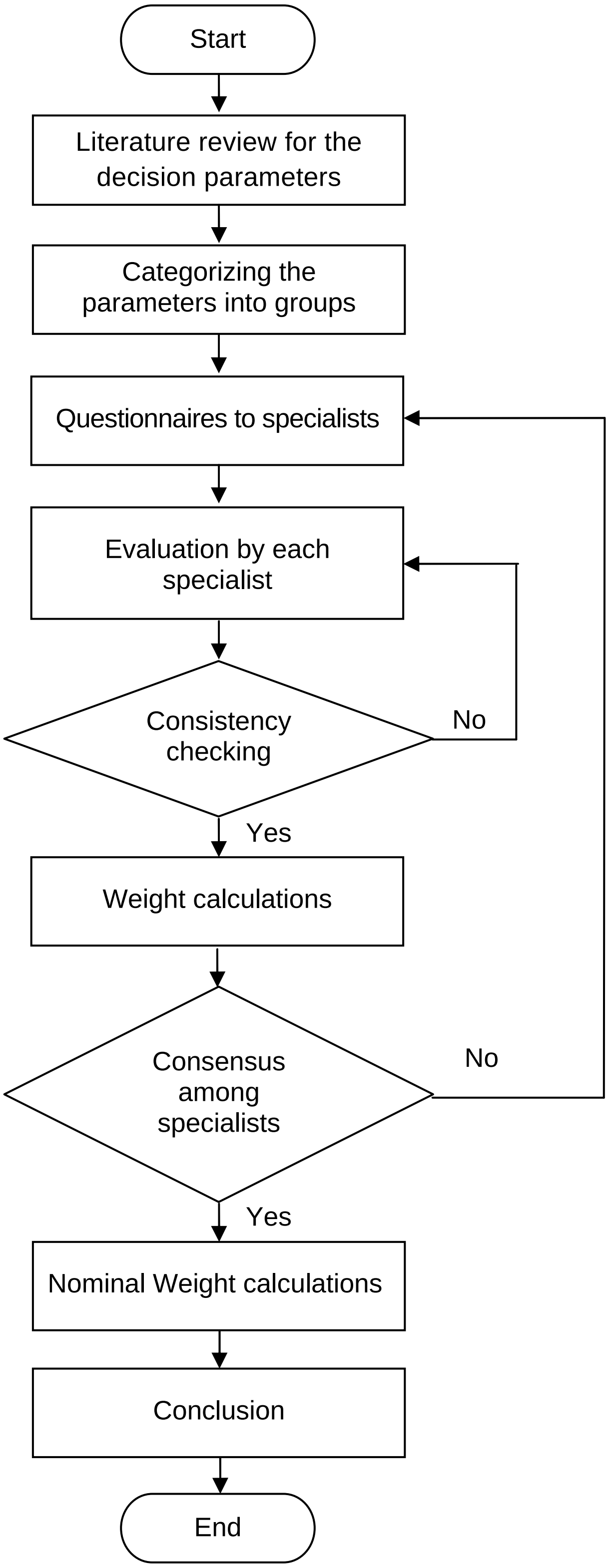


Fig. 1 Research procedure

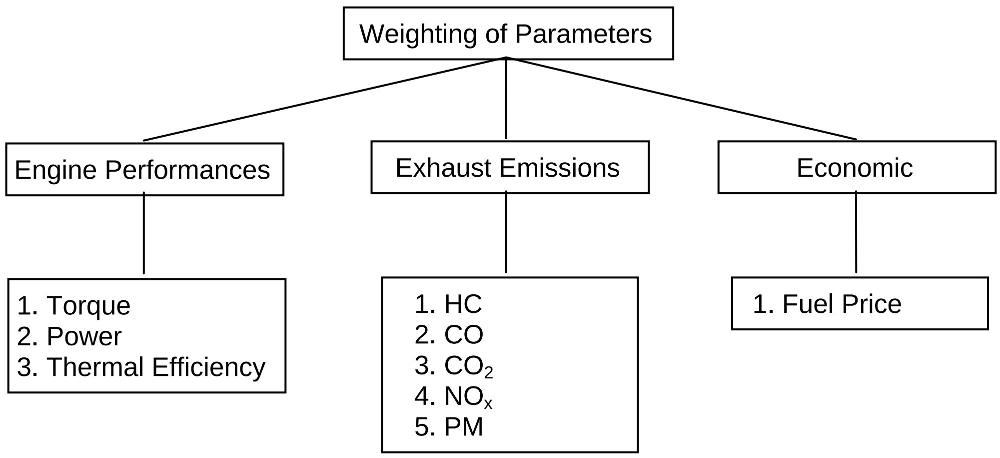


Fig. 2 AHP model for deriving the weightages of parameters

The questionnaires are sent to specialists, which are chosen on the basis of their profession reputation, work experience and research activities. All specialists have science and engineering backgrounds. The first category consists of 6 specialists from 1) universities, 2) environmental research institute, 3) Thailand ministry of energy, and 4) Thailand institute of scientific and technological research. The second category consists of 6 specialists from 1) universities, 2) Thailand ministry of energy and 3) Thailand institute of scientific and technological research. However, the third category needs no evaluation since it consists of only one parameter.

While implementing, the AHP model requires aggregating the evaluation of each groups. Weighting of each category must also be done. Specialists corresponding to this step are researchers and professors in energy, automotive, chemical, environmental engineering who also have vision in term of economic. Moreover, two officials from Thailand ministry of energy and two researchers from Thailand institute of scientific and technological research attended this process.

The results of each evaluation are checked for the consistency. If it is found that the consistency ratio is unacceptable, that specialist must reconsider until the result reaches an acceptable value. All results are aggregated by geometric mean and calculated the weight of each parameter.

Now, the Delphi technique starts in this step. The whole raw data including the analyzed data are sent to each single specialist. They have chance to see other evaluations anonymously and reconsider their results. The consistency check is also needed in this new iteration. It is normally found that the extreme value rapidly decreases and the iteration can be repeated again and again until specialists do not change their decision, which means the group decision reaches consensus. Finally, final nominal weight of each parameter can be achieved.

## 4. RESULTS AND DISCUSSIONS

The AHP-Delphi methodology is applied to the weighting of engine parameters. Researchers makes the pair-wise comparison of parameters in each group by using AHP comparison scale as shown in table 1 and the example of the questionnaire items is shown in appendix A. In the study, the AHP-Delphi process is implemented in 4 iterations. The first round gets very diverse set of opinion from specialists. Researchers synthesize the data from each specialist and summarized in graphical presentations. In the second round, specialists receive anonymous feedback from the first round. Then, each specialist is asked to repeat AHP process. The extreme value is significantly minimized in this iteration. The data from this round is also summarized and sent back to each specialist to repeat their AHP process in the third and the final rounds. The weighting for all parameters from the final round are presented in table 3 and table 4.

**Table 3** Weighting of the groups

| Group | Weight |
|---|---|
| 1. Engine Performance | 0.3965 |
| 2. Exhaust Emissions | 0.2348 |
| 3. Economic (price) | 0.3687 |
| **Group summation** | 1.0000 |

**Table 4** Weighting for engine parameters

| Group 1 | | Group 2 | | Group 3 | |
|---|---|---|---|---|---|
| **Engine Performance** | **Weight** | **Exhaust Emissions** | **Weight** | **Economic** | **Weight** |
| Torque | 0.7130 | CO | 0.1115 | Fuel price | 1.0000 |
| Power | 0.1930 | $CO_2$ | 0.0425 | | |
| Efficiency | 0.0940 | THC | 0.2278 | | |
| | | $NO_x$ | 0.0781 | | |
| | | PM | 0.5420 | | |
| **Group summation** | 1.0000 | **Group summation** | 1.0000 | **Group summation** | 1.0000 |

One method to obtain the aggregated weightages is to multiply the weights of parameters (table4) with the weight of that group (table 3). However, this method shows one weak point that the weightages decrease as the number of parameters in the group increases. Nevertheless, Ramanathan (1995) suggest a solution to solve by using equation (1) in this case

$$W_i = \left(\frac{p_i}{p*}\right) \times A \quad (1)$$

From equation (1), $p_i$ is the weight of the parameters in the group and $p*$ is the highest value, where the weight of the group is $A$. Then the final weights of engine parameters are shown in table 5.

**Table 5** Final weightages of the engine parameter

| Parameter | Weight | Nominal Weight |
|---|---|---|
| Torque | 0.39653 | 0.2920 |
| Power | 0.10734 | 0.0790 |
| Efficiency | 0.05230 | 0.0385 |
| CO | 0.04830 | 0.0356 |
| $CO_2$ | 0.01799 | 0.0132 |
| THC | 0.09827 | 0.0724 |
| $NO_x$ | 0.03385 | 0.0249 |
| PM | 0.23482 | 0.1729 |
| Fuel price | 0.36866 | 0.2715 |
| **Summation** | **1.35806** | **1.0000** |

The result clearly shows that the importance of each parameter is different. Torque seems to be the most concerning parameter. If the research works on the new alternative fuel, the fuel price becomes the second most important parameter. Then PM and power come as the third and the forth, respectively. $CO_2$ seems to be the least significant parameter from the result, which can be reasonable since $CO_2$ is not the toxic gas and it indicates the combustion efficiency. The result definitely helps researchers to make better decisions in their researches.

For example, if researchers are investigating on diesel and biodiesel blends, they are testing with B0, B10, B20 and B30. They finally get results from their engine testing measurements. They find that, as the portion of biodiesel increases, torque and fuel price decrease by the step of 1% and 5%. However, $CO_2$ increases by the step of 10%. The other parameters are assumed that there are no significantly changes. Without the result of the present research, it is definitely difficult to decide which blend is the best one. Thus, researchers can multiply their results (values) to the weights given in table 5. This will simply show the actual values of each parameter that automatically indicate their significant and lead to better decision for researchers among the four alternatives (B0, B10, B20 and B30).

The other application for this research to reach the best result is merging this process to goal programming. Goal programming generates mathematical models to find the optimal solution, which have been investigated in previous research (Ramanathan 1995, Massimo 2006). Thus, the result might not be B0, B10, B20 or B30 but the optimal result from goal programming can possibly show that B12.5 is the optimal blend.

## 5. CONCLUSIONS AND RECOMMENDATIONS

Researches in alternative energy fields have been working on various engine sizes, operating loads and speeds. But the gap of research is found that researchers could only explain the relation between parameter without final decision in real application as it deals with several criteria. This research aims to weight the frequently used engine parameters, which can help researchers to make an appropriate decision under multi-criteria situation. An integrated AHP-Delphi method is utilized since it can convert human perceptions into numerical value and also include a consistency check. Moreover, it can deal with a group decision making to obtain the consensus of a number of specialists, which are recruited on the basis of their professional reputation, work experience and research activities from different associations.

The engine parameters are classified into three groups and weighted by the integrated AHP-Delphi method. The result shows that engine torque is the most important decision parameter with the weight of 0.2920 or 29.20%. Fuel crisis is one of the most important issues that impel the alternative energy researches. Thus, fuel price shows the weight of 0.2715 or 27.15%. PM emission shows the weight of 0.1729 or 17.29% since it is the only visible emission and also very harmful to health. While the result shows that $CO_2$ is the least significant decision parameter with the weight of 0.0132 or 1.32%.

The result from this research can help researcher to select the best alternative input parameter of their researches. Moreover, merging this process to goal programming is very efficient and effective way to find the optimal results in future researches.

The engine parameters used in this research are very general parameters. Some more parameters can be added in some cases and some parameters must be removed if they do not involve the studies. For example, if the research is focusing on new design of engine parts while the type of fuel is not the input factor, fuel price should be eliminated. Thus, it is needed to be emphasized here again that this research is showing an idea of how to deal with multi-criteria decision making in engine researches. The parameters must be compatible with the context and objectives of that specific research.

**APPENDIX A:** An example for the pair-wise comparison with respect to 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 |

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