ELSEVIER

Multi-criteria analysis of alternative-fuel buses for public transportation

Gwo-Hshiung Tzeng[a,*], Cheng-Wei Lin[a], Serafim Opricovic[b,1]

[a] Energy and Environmental Research Group, Institute of Technology of Management, Institute of Traffic and Transportation, National Chiao Tung University, 1001, Ta-Hsmeh Rd, Hsinchun 300, Taiwan
[b] Faculty of Civil Engineering, University of Belgrade, Yugoslavia

Abstract

The technological development of buses with new alternative fuels is considered in this paper. Several types of fuels are considered as alternative-fuel modes, i.e., electricity, fuel cell (hydrogen), and methanol. Electric vehicles may be considered the alternative-fuel vehicles with the lowest air pollution. Hybrid electric vehicles provide an alternate mode, at least for the period of improving the technology of electric vehicles. A hybrid electric vehicle is defined as a vehicle with the conventional internal combustion engine and an electric motor as its major sources of power. Experts from different decision-making groups performed the multiple attribute evaluation of alternative vehicles. AHP is applied to determine the relative weights of evaluation criteria. TOPSIS and VIKOR are compared and applied to determine the best compromise alternative fuel mode. The result shows that the hybrid electric bus is the most suitable substitute bus for Taiwan urban areas in the short and median term. But, if the cruising distance of the electric bus extends to an acceptable range, the pure electric bus could be the best alternative.
© 2004 Elsevier Ltd. All rights reserved.

Keywords: Alternative fuel; Electric bus; Public transportation; Multi-criteria analysis; Compromise solution; TOPSIS; VIKOR

1. Introduction

In the last two decades of the 20th century, there was growing concern about pollution in major cities, and in particular about the large contribution made by road transportation sources to this problem (McNicol et al., 2001). Government legislation on ICE emissions and fuel quality substantially improved the air quality in cities through reduction in regulated pollutants. For example, in the United States, California introduced the so-called 'zero-emission vehicles (ZEV) mandate', which called for 2% of all new vehicles offered for sale in California in model years 1998–2000 to be ZEVs. Initially, it was intended that such vehicles would be battery-powered electric vehicles (EVs). Owing to the limitation of EVs development, the regulations were relaxed to allow additional time for the technology to develop. During the development period, alternative-fuel vehicles were also considered. The advantages of HEVs are regeneration of braking energy, engine shutdown instead of idling, and engine driving under high-load conditions; these advantages are more noticeable in city driving. The key weakness of EVs, on the other hand, is that time is needed to recharge the batteries (Morita, 2003). The bus system possesses such features as stable depot, route, group of commuter, time of operation, and frequency, so that the research on finding alternative-fuel modes for public transportation is of high interest. Therefore, the purpose of this research is to evaluate the best alternative-fuel buses suitable for the urban area and to explore the potential direction of development in the future.

The trends of the latest worldwide technological developments of a bus with new alternative fuel are considered in this paper. Morita (2003) thought that the leading types of automobiles in the 21st century are likely to be of the following four types: internal combustion engine vehicles (ICEVs), hybrid electric vehicles (HEVs), electric vehicles (EVs), and fuel cell vehicles (FCVs). McNicol et al. (2001) pointed out that the principal competitors of FCVs are EVs, HEVs, and advanced conventional ICE-powered vehicles (ICEVs).

*Corresponding author. Tel.: +886-35712121ext57505; fax: +886-35753926.

E-mail address: ghtzeng@cc.nctu.edu.tw (G.-H. Tzeng).

[1] Visiting professor at National Chiao Tung University (in 2002), supported by National Science Council of Taiwan.

Based on the literature mentioned above, several types of fuel are considered as alternative-fuel modes, i.e., EVs, HEVs, fuel cell (hydrogen), methanol, natural gas (Morita, 2003; McNicol et al., 2001; Sperling, 1995).

Current researches about alternative-fuel vehicles are well grounded. The scope of research includes the direction of development (Morita, 2003; Harding, 1999), comparison of alternative-fuel vehicles (Maggetto and Van Mierlo, 2001; Johnsson and Ahman, 2002), impact evaluation (Kazimi, 1997; Matheny et al., 2002; Brodrick et al., 2002; Zhou and Sperling, 2001; Kempton and Kubo, 2000), batteries (Moseley, 1999), policy (Nesbitt and Sperling, 1998), costs (DeLucchi et al., 2002; DeLucchi and Lipman, 2001), market (Sperling et al., 1995), etc. Most of the research focuses on comparing and describing the performance of single or several types of alternative-fuel vehicles.

In addition, some research is related to the evaluation of alternative fuel. Poh and Ang (1999) applied forward and backward analytic hierarchy process (AHP) to analyze the transportation fuels and policy for Singapore. Winebrake and Creswick (2003) also applied AHP to evaluate the future of hydrogen fueling systems for transportation. Both of these teams utilize scenario analysis to build their evaluation model.

A similar approach is applied in this current research. In this paper, alternative fuels are considered for their potential to displace oil as the main and only source of transport fuel. The characteristics of buses are suitable for using such fuels in populated modern cities. Therefore, evaluating a moderate fuel mode for buses in urban area is the purpose of this research.

The evaluation of alternative-fuel buses should be considered from various aspects; for example, energy efficiency, emissions, technologies, costs, facilities and so on. The multi-attribute evaluation process is thus used in this paper. The AHP is used to determine the weights of evaluation criteria. The AHP, introduced by Saaty (1980), is known as a pairwise comparison method and a popular method in evaluation problems. There is a lot of research on the application of decision analysis techniques to transportation, energy and environmental planning, such as the researches of Tzeng et al. (1992, 1994), Tzeng and Tsaur (1993, 1997). TOPSIS and VIKOR (see Appendices A and B) are compared and used to rank the alternative-fuel buses. The details of these two methods are shown in Section 5. The multi-attribute evaluation of alternative buses was performed by the experts from different decision making groups, such as bus users, the social community, and the operators. The selection of the best fuel mode has to be done according to several competing (conflicting) criteria. This decision-making problem has no solution satisfying all criteria simultaneously. The compromise solution of the problem of conflicting criteria should be determined, and the criteria could help the decision makers to reach their final decision. The compromise ranking method is applied to determine the best compromise alternative-fuel bus. For testing and verifying the usability of this methodology, we illustrate the evaluation of alternative-fuel buses of Taiwan urban areas as an empirical example. The results can prove the effectiveness of this method and illustrate the directions for future development and the weakness of the best alternative, which make it easy to implement in the future.

The rest of this paper is organized as follows: Section 2 describes the types of alternative-fuel buses evaluated in this research; Sections 3 and 4 introduce the procedure of generation and evaluation of criteria and alternatives; the evaluation methodologies, results and discussions are shown in Section 5, and the final section contains conclusions and recommendations.

2. Alternative solutions

The main parameter in defining alternative solutions is the fuel mode. According to the data collected in this study, the alternatives are classified into four groups: the conventional diesel engine, the new mode of alternative fuel, the electric vehicle, and the hybrid electric vehicle. There is a vigorous worldwide effort to develop a transportation means utilizing new alternative fuels, including methanol, fuel cell (hydrogen), and compressed natural gas. The electric vehicle operating on electricity is of high interest, but the appropriate technology is still developing. The advantages of EVs are that they perform efficiently under low-load conditions, and do not discharge any pollutants during use (Morita, 2003). Their key weakness is that time is needed to recharge the batteries. In addition, disadvantages such as a short cruising distance (usually less than 200 km) and lack of support infrastructure significantly reduce their convenience (Morita, 2003). The hybrid electric vehicle, which retains both the electric motor and internal combustion engine, has been widely accepted by the users (Griffith and Gleason, 1996; Harding, 1999; McNicol et al., 2001; Maggetto and Van Mierlo, 2001). Morita (2003) pointed out that HEVs have the potential to rank alongside conventional vehicles in terms of cost and convenience. The advantages of HEVs are regeneration of braking energy, engine shutdown instead of idling, and engine driving under high-load conditions; these advantages are more noticeable in city driving. The advantages of HEVs are that they can incorporate any type of internal combustion engine, or fuel cells and show good efficiency, no matter what type of fuel the engine uses. In this paper, the following alternatives are considered: gasoline-electric, diesel-electric, CNG electric, and LPG electric. Based on the global development results, 12 alternatives

of fuel mode are considered, and the features of each alternative-fuel mode are described in this paper.

2.1. Conventional diesel engine

The conventional diesel engine bus is employed by the Taiwanese transportation companies. In fact, the diesel engine is the most efficient of all existing internal combustion engines, making it one of the major contenders as a power source in the 21st century (Morita, 2003). It is introduced in the set of alternatives in order to compare it with the new fuel modes.

2.2. Compressed natural gas—CNG

Natural gas is used in several forms as vehicle fuel, i.e., compressed natural gas (CNG), liquid natural gas (LNG), and attached natural gas (ANG). The CNG vehicle has already been commercialized around the world and is matured in its technology (there are about four million CNG vehicles in the world). The compressed natural gas vehicle is widespread in countries with their own natural gas. CNG vehicles emit only slight amounts of carbon dioxide and have high-octane value; thus they are suitable for utilization as public transportation vehicles (Sperling, 1995). The natural gas supply, distribution, and safety are the most urgent issues needing improvement.

2.3. Liquid propane gas—LPG

There are countries that have used this mode of fuel for public transportation. In Japan, Italy, and Canada, as much as 7% of the buses are powered by LPG (Sperling, 1995), and some European countries are planning to employ LPG vehicles, due to pollution considerations.

2.4. Fuel cell (hydrogen)

The so-called fuel cell battery can transform hydrogen and oxygen into power for vehicles (Sperling, 1995); however, hydrogen is not suitable for onboard storage (Morita, 2003). The research on a fuel cell-hydrogen bus has already been concluded with success, and test results with the experimental vehicle operating on hydrogen fuel indicate that this vehicle has a broad surface in the burning chamber, low burning temperature, and the fuel is easily inflammable (DeLucchi, 1989). Daimler–Benz Company has already developed a prototype vehicle with a fuel cell. To date, the only vehicles offered for sale with fuel cell technology is the Zevco London taxi which was launched in London in July 1998 (Harding, 1999). Due to the fact that the energy to operate this vehicle comes from the chemical reaction between hydrogen and oxygen, no detrimental substance is produced and only pure water, in the form of air, is emitted. A fully loaded fuel tank can last as far as 250 km.

2.5. Methanol

The research of methanol is related to vehicles with gasoline engines. The combination rate of methanol in the fuel is 85% (so-called M85). The engine that can use this fuel with different combination rates is termed as flexible fuel vehicle (FFV). The FFV engine can run smoothly with any combination rate of gas with methanol, and methanol will act as an alternative fuel and help to reduce the emission of black smoke and nitrous oxides (NO_x). Fuel stations providing methanol are already available in Japan since 1992 (Sperling, 1995). The thermal energy of methanol is lower than that of gasoline, and the capability of continuous traveling by this vehicle is inferior to conventional vehicles. Furthermore, the aldehyde compound that comes along with burning methanol forms a strong acid, and the researchers should pay more attention to this fuel mode.

2.6. Electric vehicle—opportunity charging

The source of power for the opportunity charging electric vehicle (OCEV) is the combination of a loaded battery and fast opportunity charging during the time the bus is idle when stopped. Whenever the bus starts from the depot, its loaded battery will be fully charged. During the 10–20 s when the bus is stopped, the power reception sensor on the electric bus (installed under the bus) will be lowered to the charging supply plate installed in front of the bus stop to charge the battery. Within 10 s of a stop, the battery is charged with 0.15 kWh power (depending on the design of power supply facility), and the power supplied is adequate for it to move to the next bus stop.

2.7. Direct electric charging

This type of electric bus is in the prototype design stage. The power for this vehicle comes mainly from the loaded battery. Once the battery power is insufficient, the vehicle will have to return to the plant to conduct recharging. The development of a suitable battery is critical for this mode of vehicle. If a greater amount of electricity can be stored in the battery, the cruising distance by this vehicle will increase.

2.8. Electric bus with exchangeable batteries

The objective of an electric bus with an exchangeable battery is to effect a fast battery charge and to achieve a longer cruising distance. The bus is modified to create more on-board battery space and the number of on-

board batteries is adjusted to meet the needs of different routes. The fast exchanging facility has to be ready to conduct a rapid battery exchange so that the vehicle mobility can be maintained.

2.9. Hybrid electric bus with gasoline engine

The electric-gasoline vehicle has an electric motor as its major sources of power and a small-sized gasoline engine. When electric power fails, the gasoline engine can take over and continue the trip. The kinetic energy rendered during the drive will be turned into electric power to increase the vehicles' cruising distance.

2.10. Hybrid electric bus with diesel engine

The electric–diesel vehicle has an electric motor and small-sized diesel engine as its major sources of power. When electric power fails, the diesel engine can take over and continue the trip, while the kinetic energy rendered during the drive will be turned into electric power to increase the vehicles' cruising distance.

2.11. Hybrid electric bus with CNG engine

The electric-CNG vehicle has an electric motor and a small-sized CNG engine as its major sources of power. When electric power fails, the CNG engine takes over and provides the power, with the kinetic energy produced converted to electric power to permit continuous travel.

2.12. Hybrid electric bus with LPG engine

The electric-LPG vehicle has an electric motor and a small-sized LPG engine as its major sources of power. When electric power fails, the LPG engine takes over and provides the power, with the kinetic energy produced converted to electric power to permit continuous travel.

3. Evaluation criteria

According to the papers described above, we established the evaluation criteria in Section 3.1 and assess the criteria weight in Section 3.2.

3.1. Establishing the evaluation criteria

The evaluation of alternative fuel modes can be performed according to different aspects. Four aspects of evaluation criteria are considered in this paper: social, economic, technological, and transportation. In order to evaluate the alternatives, 11 evaluation criteria are established, as follows:

(1) *Energy supply*: This criterion is based on the yearly amount of energy that can be supplied, on the reliability of energy supply, the reliability of energy storage, and on the cost of energy supply.
(2) *Energy efficiency*: This criterion represents the efficiency of fuel energy.
(3) *Air pollution*: This criterion refers to the extent a fuel mode contributes to air pollution, since vehicles with diverse modes of fuel impact on air differently.
(4) *Noise pollution*: This criterion refers to the noise produced during the operation of the vehicle.
(5) *Industrial relationship*: The conventional vehicle industry is a locomotive industry, and it is intricately related to other industrial production; the relationship of each alternative to other industrial production is taken as the criterion.
(6) *Costs of implementation*: This criterion refers to the costs of production and implementation of alternative vehicles.
(7) *Costs of maintenance*: The maintenance costs for alternative vehicles are the criterion.
(8) *Vehicle capability*: This criterion represents the cruising distance, slope climbing, and average speed.
(9) *Road facility*: This criterion refers to the road features needed for the operation of alternative vehicles (like pavement, and slope).
(10) *Speed of traffic flow*: This criterion refers to the comparison of the average speed of alternative vehicles for certain traffic. If the speed of traffic flow is higher than the vehicle speed, the vehicle would not be suitable to operate on certain routes.
(11) *Sense of comfort*: This criterion refers to the particular issue regarding sense of comfort, and to the fact that users tend to pay attention to the accessories of the vehicle (air-conditioning, automatic door, etc.).

3.2. Assessment of criteria weights

In the assessment of criteria weights, the relevant decision-making experts participating were from the electric bus manufacturing, academic institutes, research organization, and bus operations sectors. They assessed the relative importance (subjectively) for each of the criteria. The average values of weights are presented in Table 1. This data show that the speed of traffic is the most important factor in evaluating the alternative vehicles; second in importance is air pollution, indicating the need for new alternative-fuel modes.

Table 1
Criteria weights

Criterion	Manufacture	Academic institute	Research organization	Bus operator	Average
1 Energy supply	0.0357	0.0314	0.0340	0.0249	0.0313
2 Energy efficiency	0.1040	0.0943	0.1020	0.0748	0.0938
3 Air pollution	0.1355	0.2090	0.1595	0.1605	0.1661
4 Noise pollution	0.0452	0.0697	0.0532	0.0535	0.0554
5 Industrial relationship	0.0923	0.0357	0.0480	0.0757	0.0629
6 Employment cost	0.0900	0.0680	0.0343	0.1393	0.0829
7 Maintenance cost	0.0300	0.0227	0.0114	0.0464	0.0276
8 Vehicle capability	0.1373	0.0953	0.1827	0.0803	0.1239
9 Road facility	0.0827	0.0590	0.1520	0.0283	0.0805
10 Speed of traffic flow	0.1520	0.2420	0.1400	0.2637	0.1994
11 Sense of comfort	0.0957	0.0730	0.0833	0.0523	0.0761

Good analytical procedure requires making histograms of the data, to check the form of their distribution, before proceeding with multi-criteria analysis. If the data are not normally distributed, and the standard deviation is not small, the sensitivity analysis covering the range of weights should be performed within the multi-criteria decision-making procedure.

4. Evaluation of the alternatives

The evaluation approach applied in this paper is based on the assessment by the professional experts. The average assessed value for alternative j according to criterion i is determined by the relation

$$f_{ij} = \frac{1}{N} \sum_{l=1}^{N} u_{lij},$$

where u_{lij} is the performance value given by expert l to the alternative j according to criterion i, N is the number of experts participating in the evaluation process. The "value function" u has the following properties: $0 \leqslant u \leqslant 1$, and $u_{ij} > u_{ik}$ means that the alternative j is better than the alternative k according to criterion i.

The selection of the expert group members is of extreme importance in the evaluation process of the MCA/MCDM problem. The selection of alternative-fuel buses is a problem related to the public affairs, and credible experts for evaluating this problem are really important. In Taiwan, experts from manufacturing industries, and related departments of government, academics, and research institutes, are acknowledged as credible experts. For this reason, the experts were invited from the Transportation Bureau of Taipei City, Environmental Protection Administration, the Transportation Institute of the Ministry of Communications, Vehicle Association, Energy Committee, and research personnel on electric vehicles. The investigation information found in previous researches (emissions of black

smoke, the capability of continuous traveling) was the basic reference information, and it was listed in the questionnaire prepared for the experts. Within the evaluation process (Delphi method), the evaluation results were presented to the experts for the second evaluation. They had to reconsider the performance values of each alternative-fuel mode and to re-evaluate the alternatives. Seventeen valid questionnaires were retrieved from the evaluation process.

The evaluation results following the second evaluation are presented in Table 2. According to the energy supply criterion, the average performance value is the highest for the diesel bus (0.820), and the lowest for the hydrogen bus (0.360). With respect to energy efficiency, the average performance values are very high for the electric vehicles. The average performance values for electric vehicles are the highest according to air pollution and noise pollution, but the values are very low according to the capability of the vehicle and needed road facility. Analyzing the data from Table 2, we can conclude that the electric vehicle rates very good according to the criteria of energy, environmental impact, industrial relationship, and implementation cost; the transportation mode using conventional diesel rates high according to the vehicle capability and needed (new) road features; whereas the transportation mode using natural gas, methanol and hydrogen are associated with the "middle" values.

5. Multi-criteria optimization

The MCDM methods VIKOR and TOPSIS are based on an aggregating function representing closeness to the reference point(s). For the details of these two methods, please refer to Tzeng and Opricovic (2003), which are summarized in Appendices A and B. These two methods introduce different forms of aggregating function (L_p-metric) for ranking. The VIKOR method introduces Q_j as a function of L_1 and L_∞, whereas the TOPSIS

Table 2
Values of the criterion functions

Alternatives	Energy supply	Energy efficiency	Air pollution	Noise pollution	Industrial relations	Employment cost	Maintenance cost	Capability vehicle	Road facility	Speed of traffic	Sense of comfort
1. Diesel bus	0.82	0.59	0.18	0.42	0.58	0.36	0.49	0.79	0.81	0.82	0.56
2. CNG bus	0.77	0.70	0.73	0.55	0.55	0.52	0.53	0.73	0.78	0.66	0.67
3. LPG bus	0.79	0.70	0.73	0.55	0.55	0.52	0.53	0.73	0.78	0.66	0.67
4. Hydrogen	0.36	0.63	0.86	0.58	0.51	0.59	0.74	0.56	0.63	0.53	0.70
5. Methanol	0.40	0.54	0.69	0.58	0.51	0.52	0.68	0.52	0.63	0.60	0.70
6. Charging	0.69	0.76	0.89	0.60	0.72	0.80	0.72	0.54	0.35	0.79	0.73
7. Electric dir.	0.77	0.79	0.89	0.59	0.73	0.80	0.72	0.47	0.44	0.87	0.75
8. Electric bat	0.77	0.79	0.89	0.59	0.73	0.80	0.72	0.51	0.48	0.87	0.75
9. Hybrid-gas.	0.77	0.63	0.63	0.52	0.66	0.63	0.65	0.67	0.70	0.80	0.74
10. Hyb-diesel	0.77	0.63	0.51	0.58	0.66	0.63	0.65	0.67	0.70	0.80	0.74
11. Hyb.-CNG	0.77	0.73	0.80	0.48	0.63	0.66	0.65	0.67	0.71	0.62	0.78
12. Hyb.-LPG	0.77	0.73	0.80	0.48	0.63	0.66	0.65	0.67	0.71	0.62	0.78

method introduces C_j^* as a function of L_2. They use different kinds of normalization to eliminate the units of criterion functions: the VIKOR method uses linear normalization, and the TOPSIS method uses vector normalization. The difference between these two methods is described in Section 5.1. We find the compromise solution of alternative-fuel buses selection by them, and the results are shown in Section 5.2.

5.1. Comparison of TOPSIS and VIKOR

Multiple criteria analysis (MCA) is appropriate to solve the problems relating to several aspects. TOPSIS and VIKOR are two methods that are easy to apply among the ranking methods of MCA. However, these two methods are different in basic definitions. Opricovic and Tzeng (2003, 2004) have discussed the differences of these two methods. In this current research, we applied these two methods to find the comprise solution of the alternative-fuel buses selection, and have shown the difference of these methods. The main features of VIKOR and TOPSIS are summarized here in order to clarify the differences between these two methods.

5.1.1. Procedural basis

Both methods assume that there exists a performance matrix $|f|_{nxJ}$ obtained by the evaluation of all the alternatives in terms of each criterion. Normalization is used to eliminate the units of criterion values. An aggregating function is formulated and it is used as a ranking index. In addition to ranking, the VIKOR method proposes a compromise solution with an advantage rate.

5.1.2. Normalization

The difference appears in the normalization used within these two methods. The VIKOR method uses linear normalization (Opricovic and Tzeng, 2003,2004),

and the normalized value does not depend on the evaluation unit of a criterion. The TOPSIS method uses vector normalization, and the normalized value can be different for different evaluation units of a particular criterion. A later version of the TOPSIS method uses linear normalization (Opricovic and Tzeng, 2003,2004).

5.1.3. Aggregation

The main difference appears in the aggregation approaches. The VIKOR method introduces an aggregating function, representing the distance from the ideal solution. This ranking index is an aggregation of all criteria, the relative importance of the criteria, and a balance between total and individual satisfaction. The TOPSIS method introduces the ranking index (A.6), including the distances from the ideal point and from the negative-ideal point. These distances in TOPSIS are simply summed in (A.6), without considering their relative importance. However, the reference point could be a major concern in decision making, and to be as close as possible to the ideal is the rationale of human choice. Being far away from a nadir point could be a goal only in a particular situation, and the relative importance remains an open question (see Appendix B). The TOPSIS method uses n-dimensional Euclidean distance that by itself could represent some balance between total and individual satisfaction, but uses it in a different way than VIKOR, where weight v is introduced in (A.3).

5.1.4. Solution

Both methods provide a ranking list. The highest ranked alternative by VIKOR is the closest to the ideal solution. However, the highest ranked alternative by TOPSIS is the best in terms of the ranking index, which does not mean that it is always the closest to the ideal solution. In addition to ranking, the VIKOR method proposes a compromise solution with an advantage rate.

5.2. Compromise solution

The compromise ranking method was applied with data given by the expert group (average evaluation values in Table 2, and average weights in Table 1). The obtained ranking list (by VIKOR) is presented in Table 3.

The ranking results are obtained by applying another method, named TOPSIS, which is also a modification of compromise programming. The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) was developed based on the concept that the chosen alternative should have the shortest distance from the ideal solution and the farthest from the negative-ideal solution, using Euclidean distance (Hwang and Yoon, 1981). The ranking results (by TOPSIS) are presented in Table 3.

There are four compromise solutions obtained by VIKOR, because the top four are "close". This result shows that the hybrid electric bus is the most suitable substitute bus, followed by the electric vehicles on the ranking list (Table 3).

Preference stability analysis was performed (by VIKOR) and the weight stability intervals for a single criterion are obtained, as follows.

$0.021 \leqslant w_1 \leqslant 0.213$ (input $w_1 = 0.031$); $0.000 \leqslant w_2 \leqslant 0.096$ (input $w_2 = 0.094$);

$0.116 \leqslant w_3 \leqslant 0.168$ (input $w_3 = 0.166$); $0.000 \leqslant w_4 \leqslant 0.063$ (input $w_4 = 0.055$);

$0.000 \leqslant w_5 \leqslant 0.175$ (input $w_5 = 0.063$); $0.000 \leqslant w_6 \leqslant 0.099$ (input $w_6 = 0.083$);

$0.000 \leqslant w_7 \leqslant 0.040$ (input $w_7 = 0.028$); $0.123 \leqslant w_8 \leqslant 0.298$ (input $w_8 = 0.124$);

$0.073 \leqslant w_9 \leqslant 0.358$ (input $w_9 = 0.081$); $0.105 \leqslant w_{10} \leqslant 0.202$ (input $w_{10} = 0.199$);

$0.000 \leqslant w_{11} \leqslant 0.188$ (input $w_{11} = 0.076$).

The weights' stability intervals show that the obtained compromise solution (by VIKOR, Table 3) is very sensitive to the changes in criteria weights.

With different weights from Table 1, the following sets of compromise solutions (by VIKOR) are obtained:

- Electric vehicles (three modes) are in the set of compromise solutions with the weights given by "Bus operator", and by "Academic Institute";
- Hybrid electric vehicles, with gasoline and diesel engine, are the compromise solution obtained with the weights given by "Manufacture";
- Hybrid electric vehicle with gasoline engine, fuel mode CNG and LPG, and hybrid electric vehicle with diesel engine are in the set of compromise solutions obtained with the weights given by "Research Organization".

The ranking results obtained by the TOPSIS method indicate that the electric vehicles may be considered as the best compromise solution, and the hybrid electric vehicles may be considered as the second best compromise solution.

5.3. Discussion

According to the results from Table 3, the conventional diesel engine is ranked very low, reflecting the need for an alternative-fuel mode. We can conclude that the hybrid electric bus is the most suitable substitute bus for the Taiwan urban areas in short and median term. But, if the cruising distance of the electric bus can be extended to an acceptable range, the pure electric bus could be the best alternative.

It seems that the experts have unanimously agreed that it is necessary to develop an alternative-fuel mode for public transportation.

Table 3
Multi-criteria ranking results

Ranking by VIKOR			Ranking by TOPSIS			
Rank	Alternative	Q	I Rank	Evaluation Index	II Rank	Evaluation Index
1	Hybrid electric bus—gasoline engine	0.168	4	0.749	9	0.756
2	Electric bus—exchangeable battery	0.172	1	0.945	1	0.975
3	Electric bus—opportunity charging	0.224	2	0.933	3	0.964
4	Electric bus—direct charging	0.253	3	0.931	2	0.967
5	Hybrid electric bus—diesel engine	0.281	7	0.700	11	0.488
6	Liquid propane gas (LPG)	0.479	11	0.345	8	0.830
7	Compress natural gas (CNG)	0.480	10	0.399	7	0.830
8	Hybrid electric bus with CNG	0.510	5	0.700	4	0.889
9	Hybrid electric bus with LPG	0.510	6	0.700	5	0.889
10	Conventional diesel engine	0.806	12	0.301	12	0.097
11	Methanol	0.852	9	0.527	10	0.698
12	Fuel cell (hydrogen)	0.925	8	0.563	6	0.865

In comparison with conventional vehicles, alternative-fuel vehicles would contribute significantly to the improvement of air quality in urban areas. However, the electric vehicle demands recharging, and it remains uncompetitive with the fuel-engine vehicle because of its frequent recharging needs. Because the bus system owns such features as permanent terminal, route, group of user, time of operation, and frequency, it is likely to expect that the implementation of an alternative-fuel bus might become a very important option for the development of public transportation.

Since the technology of electric vehicles remains to be matured, a hybrid electric bus would be employed as the transitional mode of transportation for the improvement of environmental quality. These vehicles will be replaced when the technological characteristics of electric vehicles, or other new technology, will be improved. In terms of a short-term implementation strategy, the Environmental Protection Administration (EPA) should devote funding from air pollution taxes to city government to conduct the development of an electric bus. For medium term, the city government should stimulate purchase of the electric vehicles by every bus company and replace old buses. For long-term consideration, it is necessary to establish the appropriate industrial policy to facilitate the development of the relevant domestic industry.

On discussion with experts on the electric bus held in the graduate institute of the Bureau of Transportation of Taipei City, the government revealed a desire to rent natural gas vehicles to operate in Taipei City, thus contributing to the improvement of air quality. It was proposed that relevant data—such as energy consumption cost of operation, cost of maintenance, and environmental impact—should be recorded when these vehicles operate in Taiwan. The collected data will be used for future study of the alternative-fuel vehicle in Taiwan.

It is widely acknowledged that the automobile industry is a locomotive industry, as it can help upgrade many of its relevant industries; therefore, if relevant industries in the country can be upgraded because of the development of electric vehicle, it would be beneficial for the domestic industry. At present, there are already many institutions, i.e., the Asia Pacific Investment Company, Min Kun Company, Fang Fu Company Limited, and New Journey Company, working on relevant technological developments for electric vehicles, and they have obtained patents covering all areas throughout the world.

The definition of electric vehicle does not include hybrid electric vehicle, and the Ministry of Transportation and Communications did not specify the electric vehicle and alternative-fuel vehicle of low pollution; thus, confusion might come up in regard to subsidy and reward when hybrid electric vehicle starts to operate in Taiwan. It is then suggested that the Ministry of Transportation and Communications of Taiwan has to clarify the positioning of the hybrid electric vehicle.

6. Conclusions

The result of multi-criteria optimization is that the hybrid electric bus is more suitable at present for public transportation in order to improve the environmental quality. These vehicles will be replaced when the technological characteristics of electric vehicles, or other new technology, will be improved.

The multi-criteria optimization of the alternative-fuel mode is performed with data given by the experts from the relevant engineering fields. The assessment method is based on gathering data and evaluating alternatives by the experts without using mathematical model of evaluating criteria, and this approach could be considered as a contribution of this paper.

The results of multi-criteria analysis indicate what to do first in developing the alternative-fuel mode, in order to improve the environmental quality. To answer the questions of how and when to implement the alternative-fuel mode improvement, the research should continue by solving the development problems under budgetary constraints.

By the compromise ranking method, the compromise solution which could be accepted by the decision makers is determined because it provides a maximum "group utility" of the "majority", and a minimum of the individual regret of the "opponent".

Appendix A. VIKOR

The compromise ranking method (known as VIKOR) is introduced as one applicable technique to implement within the MCDM. Assuming that each alternative is evaluated according to each criterion function, the compromise ranking is performed by comparing the measure of closeness to the ideal alternative (Opricovic, 1998; Opricovic and Tzeng, 2002, 2003, 2004; Tzeng et al., 2002). The multi-criteria merit for compromise ranking is developed from the L_p-metric used in the compromise programming method (Zeleny, 1982). The

various alternatives will be denoted as $a_1, a_2, ..., a_J$. For an alternative a_j, the merit of the ith aspect is denoted by f_{ij}, i.e. f_{ij} is the value of ith criterion function for the alternative a_j; n is the number of criteria.

The compromise-ranking algorithm has the following steps:

(1) Determination of the best f_i^* and the worst f_i^- values of all criterion functions. Assuming that ith function represents a benefit:

$$f_i^* = j\max f_{ij}; \; f_i^- = j\min f_{ij}.$$

(2) Compute the values S_j and R_j, $j = 1, ..., J$, by the relations

$$S_j = \sum_{i=1}^{n} w_i(f_i^* - f_{ij})/(f_i^* - f_i^-), \qquad (A.1)$$

$$R_j = i\max[w_i(f_i^* - f_{ij})/(f_i^* - f_i^-)|i = 1, 2, ..., n], \; (A.2)$$

where w_i are the weights of the criteria.

(3) Compute the values Q_j, $j = 1, ..., J$, by the relation

$$\begin{aligned} Q_j = {}& v(S_j - S^*)/(S^- - S^*) \\ & + (1 - v)(R_j - R^*)/(R^- - R^*), \end{aligned} \qquad (A.3)$$

where:

$$S^* = j\min S_j, \; S^- = j\max S_j,$$

$$R^* = j\min R_j, \; R^- = j\max R_j,$$

v is introduced as the weight of the strategy of "the majority of criteria" (or "the maximum group utility"), usually $v = 0.5$.

(4) Rank the alternatives, sorting by the values S, R and Q. The results are three ranking lists.

(5) Propose as a compromise solution, for given criteria weights, the alternative (a'), which is the best ranked by the measure Q if the following two conditions are satisfied:

C1. "Acceptable advantage" $Q(a'') - Q(a') \geqslant DQ$, where a'' is the alternative with second position in the ranking list by Q; $DQ = 1/(J - 1)$; J is the number of alternatives ($DQ = 0.25$ if $J \leqslant 4$).

C2. "Acceptable stability in decision making": The alternative a' has to be also the best ranked by S or by R, or both, as well. This compromise solution is stable within the decision-making process, which could be: "voting by majority rule" (when $v > 0.5$ is needed), or "by consensus" $v \approx 0.5$, or "with veto"($v < 0.5$). v is the weight of the decision-making strategy "the majority of criteria" (or "the maximum group utility").

If one of the conditions is not satisfied, then the set of compromise solutions is proposed,

which consists of:

● Alternatives a' and a'' if only the conditions C2 are not satisfied.
● Alternatives a', a'', ..., $a^{(k)}$ if the conditions C1 are not satisfied; $a^{(k)}$ is determined by the relation $Q(a^{(k)}) - Q(a') \approx DQ$, the positions of these alternatives are "in closeness".

By the compromise-ranking method, the compromise solution is determined, which could be accepted by the decision makers because it provides a maximum "group utility" of the "majority" (with measure S, representing "concordance"), and a minimum of the individual regret of the "opponent" (with measure R, representing "discordance"). The VIKOR algorithm determines the weight stability intervals for the obtained compromise solution with the "input" weights, given by the experts (Opricovic, 1998).

Appendix B. TOPSIS

The Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) method is presented in Chen and Hwang (1992), with reference to Hwang and Yoon (1981). The basic principle is that the chosen alternative should have the shortest distance from the ideal solution and the farthest distance from the negative-ideal solution.

The TOPSIS procedure consists of the following steps:

(1) Calculate the normalized decision matrix. The normalized value r_{ij} is calculated as

$$r_{ij} = f_{ij}/\sqrt{\sum_{j=1}^{J} f_{ij}^2} \; j = 1, ..., J; \; i = 1, ..., n.$$

(2) Calculate the weighted normalized decision matrix. The weighted normalized value v_{ij} is calculated as

$$v_{ij} = w_i r_{ij}, \; j = 1, ..., J; \; i = 1, ..., n,$$

where w_i is the weight of the ith attribute or criterion and $\sum_{i=1}^{n} w_i = 1$.

(3) Determine the ideal and negative-ideal solution.

$$\begin{aligned} A^* &= \{v_1^*, ..., v_n^*\} \\ &= \{(j\max v_{ij}|i \in I'), (j\min v_{ij}|i \in I'')\}, \end{aligned}$$

$$\begin{aligned} A^- &= \{v_1^-, ..., v_n^-\} \\ &= \{(j\min v_{ij}|i \in I'), (j\max v_{ij}|i \in I'')\}, \end{aligned}$$

where I' is associated with benefit criteria and I'' is associated with cost criteria.

(4) Calculate the separation measures using the n-dimensional Euclidean distance. The separation of each alternative from the ideal solution is given as

$$D_j^* = \sqrt{\sum_{i=1}^n (v_{ij} - v_i^*)^2}, \; j = 1, ..., J. \tag{B.1}$$

Similarly, the separation from the negative-ideal solution is given as

$$D_j^- = \sqrt{\sum_{i=1}^n (v_{ij} - v_i^-)^2}, \; j = 1, ..., J. \tag{B.2}$$

(5) Calculate the relative closeness to the ideal solution. The relative closeness of the alternative a_j with

respect to A^* is defined as

$$C_j^* = D_j^- / (D_j^* + D_j^-), \; j = 1, ..., J. \tag{B.3}$$

Rank the preference order.

Appendix C. Practical data given to the experts

The data given to the experts are summarized in Tables 4–8.

Table 4
Comparison of the functions of diesel and alternative-fuel bus

Items	Diesel bus	EVs	HEVs	Methanol/ethanol bus	Natural gas bus	Fuel-cell bus
Route	NSR[a]	Flat	Flat	NSR[a]	NSR[a]	Flat
Depot	Small	Large (REP[b])	Large (REP[b])	Small	Large (REP[b])	Small
Passengers	60–80 (S, M, L)	20–60 (S, M, L)	20–60 (S, M, L)	60–80 (L)	60–80 (L)	60–80 (L)
Max. Speed (km/h)	100–120	45–80	60–80	100–120	80	70–80
Cruising dist. (km)	400–500	60–220	90–400	200–250	200–300	300–350
Gradeability	<18	<16	<16	<18	<18	<16
Recharge time	10 min	Slow: 8–10 h; fast: 30 min	Slow: 8–10 h; fast: 30 min	10 min	Slow: 6–8 h; fast: 5–20 min	10 min methanol system

Source: Institute of Transportation (2000).
[a] NSR = No special restriction.
[b] REP = Recharge equipment provided.

Table 5
Energy efficiency of diesel and alternative-fuel bus

Bus	Energy efficiency	Fuel-heating value[a]	Comp. of energy efficiency[b]
Diesel bus	1.5 km/l (1.5–1.6)	8800 kcal/l	1.0
Pure electric bus	1.6 km/kWh (1.6–2.4)	860 kcal/kWh	10.9
Hybrid electric bus	2.31 km/l	8800 kcal/l	1.5
CNG bus	1.27 km/m^3 (1.27–1.45)	8900 kcal/m^3	0.8
Methanol bus	0.6 km/l (0.6–0.7)	4200 kcal/l	0.8
Fuel-cell bus	2.79 km/l (Diesel equivalent)	8800 kcal/l	1.9

Source: Institute of Transportation (2000).
[a] The energy efficiency of hybrid electric bus and fuel-cell bus are represented by the diesel equivalent, so their heating values are represented by the heating value of diesel.
[b] Comparison of energy efficiency = (Alternative-fuel bus energy efficiency/fuel heating value)/(Diesel bus energy efficiency/diesel heating value).

Table 6
Exhaust emission characteristics of alternative-fuel bus

Bus	PM	NO$_X$	HC	CO
Pure electric	0.00	0.00	0.00	0.00
Hybrid electric	0.23	8.64	—	—
Natural gas	0.02	7.25	9.87	0.73
Methanol	0.07	4.28	1.31	5.25
Ethanol	0.35	11.06	7.59	24.66
Fuel-cell	0.00	0.03	0.32	6.23
Diesel	1.26	15.66	1.30	10.23

Source: Institute of Transportation (2000).

Table 7
The emission characteristics of carbon dioxide of alternative-fuel buses

Bus type	CO$_2$ (kg/km)	AFV/DIESEL	(DIESEL-AFV)/DIESEL
Diesel bus	1.7	—	—
Pure electric bus	0.3	0.18	82%
Hybrid electric bus	1.1	0.64	36%
Natural gas bus	1.4	0.82	18%
Methanol bus	1.8	1.06	−6%
Fuel-cell bus	0.2	0.12	88%

Source: Institute of Transportation (2000).
The major pollutions of pure electric buses are generated from plants.

Table 8
Cost of diesel and alternative-fuel buses (unit: 1000 NT$)

Cost items		Diesel bus	Pure electric	Hybrid electric	Natural gas	Methanol bus	Fuel-cell bus
Attainment cost	Purchase cost	90,000	300,000	360,000	300,000	120,000	600,000
	Recharge equipment cost	10,000	40,000	40,000	120,000	24,000	24,000
	Total cost	100,000	340,000	400,000	420,000	144,000	624,000
Operation cost	Fuel cost	12,000	1875	5880	9450	12,495	6450
	Management cost	2000	2000	2000	2000	2000	2000
	Total cost	14,000	3875	7880	11,450	14,495	46,600
Maintenance cost	Vehicle maintenance cost	11,400	18,495	22,200	7440	9840	30,720
	Recharge equipment cost				2970	4860	
	Total cost	11,400	18,495	22,200	10,410	14,700	30,720
Lifecycle cost		298,901	521,950	643,328	598,011	373,127	1,239,482

Source: Institute of Transportation (2000).
Management cost is assumed to be 2000 thousands/year.

References

Brodrick, C.J., Lipman, T.E., Farshchi, M., Lutsey, N.P., Dwyer, H.A., Sperling, D., Gouse III, S.W., Harris, D.B., King Jr, F.G., 2002. Evaluation of fuel cell auxiliary power units for heavy-duty diesel trucks. Transportation Research Part D 7 (4), 303–315.

Chen, S.J., Hwang, C.L., 1992. Fuzzy Multiple Attribute Decision Making: methods and applications. Springer-Verlag, Berlin.

DeLucchi, M.A., 1989. Hydrogen vehicles: an evaluation of fuel storage, performance, safety, environmental impacts, and cost. International Journal of Hydrogen Energy 14 (2), 81–130.

DeLucchi, M.A., Lipman, T.E., 2001. An analysis of the retail and lifecycle cost of battery-powered electric vehicles. Transportation Research Part D 6 (6), 371–404.

DeLucchi, M.A., Murphy, J.J., McCubbin, D.R., 2002. The health and visibility cost of air pollution: a comparison of estimation methods. Journal of Environmental Management 64 (2), 139–152.

Griffith, P., Gleason, G., 1996. Six years of battery-electric bus operation at the Santa Barbara metropolitan Transit District. Proceedings of the 13th Electric Vehicle Symposium in Osaka, Japan.

Harding, G.G., 1999. Electric vehicles in the next millennium. Journal of Power Sources 78 (2), 193–198.

Hwang, C.L., Yoon, K., 1981. Multiple Attribute Decision Making—Methods and Applications. Springer, New York.

Johnsson, B., Ahman, M., 2002. A comparison of technologies for carbon-neutral passenger transport. Transportation Research Part D 7 (3), 175–196.

Kazimi, C., 1997. Evaluating the environmental impact of alternative-fuel vehicles. Journal of Environmental Economics and Management 33 (2), 163–185.

Kempton, W., Kubo, T., 2000. Electric-drive vehicles for peak power in Japan. Energy Policy 28 (1), 9–18.

Maggetto, G., Van Mierlo, J., 2001. Electric vehicles, hybrid electric vehicles and fuel cell electric vehicles: state of the art and perspectives. Annales de Chimie Science des Materiaux 26 (4), 9–26.

Matheny, M.S., Erickson, P.A., Niezrecki, C., Roan, V.P., 2002. Interior and exterior noise emitted by a fuel cell transit bus. Journal of Sound and Vibration 251 (5), 937–943.

McNicol, B.D., Rand, D.A.J., Williams, K.R., 2001. Fuel cells for road transportation purpose—yes or no? Journal of Power Sources 100 (1), 47–59.

Morita, K., 2003. Automotive power source in 21st century. Journal of Society of Automotive Engineers of Japan 24 (1), 3–7.

Moseley, P.T., 1999. High-rate, valve-regulated lead-acid batteries—suitable for hybrid electric vehicles? Journal of Power Sources 84 (2), 237–242.

Nesbitt, K., Sperling, D., 1998. Myths regarding alternative fuel vehicle demand by light-duty vehicle fleets. Transportation Research Part D 3 (4), 259–269.

Opricovic, S., 1998. Multicriteria optimization of civil engineering systems. Faculty of Civil Engineering, Belgrade.

Opricovic, S., Tzeng, G.H., 2002. Multicriteria planning of post-earthquake sustainable reconstruction. Computer-Aided Civil and Infrastructure Engineering 17 (3), 211–220.

Opricovic, S., Tzeng, G.H., 2003. Fuzzy Multicriteria Model for Post-Earthquake Land-Use Planning. Natural Hazards Review 4 (2), 59–64.

Opricovic, S., Tzeng, G.H., 2004. Compromise solution by MCDM methods: a comparative analysis of VIKOR and TOPSIS. European Journal of Operational Research. forthcoming.

Poh, K.L., Ang, B.W., 1999. Transportation fuels and policy for Singapore: an AHP planning approach. Computers and Industrial Engineering 37 (4), 507–525.

Sperling, D., 1995. Future Drive—Electric Vehicles and Sustainable Transportation. Island Press, Washington, DC.

Sperling, D., Setiawan, W., Hungerford, D., 1995. The target market for methanol fuel. Transportation Research Part A 29A (1), 33–45.

Tzeng, G.H., Tsaur, S.H., 1993. Application of multicriteria decision making to old vehicle elimination in Taiwan. Energy and Environment 4 (2), 268–283.

Tzeng, G.H., Tsaur, S.H., 1997. Application of multiple criteria decision making for network improvement. Journal of Advanced Transportation 31 (1), 49–74.

Tzeng, G.H., Shiau, T.A., Lin, C.Y., 1992. Application of multicriteria decision making to the evaluation of a new energy system development in Taiwan. Energy 17 (10), 983–992.

Tzeng, G.H., Shiau, T.A., Teng, J.Y., 1994. Multiobjective decision making approach to energy supply mix decisions in Taiwan. Energy Sources 16 (3), 301–316.

Tzeng, G.H., Teng, M.H., Chen, J.J., Opricovic, S., 2002. Multicriteria selection for a restaurant location in Taipei. International Journal of Hospitality Management 21 (2), 171–187.

Winebrake, J.J., Creswick, B.P., 2003. The future of hydrogen fueling systems for transportation: an application of perspective-based scenario analysis using the analytic hierarchy process. Technological Forcasting and Social Change 70 (2), 359–384.

Zeleny, M., 1982. Multiple Criteria Decision Making. McGraw-Hill, New York.

Zhou, H., Sperling, D., 2001. Traffic emission pollution sampling and analysis on urban streets with high-rising buildings. Transportation Research Part D 6 (4), 269–281.